Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

School of Mathematical and Computing Sciences
Te Kura Pangarau, Rorohiko

Cosmology: Where are the bodies buried?

Matt Visser

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

"It is important to keep an open mind; just not so open that your brains fall out"

--- Albert Einstein

Overview:

The general framework of of modern cosmology is based on a large corpus of high-quality data. There is no doubt that the universe is expanding, that the linear Hubble law is a good approximation to that expansion, and that the cosmic microwave background represents the afterglow of the big bang.

But there are a number of troublesome issues where some caution is called for. In this talk I will focus on the bits that we don't understand so well, to show where the bodies are buried, and to give some idea of where current research is most active.

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

"There is something fascinating about science.
One gets such wholesome returns of conjecture out of such a trifling investment of fact."

--- Mark Twain

What parts of cosmology are rock solid?

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

Recession of galaxies

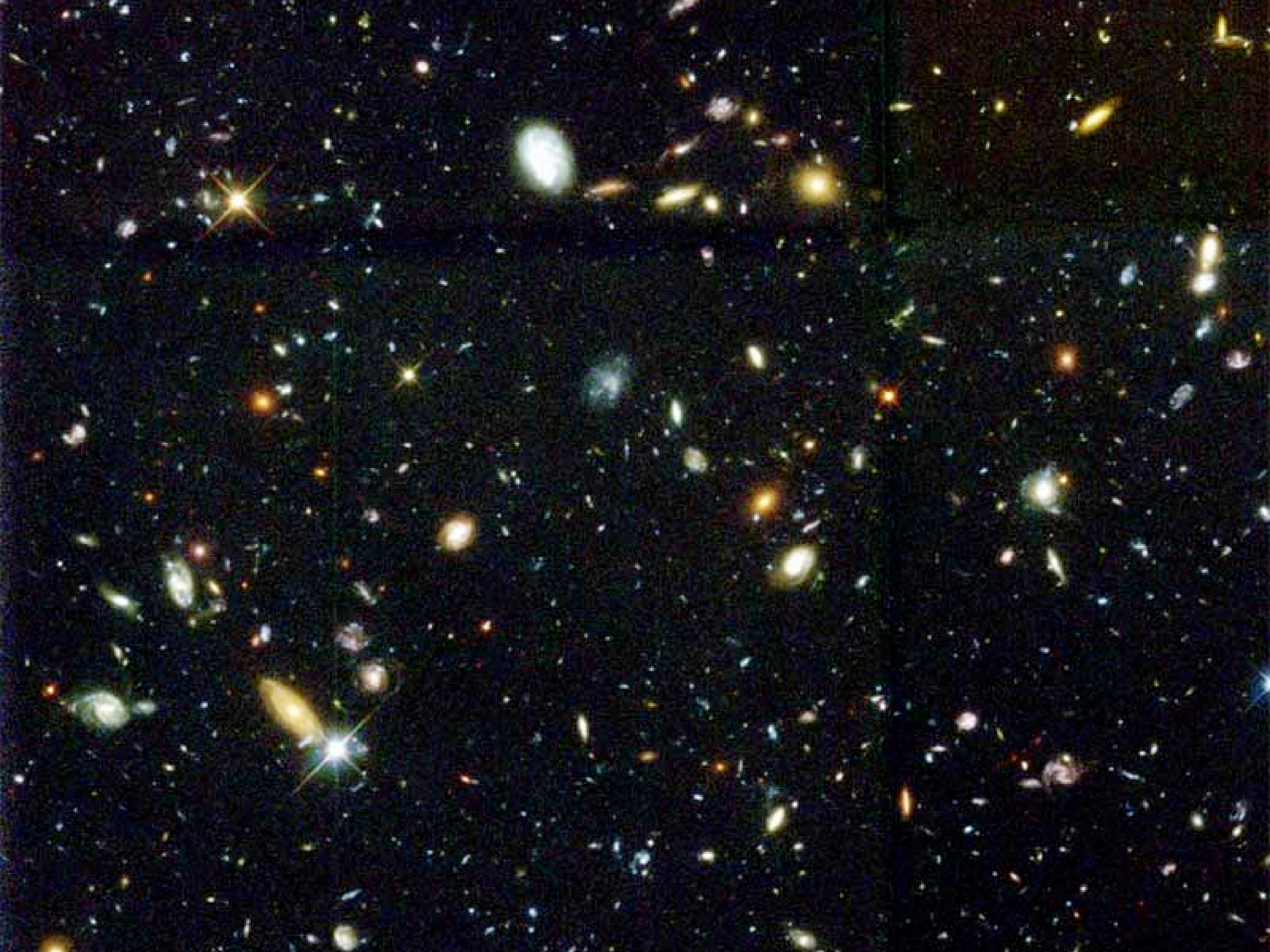
Approximate linear Hubble law

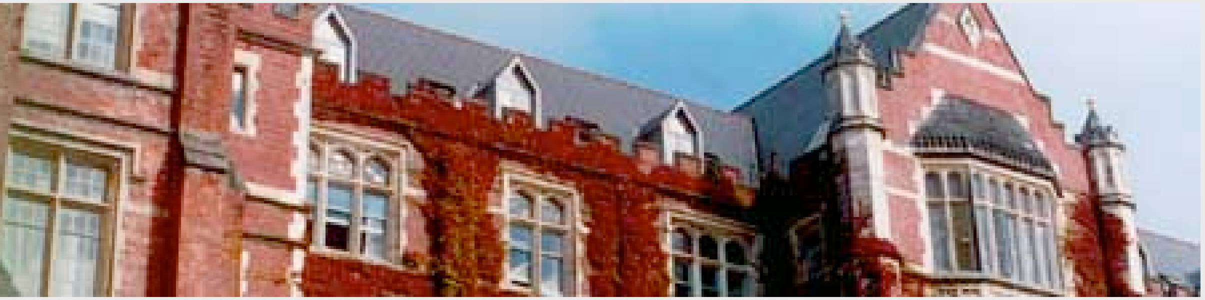
Galactic evolutionary effects

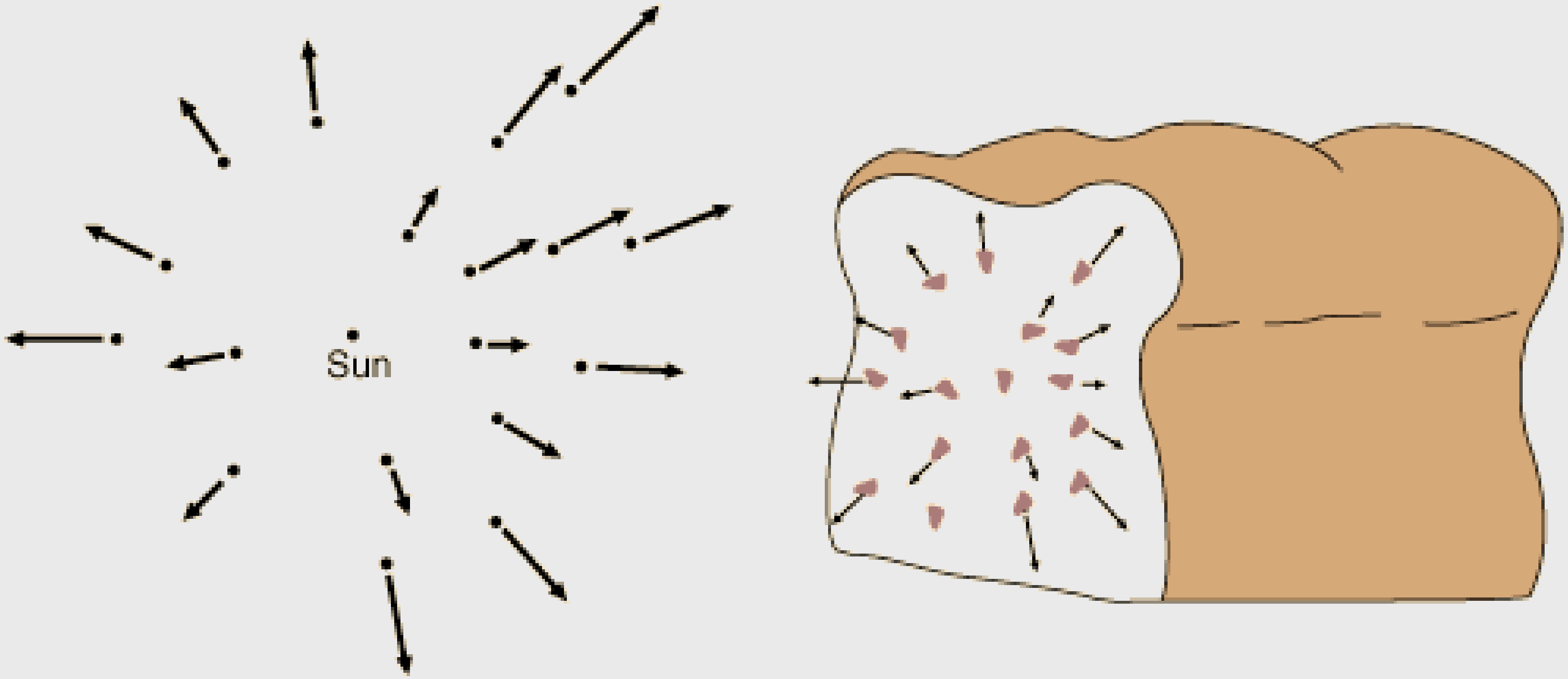
Cosmic Background Radiation

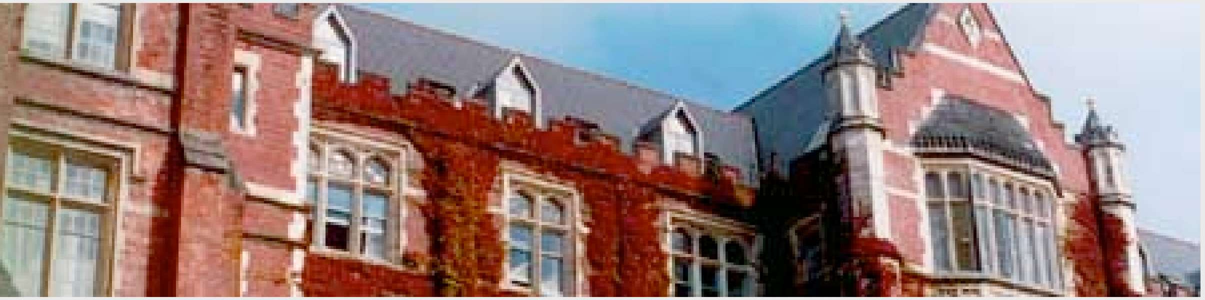
Stellar structure and evolution

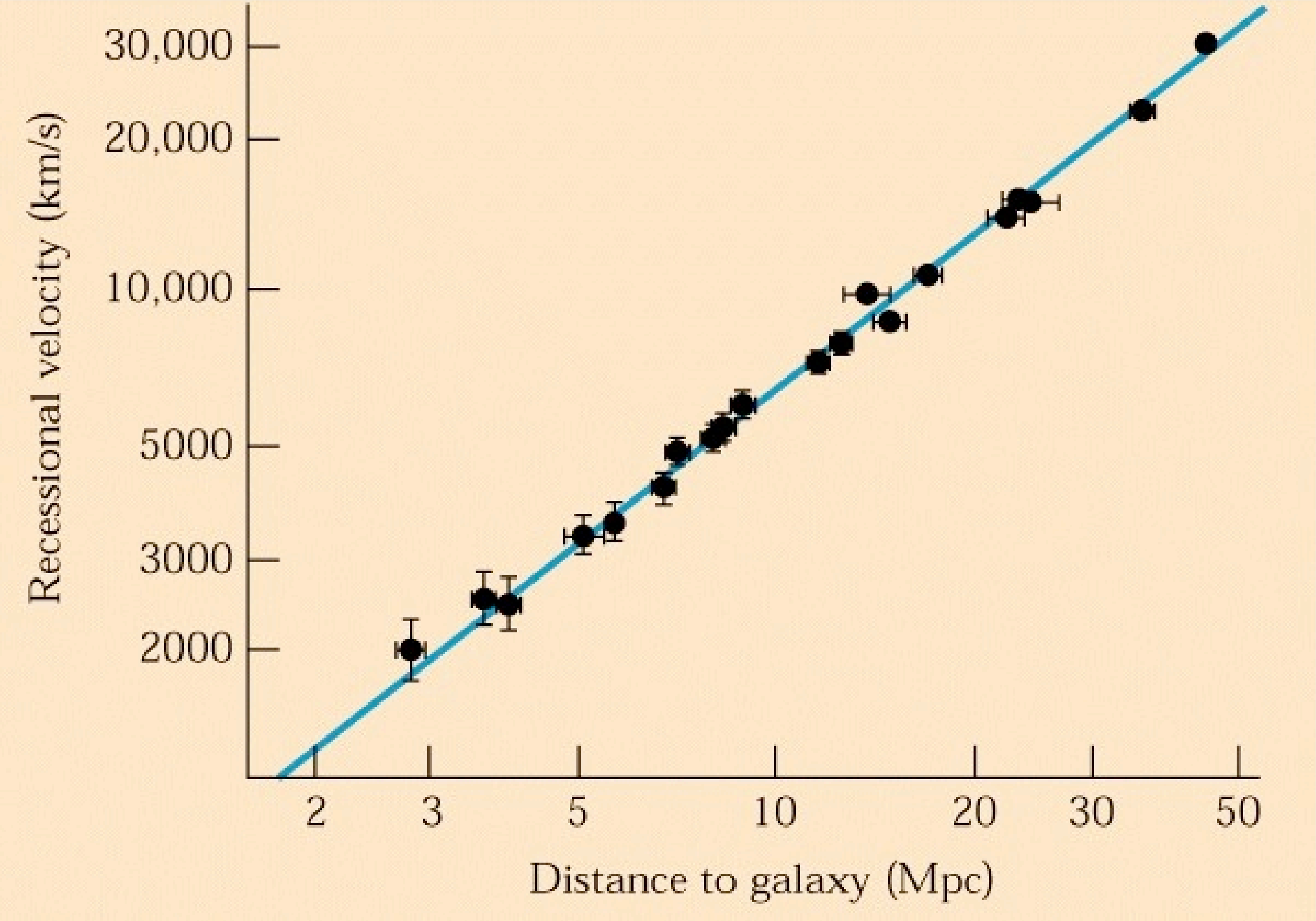
Big bang physics
(at least back to cosmological nucleosynthesis)

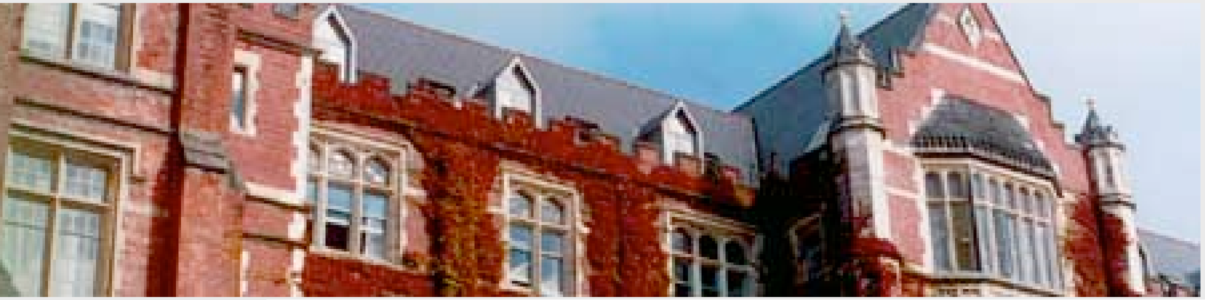




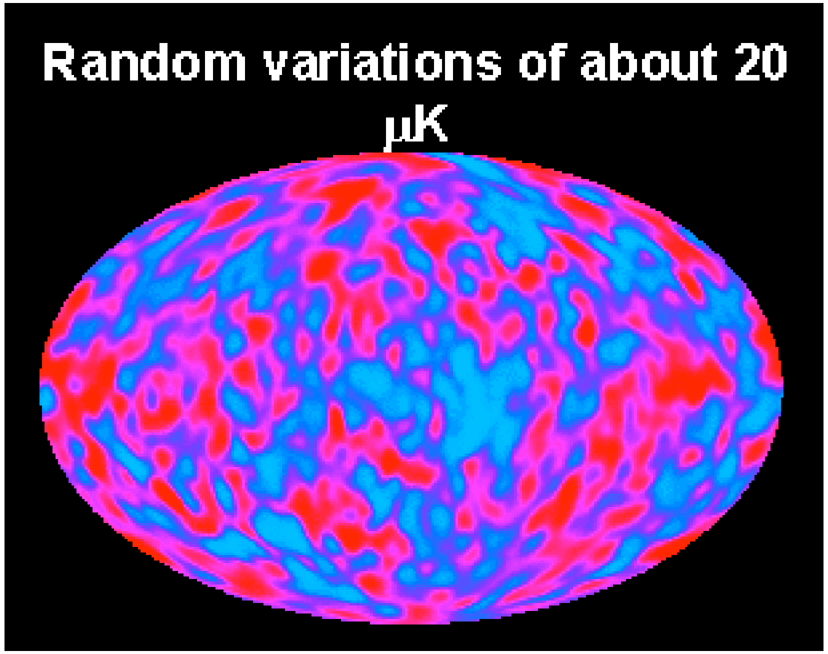

Sun

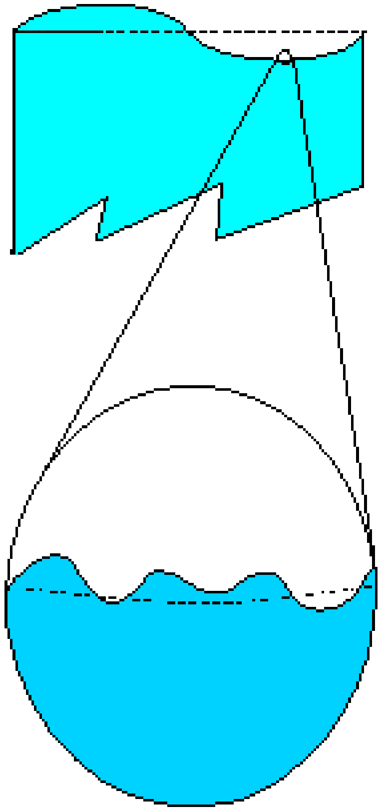



30,000
20,000
10,000
5000
3000
2000
Recessional velocity (km/s)
2
3
5
10
20
30
50
Distance to galaxy (Mpc)

