Dark Matter
Experiments and Searches

R.J.Cashmore
Principal Brasenose College,Oxford
and
Dept of Physics,Oxford

Matter in the Universe

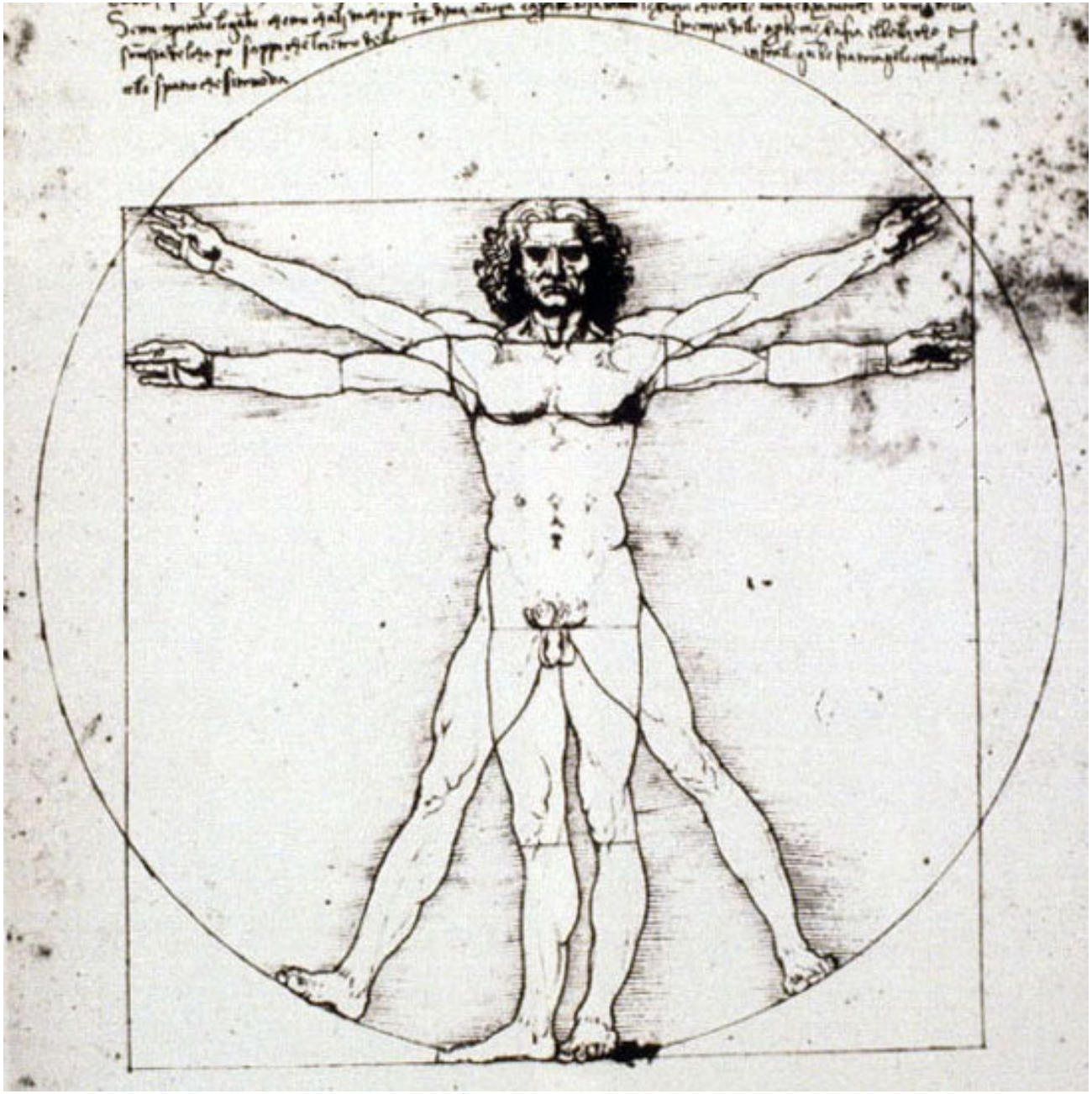
- The Matter of the Universe
- The Origin of Mass

The World Around Us

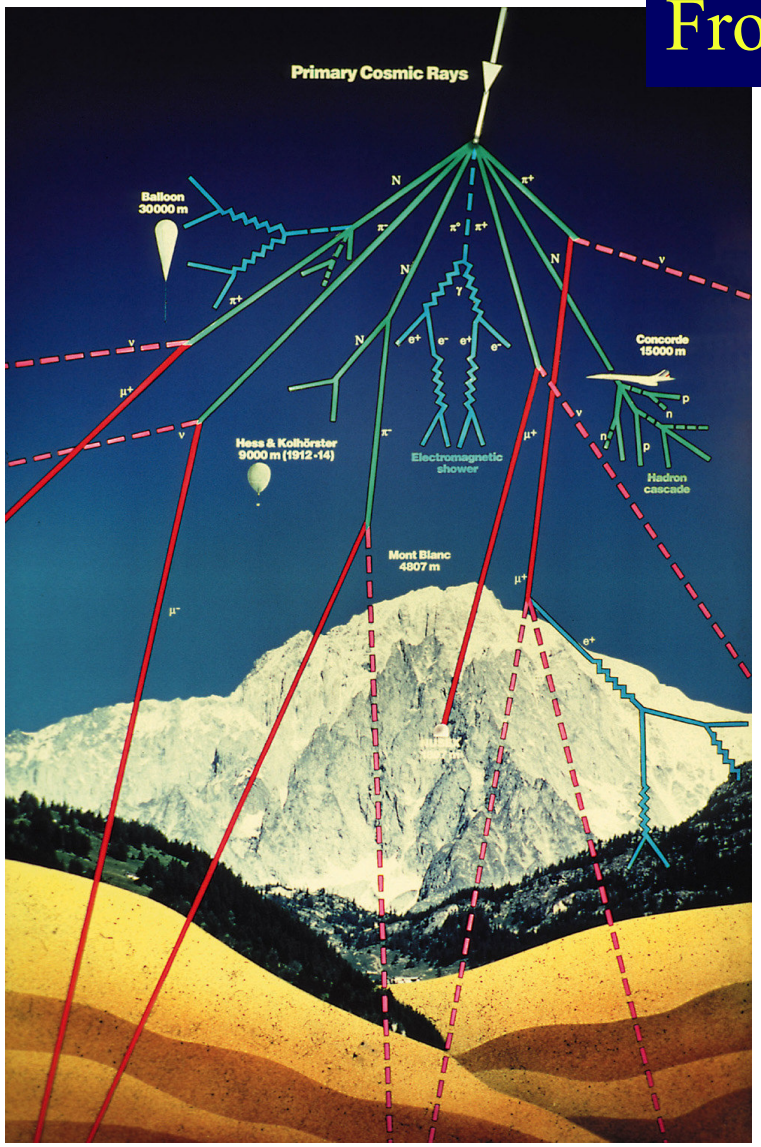
- Begin with what we know best

OR

- Think we know best



From Cosmic Rays … to CERN



P. Auger, E. Amaldi, L. Kowarski

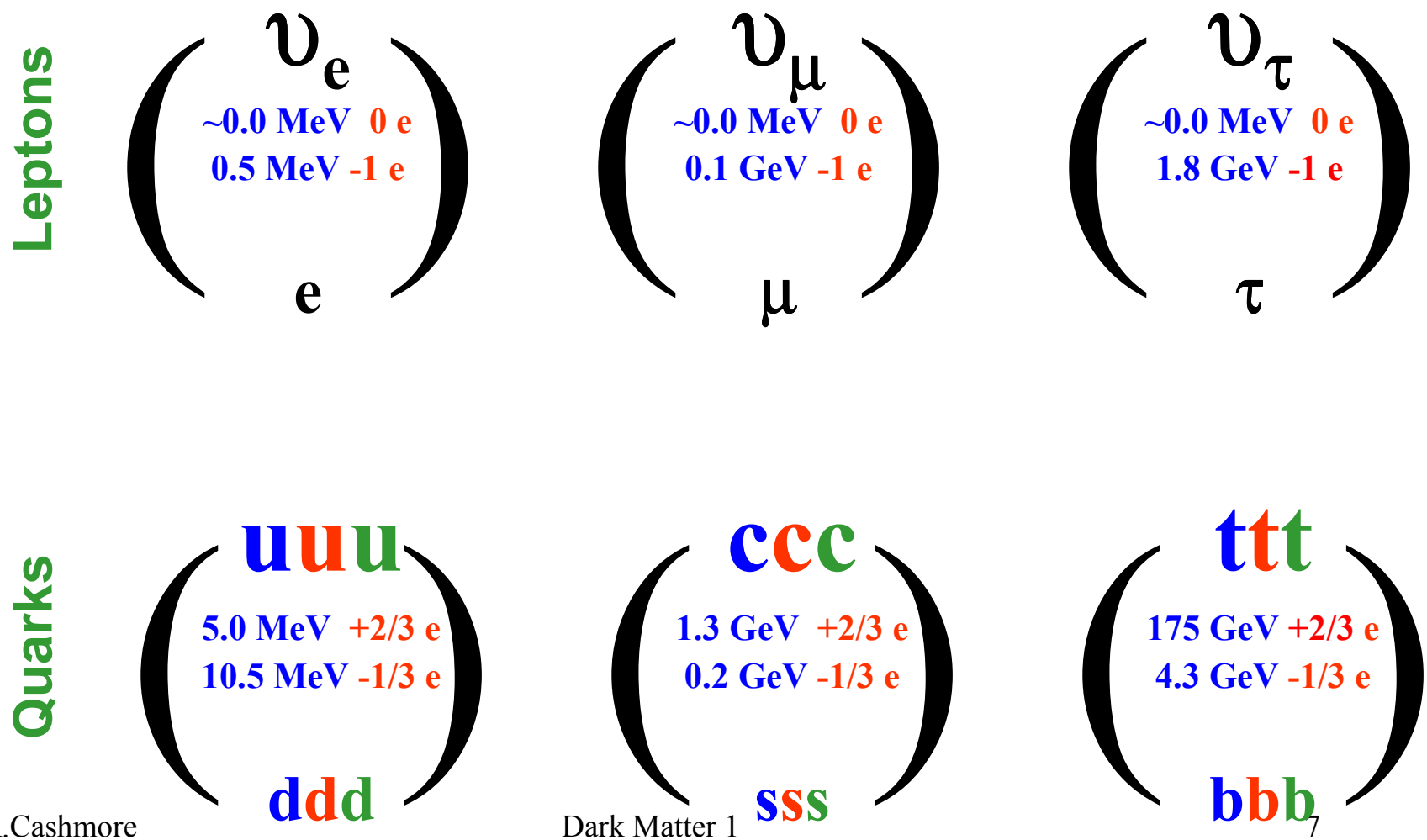
Established in 1954, CERN is the basic facility for High Energy Physics in Europe

Obvious Questions

1. Of what is he made?

2. Why is he the size he is?

The Fundamental Particles



The Particles of the Standard Model
Bosons

γ (Photon)	0.0 MeV	0 e	Electro-magnetism
$W^{+/-}$	80 GeV	+/-1 e	Nuclear Decay
Z^0	91 GeV	0 e	Electro-weak
g (8 gluons)	0.0 MeV	0 e	Strong Force

Why is he the size he is?

$$\text{Size of atom } \alpha \quad \frac{1}{M_e}$$

Mass important to understand

MAJOR PROBLEM

Mass of all particles is **0**

ELEGANT SOLUTION

(due to Peter Higgs)

New Interaction (field) with all particles

Fields have quantum excitations

(eg. the photon)

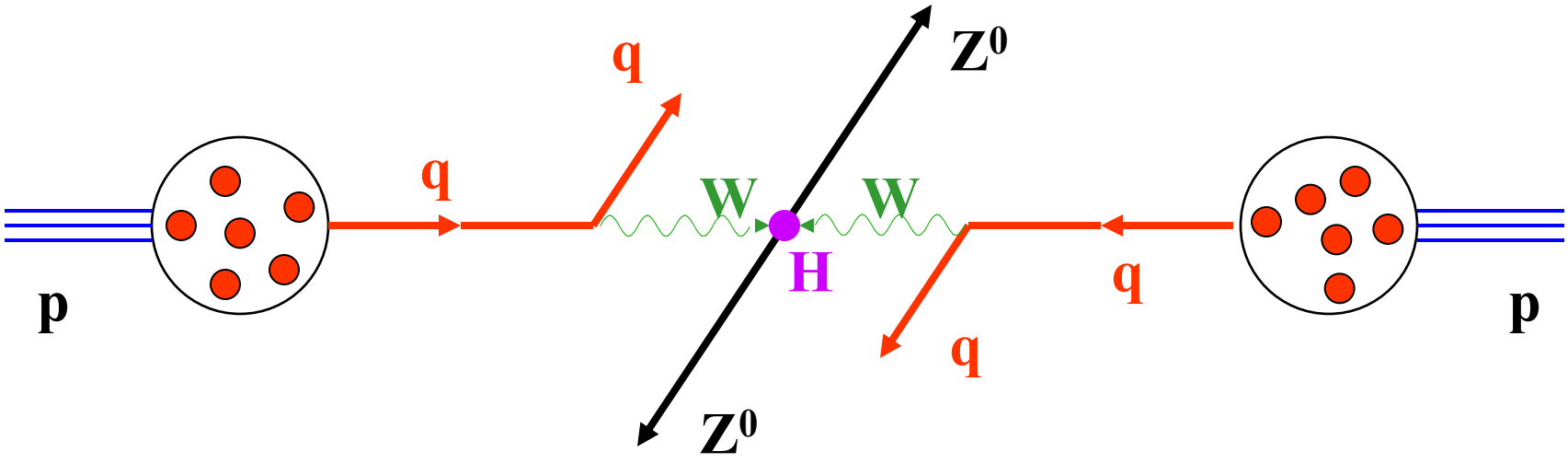
Search for the HIGGS BOSON

HIGGS BOSON

- Mass unknown
- Mass <1000 GeV

$E = mc^2$

↙ $E \geq 1000$ GeV



$M_H \sim 1000$ GeV

↙ $E_W \geq 500$ GeV

↙ $E_q \geq 1000$ GeV (1 TeV)

↙ $E_p \geq 6000$ GeV (6 TeV)

⇧ **LHC $E_p \geq 7$ TeV**

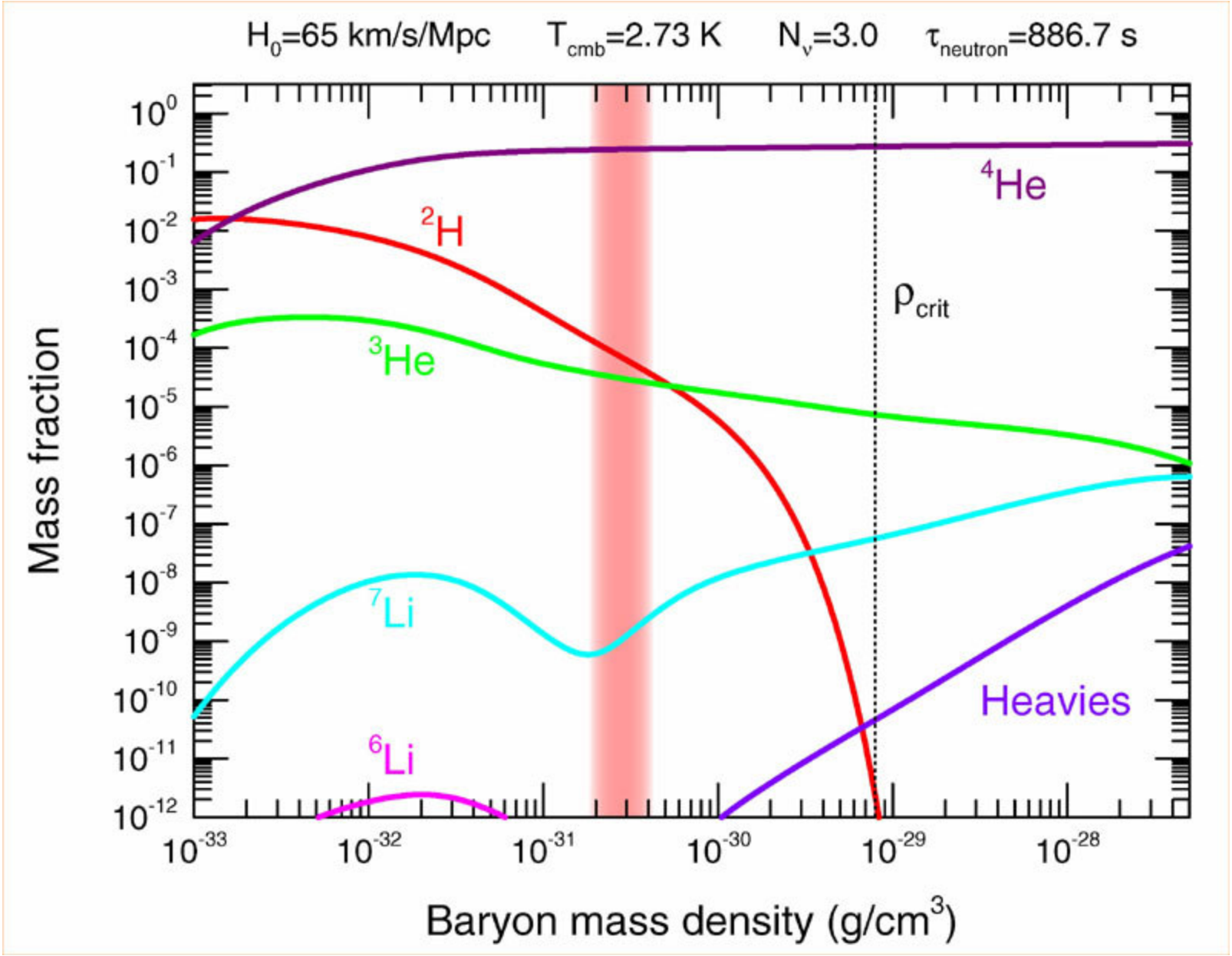
Not The Whole Answer

- Most of the mass lies in the gluon fields
- $M = E/c*2$
- Not in the quarks and leptons

A Big Mystery of the Universe

- What really is the Matter in the Universe?

Critical Density and Nucleosynthesis

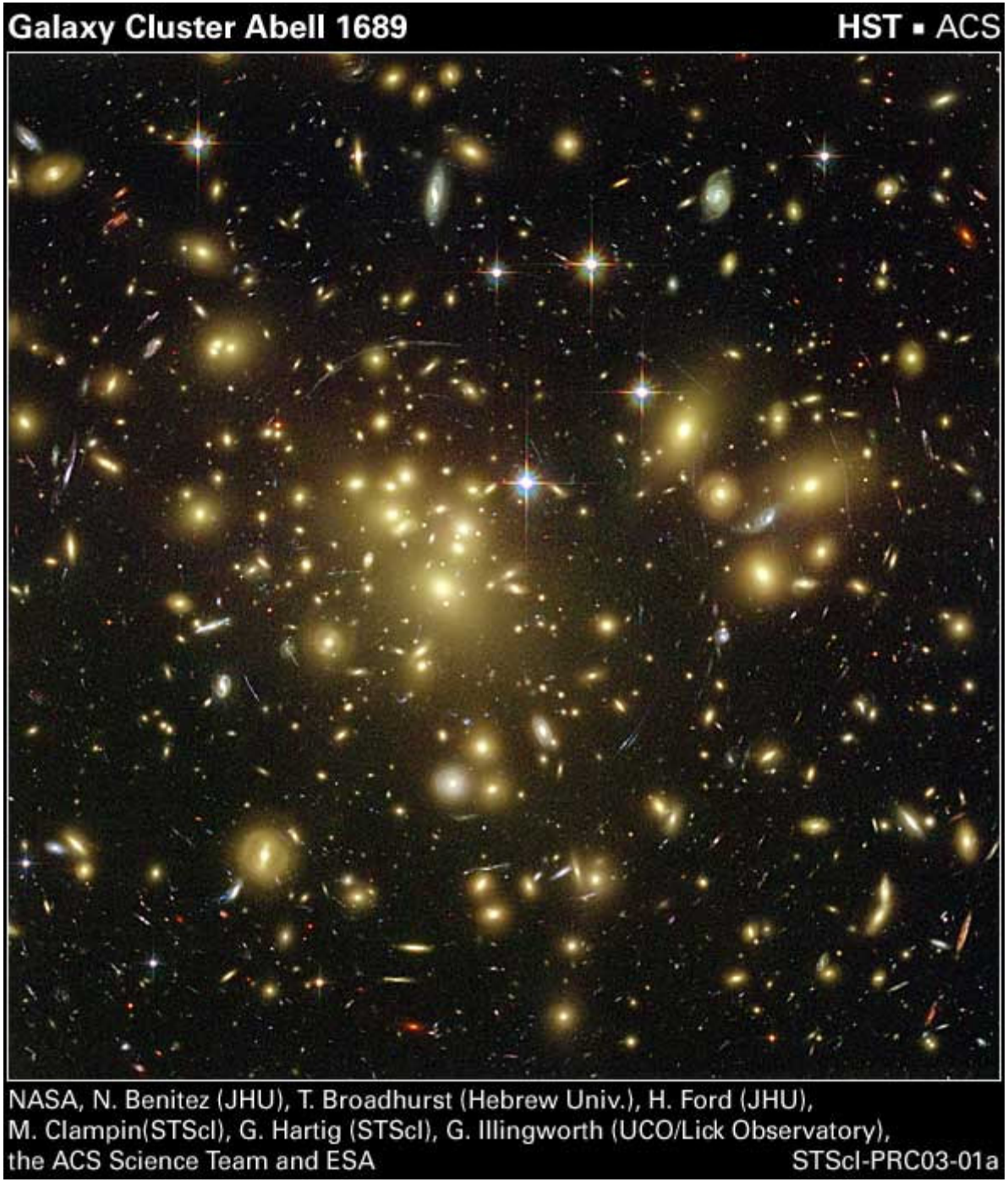

H0=65 km/s/Mpc
Tcmb=2.73 K
Nν=3.0
τneutron=886.7 s
Mass fraction
Baryon mass density (g/cm3)
4He
2H
3He
7Li
6Li
Heavies
ρcrit

