PHILOSOPHY OF COSMOLOGY 2009

CHARACTERISING SCIENCE AND BEYOND
A conference in honour of George Ellis

John Templeton Foundation

UNIVERSITY OF OXFORD

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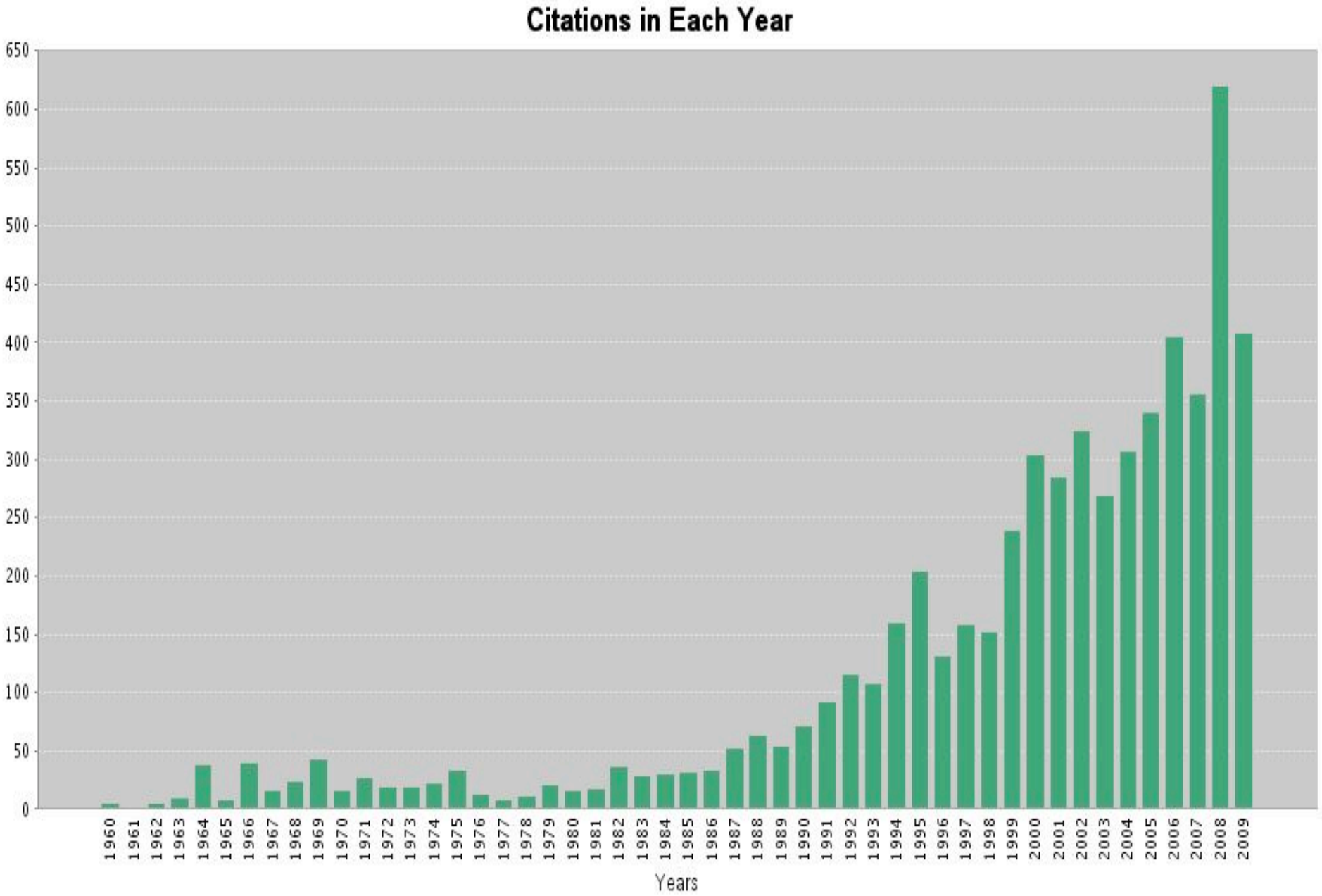
Dates: 20th-22nd September 2009

Arrival pm Sat 19, departure am Wed 23

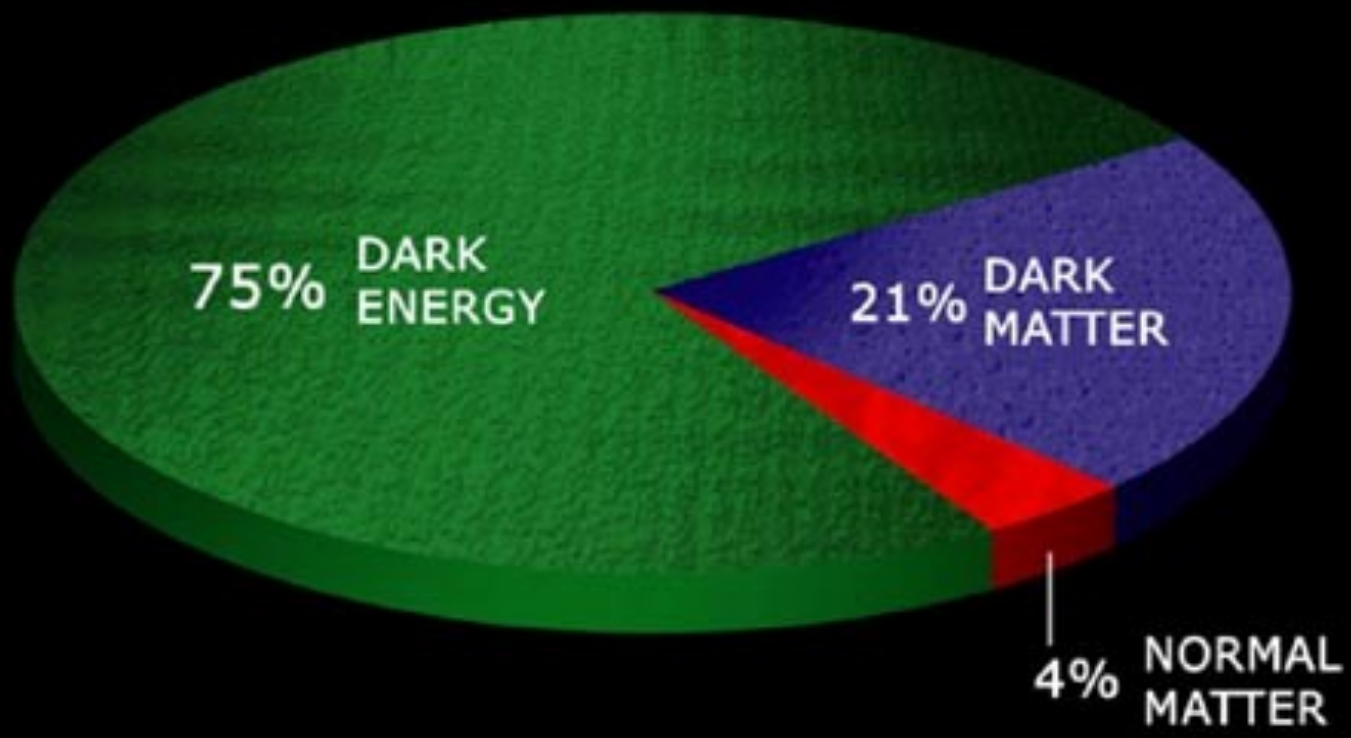
Venue: St Anne's College Oxford

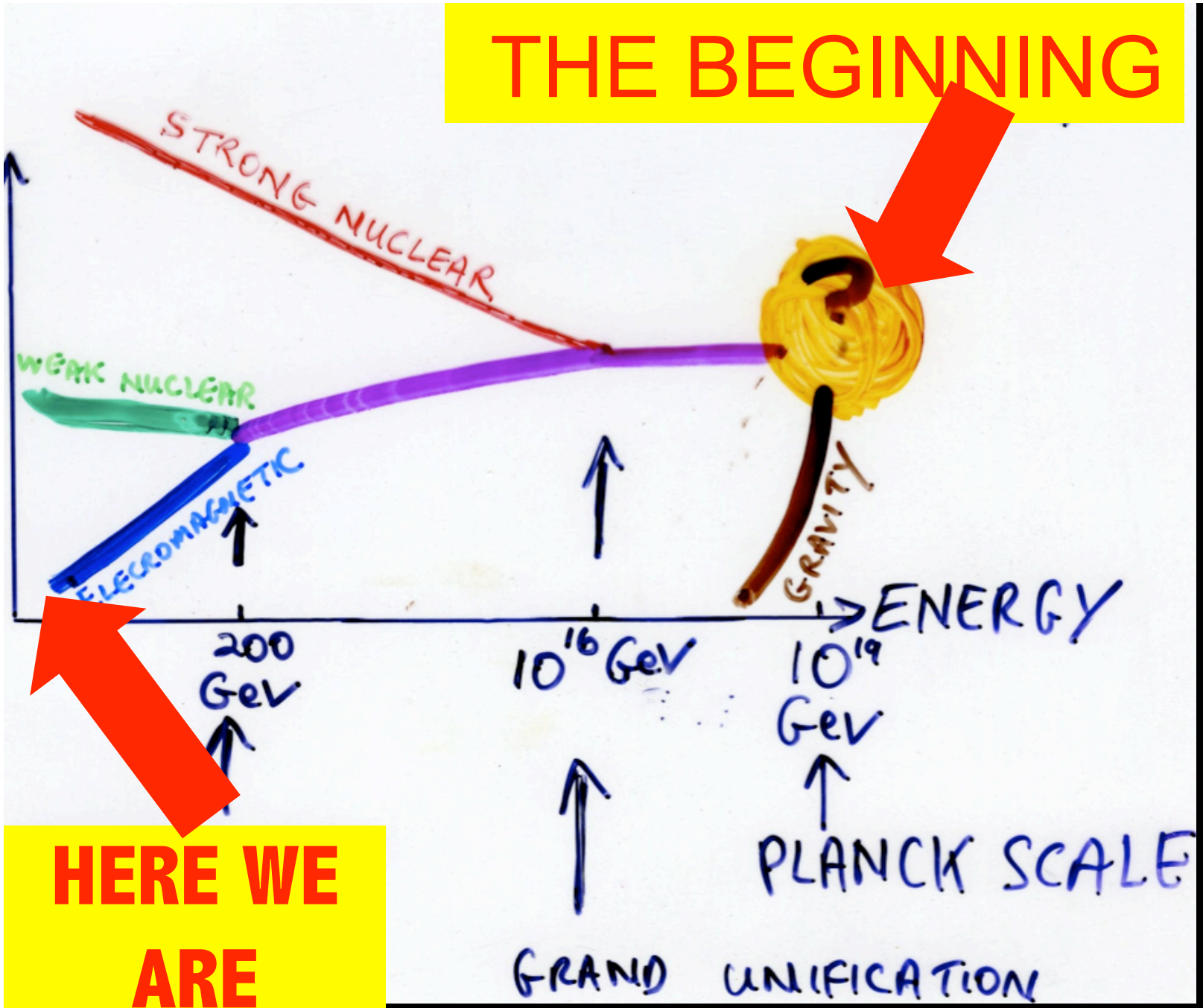
- Scientific Organizing Committee: John Barrow, Jeremy Butterfield, George Ellis, Simon Saunders and Joe Silk
- Local Organizing Committee: Khalil Chamcham, Daniel Darg, Vanessa Ferraro-Wood, Jo Probert, Simon Saunders and Joe Silk

GEORGE ELLIS

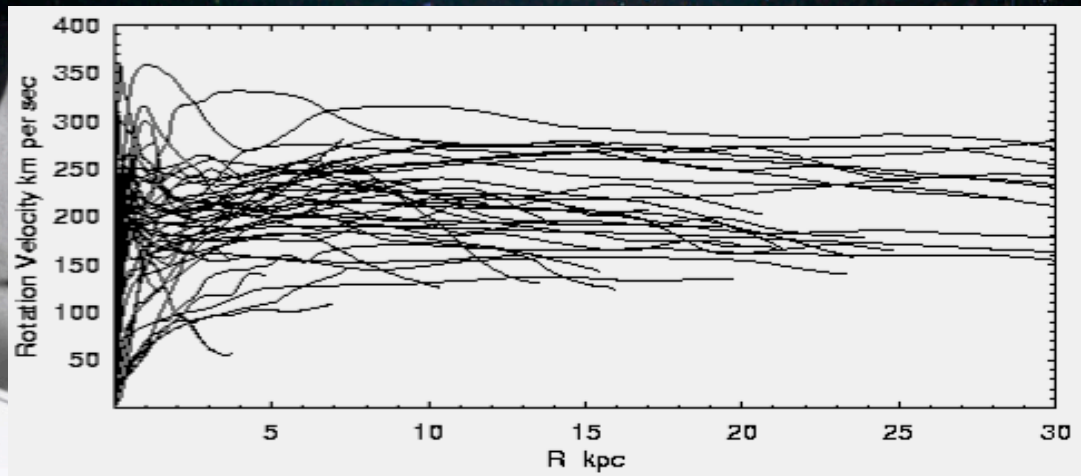


THE STATE OF COSMOLOGY TODAY




THE BEGINNING
STRONG NUCLEAR
WEAK NUCLEAR
ELECTROMAGNETIC
GRAVITY
ENERGY
200 GeV
10^{16} GeV
10^{19} GeV
PLANCK SCALE
GRAND UNIFICATION
HERE WE ARE

Dark Matter in Galaxies



HELVETICA PHYSICA ACTA
Volumen VI Fasciculus Secundus.

3 5

Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

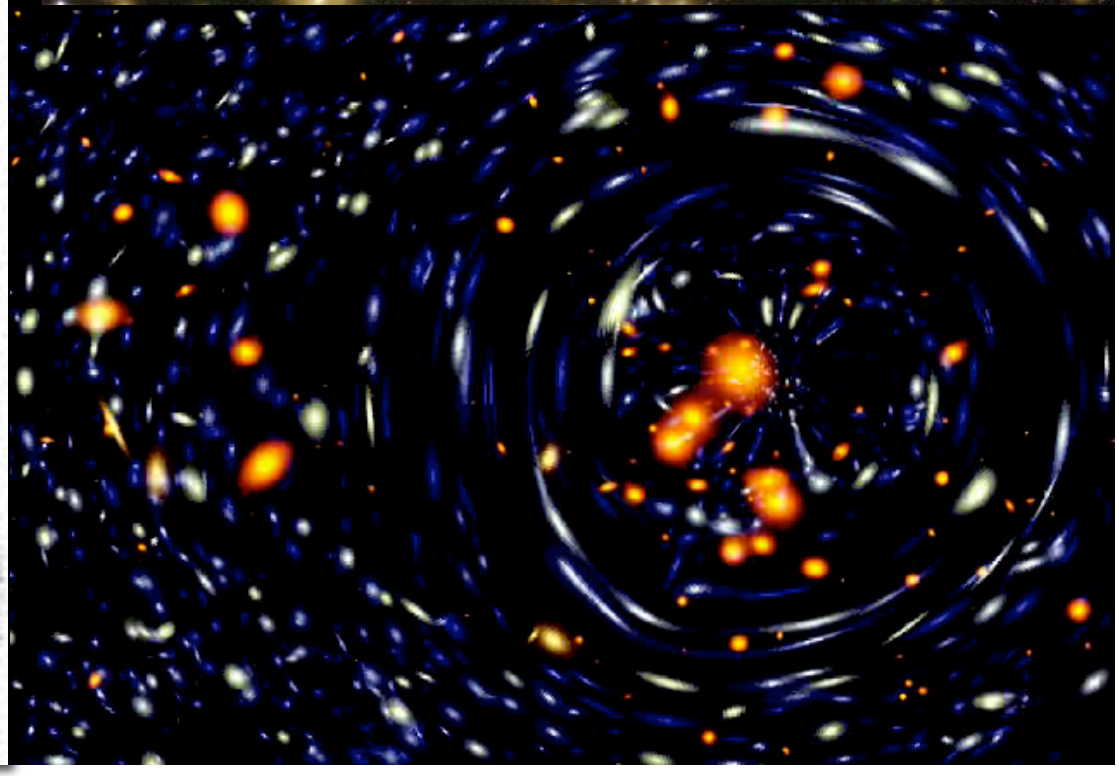
§ 1. Einleitung.