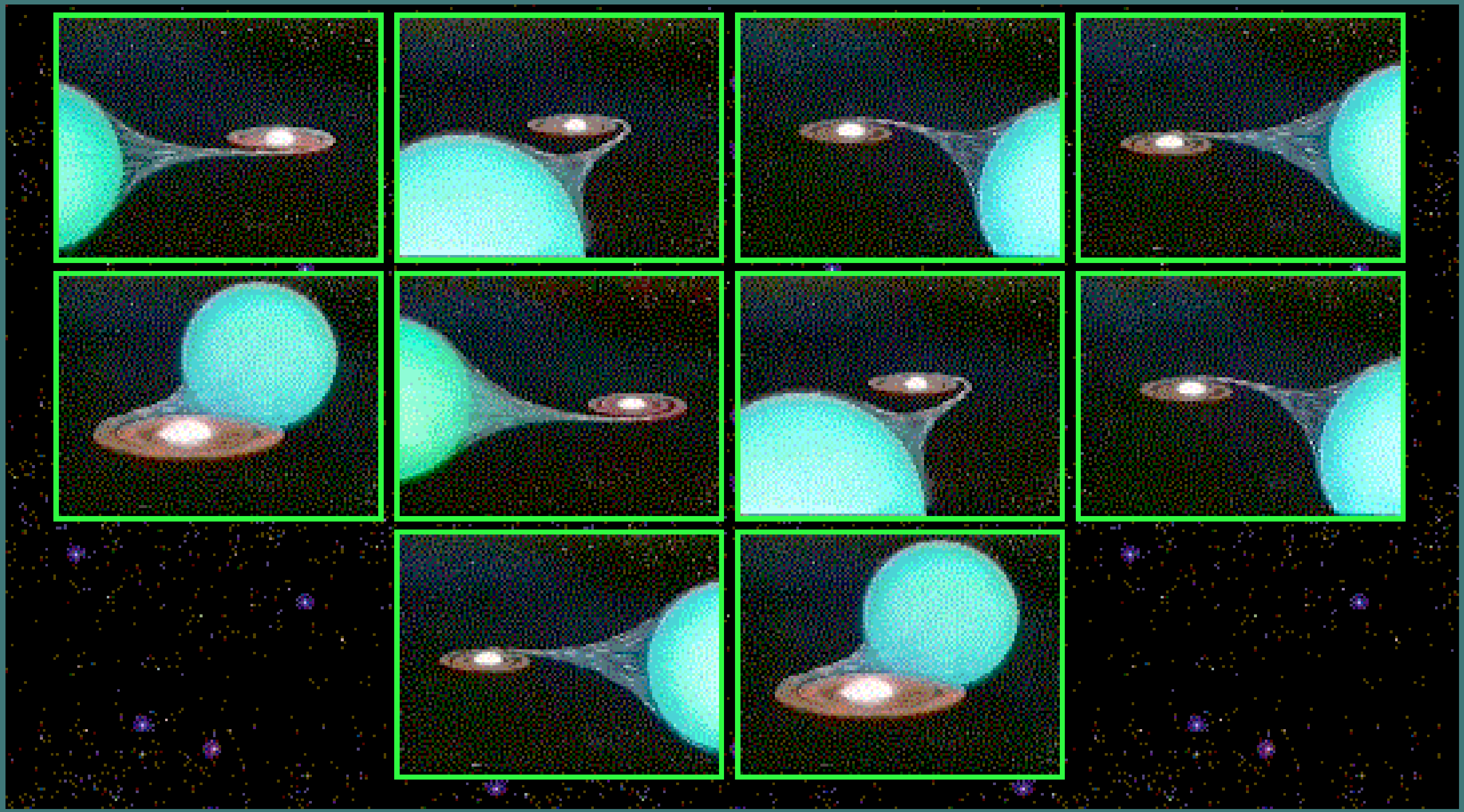


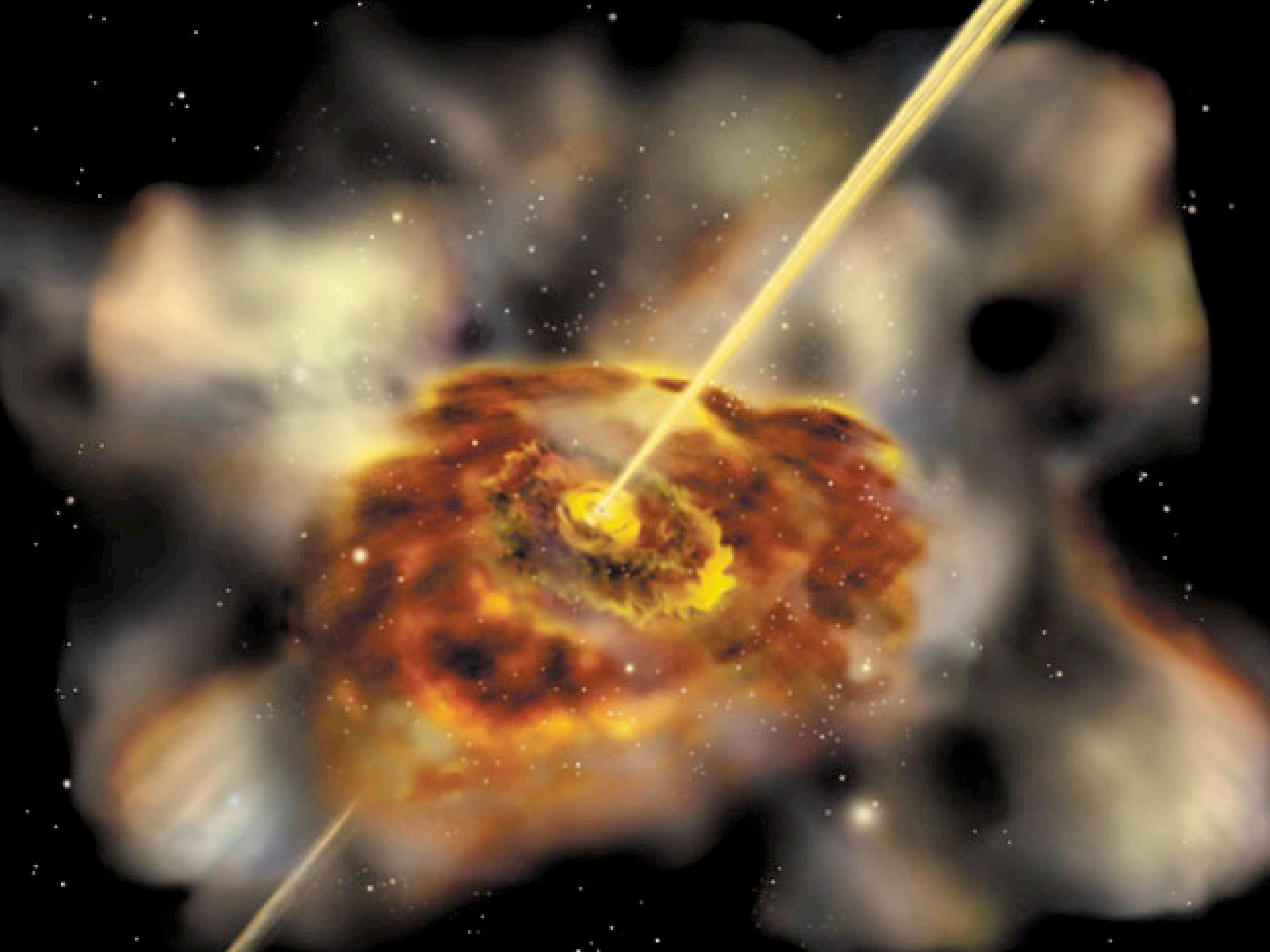
EVEN SMALLER VARIATIONS IN T_{CBR}





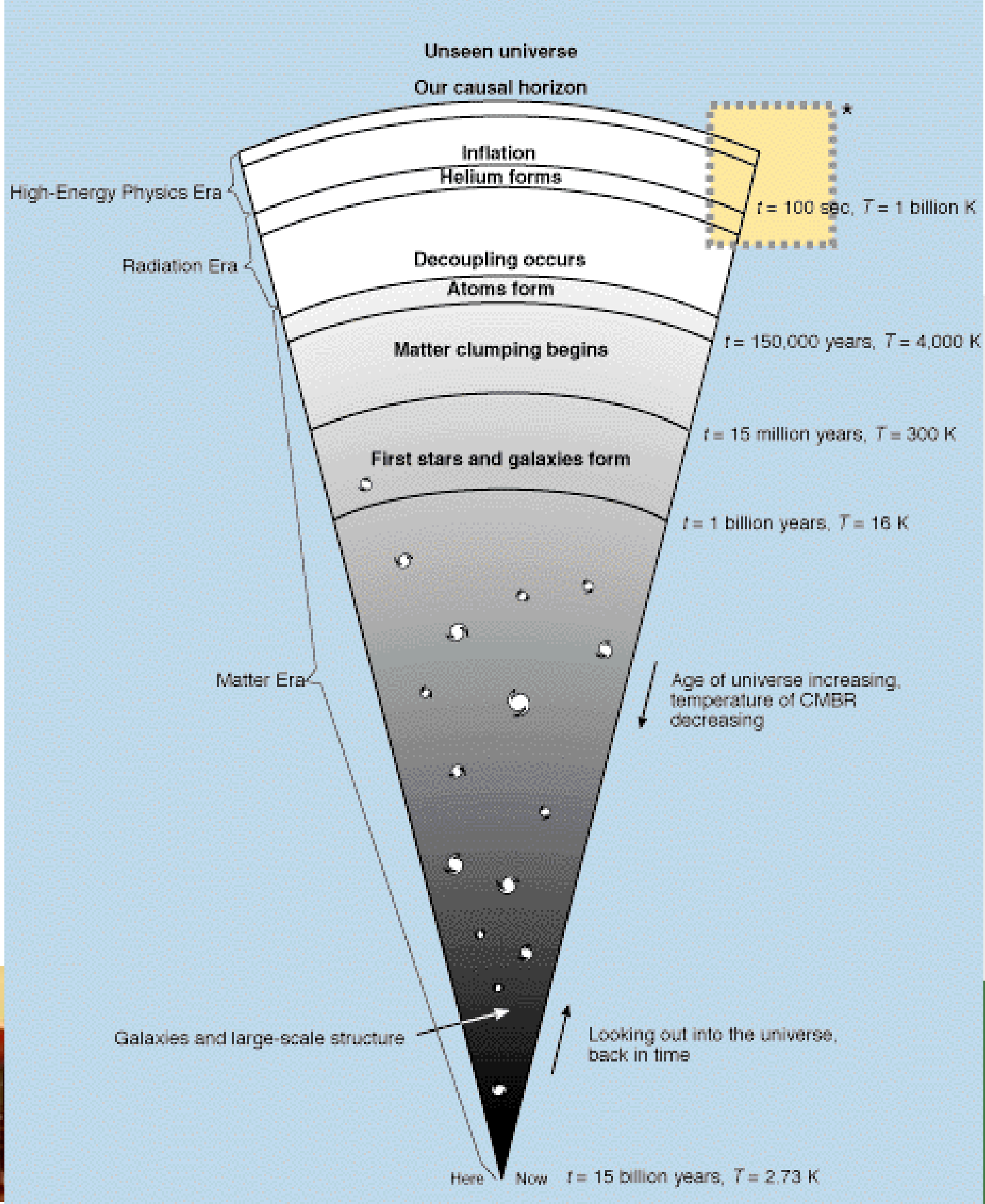
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui



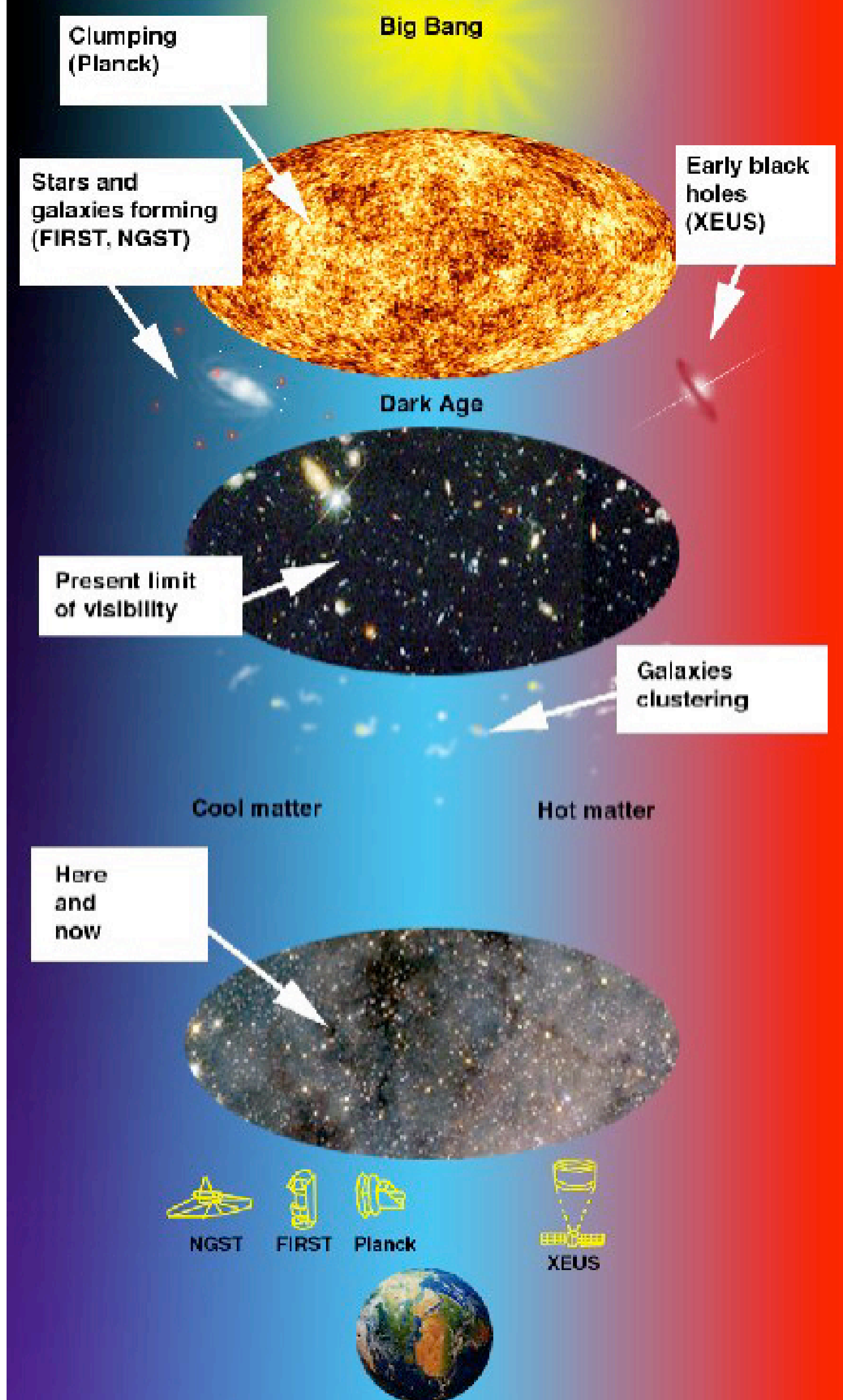


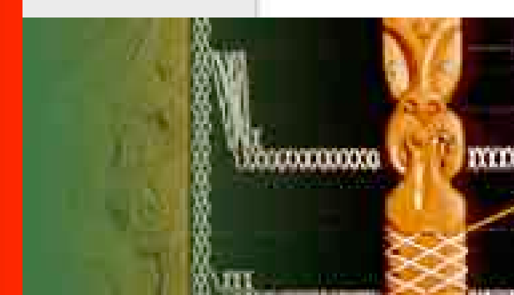
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

The Cosmic Picture



Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga o te Ūpoko o te Ika a Māui





What parts of cosmology are firm?

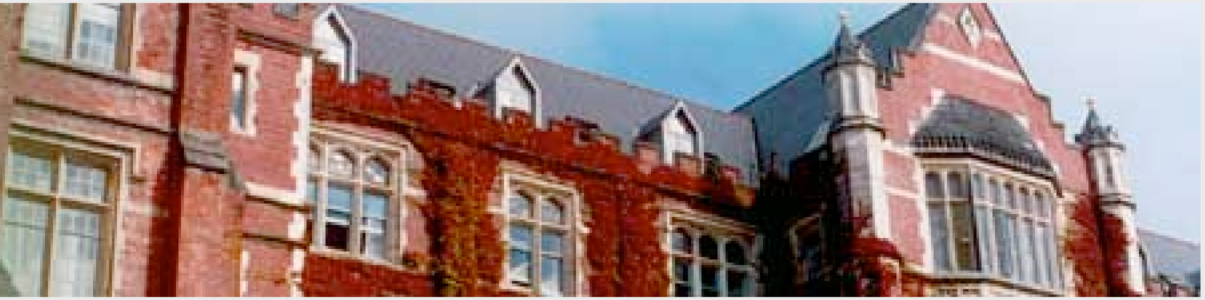
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

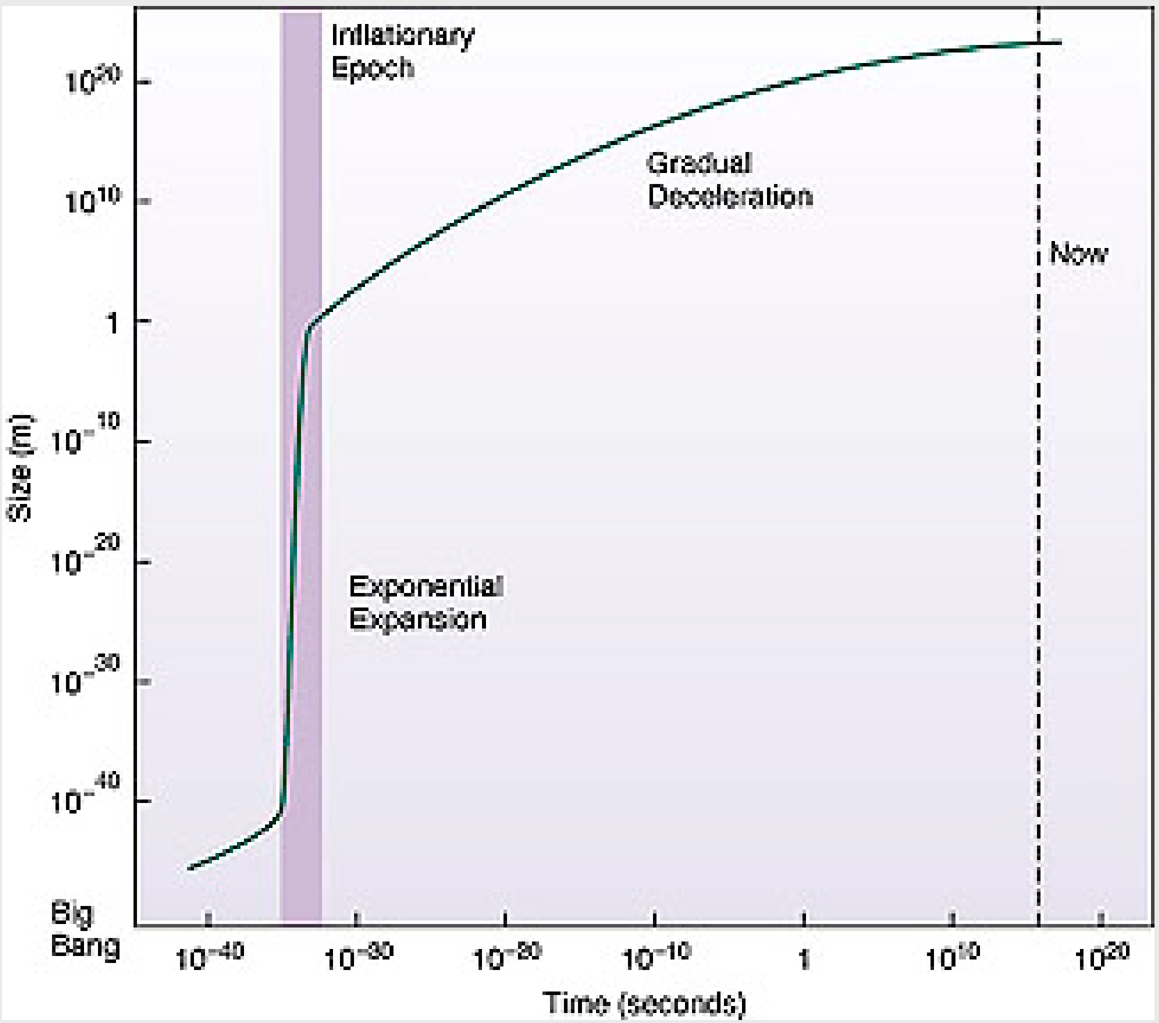
Cosmological inflation

Galaxy-galaxy correlations

Large-scale structure

Fractal universe?

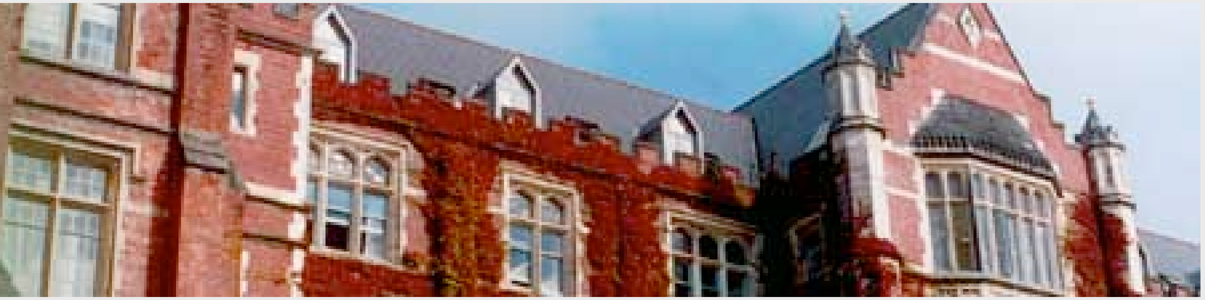




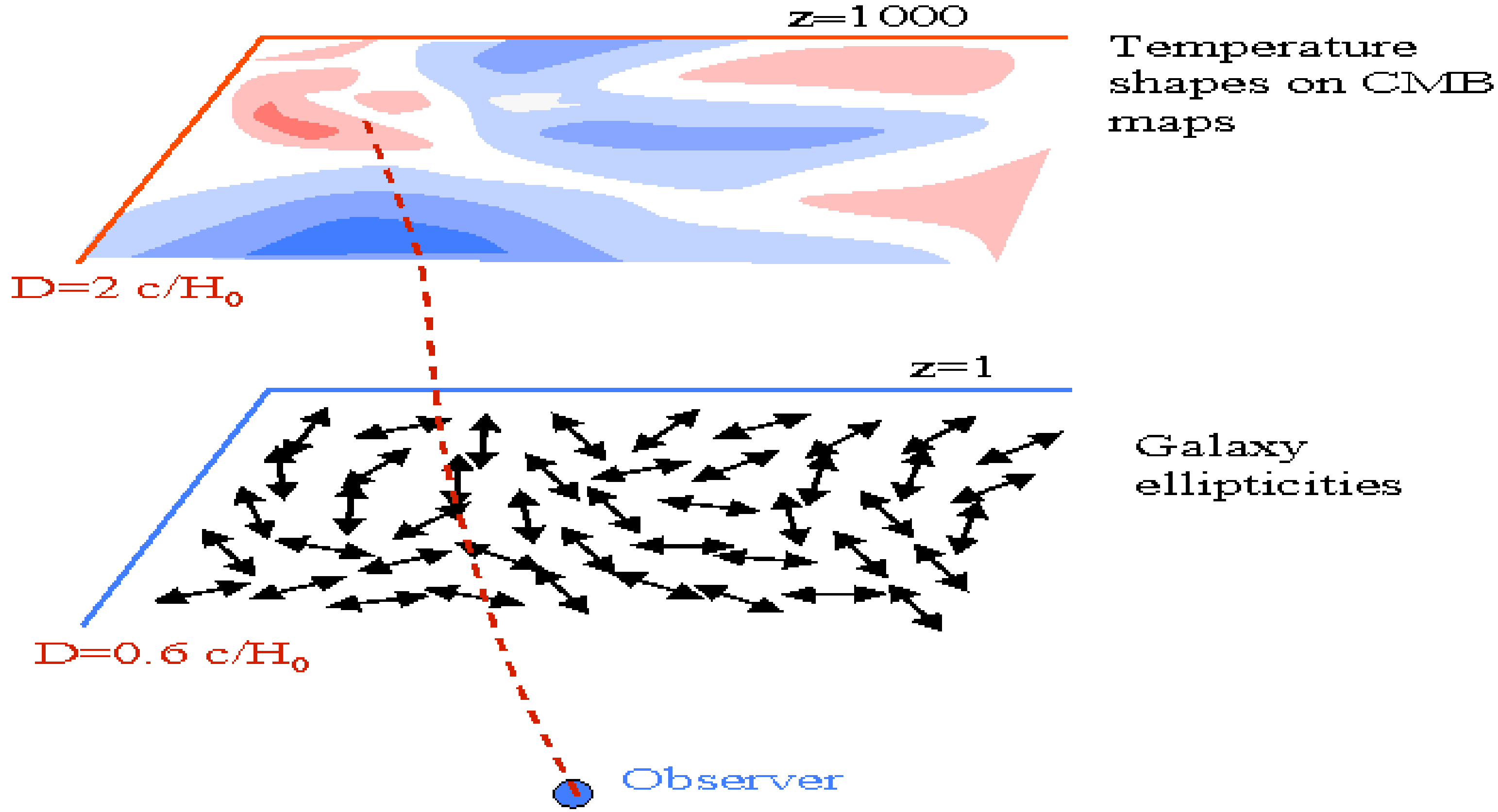
Cosmological inflation.

The effect is almost certainly real.

The cause?

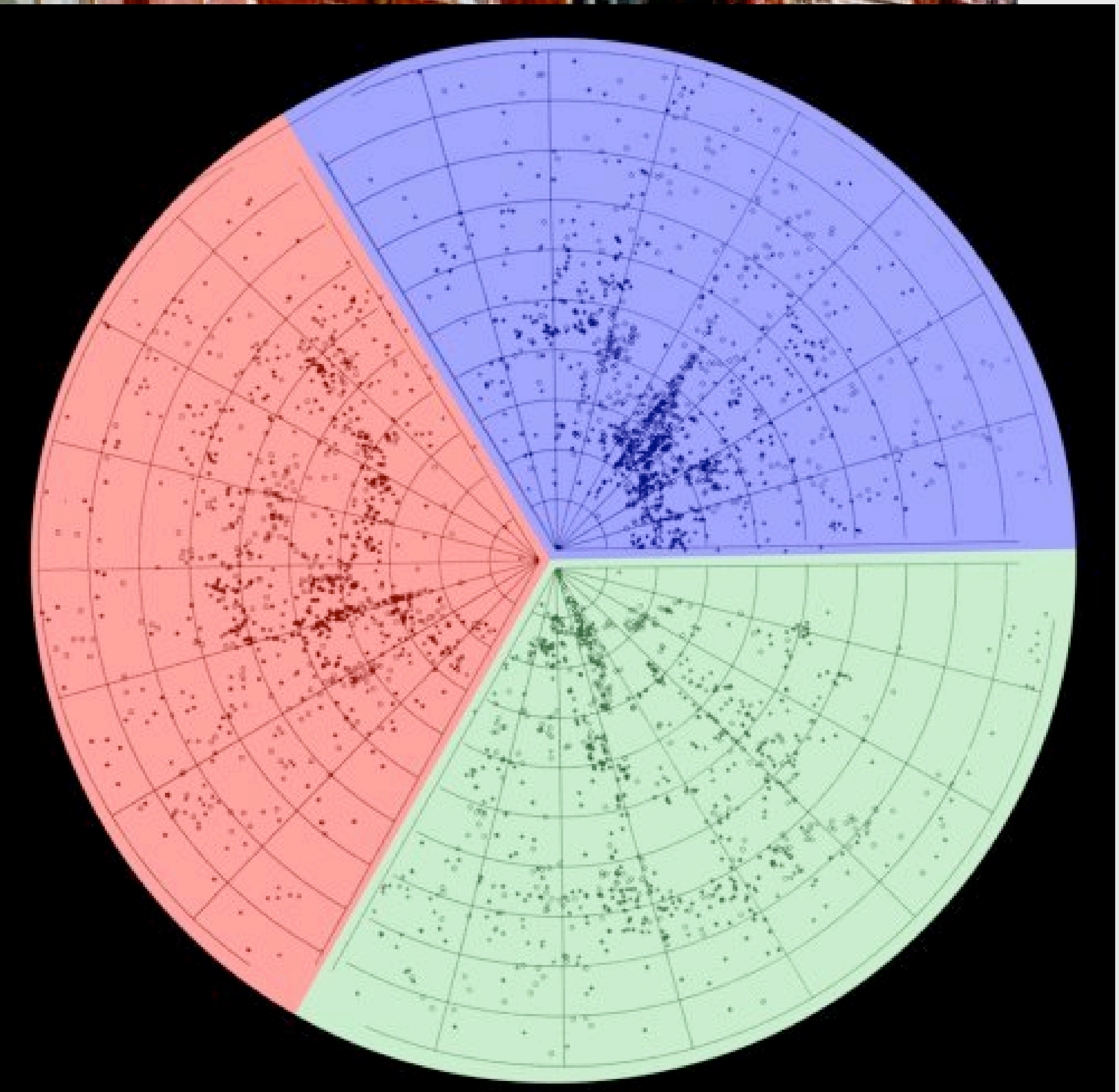


Galaxy-CMB shape correlations



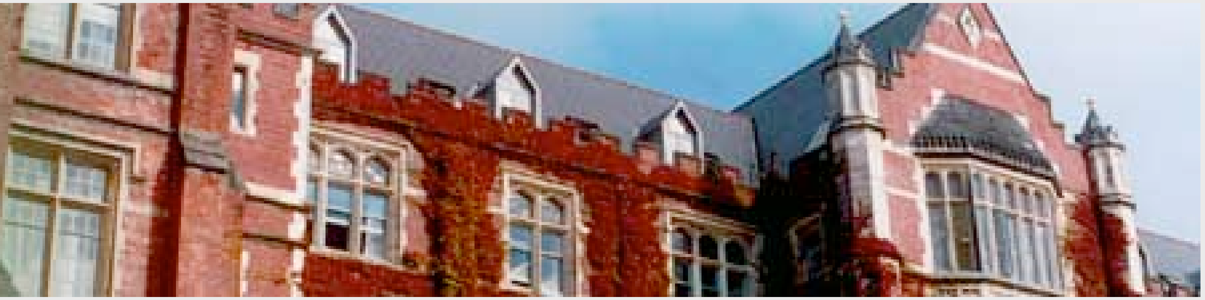
Is there a significant amount of correlation?

