Dark matter in the universe

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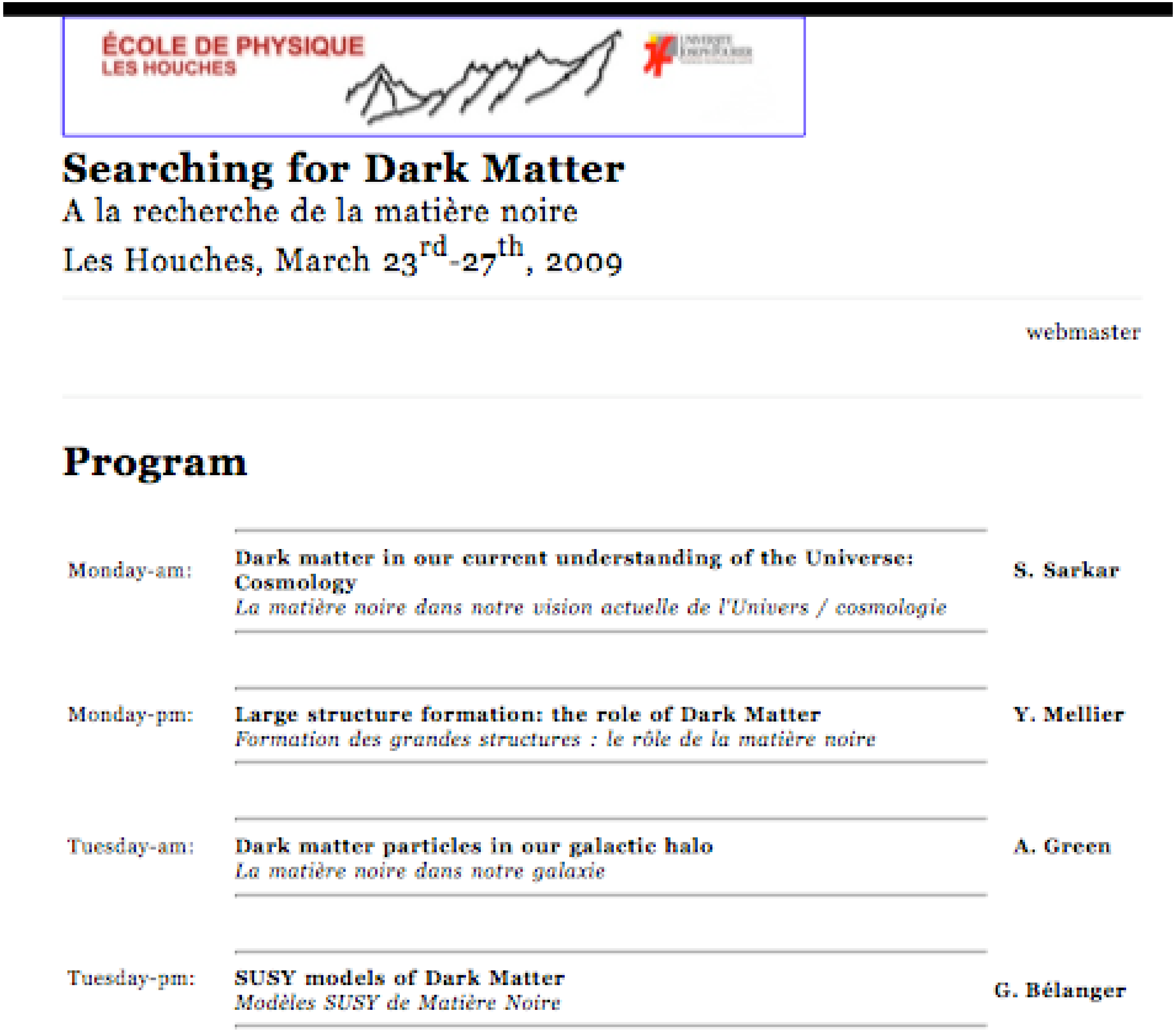
UNIVERSITY OF OXFORD

Searching for Dark Matter, Ecole de Physique, Les Houches, 23-27 March 2009



ÉCOLE DE PHYSIQUE
LES HOUCHES

Searching for Dark Matter

A la recherche de la matière noire

Les Houches, March 23rd-27th, 2009

webmaster

Program

Monday-am:	**Dark matter in our current understanding of the Universe: Cosmology** *La matière noire dans notre vision actuelle de l'Univers / cosmologie*	**S. Sarkar**
Monday-pm:	**Large structure formation: the role of Dark Matter** *Formation des grandes structures : le rôle de la matière noire*	**Y. Mellier**
Tuesday-am:	**Dark matter particles in our galactic halo** *La matière noire dans notre galaxie*	**A. Green**
Tuesday-pm:	**SUSY models of Dark Matter** *Modèles SUSY de Matière Noire*	**G. Bélanger**

Wednesday-am:	**Direct detection experiments: scintillators and gas detectors** *Détection directe ; scintillateurs et détecteurs gazeux*	**E. Aprile**
Wednesday-pm:	**Direct detection experiments: cryogenic and other detectors** *Détection directe ; détecteurs cryogéniques et autres*	**G. Chardin**
Thursday-am:	**Indirect detection of Dark Matter** *Détection indirecte*	**P. Picozza**
Thursday-pm:	**Special Workshop: exploring SUSY Dark Matter with direct and indirect detection using the web-based tool "Damned"** *Atelier calculs, exploration SUSY / détection directe / indirecte avec le site interactif Damned*	**R. Lemrani**
Friday-am:	**Discovering SUSY at LHC** *Découvrir SUSY au LHC*	**D. Denegri**

Sept. 23, 1846: Neptune Right Where They Said It Would Be

By Tony Long 09.23.08

The planet Neptune was right where French mathematician Urbain Le Verrier predicted it would be, when German astronomer Johann Gottfried Galle went looking for it.
Courtesy NASA

Believing in Newton pays off!

NB: John Adams had said so already a year earlier but had not taken much notice of by the British Astromer Royal!

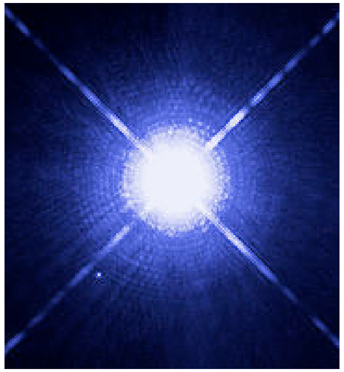
Discovery of dark matter →new (astro)physics

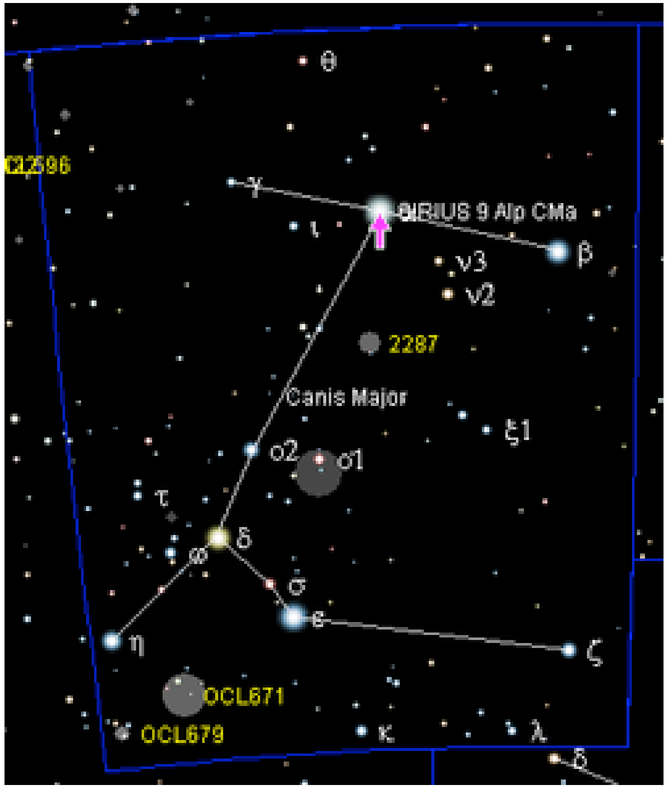
Friedrich Wilhelm Bessel (1832) finds the position of *Sirius* to be oscillating, indicating the presence of an unseen companion

Ivan Clark (1862) discovers *Sirius B* visually

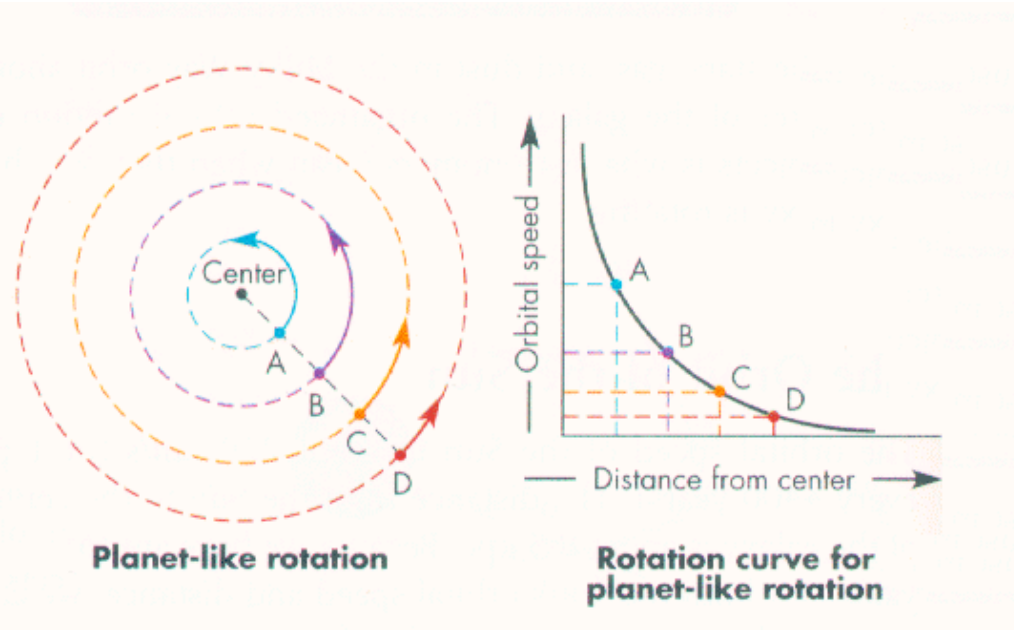
Walter Adams (1915) obtains spectrum of *Sirius B* … faint star ~3 times hotter than *Sirius,* hence size ~ Earth but mass ~ Sun!

Subrahmanyan Chandrasekhar (1930) applies quantum ideas to stellar structure … infers that when the Sun exhausts its nuclear fuel it will collapse under gravity until held up by Pauli exclusion principle (electron degeneracy pressure) … but stars heavier than $1.4M_0$ will continue to collapse and *"… one is left speculating on other possibilities"* (neutron stars and black holes!)





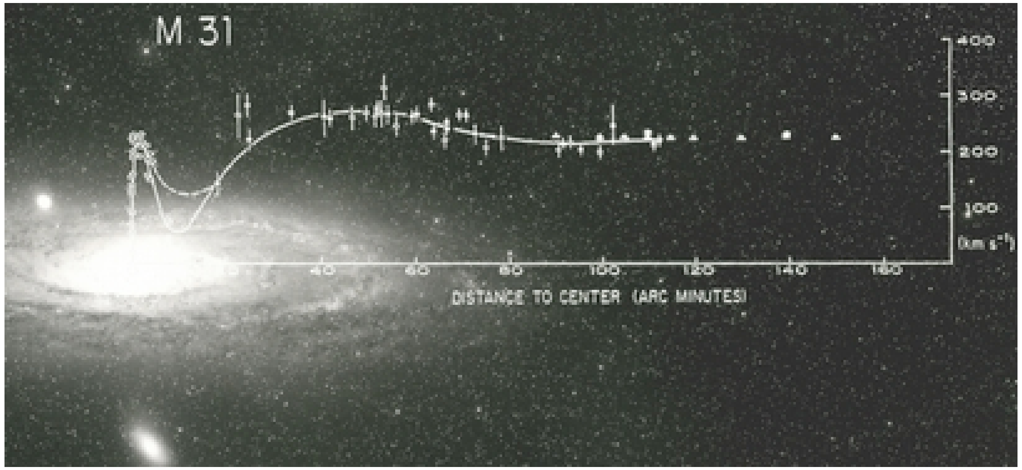
The modern saga of dark matter starts with the rotation curves of spiral galaxies …



At large distances from the centre, beyond the edge of the visible galaxy, the velocity would be expected to fall as $1/\sqrt{r}$ *if* most of the matter is contained in the optical disc

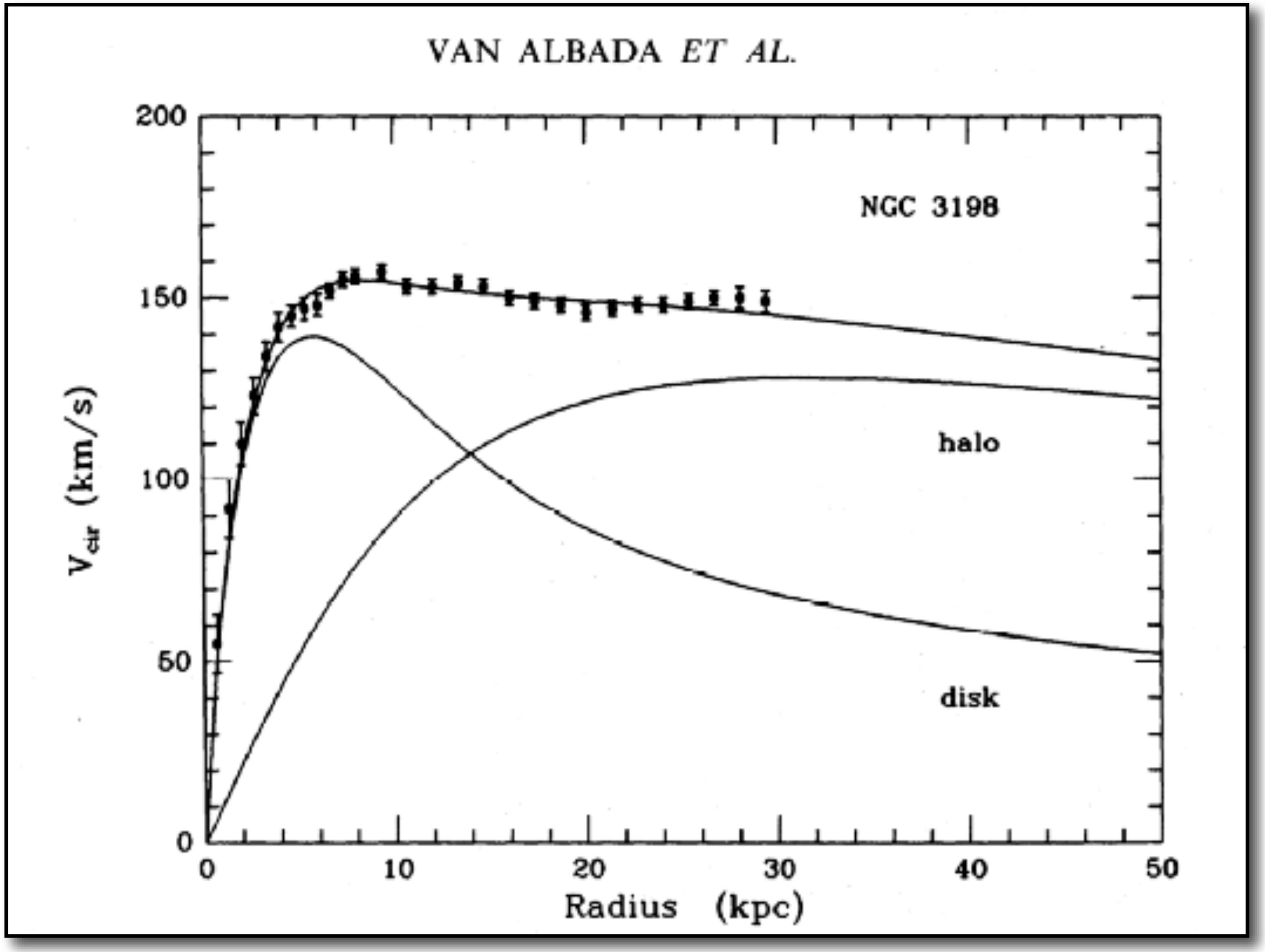
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

… but Vera Rubin *et alia* (1970) observed that the rotational velocity remains ~constant in Andromeda, implying the existence of an extended (dark) halo

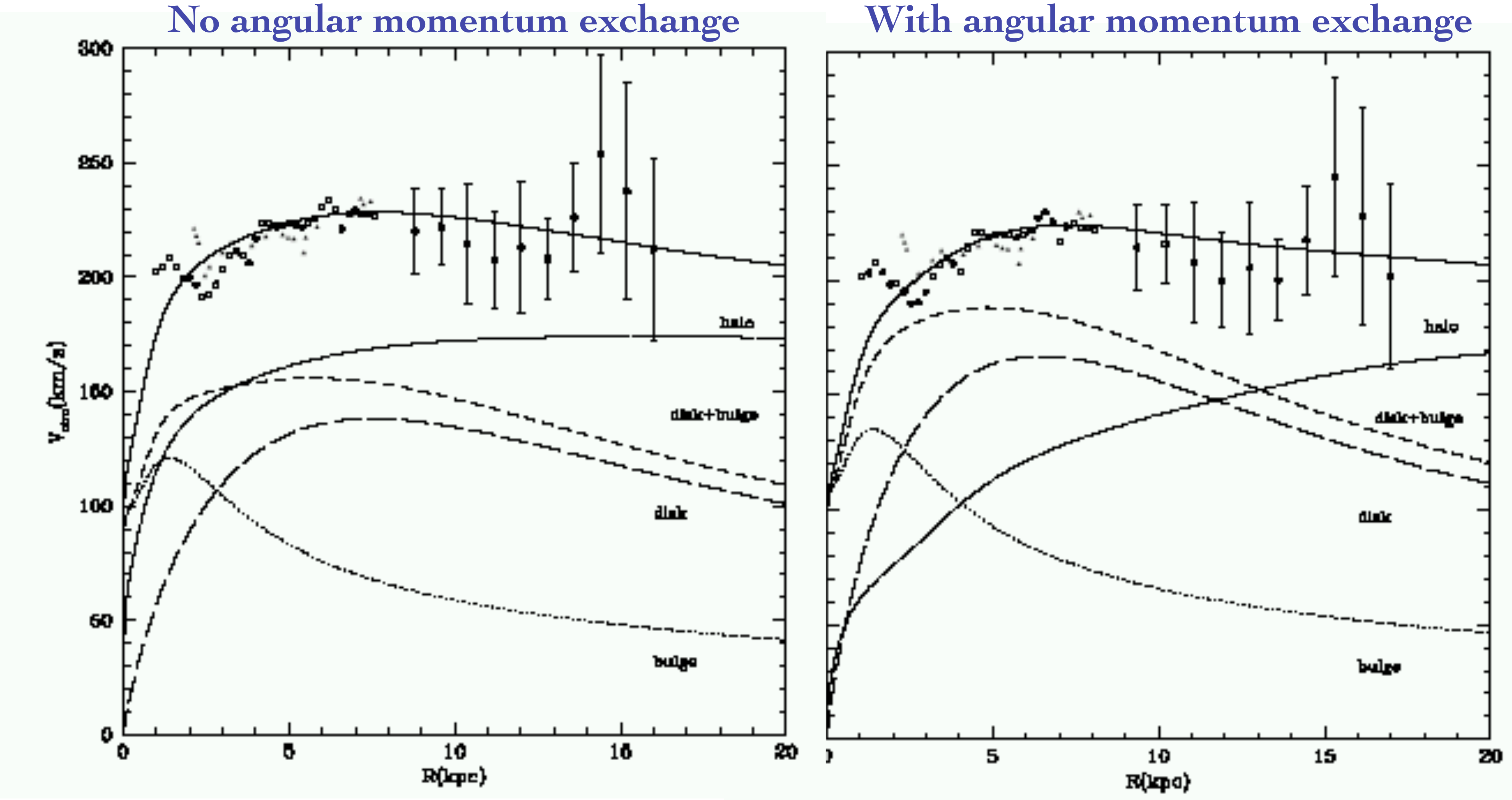


$$v_{\rm circ} \sim \text{constant} \quad \Rightarrow \quad M(<r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

The *really* compelling evidence for **extended halos of dark matter** came from 21 cm observations in the 1980's of neutral hydrogen (orbiting around Galaxy at ~constant velocity) *beyond* the visible disk



More sophisticated modelling needs to account for multiple components and the coupling between baryonic & dark matter



No angular momentum exchange

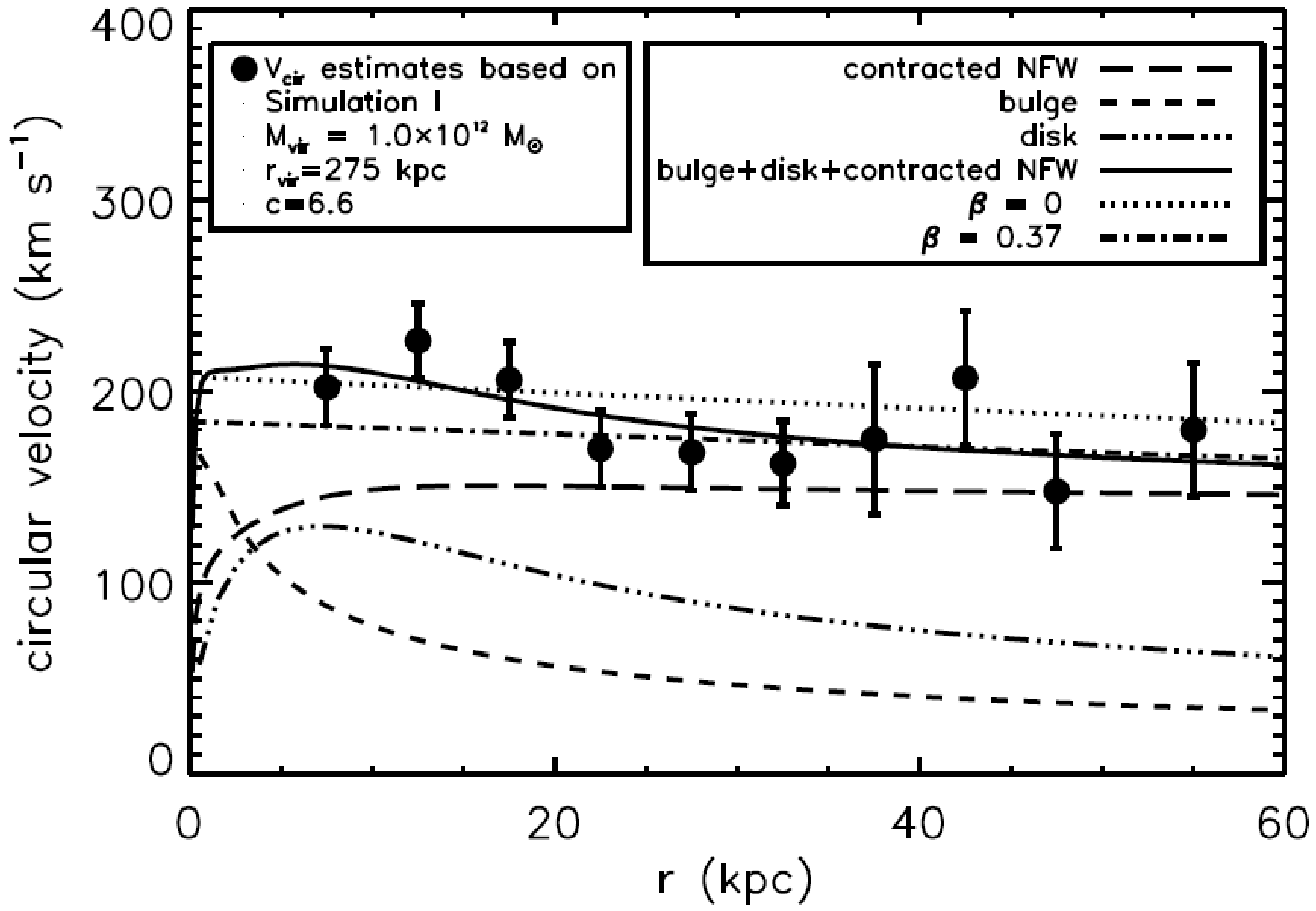
With angular momentum exchange

Klypin, Zhao, Somerville [astro-ph/0110390]