Es ist schon seit langer Zeit bekannt, dass es im Weltraum gewisse Objekte gibt, welche, wenn mit kleinen Teleskopen beobachtet, als stark verschwommene, selbstleuchtende Flecke erscheinen. Diese Objekte besitzen verschiedenartige Strukturen. Oft sind sie kugelförmig, oft elliptisch, und viele unter ihnen haben

m, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls ch dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

2. Man kann auch annehmen, dass das Comasystem sich nicht im stationären Gleichgewicht befindet, sondern dass die ganze verfügbare potentielle Energie als kinetische Energie er-

Dark Matter in Galaxy Clusters



Dark matter: baryonic

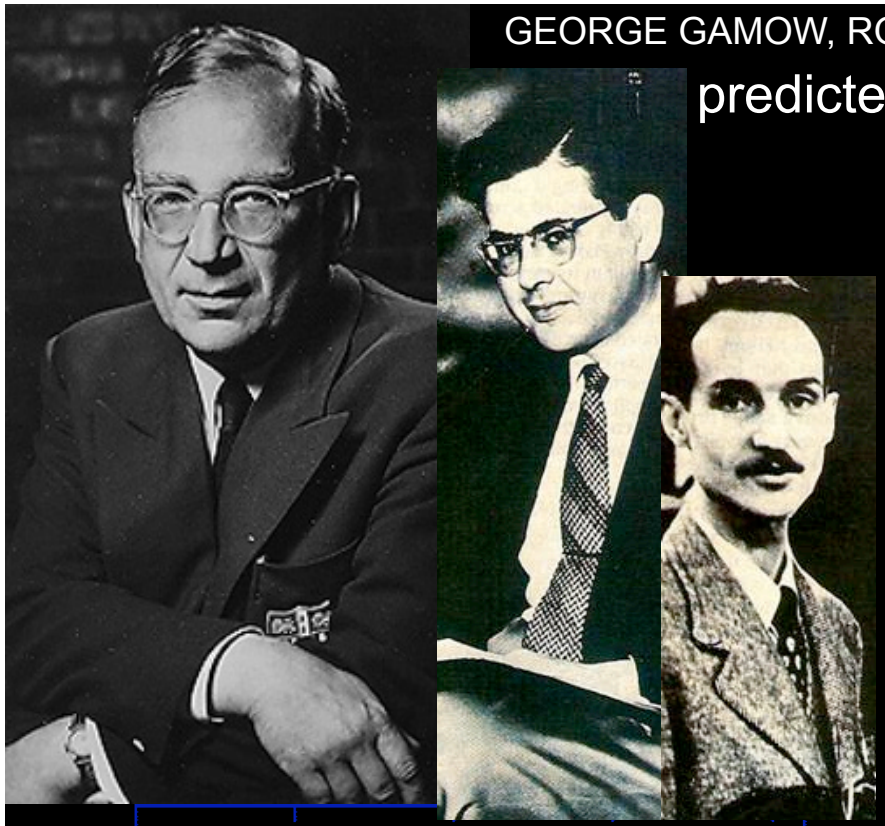
Canberra Times

April 1990

AS the cerebral discussions on the composition of the universe continue among the world's academics, Professor J. Silk, from the Departments of Astronomy and Physics at the University of California arrives at the ANU to deliver a recitation on Baryonic Dark Matter, summarised in an advance notice thus: "At least 90 per cent of the mass of the university is in the form of non-luminous matter." Rumours that a class defamation action is pending are as yet unsubstan-

GEORGE GAMOW, ROBERT HERMAN, RALPH ALPHER

predicted fossil radiation in 1949

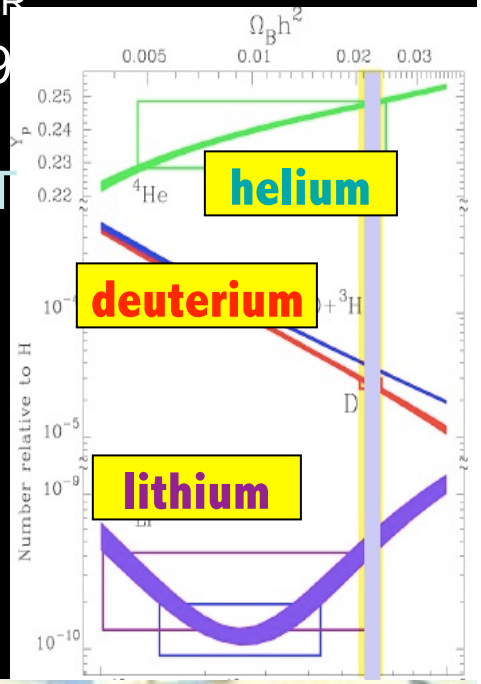


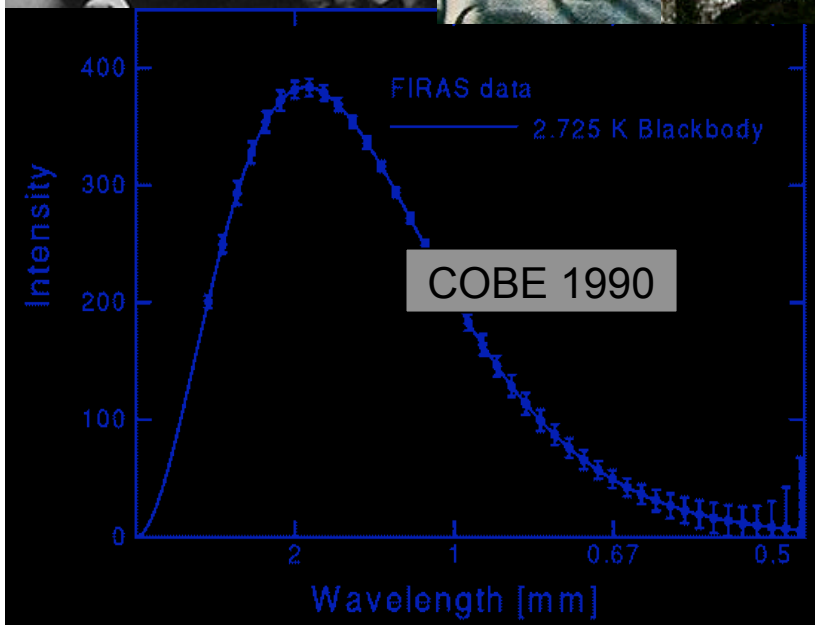
THE MATTER BUDGET

Ω_b=0.03

Ω_*=0.005

Ω_{dm}=0.2





RELIC RADIATION DISCOVERED BY ARNO PENZIAS AND ROBERT WILSON IN 1964

90% OF THE DARK MATTER IS NONBARYONIC

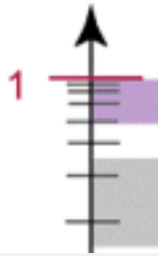
Dark matter: neutrinos

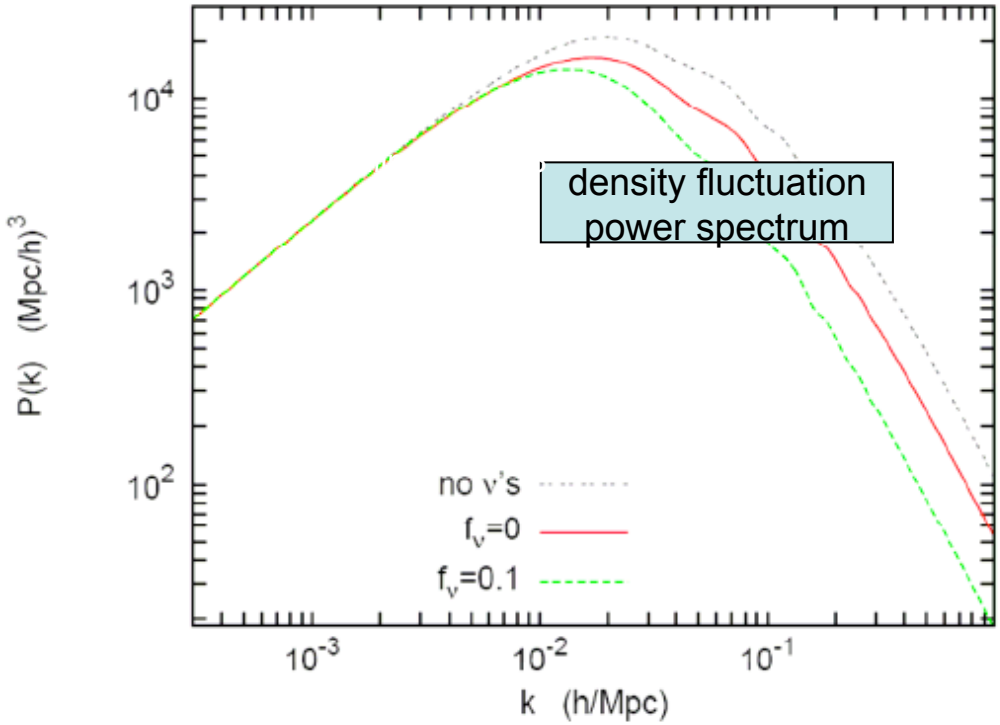
NEUTRINO DARK MAT

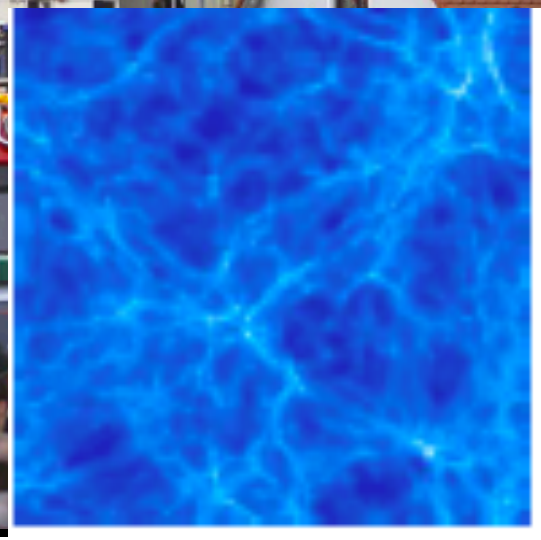
primordial neutrinos as hot dark matter

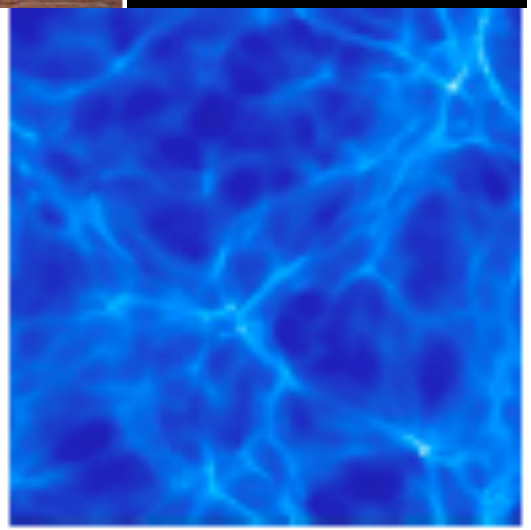
$\Omega_\nu h^2 = \Sigma m_\nu / 92$ eV

Hubble parameter h= 0.65 (65 km/s/Mpc)





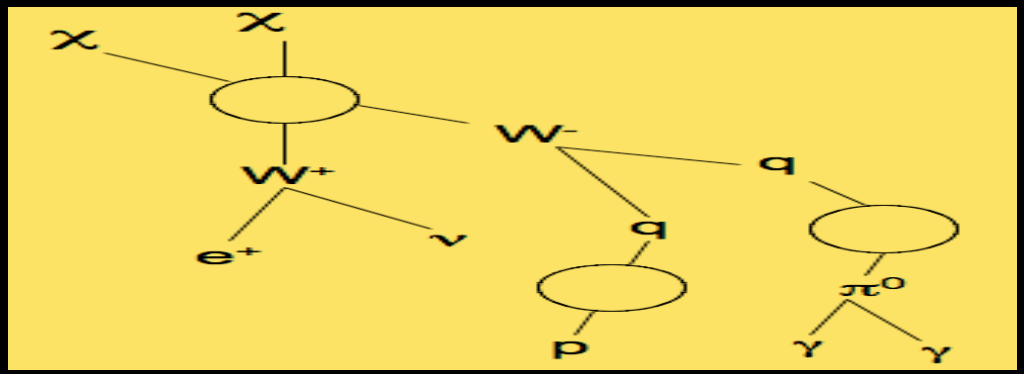




Dark matter: neutralinos

NEUTRALINO DARK MATTER

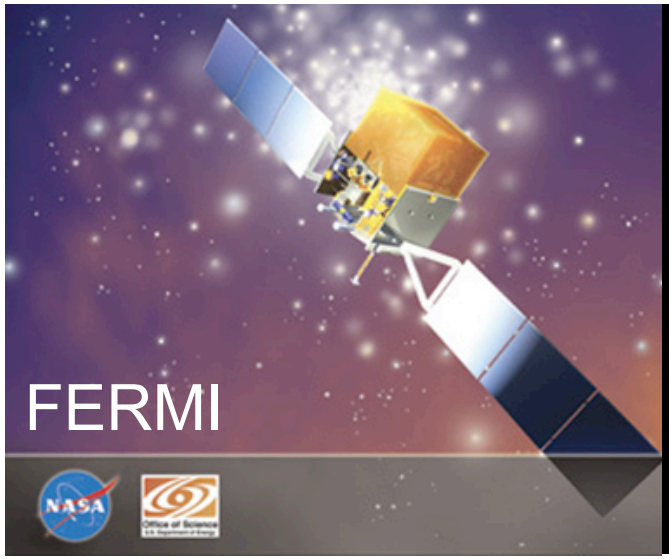
DETECTION IN SPACE OR DEEP UNDERGROUND OFFERS STRATEGY TO PROBE MASS RANGE THAT COMPLEMENTS ANY FUTURE COLLIDERS



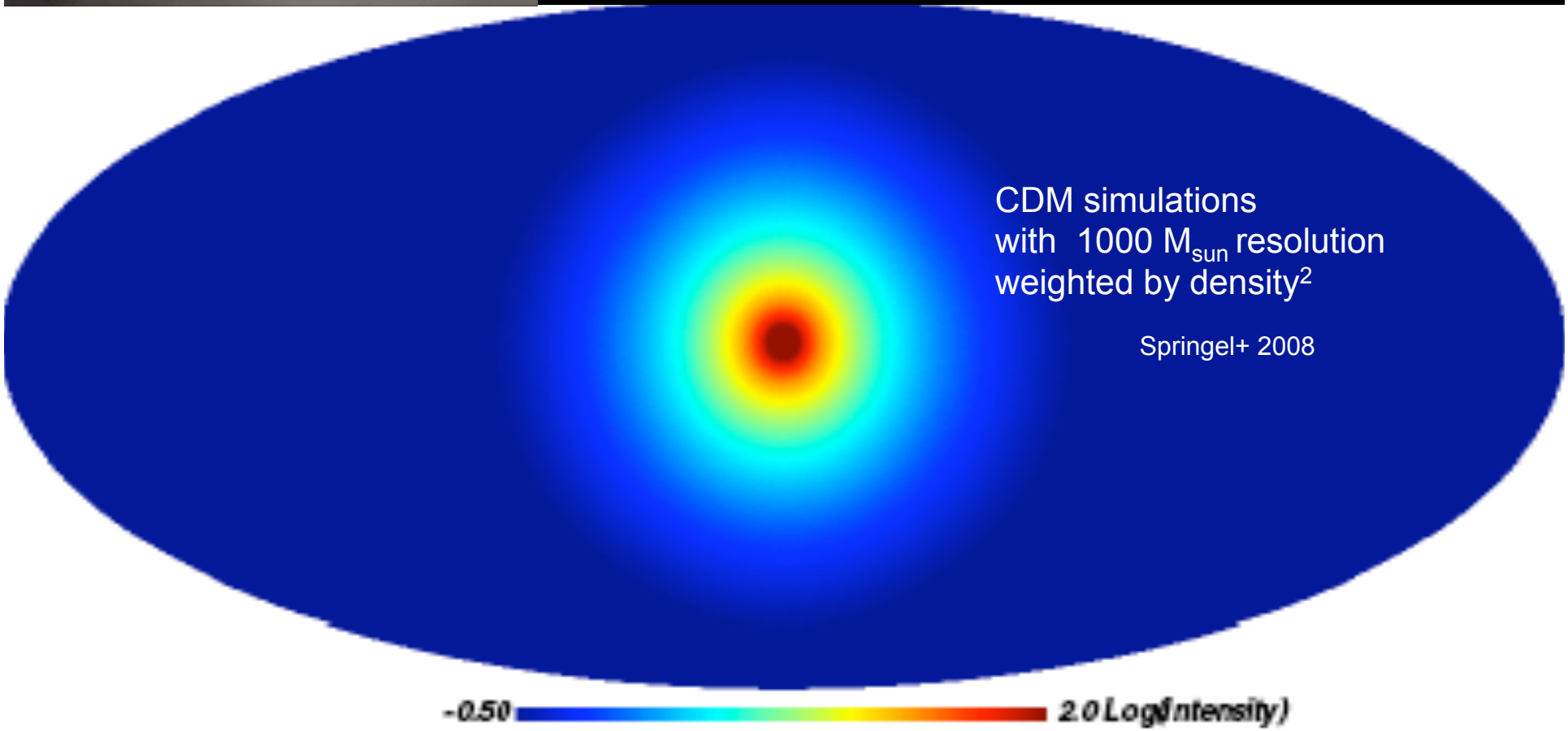
~10^{39} GeV/s in total annihilation power in energetic gamma rays, e+ , pbar , ν

Dark matter detection

The gamma ray sky may be glowing with
dark matter annihilations, towards the inner galaxy



The gamma ray sky



CDM simulations
with 1000 M_{sun} resolution
weighted by density^2

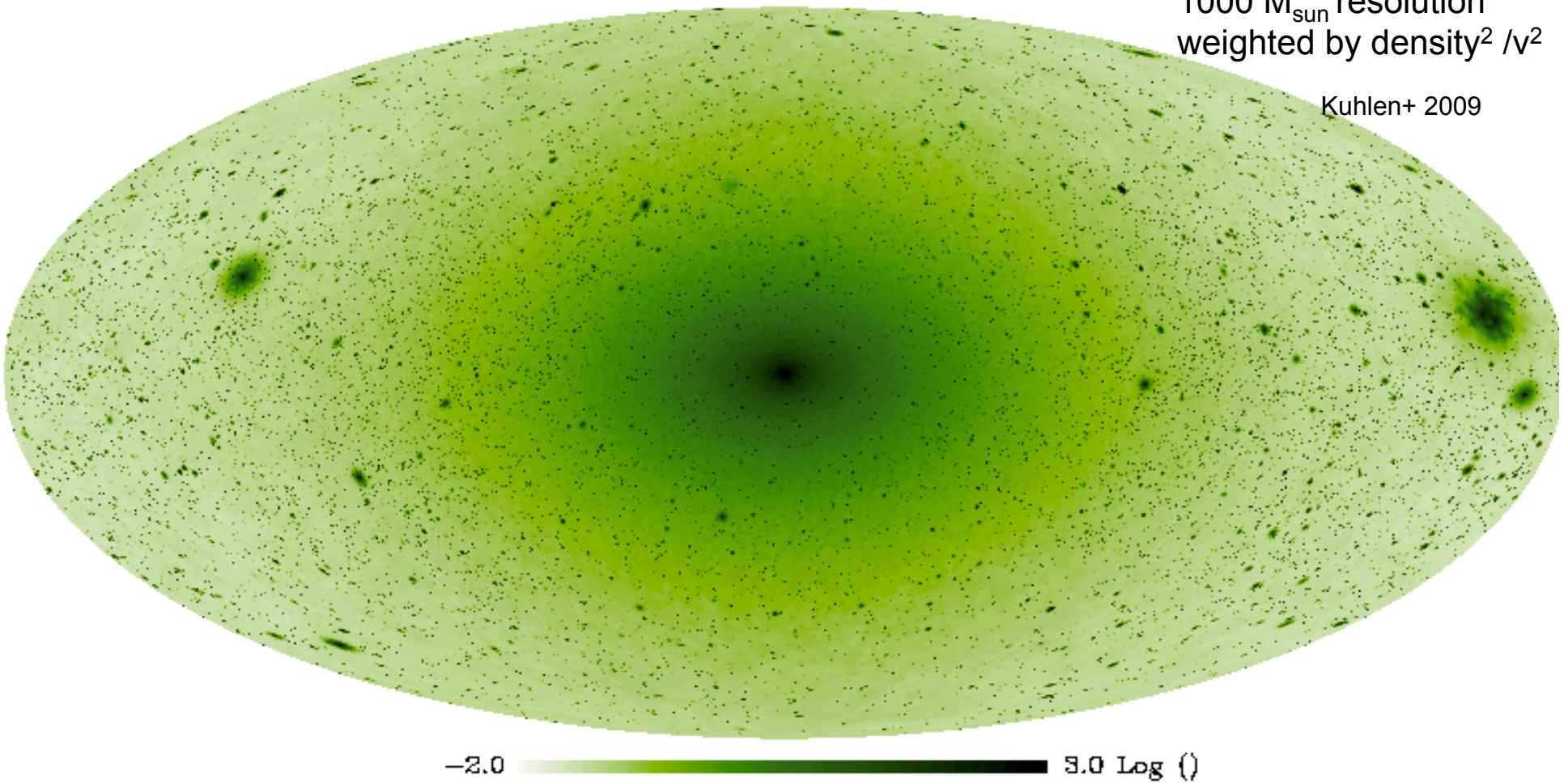
Springel+ 2008

The gamma ray sky (ctd)