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui



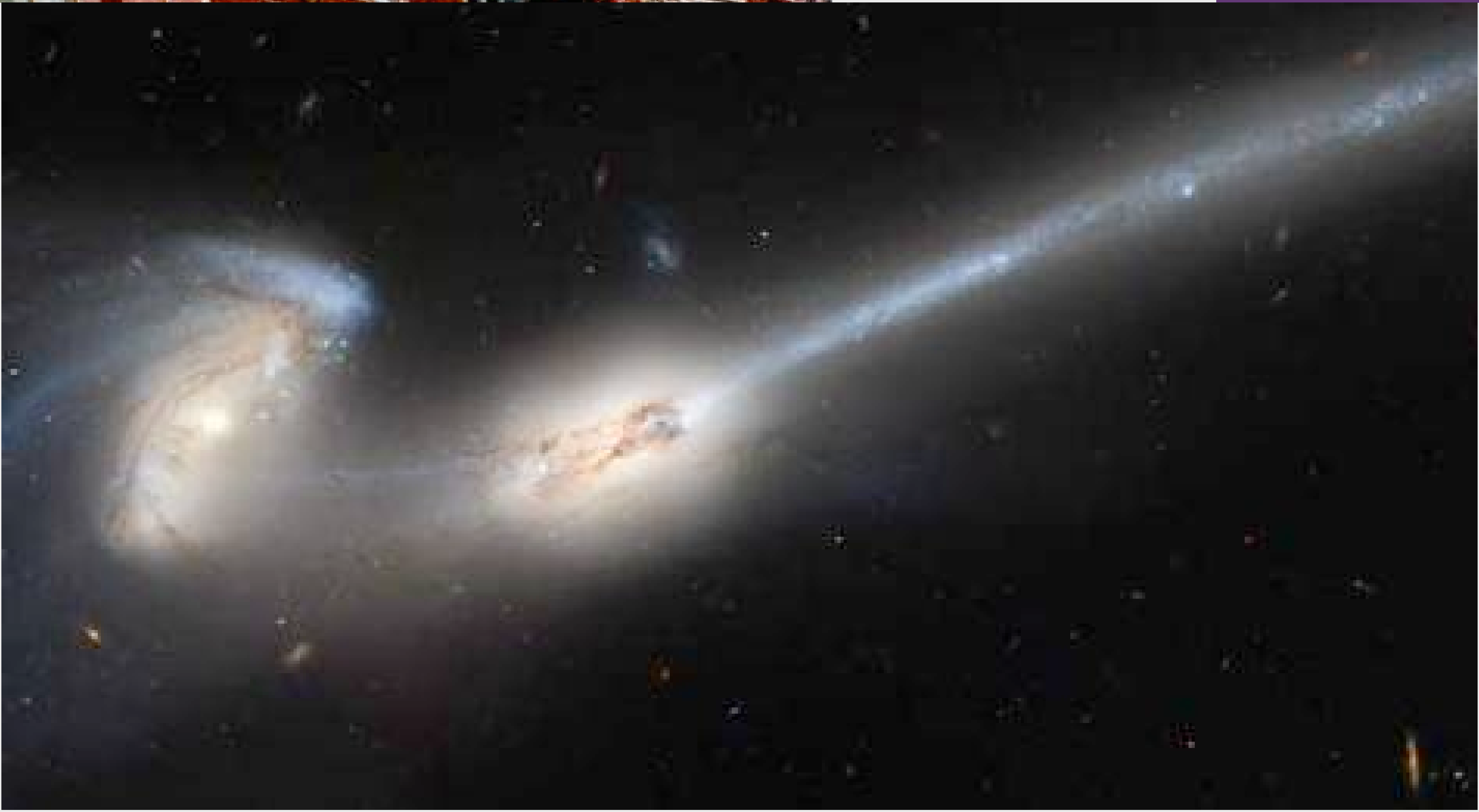
Two of these are simulations of galaxy distributions,
one is observational data...

Chain of galaxies



Tadpole galaxy

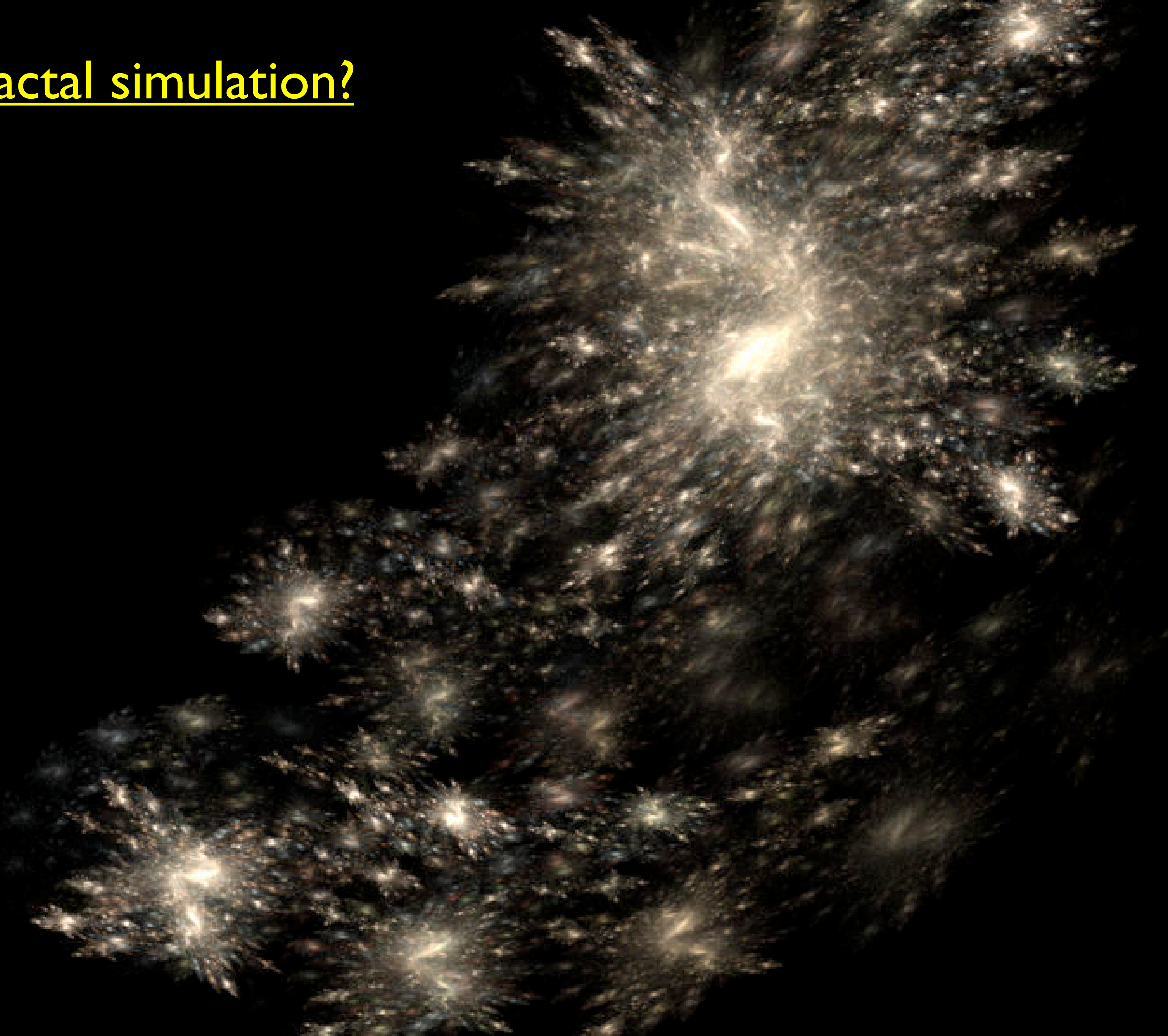
Mice



There’s more to structure than just galaxies!

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

Fractal simulation?



Where are the bodies buried?

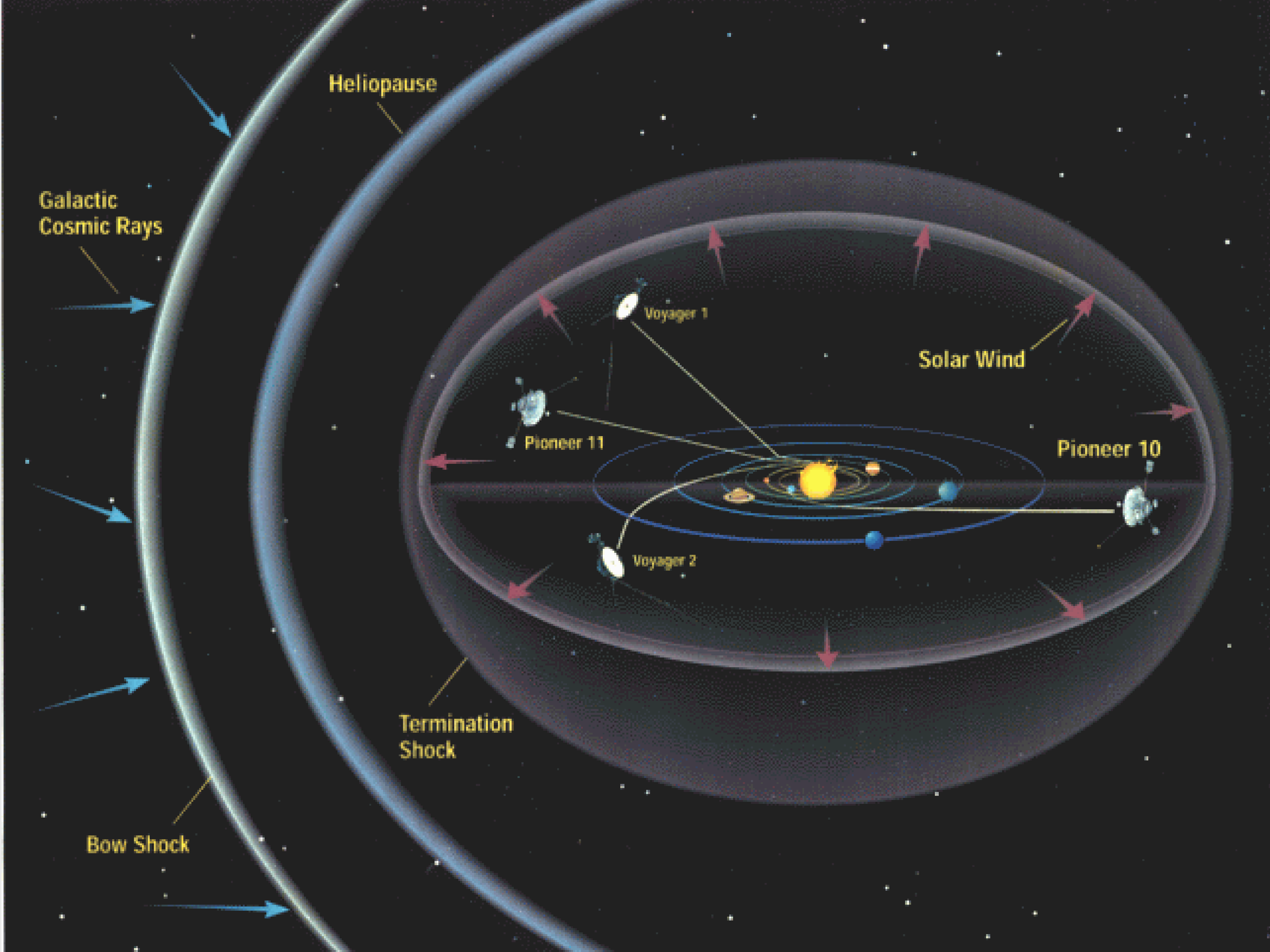
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

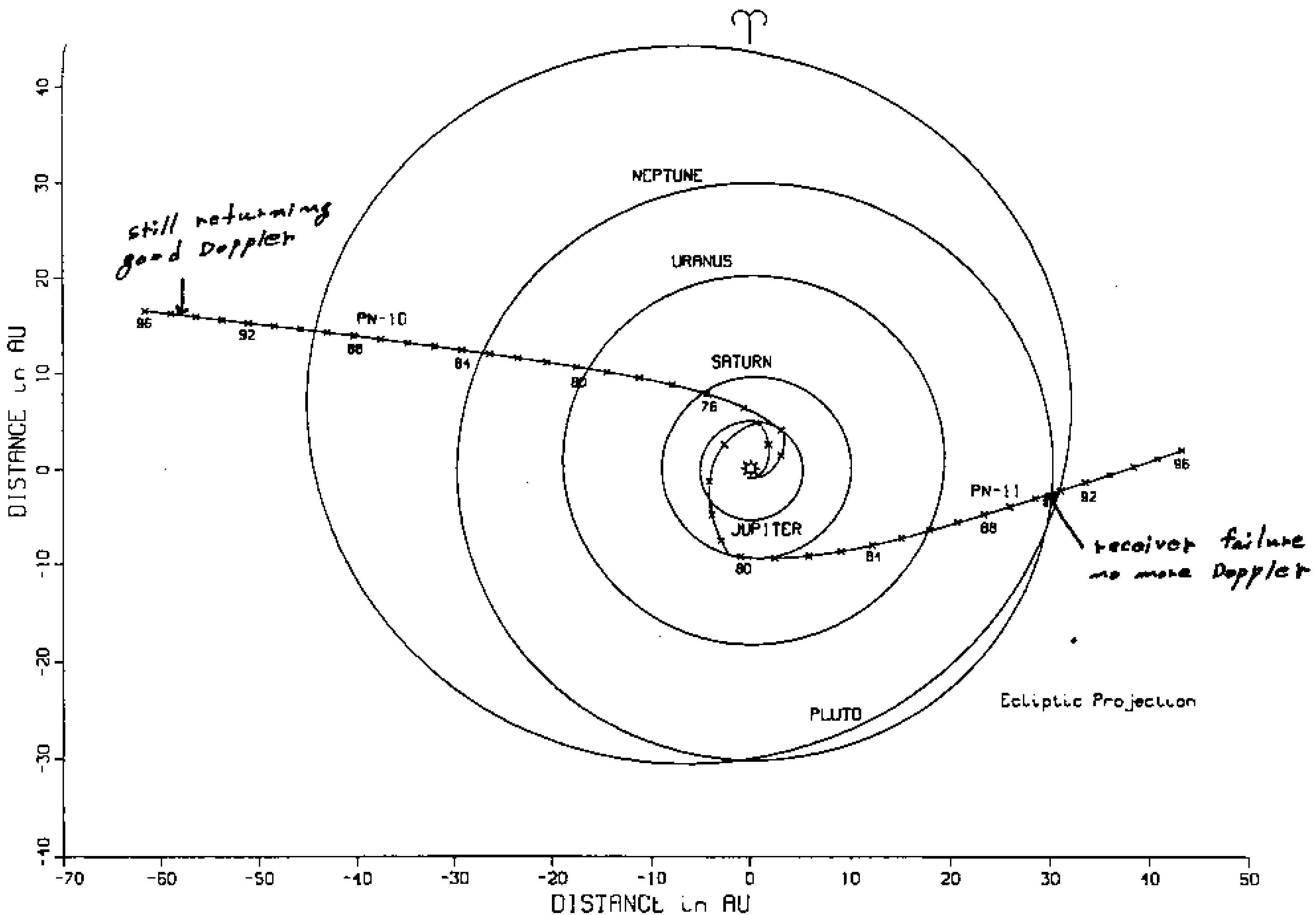
Pioneer anomaly

Dark matter

Dark energy

Overall mass-energy budget


Heliopause
Galactic
Cosmic Rays
Voyager 1
Solar Wind
Pioneer 11
Pioneer 10
Voyager 2
Termination
Shock
Bow Shock



NASA/AMES
PPO/88-1.1-2
D' 3/2/94

Pioneer anomaly?

Pioneer 10 and 11 have been tracked for about 30 years.

They are not quite doing what we expect.

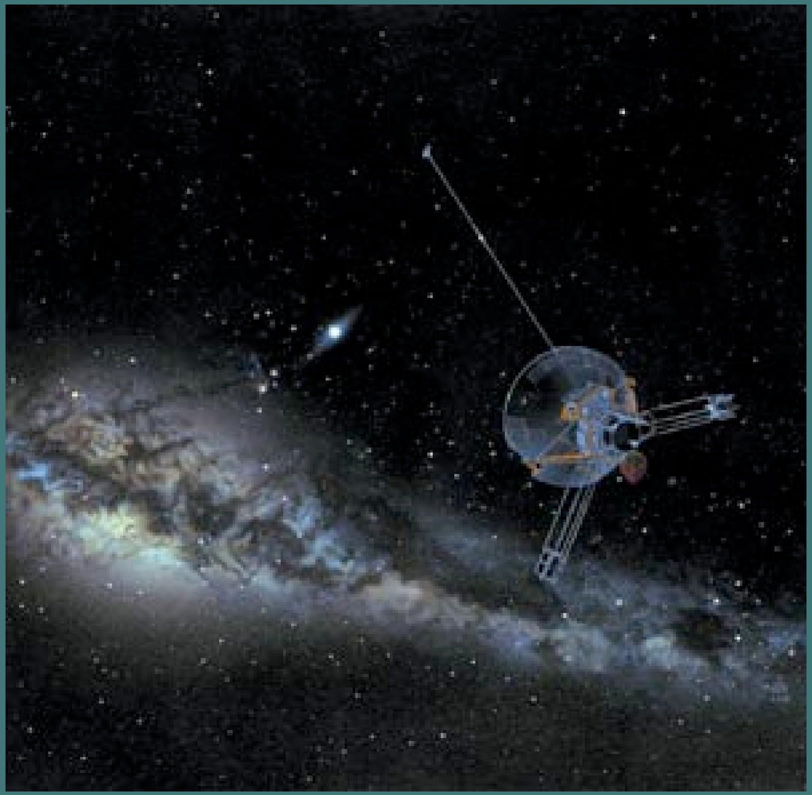
Small "anomalous" acceleration.

Directed toward the Sun.

Magnitude: $$a_{\mathrm{anomalous}} \approx c\, H_0$$

Pioneer anomaly?

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui



Say what?

What's the Hubble parameter doing in solar system physics?

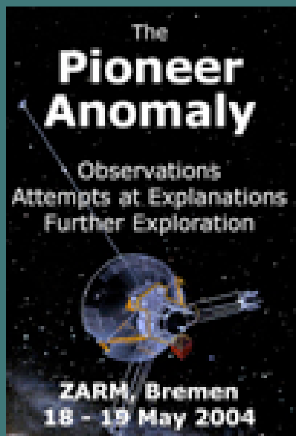
There's no really good model for what is going on.

It could just be noise: $a_{\text{anomalous}} \approx 10^{-9}\, m\, s^{-2} \approx 10^{-10}\, g$

But if it's real, it's just plain weird...

Pioneer anomaly?

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga o te Ūpoko o te Ika a Māui



People are still very puzzled...

Breakdown of inverse square law at solar system scales?

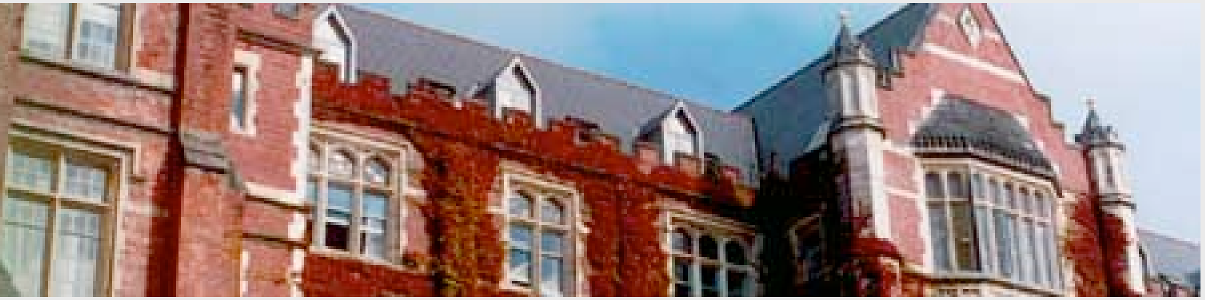
F= G m m' /r^2 + m' a_P + ... ?

$$a_P = (8.74 \pm 1.33) \times 10^{-8} cm/s^2$$

Dark matter?