The *local* halo density of dark matter is ~0.3 GeV cm^{-3} (uncertainty x2)

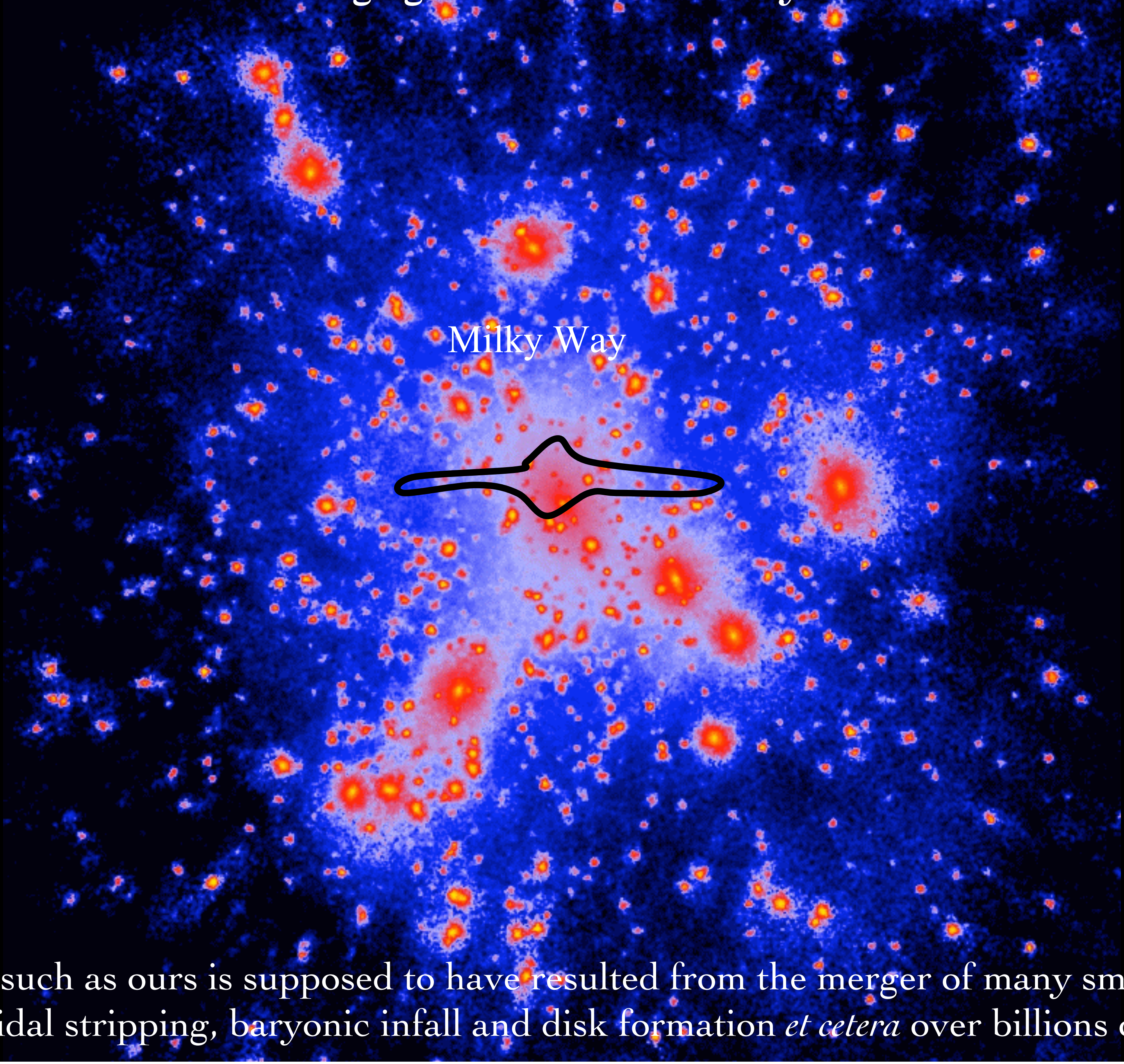
Recent SDSS observations of 2401 blue horizontal-branch halo stars (+ simulations) measure the Milky Way's rotation curve out to 55 kpc

Xue *et al* [arXiv:0801.1232]



(However some conflict with previous estimates from satellites - Wilkinson & Evans)

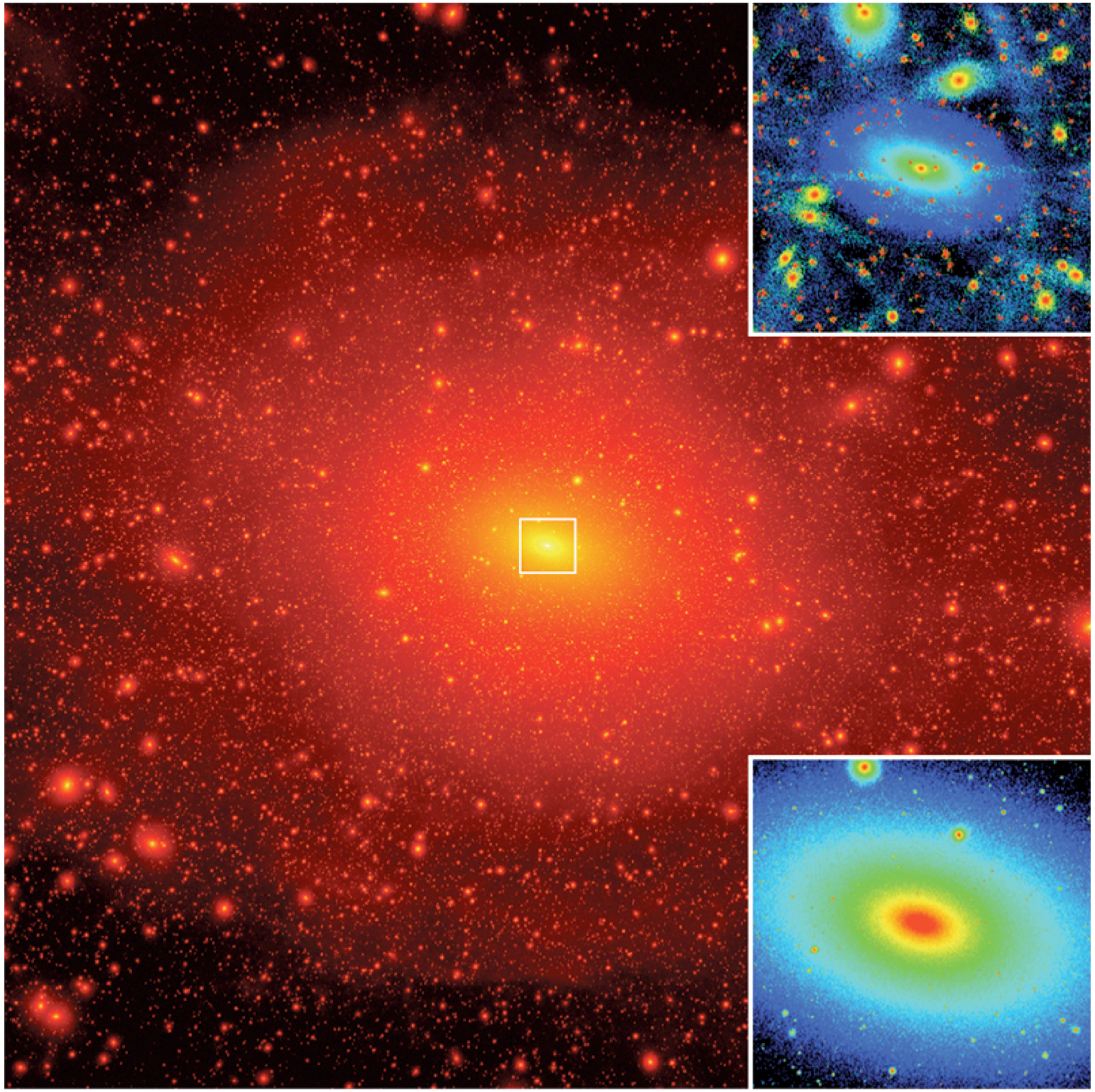
We can get an idea of what the Milky Way halo looks like from numerical simulations of **structure formation through gravitational instability in cold dark matter**



A galaxy such as ours is supposed to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation *et cetera* over billions of years

So the phase space structure of the dark halo is pretty complicated …

Via Lactea II projected dark matter (squared-) density map



phase
space

real
space

Diemand, Kuhlen, Madau, Zemp, Moore, Potter & Stadel [arXiv:0805.1244]

But real galaxies appear *simpler* than expected!

Disney, Romano, Garcia–Appadoo, West, Dalcanton & Cortese, Nature 455 (2008) 1082

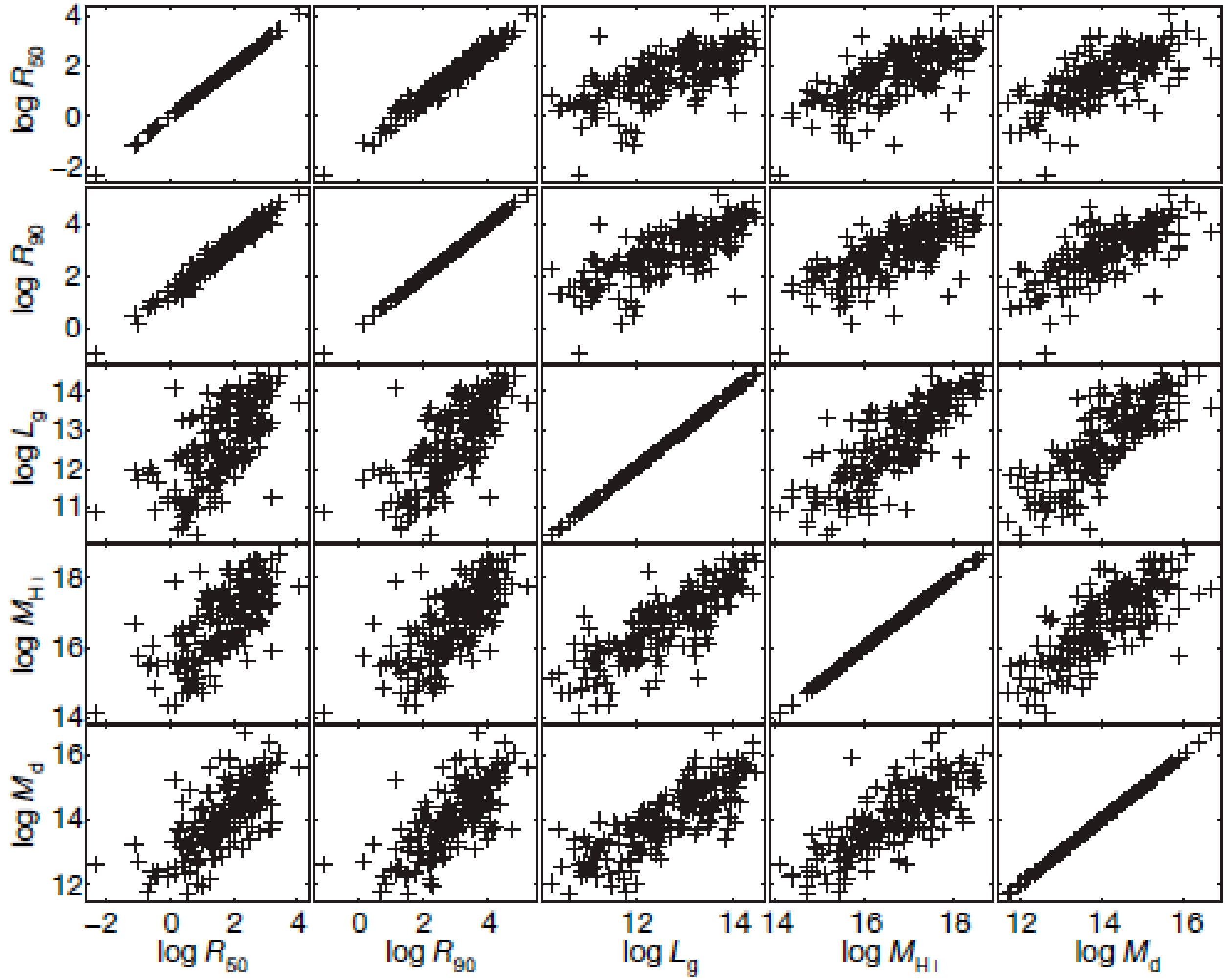
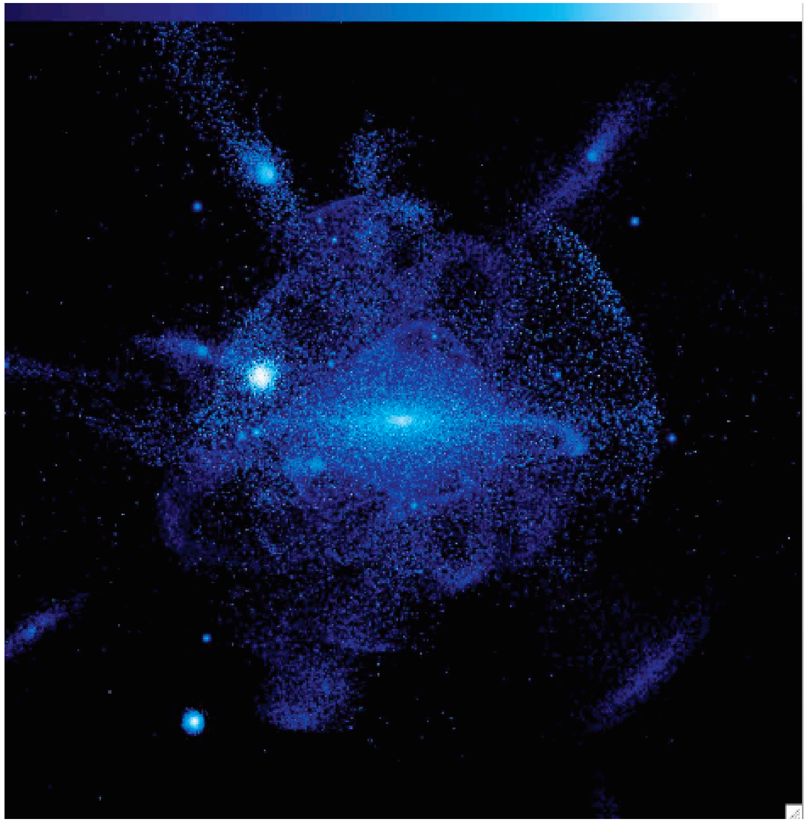
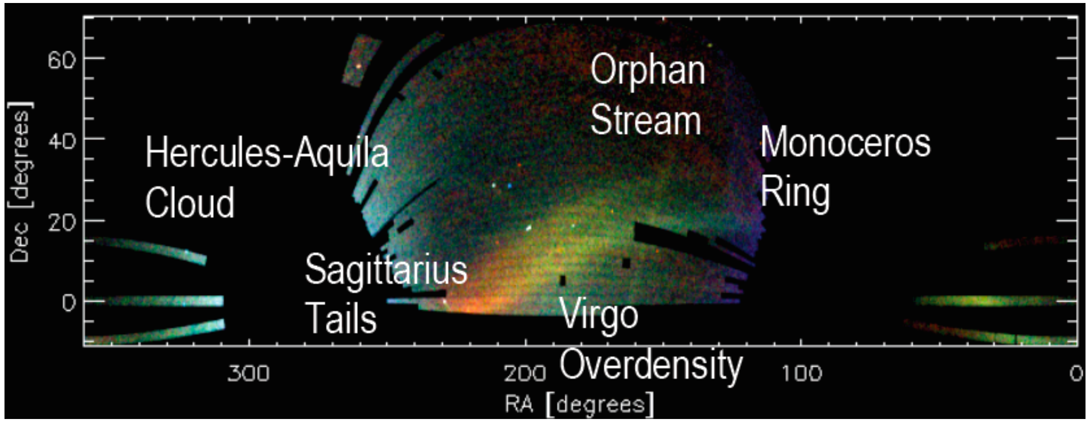


Figure 1 | Scatter plots showing correlations between five measured variables, not including colour. The variables are two optical radii, R_{50} and R_{90} (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, L_g; neutral hydrogen mass, $M_{\rm H\,I}$; and dynamical mass, M_d (inferred from the 21-cm linewidth, the radius and the inclination in the

Whereas the Milky Way does have satellite galaxies and substructure, it appears to be a lot *less* than expected from numerical simulations

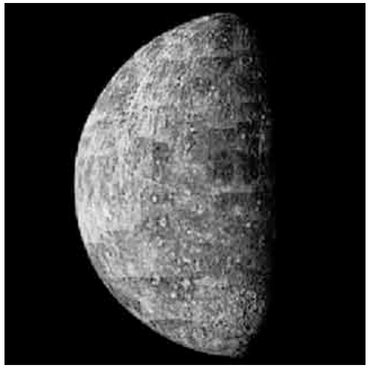




Inferences of dark matter are not always right … it may instead be a change in the *dynamics*

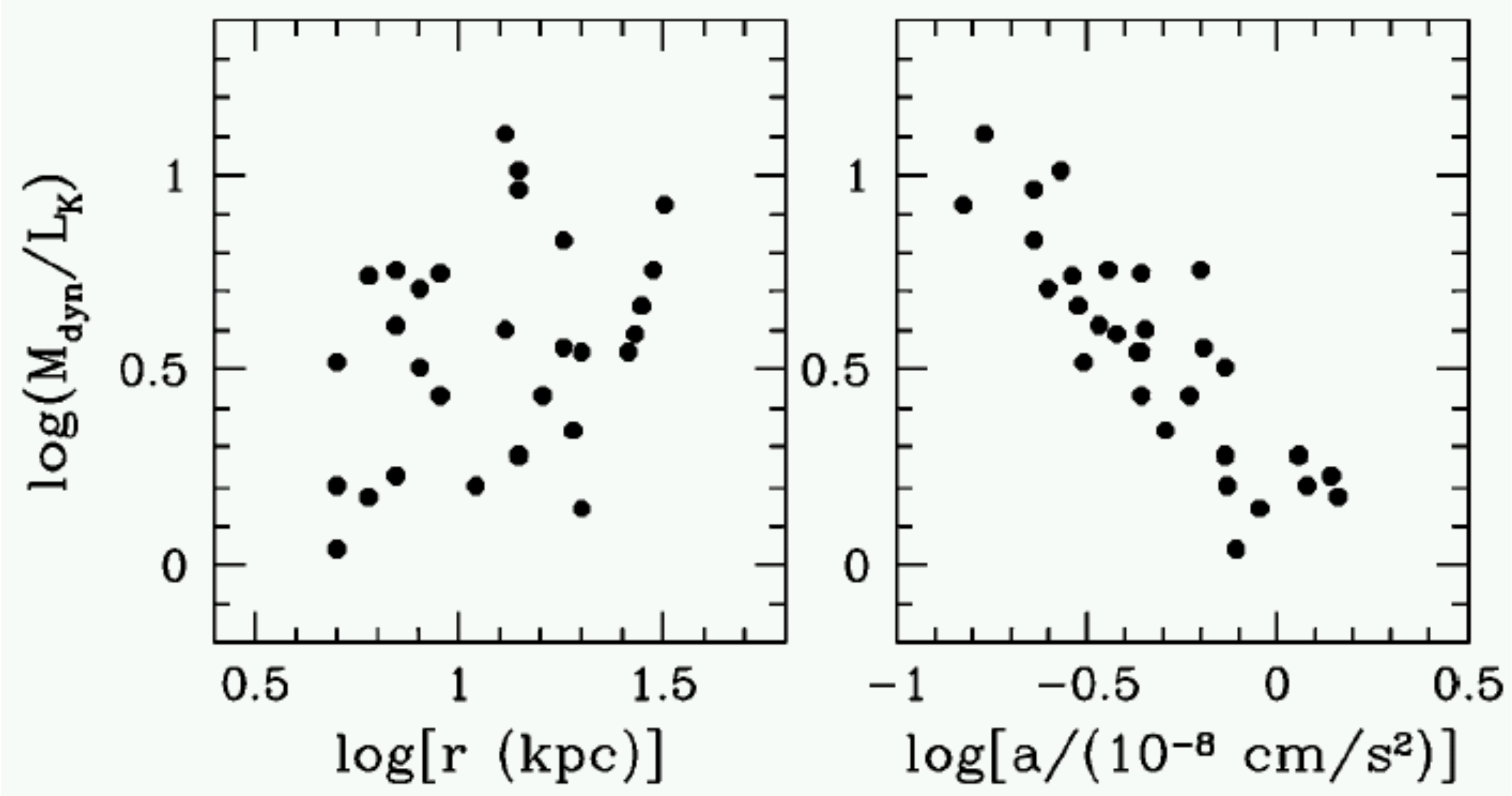
2 Jan 1860: *"Gentlemen, I Give You the Planet Vulcan"*
French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris.

Some astronomers even saw Vulcan in the evening sky!