[redacted]

CDM simulations with
1000 M_{sun} resolution
weighted by density^2 /v^2

Kuhlen+ 2009



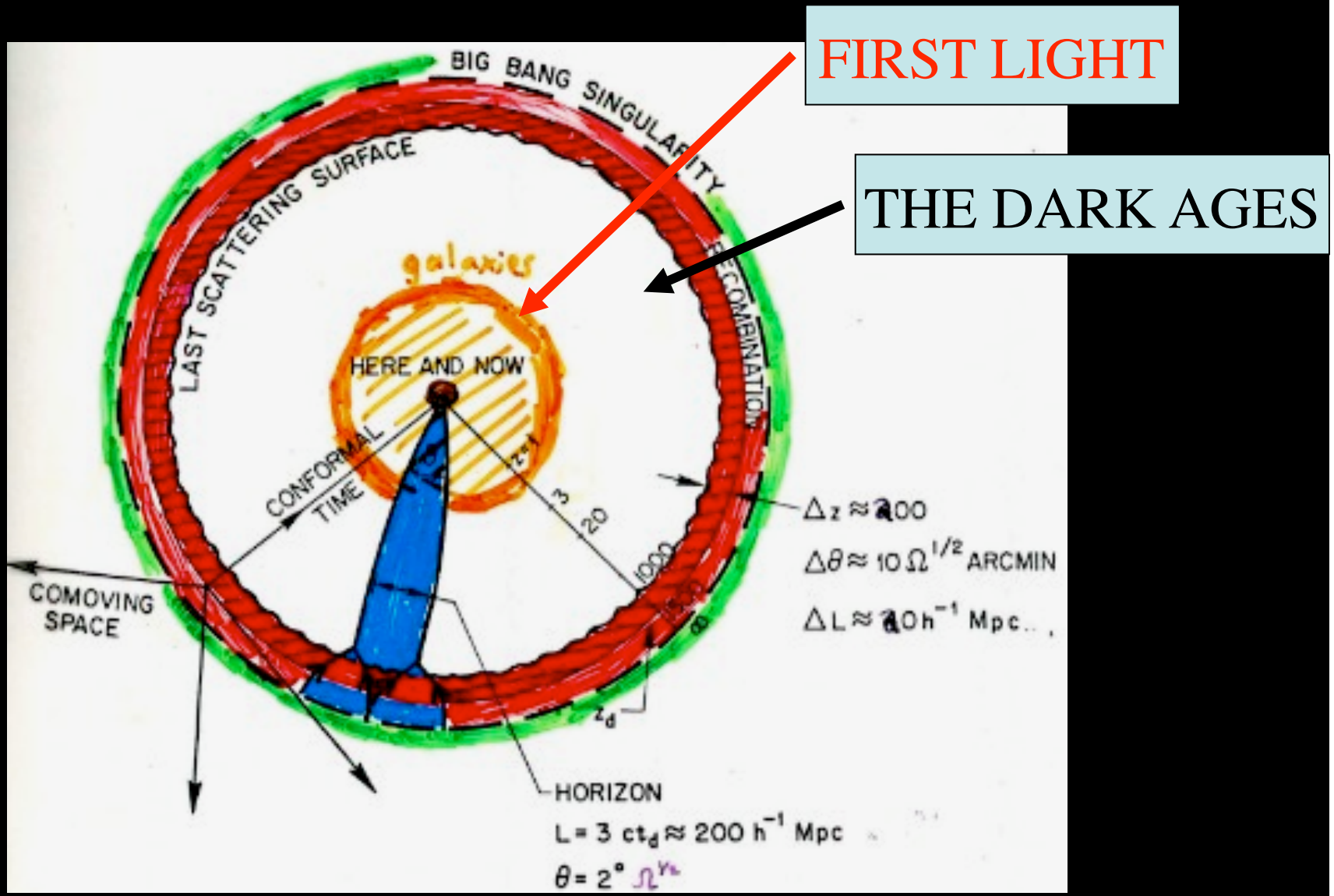
CMB

Cosmic microwave background

Predictions of the Big Bang Theory

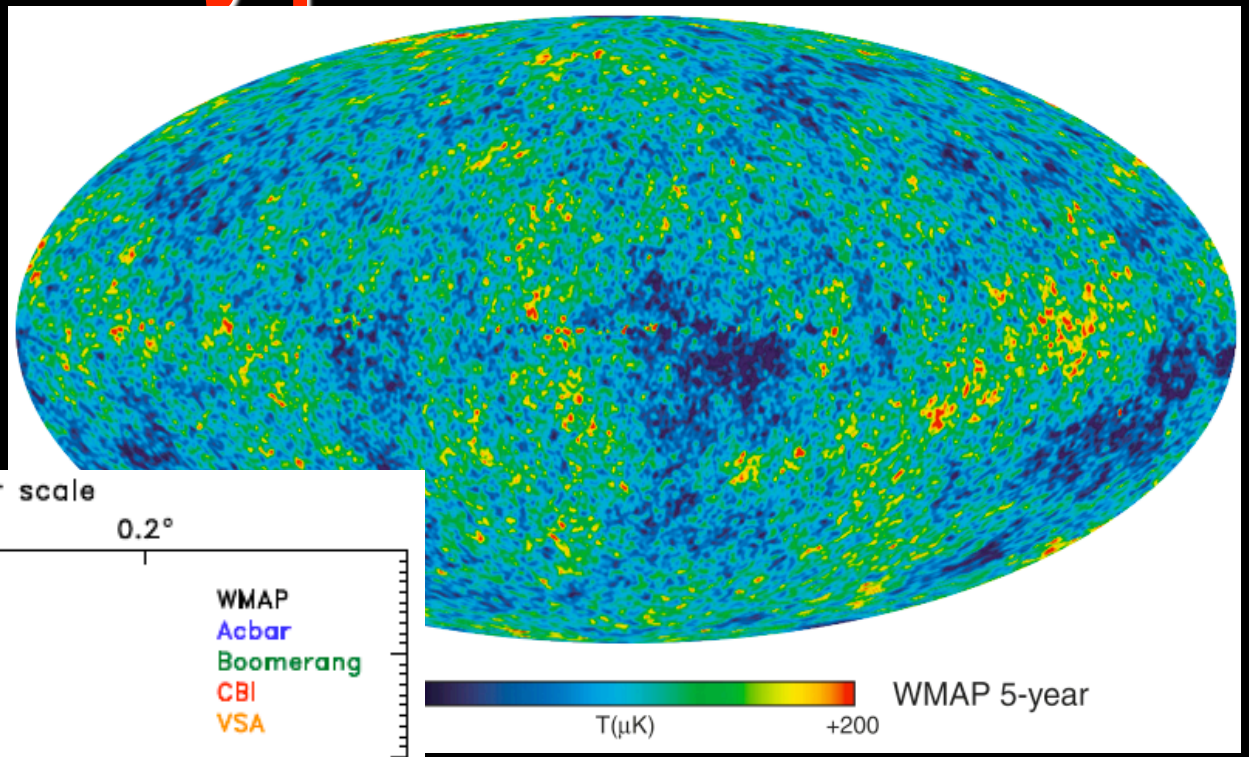
- Expansion
- Light element synthesis
- Fossil thermal radiation
- Density fluctuations

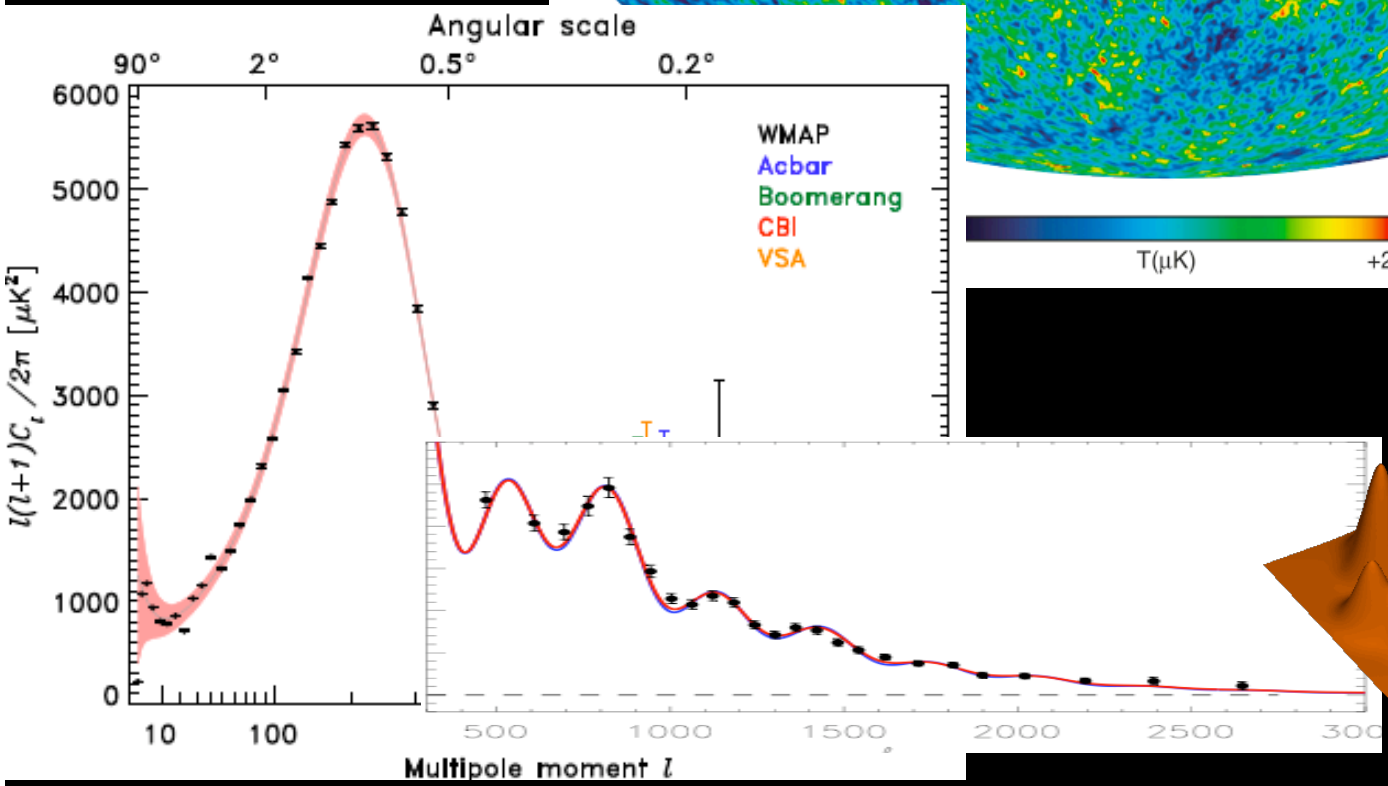
A SPACE-TIME DIAGRAM OF THE UNIVERSE

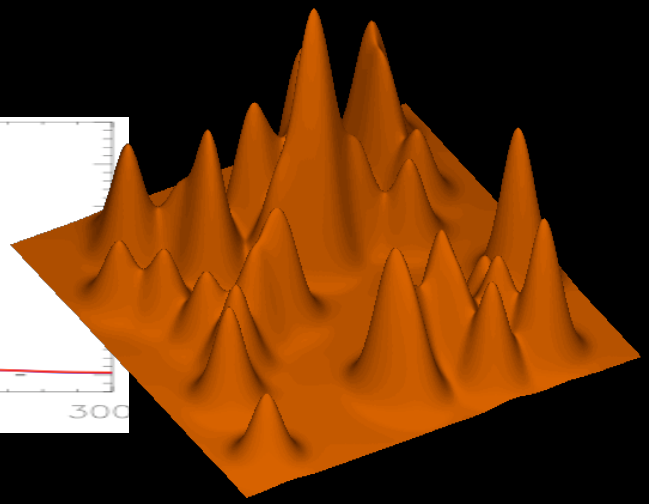


ON ANGULAR SCALES ABOVE A DEGREE, WE ARE VIEWING QUANTUM FLUCTUATIONS IN THE SKY!

CMB may probe inflation







Inflation theory predicts a background of gravity waves and logarithmic correction to scale invariance $\delta n \sim -0.003$

Some day we may measure tensor/scalar ratio and verify inflation…but there is no guarantee: indeed some inflation models predict unmeasurably small gravity wave background

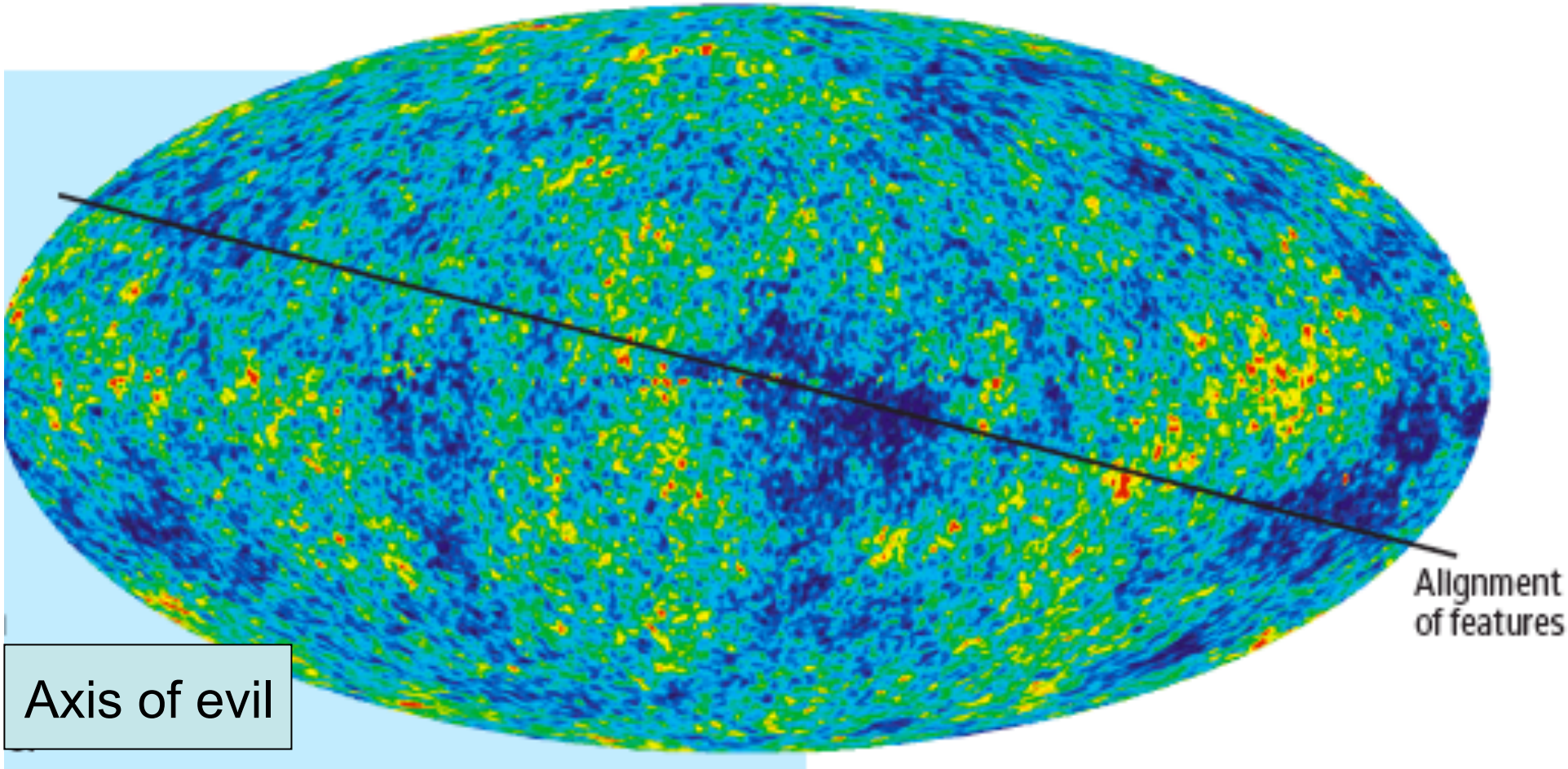
deviations from scale-invariant density fluctuation spectrum probe inflation

string theory can lead to inflation…but requires fine tuning

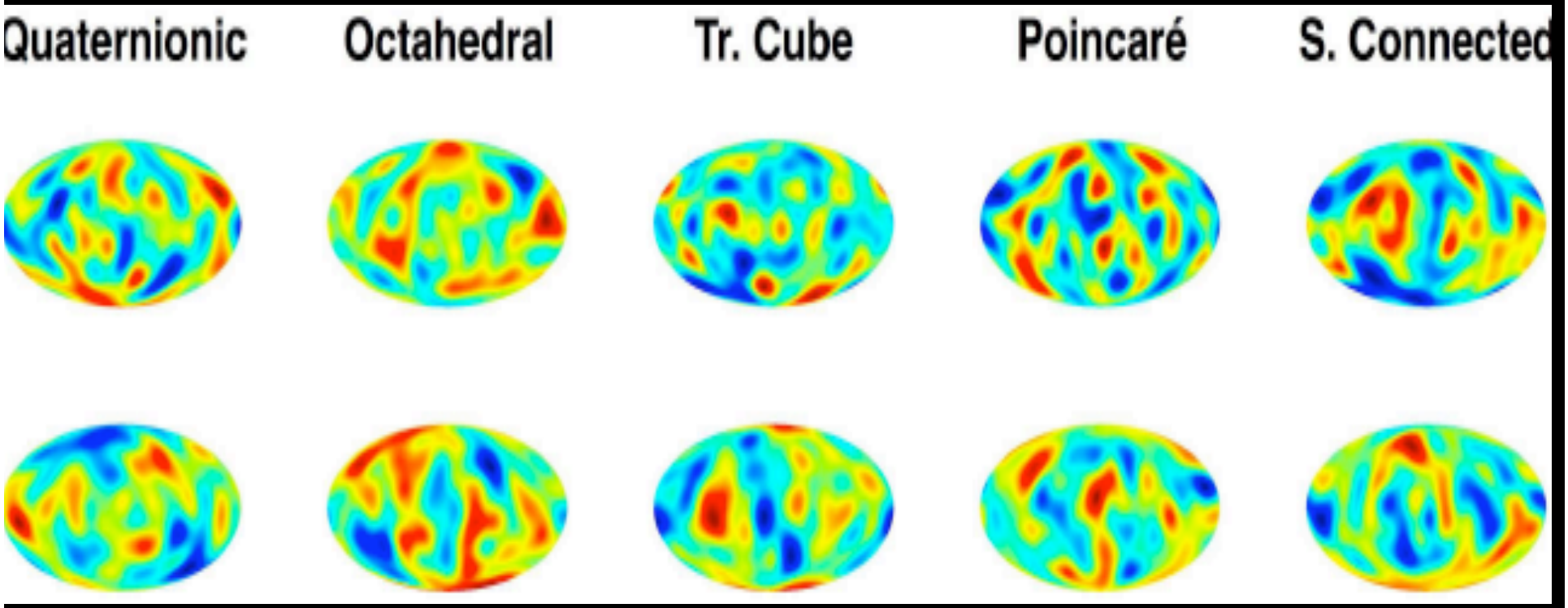
Perhaps the fine tuning was imperfect

Eg: an anisotropic universe is more generic…..

