Cosmology beyond the Standard Model

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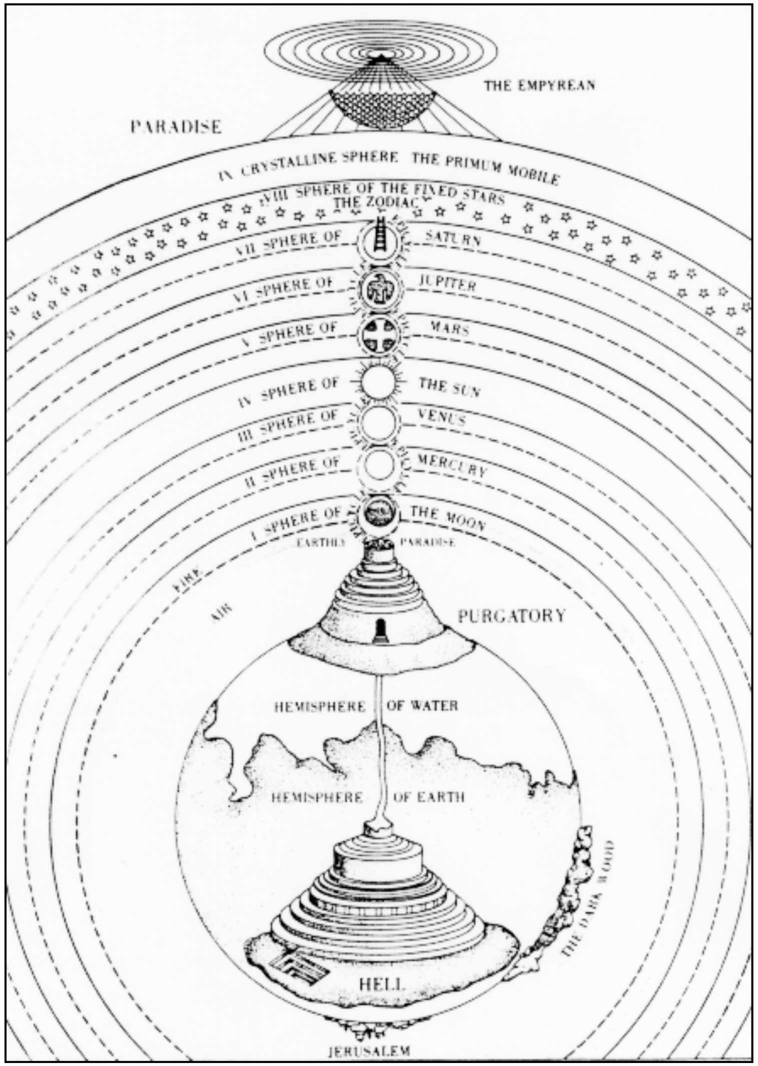
In the Aristotlean 'standard model' of cosmology (circa 350 BC)