But the precession of Mercury is *not* due to a dark planet
… but because Newton is superseded by Einstein

Dark matter appears to be required only where the test particle acceleration is *low* - below $a_0 \sim 10^{-8}$ cm/s^2 (it is *not* a spatial scale-dependent effect)

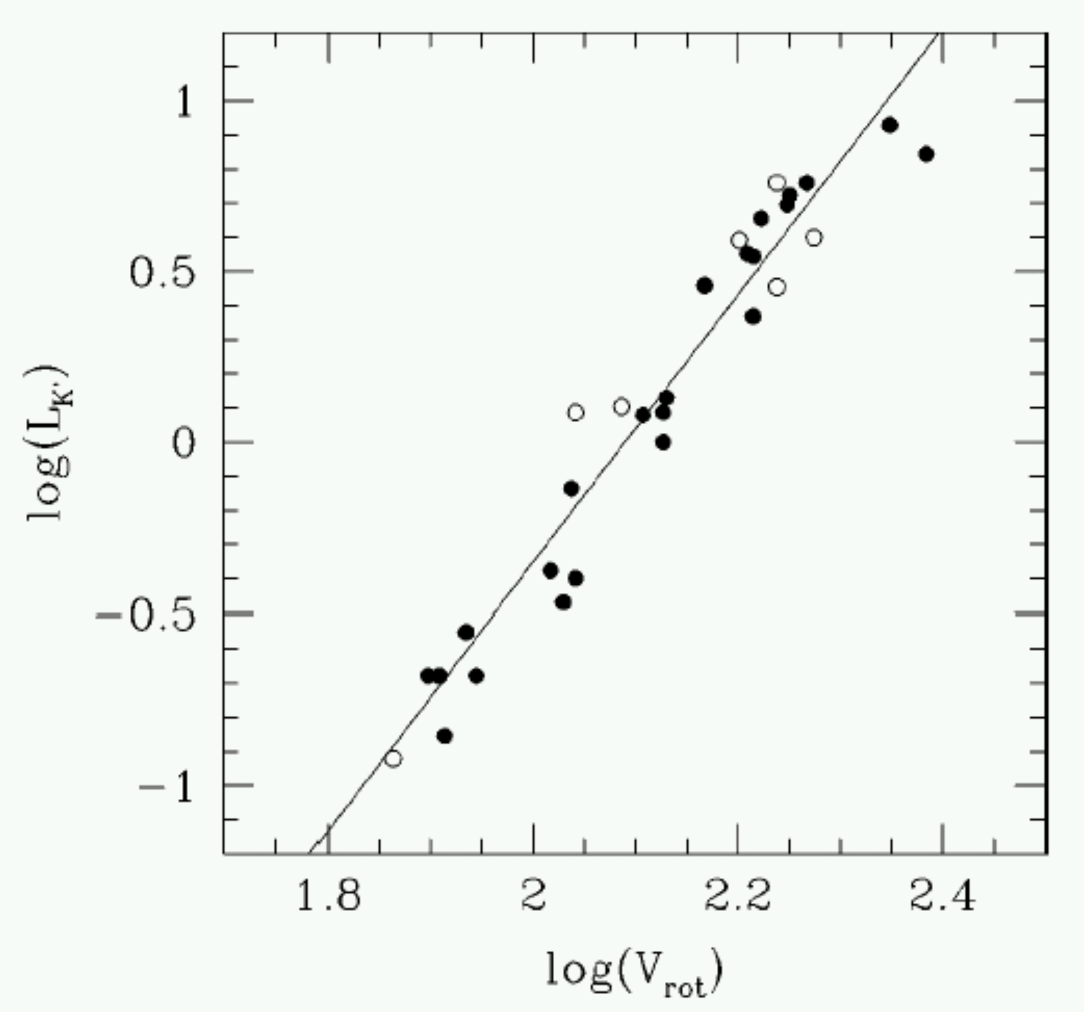


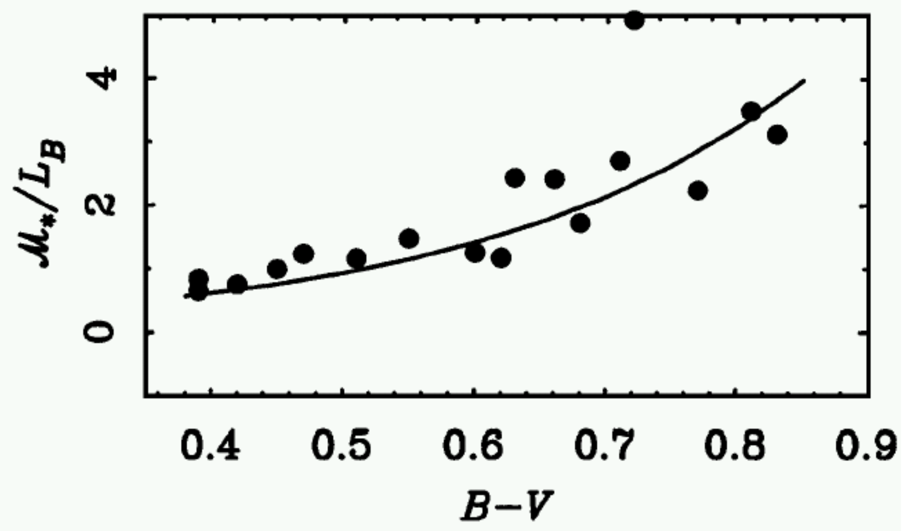
What if Newton's law is modified in weak fields?

$$F_{\rm N} \rightarrow \sqrt{\frac{GM}{r^2} a_0}$$

Milgrom (1983)

$$\frac{v^4}{r^2} = \frac{GM}{r^2} a_0 \quad \Rightarrow \quad M \propto v^4 \quad \left(\text{Tully–Fisher if } \frac{M}{L} = \text{const}\right)$$





… the fitted M/L value *agrees* well with population synthesis models

Sanders & Verheijen [astro-ph/9802240]

This is an impressive correlation for which dark matter has *no* explanation

The rotation curve of the outer Milky Way ($a < 10^{-8}$ cm s^{-2}) … well fitted *without* dark matter

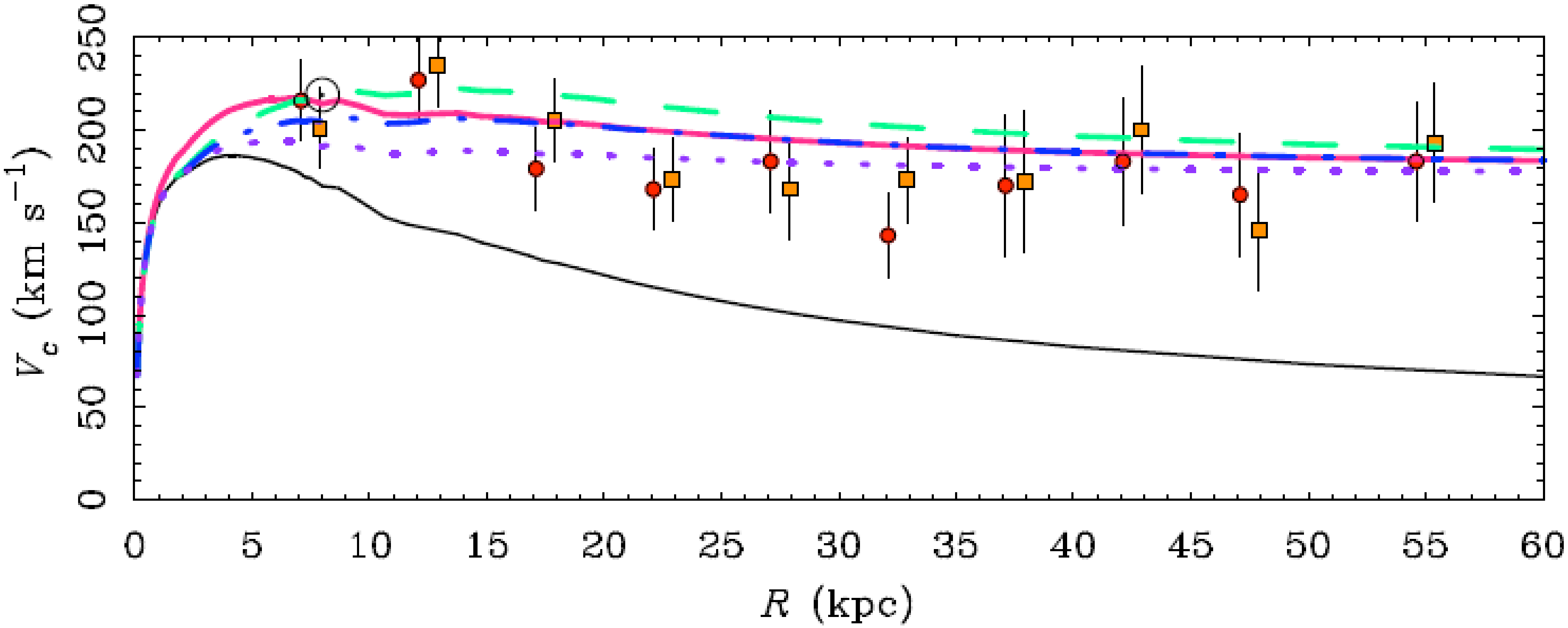


Fig. 7.— The outer rotation curve predicted by MOND for the Milky Way compared to the two realizations of the Blue Horizontal Branch stars in the SDSS data reported by Xue et al. (2008). The data points from the two realizations have been offset slightly from each other in radius for clarity; lines as per Fig. 2. The specific case illustrated has $R_d = 2.3$ kpc, but the rotation curve beyond 15 kpc is not sensitive to this choice. While the data clearly exceed the Newtonian expectation (declining curve), they are consistent with MOND.

McGaugh [arXiv:0804.1314]

Critical surface density (brightness)

Rewrite a_0 as surface density: $\Sigma_c = a_0/G$

$$\Sigma_c \approx 0.6\ g/cm^2 \quad \approx 860\ M_o / pc^2$$

With M/L = 1-2 implies critical surface brightness.

$$I_B = 22\ mag/arcsec^2$$

When $\Sigma \gg \Sigma_c$ then small discrepancy (HSB galaxies)

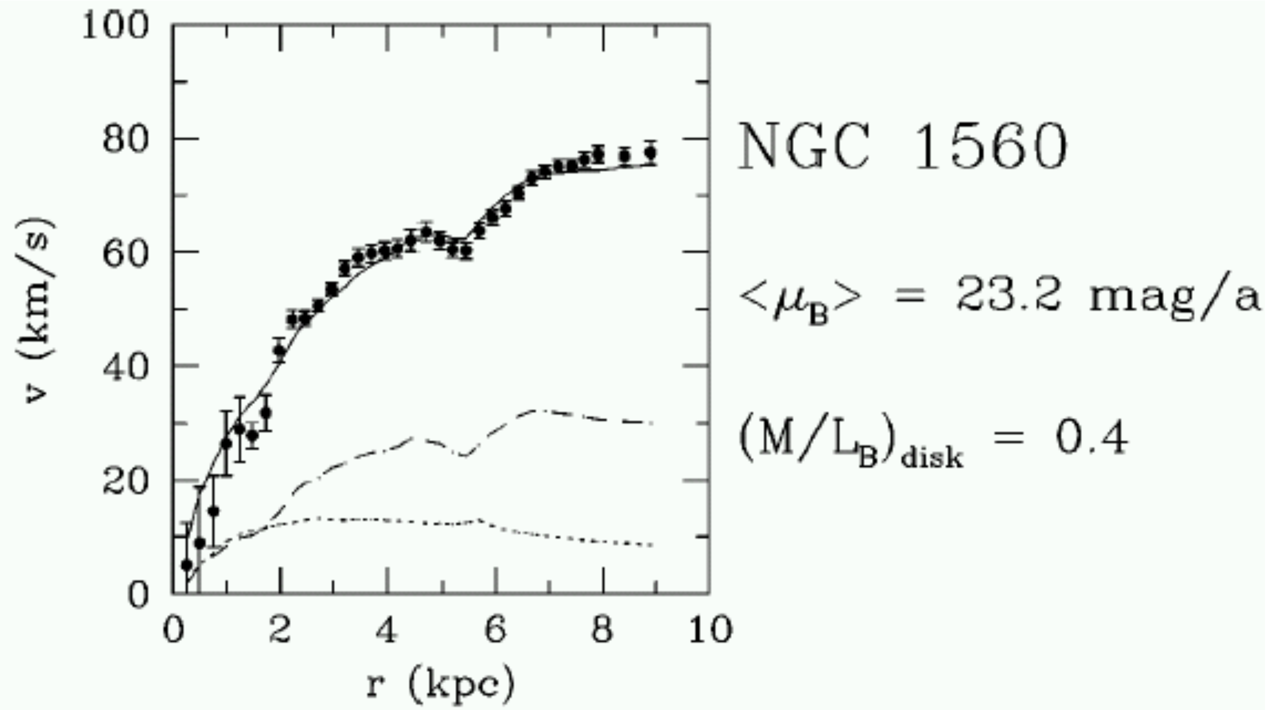
(Globular clusters, luminous ellipticals)

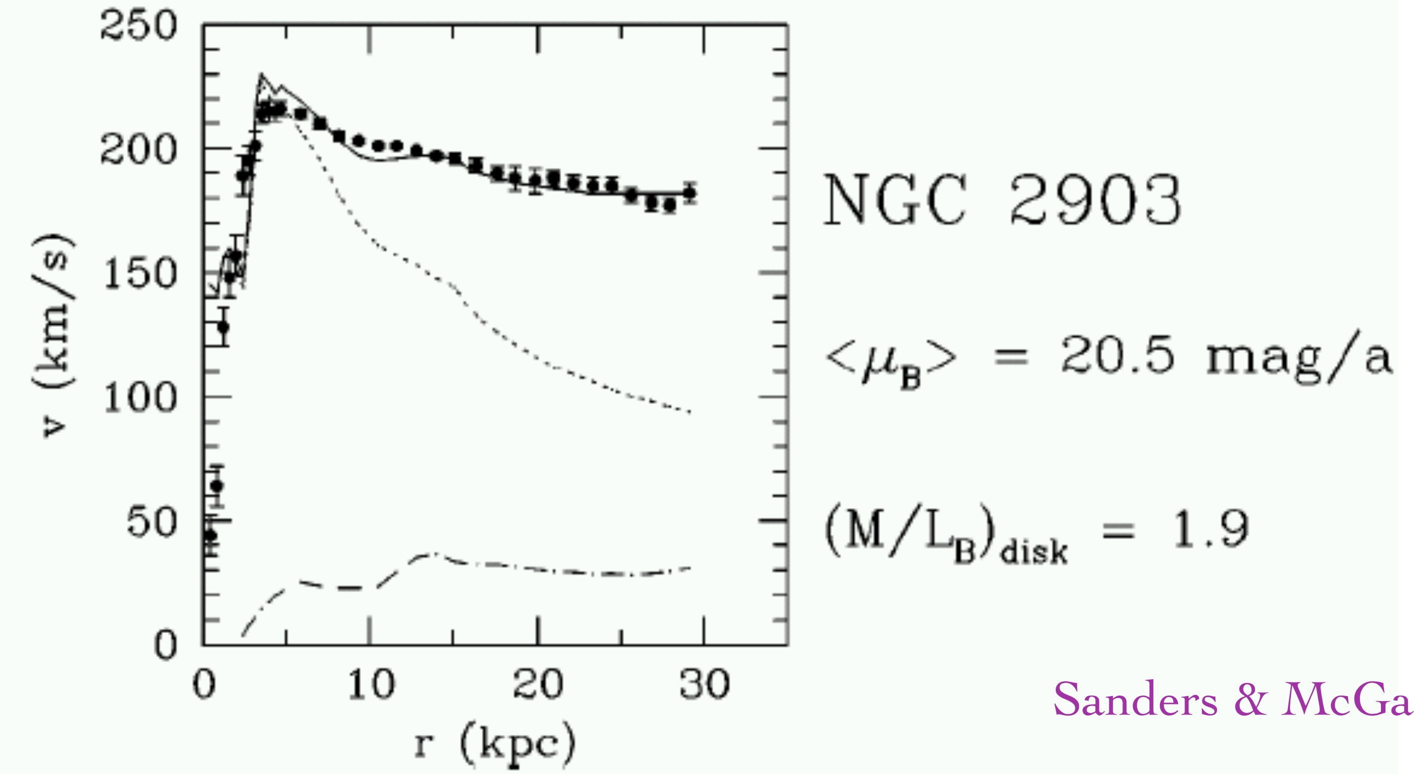
When $\Sigma \ll \Sigma_c$ then large discrepancy (LSB galaxies)

(dwarf spheroidals, LSB spirals)

Courtesey: Bob Sanders

Excellent fits to galactic rotation curves with $a_0 = 1.2 \times 10^{-8}$ cm s^{-2}

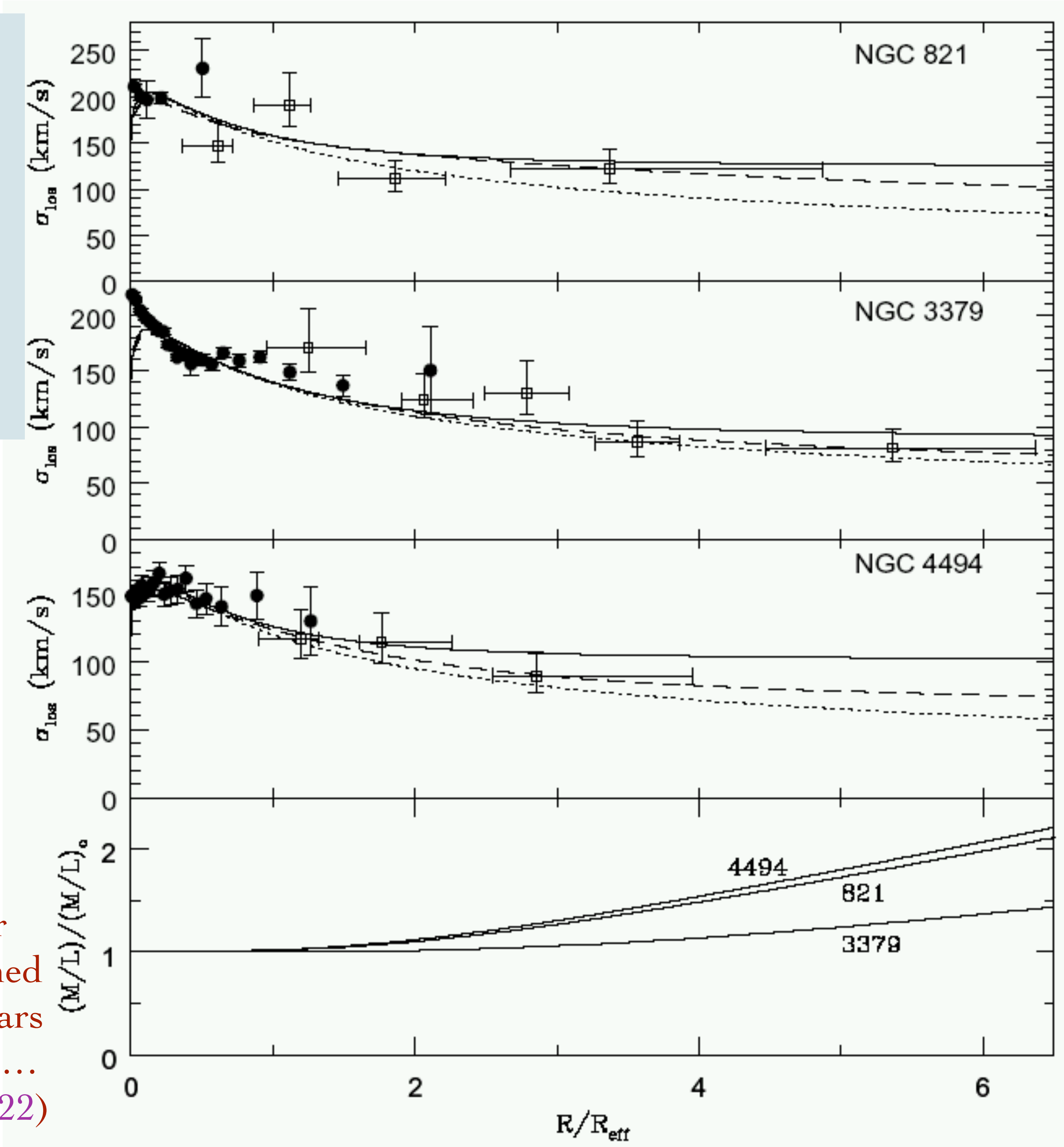




Features in the *baryonic* disc are clearly reproduced

Sanders & McGaugh [astro-ph/0204521]

Moreover some giant elliptical galaxies do exhibit Keplerian fall-off of the random velocity dispersion as was *predicted* by MOND!