CMB



Non-trivial topologies



Niarchou & Jaffe 2007

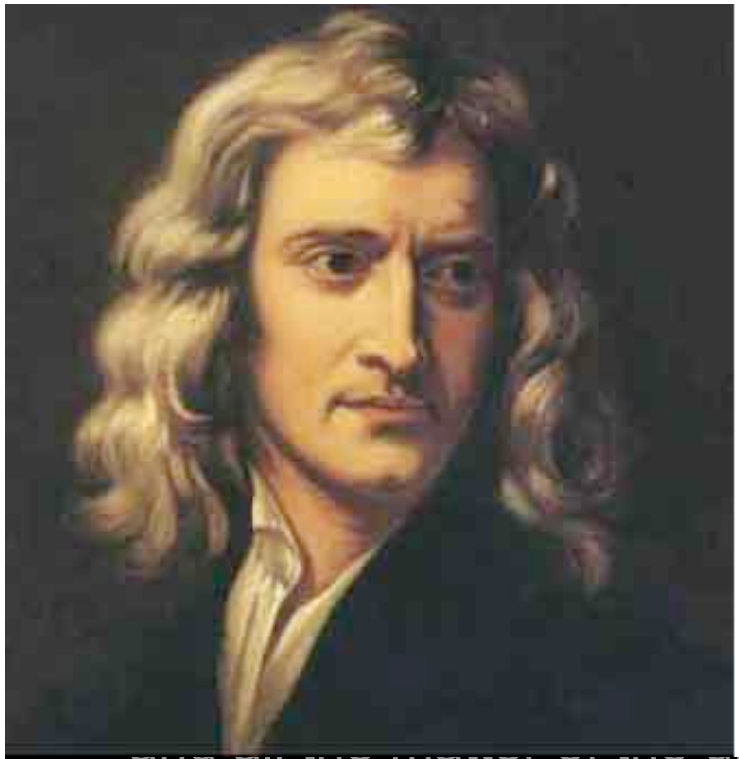
We have no prediction for the topology of the universe

ONE OF EUCLID'S EARLIER PROPOSITIONS.

Predictions of the Big Bang Theory

- Expansion
- Light element synthesis
- Fossil thermal radiation
- Density fluctuations
- Hierarchical structure formation

structure formation



Isaac Newton 1643-1727

s to me that if the matter of our sun and planets
and all the matter of the universe were evenly scattered throughout all the heavens,and every particle had an innate gravity toward all the rest, and the whole space throughout which this matter was scattered was but finite, the matter on the outside of this space would, by its gravity, tend toward all the matter on the inside and, by consequence, fall down into the middle of the whole space and there compose one great spherical mass. But if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space.And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.

December 10, 1692

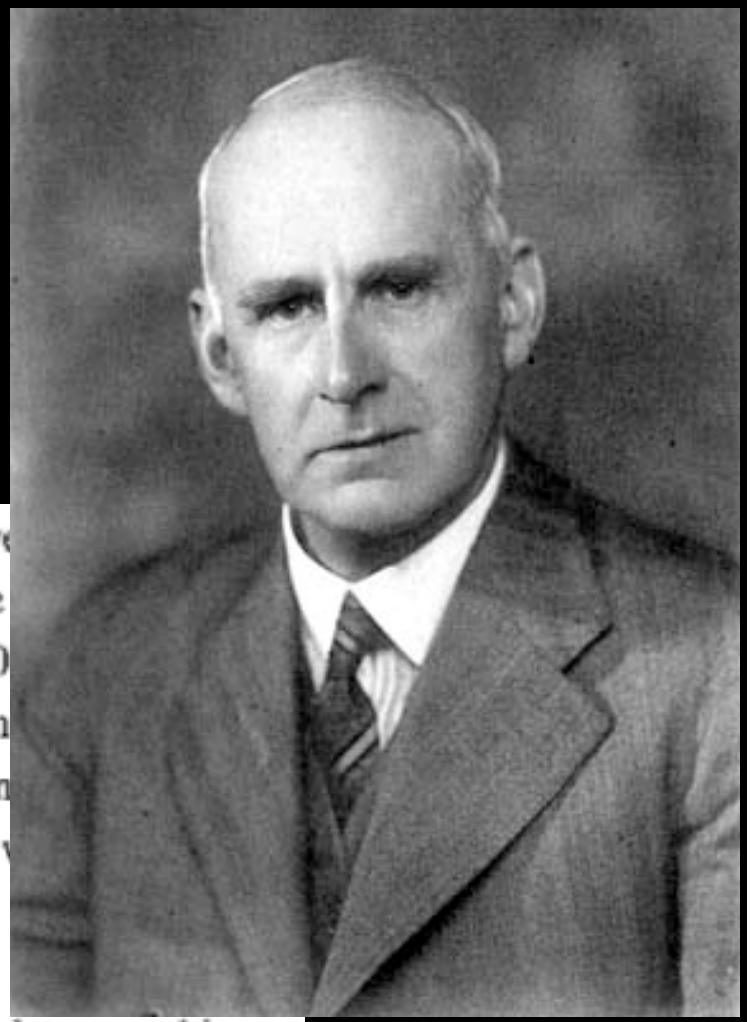
James Jeans (1877-1946)

"We have found that as Newton first conjectured, a chaotic mass of gas of approximately uniform density and of very great extent would be dynamically unstable: nuclei would tend to form in it, around which the whole matter would eventually condense. All celestial bodies originate by a process of fragmentation of nebulae out of chaos, of stars out of nebulae, of planets out of stars and satellites out of planets."

“From the intrinsic evidence of his creation, the Great Architect of the Universe now begins to appear as a pure mathematician.’’

imagine a physicist calculating on a cloud-bound planet and ending with the dramatic conclusion, "What 'happens' is the stars."

Arthur Eddington (1882-1946)

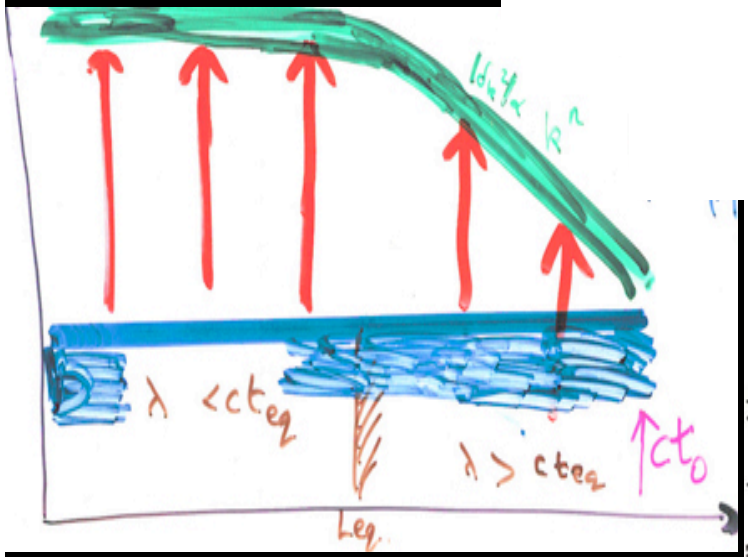


"We can imagine a physicist on a cloud-bound planet who has neve
the stars calculating the ratio of radiation pressure to gas pressure
globes of gas of various sizes, starting, say, with a globe of mass 10
gm., 1000 gm., and so on, so that his *n*th globe contains 10^n gm
as a tussle between matter and aether (gas pressure and radiation
contest is overwhelmingly one-sided except between Nos. 33-35, v
expect something interesting to happen.
What 'happens' is the stars.
We draw aside the veil of cloud beneath which our physicist has been working and let him look up at the sky. There he will find a thousand million globes of gas nearly all of mass between his 33rd and 35th globes – that is to say, between $\frac{1}{2}$ and 50 times the sun's mass."

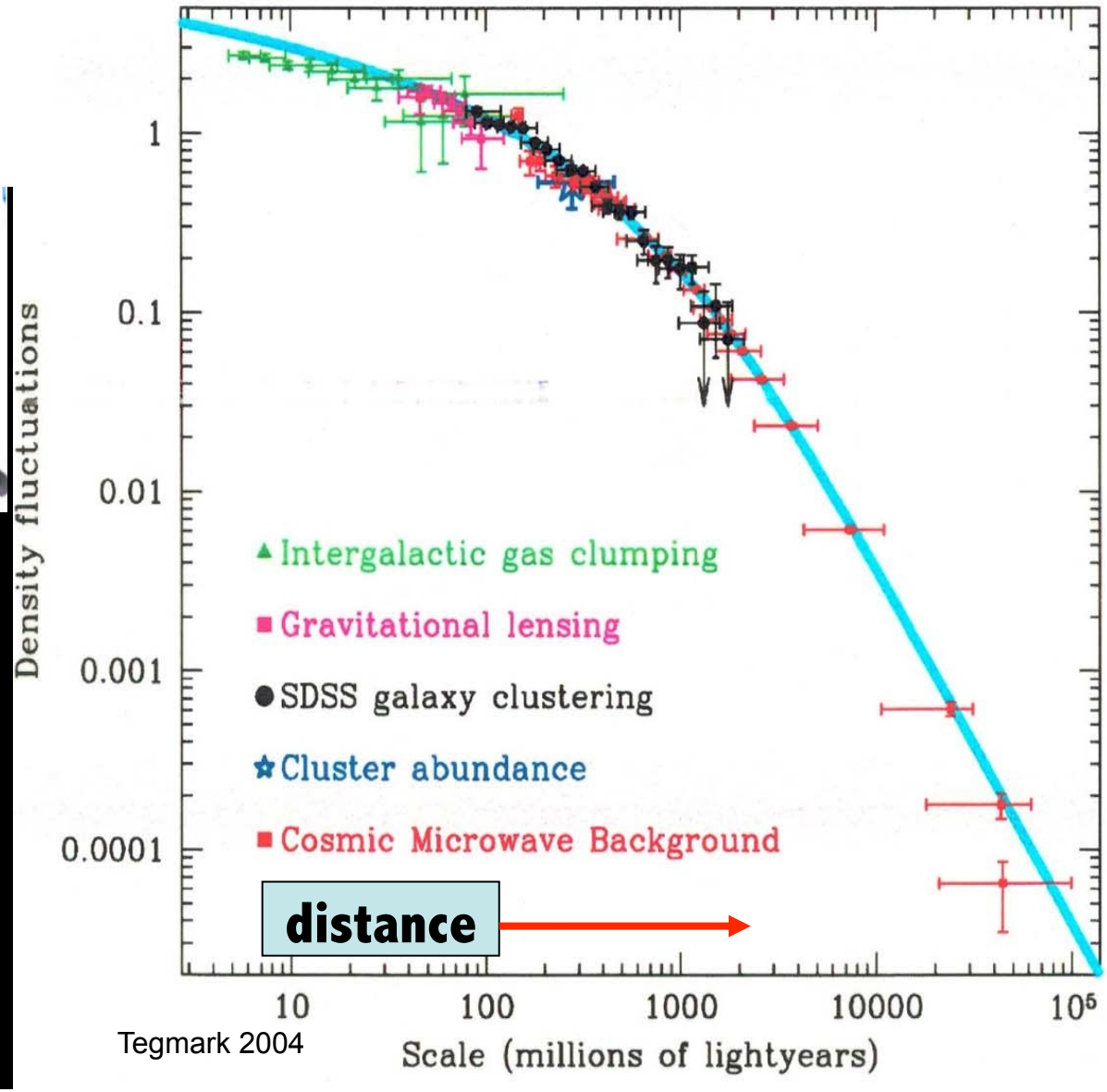
Sir Arthur S. Eddington: The Internal Constitution of the Stars, 1926

PRIMORDIAL DENSITY FLUCTUATION SPECTRUM

Cosmic microwave background and large-scale structure constraints overlap

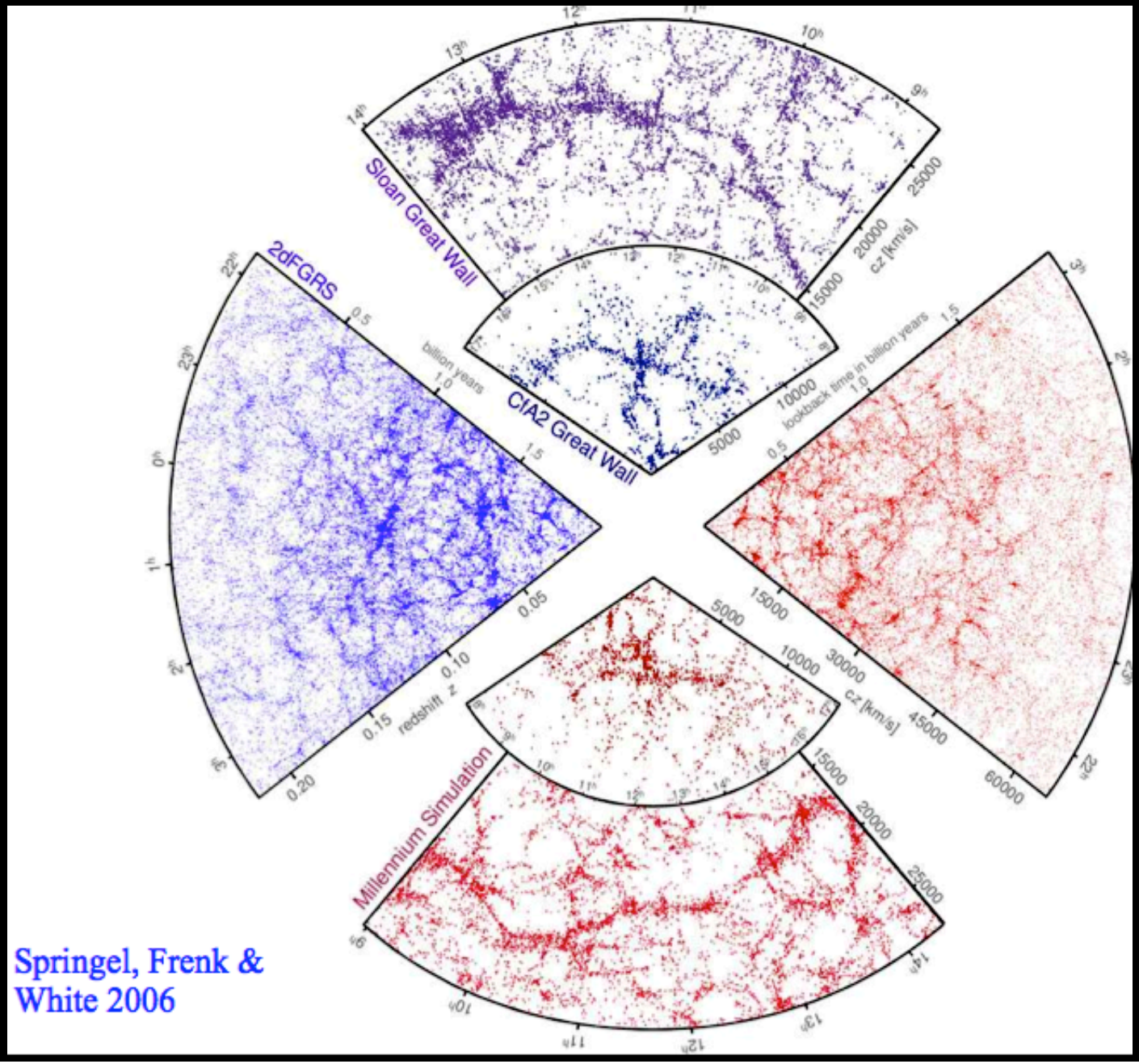


inflation prediction



Tegmark 2004

Dark Matter is Cold



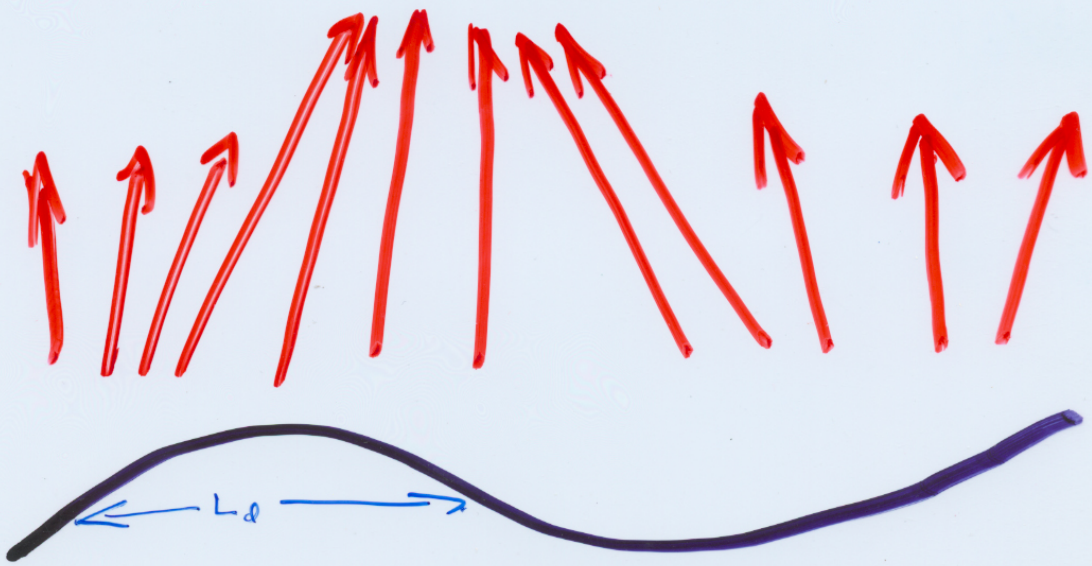
Springel, Frenk & White 2006

galaxy formation

Zel'dovich pancake

1-D solution (Zel'dovich)

$$z(t, z_i) = a(t)\left[z_i - \frac{a(t)}{a_p}\frac{L_d}{\pi}\sin\left(\pi\frac{z_i}{L_d}\right)\right]$$