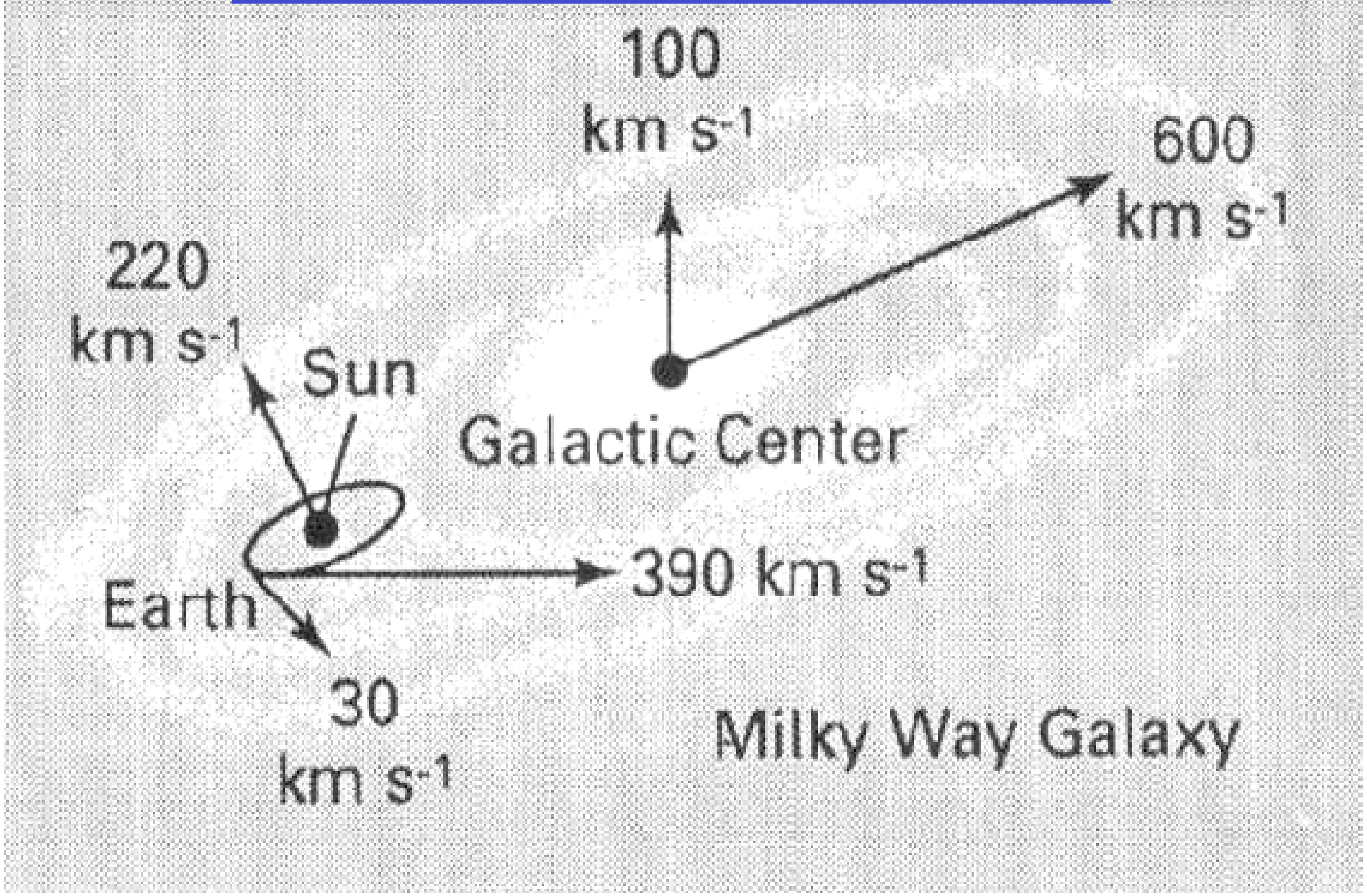
AKA: Galactic "missing mass"

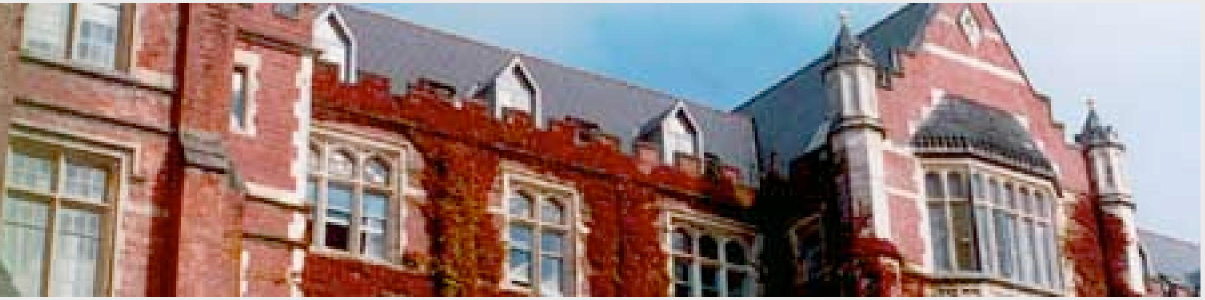
Buzz phrase: Galaxy rotation curves



Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

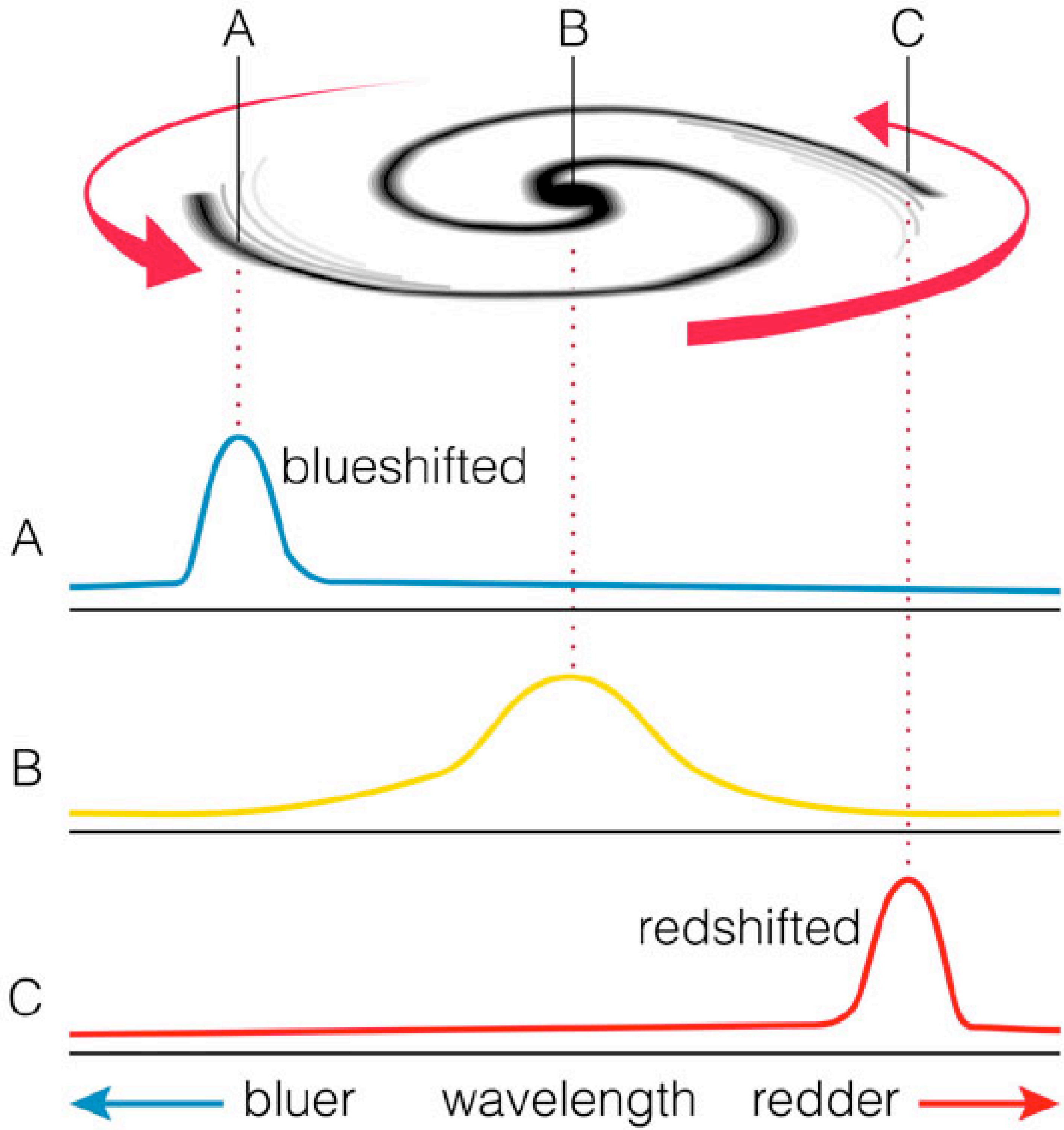
This is our vantage point in the Universe

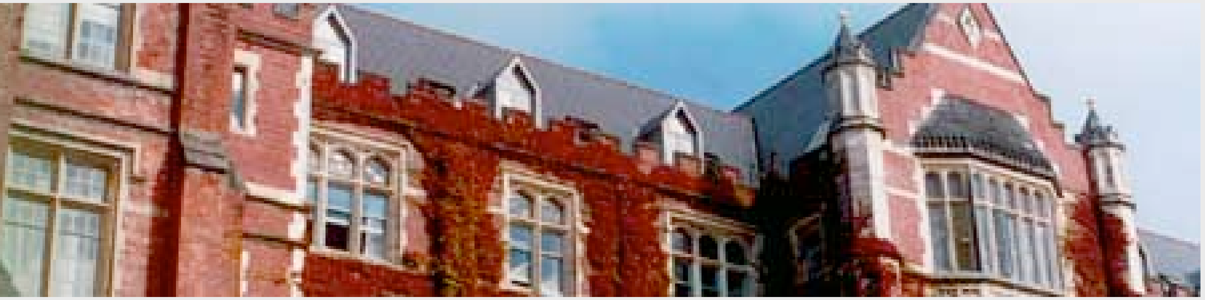


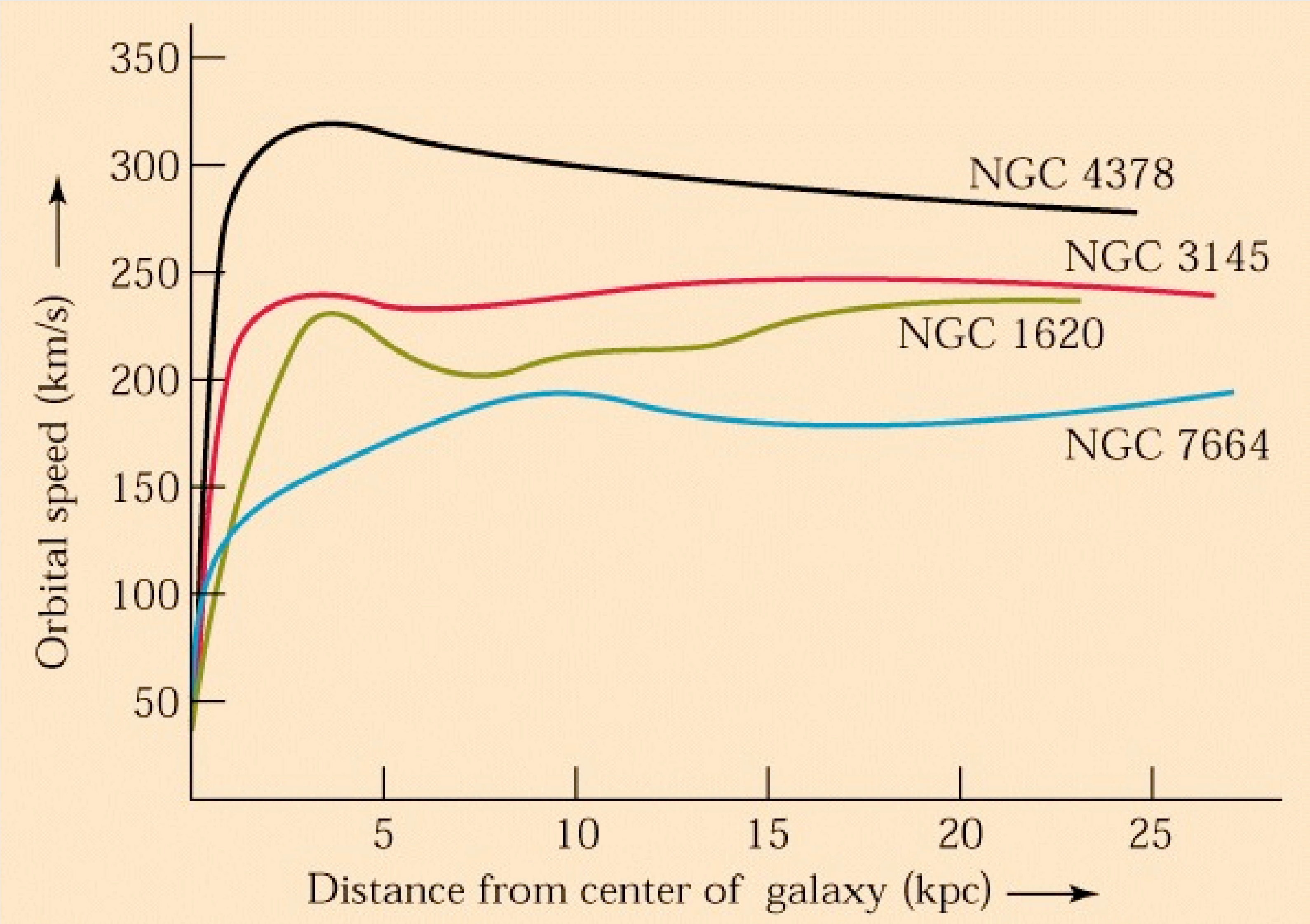


Andromeda galaxy

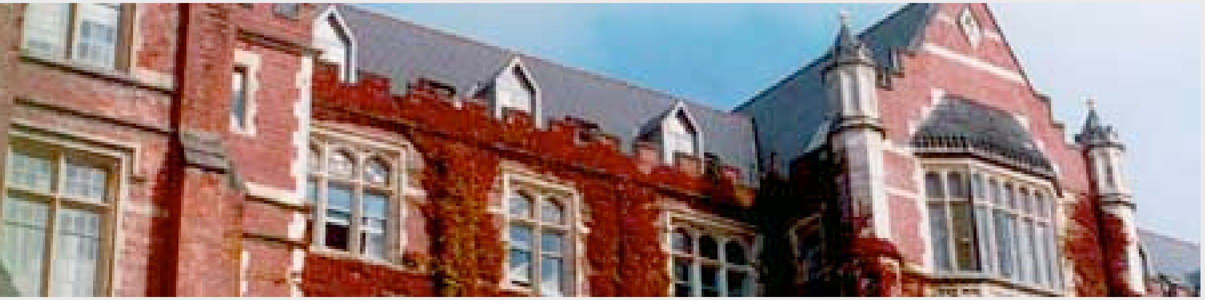
Magellanic clouds

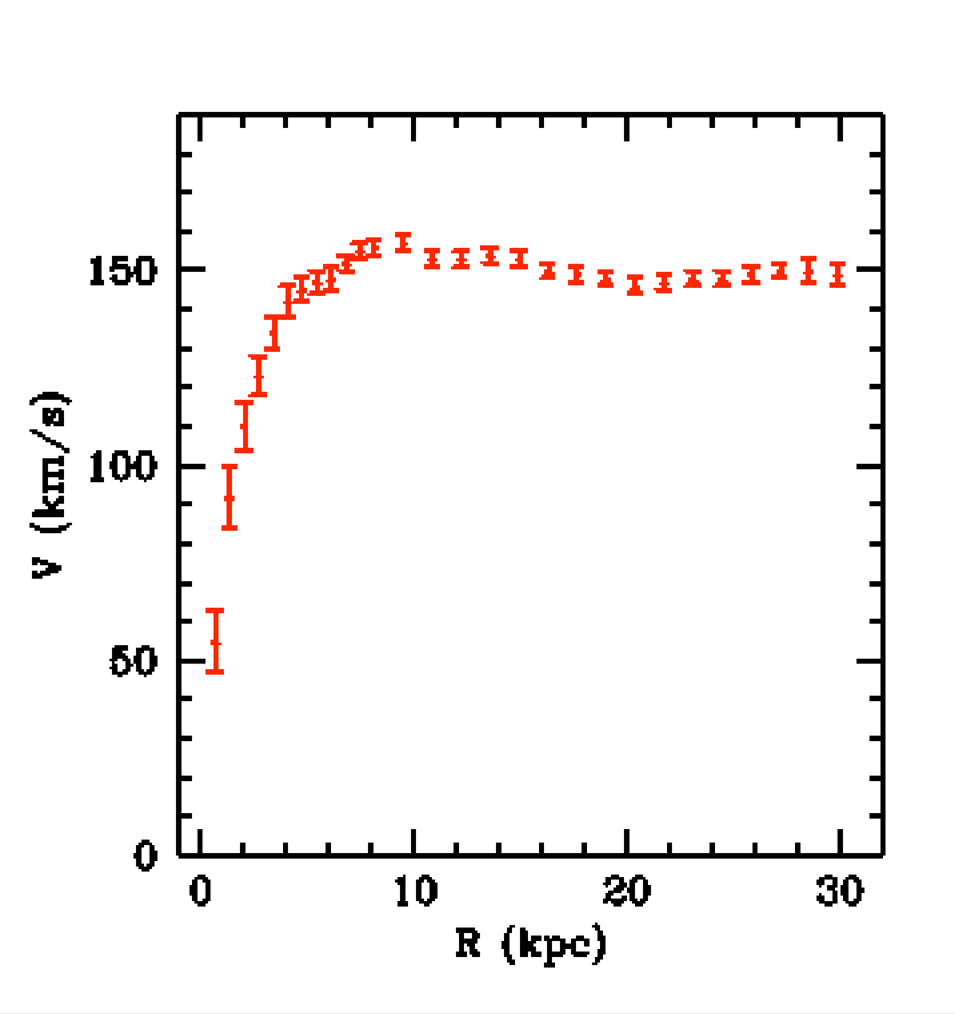

A
B
C
blueshifted
A
B
redshifted
C
bluer
wavelength
redder



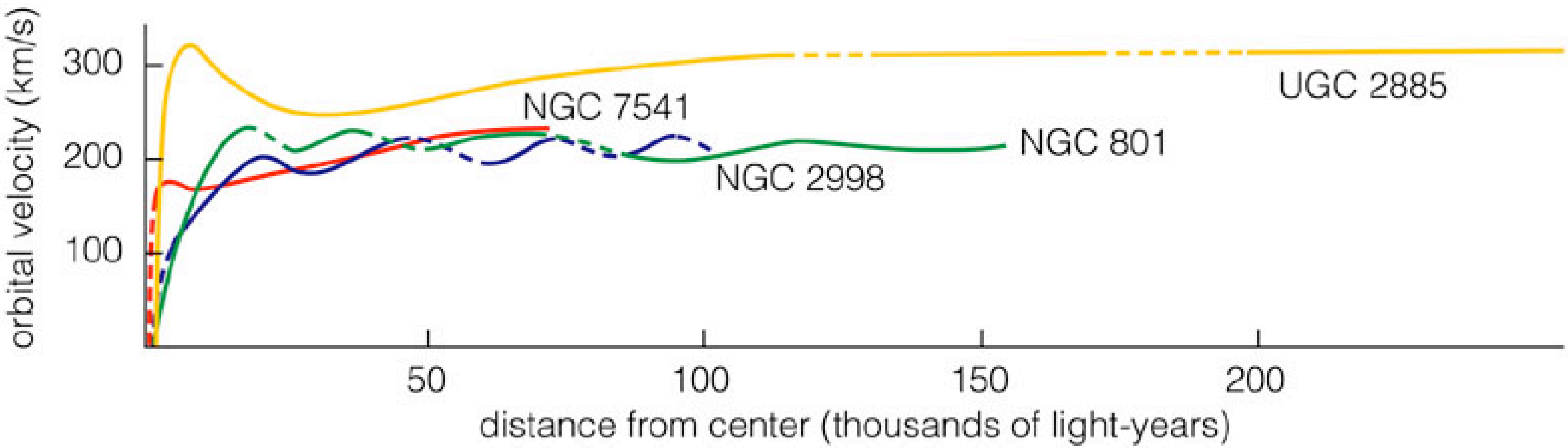


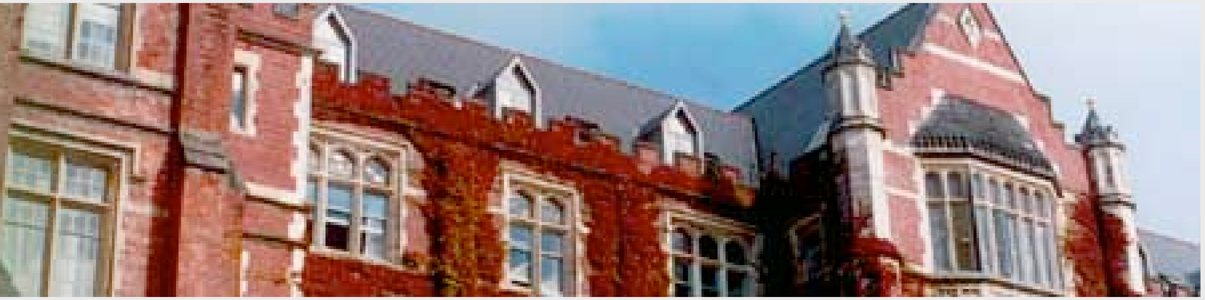
350
300
250
200
150
100
50
Orbital speed (km/s)
NGC 4378
NGC 3145
NGC 1620
NGC 7664
5
10
15
20
25
Distance from center of galaxy (kpc)

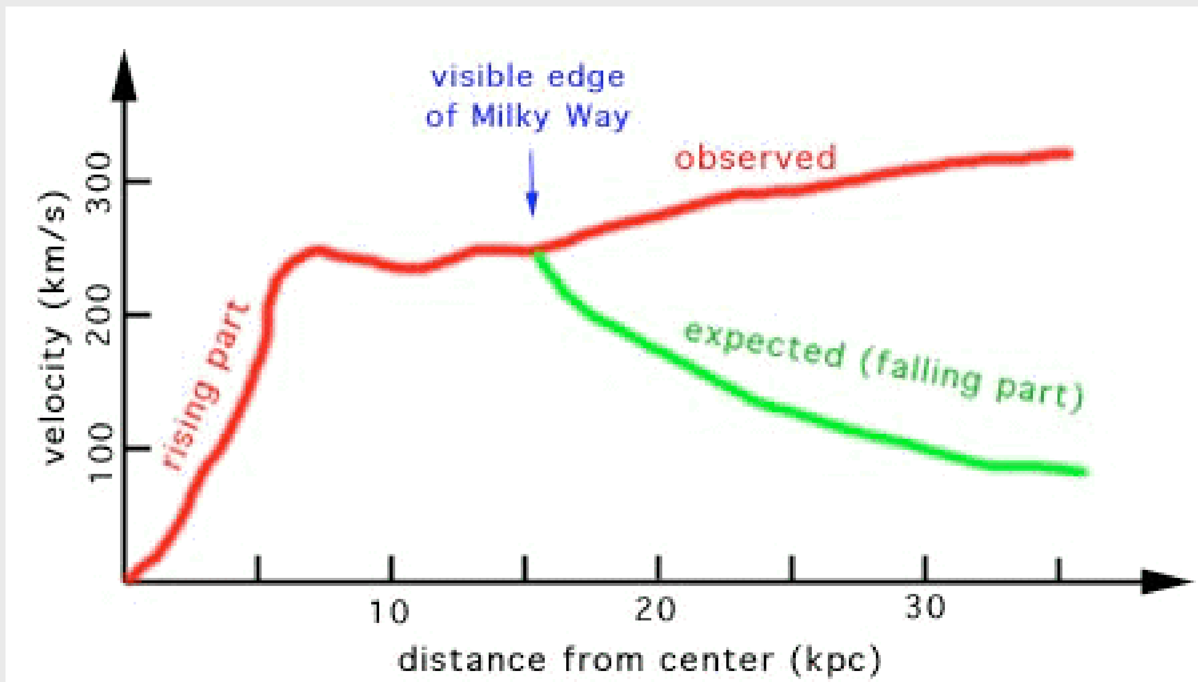




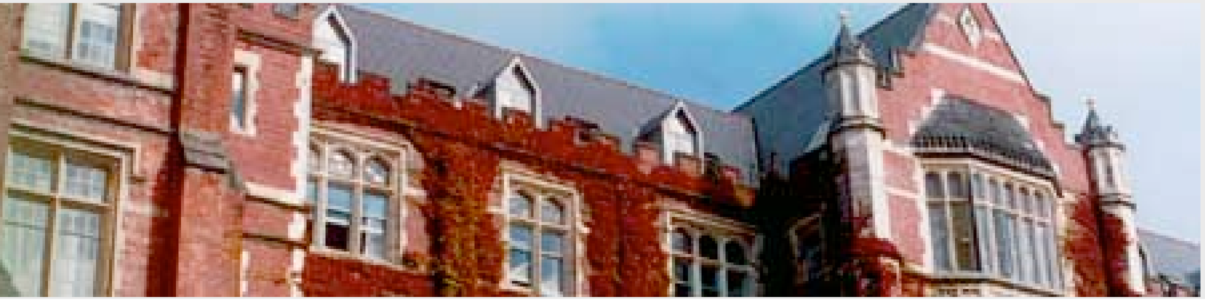
NGC3198

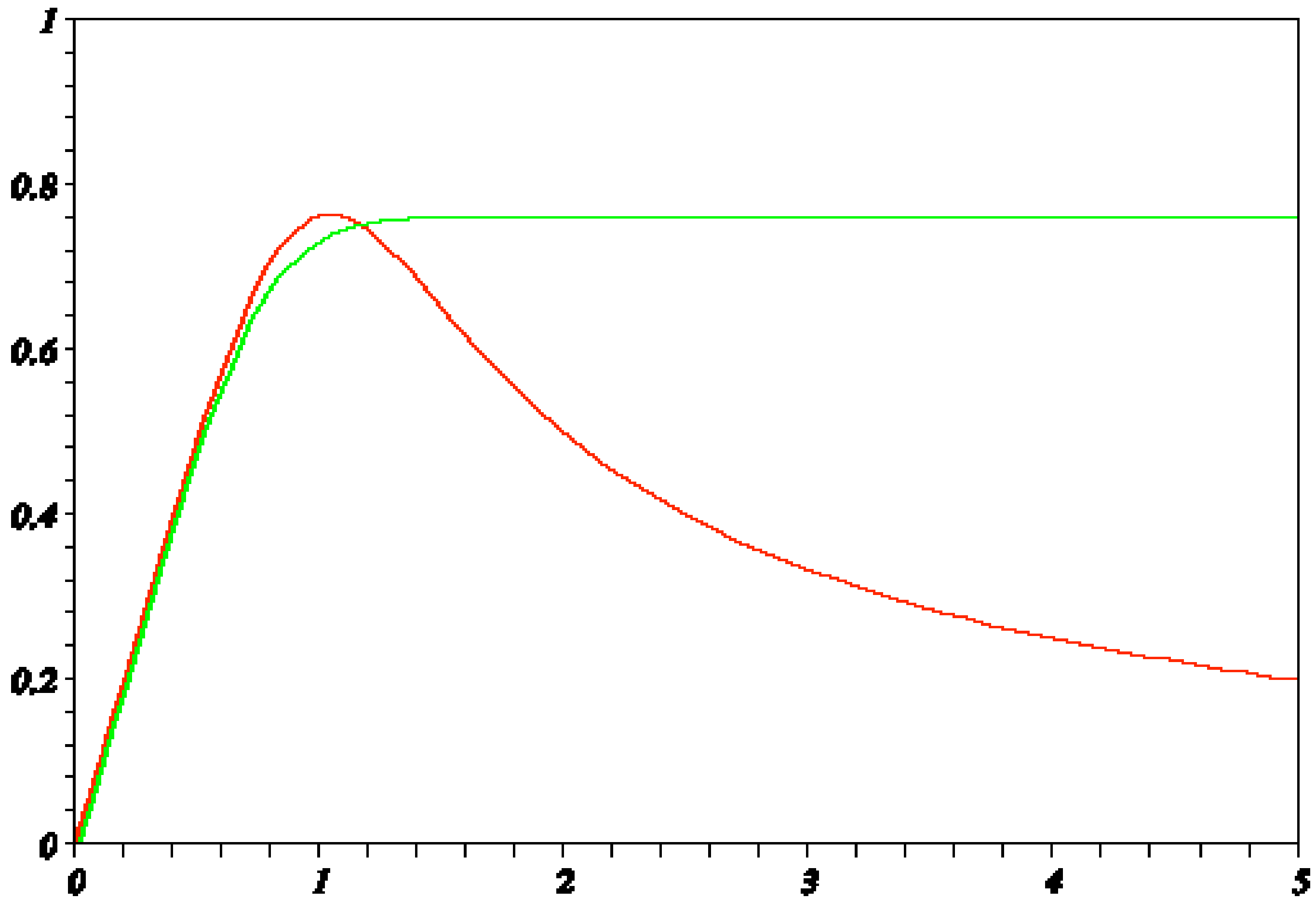

orbital velocity (km/s)
300
200
100
50
100
150
200
distance from center (thousands of light-years)
UGC 2885
NGC 7541
NGC 801
NGC 2998





Our own galaxy --- the Milky way --- shows the same effect.