Critical Density and Nucleosynthesis

- density = critical density
    - Inflationary universe
- baryons only 3% of the matter

The Coma Cluster (Abell 1656)

- 300 million light years away
- A cluster of 1000s of galaxies
- And each galaxy has billions of stars…


Galaxy Cluster Abell 1689
HST ▪ ACS
NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU),
M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory),
the ACS Science Team and ESA
STScI-PRC03-01a

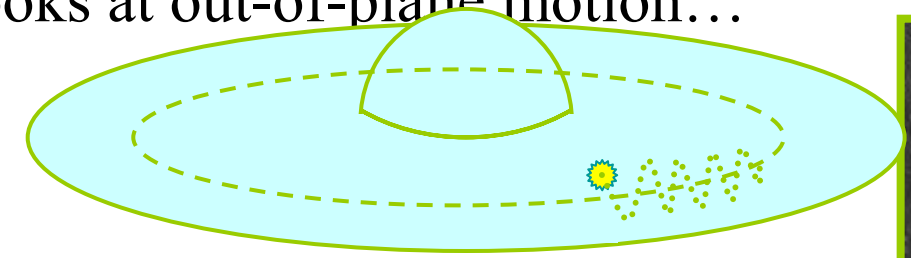
First evidence – 1930's observations…

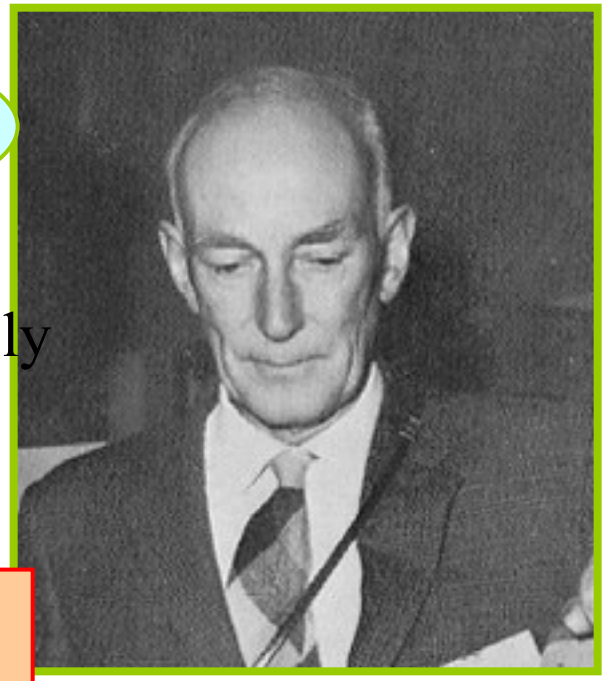
- 1933. F. Zwicky measured the velocities of 8 galaxies in the Coma Cluster.
- He found their mean velocity to be much higher than expected [applet]. This has since been found to be a general feature.
- *"If this [over-density] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in the Coma cluster] with a much greater density than luminous matter"* Zwicky, 1933

The implications were generally not accepted at the time…

First evidence – 1930's observations…

- 1932. Jan Oort – recently having proven that our Galaxy is rotating (~once every 250 Myr). Now looks at out-of-plane motion…





- Out-of-plane motion is approximately SHM!
- Observation was that the restoring

At the time, it was simply thought that more stars/planets/asteroids were yet to be seen.

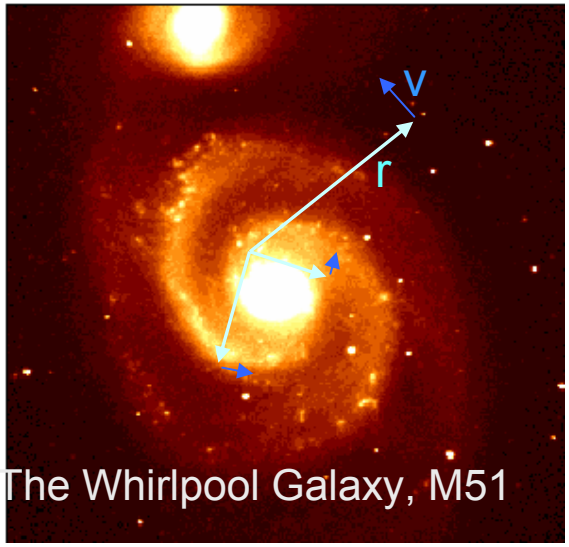
stars

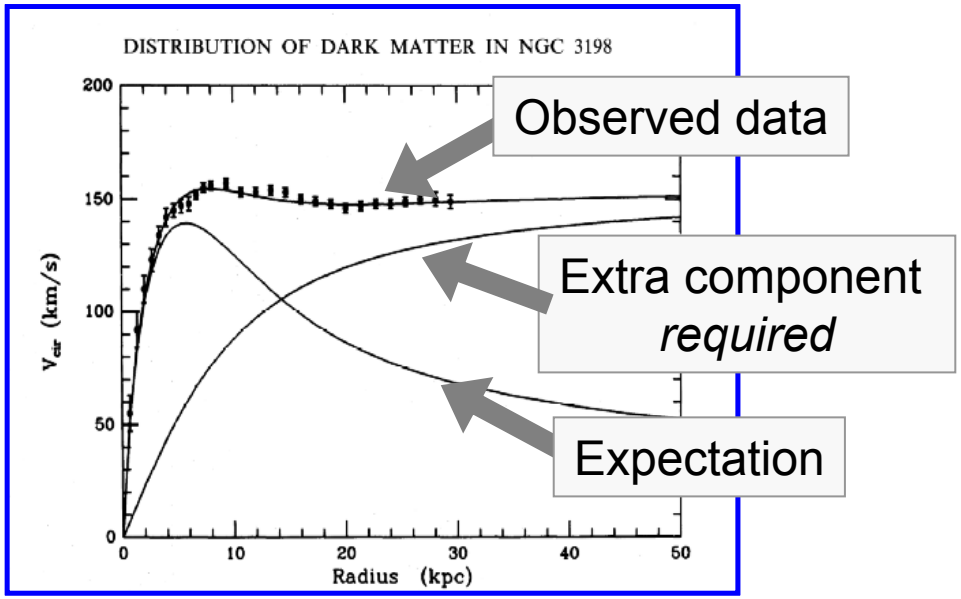
Rotation curves

- Newtonian gravity:
  - If ‘test particle’ inside mass distribution, ‘tidal locking’ $v \propto r$
  - Otherwise, equate $GM/r^2 = v^2/r$ → $v \propto 1/\sqrt{r}$

- Oort (1940) studied the edge-on galaxy NGC 3115.
  - Used Doppler shifts to measure velocities,
  - ‘known’ distance to infer radii of individual stars
  - Plot speed against radius.

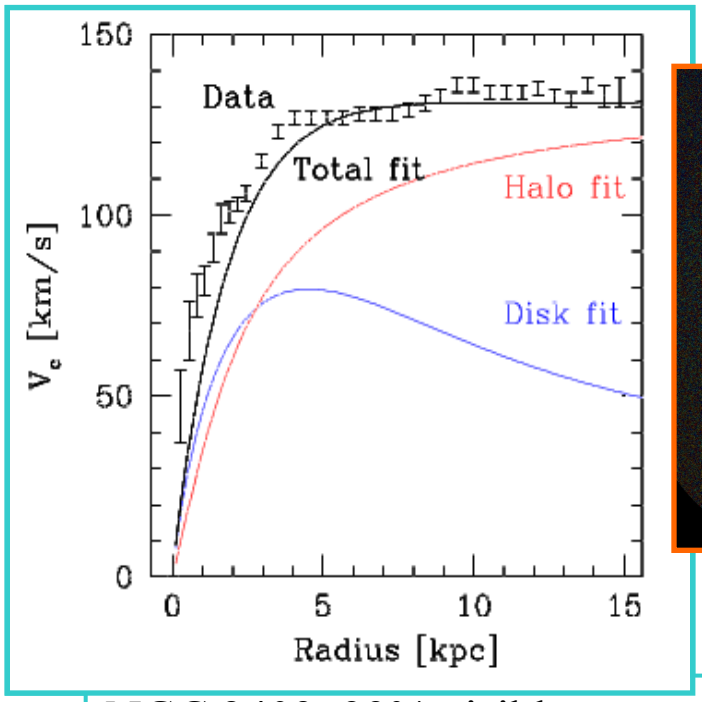
Rotation Curves





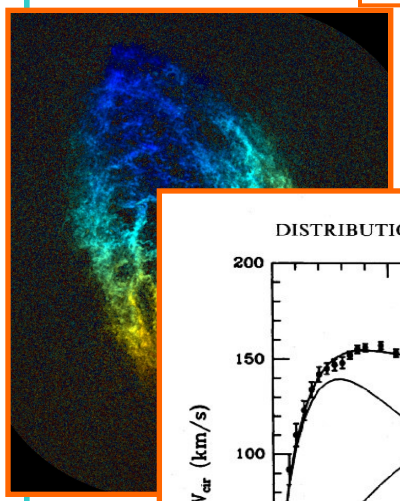
- To match what is observed we need an extra invisible matter

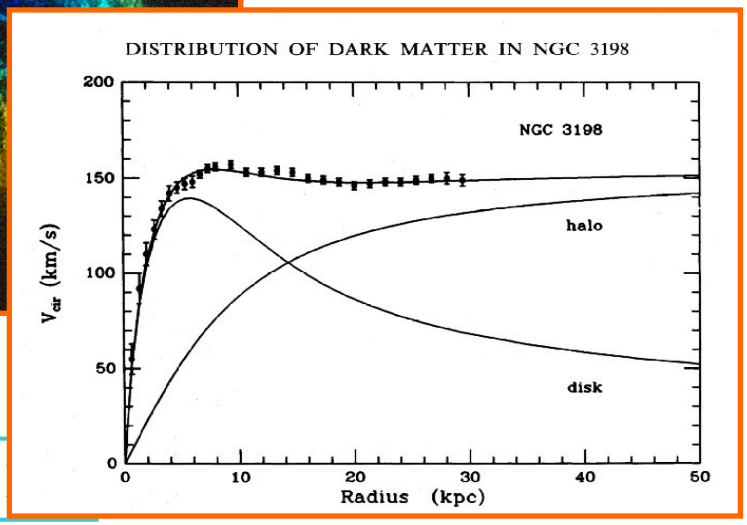
Rotation curves II

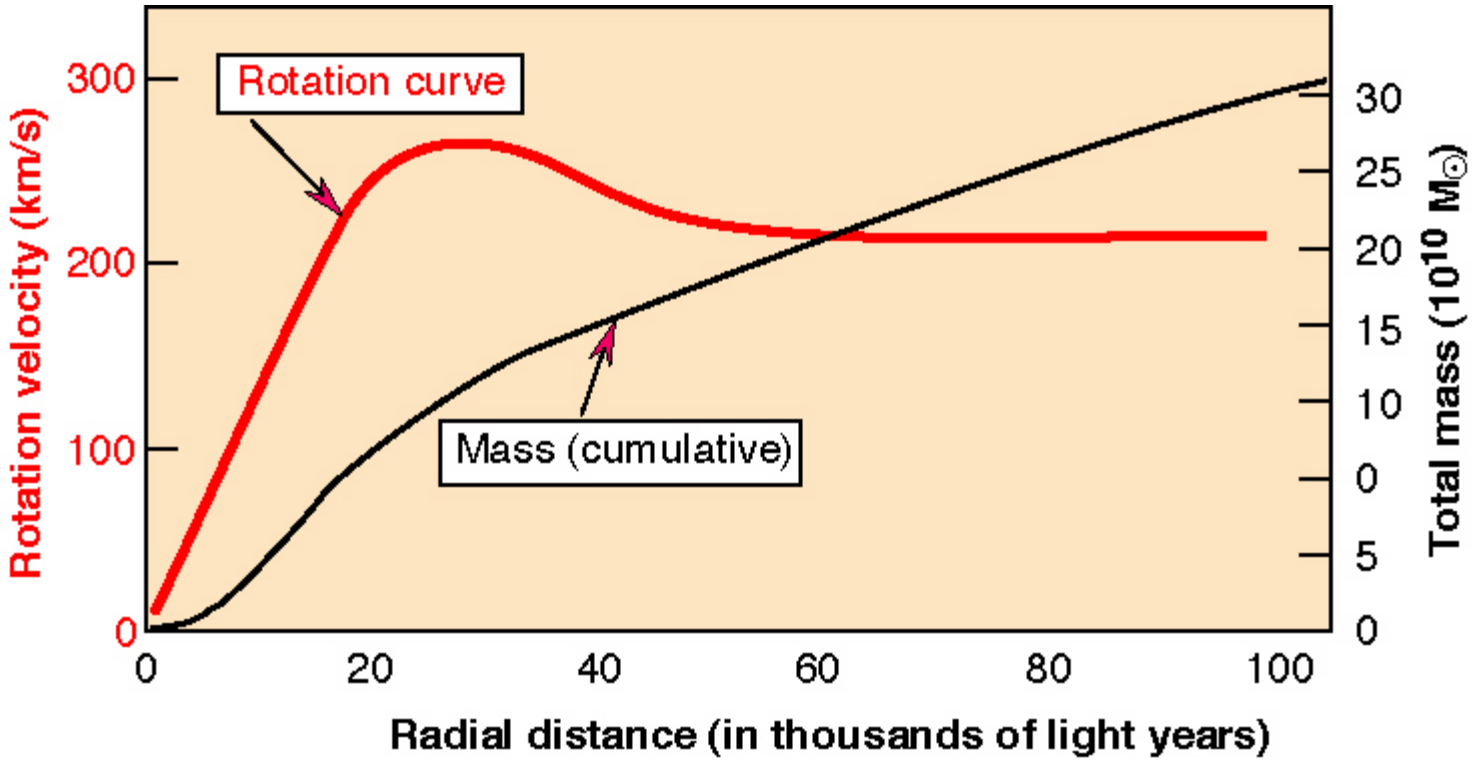


NGC 2403, 99% visible mass at <15

NGC 3198






Rotation curve
Mass (cumulative)
Rotation velocity (km/s)
300
200
100
0
0
20
40
60
80
100
Radial distance (in thousands of light years)
30
25
20
15
10
0
5
0
Total mass (10^10 M⊙)

Rotation curves III

- Rotation curves similar for *all available data* (galaxies and clusters).

- Fits [illegible] of mass is 'dar[illegible] spher[illegible]

"The distribution of mass in this system appears to bear almost no relation to the light"

Jen Oort 1940

Link with Zwicky's observations not made until much later…

More evidence – things moving *fast*

Sinclair Smith 1936

Observed galaxies in the Virgo cluster moving 'very fast'

Horace Babcock, 1939

Observed that individual stars in M31 (Andromeda) moving 'very fast'

Q: So, what is 'very fast'?

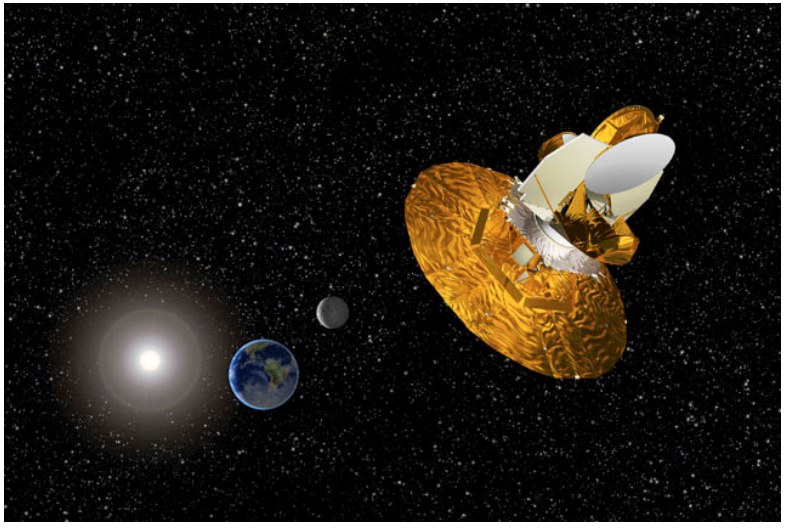
A: Well in excess of the expected escape velocity

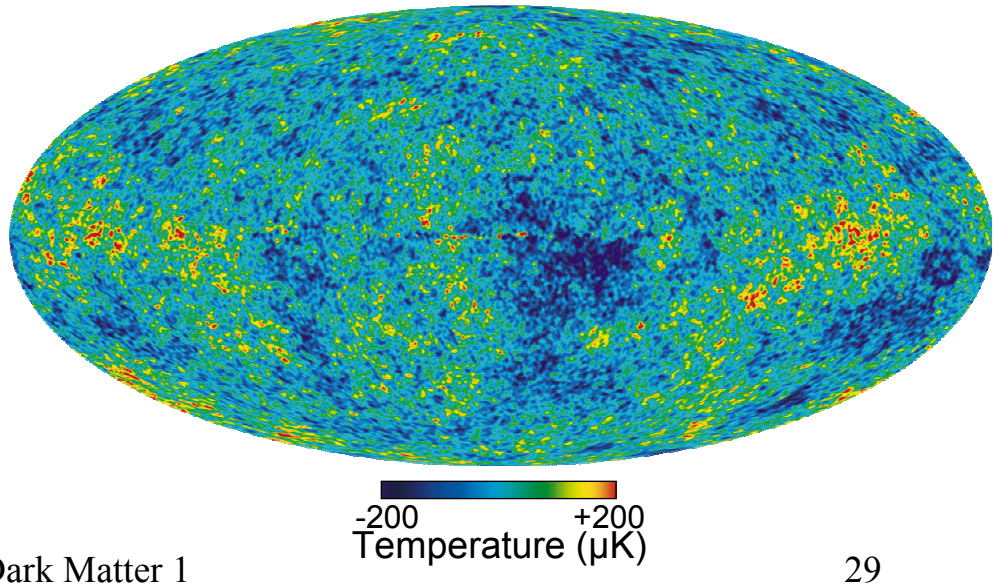
$$Vesc = \sqrt{\frac{2GM}{R}}$$

→ Need more mass to bind those stars to the galaxy/cluster!

Dark Matter: The Science Case

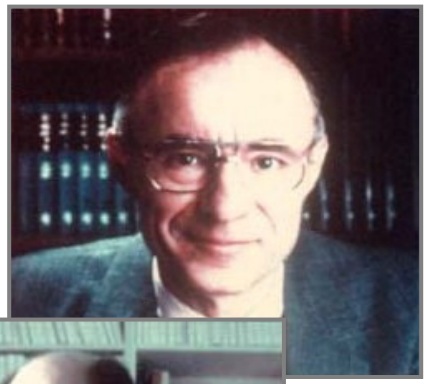
- Evidence from Astronomy
  - The Cosmic Microwave Background
  - Predicted ‘echoes’ of the Big Bang
  - Now well observed by satellite data
  - We only understand the pattern that is seen if there is dark matter





The Cosmic microwave background

- 1948 Predicted by George Gamow
- 1965 Discovered by Penzias and Wilson
  - By accident
  - Still won a Nobel Prize…
    - The scenario: 380,000 yrs after the Big Bang, temperatures cool enough for electrons and protons to form Hydrogen (about 3000 K)
    - Optical depth massively increases (radiation decouples from matter)
    - Hubble's Law + Doppler effect…



Looking into the Universe now we see the '3000K blackbody' spectrum redshifted to 2.73K

Microwave Sky (c. 1992)

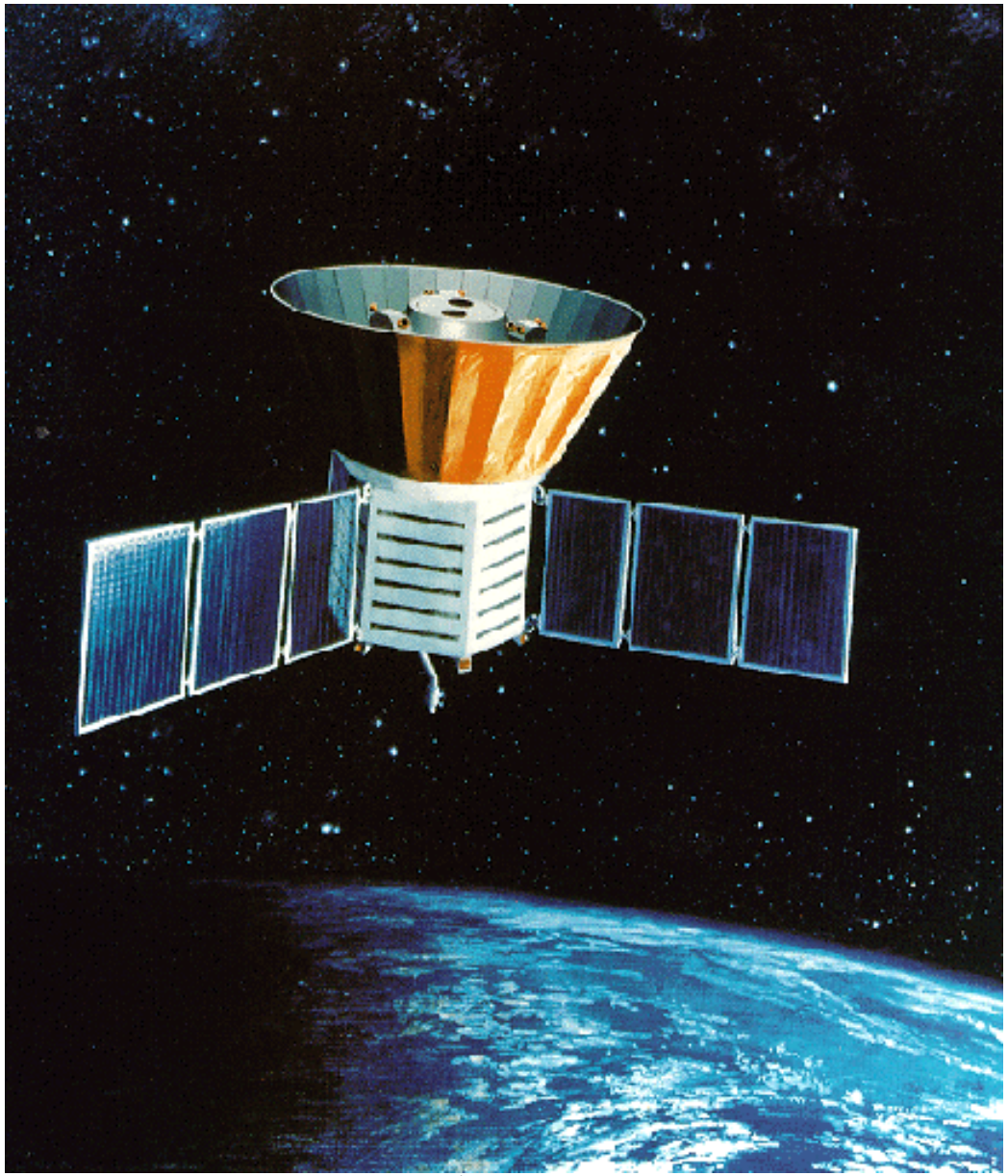
- The sky temperature with range from 0 - 4 Kelvin
- Microwave background is very uniform at nearly 2.73 Kelvi