the universe was *static* and *finite* and *centred on the Earth*

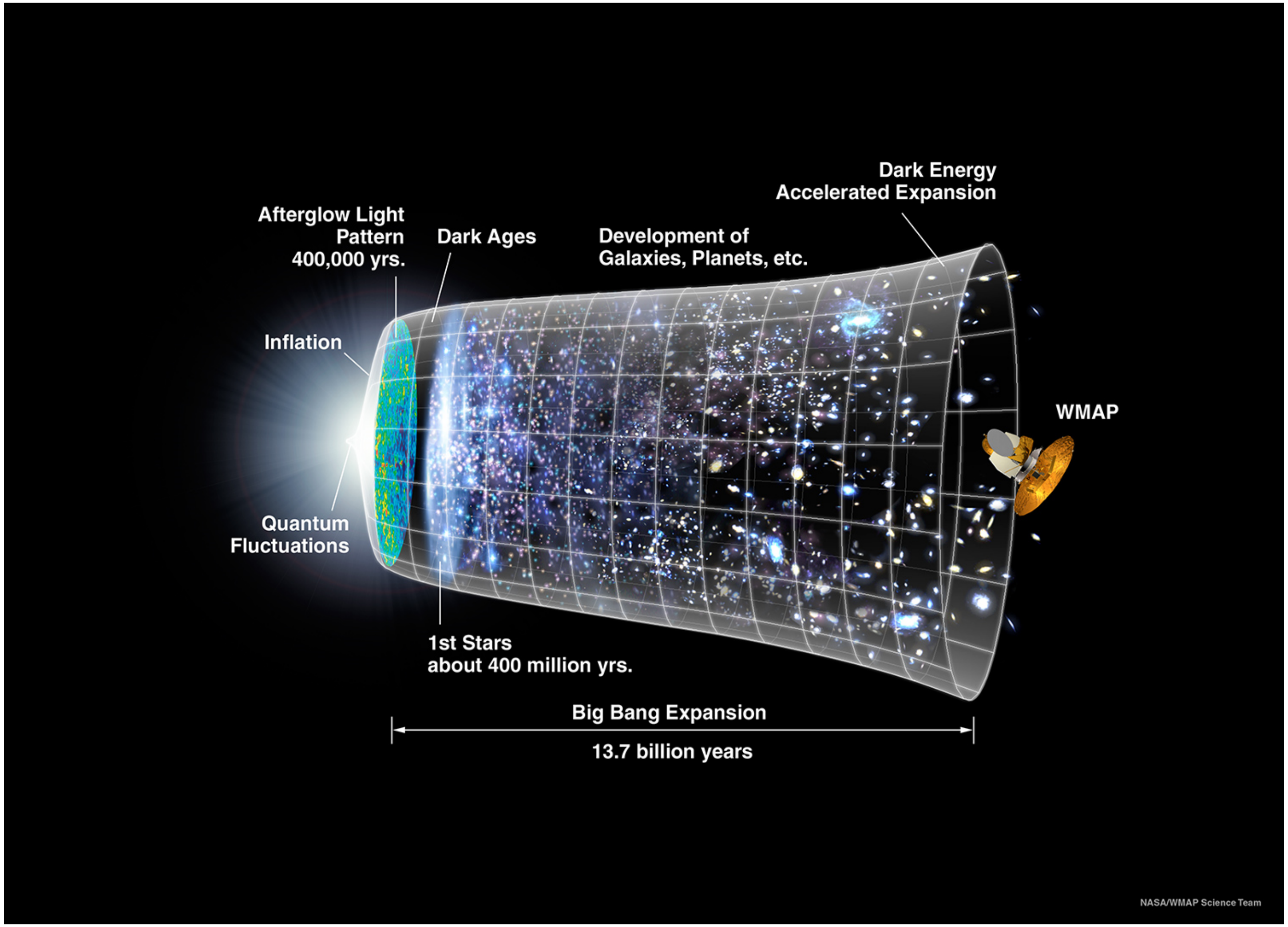


The Divine Comedy, Dante Alligheri (1321)

This was a 'simple' model and fitted all the observational data

… but the underlying principle was unphysical

Today we have a new 'standard model' of the universe …
dominated by dark energy and undergoing accelerated expansion



Courtesy: NASA/WMAP Science Team (2007)

It too is 'simple' and fits all the observational data
but lacks an underlying physical basis

The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model** provides an exact description of all *microphysics* (up to some high energy cut-off scale M)

Cosmological constant *Higgs mass divergence*

$$\mathcal{L}_{\text{eff}} = M^4 + M^2\Phi^2 \qquad \textbf{super-renormalisable}$$

$$+ (D\Phi)^2 + \bar{\Psi}\, \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2 \qquad \textbf{renormalisable}$$

$$+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots \qquad \textbf{non-renormalisable}$$

The effects of *new* physics beyond the SM (neutrino mass, nucleon decay, FCNC ...)
➔ **non-renormalisable operators** suppressed by M^n … which 'decouple' as $M \to M_P$

But as M is raised, the effects of the **super-renormalisable operators** are *exacerbated*

Solution for 2nd term → 'softly broken' supersymmetry at M ~ 1 TeV (10^2 new parameters)

This suggests possible mechanisms for **baryogenesis**, candidates for **dark matter**, …
(as do other proposed extensions of the SM, e.g. new dimensions @ TeV scale)

The 1st term **couples to gravity** so the *natural* expectation is $\rho_\Lambda \sim (1\ \text{TeV})^4$
i.e. the universe should have been inflating since (or recollapsed at) $t \sim 10^{-12}$ s!