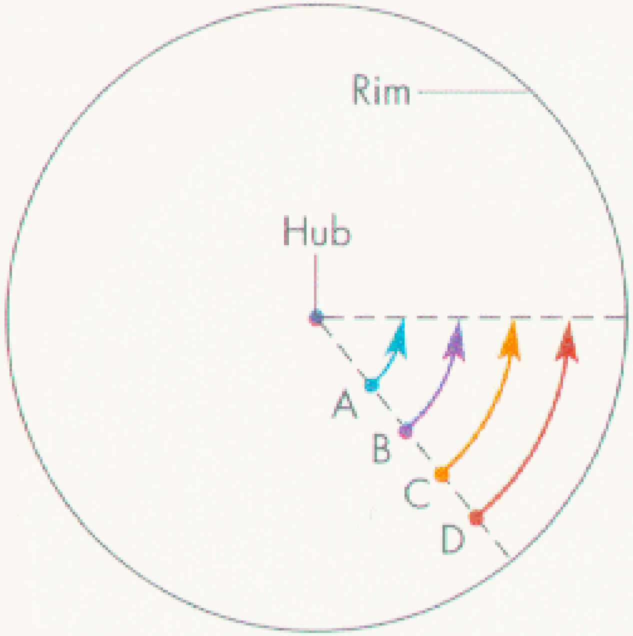




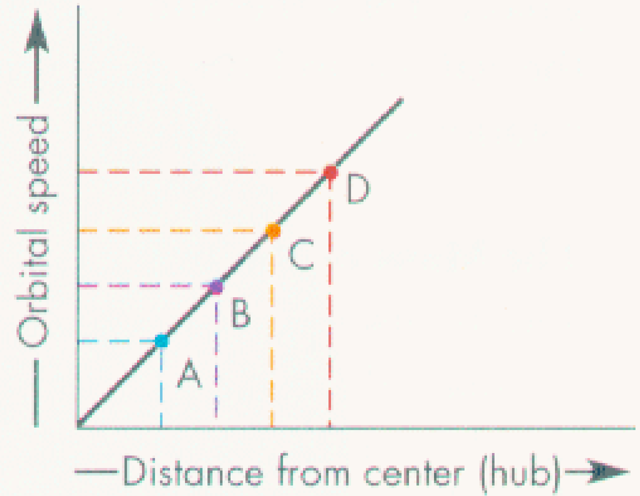
Observed:
Approximately constant

Expected:
Kepler falloff

Schematic galaxy rotation curve

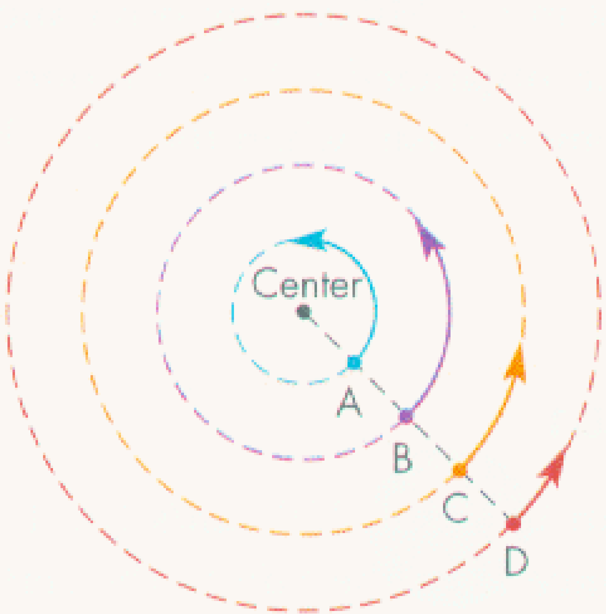


Wheel-like rotation

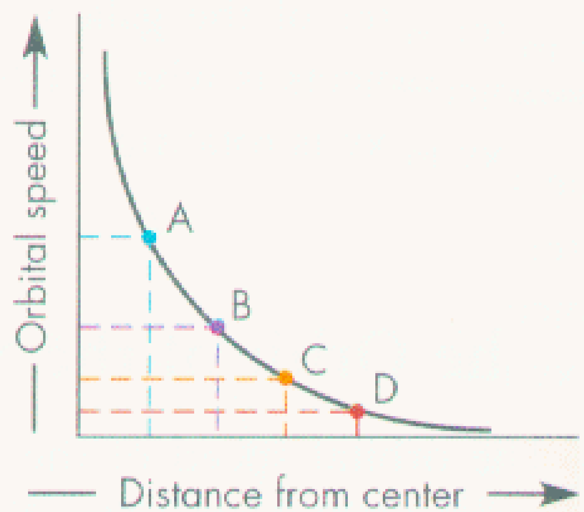


Rotation curve for wheel-like rotation

We do see this in the galactic core

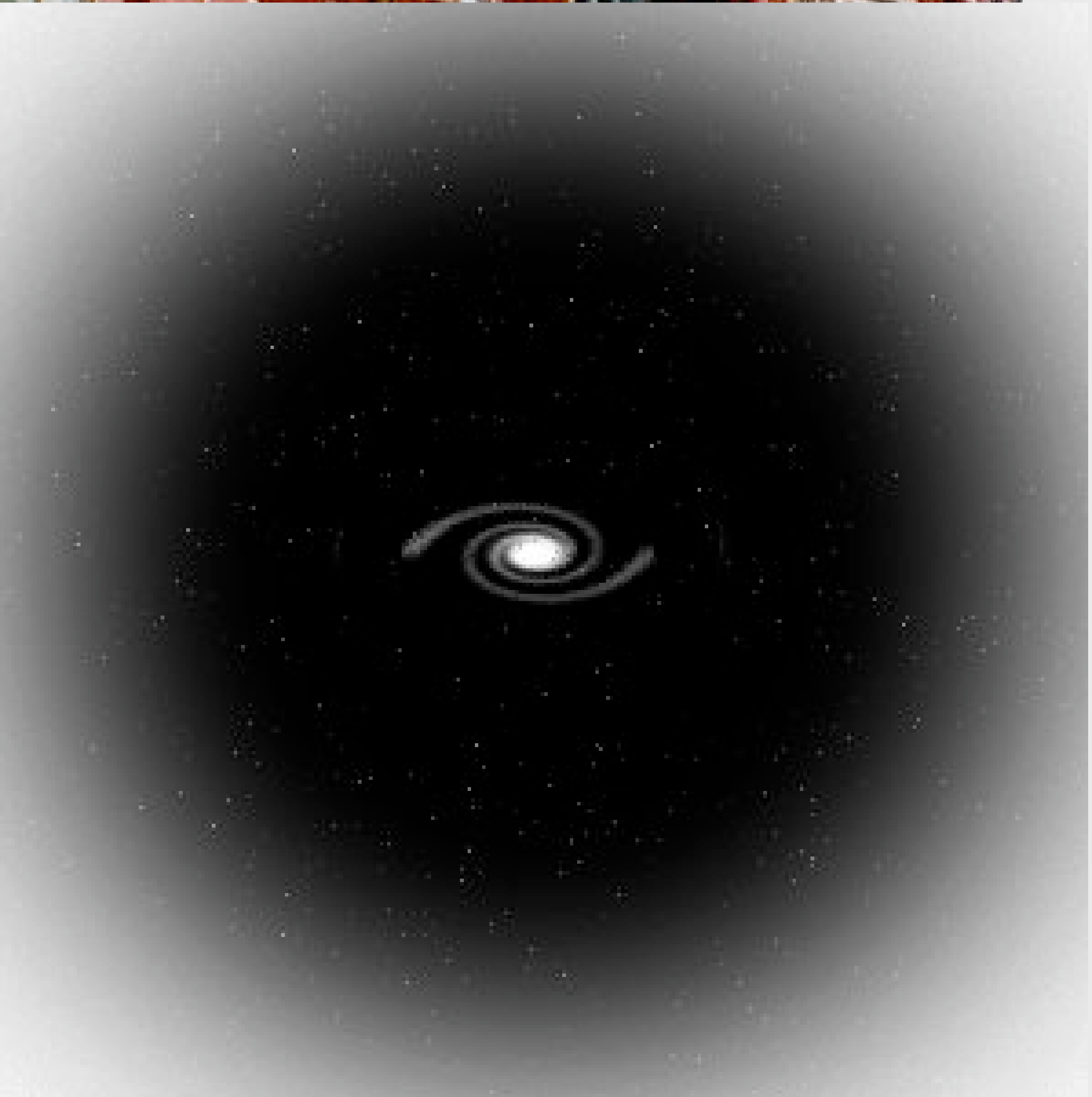


Planet-like rotation



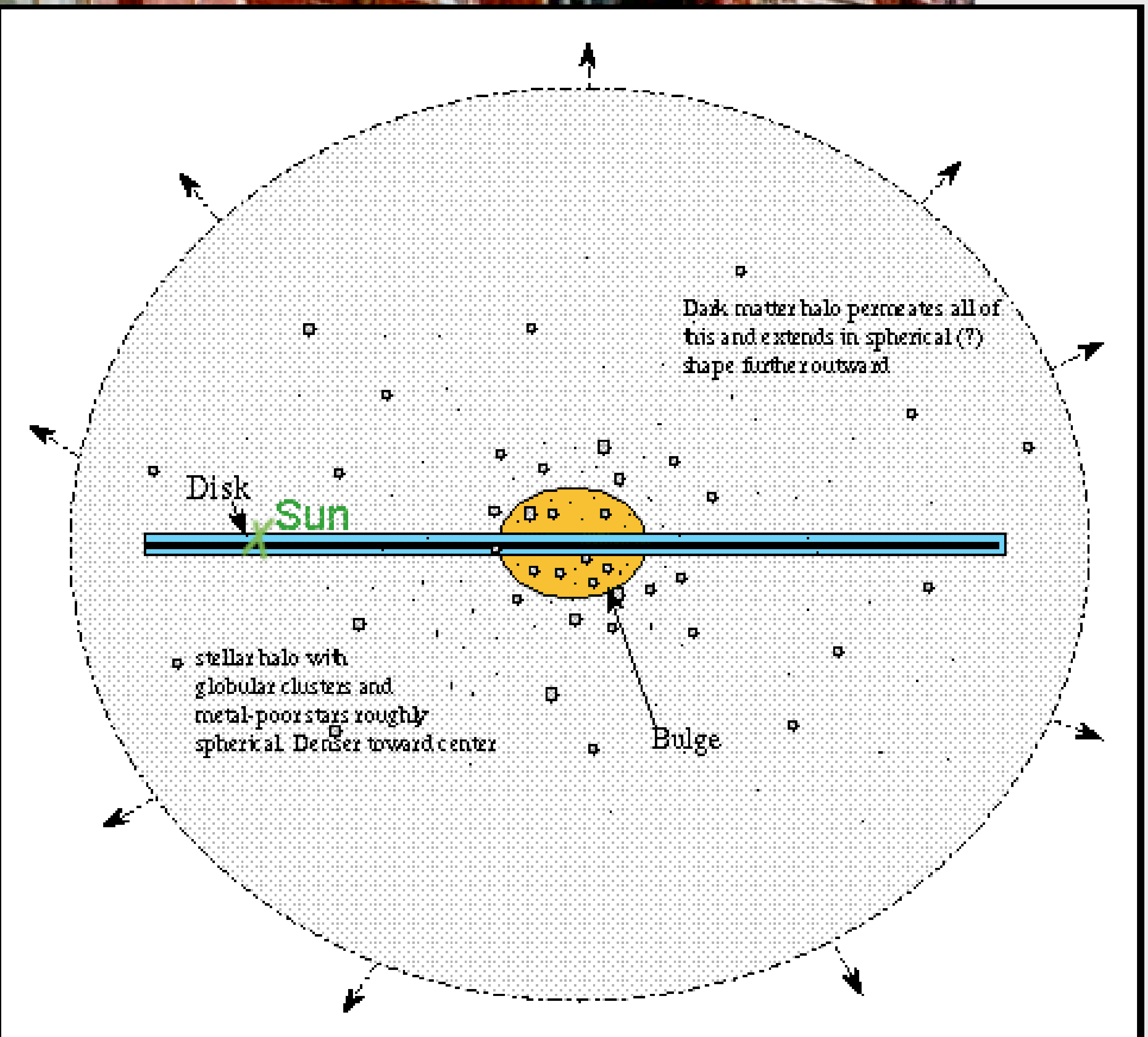
Rotation curve for planet-like rotation

We expect this, but don't see this, in the galactic disk



What a spiral galaxy really looks like....

Dark matter halo out to beyond the visible disk



Density falloff:

1/r^2

But what is the dark matter?

Nobody knows

Dark matter?

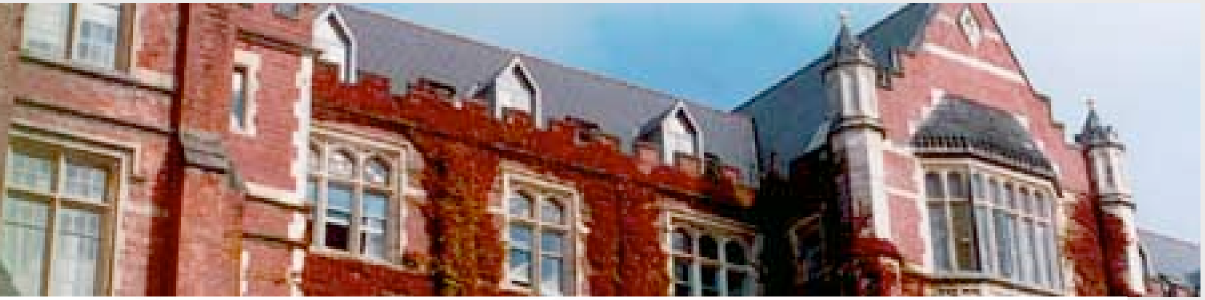
Dark matter makes up about 90% of the mass of typical spiral galaxies

We only detect it through its gravitational effects

As yet we have no direct verification of its existence

Possibilities:

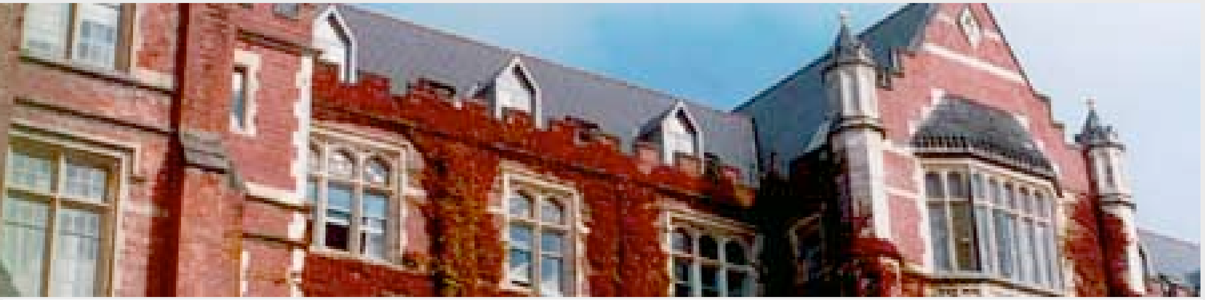
- Massive neutrinos
- Axions
- Wimps
- Sparticles
- Bose condensates



Axion (invisible axion):

mysterious particle beloved by particle physicists

SUSY:



Particles and Sparticles

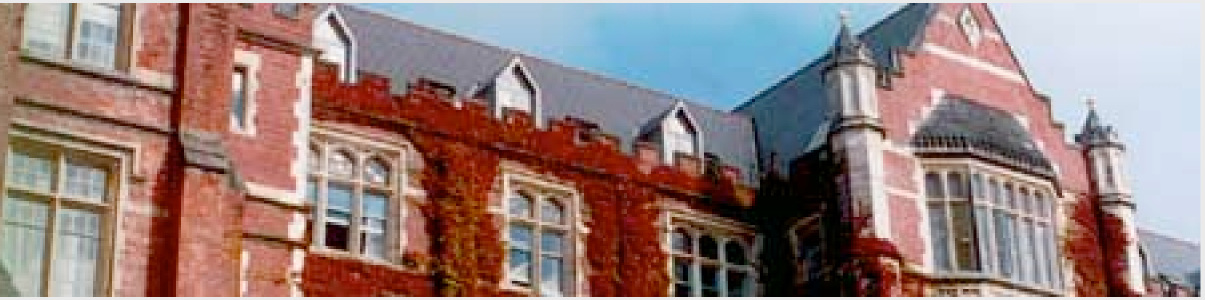
Matter particles and their proposed superpartners		Force particles and their proposed superpartners	
Particle Name	Superpartner Particle	Particle Name	Superpartner Particle
Quark	Squark	Graviton*	Gravitino
Neutrino	Sneutrino	$W^{+/-}$	$Wino^{+/-}$
Electron	Selectron	Z^0	Zino
Muon	Smuon	Photon	Photino
Tau	Stau	Gluon	Gluino
		Higgs* boson	Higgsino

Supersymmetry doubles the particle spectrum

The lightest susy-partner is likely to be stable

Wimps

Weakly interacting massive particles



Wimps

Suspect Relic	Mass	Origin t, T	Abundance cm^{-3}
Invisible Axion	10^{-5}eV	10^{-30}sec, 10^{12}GeV	10^{9}
Light Neutrino	30 eV	1 sec, 1 MeV	100
Photino—Gravitino	keV	10^{-4}sec, 100 MeV	10
Photino—Sneutrino—Neutralino—Axino—Heavy Neutrino	GeV	10^{-3}sec, 10 MeV	10^{-5}
Magnetic Monopoles	10^{16}GeV	10^{-34}sec, 10^{14}GeV	10^{-21}
Pyrgons—Maximons—Newtorites	10^{19}GeV	10^{-43}sec, 10^{19}GeV	10^{-24}
Quark Nuggets	$\simeq 10^{15}$g	10^{-5}sec, 300 MeV	10^{-44}
Primordial Black Holes	$\gtrsim 10^{15}$g	$\gtrsim 10^{-12}$sec, $\lesssim 10^{3}$GeV	$\lesssim 10^{-44}$

Table 9.1: WIMP candidates for the dark matter. The cosmic abundance required for closure density is $n_{\rm WIMP} \simeq 1.05h^2 \times 10^{-5}{\rm cm}^{-3}/m_{\rm WIMP}({\rm GeV})$.

There are many wimp candidates

Dark matter?

Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

Really weird possibilities:

MOND: (MOdified Newtonian Dynamics?)

F = m a f(a/a_0); a_0 approx 10^{-11} g.

Breakdown of inverse square law at galactic scales?

F= G m m' /r^2 + G m m'/(r R) + ...