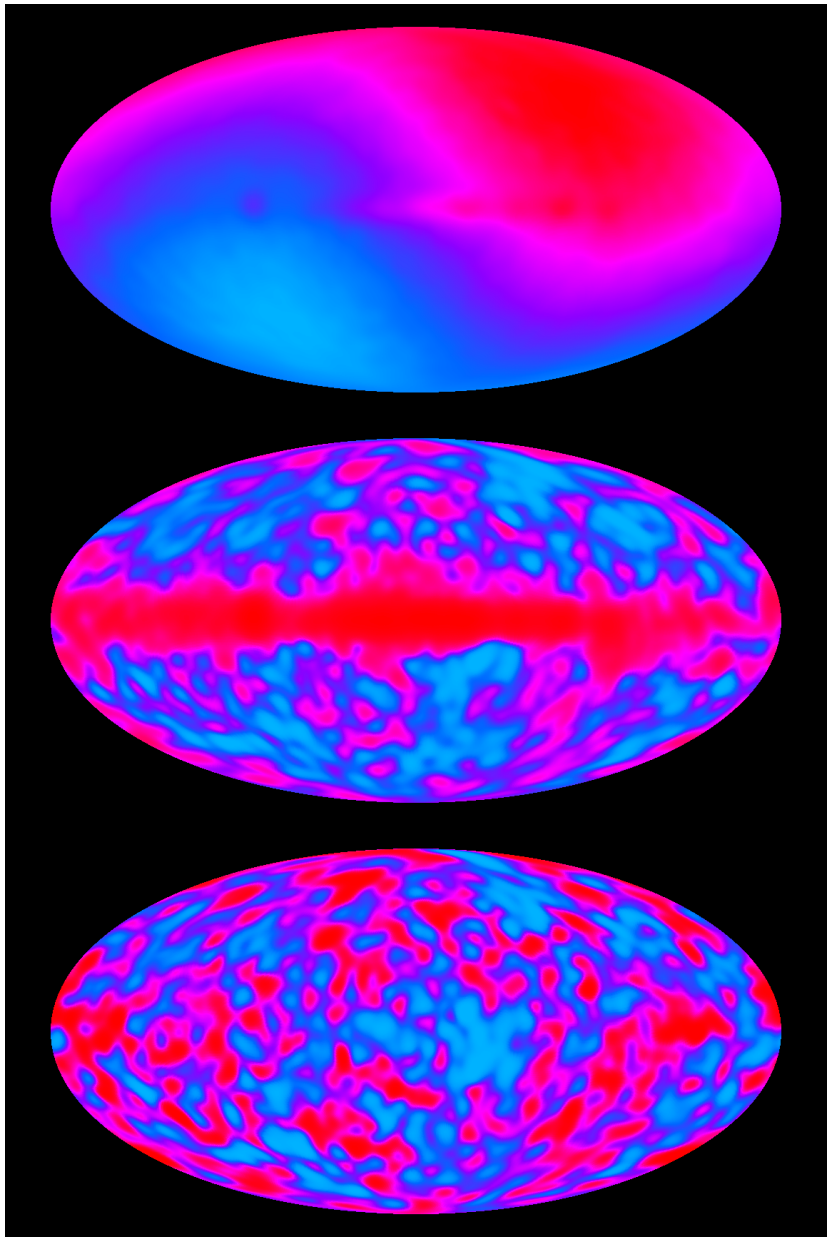
Red: hotter
Blue: cooler

There is a microwave background at T=2.73 K, same in all directions

Big Bang hypothesis is *'confirmed'*

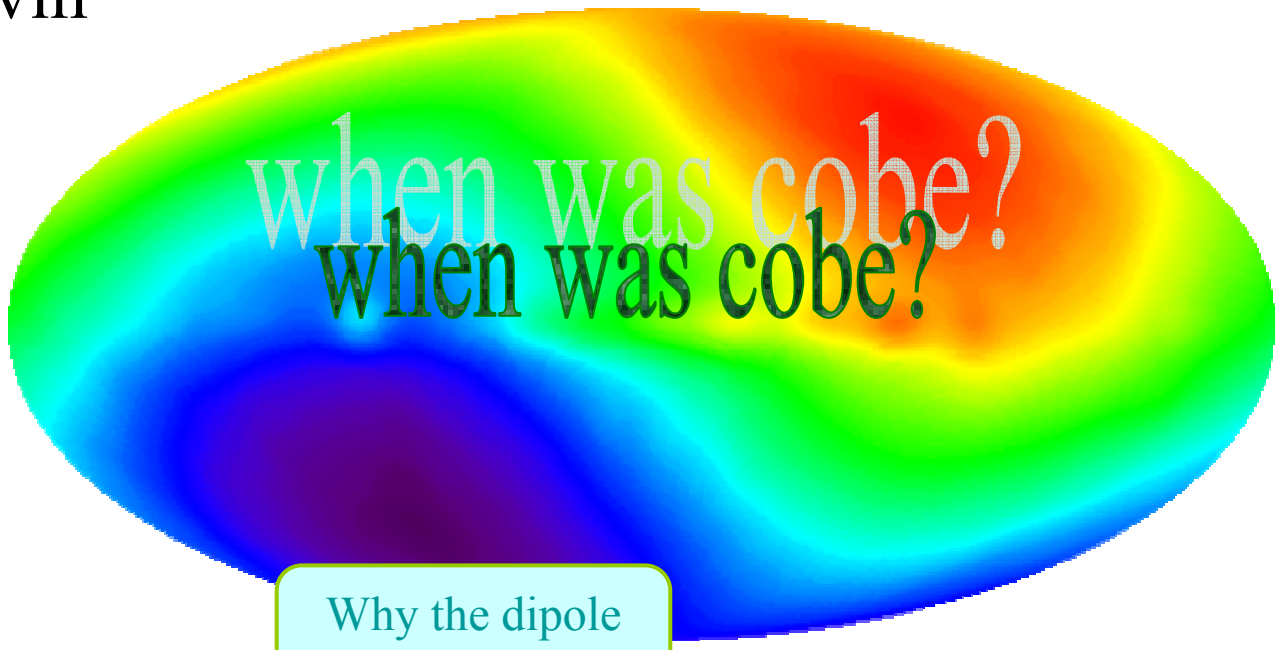
Image courtesy COBE homepage.





COBE Microwave sky

- The sky temperature with range from 2.724 - 2.732 Kelvin



Why the dipole asymmetry?

The sun is moving with respect to the CMBR

Image courtesy COBE homepage.

COBE microwave sky

The sky temperature ranging from 2.7279 to 2.7281 Kelvin.
Dipole removed.

Real fluctuations in temperature away from Milky Way of 1 part in 100,000

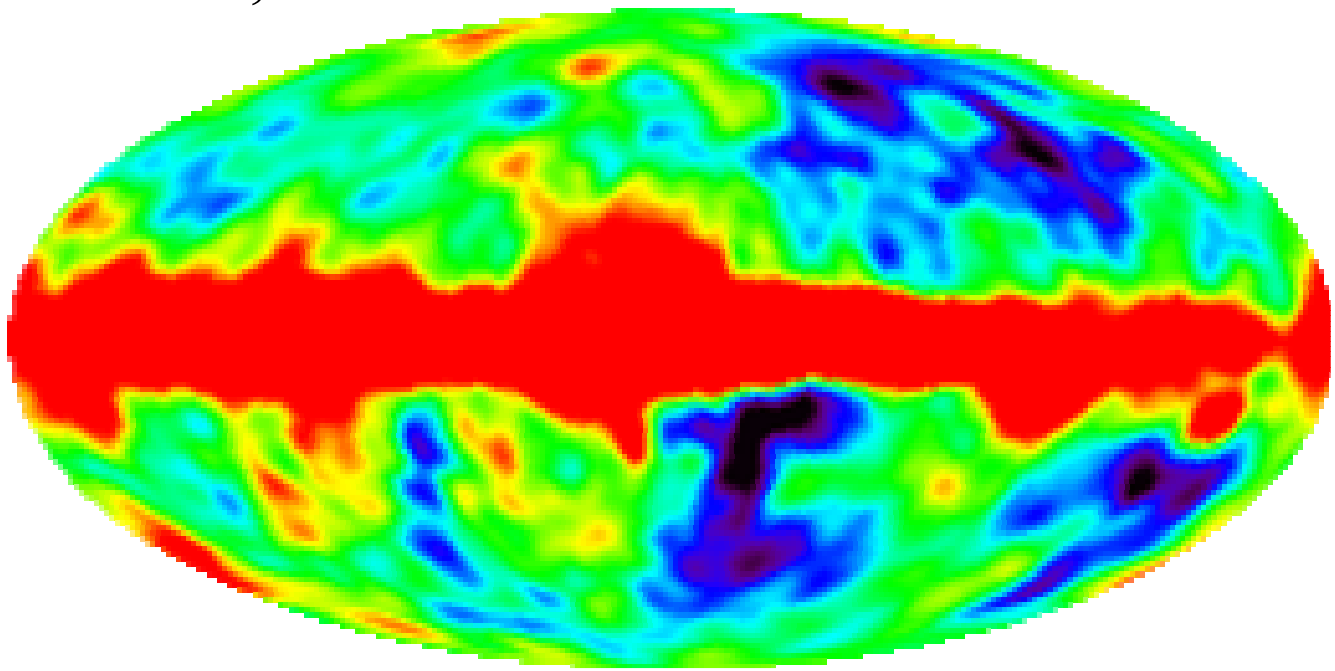
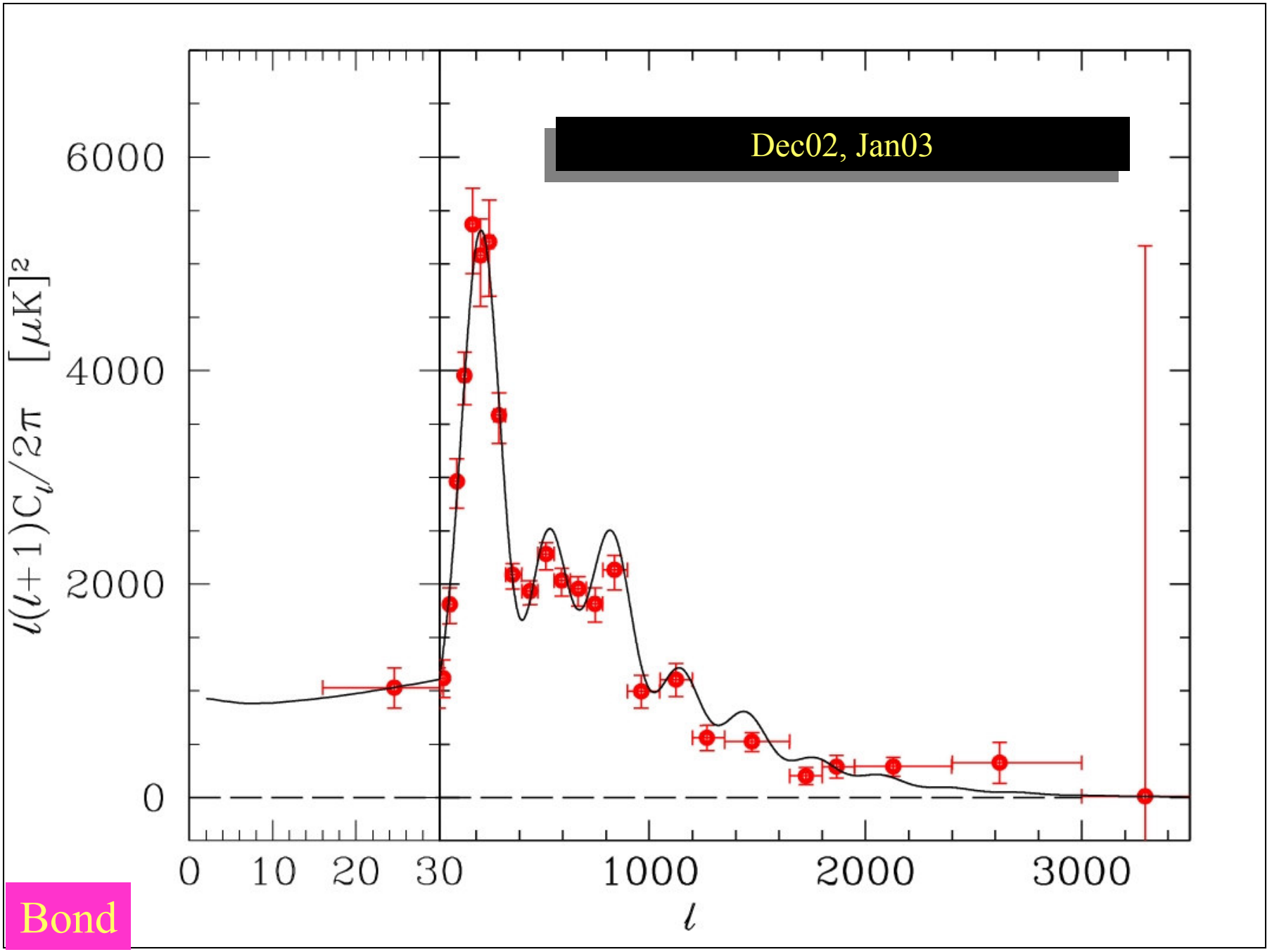
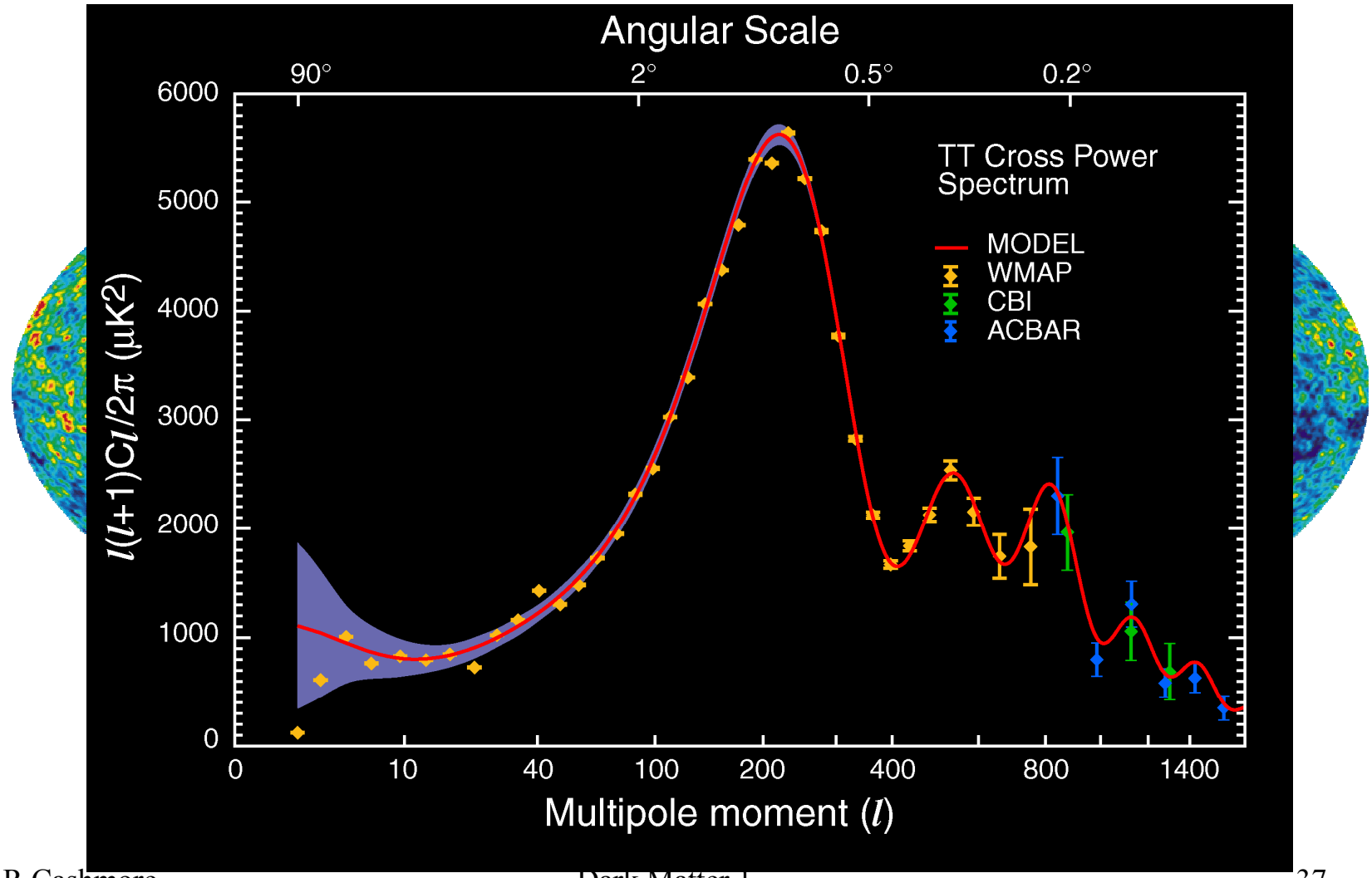


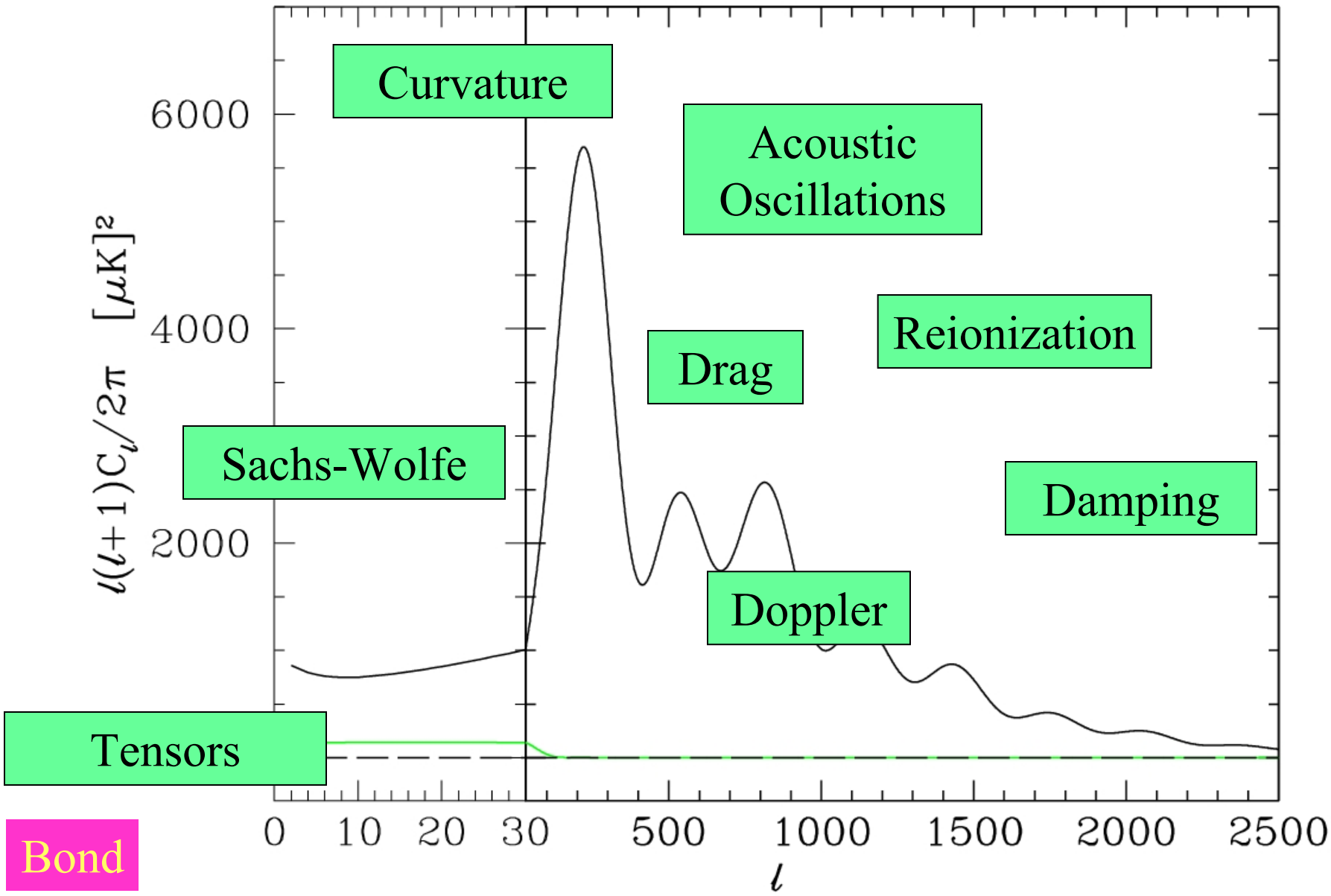
Image courtesy COBE homepage.