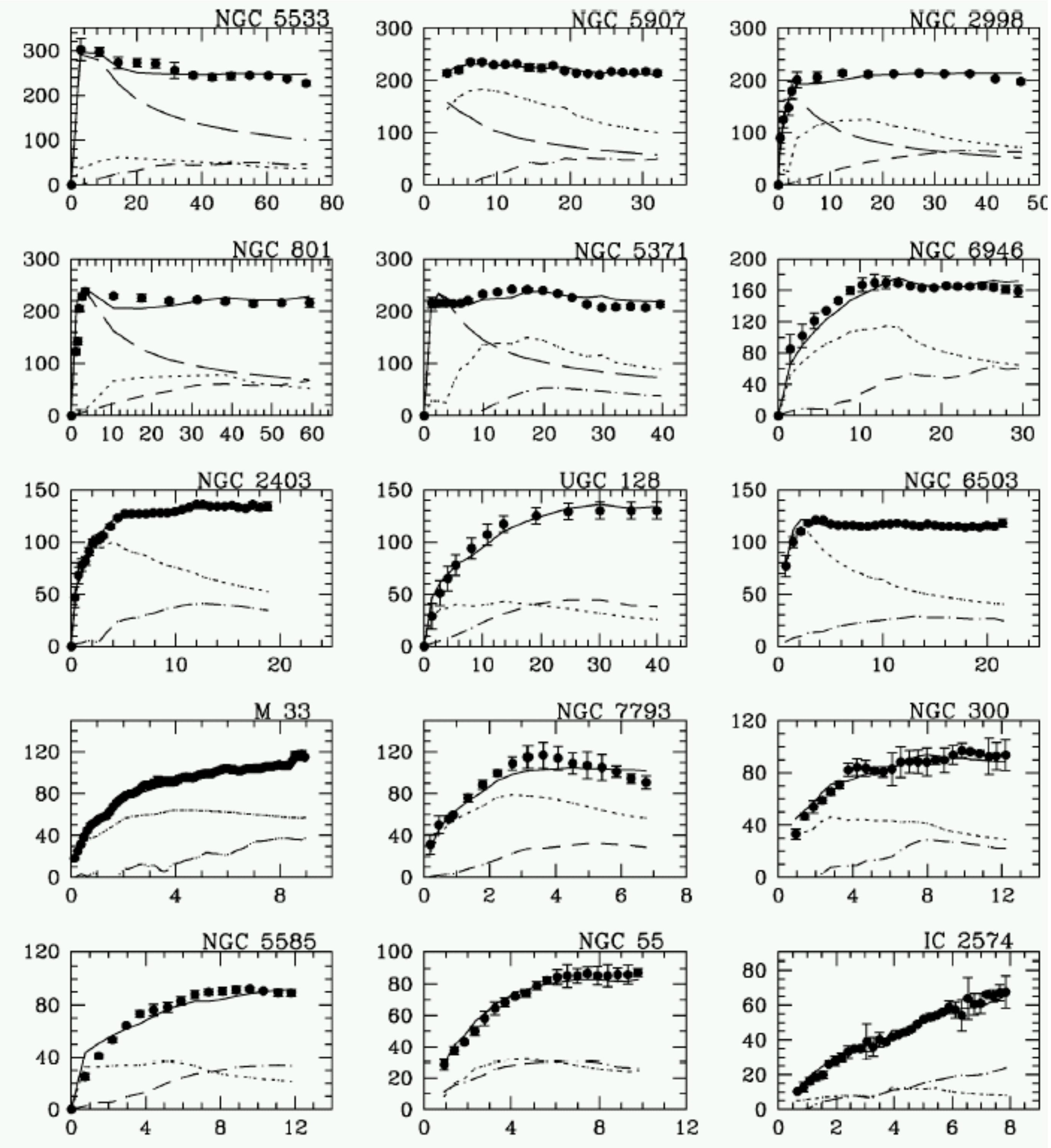


Data:
Romanowsky *et al*
[astro-ph/0308518]

Models:
Milgrom & Sanders
[astro-ph/0309617]

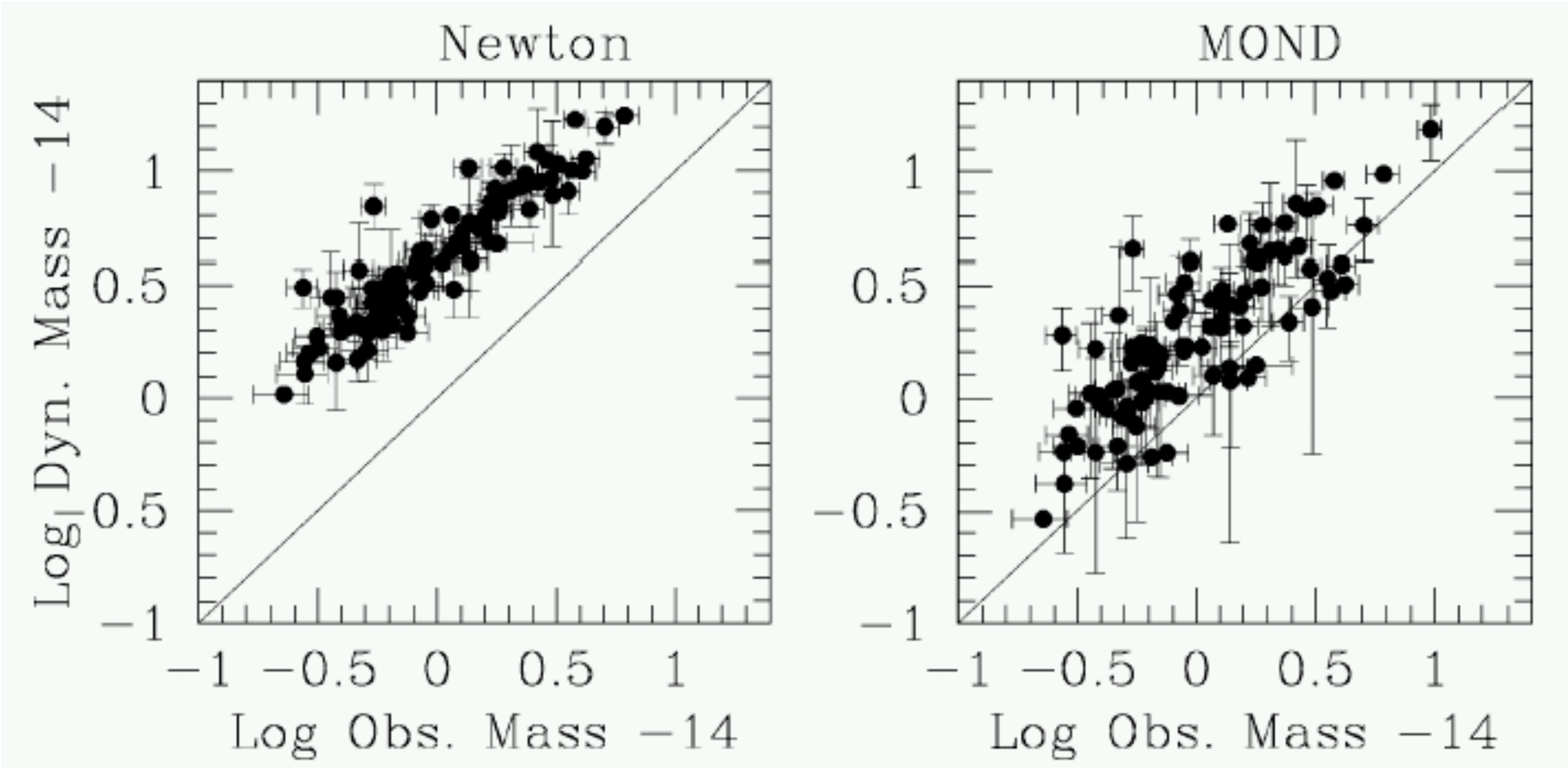
It has been argued however that this can also be explained in a dark matter model if stars are on very elliptical orbits … Dekel *et al* [astro-ph/0501622)

A huge variety of rotation curves can thus be well fitted by MOND

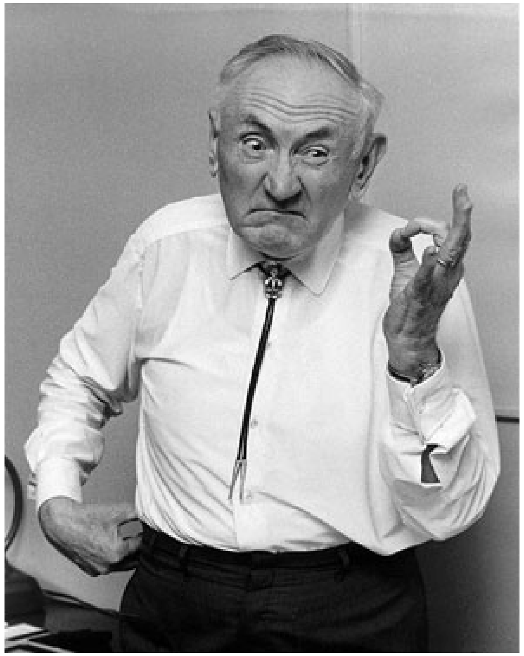


Sanders & Verheijen [astro-ph/9802240]

However MOND *fails* on the scale of clusters of galaxies



The "missing mass" cannot be accounted for entirely by invoking MOND … **dark matter *is* required** (thus vindicating the original proposal of Zwicky)



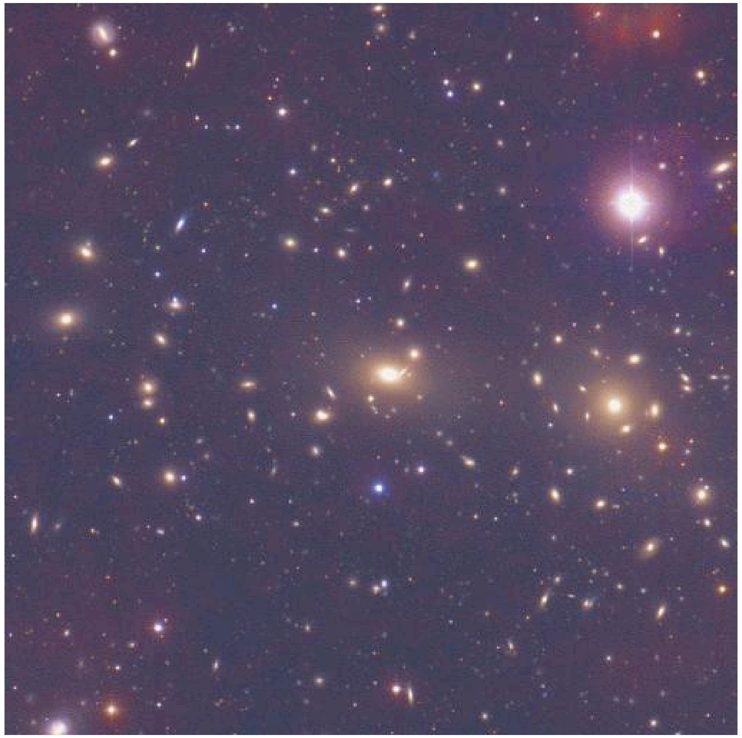
Fritz Zwicky (1933) measured velocity dispersion in the Coma cluster to be ~1000 km/s ⇒ M/L ~ O(100) Mo/Lo

"… If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present (in Coma) with a much greater density than luminous matter"

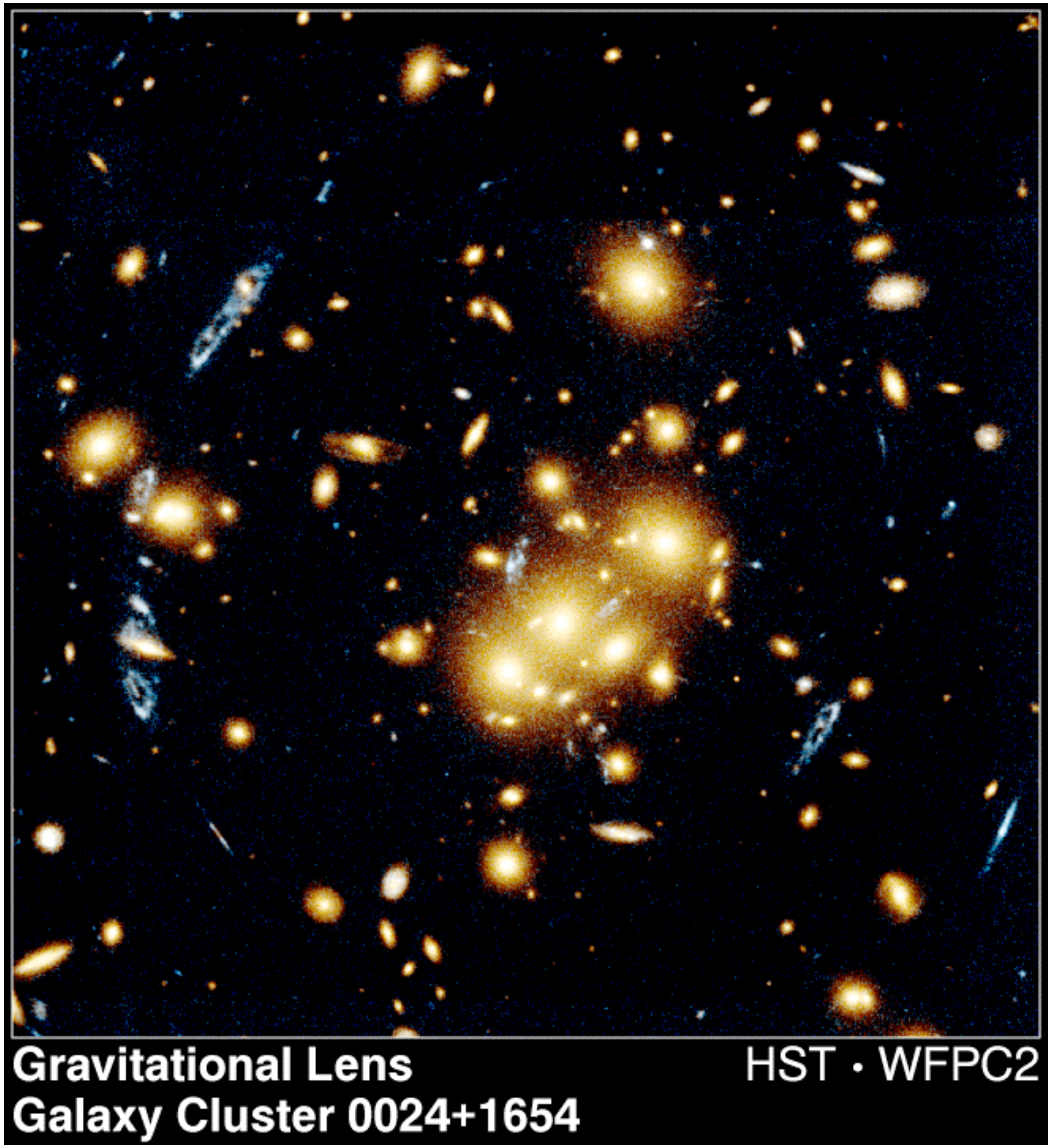
Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

$$V = -\frac{N^2}{2} G_{\rm N} \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle m v^2 \rangle}{2}$$

$$M = N\langle m \rangle \sim \frac{2\langle r \rangle \langle v^2 \rangle}{G_{\rm N}} \gg \sum m_{\rm galaxies}$$

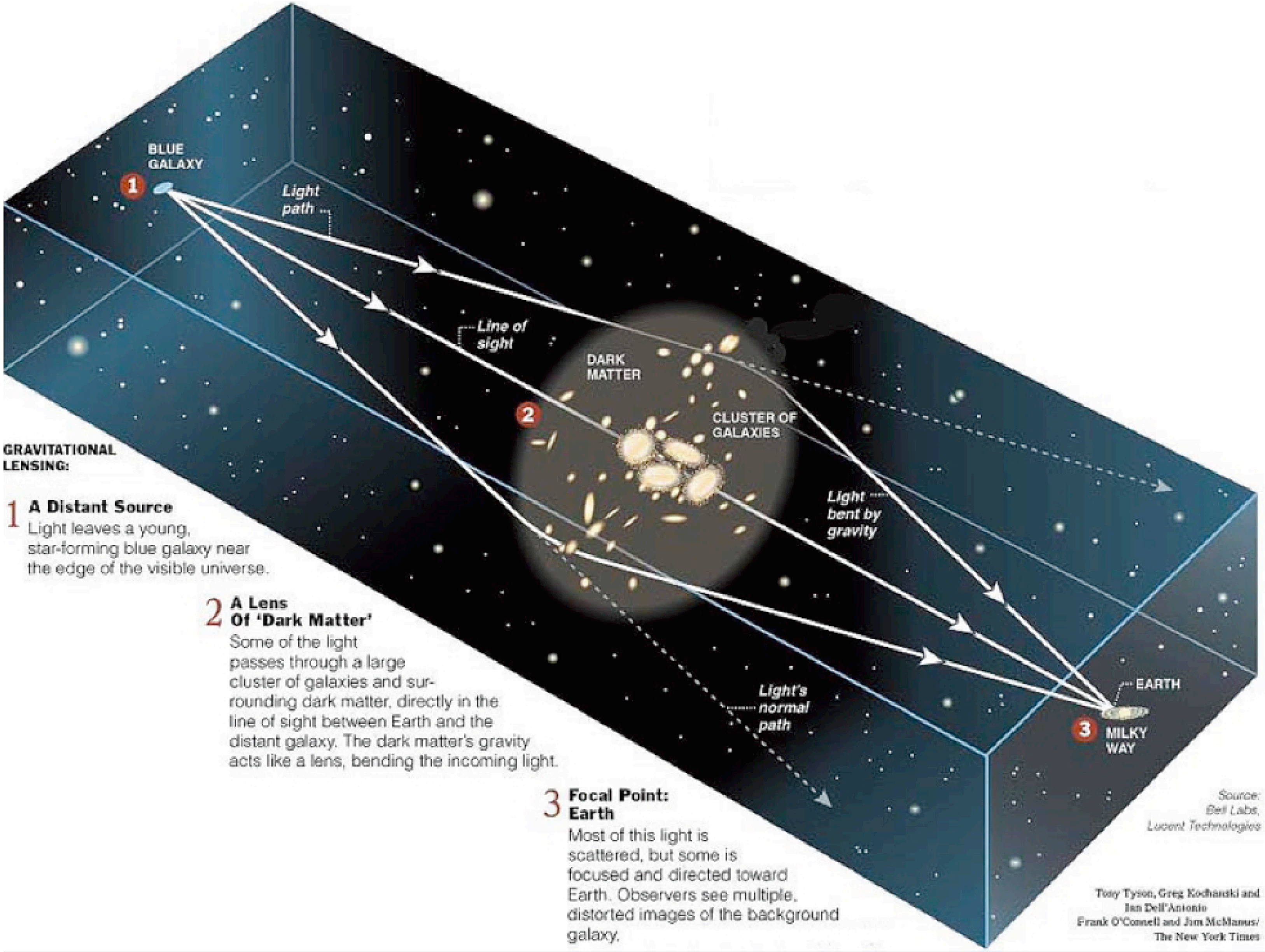


Further evidence comes from observations of **gravitational lensing** of distant sources by a foreground cluster … enabling the potential to be reconstructed



Gravitational Lens
Galaxy Cluster 0024+1654

HST • WFPC2



GRAVITATIONAL LENSING:

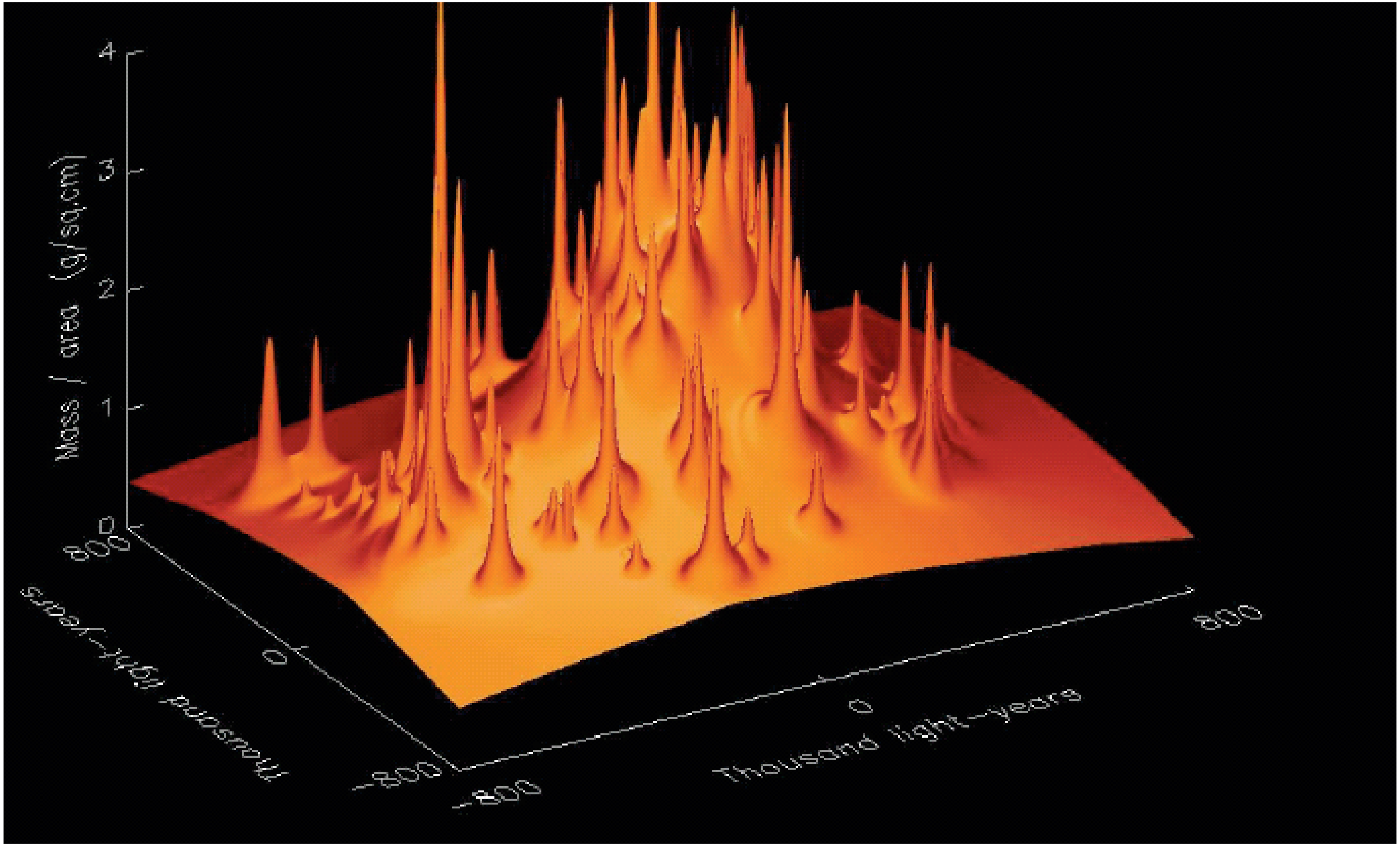
1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

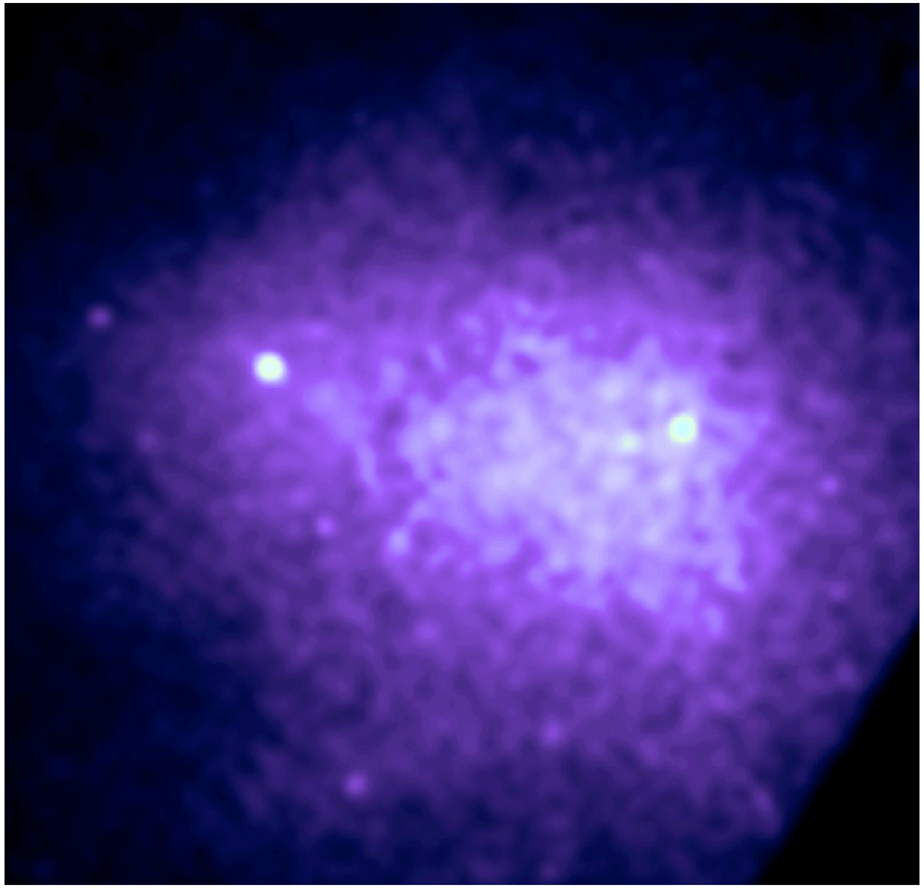
Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/
The New York Times



This reveals that the gravitational mass is dominated by an extended smooth distribution of *∂ark* matter

The gravitating mass can also be obtained from X-ray observations of the hot gas in the cluster