R approx 10 kilo-parsec

Does not mesh well with the Pioneer anomaly

Dark energy:

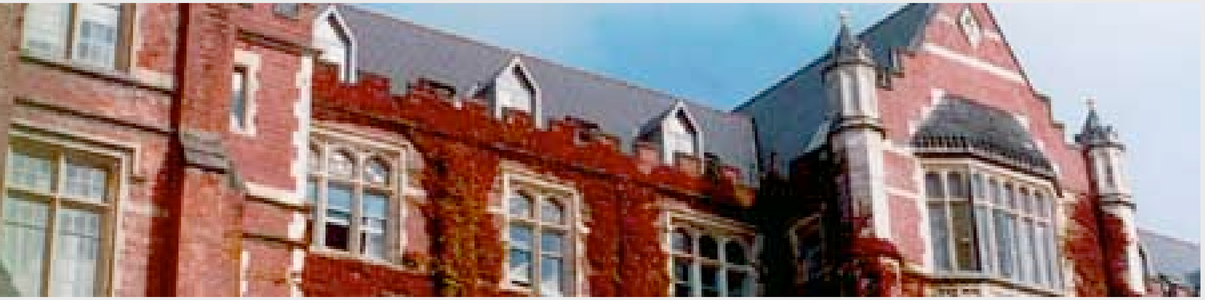
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga o te Ūpoko o te Ika a Māui

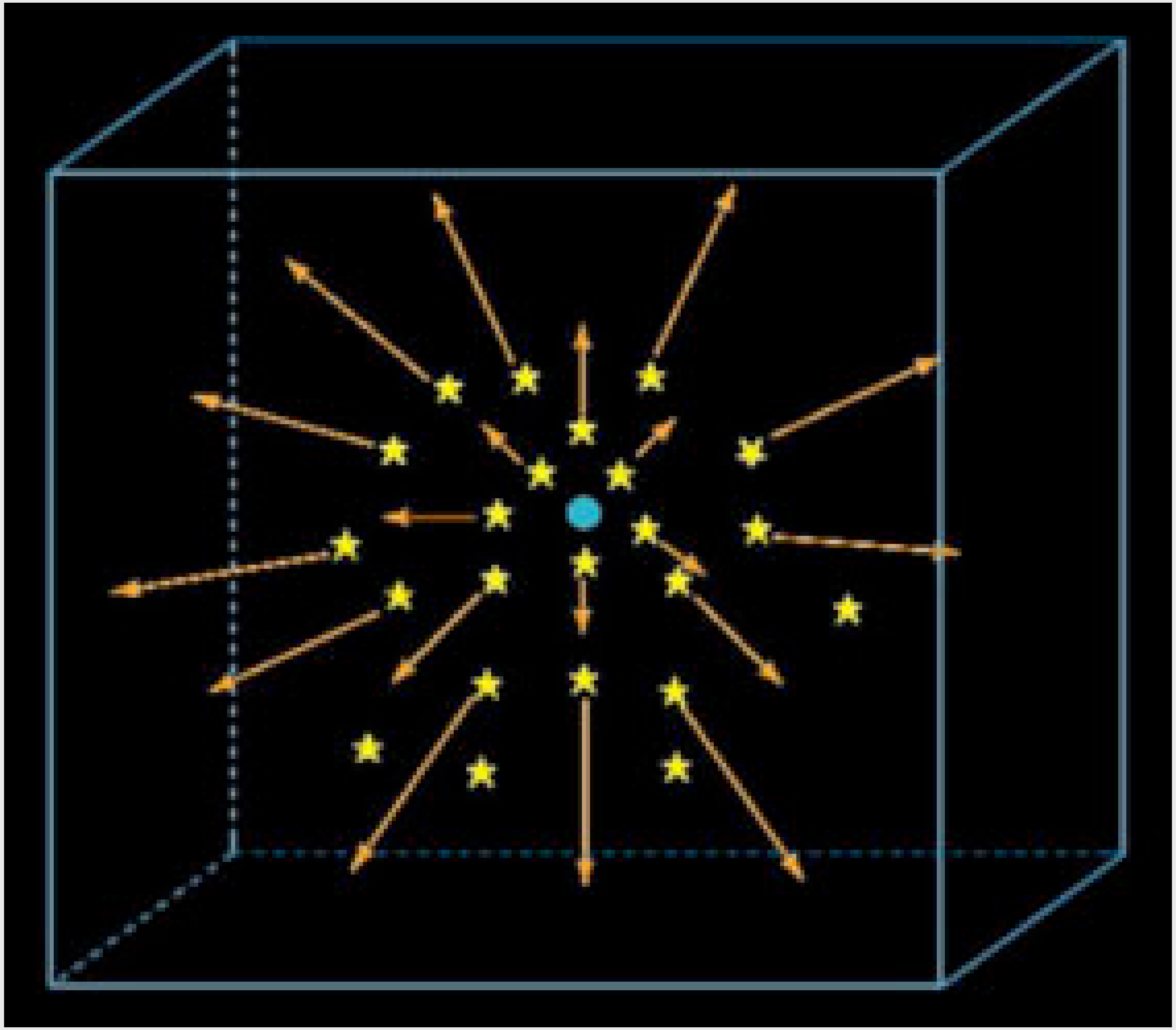
AKA: Cosmological constant

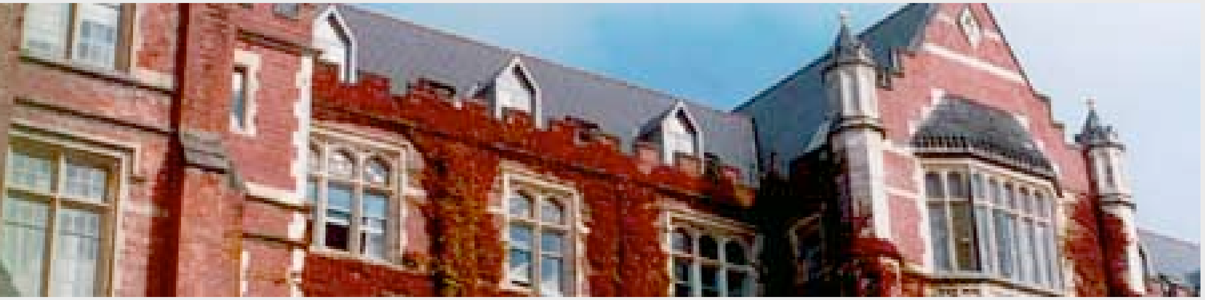
AKA: Quintessence

AKA: Accelerating universe

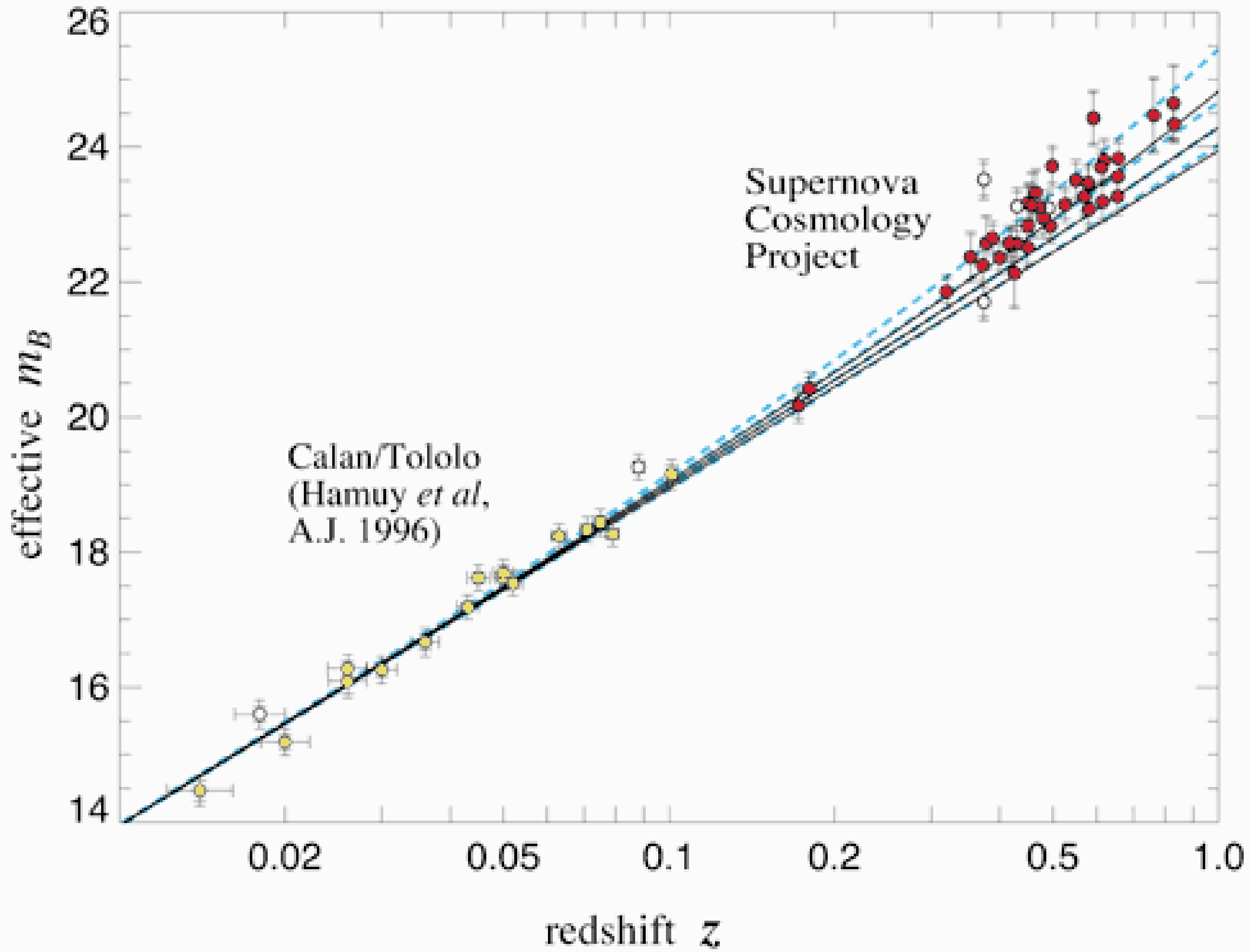

DARK
ENERGY
PLANT NUTRIENT ADDITIVE
It Stinx
But
It Rocks!!

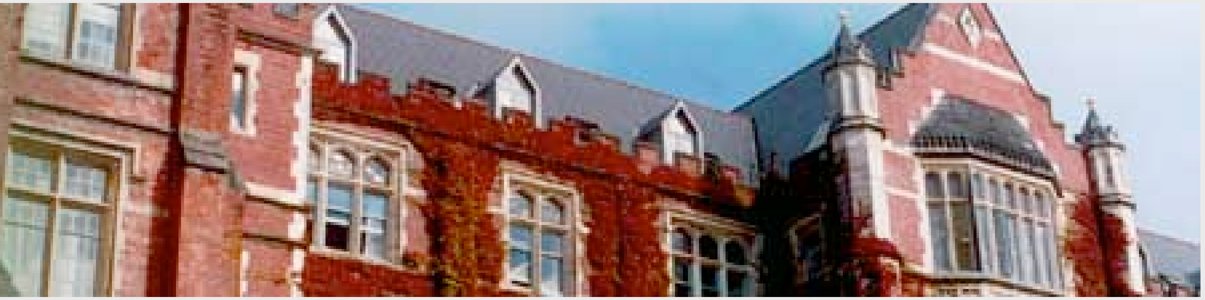


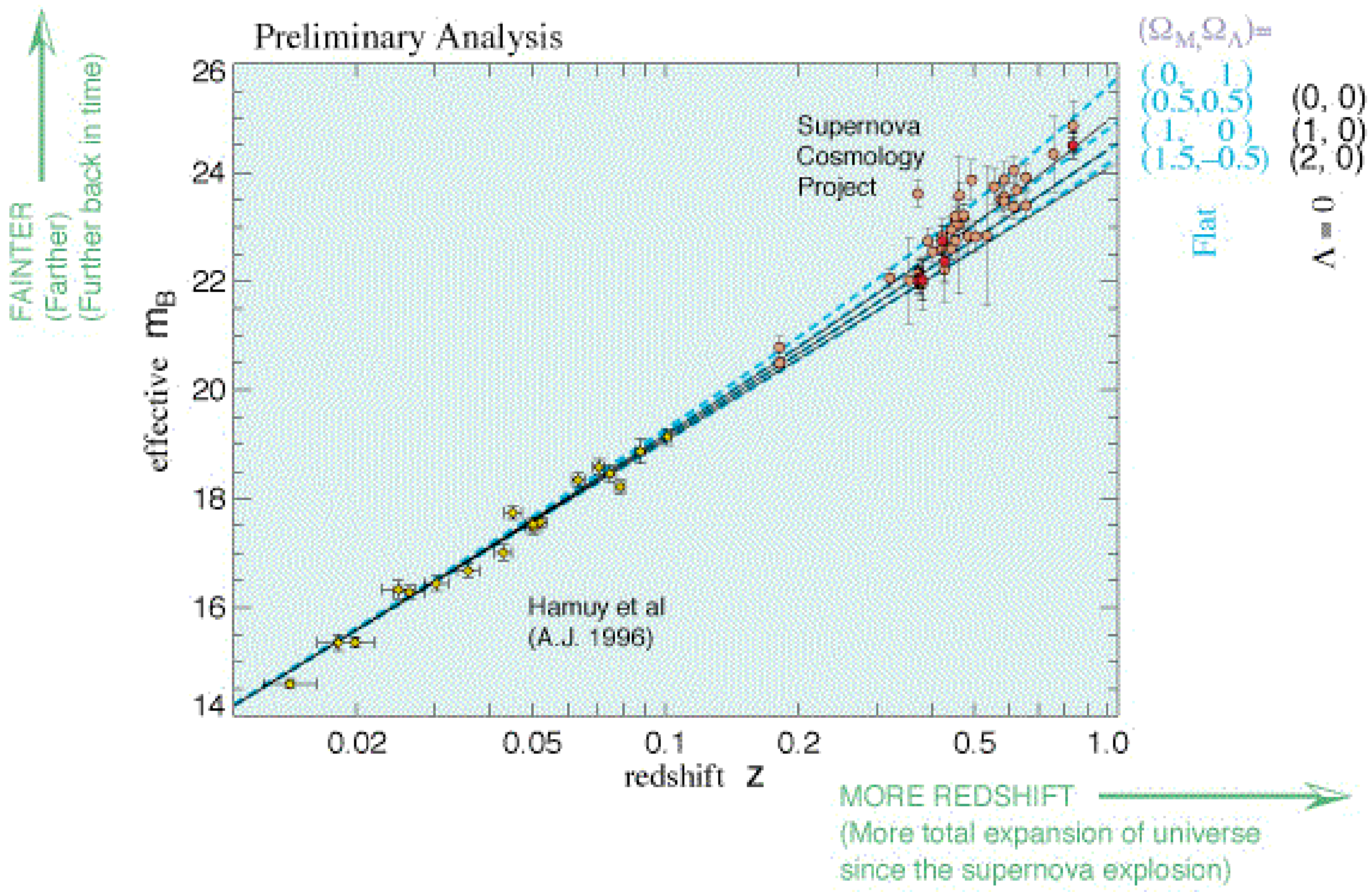




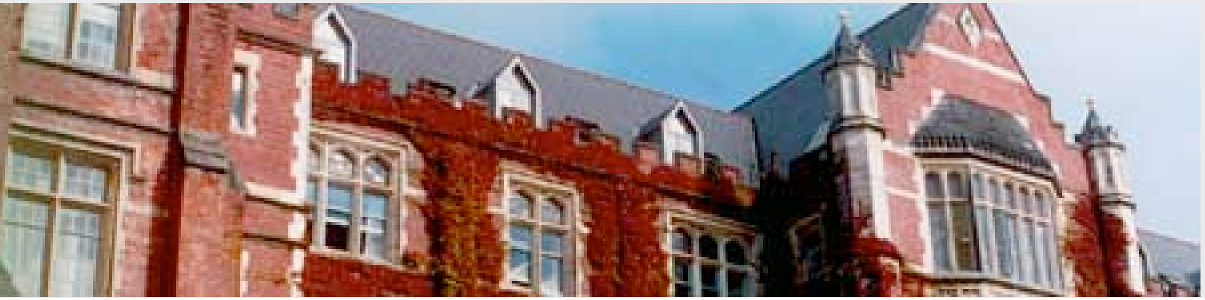
Supernova Cosmology Project
Perlmutter *et al.* (1998)

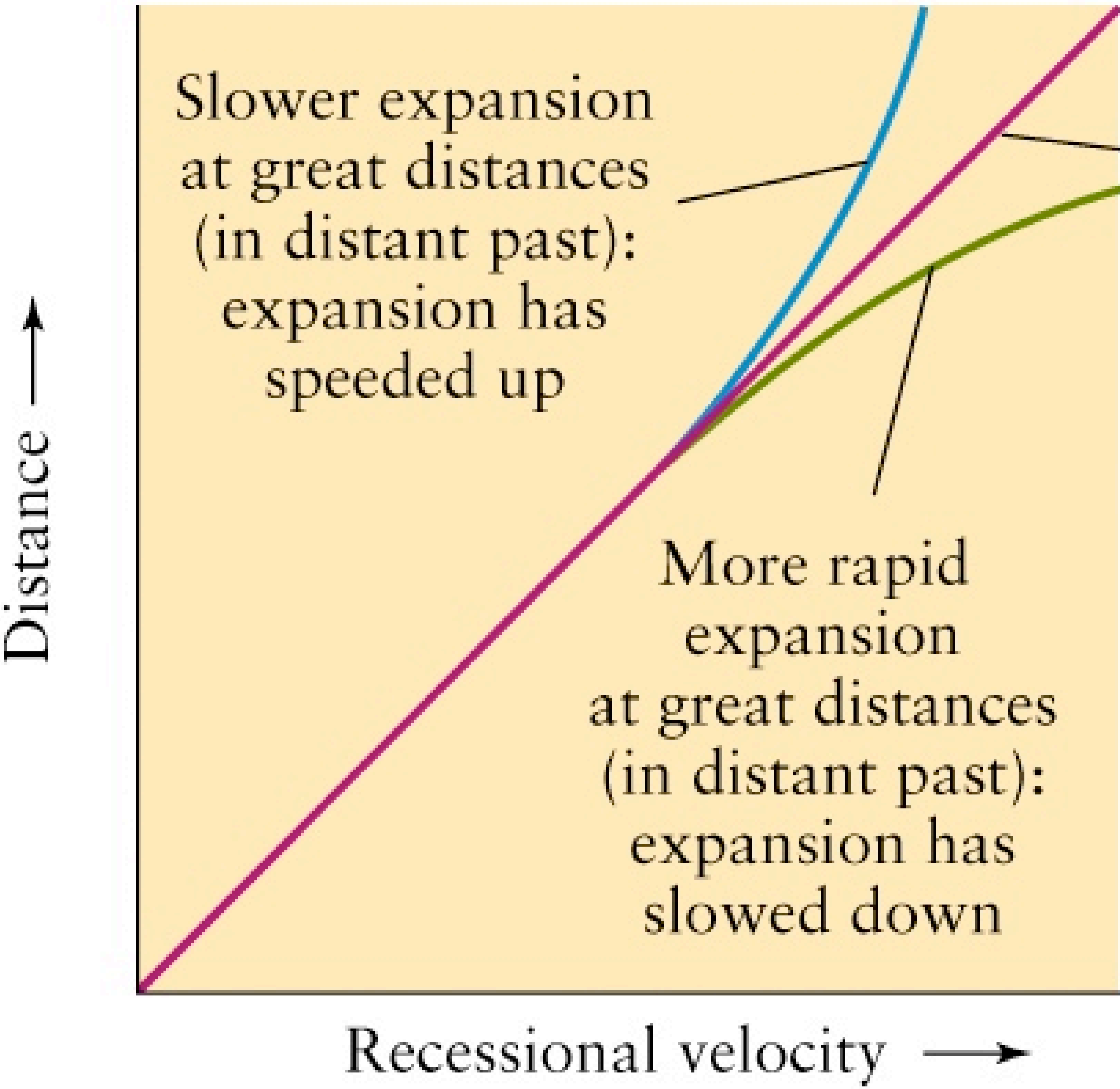


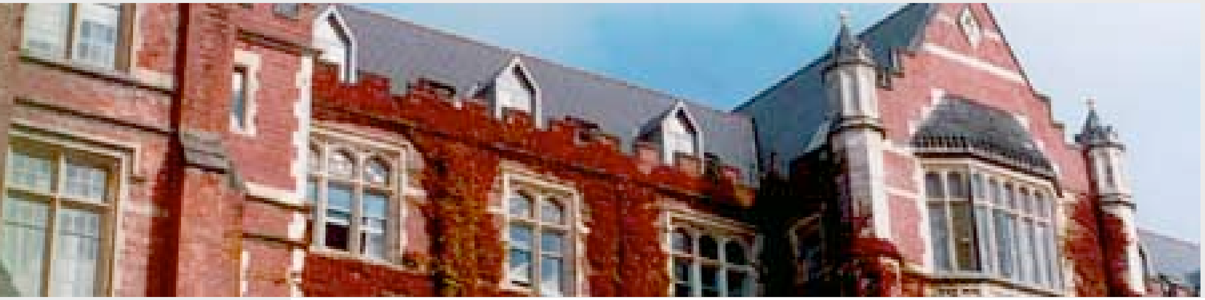




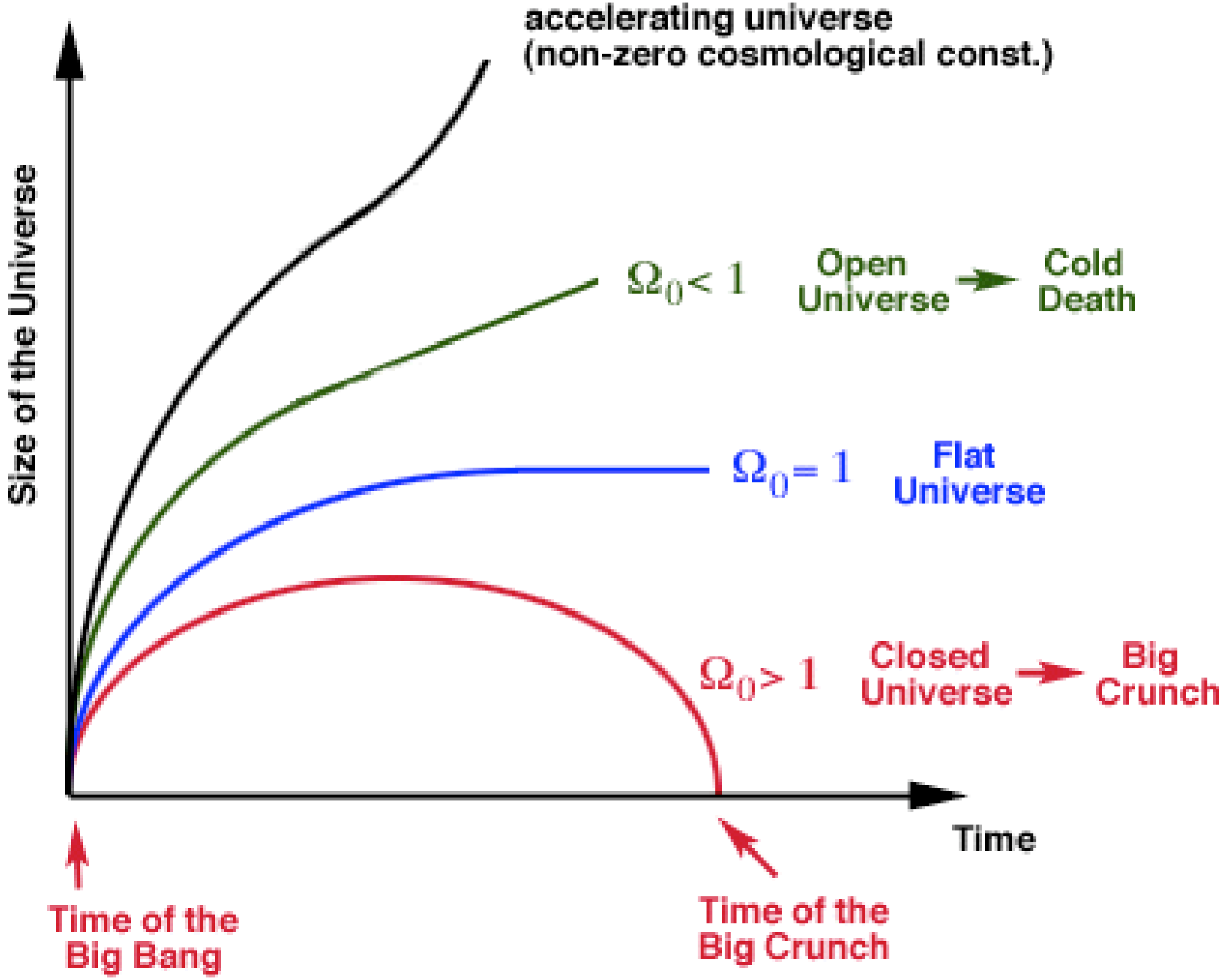
Preliminary Analysis
Supernova
Cosmology
Project
Hamuy et al
(A.J. 1996)
effective m_B
redshift z
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
$(\Omega_M, \Omega_\Lambda) =$
(0, 1)
(0.5,0.5)
(1, 0)
(1.5,–0.5)
Flat
(0, 0)
(1, 0)
(2, 0)
$\Lambda = 0$
FAINTER
(Farther)
(Further back in time)
MORE REDSHIFT
(More total expansion of universe
since the supernova explosion)