Dec02, Jan03
6000
4000
2000
0
$l(l+1)C_l/2\pi \quad [\mu K]^2$
0
10
20
30
1000
2000
3000
l
Bond

WMAP: Wilkinson Microwave Anisotropy



Sound & Light in the Early Universe



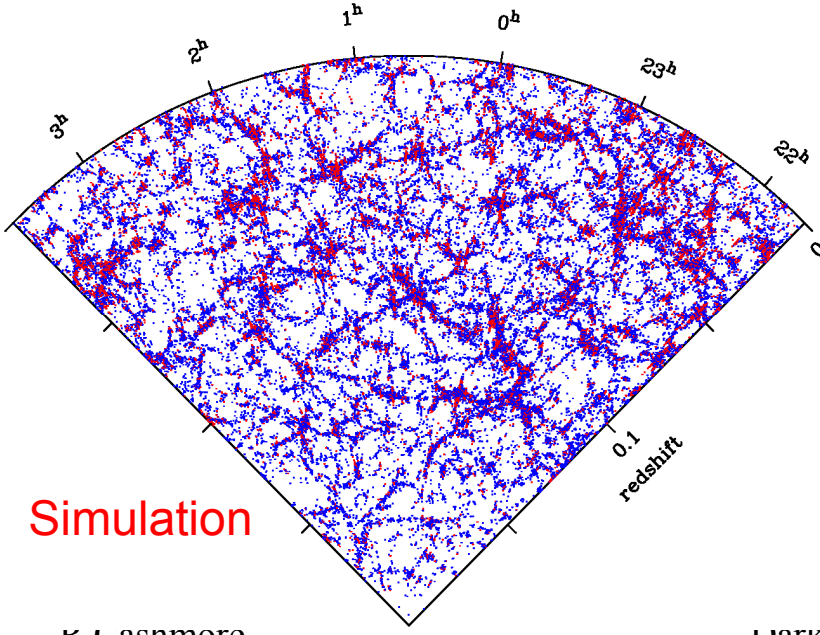
So what does the CMBR tell us…?

- The fluctuations are ‘echoes’ of the Big bang
- The typical size of the structures tell us over what scale things were causally connected
  - Acoustic resonances strongly s*upport inflation*.
- These are the ***original*** density perturbations that have grown into the Large Scale Structure of the Universe
- Details in power spectrum are related to aspects of cosmology
  - ***l*** of big peak → Curvature of space
  - Height of spectrum → total density
  - Ratio of heights of 1^{st} to 2^{nd} peak → baryon-to-photon ratio
  - Etc
- Acceptable fits all suggest cold dark matter. Preferred option is ‘ΛCDM’

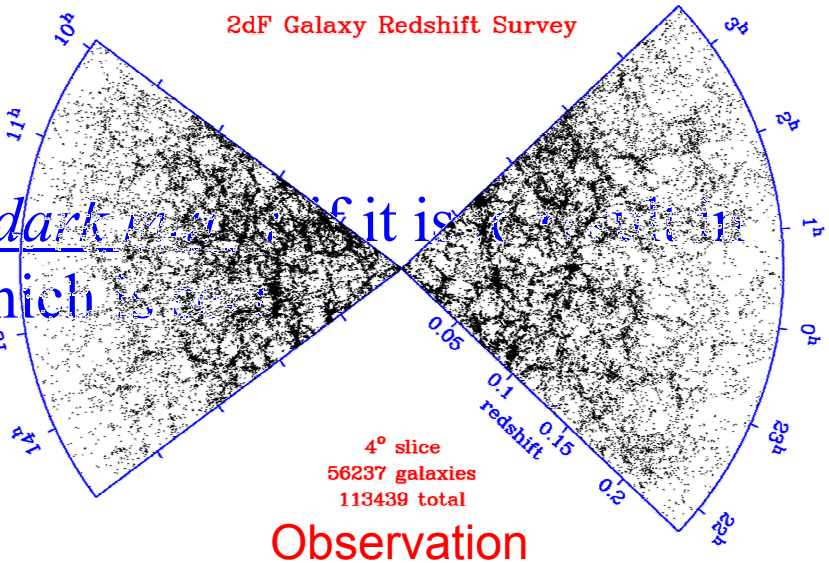
Large Scale Structure in the Universe

Dark Matter: The Science Case

- Evidence from Astronomy
  - Large scale structure
  - This is a simulation of galaxies forming [file]
  - Project a slice of this and compare it to reality

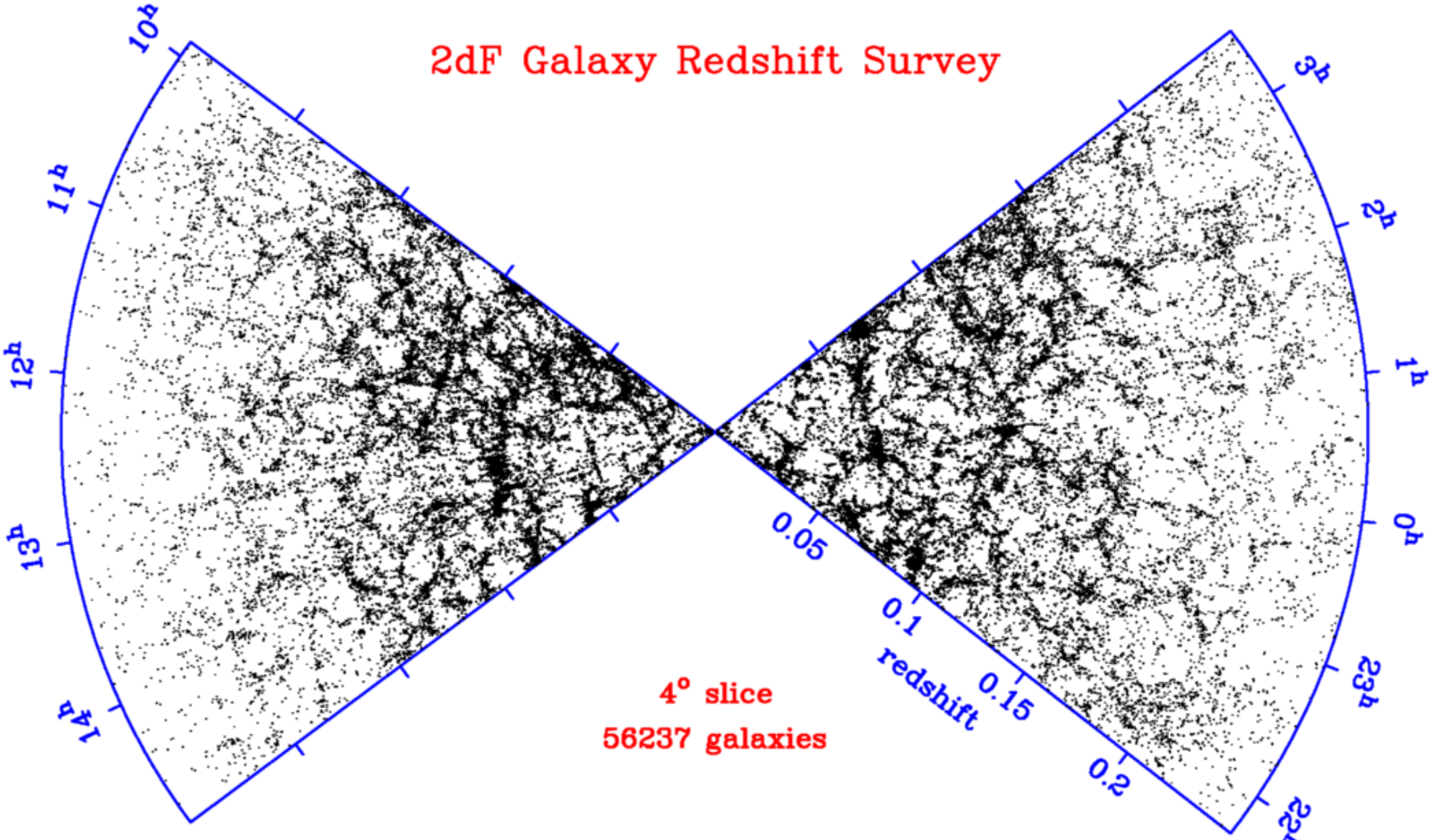


Simulation

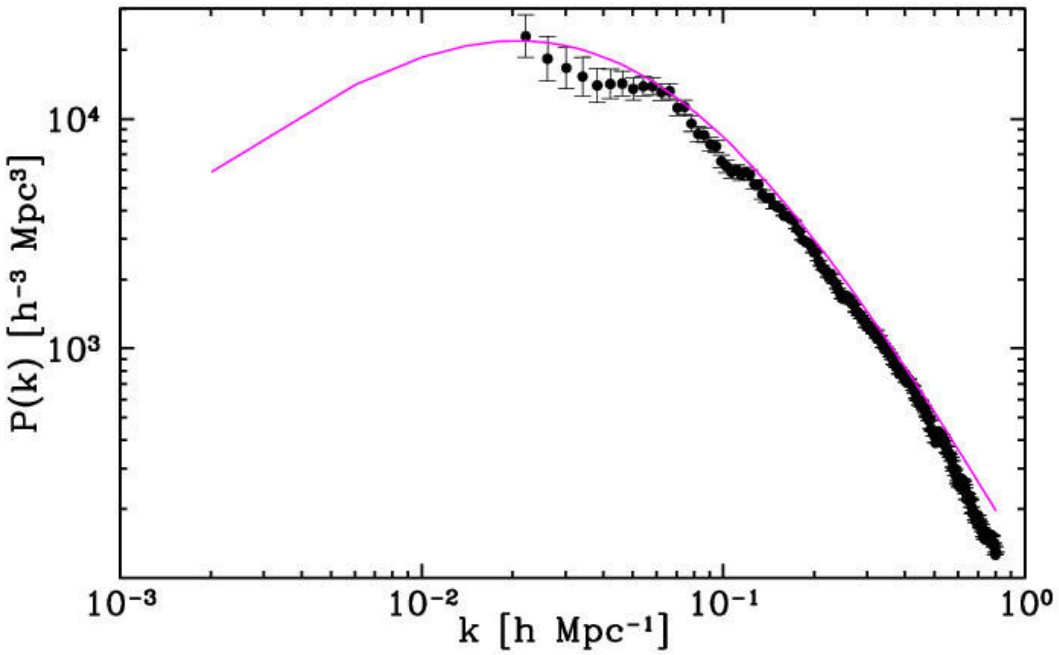


Observation

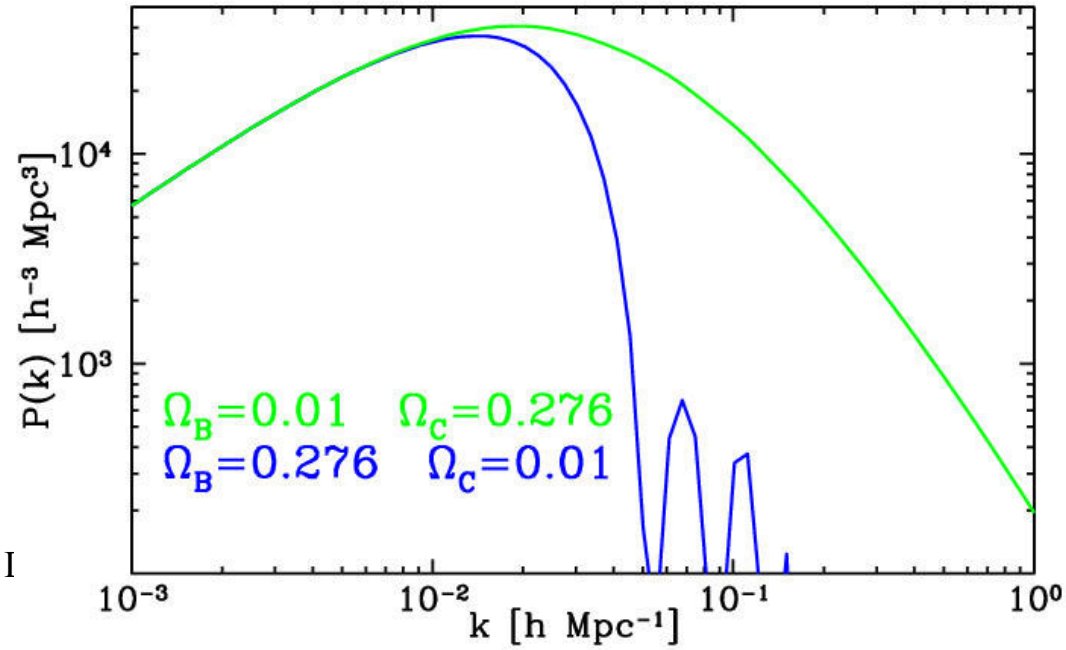
2dFGRS cone diagram: 4-degree wedge



Peacock



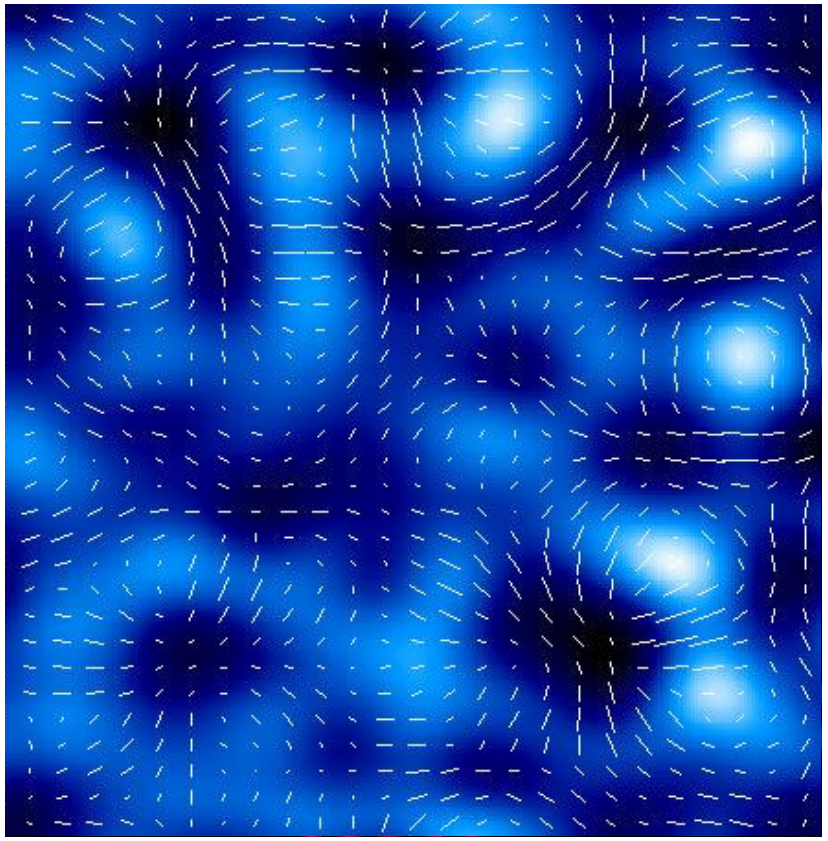
Baryons are not enough!



Kolb, Peacock

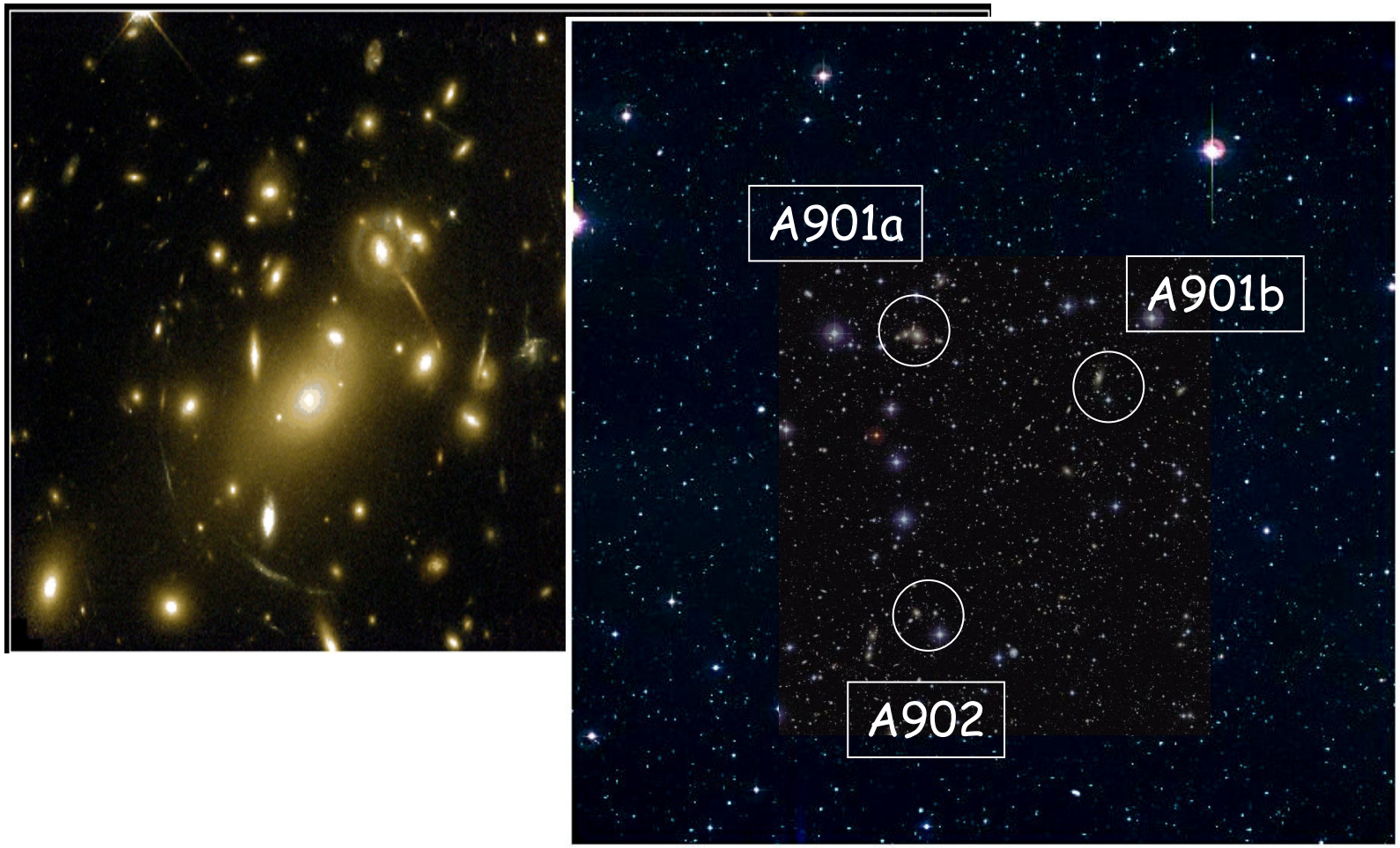
Weak Gravitational lensing

- Distortion is due to a lens
- Amount and direction of 'shear' tells you where and how strong the *lens* is.
- Apply this to images of distant galaxies being distorted by intervening dark matter lenses
- Can extend it in to 3D



(Courtesy A. Refregier)