… assuming it is in thermal equilibrium:

$$\frac{1}{\rho_{\rm gas}}\frac{{\rm d}P_{\rm gas}}{{\rm d}r} = \frac{G_{\rm N}M(<r)}{r^2}$$

The *Chandra* picture of the ‘bullet cluster’ shows that the X-ray emitting baryonic matter is *displaced* from the galaxies and the dark matter (inferred through gravitational lensing)

… for many this is convincing evidence of dark matter

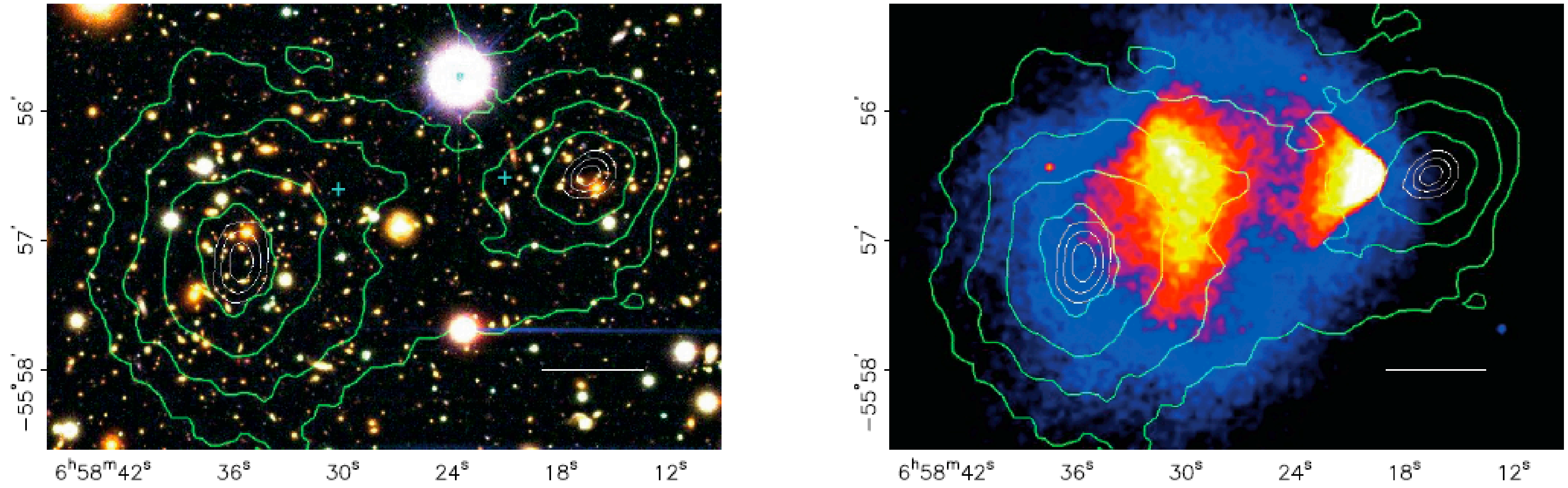
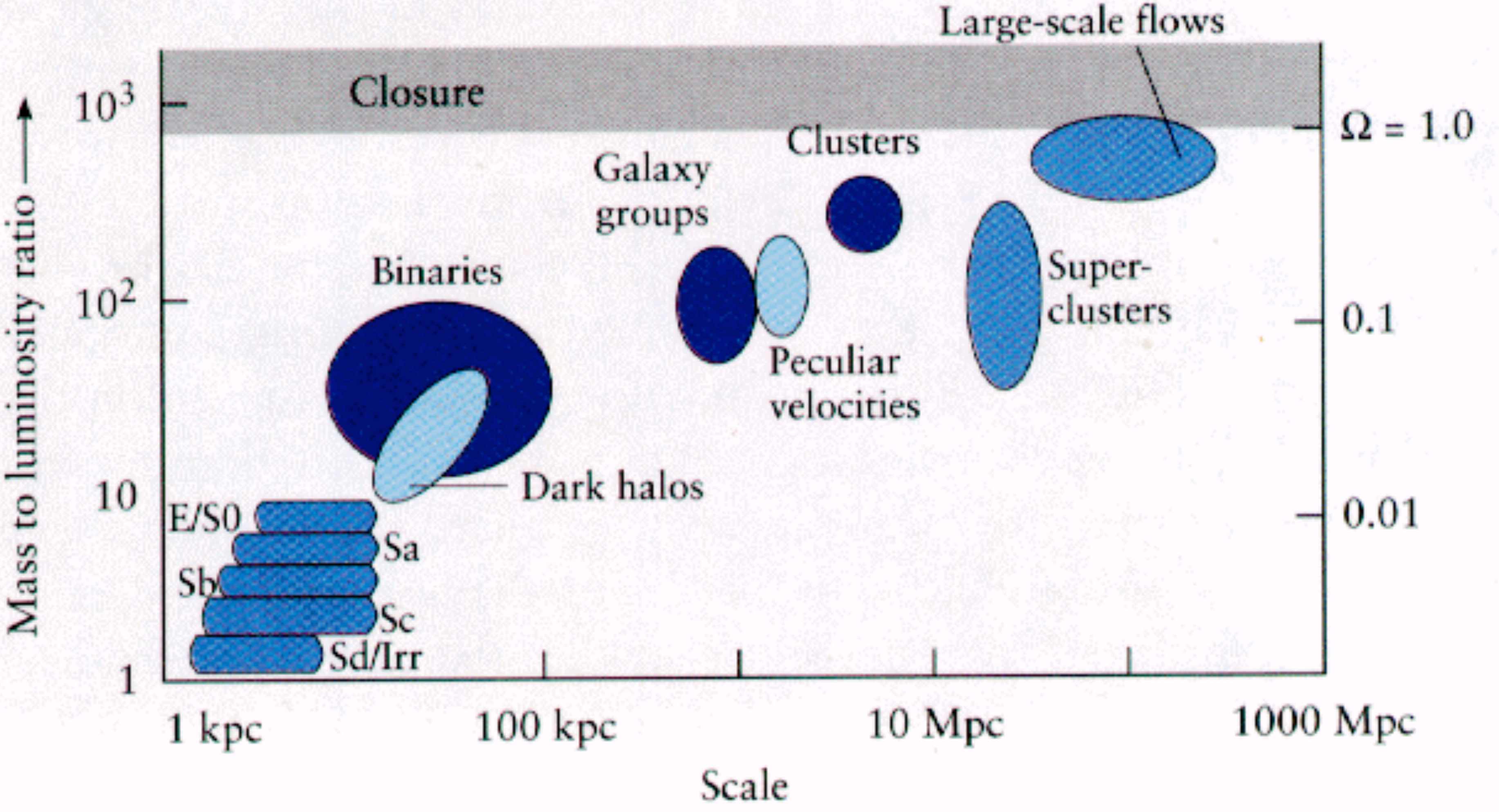


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

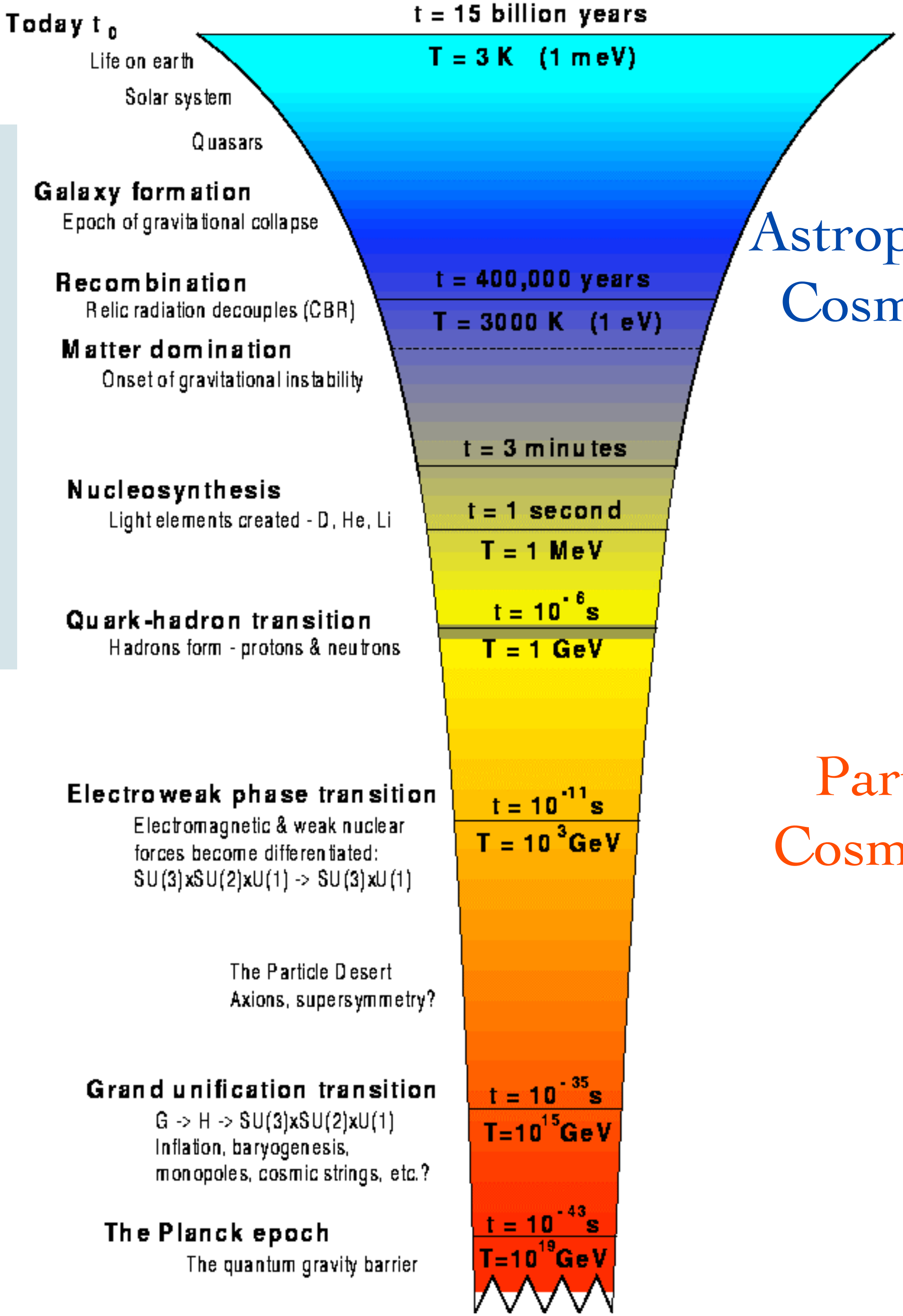
Clowe *et al* [astro-ph/0608407]



A variety of dynamical observations indicate the total matter density is $\Omega_m \sim 0.3$, while arguments based on primordial nucleosynthesis and anisotropies in the CMB indicate that baryons make up ~1/6 of this

On the basis of known microphysics, the evolution of the universe can be extrapolated into our past, reliably up to the nucleosyntheis era and (with some caveats) back through the chiral/QCD phase transition up to the electroweak unification epoch

New physics is required to account for the observed asymmetry between matter and antimatter, to explain dark matter, and also generate the density fluctuations which seeded the formation of structure



Astrophysical Cosmology

Particle Cosmology

The Standard Model of the Early Universe

Thermodynamics of ultra-relativistic plasma:

Number density: $n = \frac{\xi(3)}{\pi^2} g'(T) T^3$

Energy density: $\rho = 3p = \frac{\pi^2}{30} g(T) T^4$

Entropy density: $s \equiv \frac{p+\rho}{T} = \frac{2\pi^2}{45} g(T) T^3$

Where, the number of relativistic degrees of freedom *sum* over all bosons and fermions with appropriate weight:

$$g'(T) = g_b(T) + \frac{3}{4} g_f(T)$$

$$g(T) = g_b(T) + \frac{7}{8} g_f(T)$$

In the absence of dissipative processes (e.g. phase transitions which generate entropy) the **comoving entropy** is *conserved*:

$$\frac{d}{dt}(sa^3) = 0 \quad \Rightarrow \quad s \propto 1/a^3 \qquad \text{i.e.} \quad T \propto 1/a$$

At early times the curvature term becomes negligible (compared to radiation) so the Friedmann equation simplifies to:

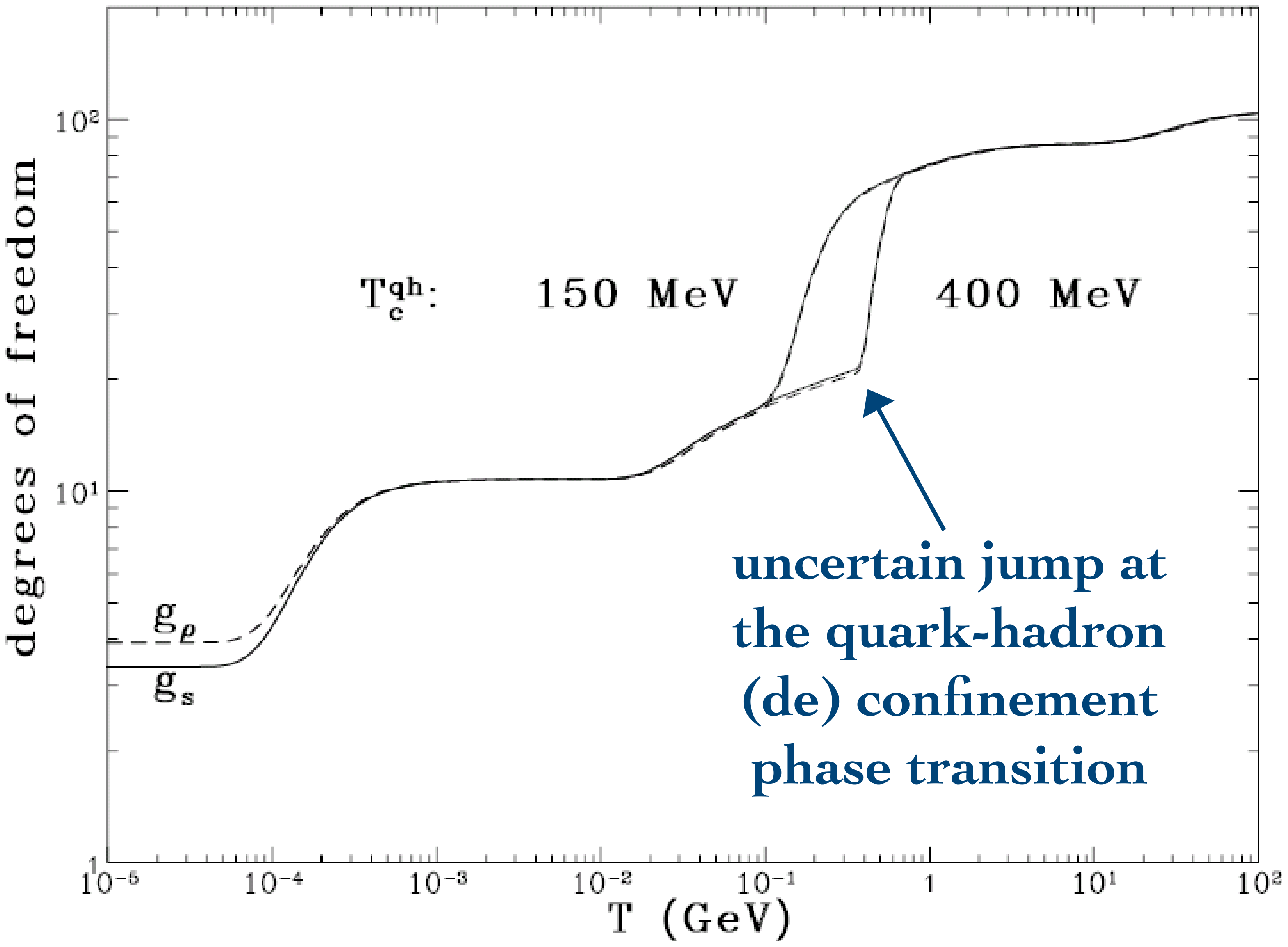
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3}$$

Integrating this yields the time-temperature relationship:

$$t\ (\mathrm{s}) = 2.42\, g^{-1/2}\, (T/\mathrm{MeV})^{-2}$$

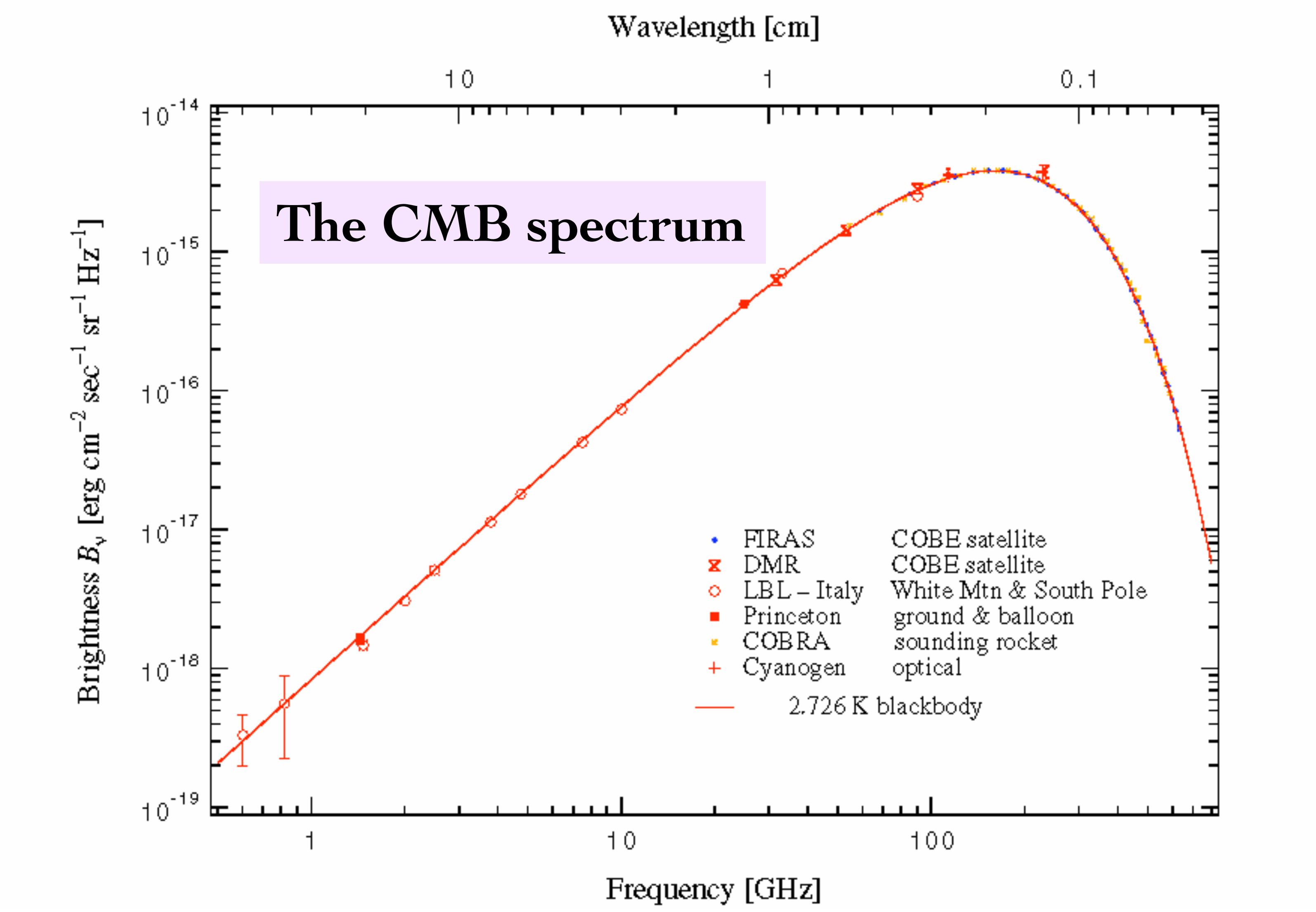
So we can work out when events of *physical significance* occurred in our past (according to the **Standard Model** of particle physics)

To get this right we need to count all the bosons and fermions contributing to the relativistic degrees of freedom … and take into account our uncertain knowledge of possible phase transitions



uncertain jump at the quark-hadron (de) confinement phase transition

The CMB spectrum



Such a perfect blackbody is testimony to our hot, dense past and directly demonstrates that the expansion was adiabatic (with negligible energy release) back at least to t ~ 1 day

… we can go back further to t ~ 1 s by studying element synthesis

Weak interactions and nuclear reactions in expanding, cooling universe

(Gamow 1948; Hayashi 1950; **Alpher, Follin, Herman 1953**; Peebles 1966; Wagoner, Fowler, Hoyle 1967)

Dramatis personae:

Radiation (dominates) $\gamma, e^{\pm}, 3\nu\bar{\nu}$

Matter n, p

baryon-to-photon ratio (only free parameter) $n_{\rm B}/n_{\gamma} \equiv \eta \simeq 2.74 \times 10^{-8}\Omega_{\rm B}h^2$

Initial conditions: $T >> 1$ MeV, $t << 1$ s

n-p weak equilibrium: $n + \nu_e \leftrightarrow p + e^-$

neutron-to-proton ratio: $p + \nu_e \leftrightarrow n + e^+$

Weak freeze-out: $T_{\rm f} \sim 1$ MeV, $t_{\rm f} \sim 1$ s

which fixes:

$$\tau_{\rm weak}(n \leftrightarrow p) \geq t_{\rm universe} \Rightarrow T_{\text{freeze-out}} \sim \left(G_N / G_F^2\right)^{1/3}$$

$$n/p = e^{-(m_n - m_p)/T_{\rm f}} \approx 1/6$$

Deuterium bottleneck: $T \sim 1 \rightarrow 0.07$ MeV

D created by $np \rightarrow D\gamma$

but destroyed by high-E photon tail: $D\gamma \rightarrow np$

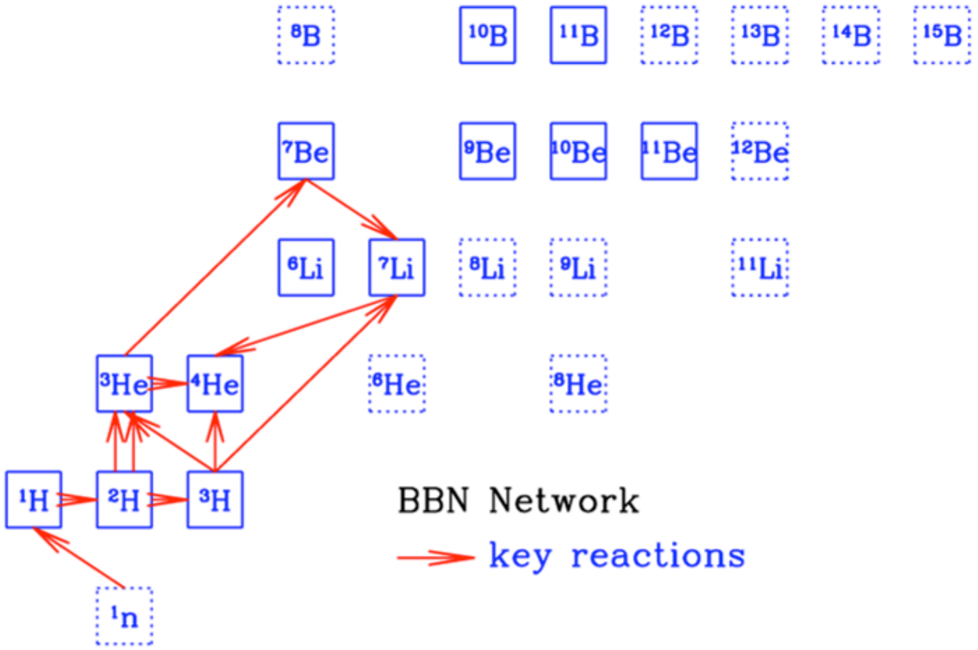
so nucleosynthesis halted until: $T_{\rm nuc} \sim \Delta_{\rm D}/\text{-}\ln(\eta)$