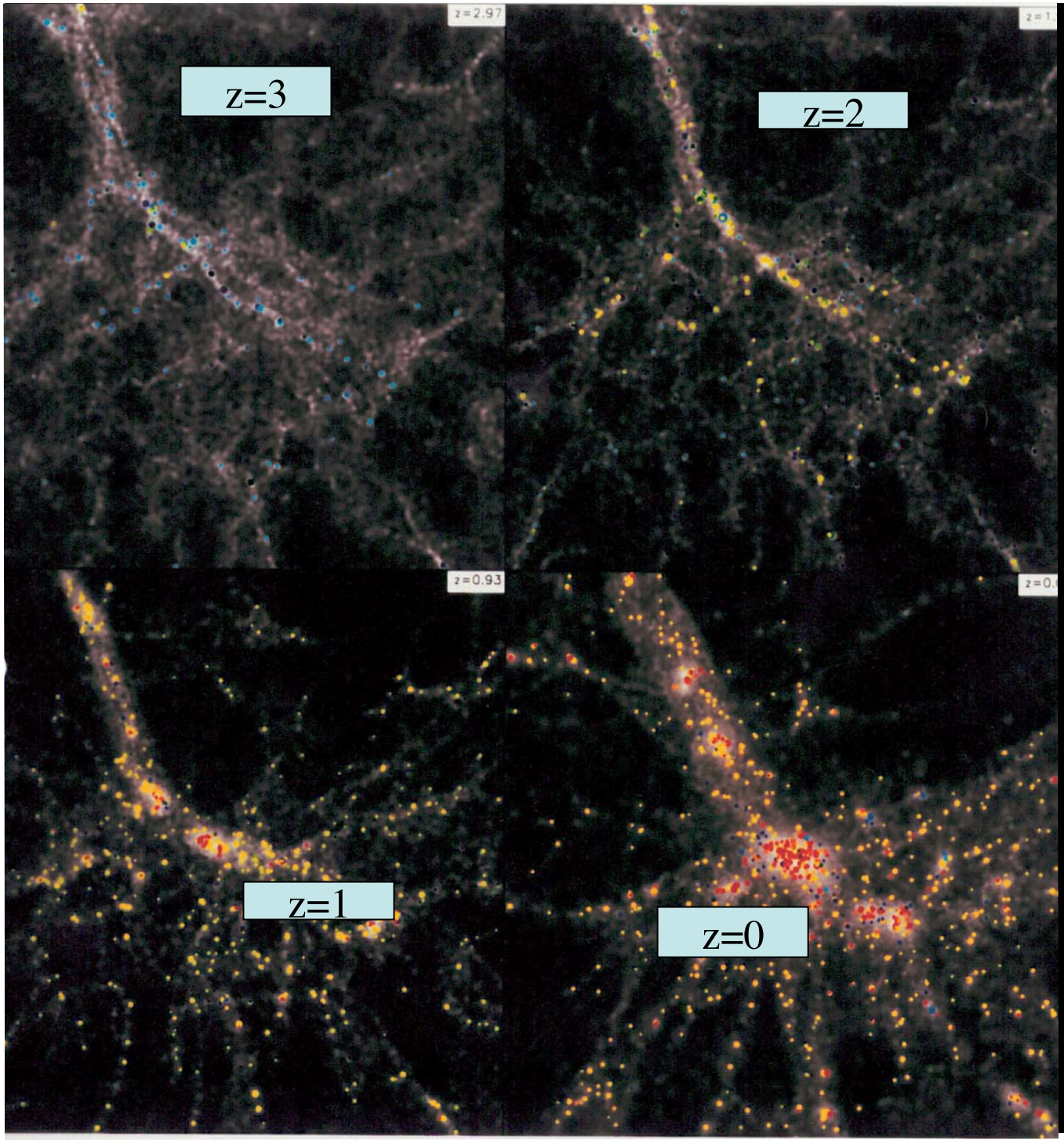


velocity perturbation

1-D trajectories

Caustic develops

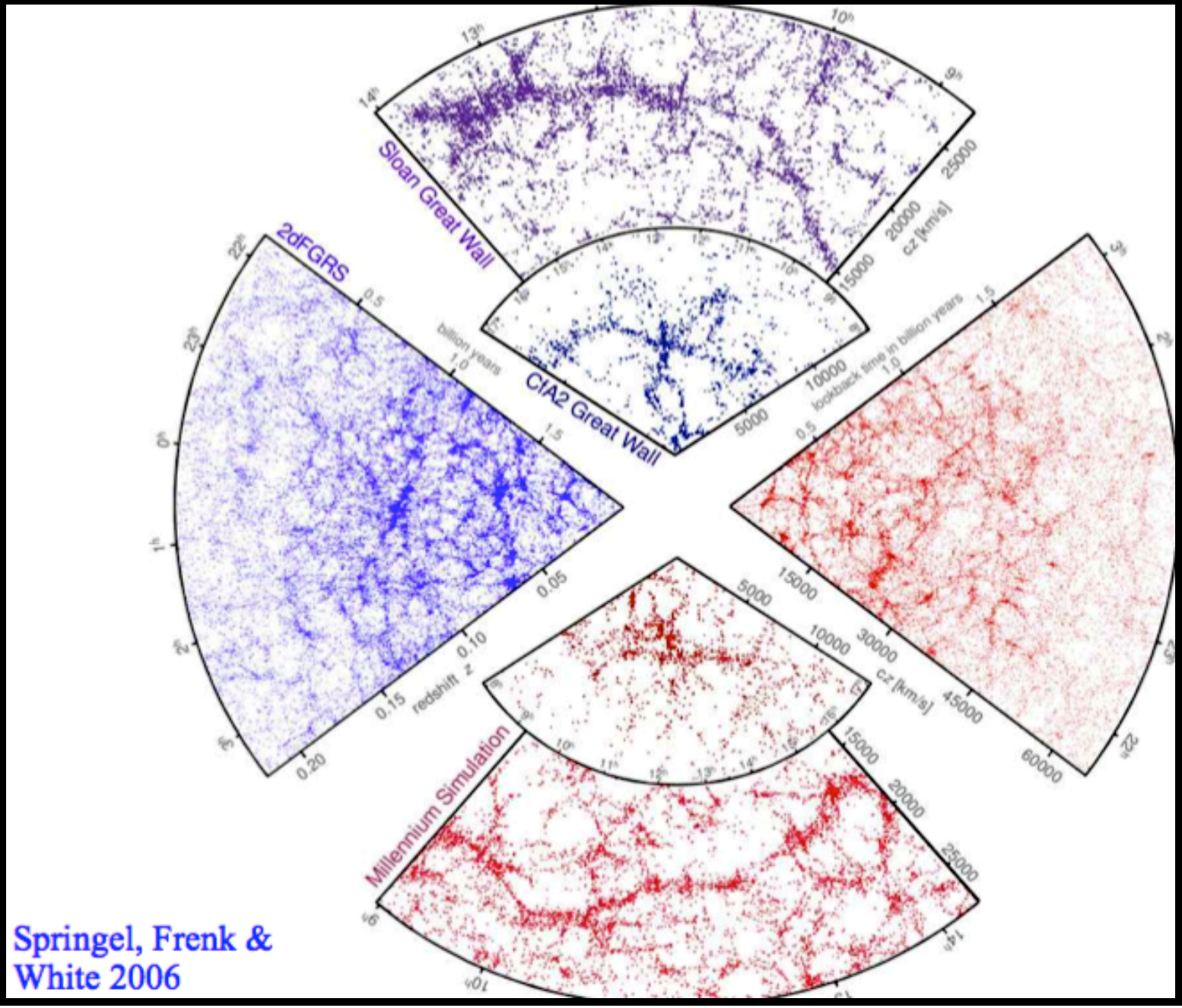
$$\rho = \frac{\rho_0}{1 - \frac{a(t)}{a_p}\cos\frac{\pi z_i}{L_d}}$$



Galaxies form
early in rare peaks

G, Kauffmann…..

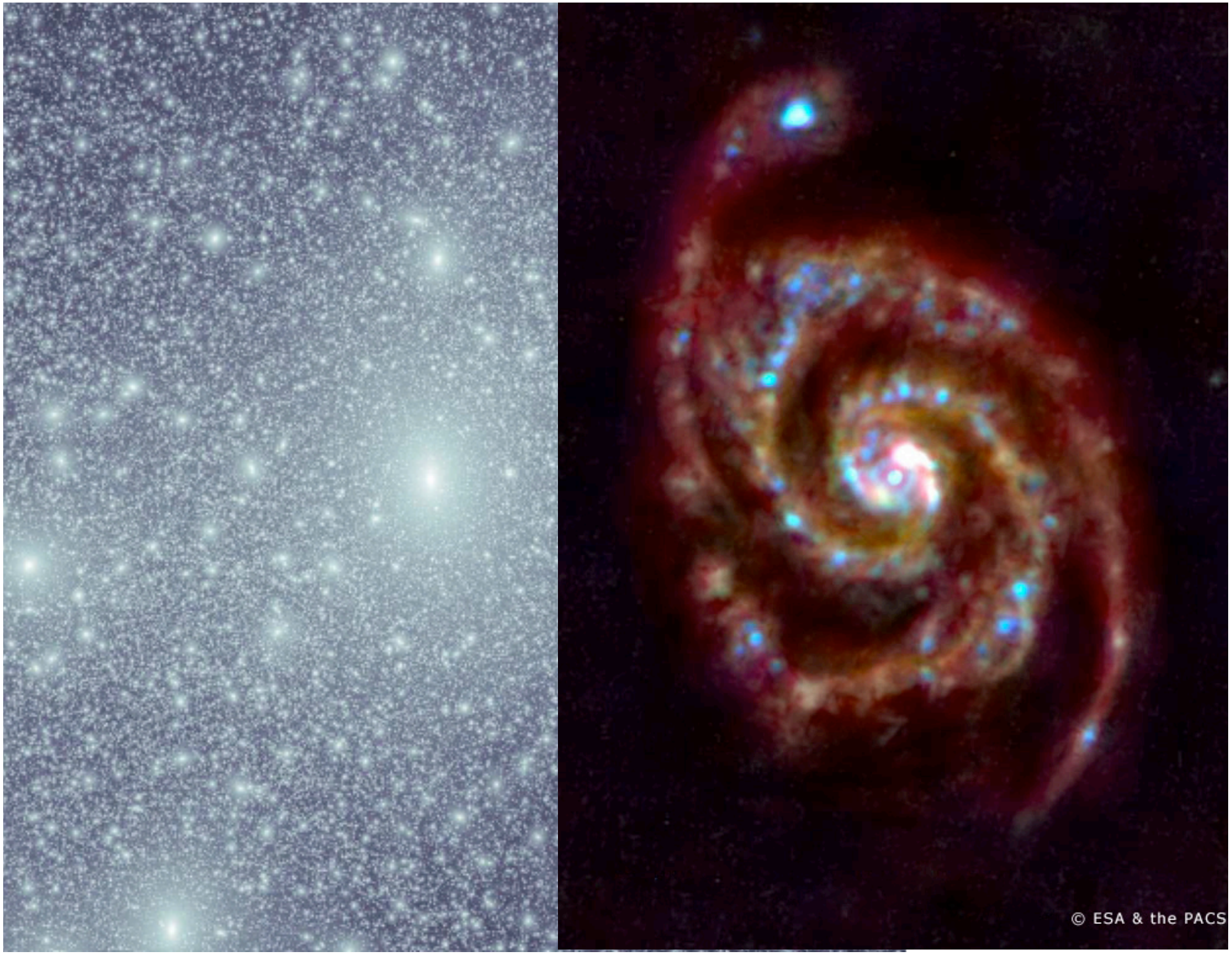
Virtual universe Observed universe



Springel, Frenk & White 2006

Simulation

Galaxy



"I see here that the universe is now thought to be full of inexplicably dense clumps."

not rocket science, it's only stars that are needed

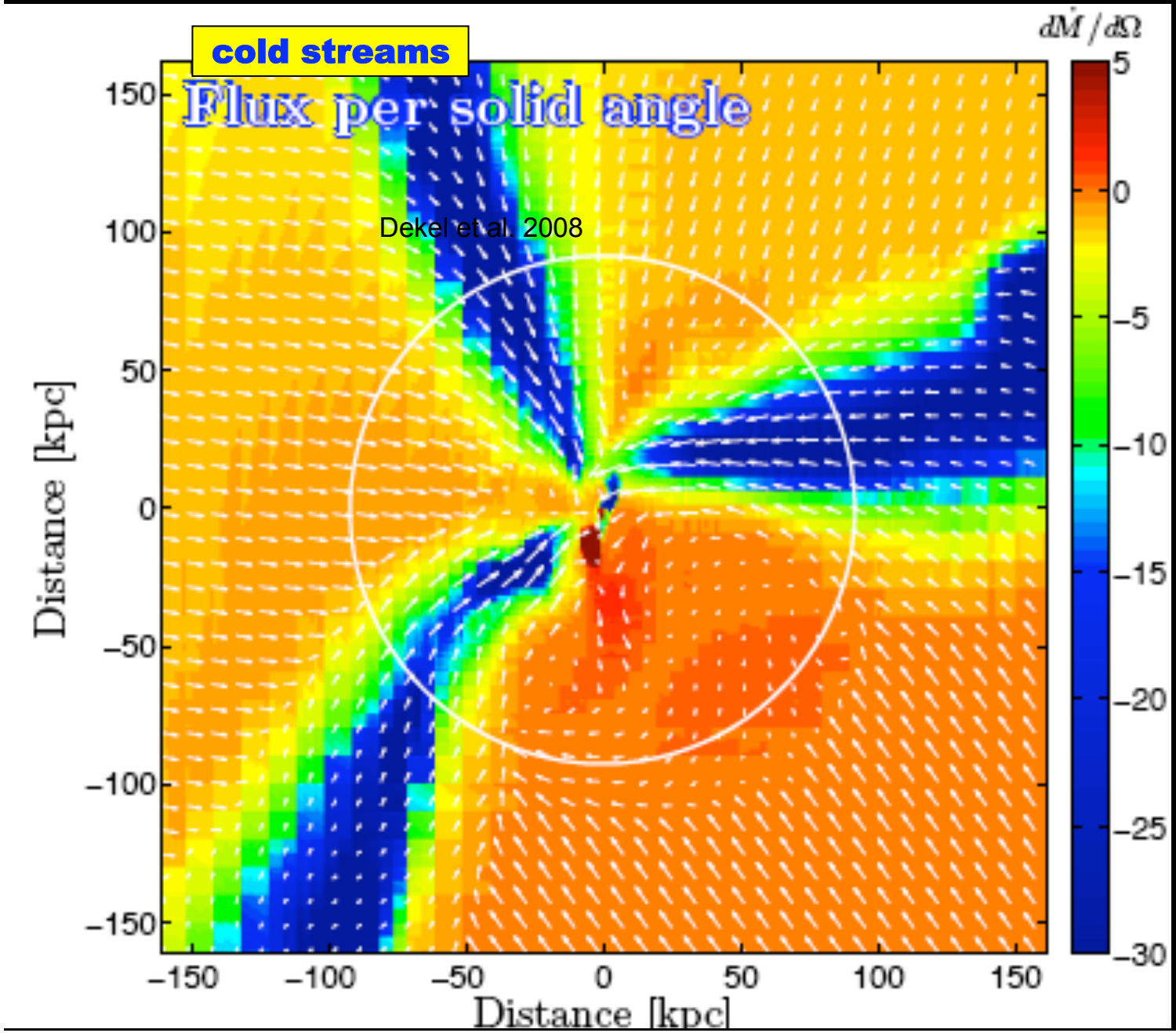
N body simulation

gas dissipation

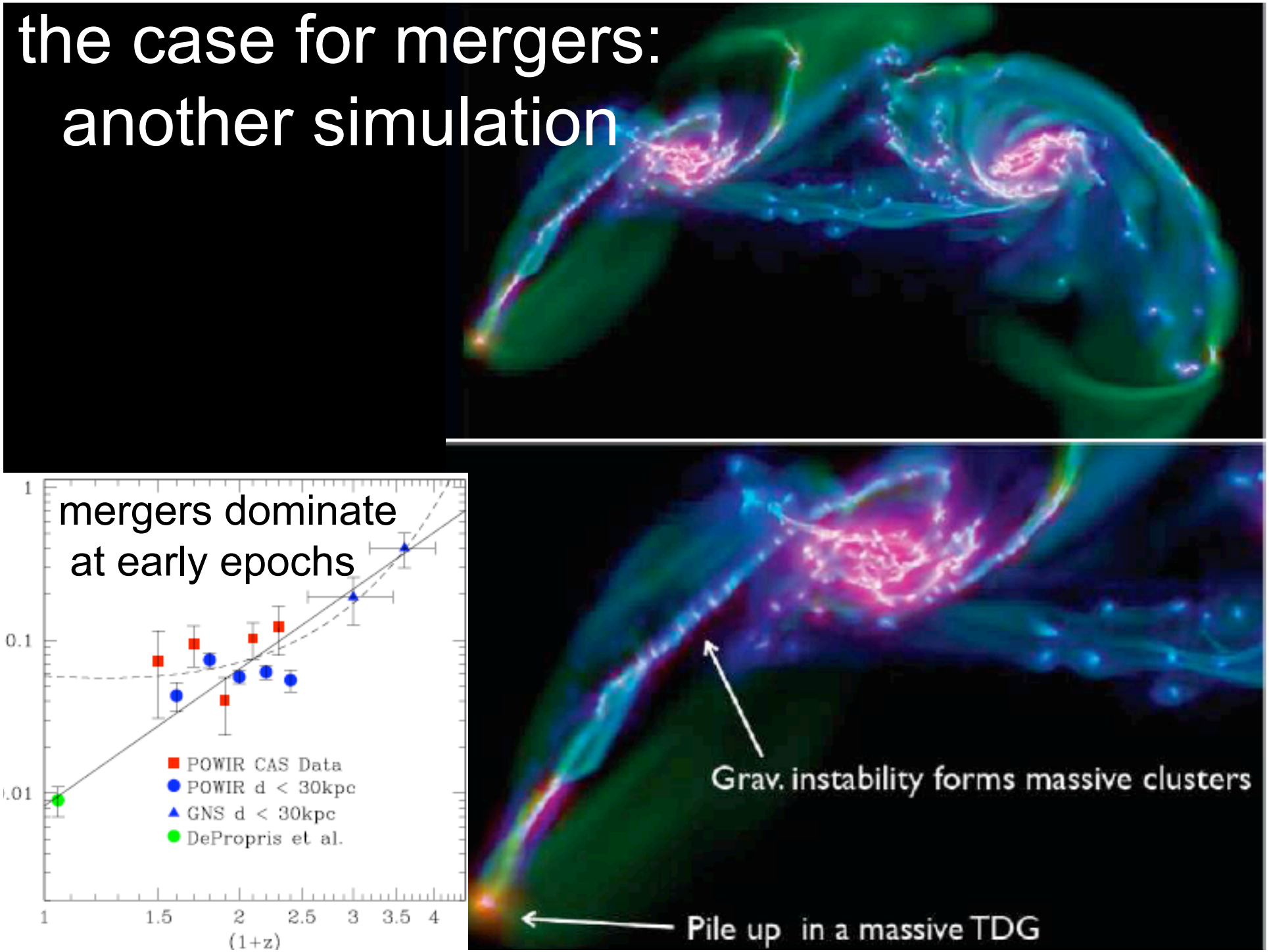
star formation

Is growth of galaxies by infall or by merging?