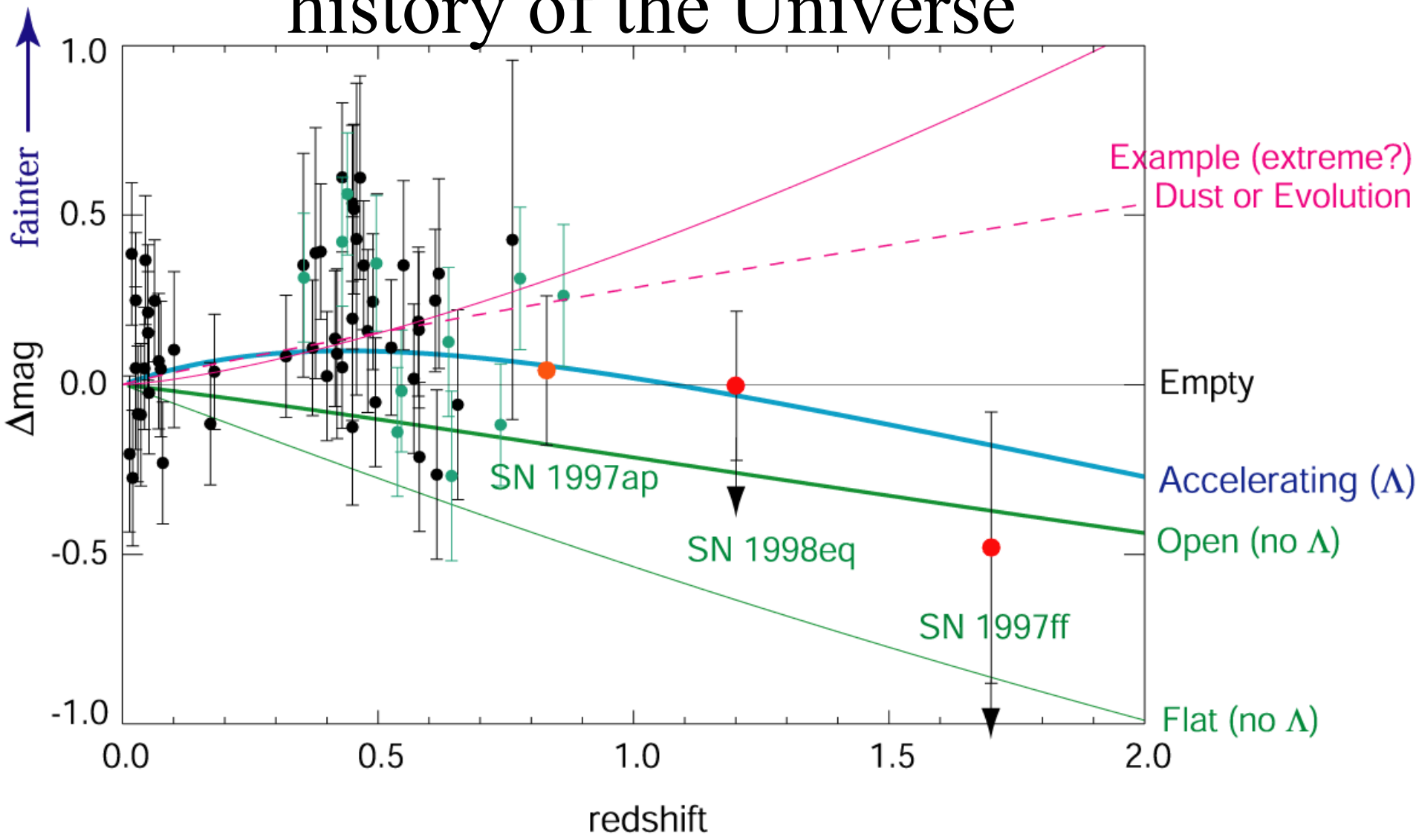
Weak lensing…



Supernovae

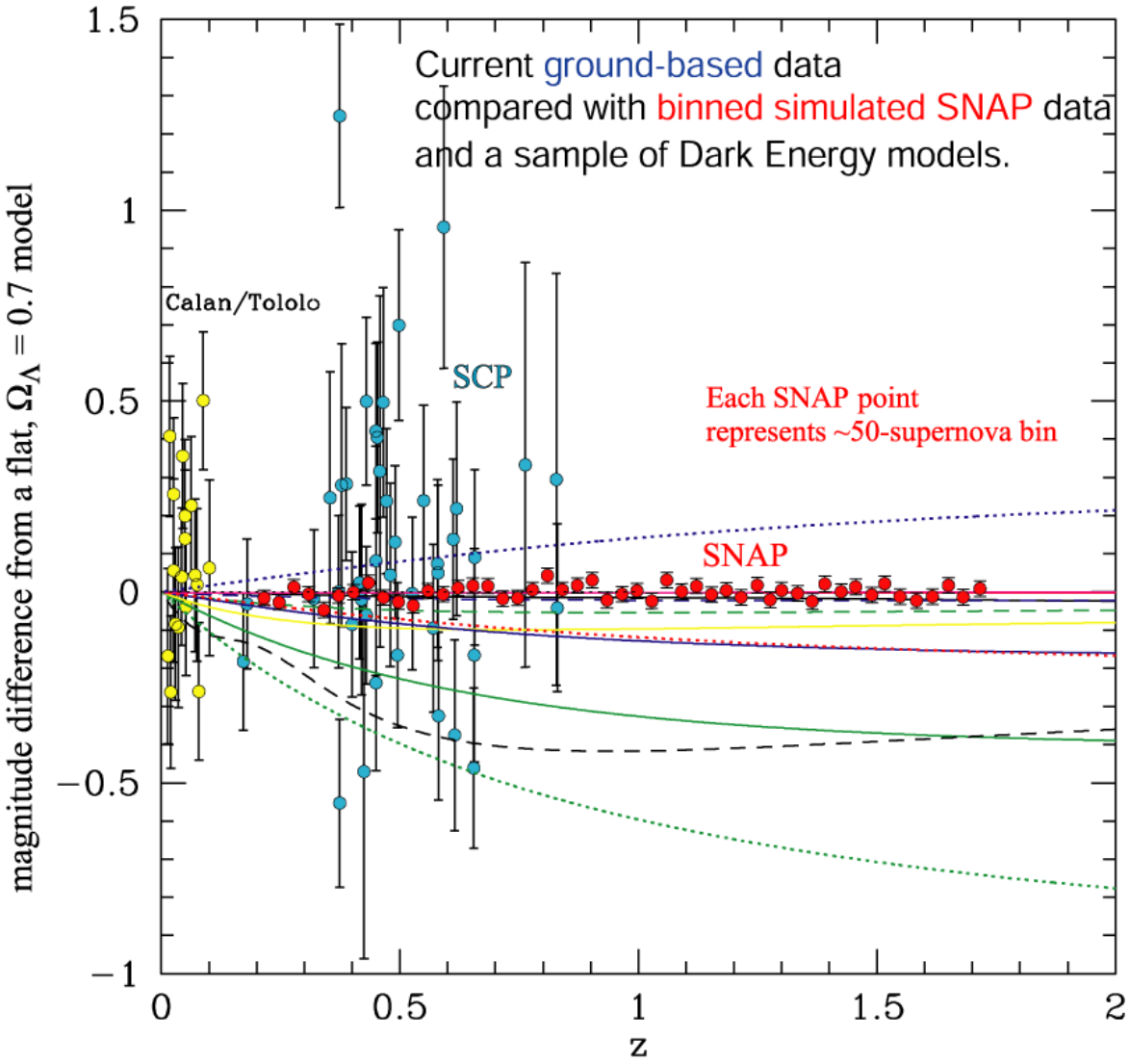
Supernovae probe the *Ac(de)celeration* history of the Universe

Perlmutter



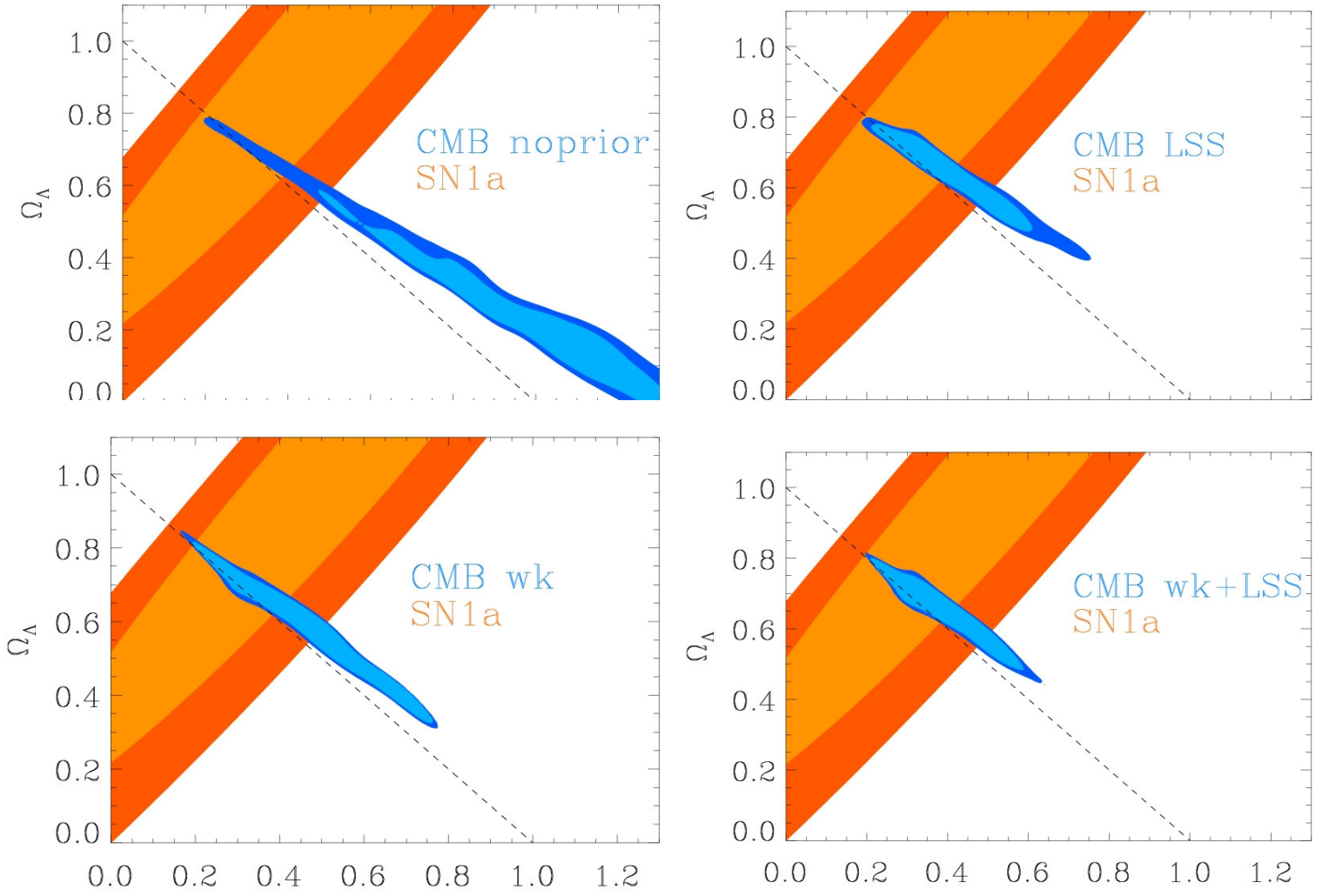
New Measurements

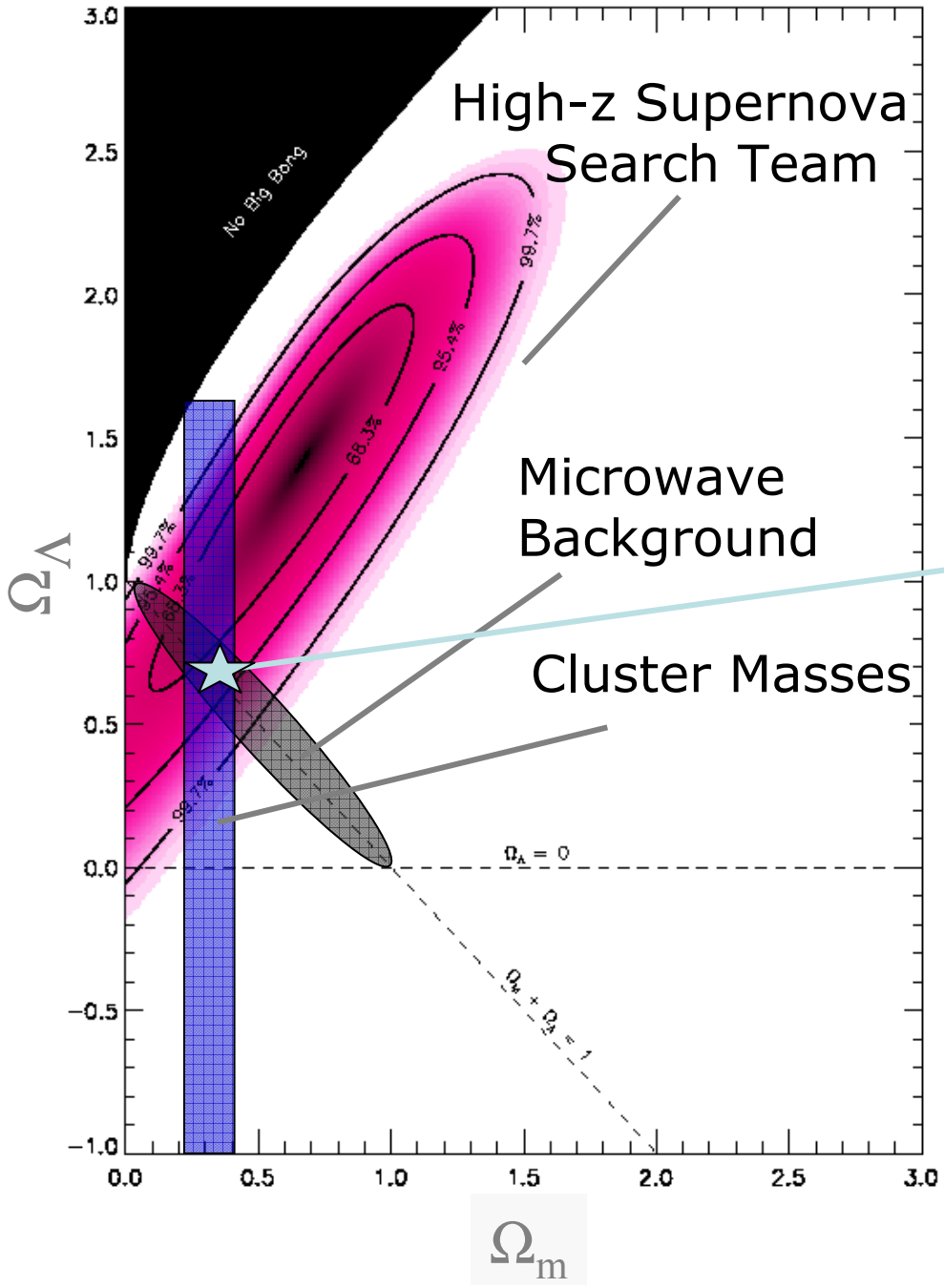
- High z SNe discovery and follow-up
- Observe detailed evolution of DE back to deceleration era
- Eliminate gray dust as a potential source of systematic error (multi-spectral light curve)



based on
Weller & Albrecht (2001)

Combining CMB with other Data





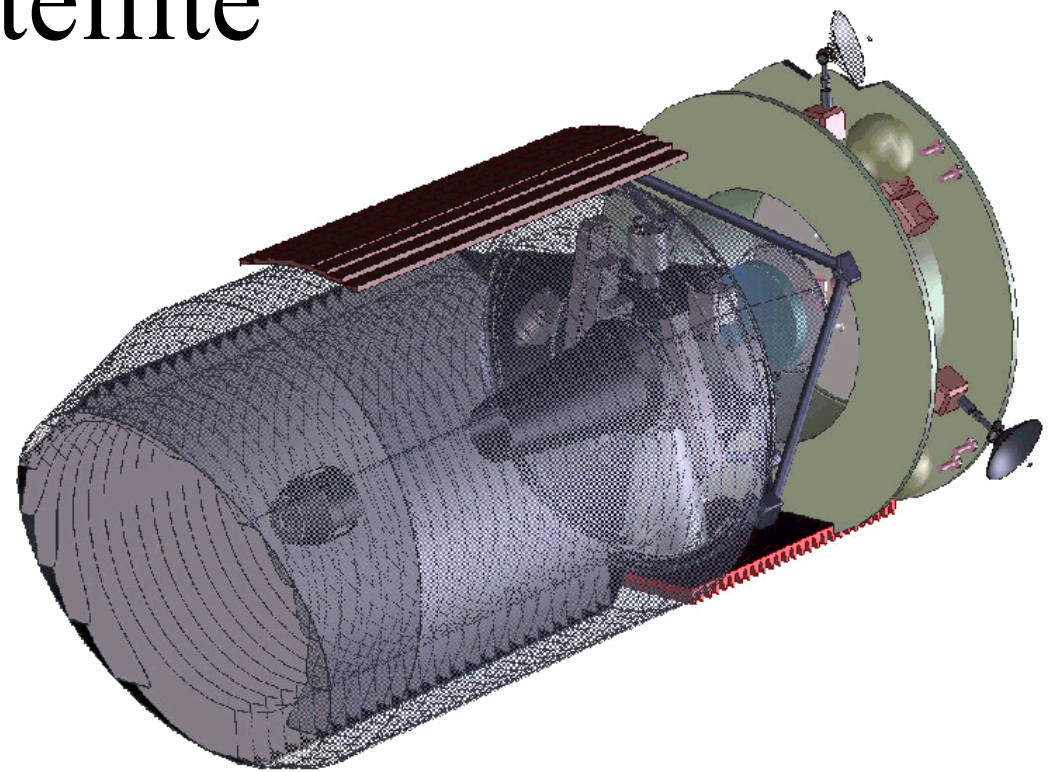
Best fit:

$\Omega_{mass} \sim 0.3$

$\Omega_\Lambda \sim 0.7$

Λ?

SNAP Satellite



- **~2 m aperture telescope**
  Can reach very distant SNe.
- **1 square degree mosaic camera, 1 billion pixels**
  Efficiently studies large numbers of SNe.
- **0.35um -- 1.7um spectrograph**
  Detailed analysis of each SN.

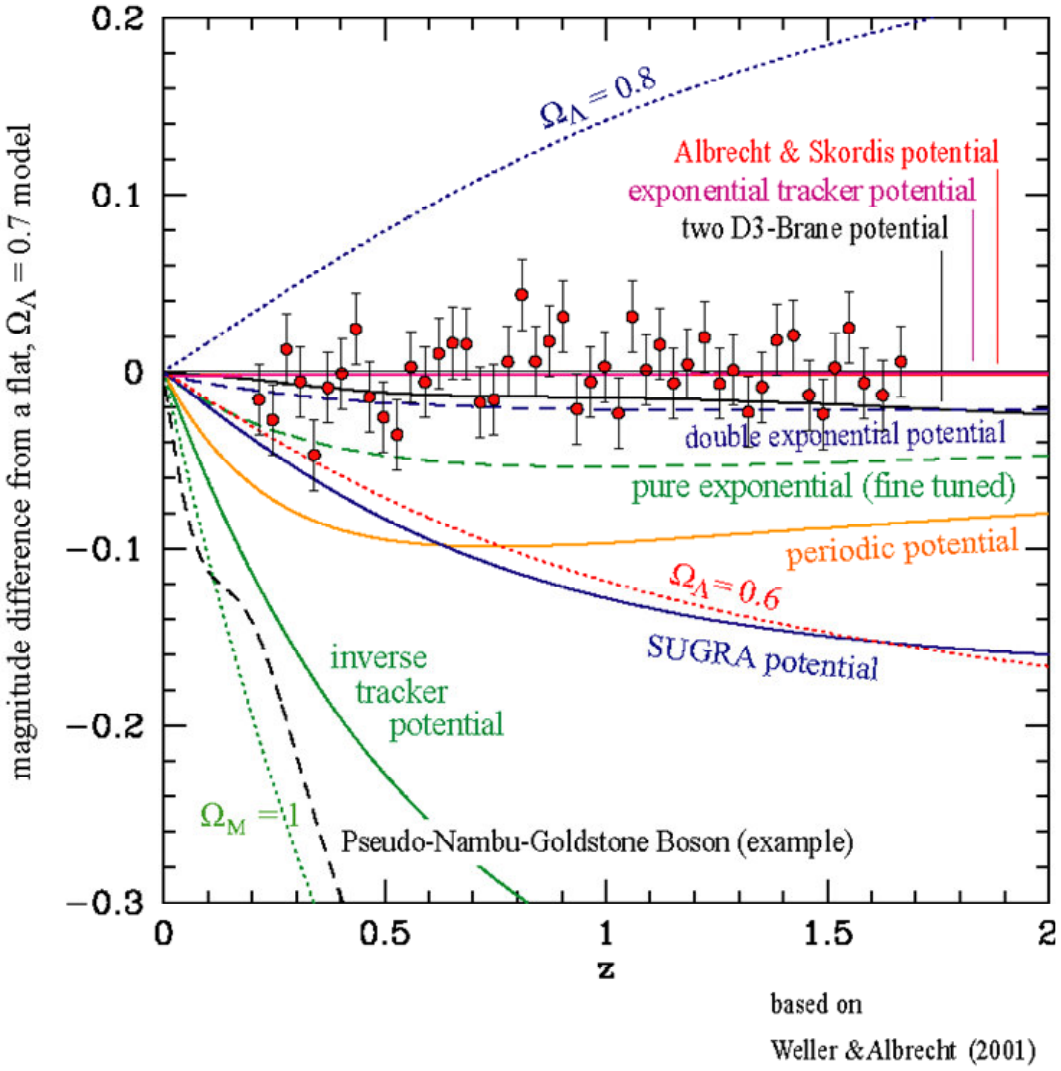
Dedicated instrument designed to repeatedly observe an area of sky.

Essentially no moving parts.

3-year operation for experiment (lifetime open-ended).

Understanding Dark Energy

Binned simulated SNAP data compared with
Dark Energy models currently in the literature.