Element synthesis: $T_{\rm nuc} \sim 0.07$ MeV, $t_{\rm nuc} \sim 3$ min

(meanwhile $n/p \rightarrow 1/7$ through neutron β-decay)

essentially all $n \rightarrow {}^4$He ($Y_{\rm P} \sim 25\%$ by mass) + 'left-over' traces of D, ^{3}He, ^{7}Li (with ^{6}Li/^{7}Li ~ 10^{-5})

No heavier nuclei are formed in standard, homogeneous hot Big Bang … must wait for stars to form after a ~billion years and synthesise all the other nuclei in the universe (s-process, r-process, …)

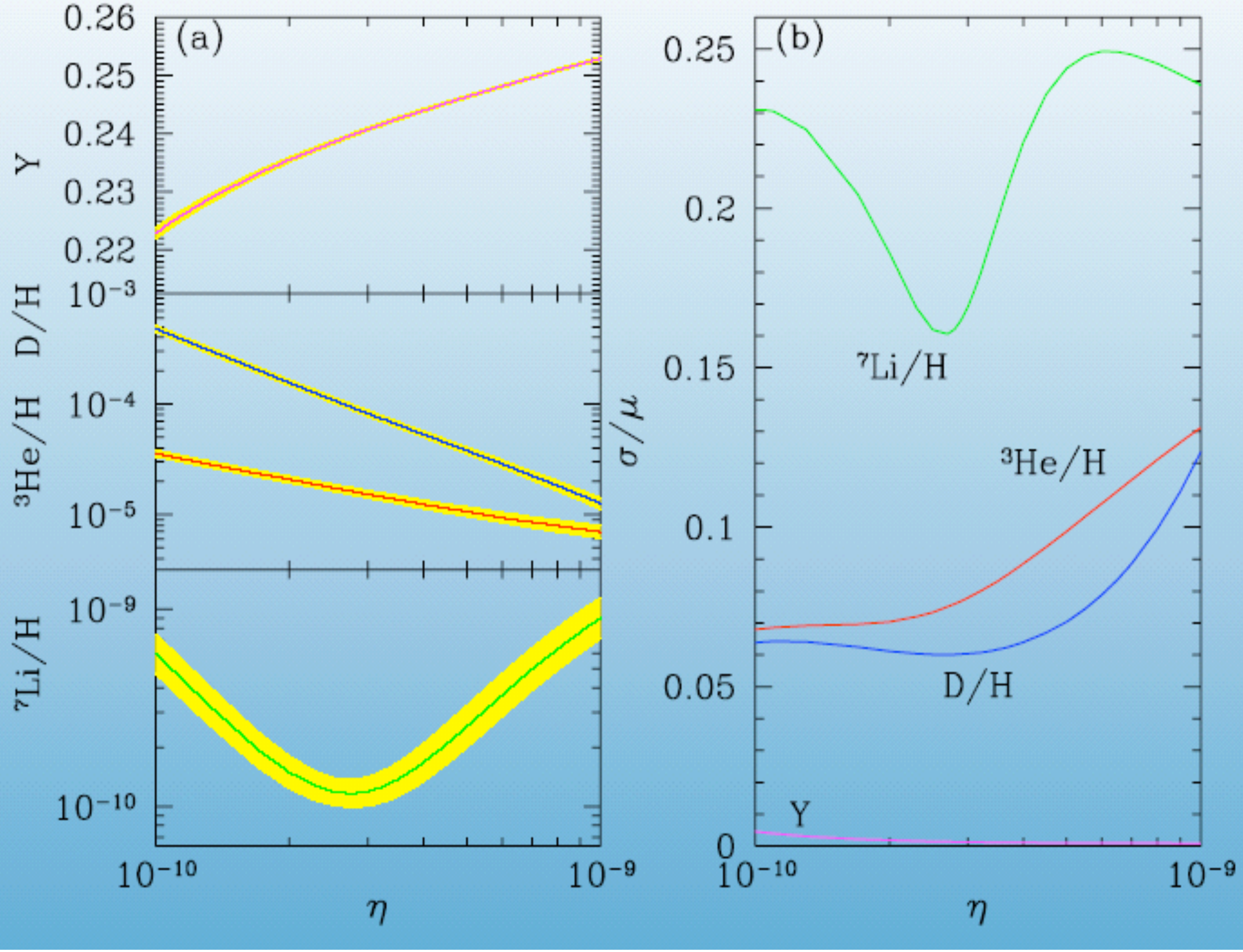


All reactions measured in lab at relevant energies

- Computer code by Wagoner (1969, 1973) .. updated by Kawano (1992)
- Coulomb & radiative corrections, ν heating *et cetera* (Dicus *et al* 1982)
- Nucleon recoil corrections (Seckel 1993)
- Covariance matrix of correlated uncertainties (Fiorentini *et al* 1998)
- Updated nuclear cross-sections (NACRE 2003)

BBN Predictions

line widths ⇒ theoretical uncertainties (neutron lifetime, nuclear cross sections)



Nucleosynthesis *without* a computer

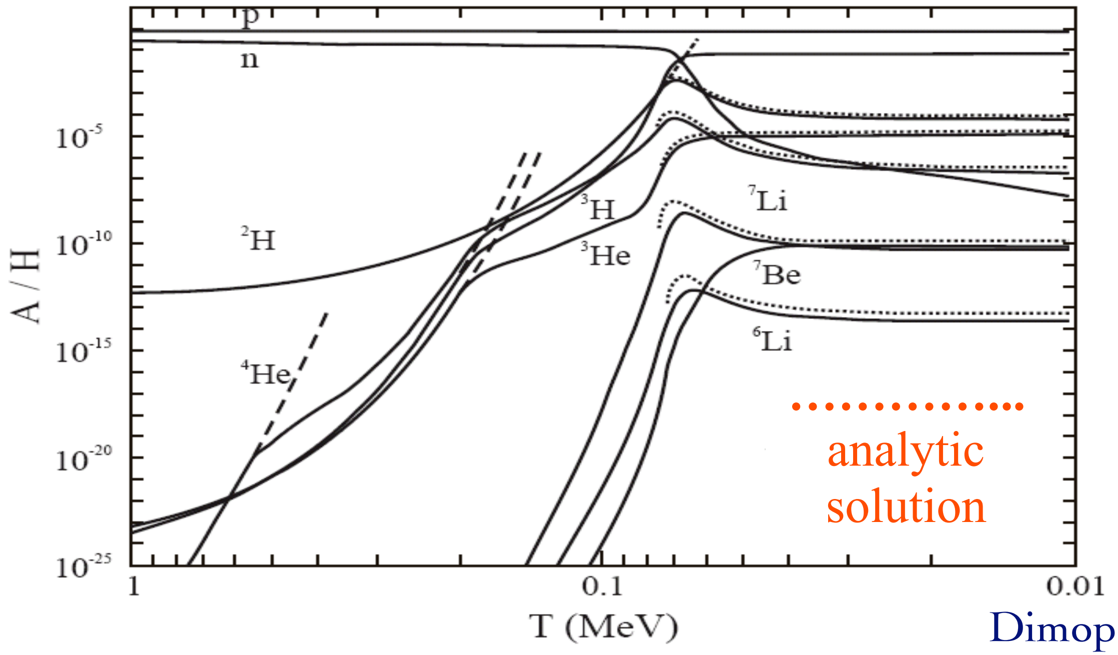
$$\frac{\mathrm{d}X}{\mathrm{d}t} = \underset{\text{source}}{J(t)} - \underset{\text{sink}}{\Gamma(t)}X \qquad \Rightarrow \qquad X^{\mathrm{eq}} = \frac{J(t)}{\Gamma(t)}$$

… but general solution is:

$$X(t) = \exp\left(-\int_{t_{\mathrm{i}}}^{t} \mathrm{d}t'\ \Gamma(t')\right)\left[X(t_{\mathrm{i}}) + \int_{t_{\mathrm{i}}}^{t} \mathrm{d}t'\ J(t')\ \exp\left(-\int_{t_{\mathrm{i}}}^{t} \mathrm{d}t''\ \Gamma(t'')\right)\right]$$

If $\left|\frac{\dot{J}}{J} - \frac{\dot{\Gamma}}{\Gamma}\right| \ll \Gamma$ … then abundances approach equilibrium values

Freeze-out occurs when: $\Gamma \simeq H$ $\quad\Rightarrow\quad X(t \to \infty) \simeq X^{\mathrm{eq}}(t_{\mathrm{fr}}) = \frac{J(t_{\mathrm{fr}})}{\Gamma(t_{\mathrm{fr}})}$



Examine reaction network to identify the largest 'source' and 'sink' terms …

obtain D, ^{3}He and ^{7}Li to within a factor of ~2 of exact numerical solution, and ^{4}He to within a few %

Dimopoulos, Esmailzadeh, Hall, Starkman (1988)

… can use this formalism to determine *joint* dependence of abundances on expansion rate as well as baryon-to-photon ratio

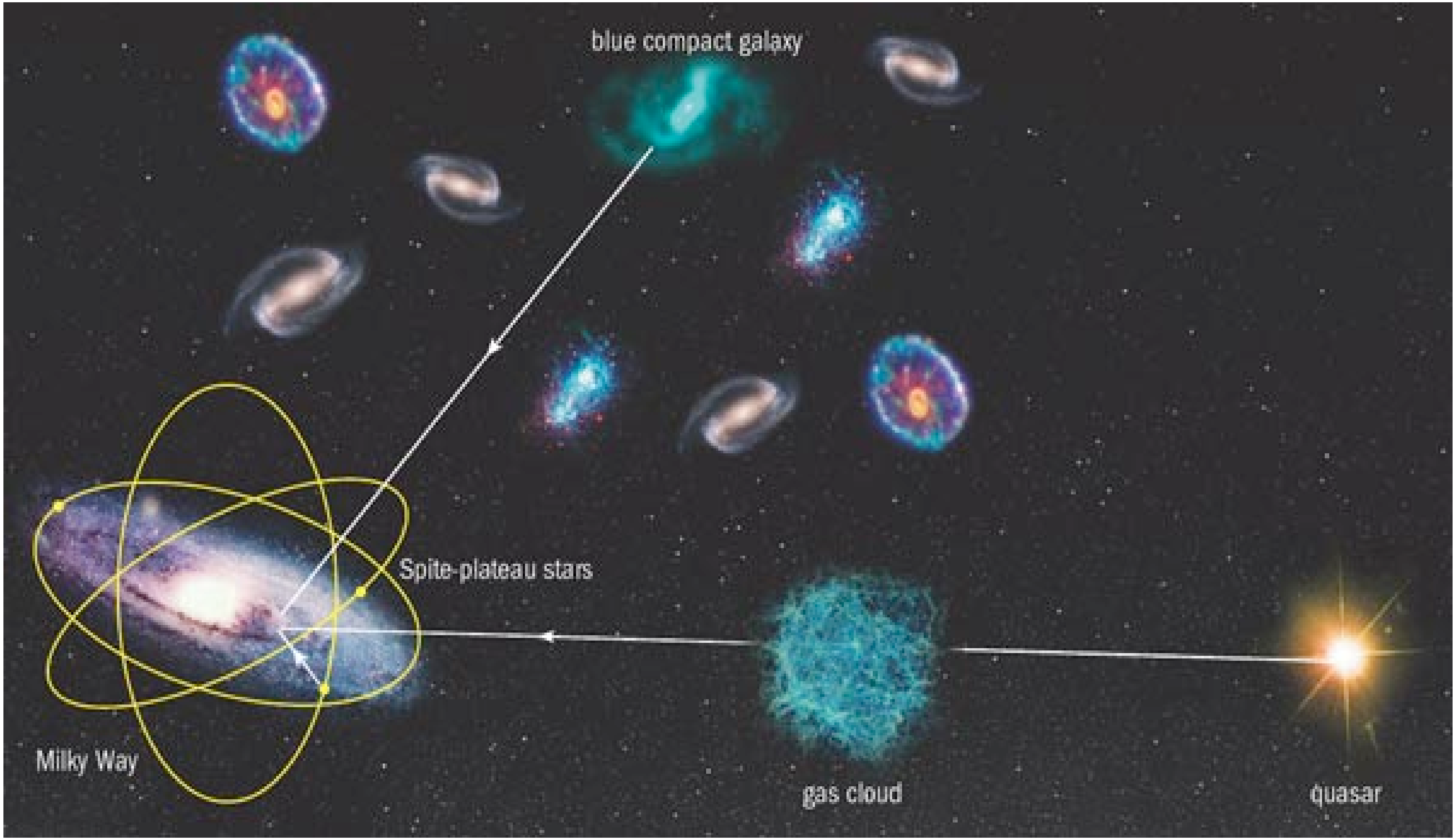
$$\frac{\mathrm{d}Y_i}{\mathrm{d}t} \propto \eta \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_T \quad \text{and} \quad dT/dt \propto -T^3 \sqrt{g_\star} \quad \text{so:}$$

$$\frac{\mathrm{d}Y_i}{\mathrm{d}T} \propto -\frac{\eta}{g_\star^{1/2}} T^{-3} \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_T \Rightarrow \log \eta - \frac{1}{2} \log g_\star = \mathrm{const}$$

… can now employ simple χ^2 statistics to determine best-fit values and uncertainties (*faster* than Monte Carlo + Maximum Likelihood)

Lisi, Sarkar & Villante (2000)

Inferring primordial abundances



Courtesey: Physics World

Inferred primordial abundances

^{4}He observed in extragalactic HII regions:

$$Y_{\mathrm{p}} = 0.249 \pm 0.009$$

^{2}H observed in quasar absorption systems (and ISM):

$$\mathrm{D/H}|_{\mathrm{p}} = (2.84 \pm 0.26) \times 10^{-5}$$

^{7}Li observed in atmospheres of dwarf halo stars:

$$\mathrm{Li/H}|_{\mathrm{p}} = (1.7 \pm 0.02^{+1.1}_{-0}) \times 10^{-10}$$

Systematic errors have been *reevaluated* based on scatter in data

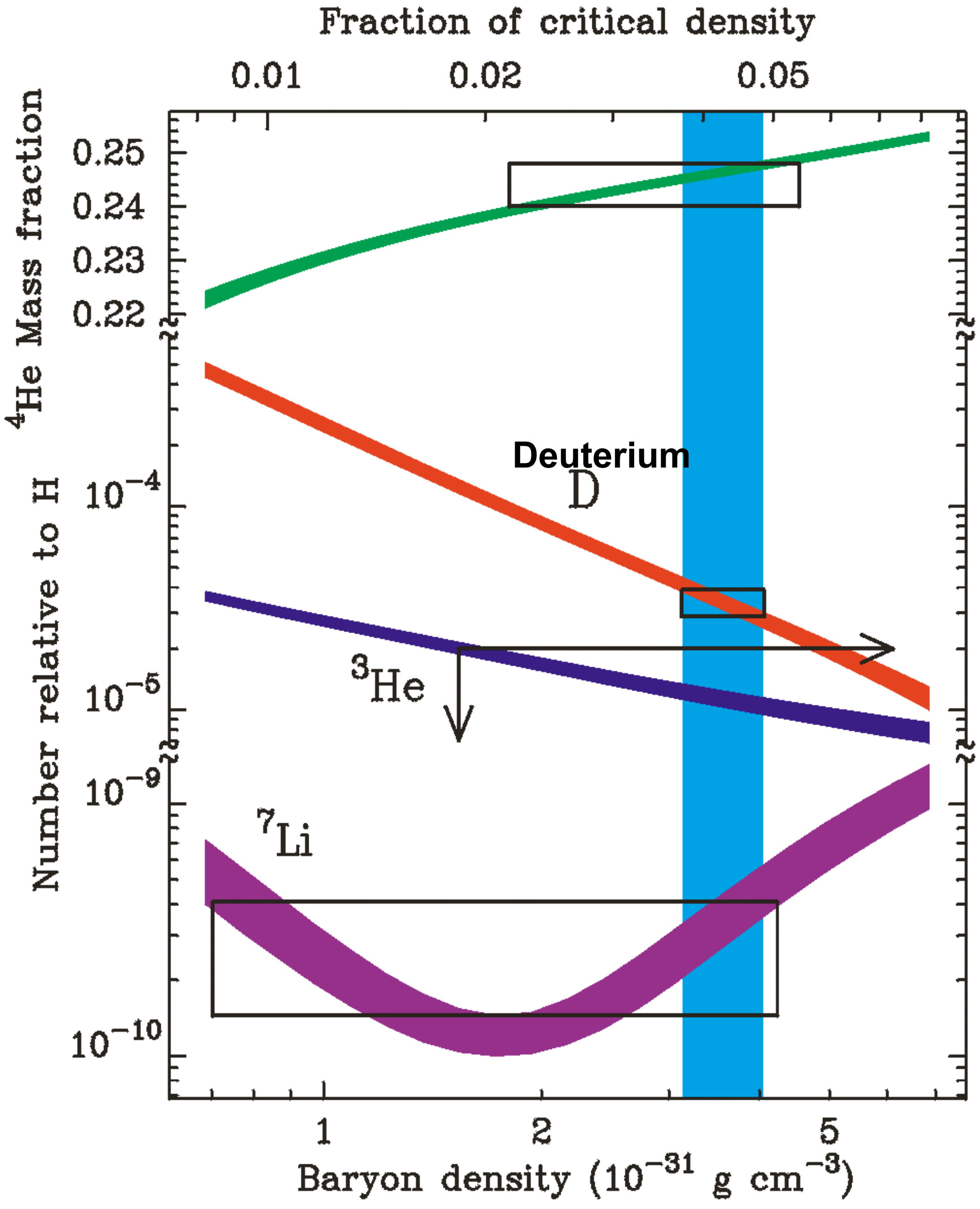
(for details see Particle Data Group: Fields & Sarkar 2008)

Cosmic Concordance

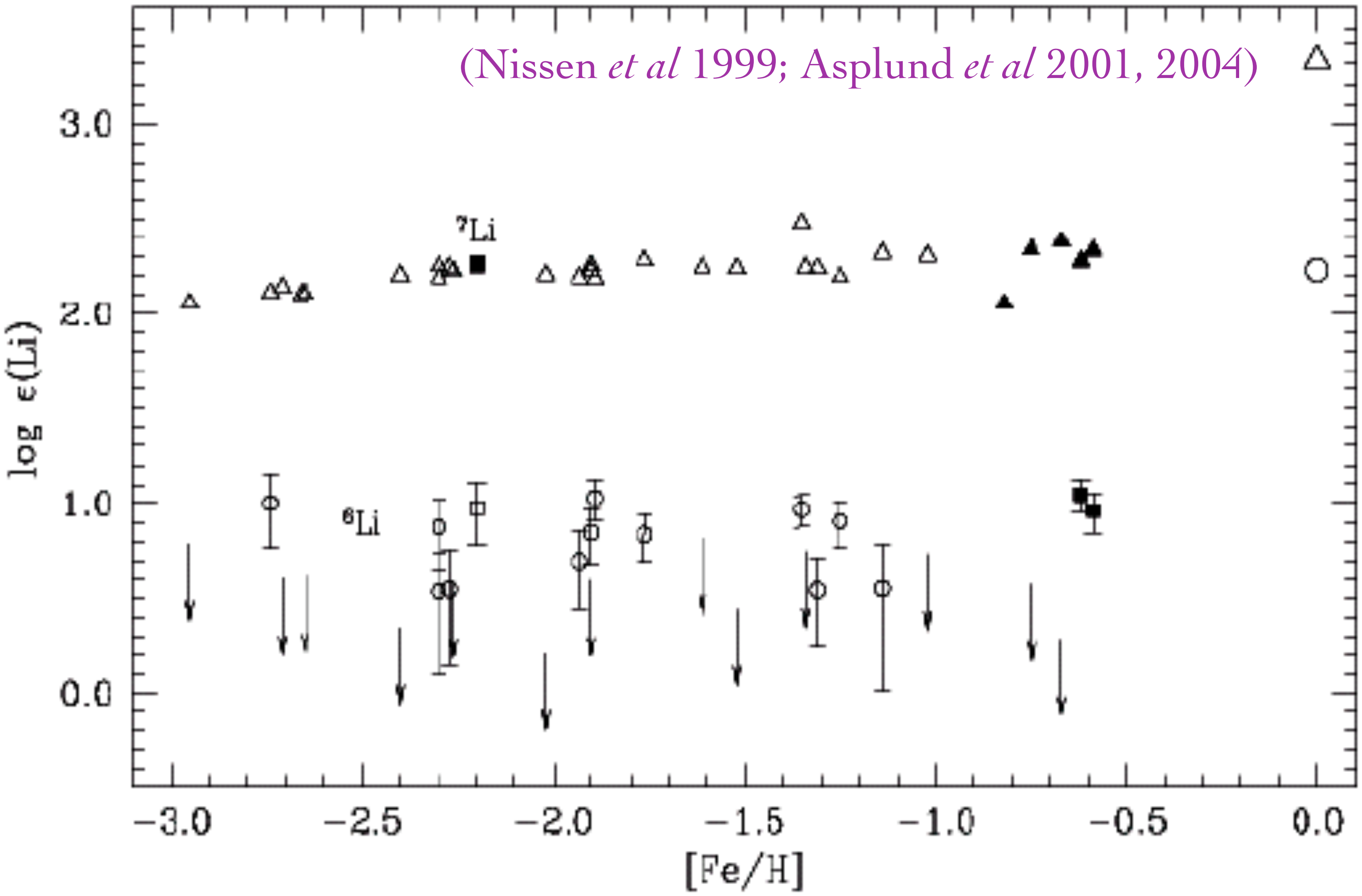
- **Primordial nucleosynthesis**
  - explains observed light element abundances if the density of baryonic matter is ~3.5×10^{-31} g/cm^3 or ~0.21 hydrogen atoms/m^3

- **Radical possibility**
  - Even if baryons make up the critical density so that *only* ^{4}He is synthesised, the right amounts of D and ^{7}Li can result from photofission if there are decaying relic particles creating radiation cascades in the plasma (Esmailzadeh *et al* 1988)!