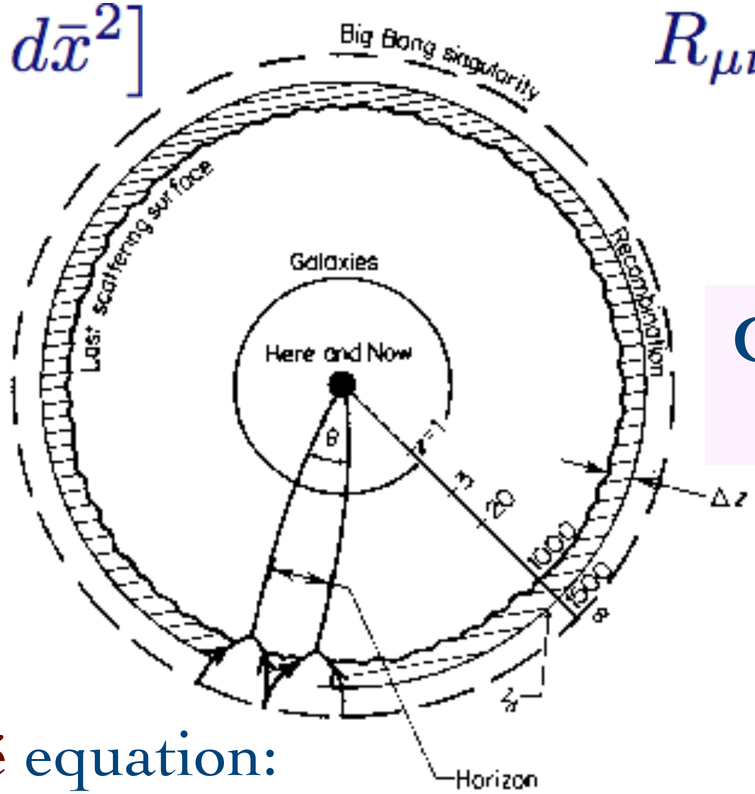
There *must* be some reason why this did not happen (Λ ➔ 0?)

The **standard cosmological model** is based on several key assumptions:
maximally symmetric **space-time + general relativity +** ***ideal fluids***