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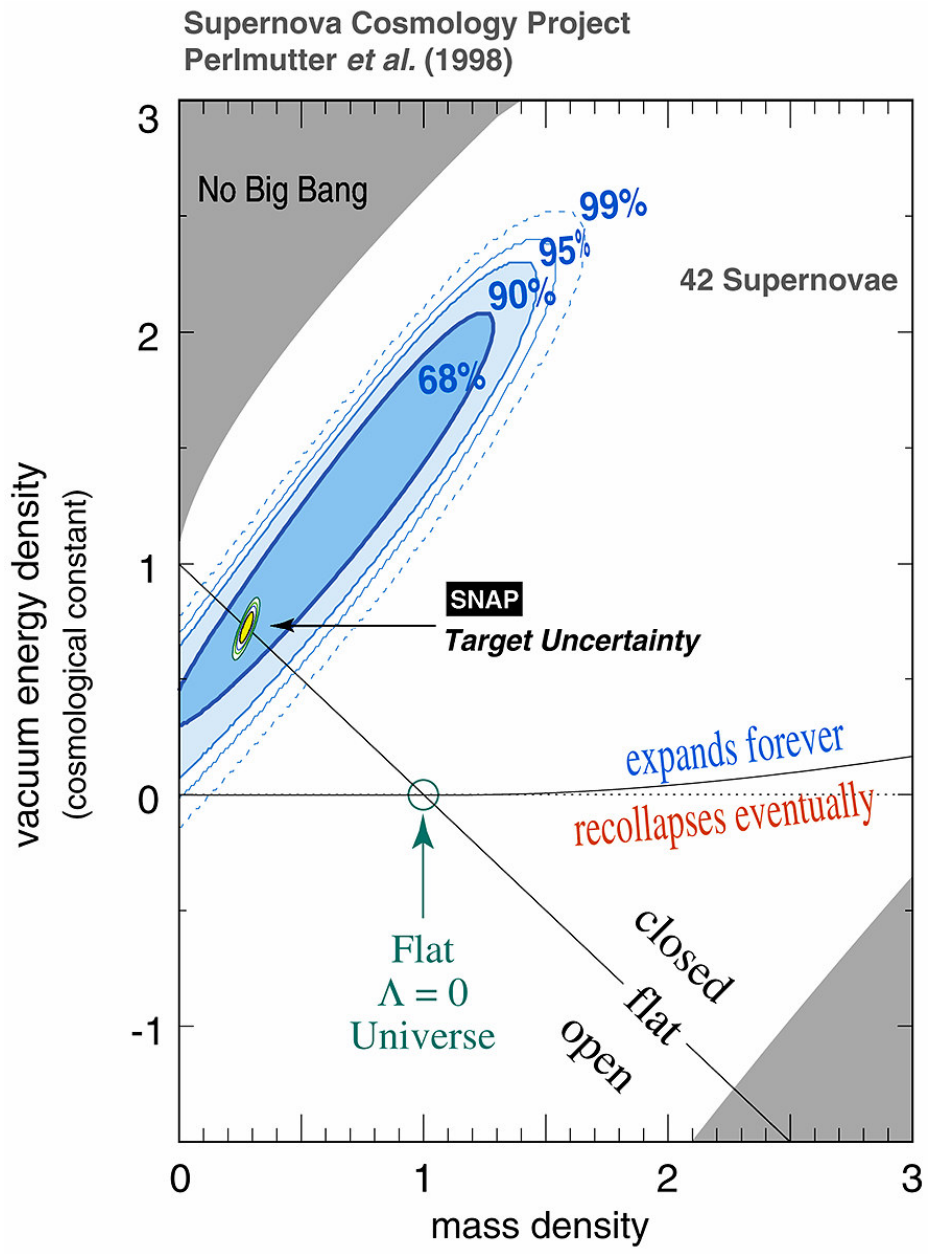
SNAP Target Uncertainty



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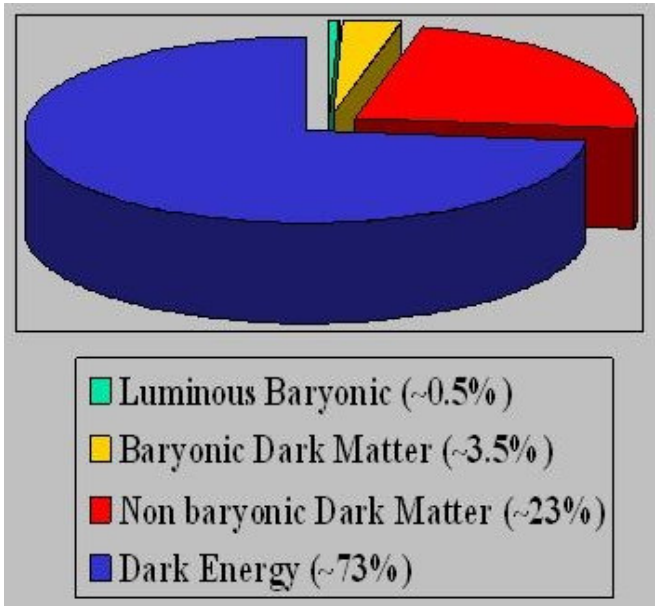
The evidence

There's now a huge body of evidence for cold dark matter…

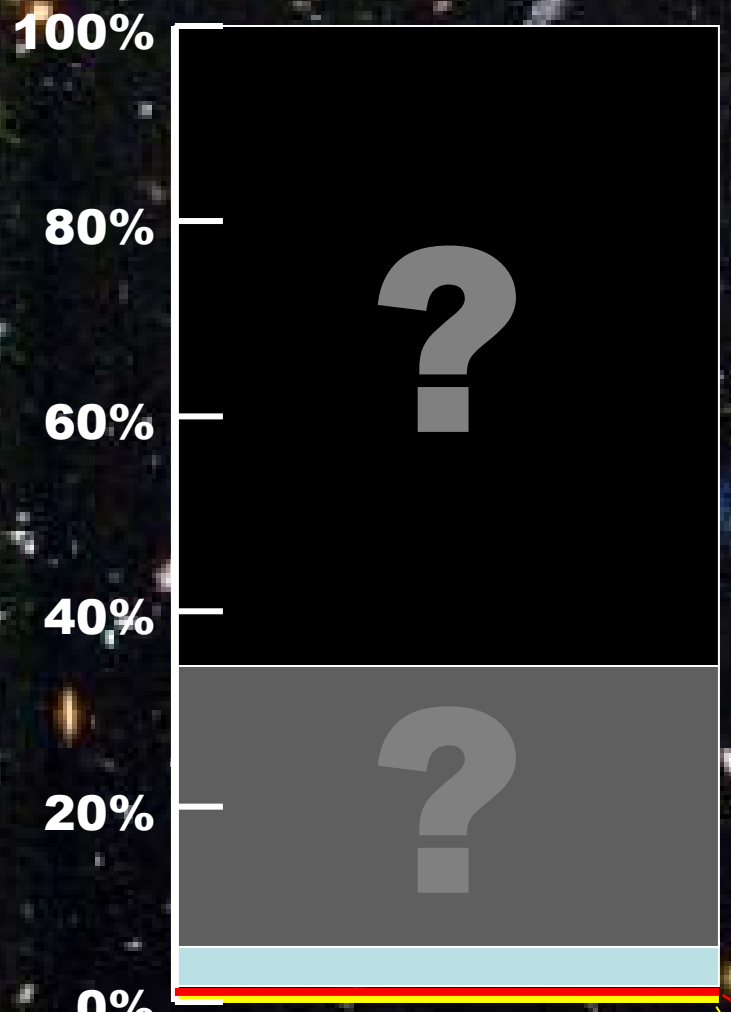
- Galactic X-ray emission
- Motion of distant quasars
- Motion within our Galaxy
- Cosmic microwave background radiation
- Motion of Galaxy Clusters
- Big Bang Nucleosynthesis
- Motions Galaxys
- Weak lensing



Evidence comes at all scales (Galactic, Cluster, Large Scale Structure, CMB)

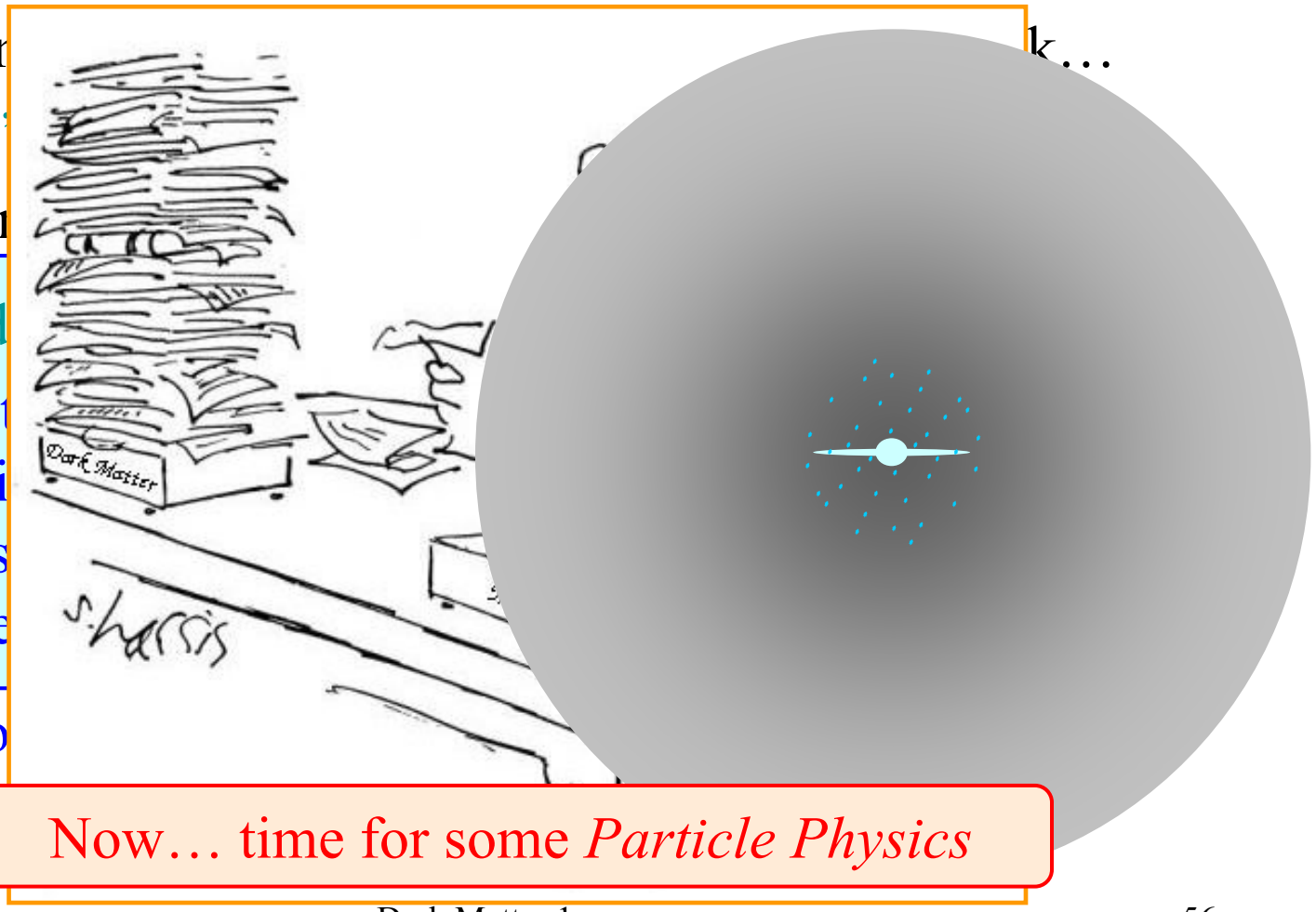
Consistent DM fractions found

Our view of the Universe



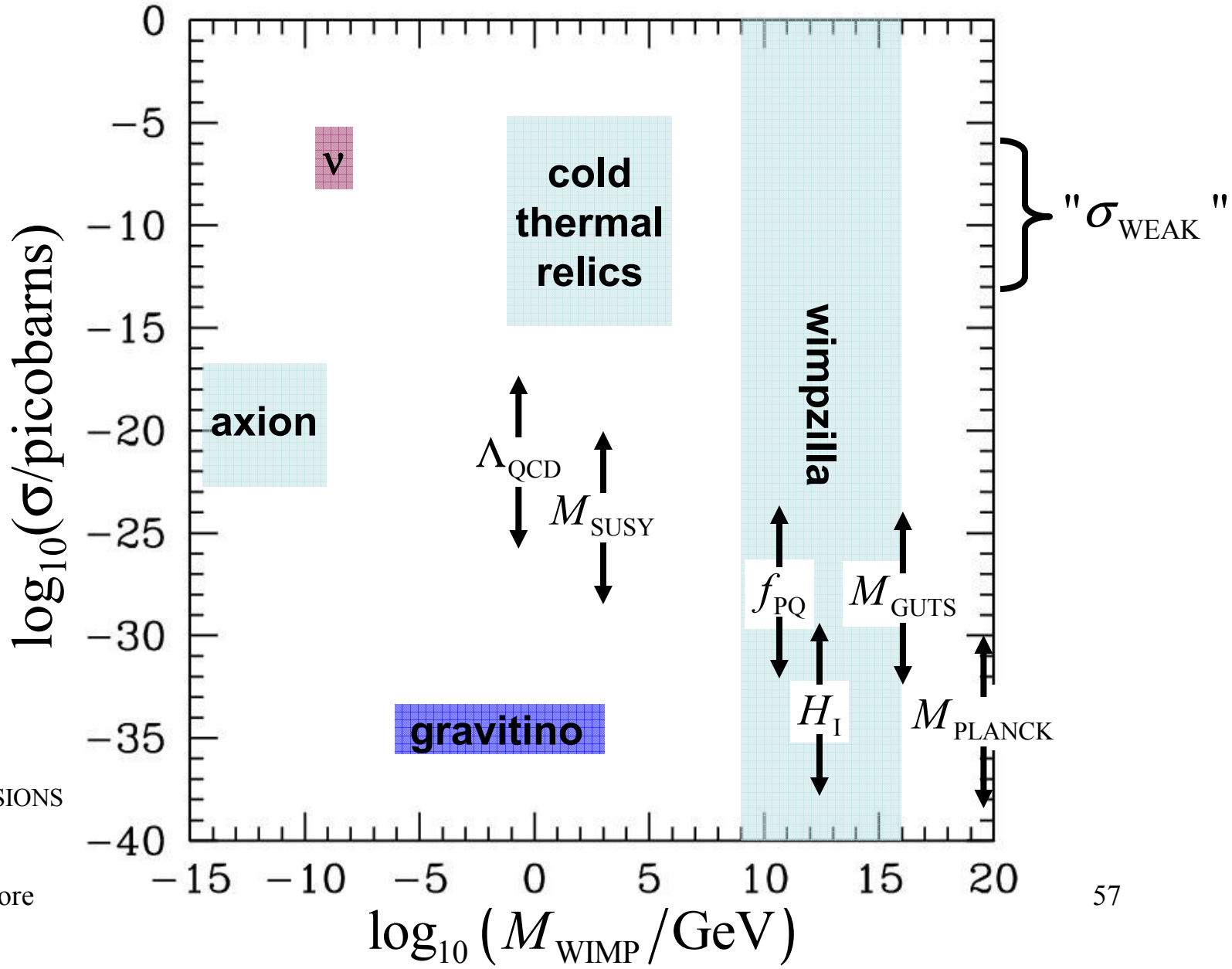
What might the Dark Matter be?

- Non-exister…
  - 'MoND'
- Unseen plan
- So, the evid… 9/10th of t… Universe i… clumpy gas… neve…
  - In the fo…



Now… time for some *Particle Physics*

Particle Dark Matter Candidates



Other Scales:

M_{EWK}

M_{STERILE}

M_{STRING}

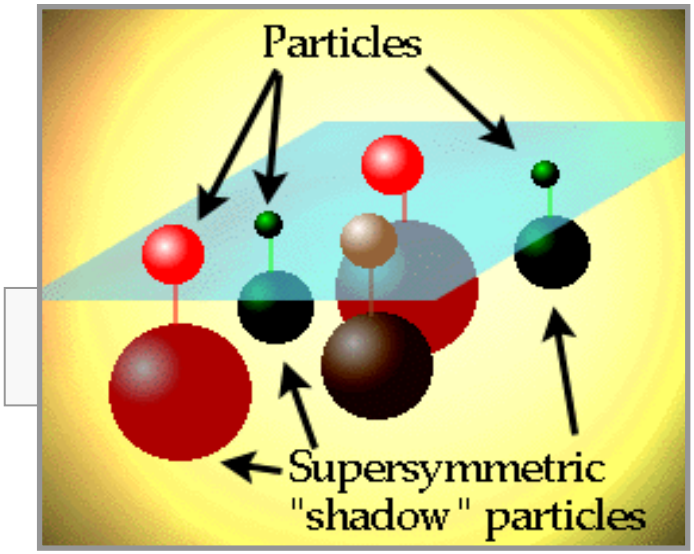
$M_{\text{TECHNICOLOR}}$

$M_{\text{EXTRA DIMENSIONS}}$

Kolb ashmore

Supersymmetry

- Particle physics has long asked *"why do the particles we observe have the properties they do?"*
- We still do not know the answer…
- The patterns we see make more ***sense*** if there is a 'shadow partner' to each particle we see



Weakly Interacting Massive Particles

- The lightest of these new particles is an ideal candidate for dark matter
- Would have been created in the Big Bang
- A ***natural*** solution – makes it extremely attractive!

Now we need to detect these particles!

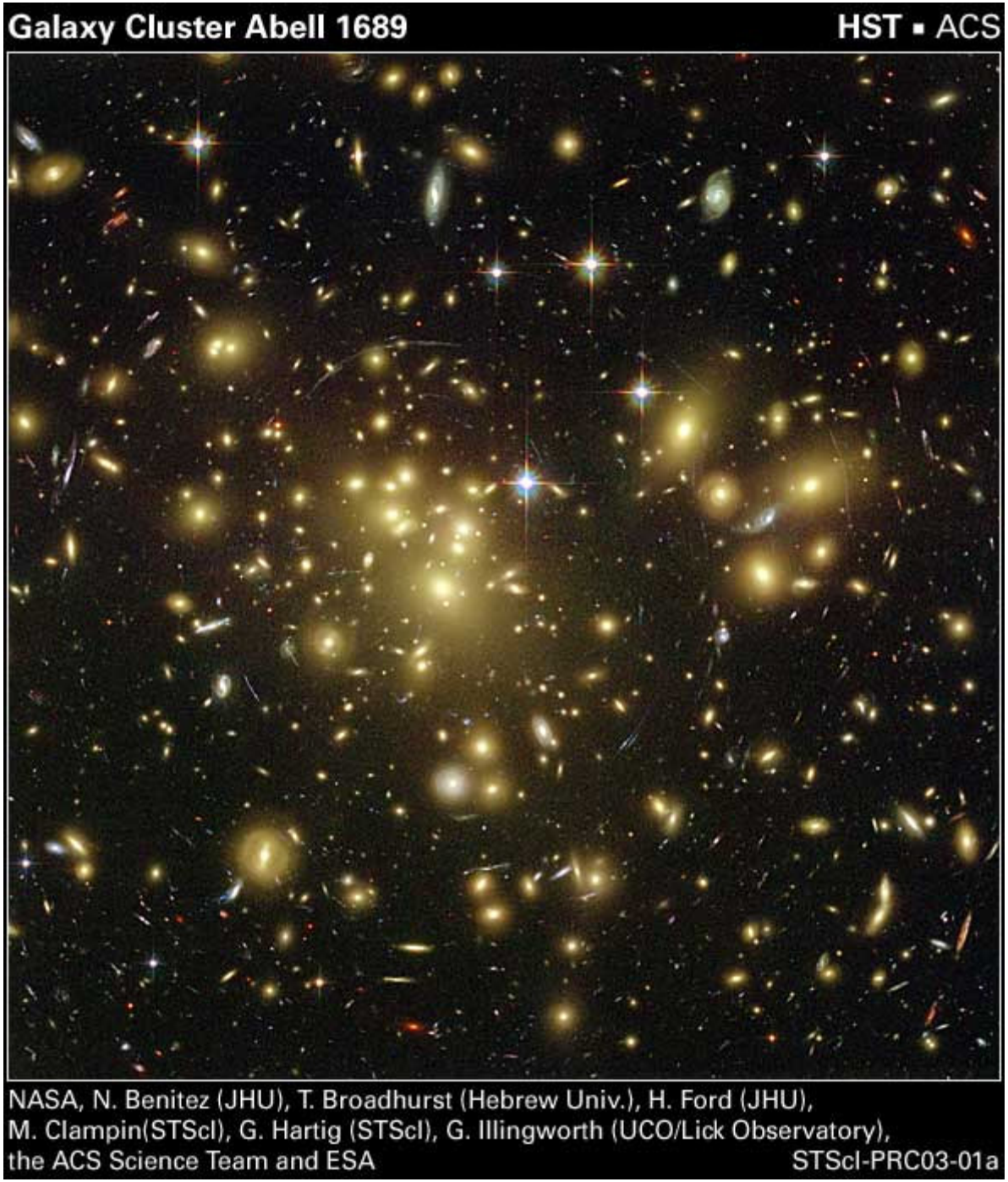
Particle type	Particle	Super partner
Fermion	Quark	Squark
	Neutrino	Sneutrino
	Electron	Selectron
	Muon	Smuon
	Tau	Stau
Boson	W	Wino
	Z	Zino
	Photon	Photino
	Gluon	Gluino
	Higgs	Higgsino

Summary

- Dark Matter is there in the universe

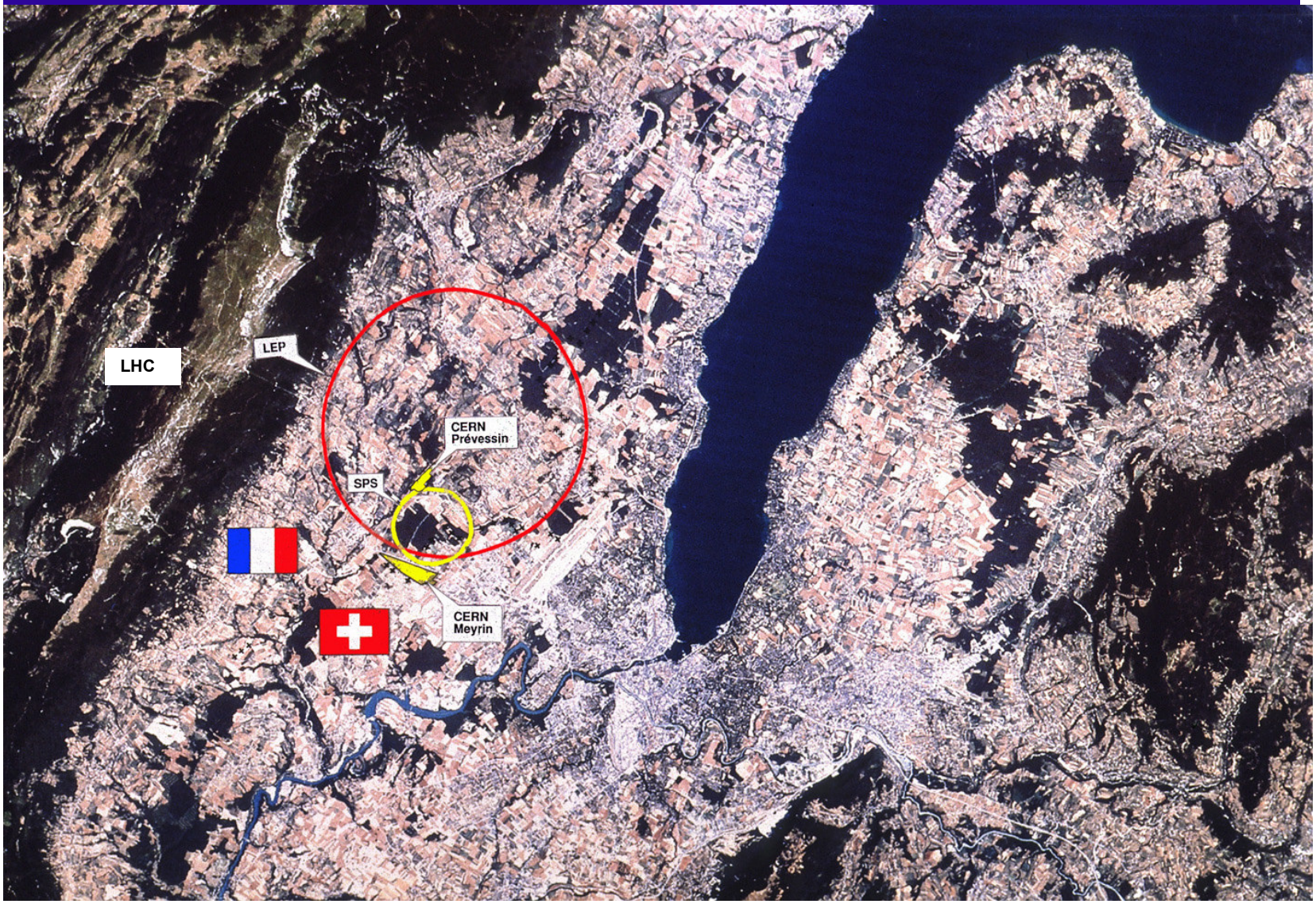
  What is it?