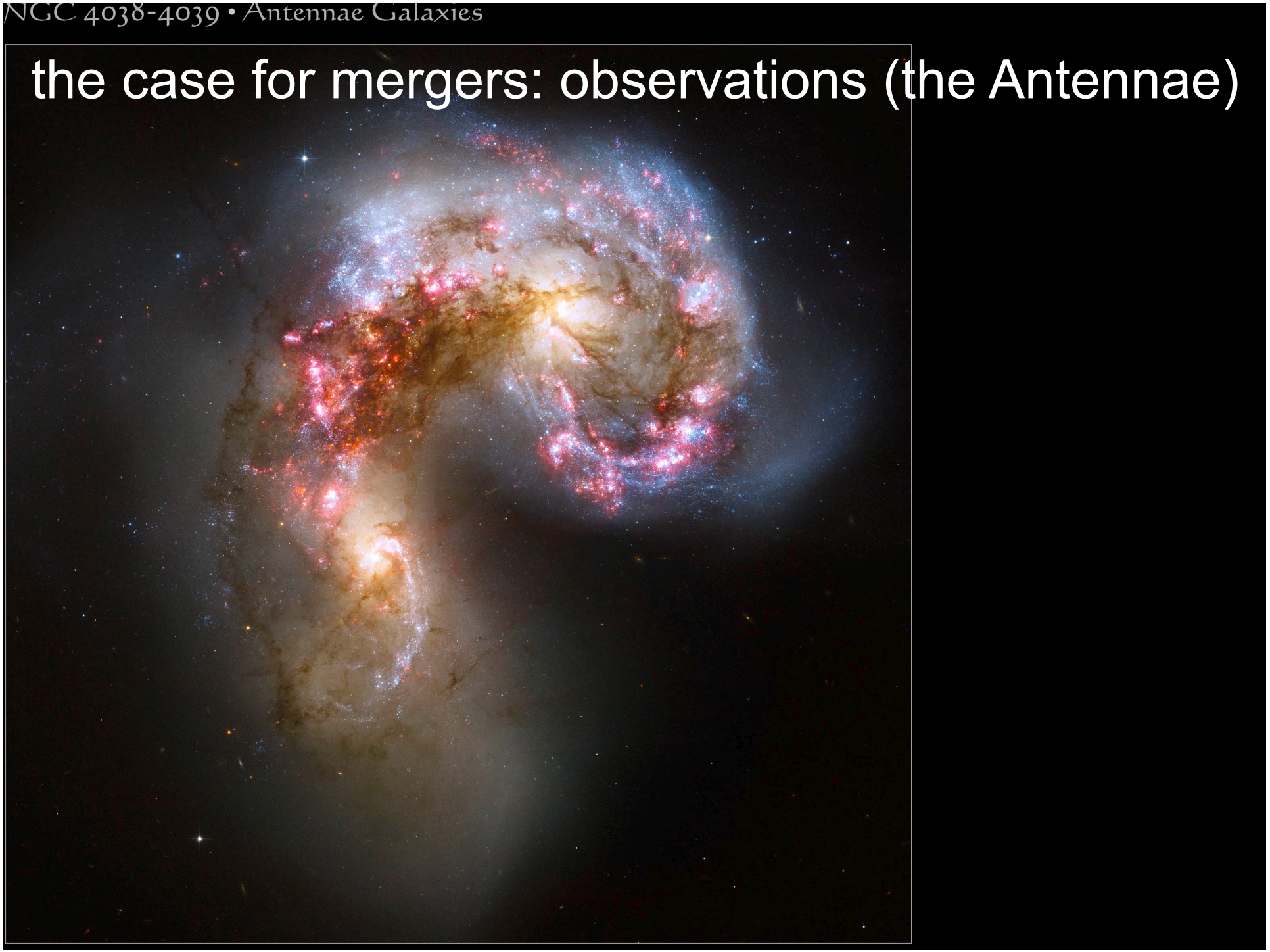
the case for infall: a simulation



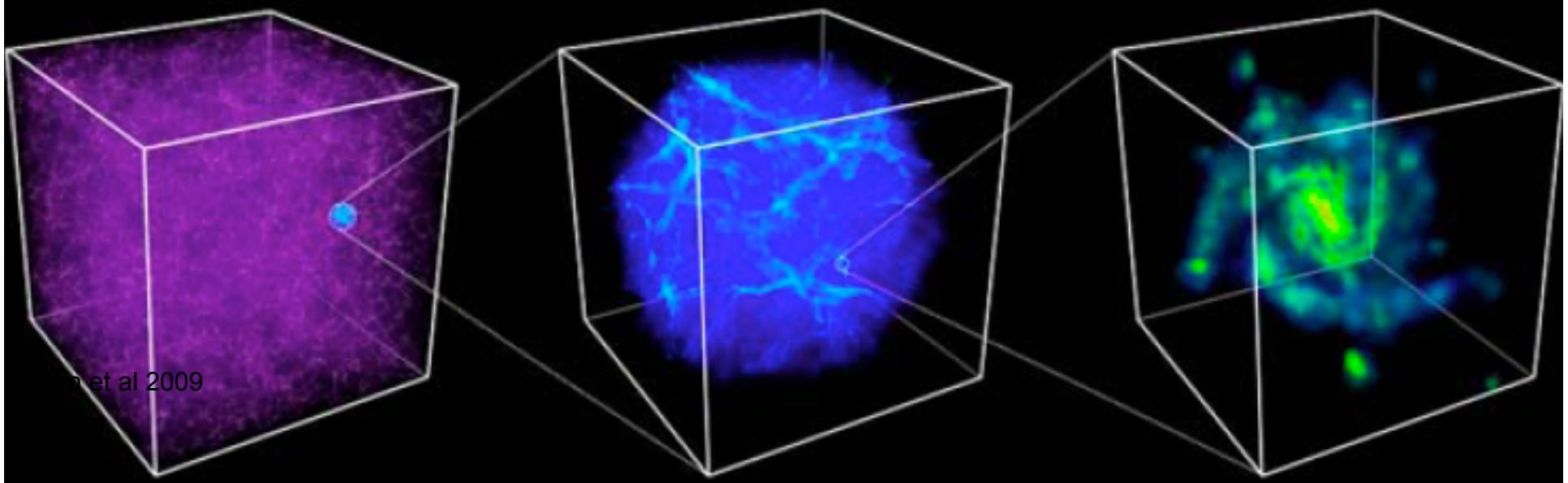
the case for mergers: another simulation



the case for mergers: observations (the Antennae)



The largest simulation to date



500 Mpc

50 Mpc

50 kpc

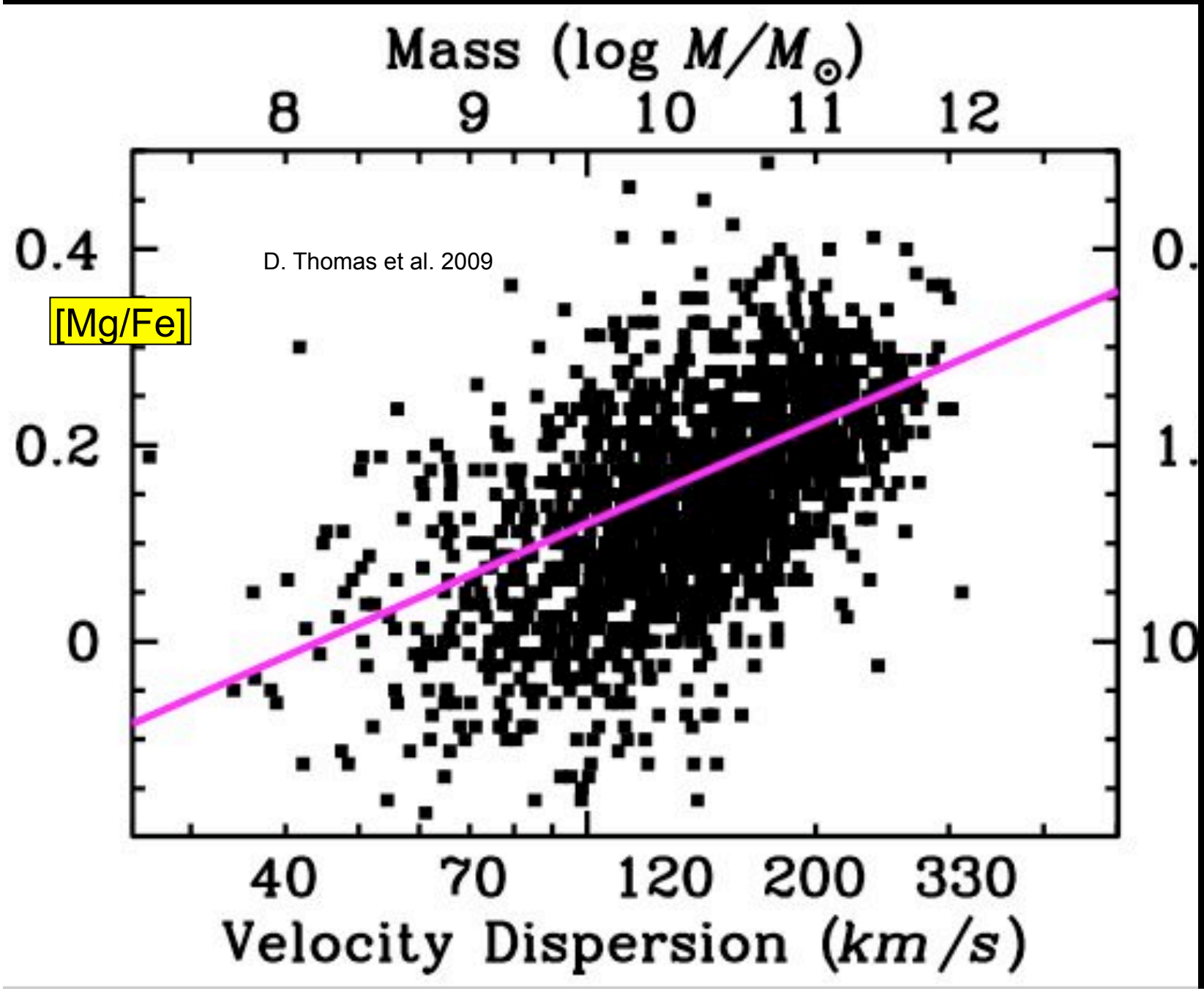
The biggest challenge?

Kormendy 2007

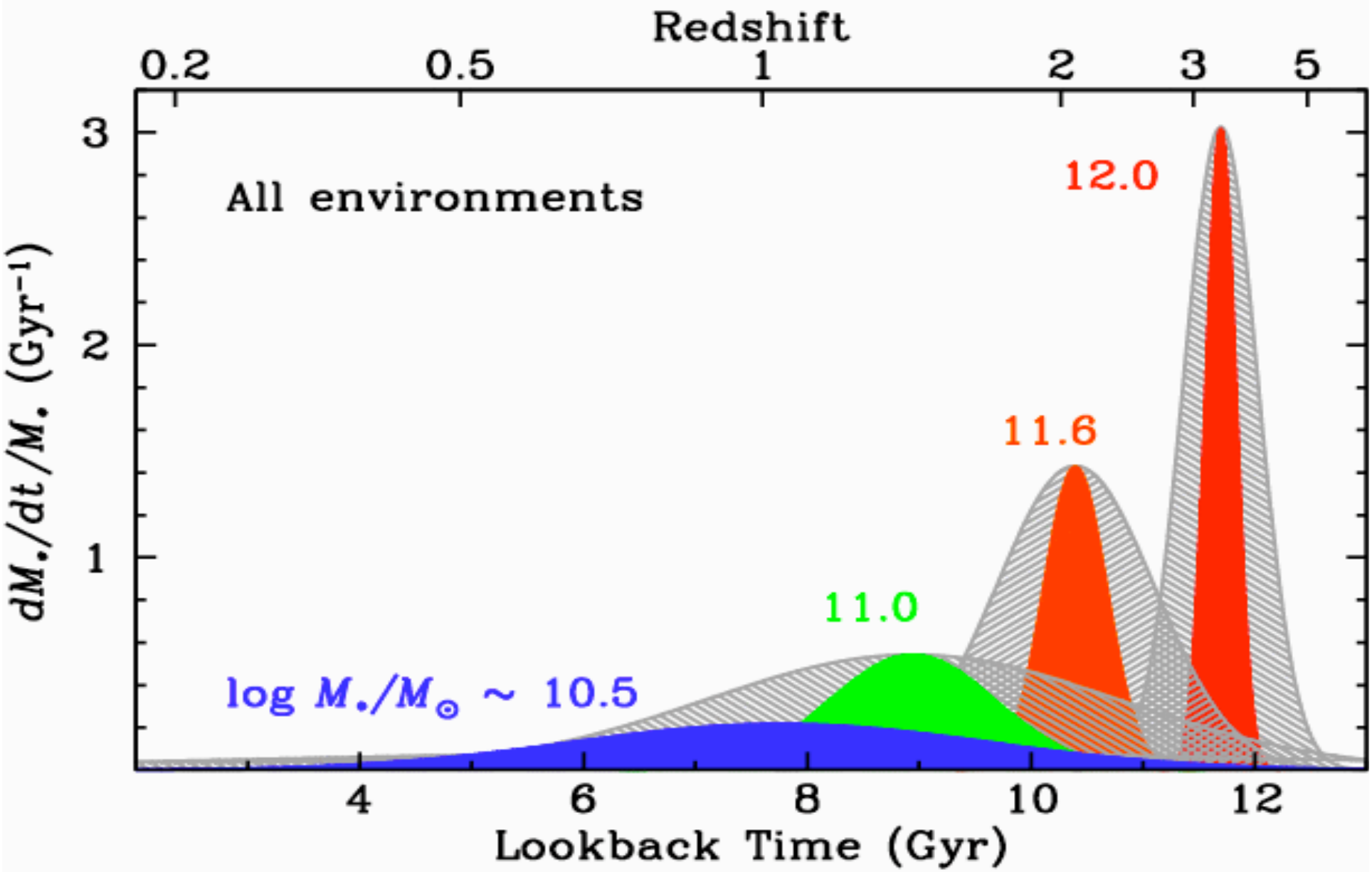
galaxies downsize: a surprise!

A cosmic clock: incorporation into stars of debris from SNII (10^6 yr) vs SNI (10^{10} yr)