$$ds^2 = a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$

$$a^2(\eta)d\eta^2 \equiv dt^2$$

Space-time metric
Robertson-Walker



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

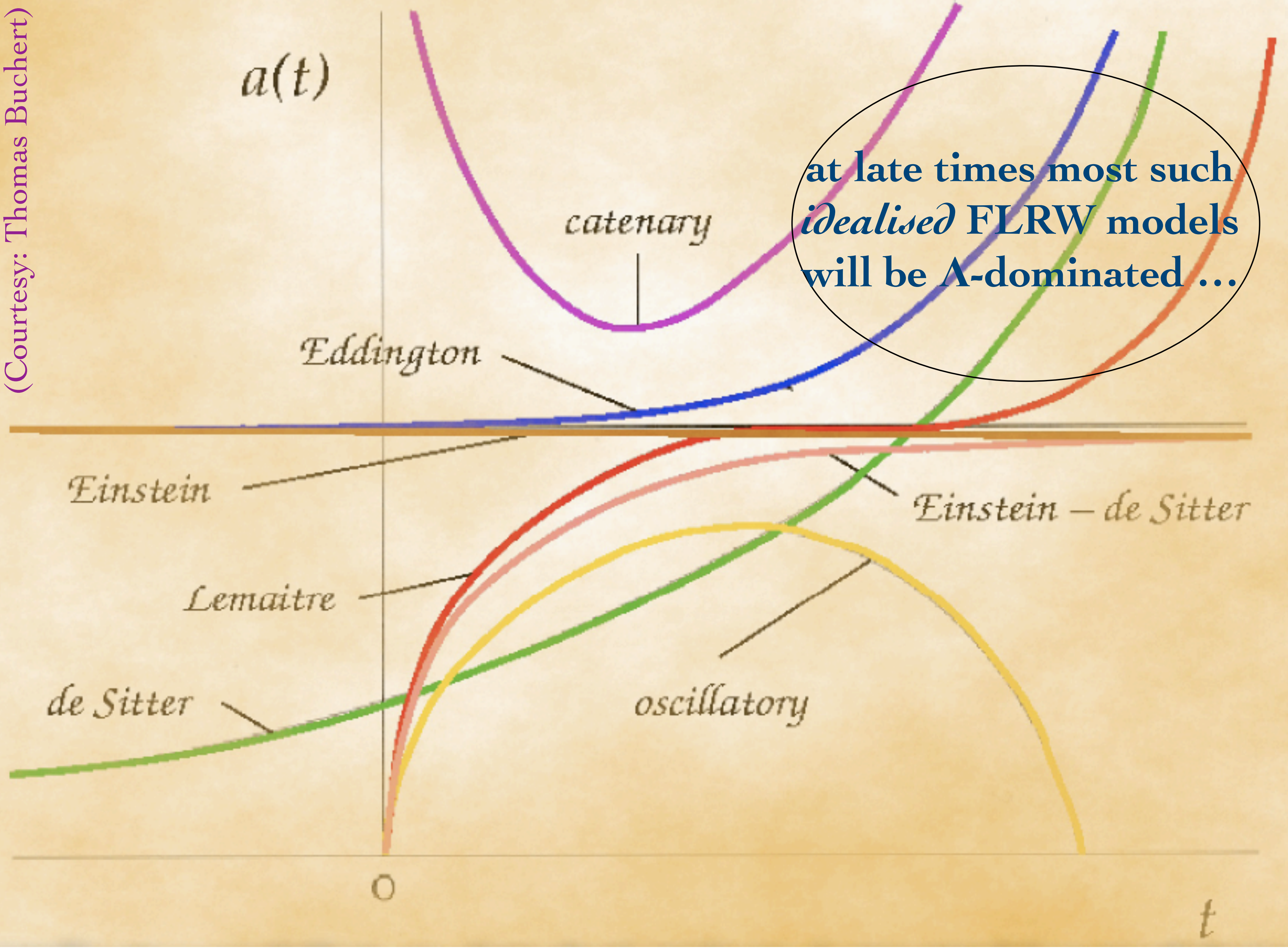
Geometrodynamics
Einstein

Friedmann-Lemaitré equation:

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\mathrm{N}}\rho_{\mathrm{m}}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

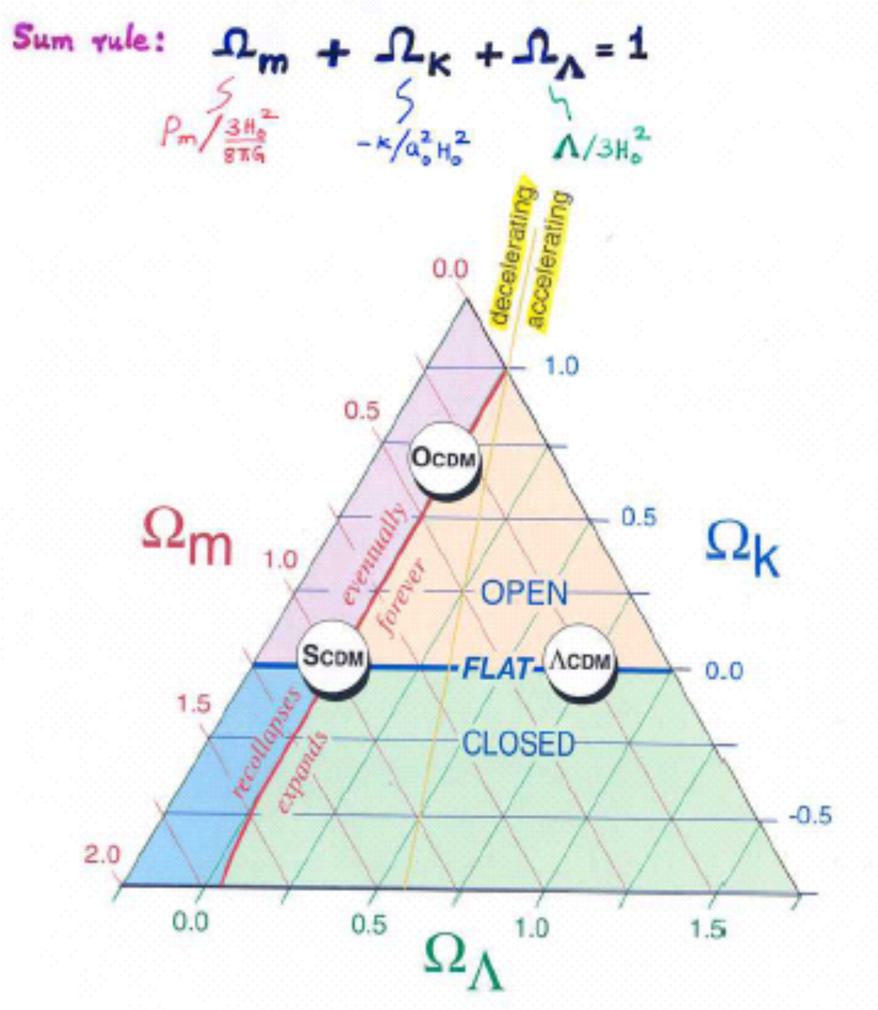
$$\equiv {H_0}^2\left[\Omega_{\mathrm{m}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