- Direct Searches … we are moving through it
- Produce candidate particles … experiments at the LHC


Galaxy Cluster Abell 1689
HST ▪ ACS
NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU),
M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory),
the ACS Science Team and ESA
STScI-PRC03-01a

Earth from Apollo 17 (NASA)

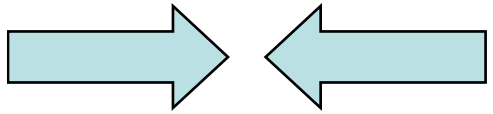
Satellite view of Geneva and CERN site



The Large Hadron Collider in the LEP Tunnel

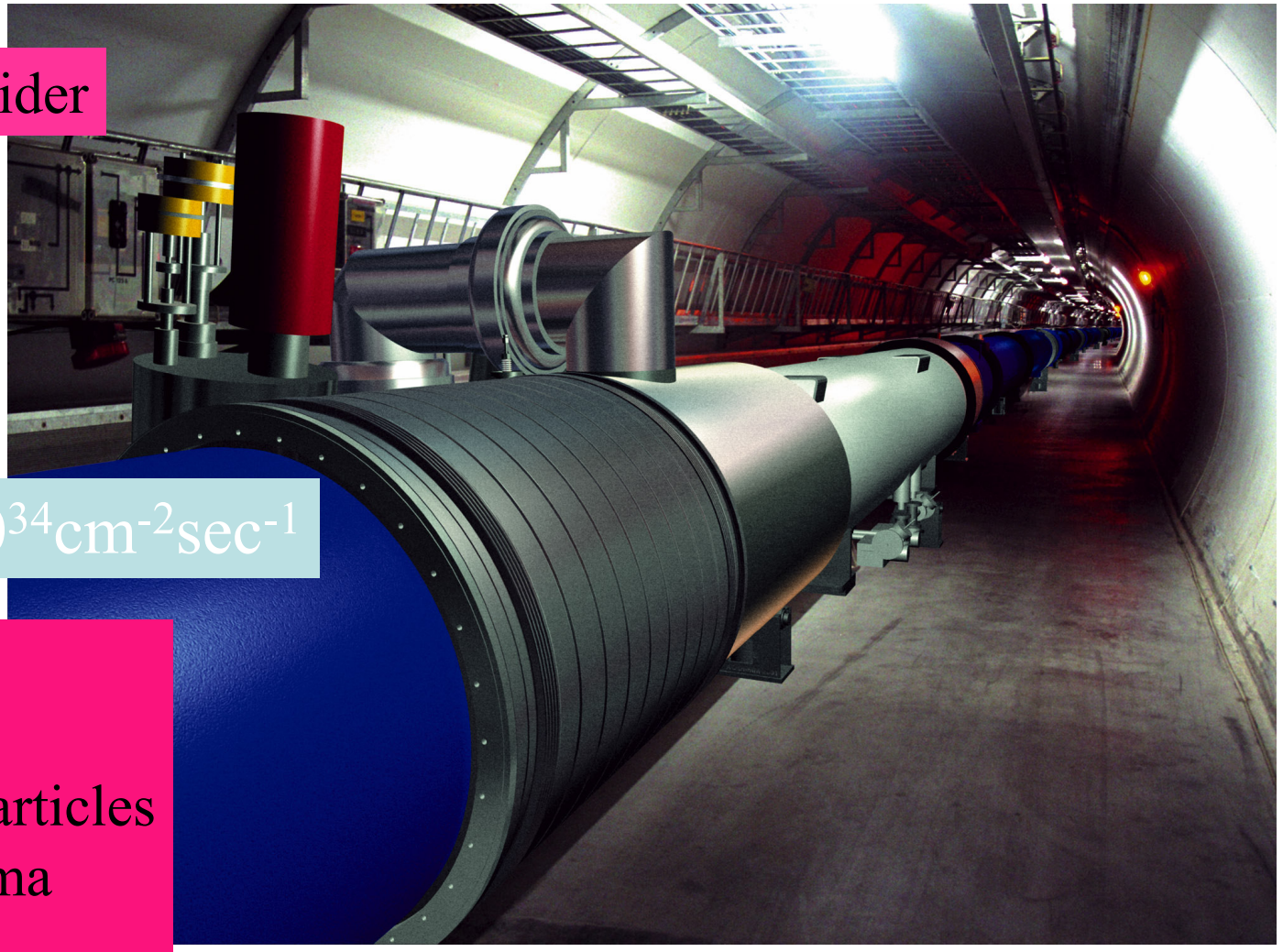
Proton- Proton Collider

7 TeV + 7 TeV

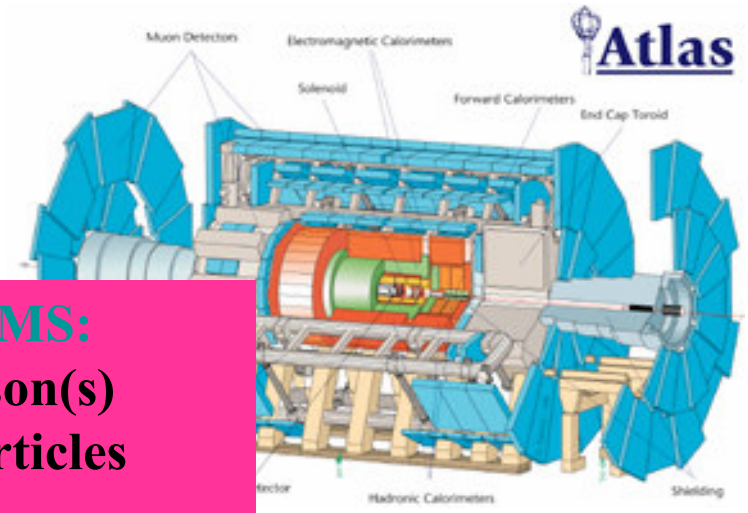


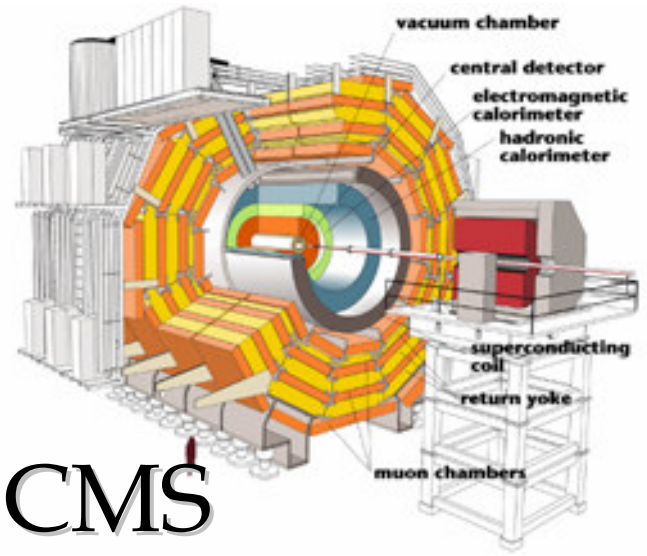
Luminosity = $10^{34}cm^{-2}sec^{-1}$

The Physics:
- Higgs boson (s)
- Supersymmetric Particles
- Quark-Gluon Plasma
- CP violation in B



LHC Experiments





ATLAS, CMS:

- Higgs boson(s)

- SUSY particles

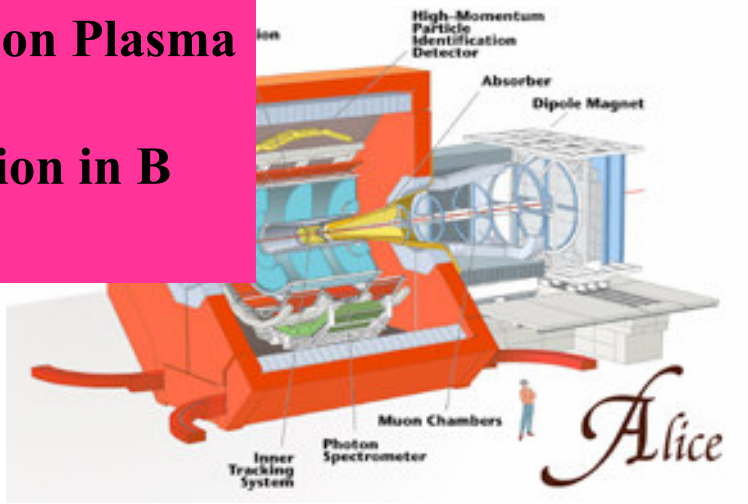
- …??

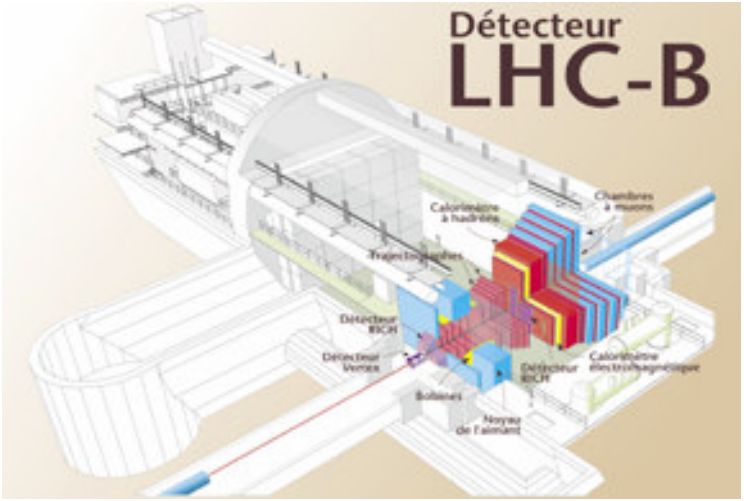
ALICE:

Quark Gluon Plasma

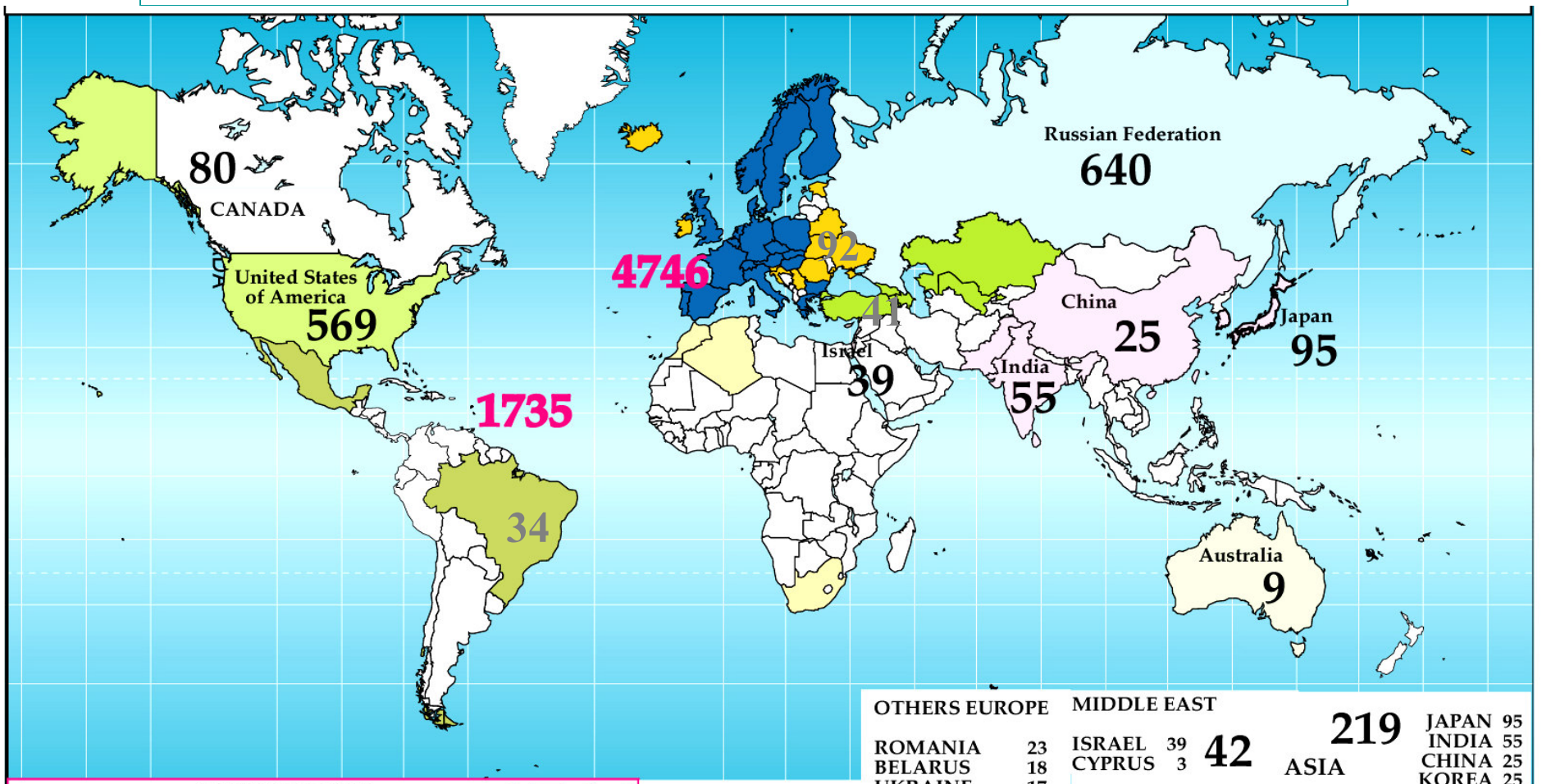
LHC-B:

- CP violation in B





Worldwide Scientific Collaboration



MEMBER STATES — 4746

AUSTRIA	GERMANY	PORTUGAL
BELGIUM	GREECE	SLOVAKIA
BULGARIA	HUNGARY	SPAIN
CZECH REPUBLIC	ITALY	SWEDEN
DENMARK	NETHERLANDS	SWITZERLAND
FINLAND	NORWAY	UNITED KINGDOM
FRANCE	POLAND	