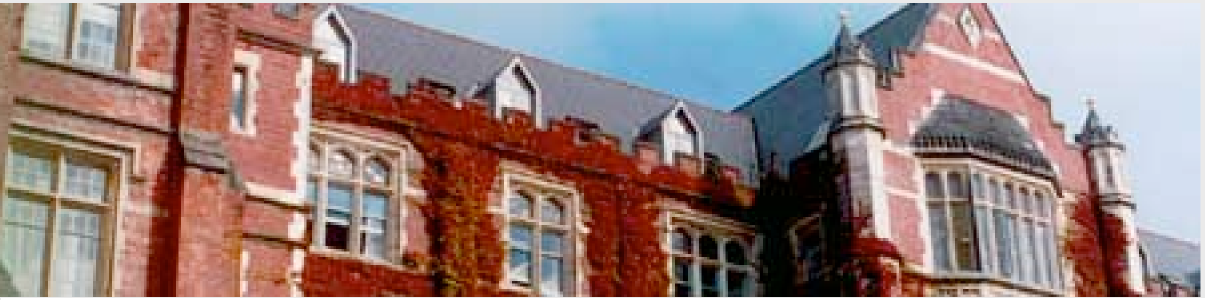


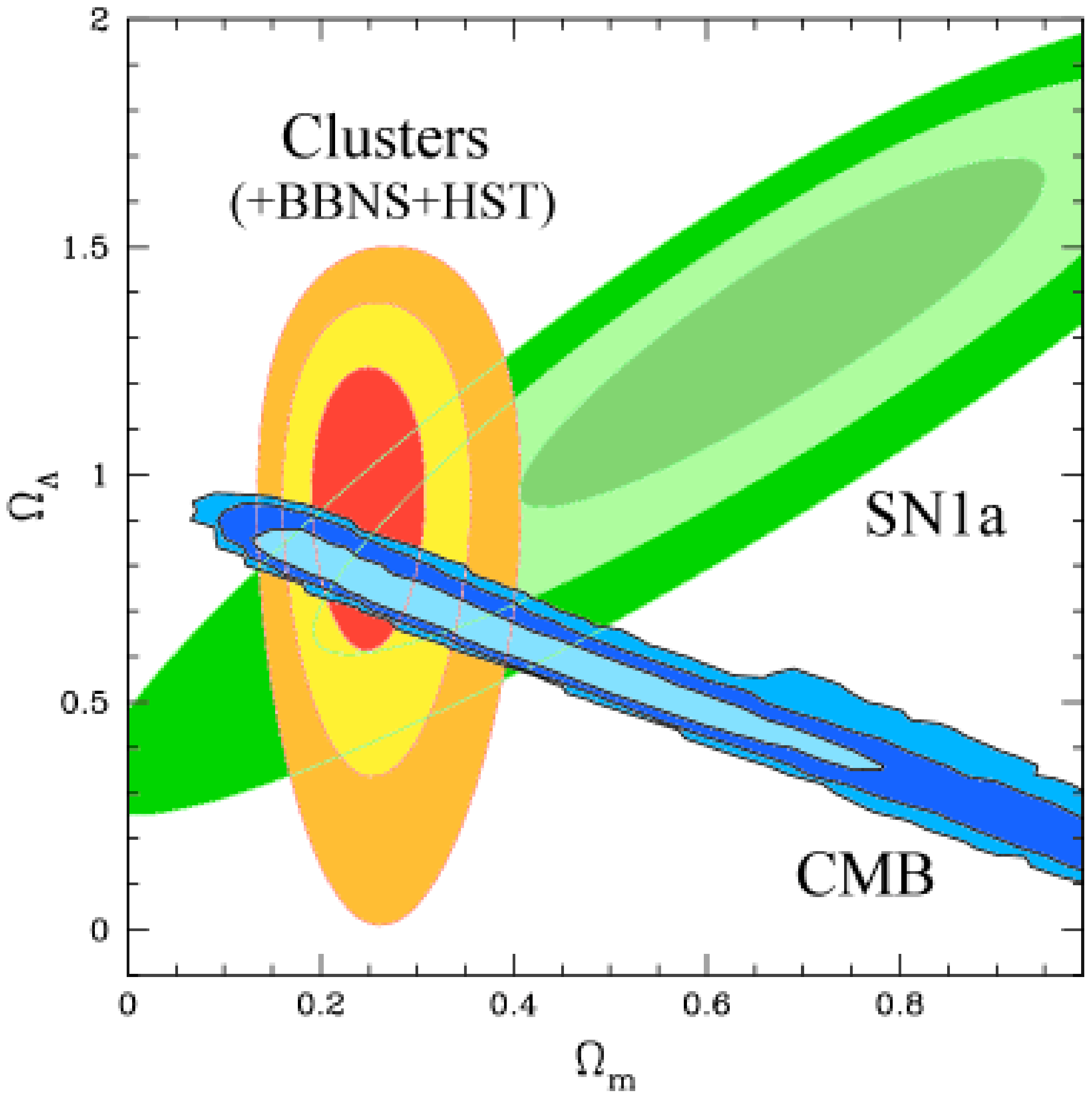

Slower expansion at great distances (in distant past): expansion has speeded up
Universe expands at a steady rate
More rapid expansion at great distances (in distant past): expansion has slowed down
Distance
Recessional velocity



Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui





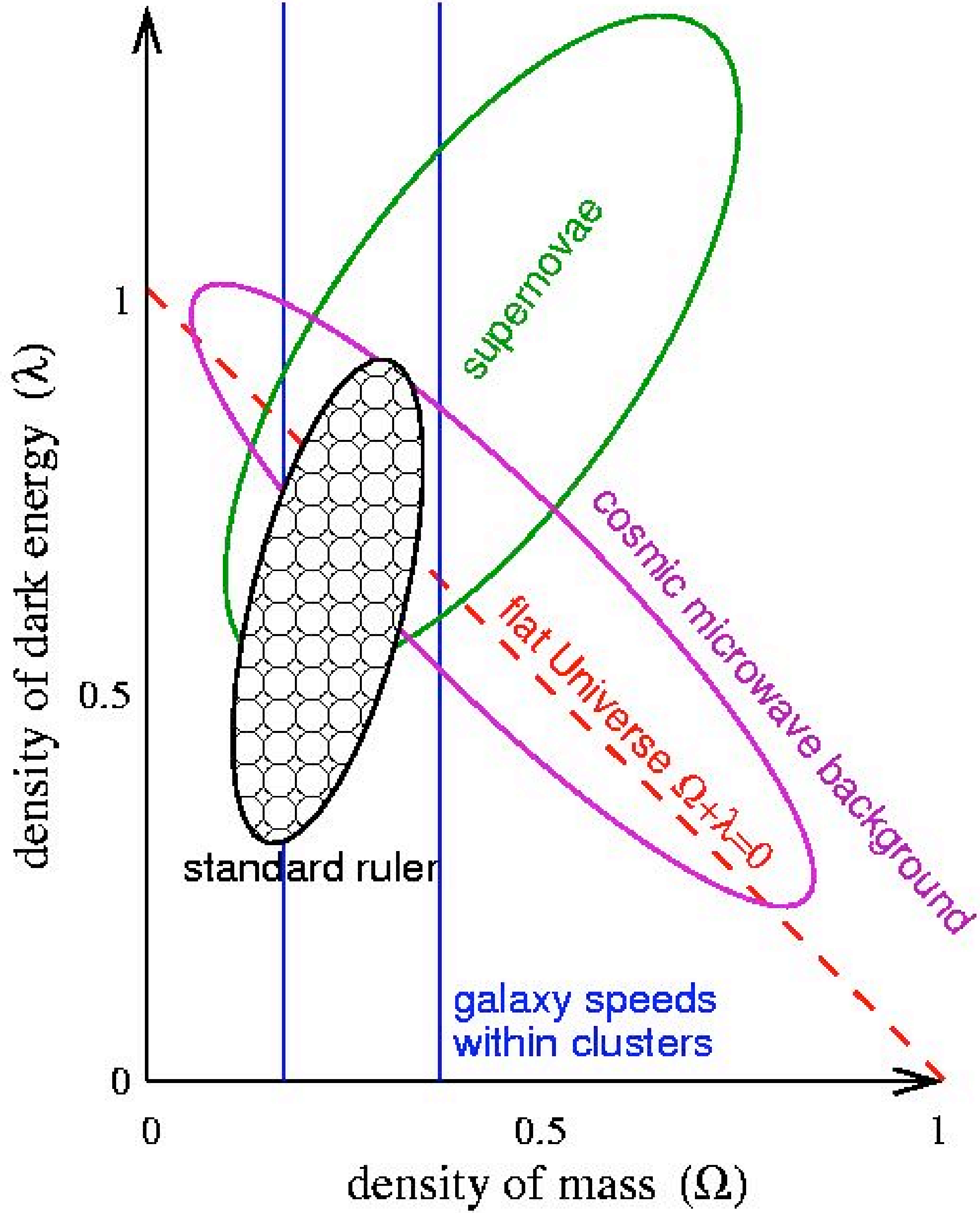


Consenus opinion:

The cosmological constant is “big”.

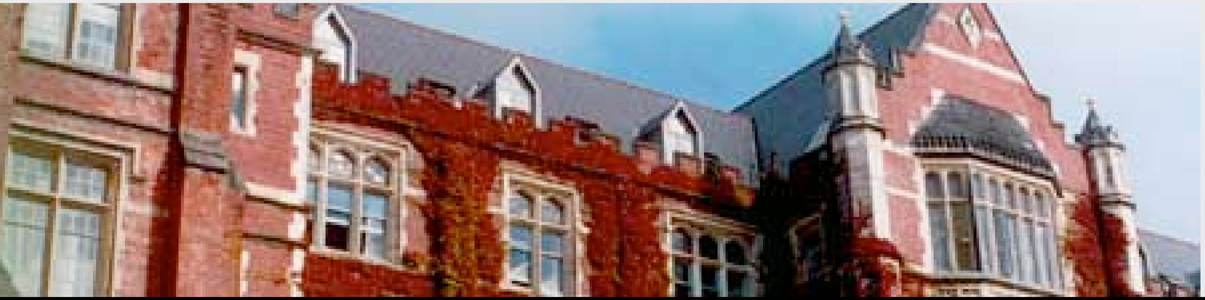
The quantity of clumped matter is relatively “small”.

Cosmological constant dominates over clumped matter.



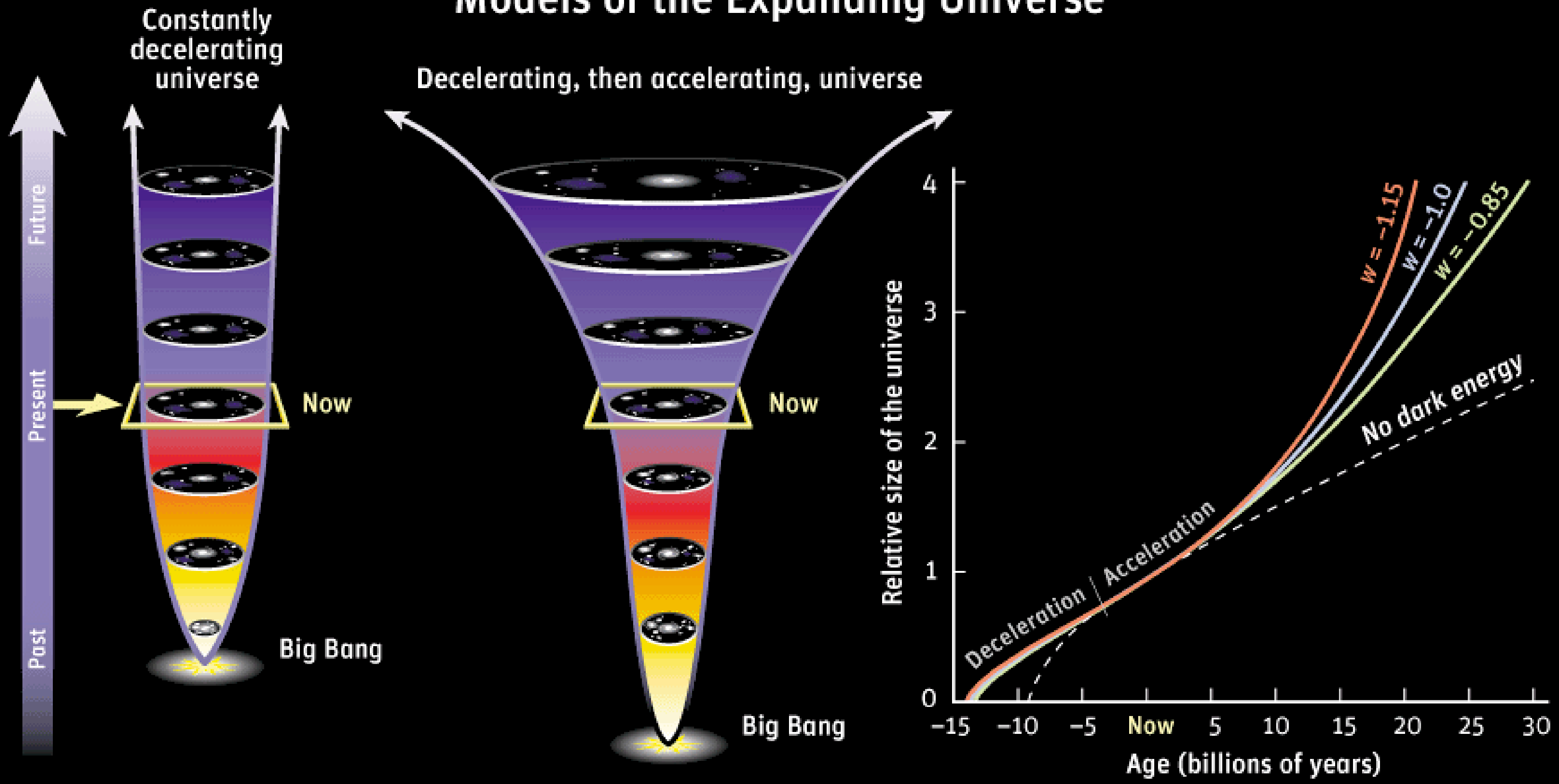
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui

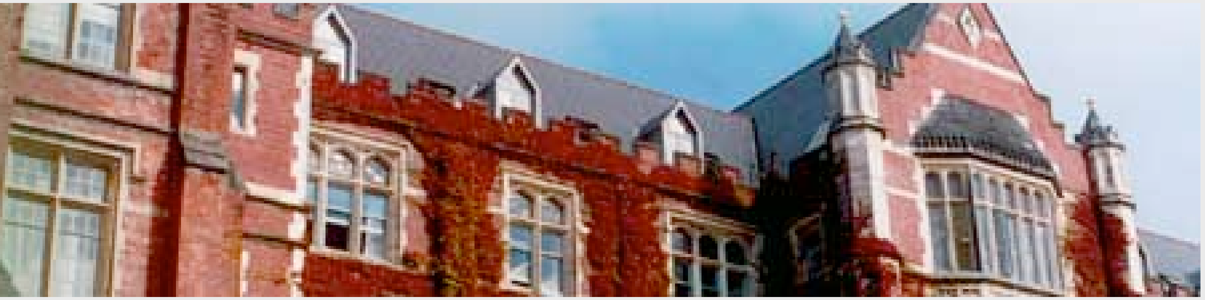
Different data set, one extra technique, broad agreement on results.

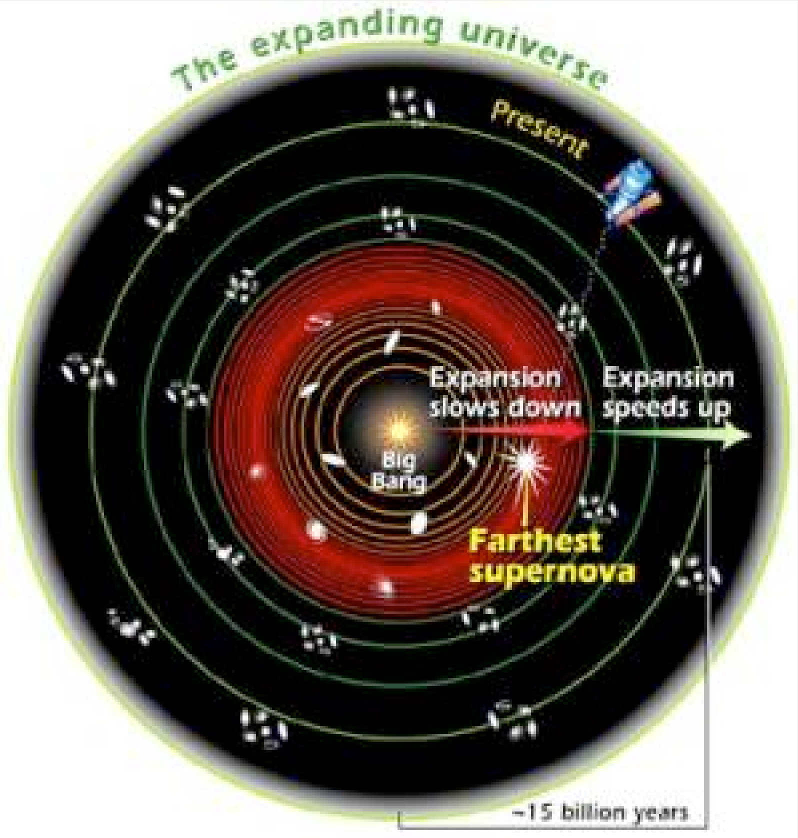


Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga o te Ūpoko o te Ika a Māui

Models of the Expanding Universe



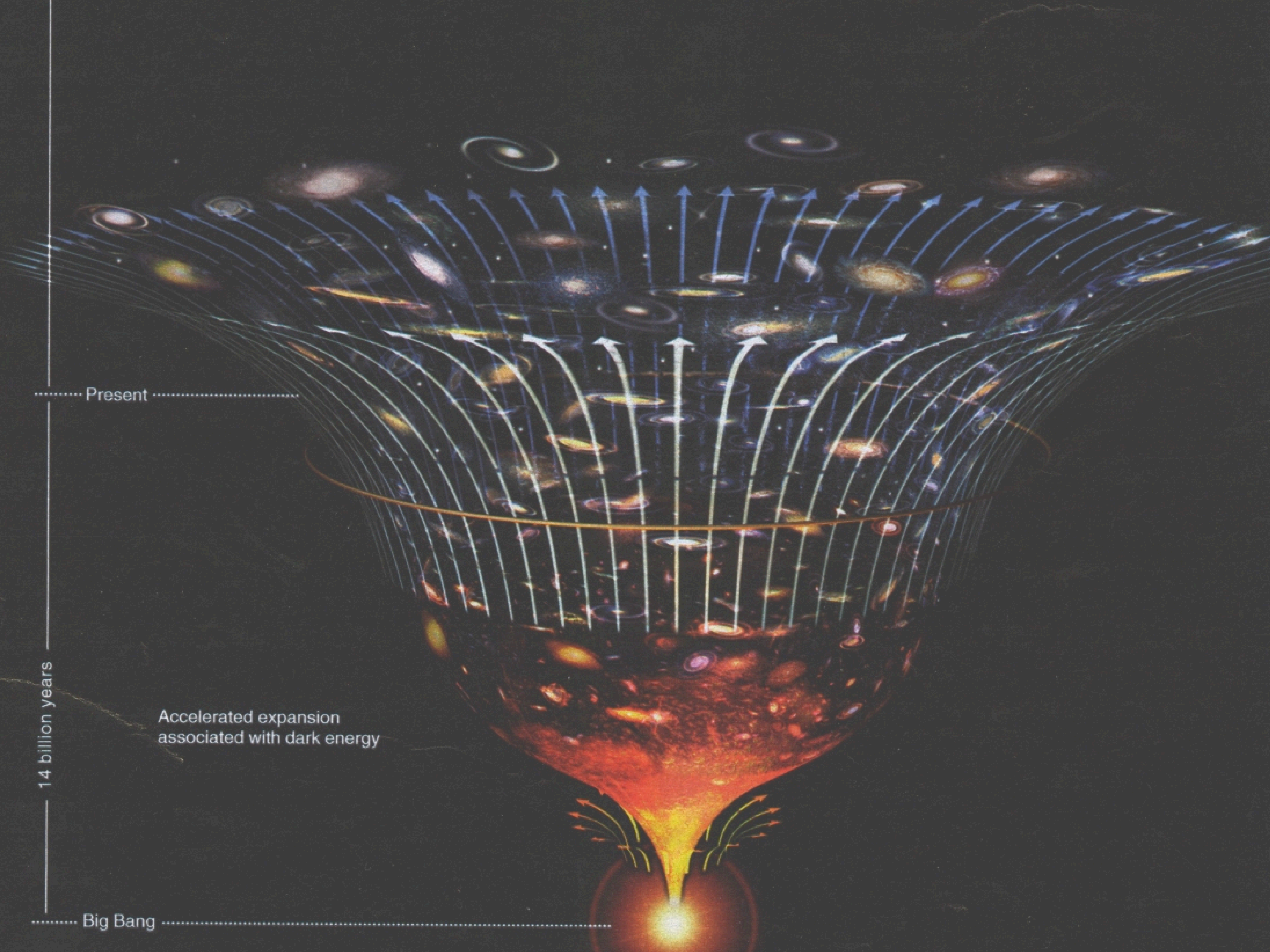




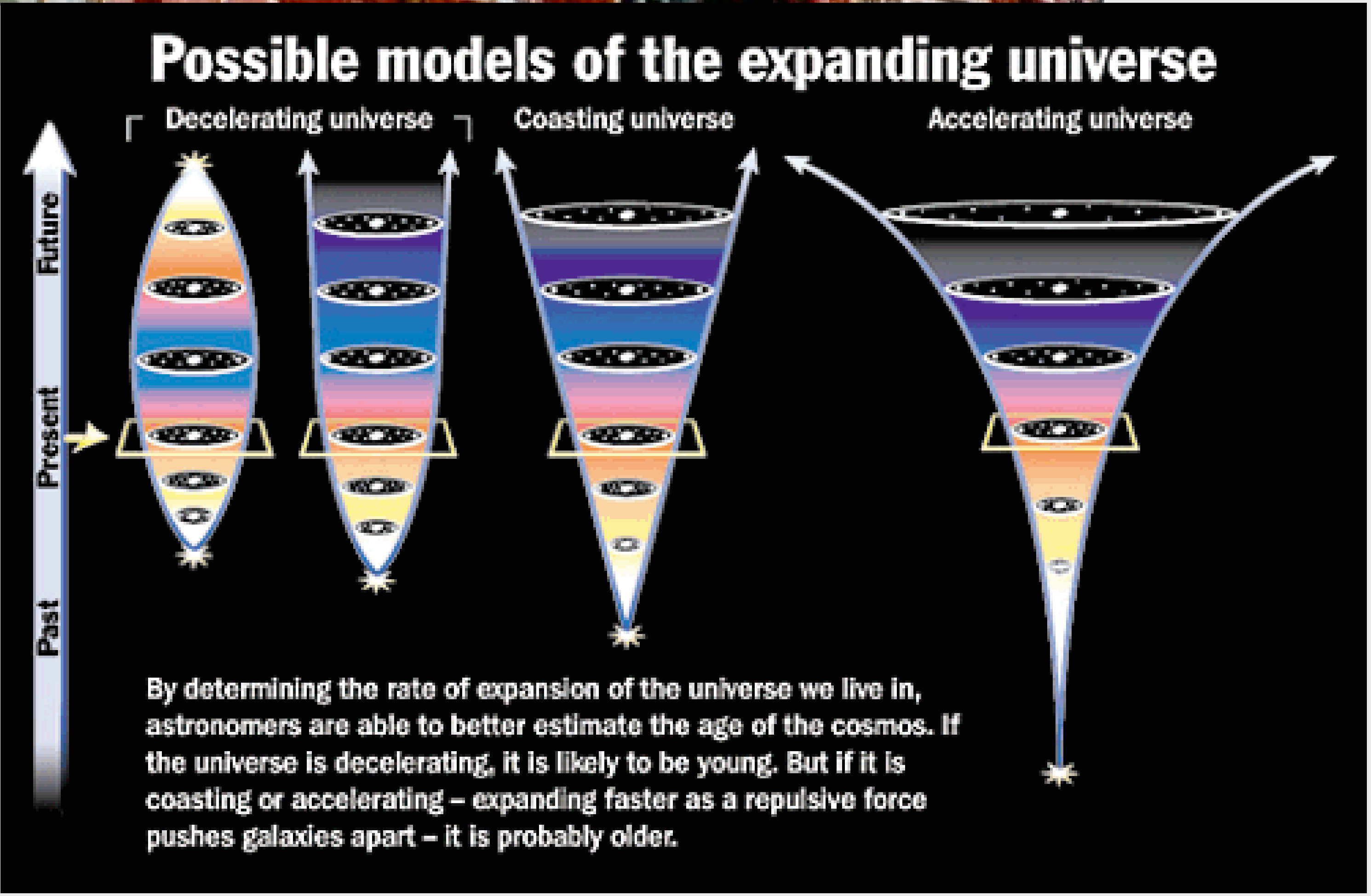
Dark matter clumps

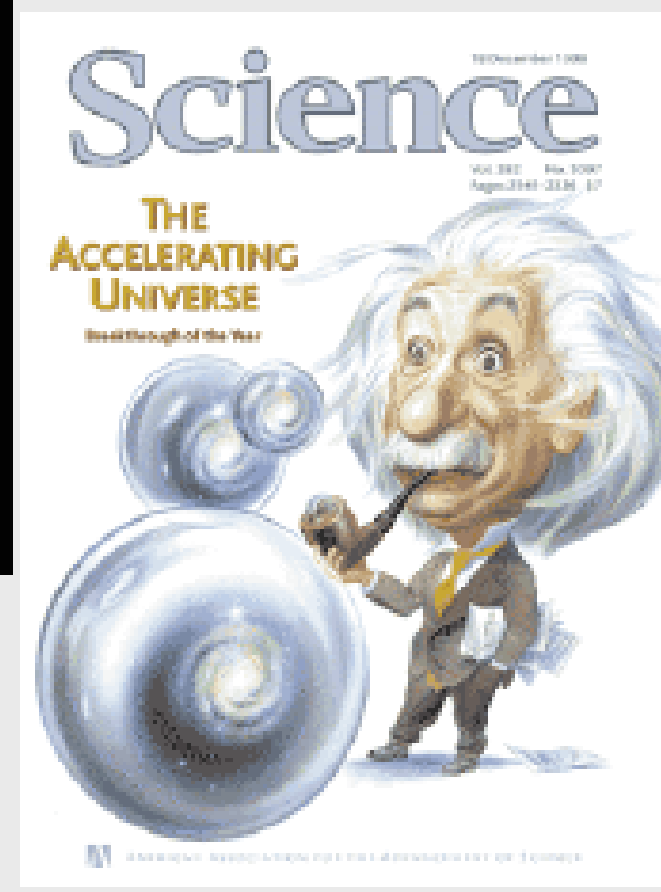
Dark energy does not clump

(by definition,
not deduction)