… and *naturally* exhibits 'dark energy' at late times ($z \rightarrow 0$)!



(Courtesy: Thomas Buchert)

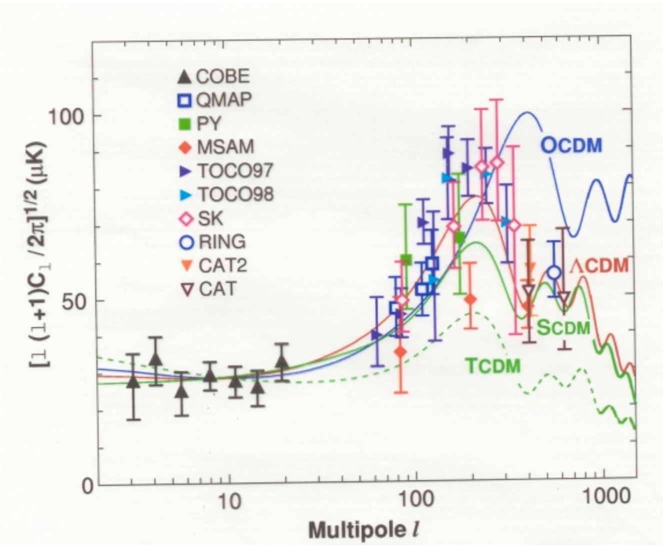
Since $H_0 \sim 10^{-42}$ GeV^{-1} is the *only* scale in the FRLW model entering all geometrical measures, it is *natural* for data interpreted in this model to yield $\Lambda \sim H_0^2$



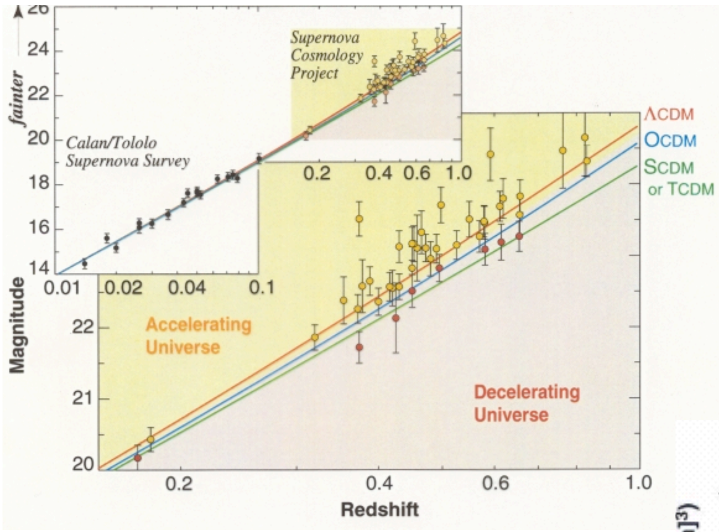
Bahcall, Ostriker, Perlmutter & Steinhardt (1999)

… so not surprising if we infer Ω_Λ $(= \Lambda/3H_0^2)$ to be of $O(1)$ from the **cosmic sum rule**, given the uncertainties in measuring Ω_m and Ω_k *and* the possibility of any other components (Ω_x) which are *unaccounted for*