LATIN AMERICA — 34

BRAZIL	26
MEXICO	8

OTHERS EUROPE — 92

ROMANIA	23
BELARUS	18
UKRAINE	17
SLOVENIA	15
CROATIA	12
SERBIA	2
IRELAND	2
ESTONIA	2
MALTA	1

MIDDLE EAST — 42

ISRAEL	39	
CYPRUS	3	
AFRICA		9
MOROCCO	4	
SOUTH AFRICA	4	
ALGERIA	1	

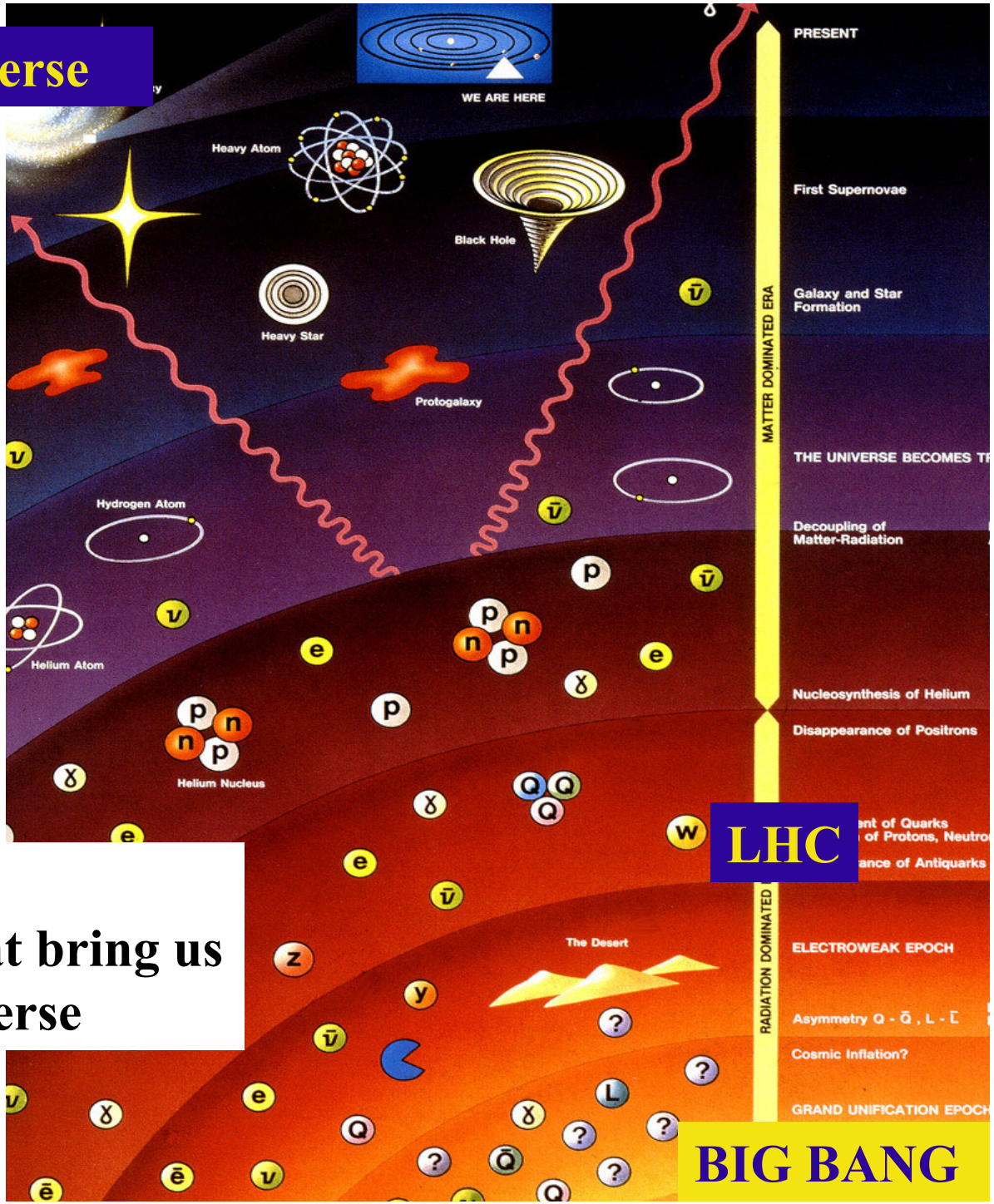
ASIA — 219

JAPAN	95
INDIA	55
CHINA	25
KOREA	25
TAIWAN	13
PAKISTAN	6
TURKEY	17
ARMENIA	15
GEORGIA	7
AZERBAIJAN	1
UZBEKISTAN	1

41

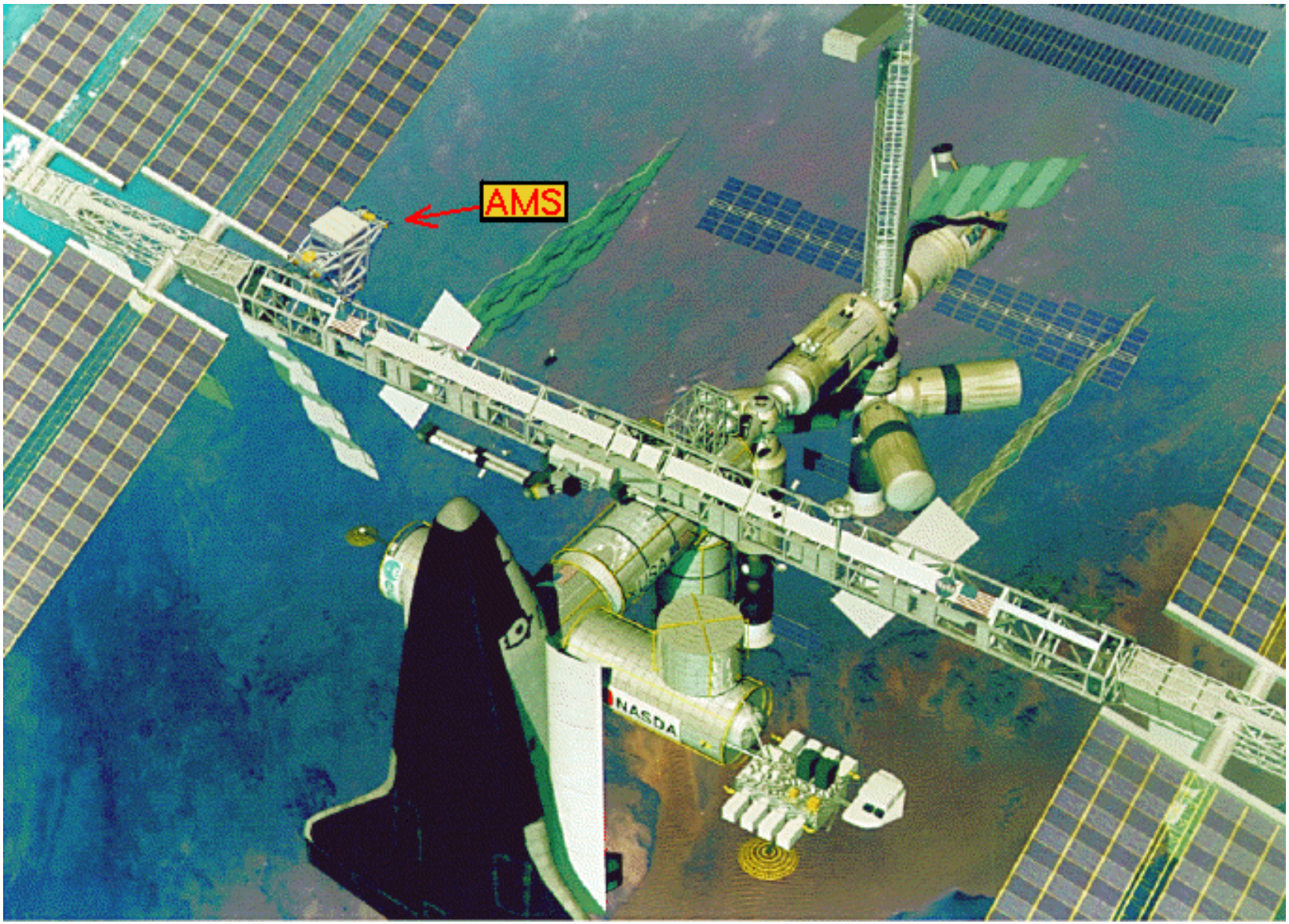
The History of the Universe

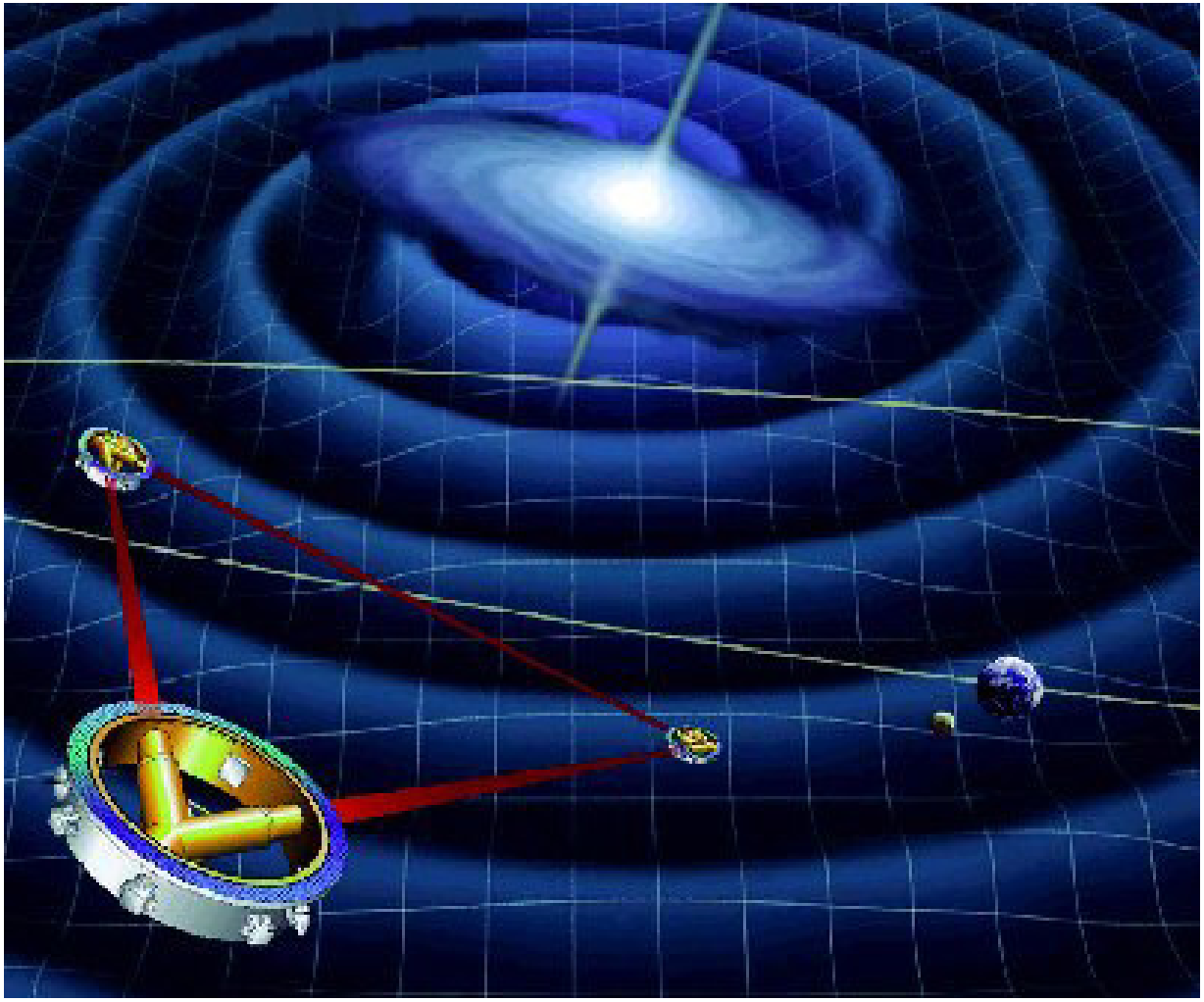
Time



Particle Accelerators are Time-Machines that bring us back to the Early Universe

R.Cashmore

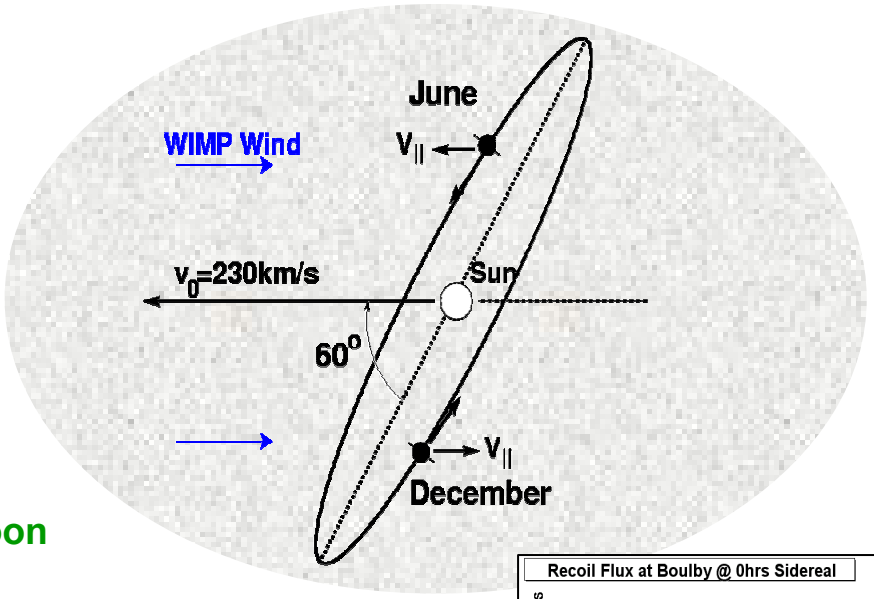

AMS
NASDA

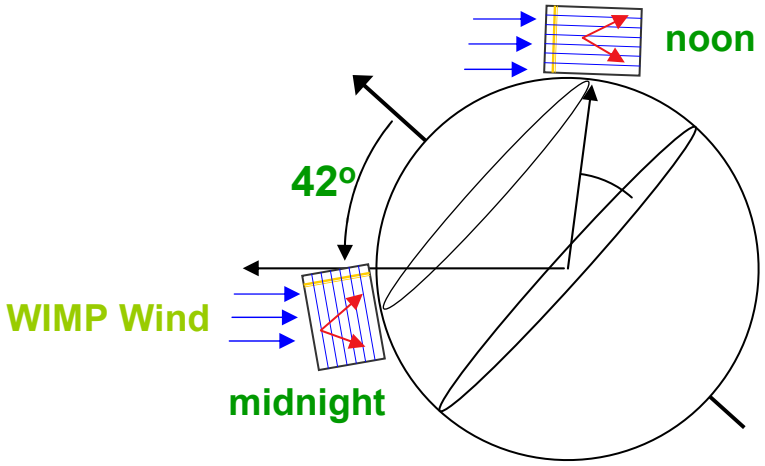


Modulation Signatures

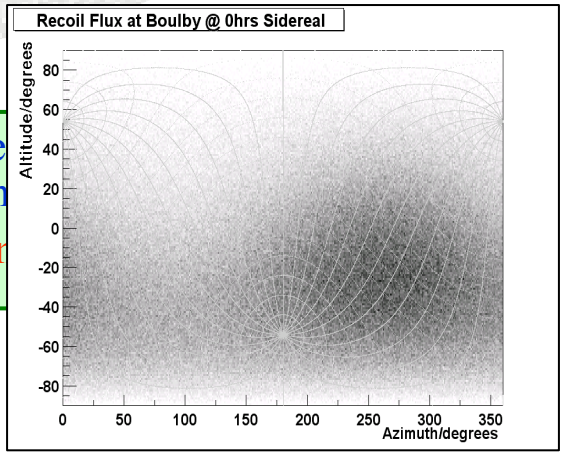
- WIMP halo will manifest itself as a WIMP wind

Annual modulation
~10% variation in signal strength



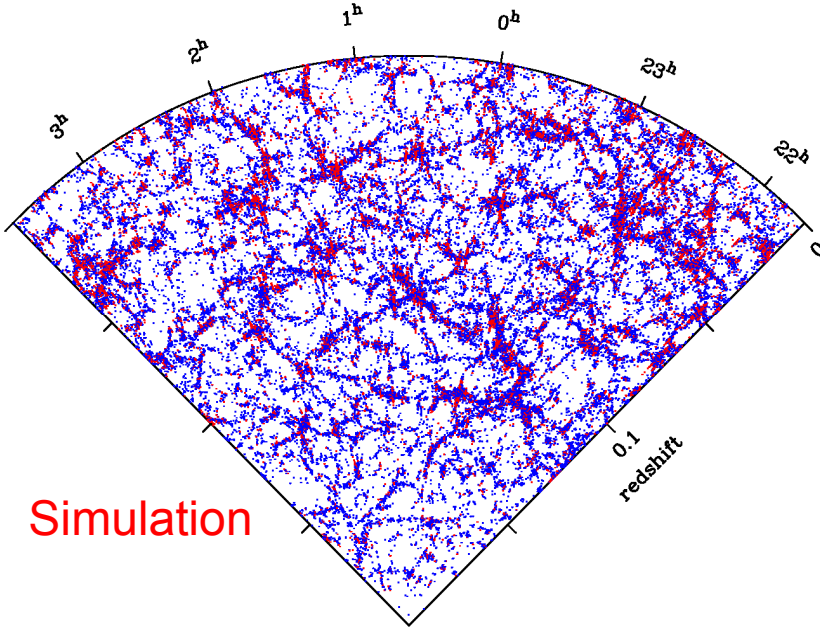


Diurnal signature - goe
with solar day-nigh
Directional asymm

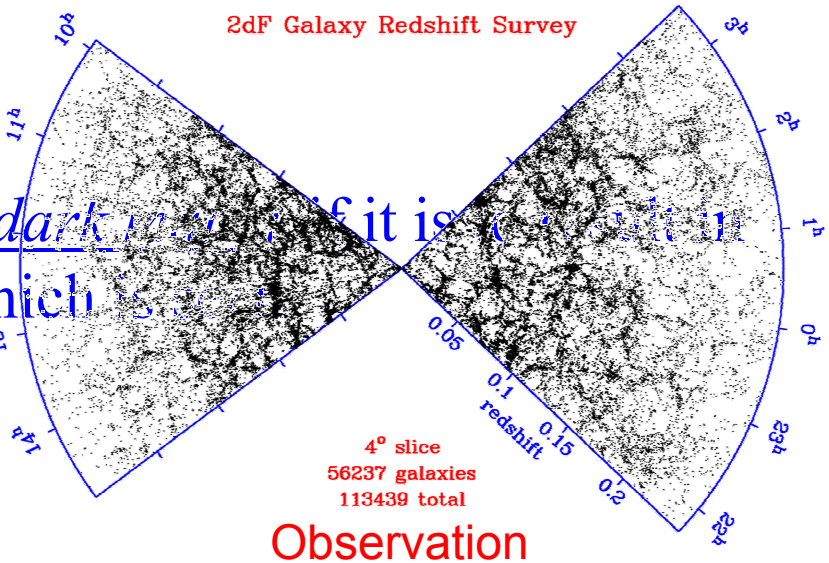


Dark Matter: The Science Case

- Evidence from Astronomy
  - Large scale structure
  - This is a simulation of galaxies forming [file]
  - Project a slice of this and compare it to reality



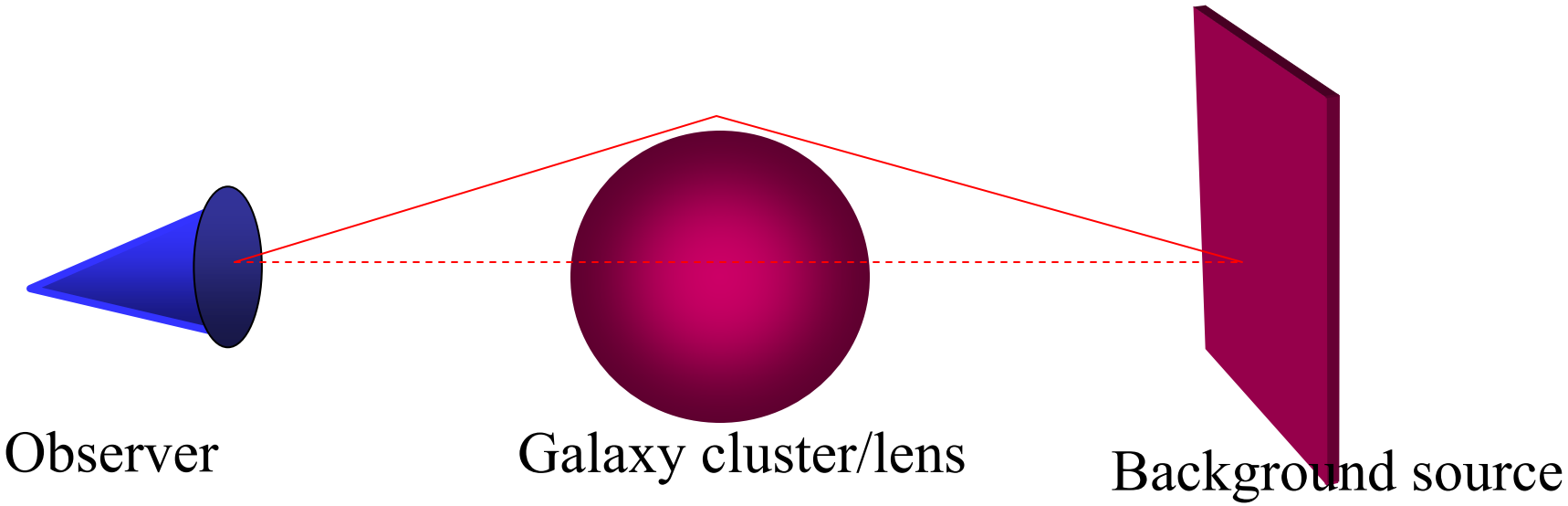
Simulation



Observation

- A simple scattering

ex $ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Phi)dr_i dr^i$

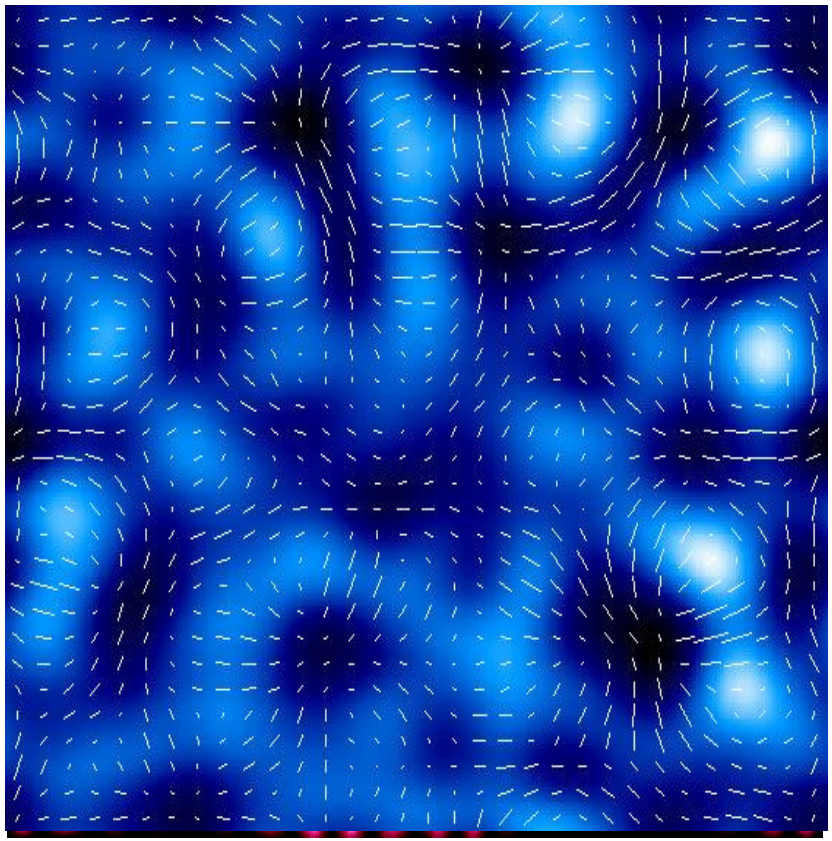


Surface potential

$$\phi = 2\partial^{-4}\partial_i\partial_j\gamma_{ij}$$

Surface density

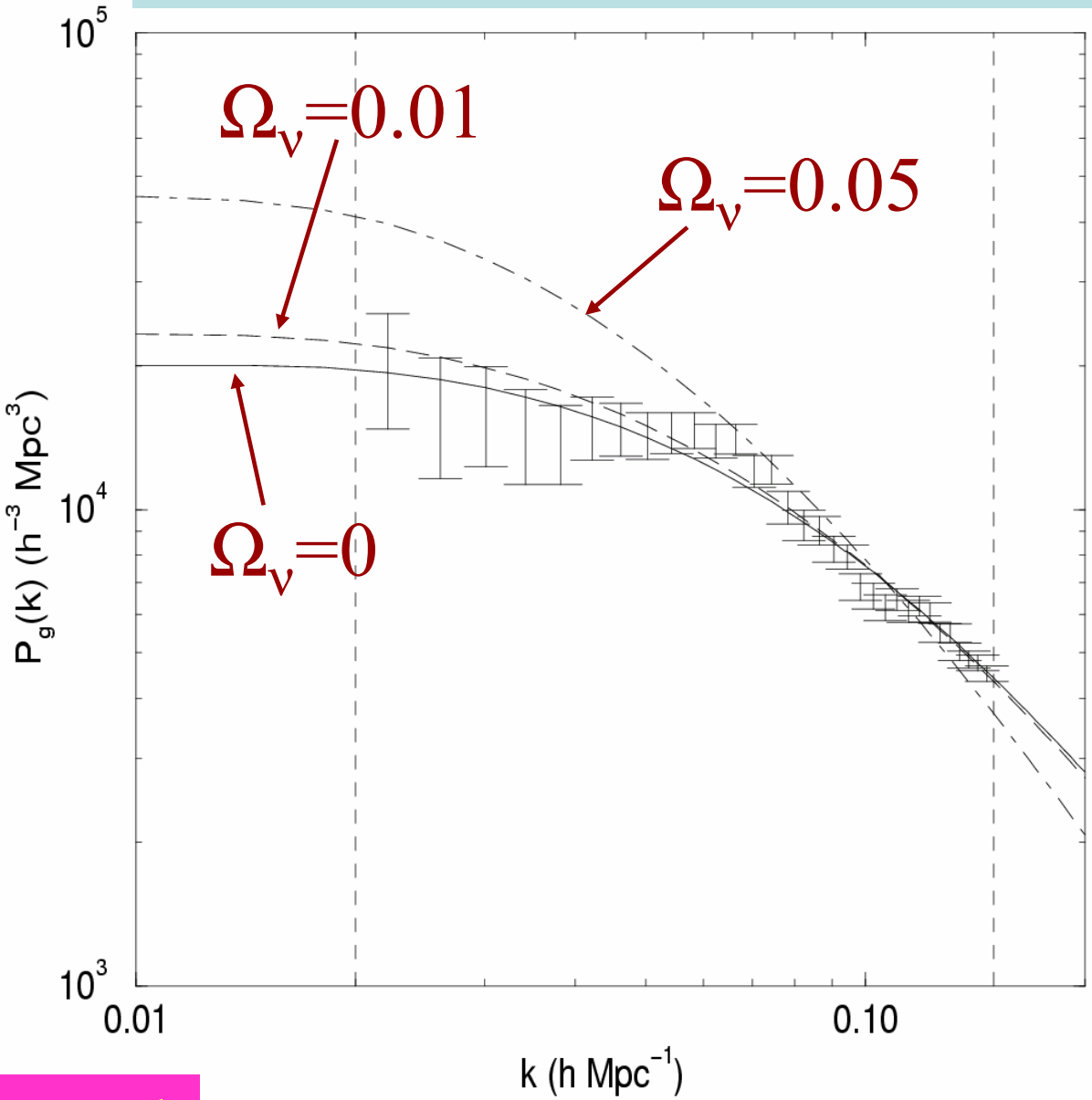
$$\kappa = \tfrac{1}{2}\partial^2\phi$$



oyal Society
Jan. 22
'03

Neutrino mass...

Not much neutrino mass density



2dF team: astro-ph/0204152

Wark, Peacock

Sum of m_ν < 1.8 eV

...measurements

Dave War
University of Sussex/