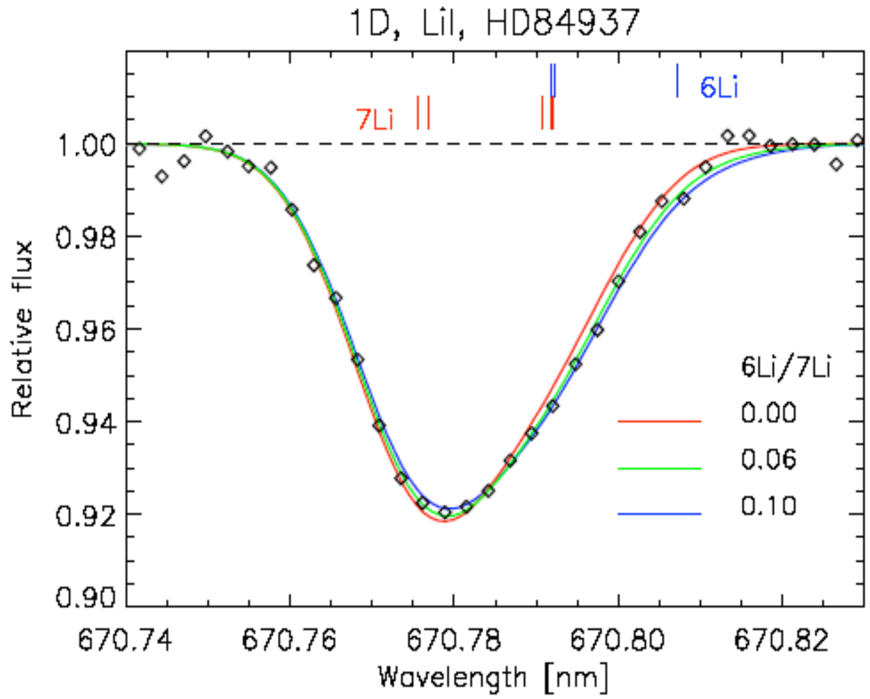
  → Was considered to be ruled out because this should also make unobserved ^{6}Li ~ ^{7}Li



Recently a primordial ‘plateau’ in ^{6}Li has indeed been detected with ^{6}Li/^{7}Li ~ 0.1 (cf. standard expectation ^{6}Li/^{7}Li ~ 10^{-5})



Coupled with the fact that the ^{7}Li abundance is ~3 times smaller than expected, this has refocussed interest on non-standard BBN



The Li I 6707 Å resonance doublet in HD 84937 from Smith et al. (1993). The wavelengths of the ^{7}Li and ^{6}Li re indicated at the top of the figure. Synthetic profiles for three ^{6}Li/^{7}Li ratios are shown – courtesy of Martin Asplund.

However the 'detection' of ^{6}Li is based on detailed fits to the line shape … need much more data to establish the reality of a '^{6}Li plateau'

Also stars in which ^{6}Li is detected are close to the main-sequence turn-off in the H-R diagram

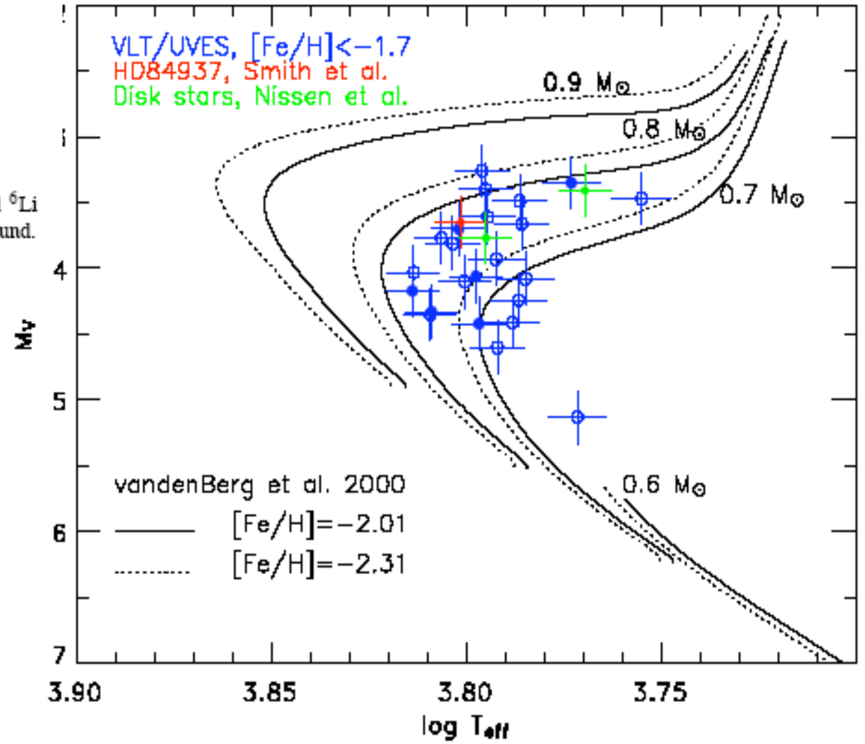
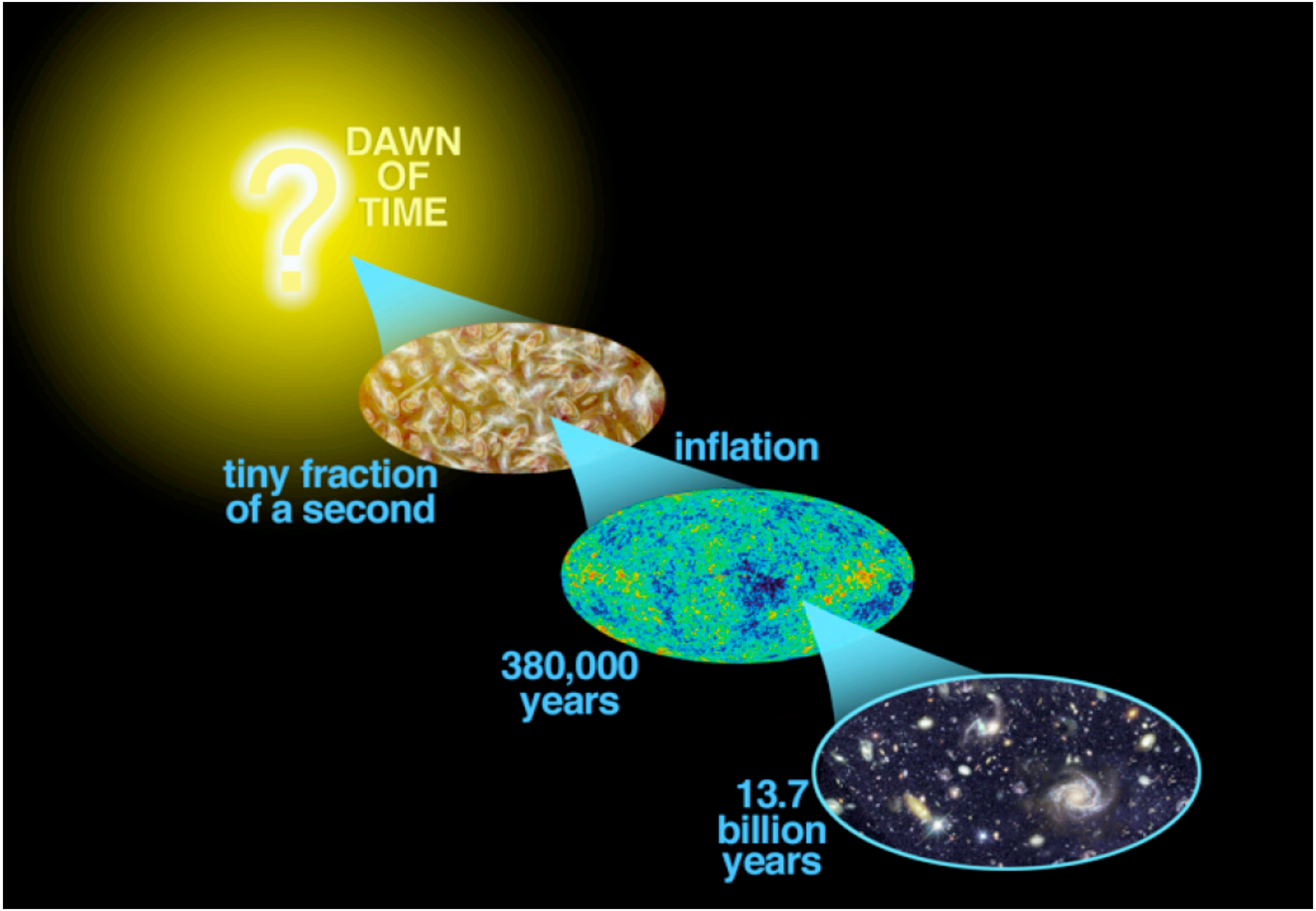


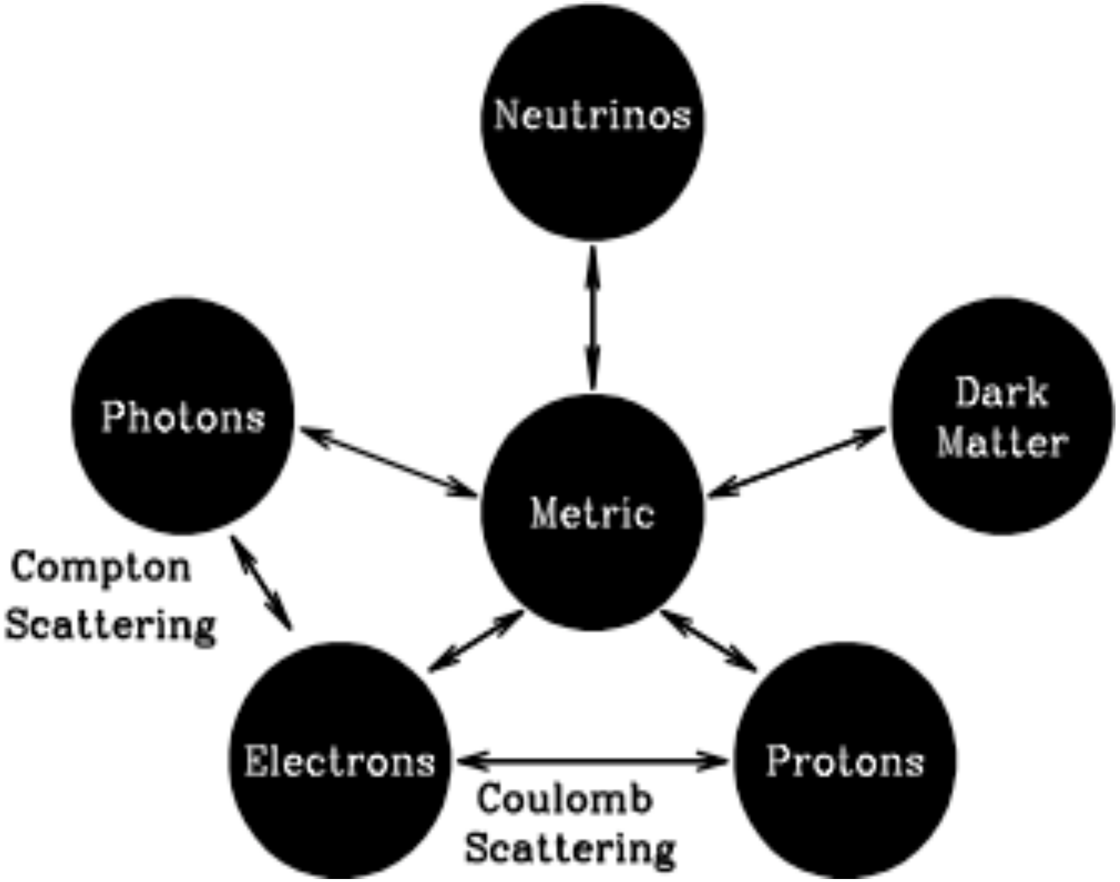
FIGURE 4. The Hertzsprung-Russell diagram for stars from Figure 3 with [Fe/H] < -1.7. Filled symbols denote stars with a detection of ^{6}Li according to the key in the top left corner of the figure. Evolutionary tracks for the indicated stellar masses and metallicities are from VandenBerg et al. (2000).

Lambert (2005)

Another argument comes from considerations of structure formation in the universe

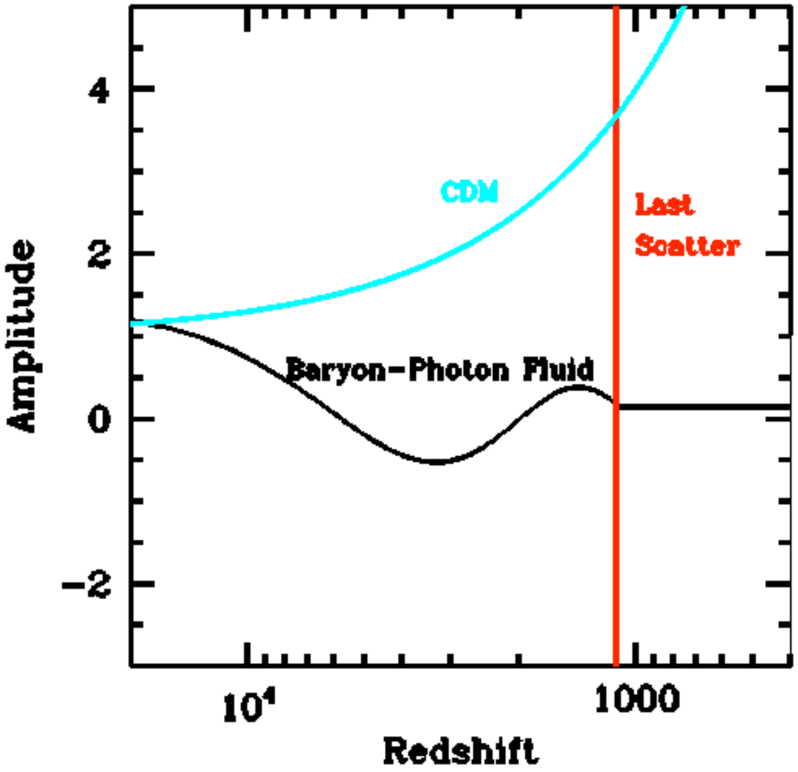


Perturbations in metric (generated during inflation) induce perturbations in photons and (dark) matter

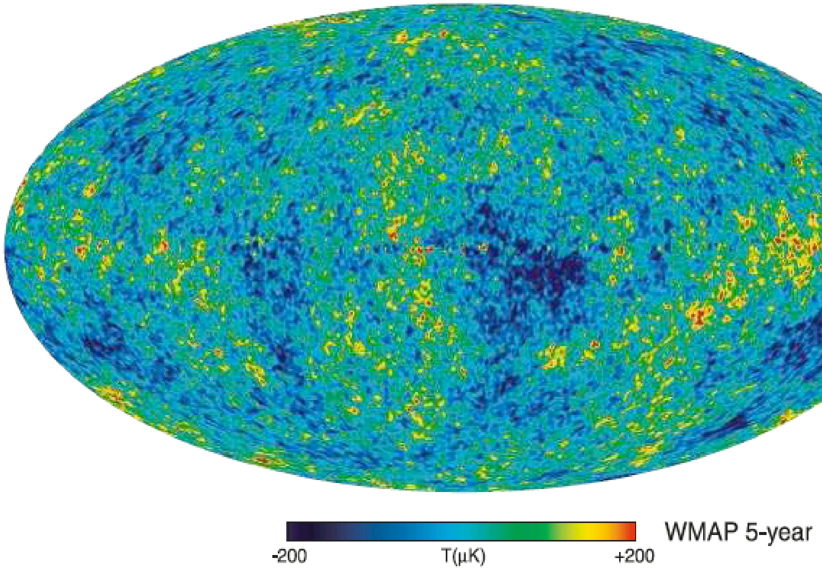


These perturbations begin to grow through gravitational instability after matter domination

Before recombination, the primordial fluctuations just excite sound waves in the plasma, but can start growing already in the sea of *collisionless* dark matter …



Courtesey David Spergel



These sound waves leave an imprint on the *last scattering surface* of the CMB as the universe turns neutral and transparent … sensitive to the baryon/CDM densities

For a statistically isotropic gaussian random field, the **angular power spectrum** can be constructed by decomposing in spherical harmonics:

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$

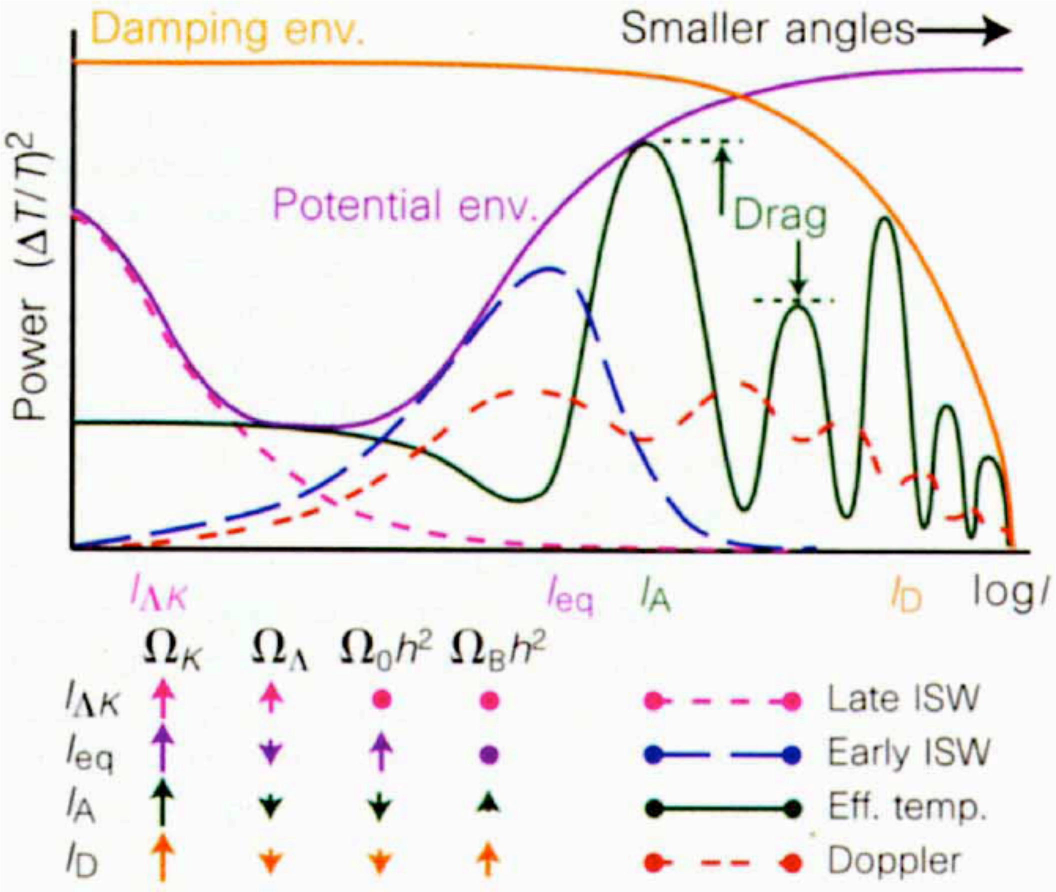


Figure 1 Schematic decomposition of the anisotropy spectrum and its dependence on cosmological parameters, in an adiabatic model. Four fundamental angular scales characterized by the angular wavenumber $l \propto \theta^{-1}$ enter the spectrum: $l_{\Lambda K}$ and l_{eq} which enclose the Sachs-Wolfe plateau in the potential envelope, l_A the acoustic spacing, and l_D the diffusion damping scale. The inset table shows the dependence of these angular scales on four fundamental cosmological parameters: $\Omega_K (\equiv 1 - \Omega_\Lambda - \Omega_0)$, Ω_Λ, $\Omega_0 h^2$ and $\Omega_B h^2$ (see Box 1 for definitions). Baryon drag enhances all compressional (here, odd) maxima of the acoustic oscillation, and can probe the spectrum of fluctuations at last scattering and/or $\Omega_B h^2$. Projection effects smooth Doppler more than effective-temperature features.