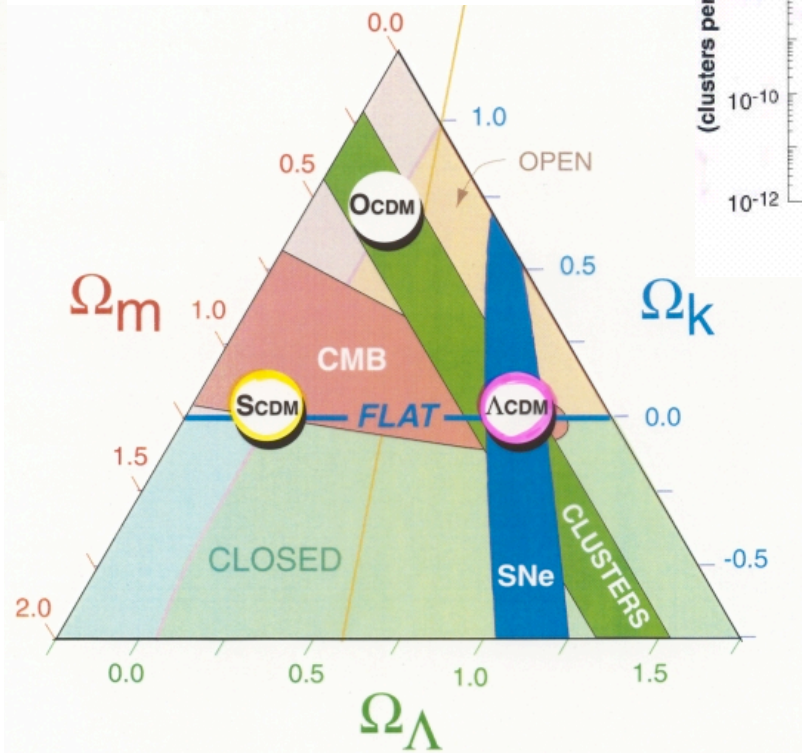
Indeed complementary observations suggest that $\Omega_\Lambda \sim 0.7$, $\Omega_m \sim 0.3$