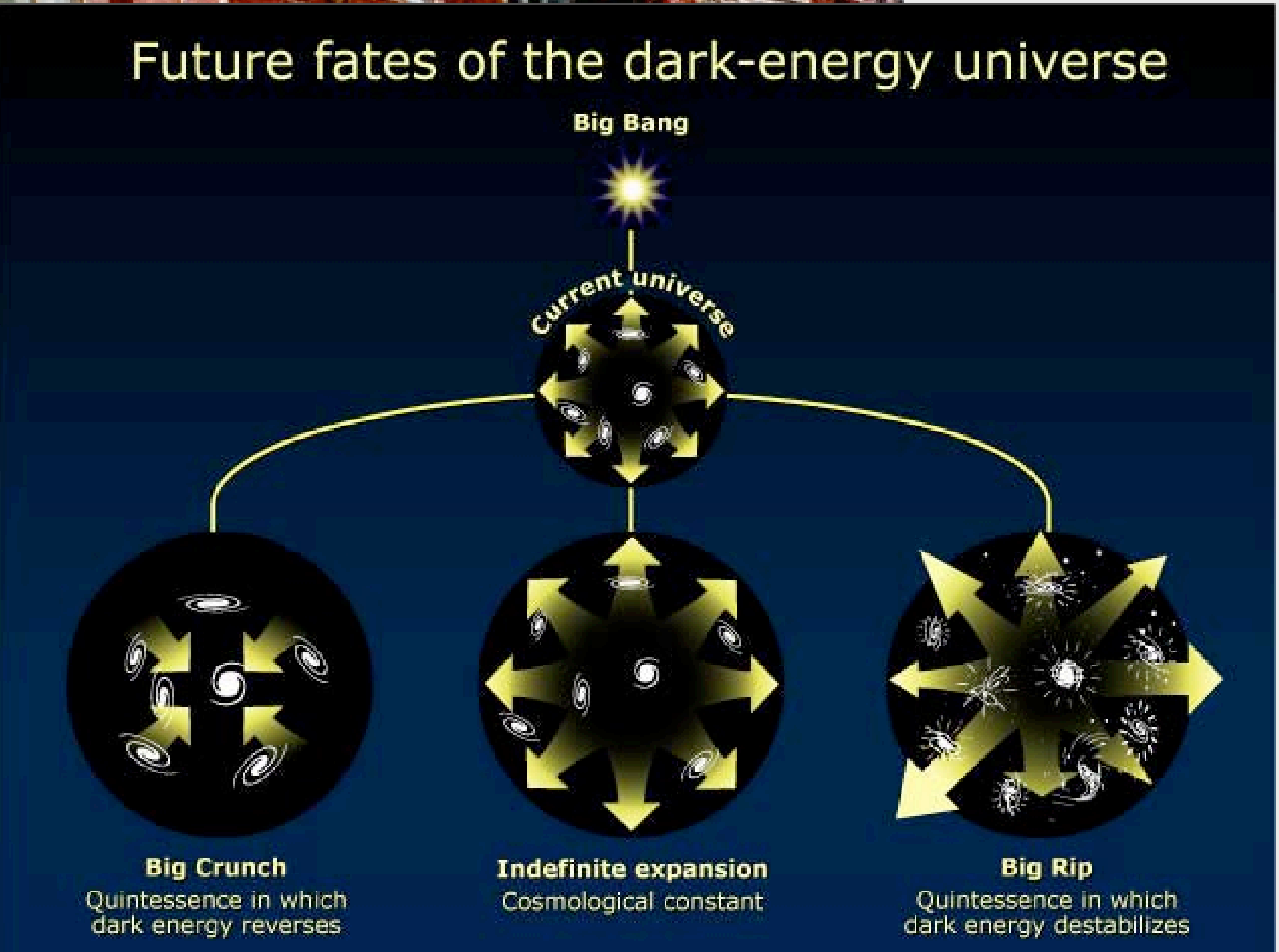

Present
14 billion years
Accelerated expansion
associated with dark energy
Big Bang

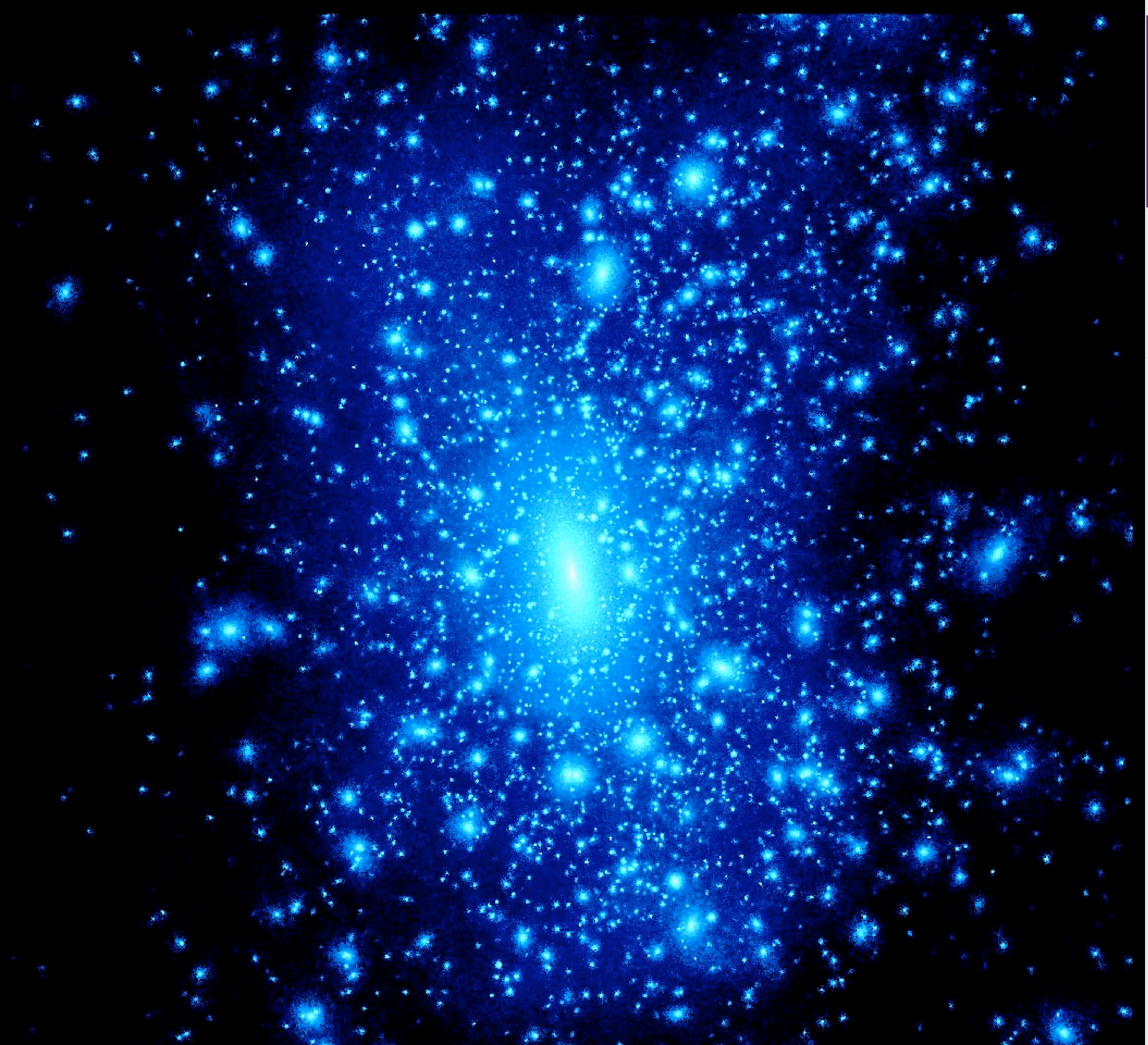
Victoria
UNIVERSITY OF WELLINGTON
Te Whare Wānanga
o te Ūpoko o te Ika a Māui





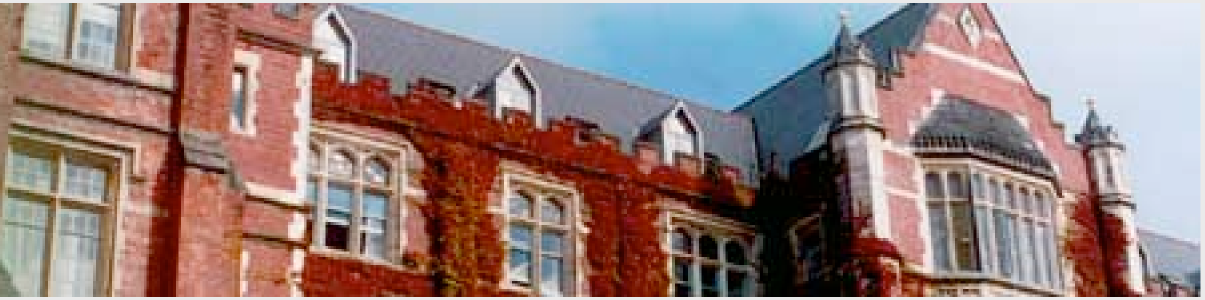
Big rip?


Future fates of the dark-energy universe
Big Bang
current universe
Big Crunch
Quintessence in which dark energy reverses
Indefinite expansion
Cosmological constant
Big Rip
Quintessence in which dark energy destabilizes



Simulation:

Dark matter clumping in a dark energy universe.



But wait --- Breaking news:

Viable exact model universe without dark energy from primordial inflation

David L. Wiltshire*

Department of Physics & Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

Late time failure of Friedmann equation

Alessio Notari*

Physics Department, McGill University, 3600 University Road, Montréal, QC, H3A 2T8, Canada

(Dated: March 31, 2005)

Primordial inflation explains why the universe is accelerating today

Kolb, Mataresse, Notari, Riotto

Dark energy?

Latest suggestion: We are living in a large under-dense bubble in an otherwise simple universe.

Size of bubble: Much bigger than Hubble radius

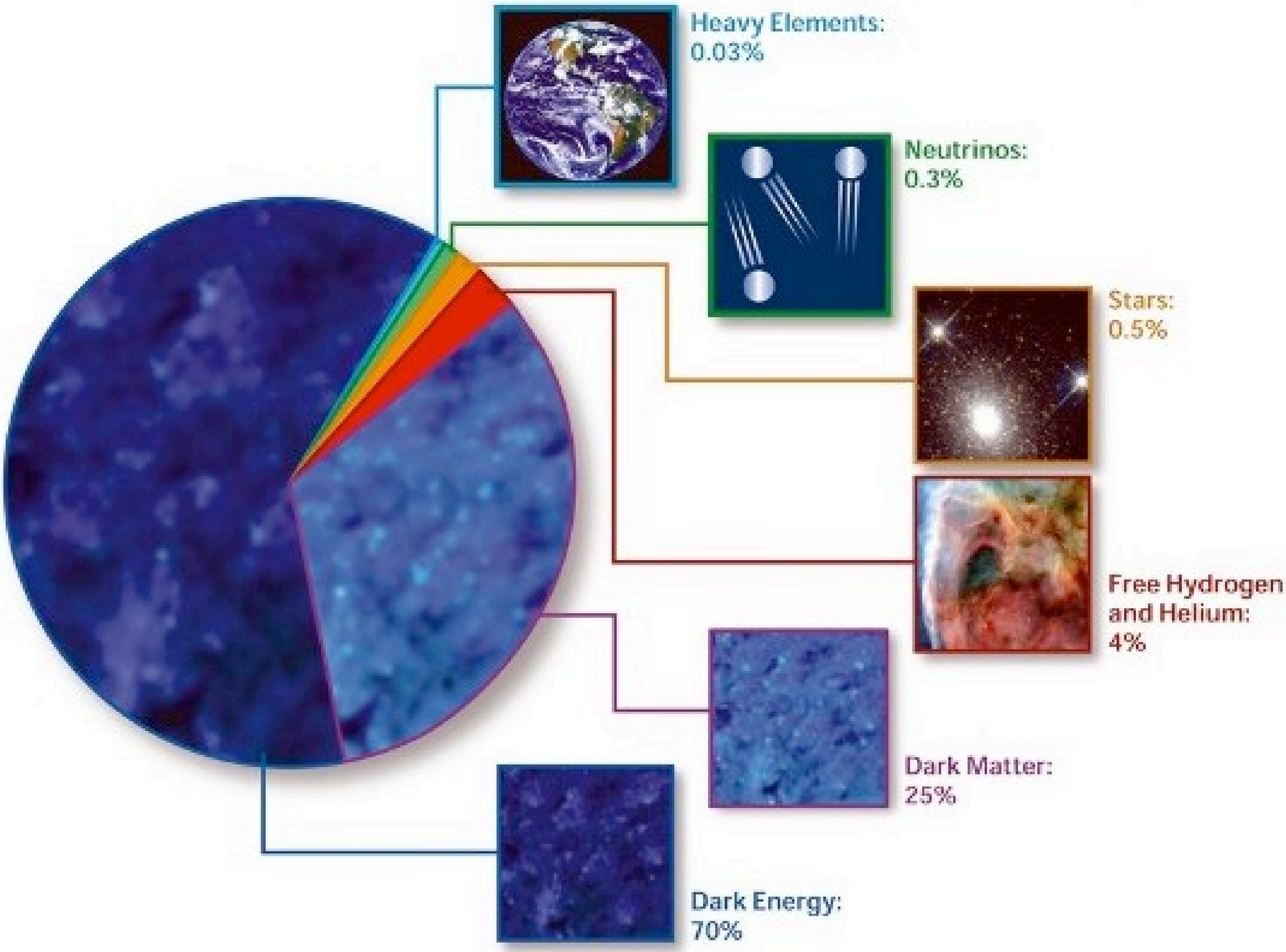
$R = c/H_0$

If this idea works it would improve some of our picture, at the cost of giving up large-scale homogeneity.

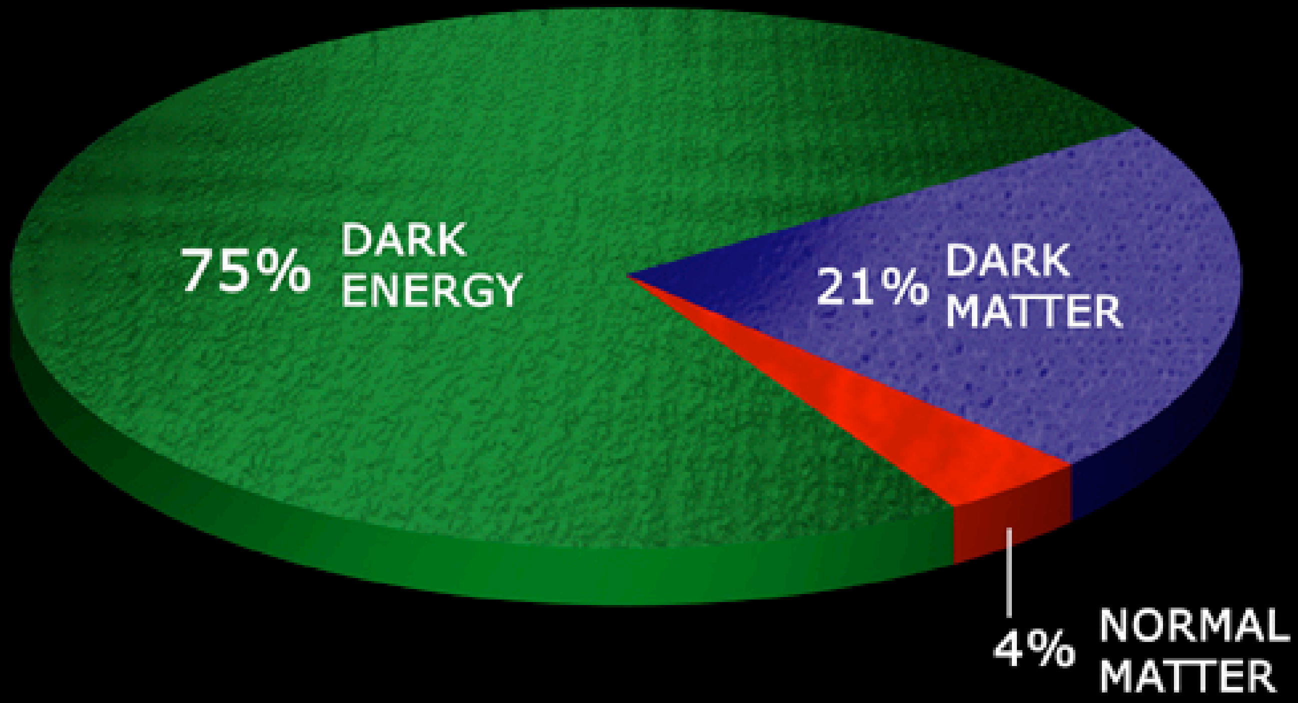
The universe we see would not be "typical".

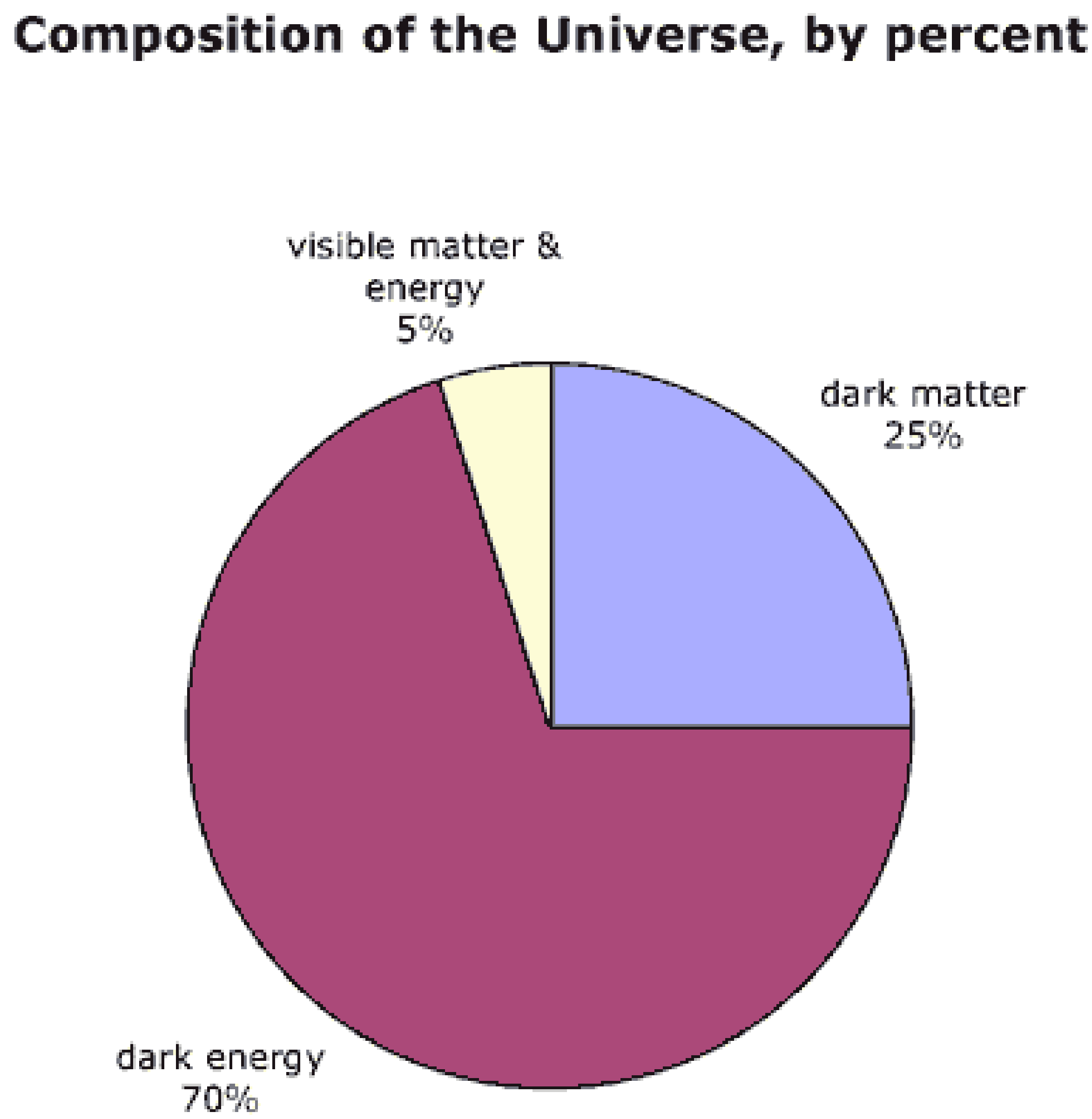
Could get rid of the "dark energy".

Mass-energy budget?



Overall mass-energy budget?





If you succeed in getting rid of dark energy, we are looking at big changes...

Conclusions:

1) The "big bang" is alive and well...

2) There is a lot of good high-quality data coming in, this helps keep the theorists on track...

3) There is a lot of room for debate at the margins, but the core of the "big bang" is rock solid.

"Sometimes I wonder whether the world is being run by smart people who are putting us on, or by imbeciles who really mean it."

--- Mark Twain