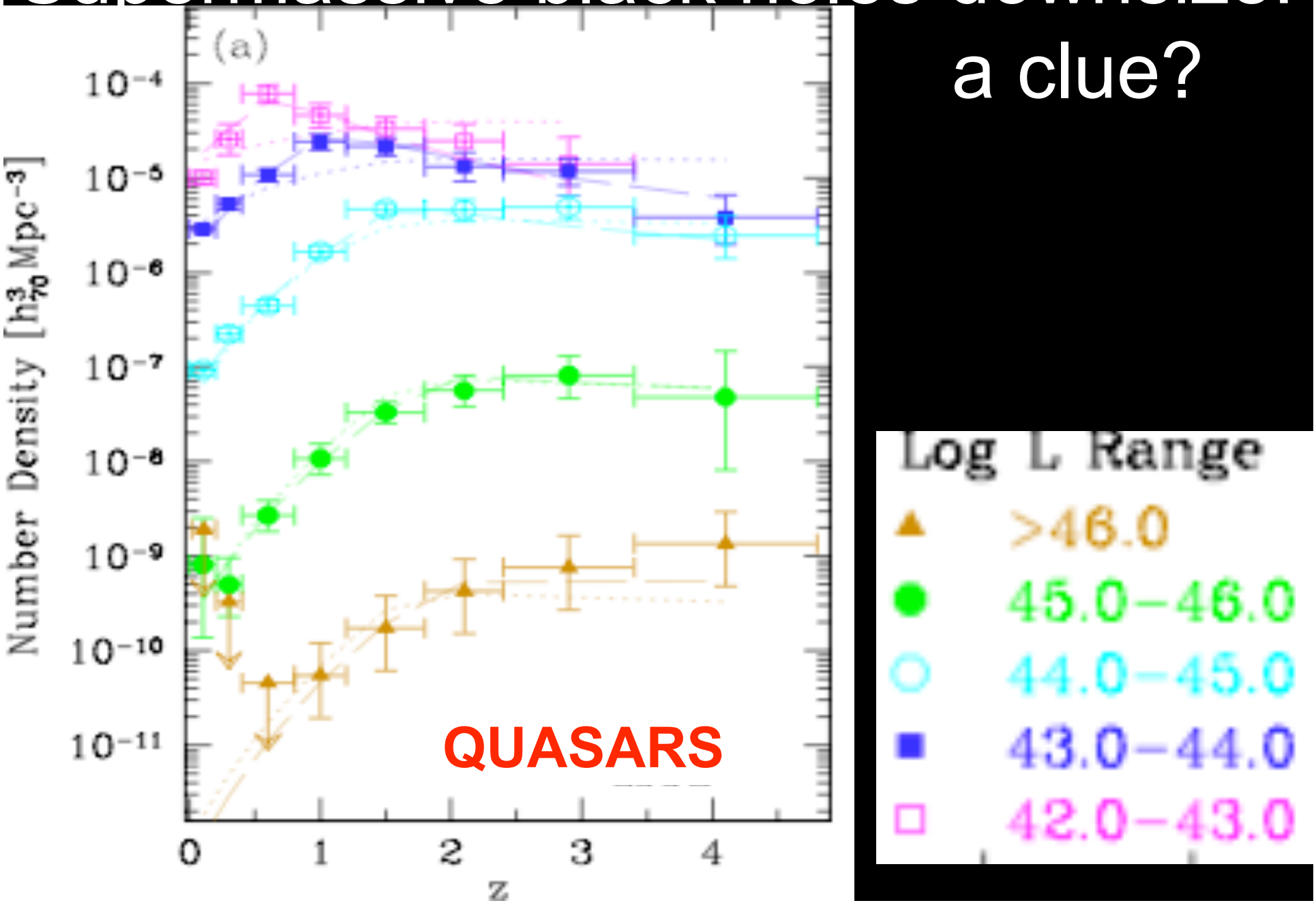
DOWNSIZING INFERRED



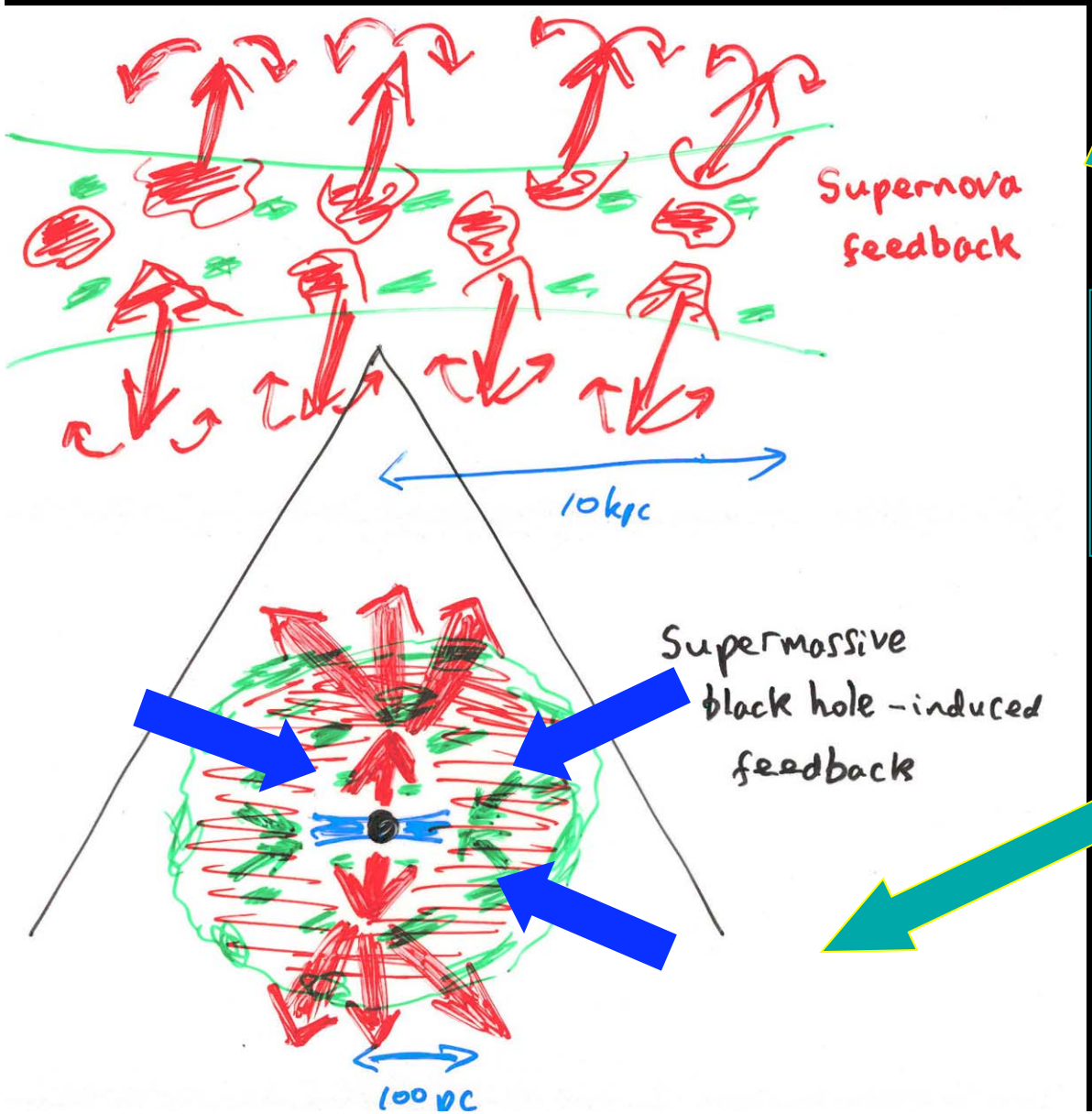
Galaxies downsize



Supermassive black holes downsize: a clue?



A UNIFIED THEORY….feedback is essential



LATE

cooling in halos

dry mergers

improved resolution in theory and observation will help…

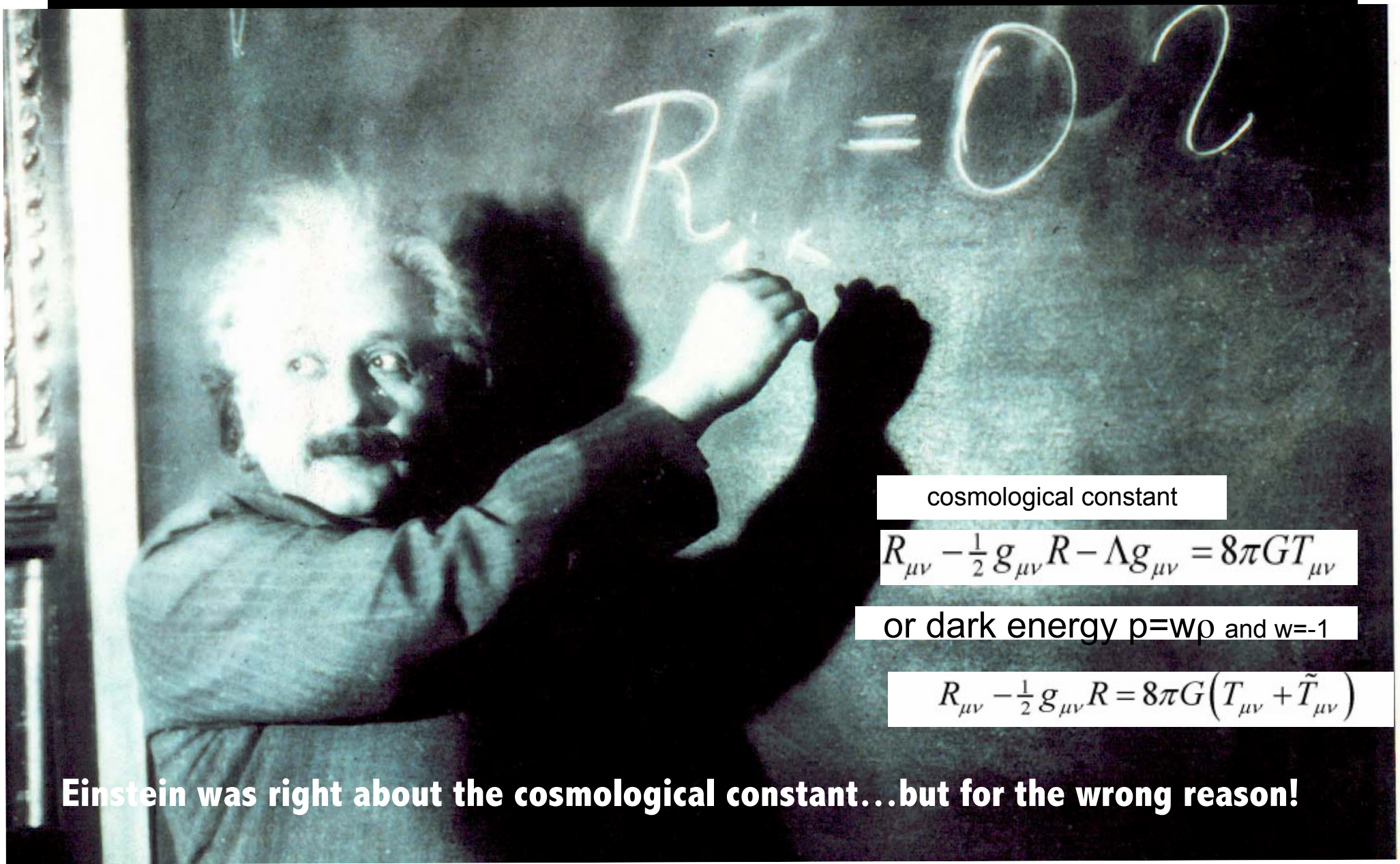
EARLY

cold flows in filaments

wet mergers

dark energy

WHERE DARK ENERGY ORIGINATED



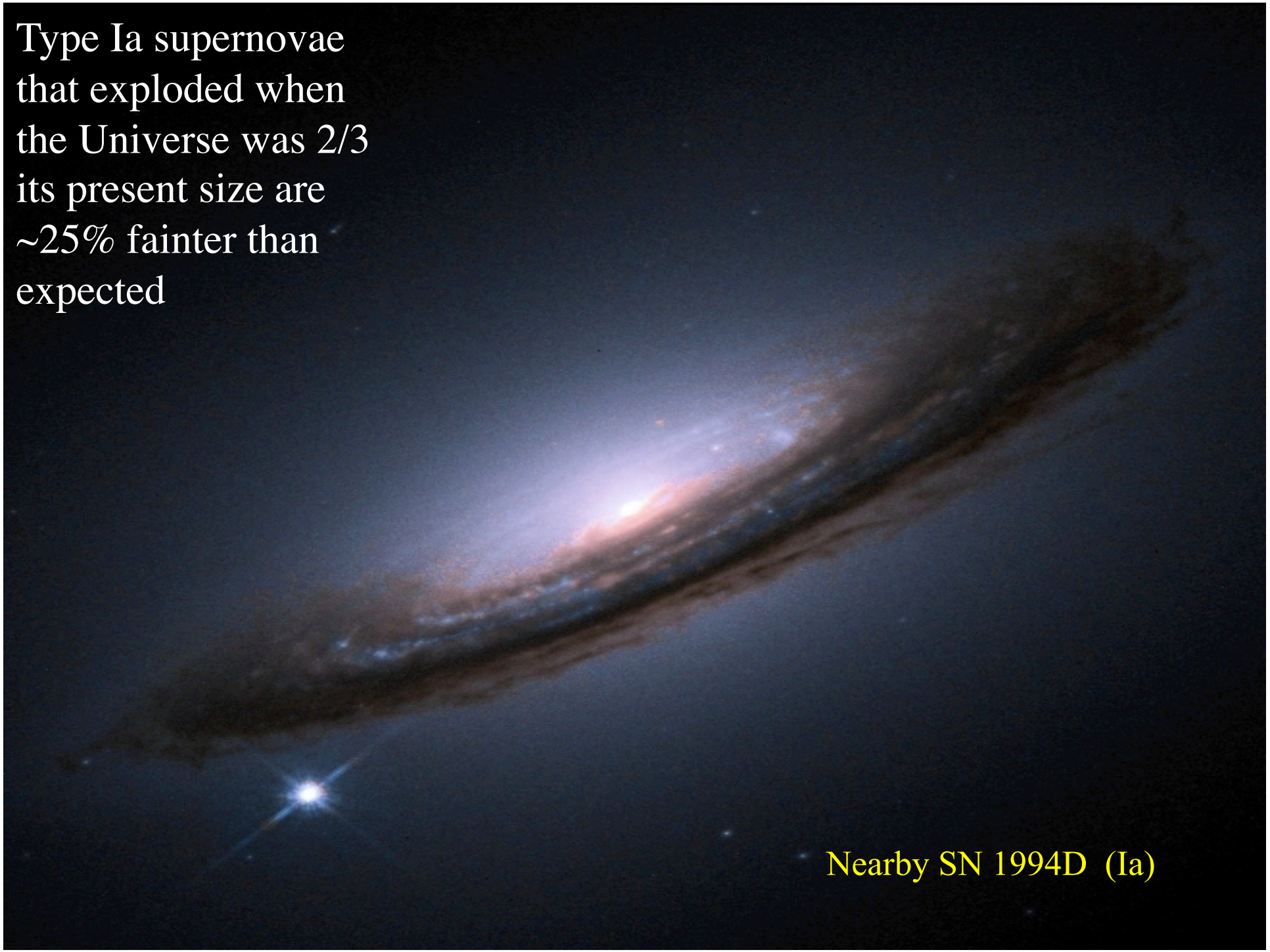
cosmological constant

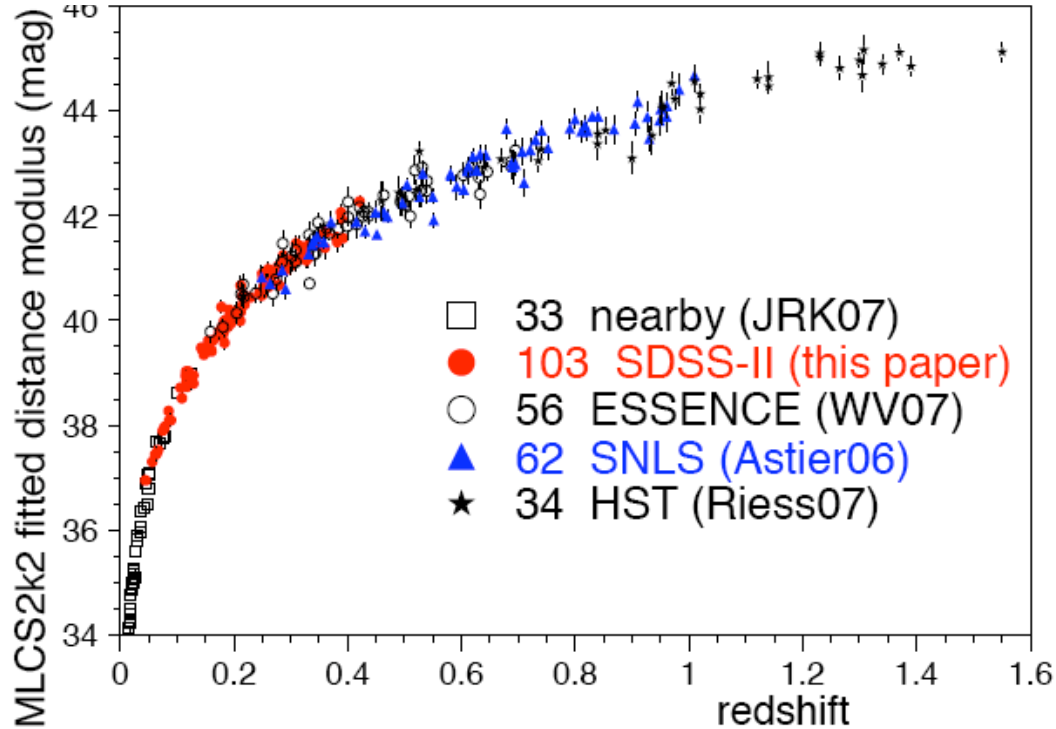
$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

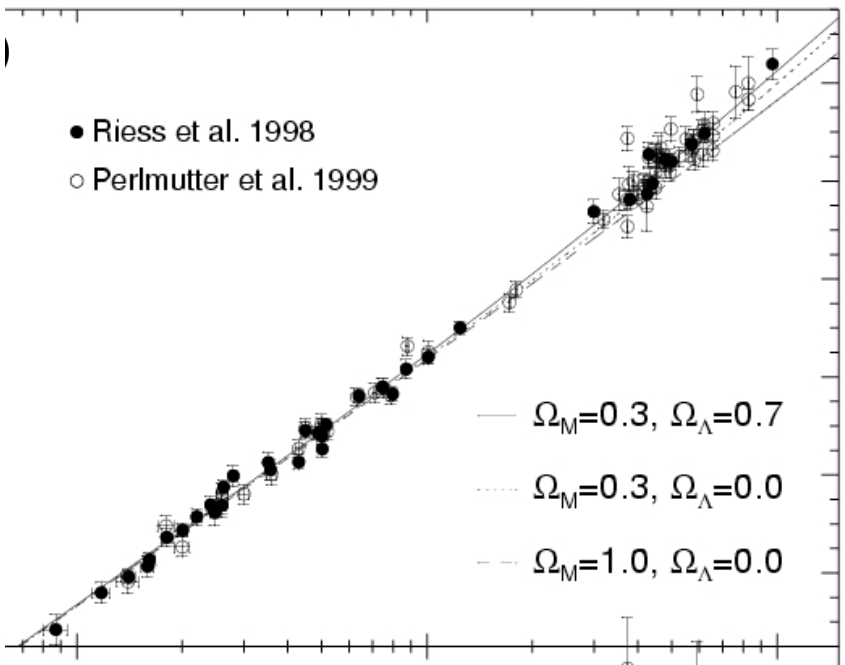
or dark energy $p = w\rho$ and $w=-1$

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + \tilde{T}_{\mu\nu} \right)$$

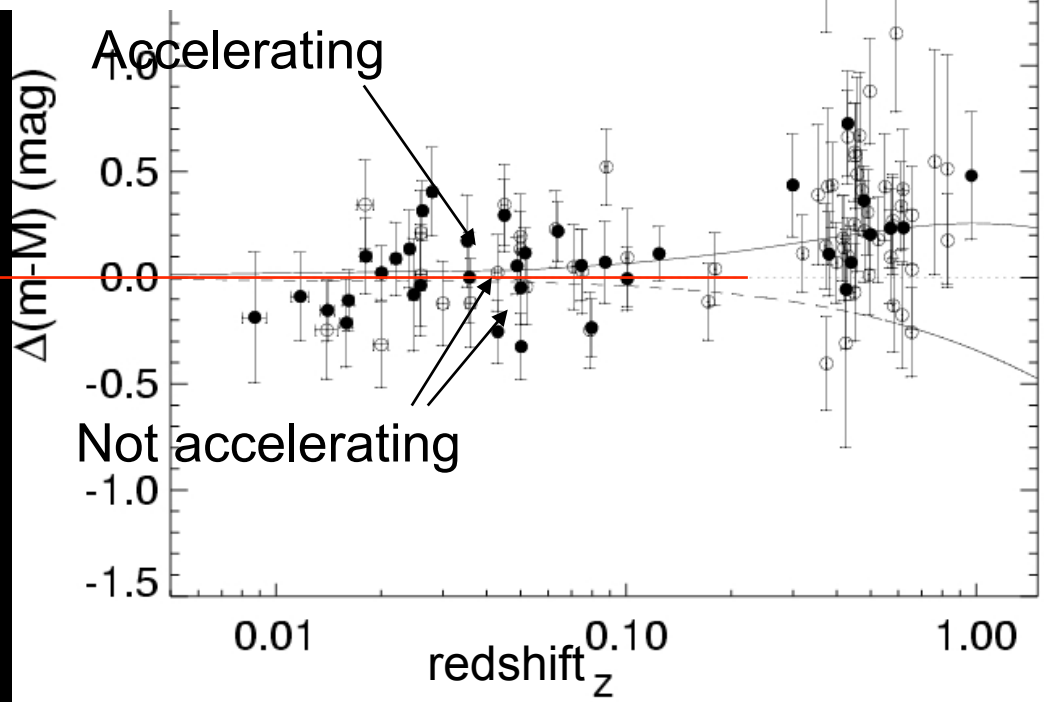
Einstein was right about the cosmological constant…but for the wrong reason!


Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected
Nearby SN 1994D (Ia)





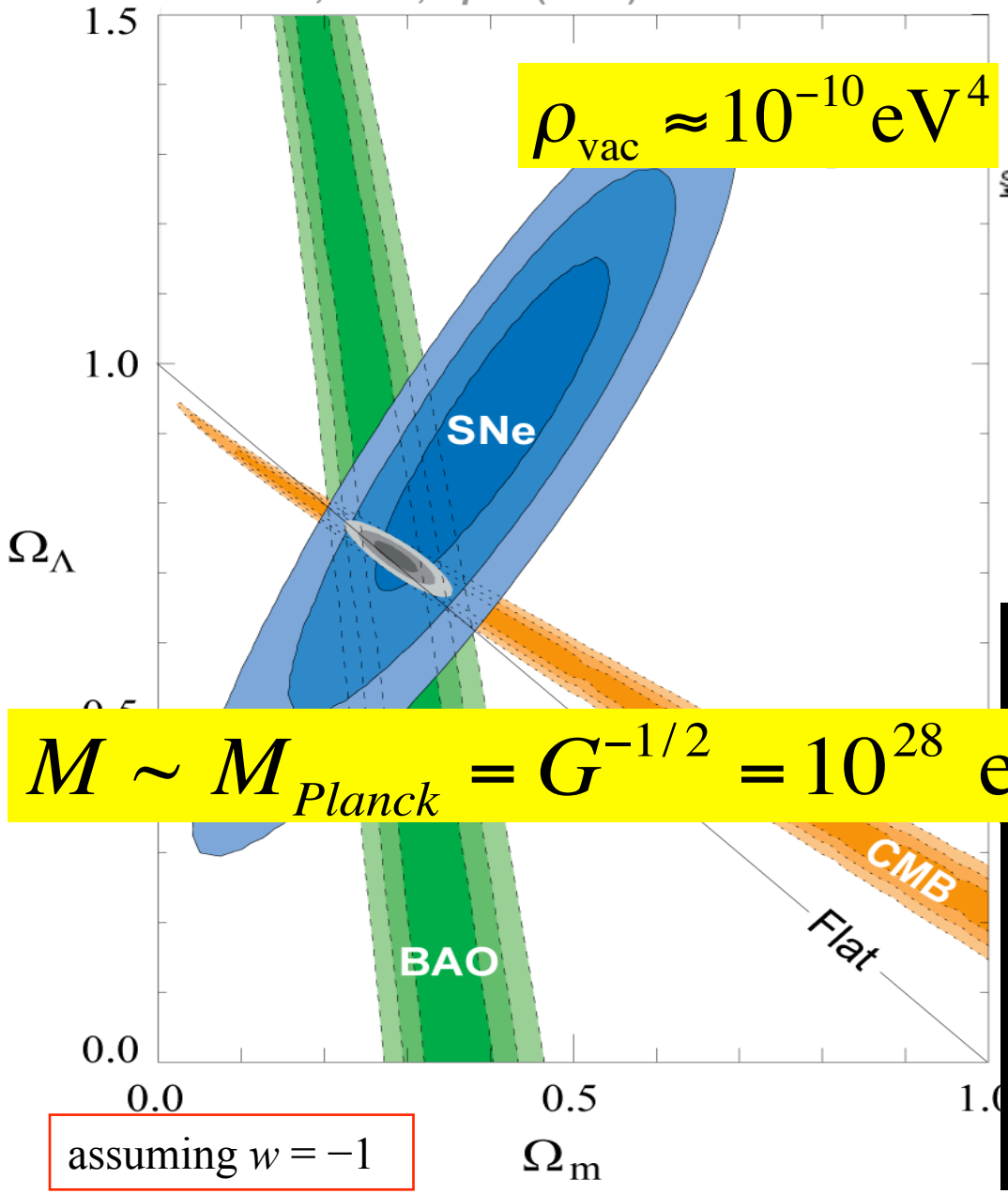
$\Omega_\Lambda = 0.75$
$\Omega_m = 0.21$
$\Omega_b = 0.04$



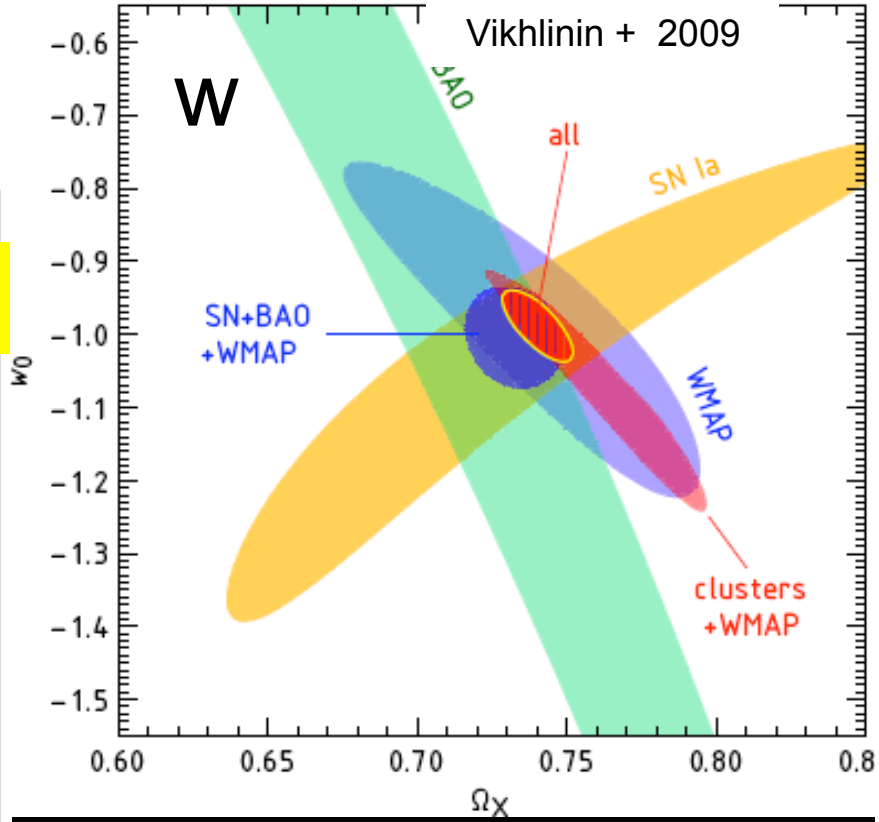
Vacuum density

Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)

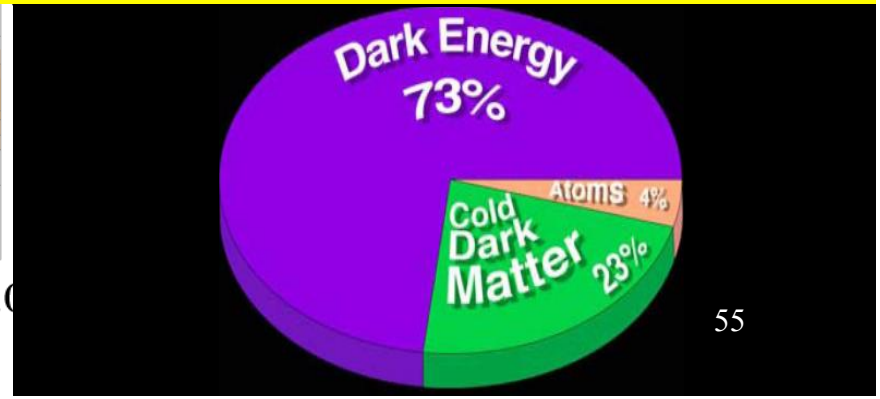
$$\rho_{\rm vac} \approx 10^{-10}\,{\rm eV}^4$$



assuming $w = -1$



$$M \sim M_{Planck} = G^{-1/2} = 10^{28}\ {\rm eV} \Rightarrow \rho_{vac} \sim 10^{112}\,{\rm eV}^4$$

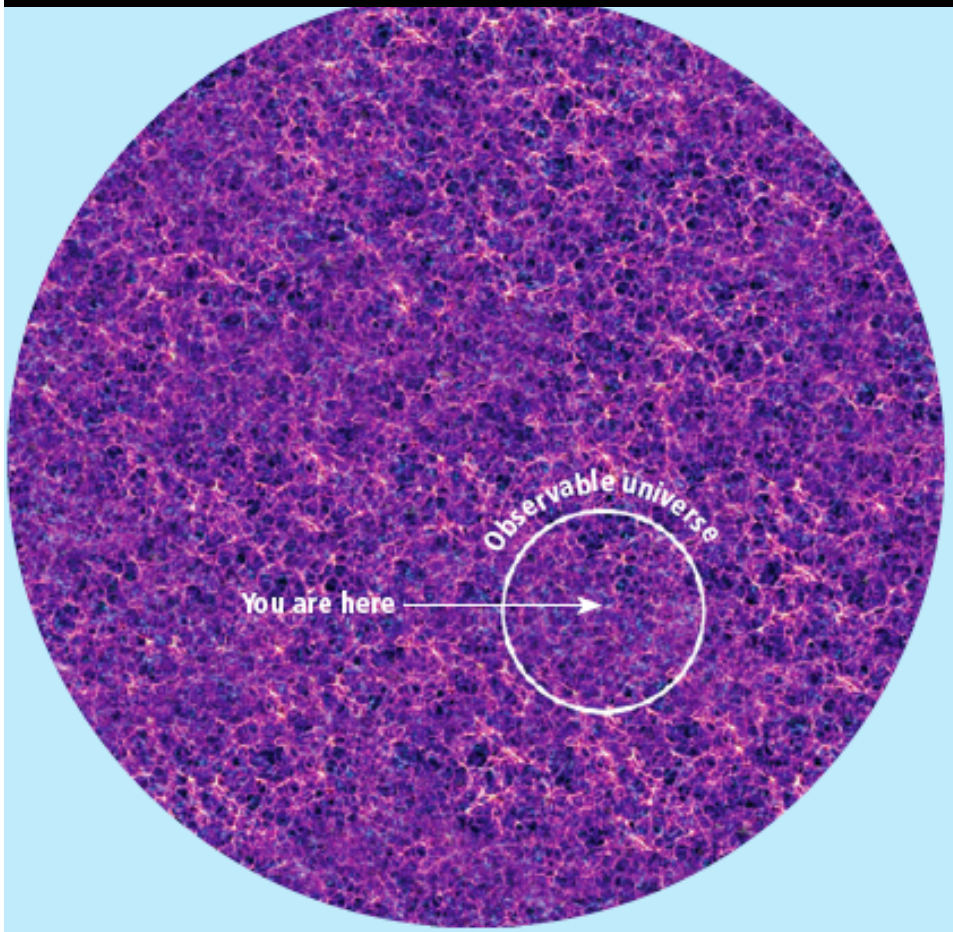


dark energy or cosmological constant

cosmological constant is favoured by data

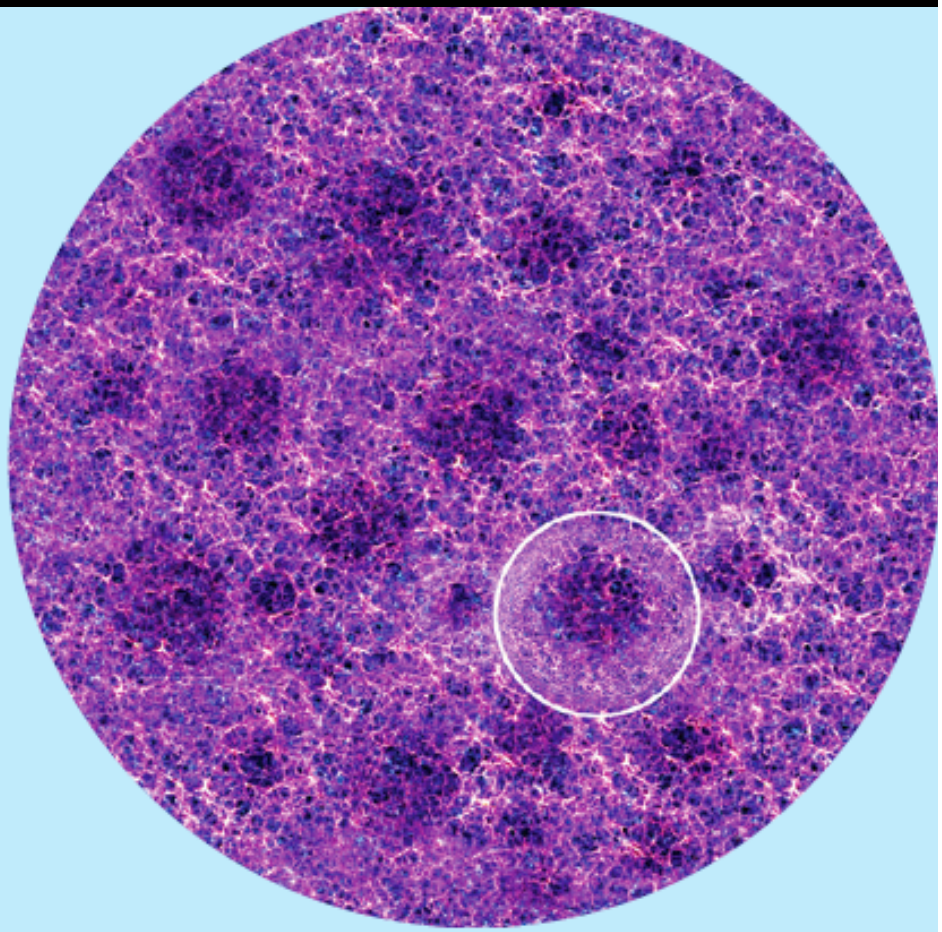
BUT SYSTEMATICS DOMINATE ERRORS

Clifton & Ferreira 2008



HOMOGENEOUS UNIVERSE: OUR LOCATION IS TYPICAL

In the standard view, galaxies are lined up in a spidery pattern, but overall space looks much the same everywhere, and Earth's position is nothing special.

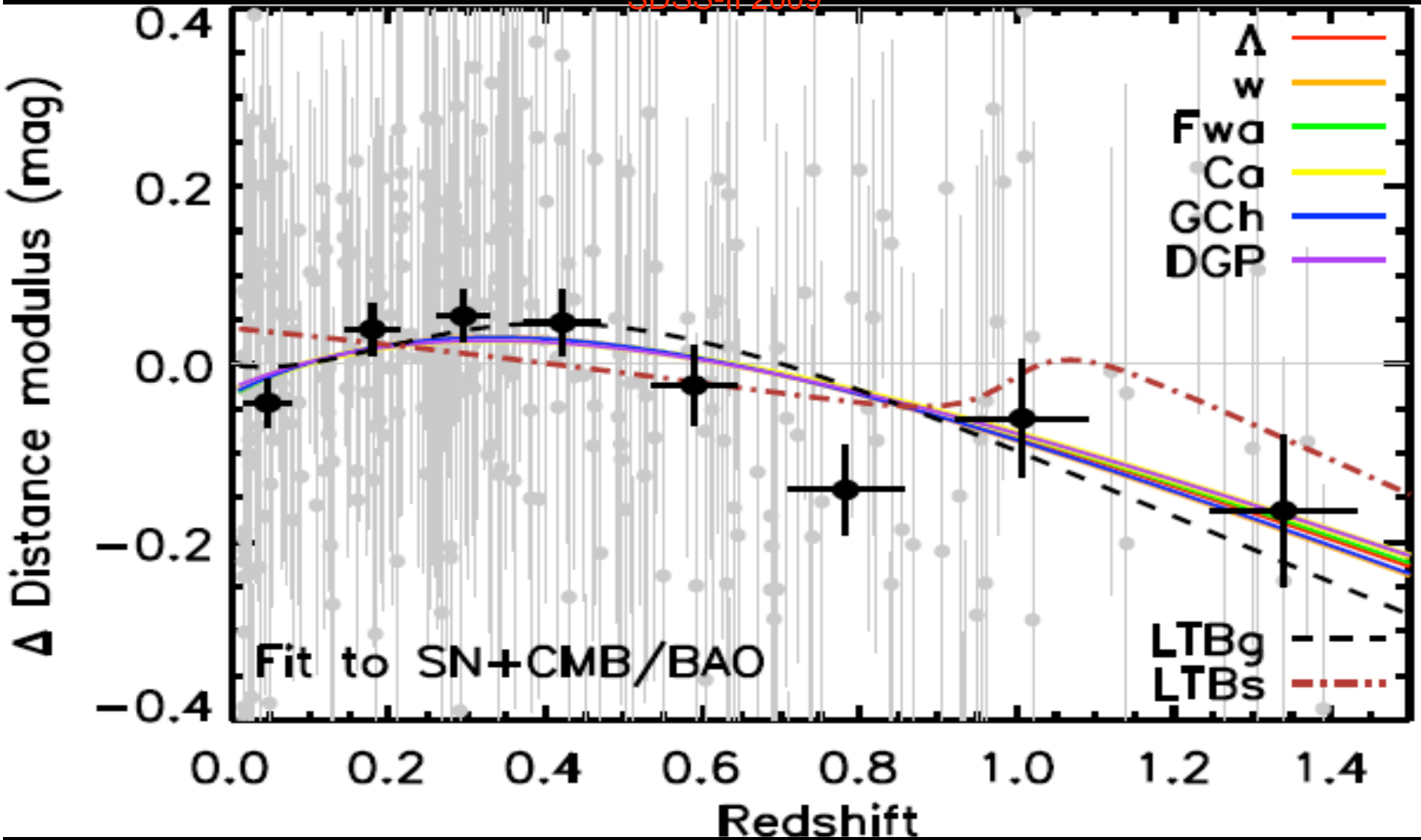


INHOMOGENEOUS UNIVERSE: OUR LOCATION IS SPECIAL

Alternatively, the density of matter could vary on large scales, and Earth may lie at or near the center of a relatively less dense region, or void.

CAN REPLACE ACCELERATION BY A GIANT LOCAL VOID in Lemaitre-Tolman-Bondi model

SDSS-II 2009



Which hypothesis is more “fine-tuned”?

some answers, some questions

Friedmann-Lemaitre cosmology does reasonably well at data fitting, but not from a Bayesian perspective…. but

We have no theory of how to quantitatively convert gas into stars
We use phenomenology and simulate. This will improve.

We have many unproven theories for Dark Energy
Standard Model deviations may yield a hint of a preferred theory

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Relic gravity waves and deviation from n=1 probe inflation

We are searching for Dark Matter by diverse techniques

We understand the origin of large-scale structure in terms of primordial fluctuations that have been detected

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We do not understand the origin of the primordial fluctuations