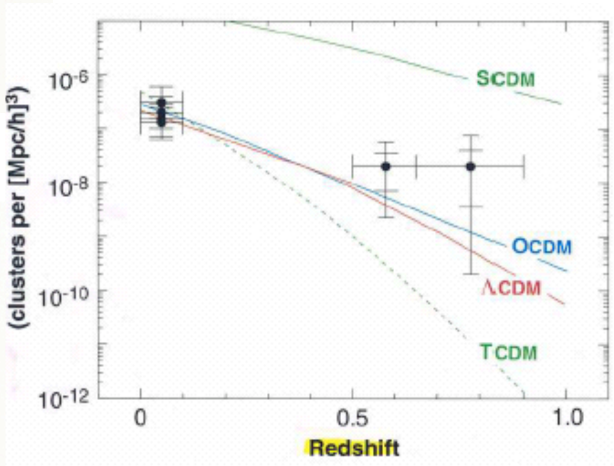


$\Omega_m + \Omega_\Lambda \approx 1.0 \pm 0.03$



$0.8\Omega_m - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$



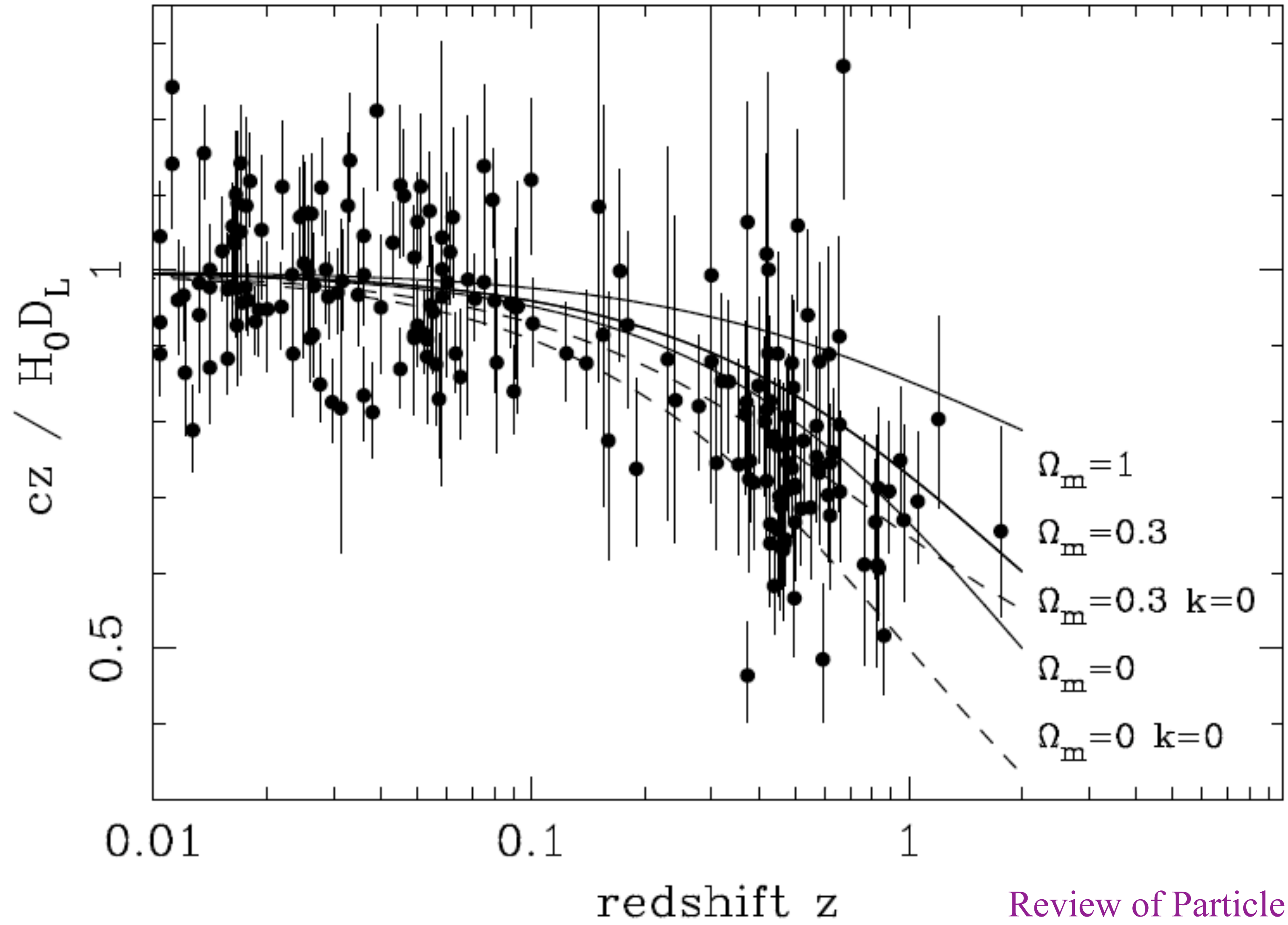


$\Omega_m \sim 0.3$

Bahcall *et al* (1999)