Hu, Sugiyama, Silk [astro-ph/9604166]

The Cosmic Microwave Background

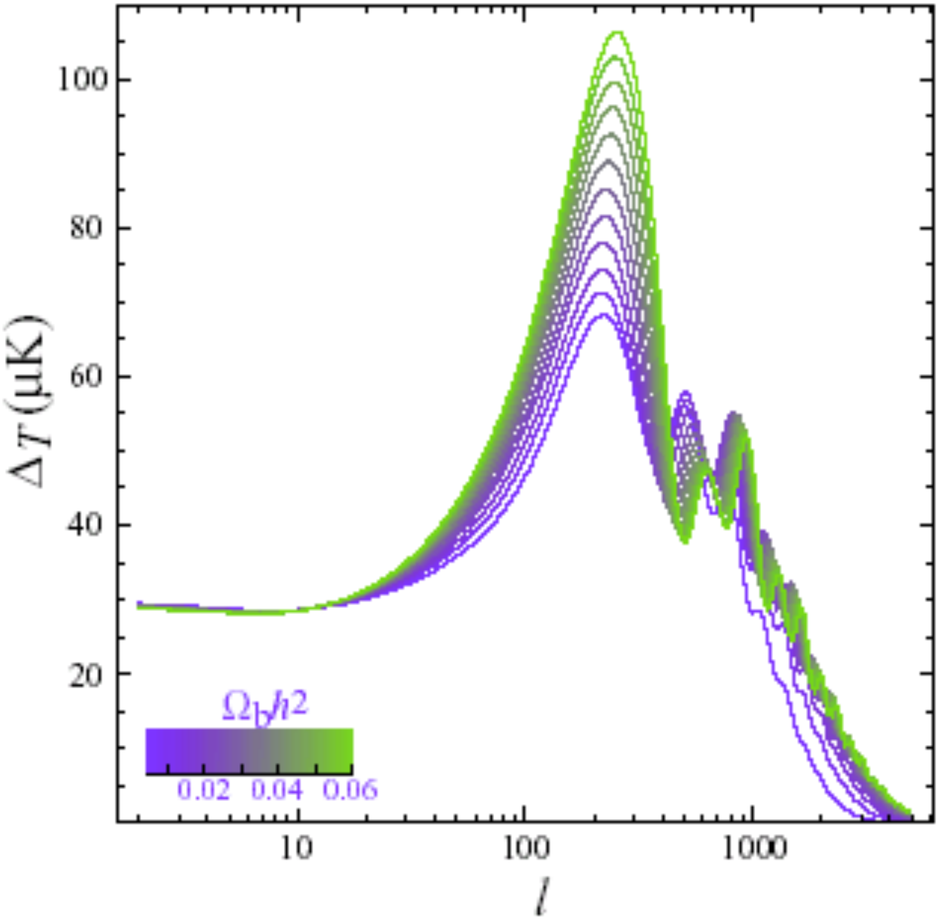
ΔT_ℓ provide *independent* measure of $\Omega_B h^2$

Acoustic oscillations in (coupled) photon-baryon fluids imprint features at small angles (< 1°) in angular power spectrum

Detailed peak positions, heights, … sensitive to cosmological parameters
e.g. 2nd/1st peak ⇒ baryon density

WMAP-5 best-fit:

$$\Omega_B h^2 = 0.02273 \pm 0.00062$$



Bond & Efstathiou (1984)
Dodelson & Hu (2003)

BBN versus CMB

η_{BBN} is in *agreement* with η_{CMB}

allowing for large systematic uncertainties
in the inferred elemental abundances

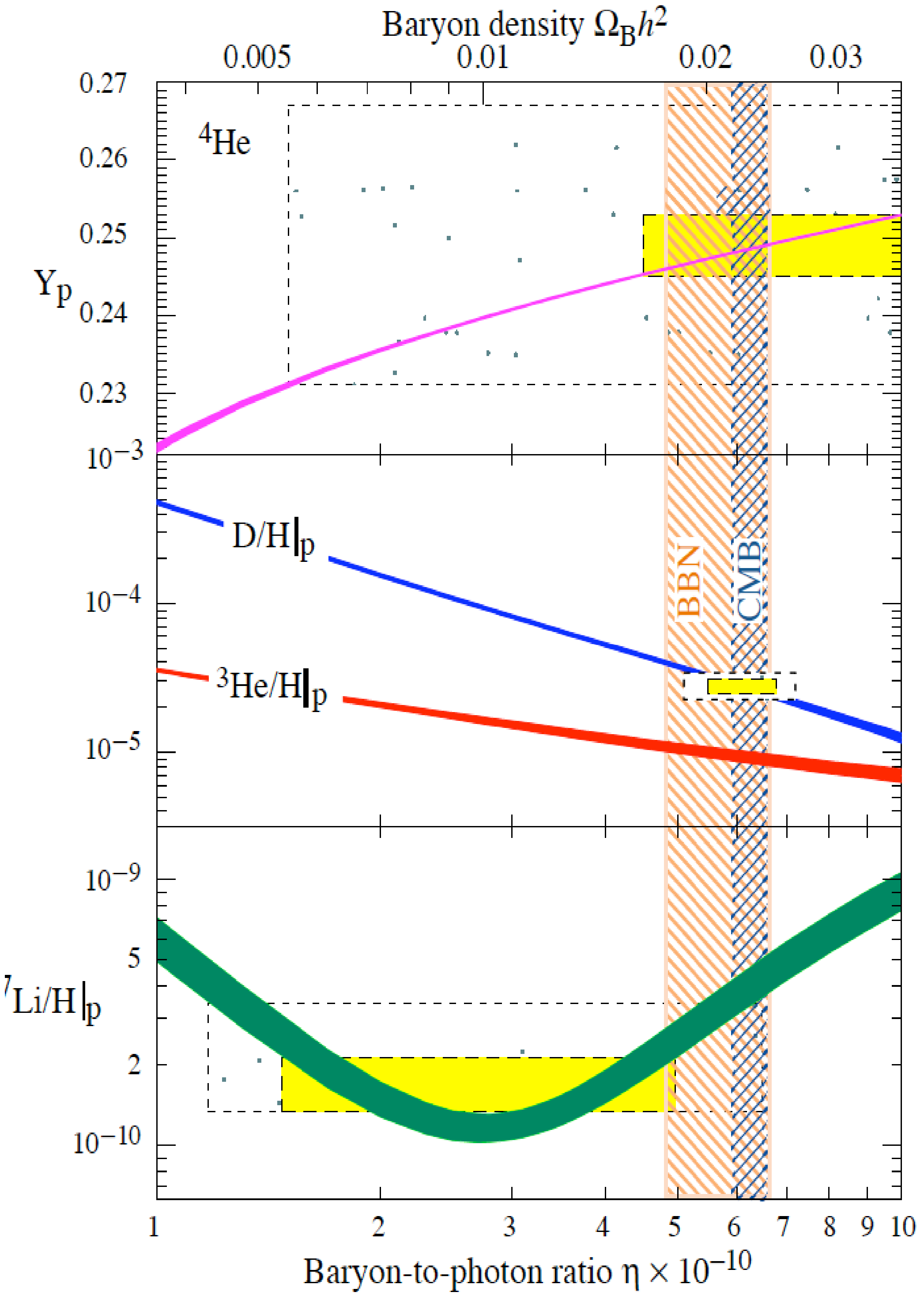
$$4.7 \le \eta_{10} \le 6.5 \ (95\% \ \mathrm{CL})$$

Confirms and sharpens the case for
(*two* kinds of) dark matter

Baryonic Dark Matter:
warm-hot IGM, Ly-α, X-ray gas …

+

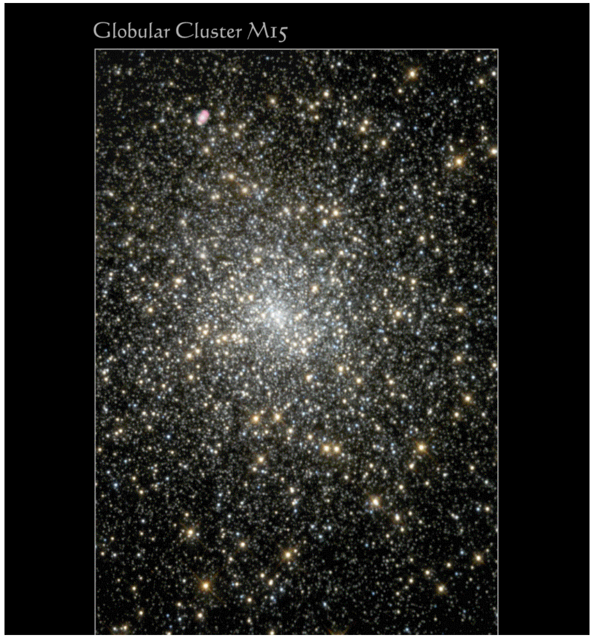
Non-baryonic dark matter:
neutralino? axion? …



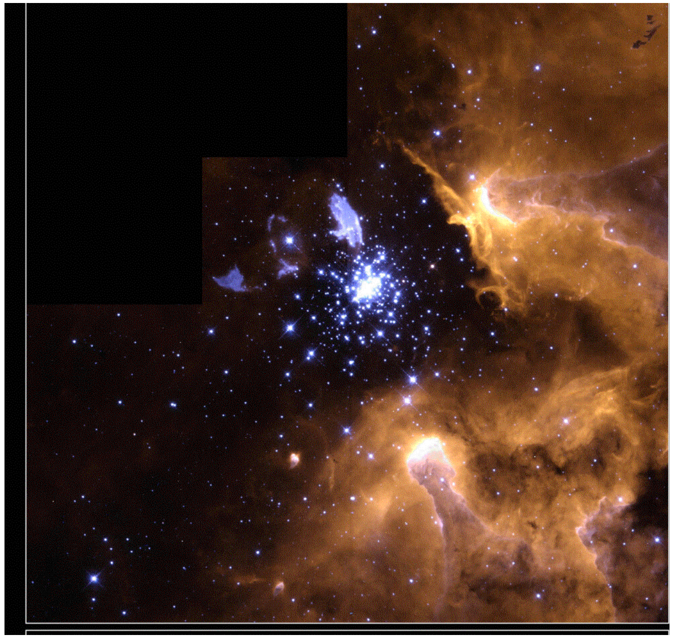
Particle data Group: Fields & Sarkar (2008)

We know that *some* baryons must be dark because BBN requires $\Omega_b \sim 0.02h^{-2}$, whereas $\Omega_{\mathrm{luminous}} \sim 0.024h^{-1}$

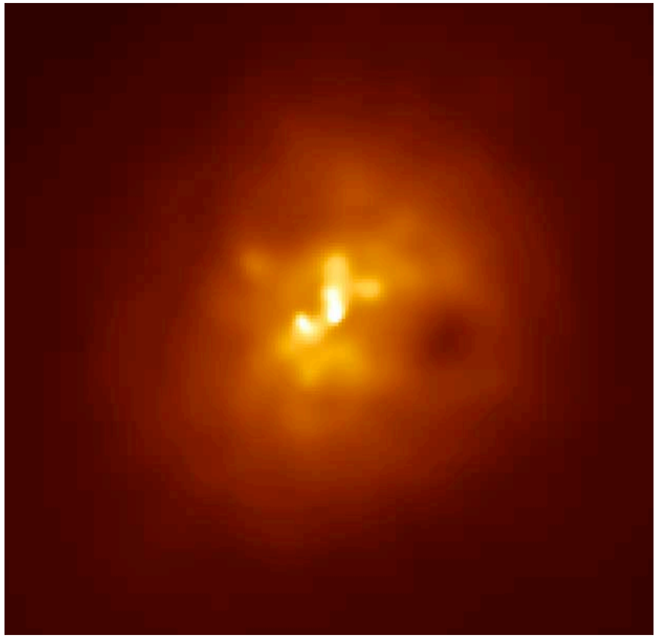
Stars
$\Omega \sim 0.005$



Interstellar gas
$\Omega \sim 0.005$



Hot gas in clusters
$\Omega \sim 0.03$



In fact observations indicate $\Omega_m \sim 0.3$ so most of the matter in the universe must be dark and *non-baryonic*

Whereas structure formation can in principle also occur in alternative ways, the best understood and most satisfactory model at present is dark matter (+GR)

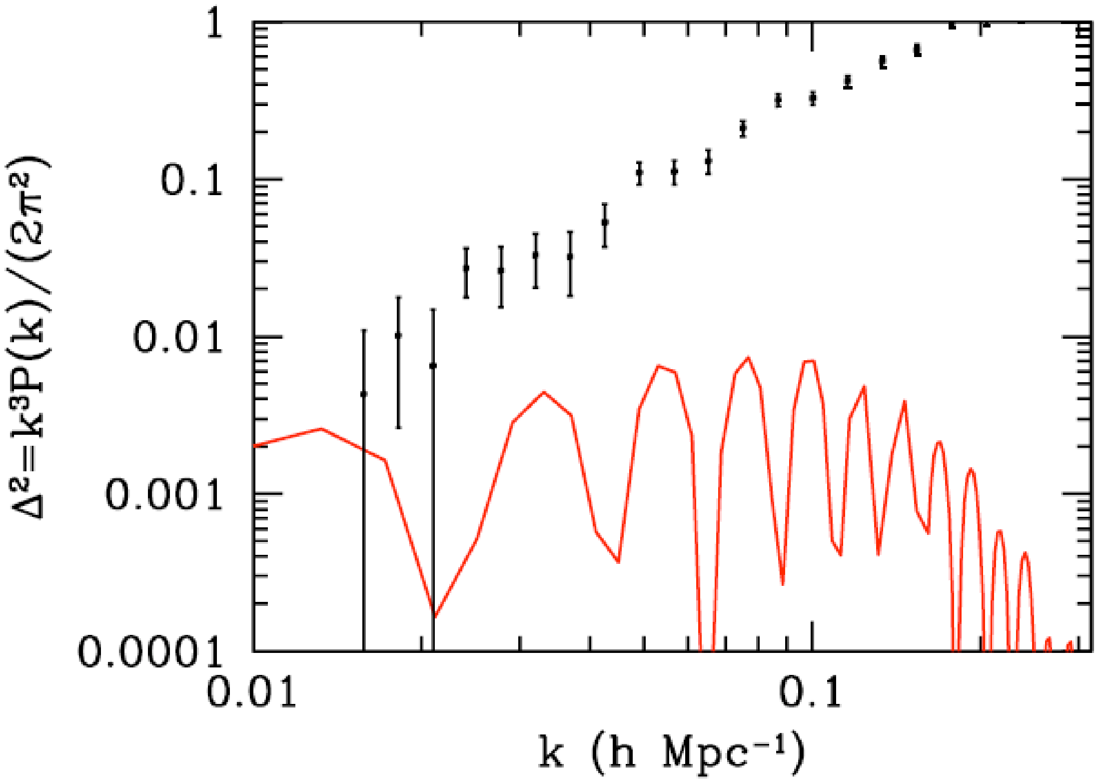
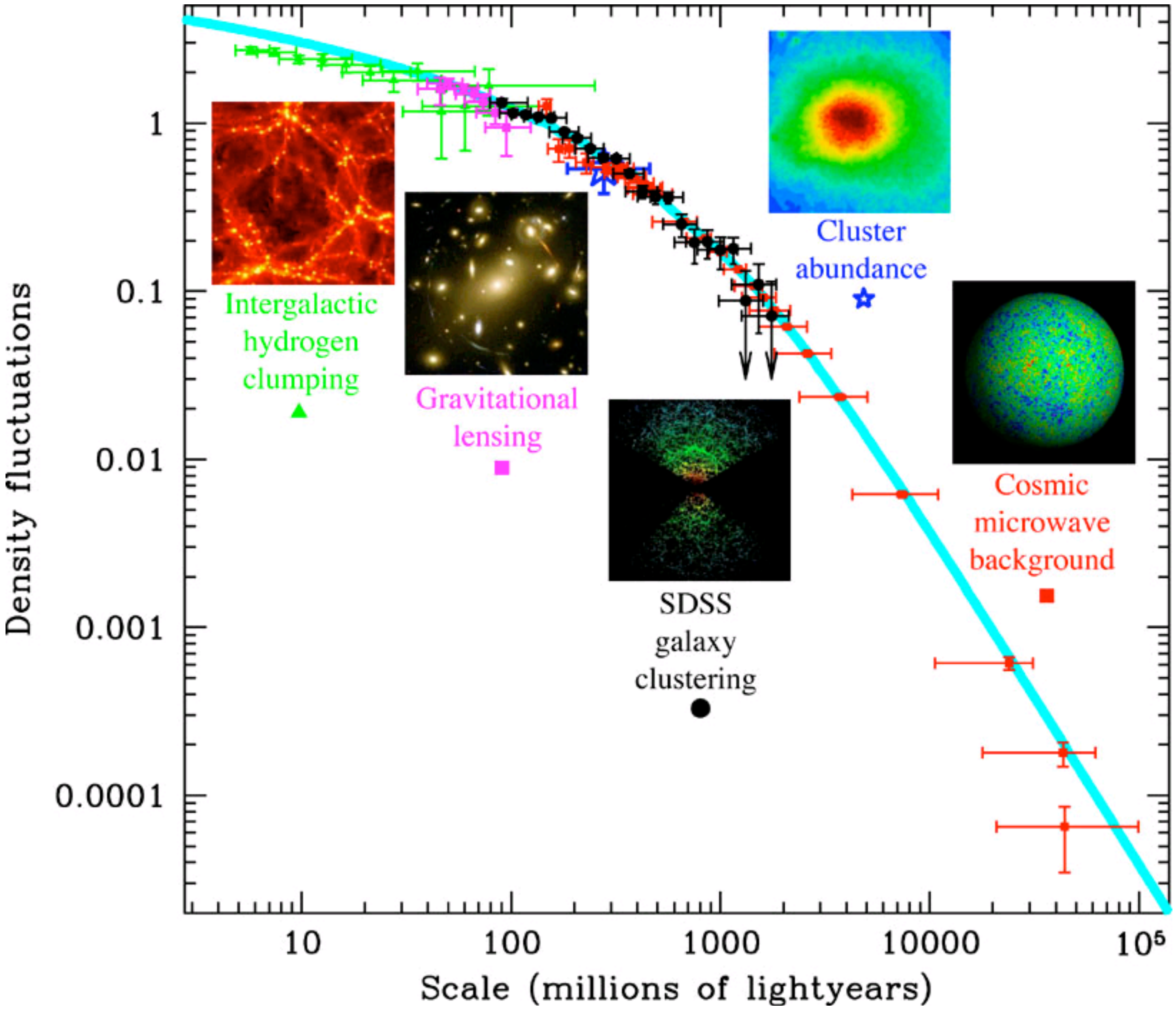


FIG. 1: Power spectrum of matter fluctuations in a theory without dark matter as compared to observations of the galaxy power spectrum. The observed spectrum [14] does not have the pronounced wiggles predicted by a baryon-only model, but it also has significantly higher power than does the model. In fact Δ^2, which is a dimensionless measure of the clumping, never rises above one in a baryon-only model, so we would not expect to see any large structures (clusters, galaxies, people, etc.) in the universe in such a model.

Dodelson & Liguori [astro-ph/0608602]

Dark matter undoubtedly rules OK on cosmological scales … fit to CMB and large-scale structure requires $\Omega_m >> \Omega_B$



Courtesy: Max Tegmark

All these observations (and others) indicate that the bulk of the matter in the universe is *dark* (dissipationless, collisionless, classical, mainly cold, fluid)

There is a generic expectation that it consists of a new stable particle from *physics beyond the Standard Model*

… it *cannot* have electric or colour charge (otherwise would bind to ordinary nuclei creating anomalously heavy isotopes - ruled out experimentally at a high level)

… it cannot couple too strongly to the Z^0 (or would have been seen already in acclerator searches)

Determining the identity of the ‘**dark matter**’ is an outstanding experimental challenge …

What should the world be made of ?

Mass scale	Particle	Symmetry/ Quantum number	Stability	Production	Abundance
Λ_{QCD}	Nucleon	baryon number	$\tau > 10^{31}$ yr dim-5 SUSY-GUTs	freeze-out from thermal equilibrium ×	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$!
$1/\sqrt{G_F}$	Neutralino? Technibaryon?	R-parity? technicolour	violated? gauge symmetry	freeze-out from thermal equilibrium Asymmetric (just like baryons)	$\Omega_{LSP} \sim 1$ $\Omega_{TB} \sim 1$
$\Lambda_{\text{hidden sector}}$ $=(M_{Pl}/\sqrt{G_F})^{1/2}$	Crypton?	discrete (*very* model-dependent)	$\tau \sim 10^{10\text{-}18}$ yr for $m_x \sim \Lambda_{hs}$.	not in thermal equilibrium … But inflation →	$\Omega_X \sim 1$?
M_{string}/M_{Pl}	Kaluza-Klein states? Axions	? Peccei-Quinn	? OK	? field oscillations	? Ω_a » 1!

No definite indication from theory … must decide by experiment!

Being strongly interacting, nucleons and anti-nucleons should have annihilated each other nearly completely in the early universe …

Annihilation rate: $\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} \mathrm{e}^{-m_N/T} \frac{1}{m_\pi^2}$

cf. expansion rate: $H \sim \frac{\sqrt{g} T^2}{M_\mathrm{P}}$

i.e. 'freeze-out' at T ~ $m_N/45$, with: $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$

However the observed ratio is 10^9 times *bigger* for baryons, and there are *no* antibaryons present, so there must have been an **initial asymmetry** of:

$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$

i.e. for every 10^9 baryon-antibaryon pairs there was 1 *extra* baryon

Sakharov conditions for baryogenesis:

1. Baryon number violation

2. *C* and *CP* violation

3. Departure for thermal equilibrium

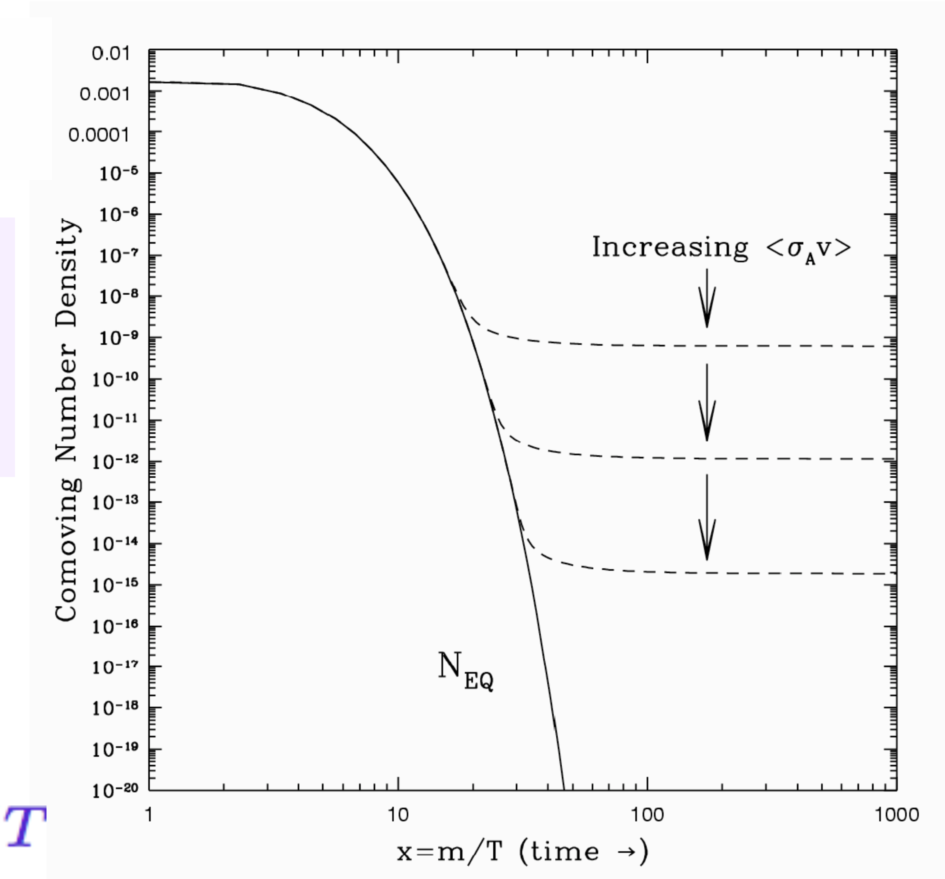
In principle baryon number violation can happen even in the Standard Model through non-perturbative processes if the electroweak symmetry breaking phase transition is 1st order and therefore out-of-equilibrium … but CP-violation is *too weak*

Thus the generation of the observed matter-antimatter asymmetry *requires* new BSM physics (could be related to neutrino masses … likely to be due to violation of lepton number → **leptogenesis**)

A new electroweak-scale particle which shares in this asymmetry (e.g. technibaryon) would *naturally* have a relic abundance ~ dark matter

Thermal Relics

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$



Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'Freeze-out' may occur when the annihilating particles are:

1) Relativistic: $n \sim n_\gamma$

2) Non-relativistic: $n \sim n_\gamma \mathrm{e}^{-m/T}$

$$\text{Example 1}: \quad \sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\mathrm{eV}$$

$$\text{Example 2}: \quad \Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle \sigma v \rangle_{T=T_\mathrm{f}}}$$

Is it possible that **dark matter** is illusory?

Modified Newtonian Dynamics (MOND) accounts better for galactic rotation curves than does dark matter - moreover it *predicts* the observed correlation between luminosity and rotation velocity:

$L \propto v_{rot}^4$ ("Tully-Fisher relation")

… however MOND *fails* on the scale of galaxy clusters

Also MOND is *not* a physical theory - such theories have indeed been constructed (viz. TeVeS by Bekenstein) and yield interesting insights into the nature of gravity … however they have not provided as satisfactory an understanding of anistortropies in the CMB and structure formation in the universe as the dark matter cosmology

Summary

Experimental situation reminiscent of search for temperature fluctuations in the CMB in the '80s … clear theoretical predictions but only upper limits on detection (on verge of causing crisis for theory)

Finally breakthrough that transformed cosmology

The theoretical expectations for dark matter are not as clear (being based on BSM physics) but there are many experimental approaches and interesting complementarities between them

We wish dark matter hunters good luck
… they will need it!