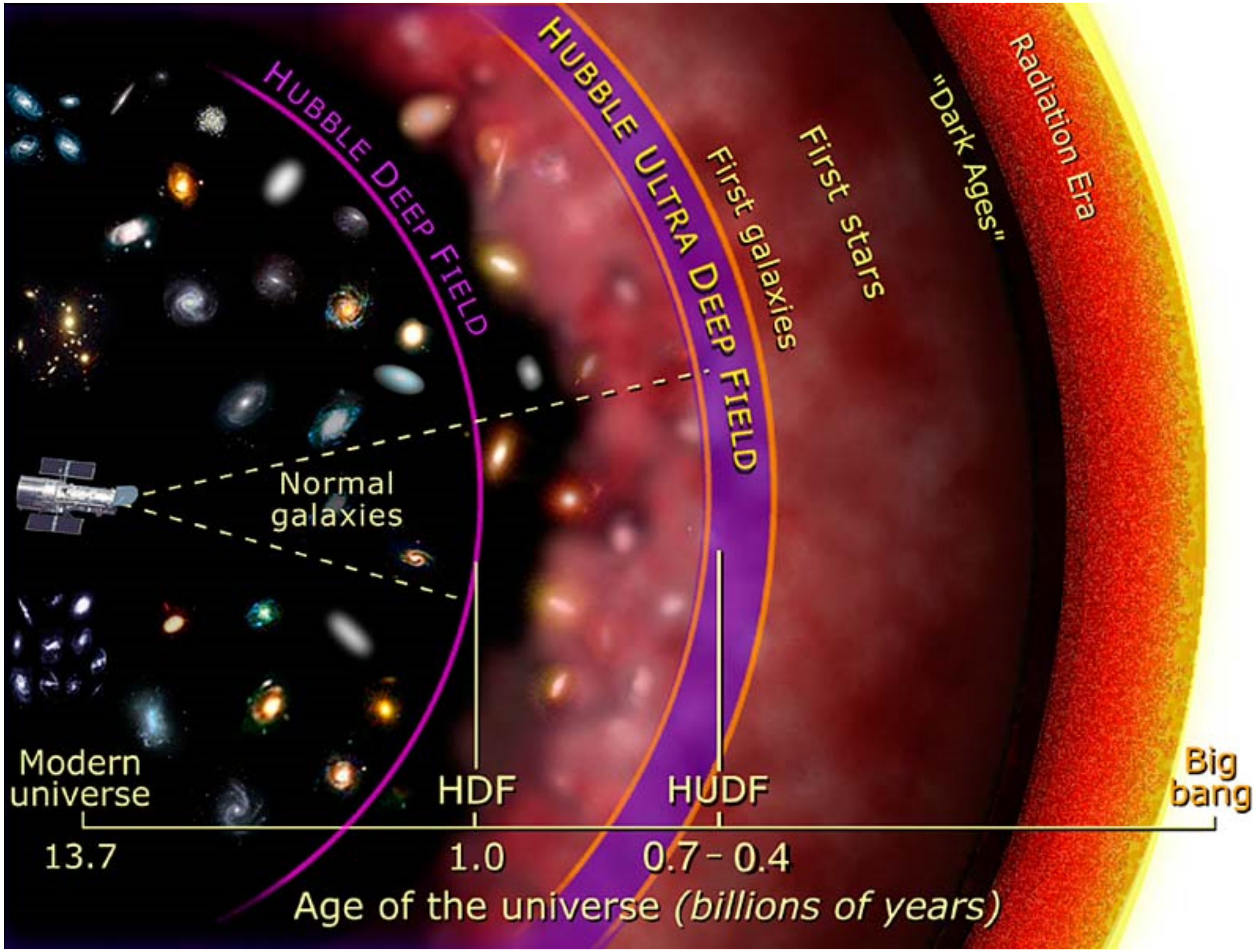
Distant SNIa appear fainter than expected for "standard candles" in a homogeneous decelerating universe ➔ *accelerated* expansion below $z \sim 0.5$

… however there is presently no reliable data in the range $z \sim 0.1$-0.4, so the *assumption* of homogeneity has not been tested rigorously



Review of Particle Physics (2009)

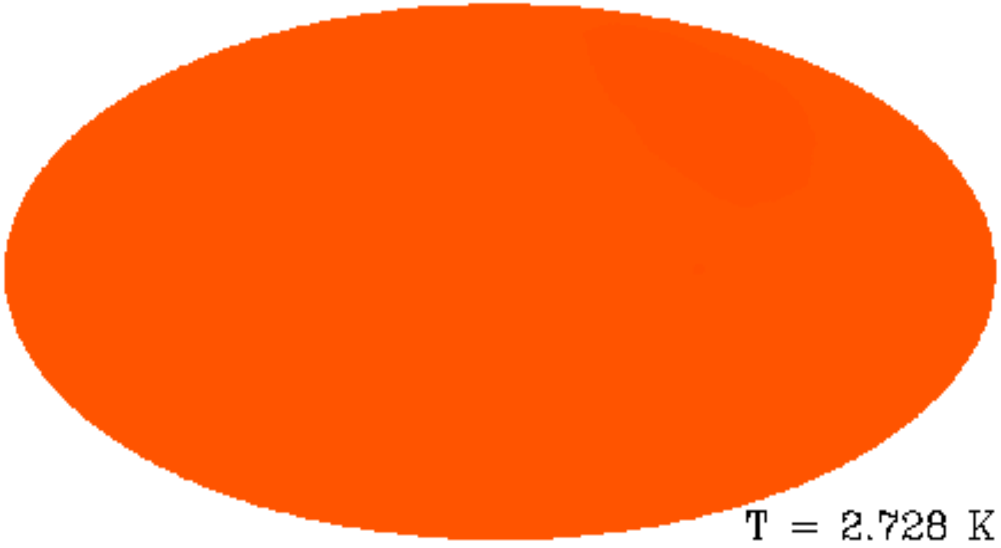
When the universe was younger, it was denser therefore hotter …

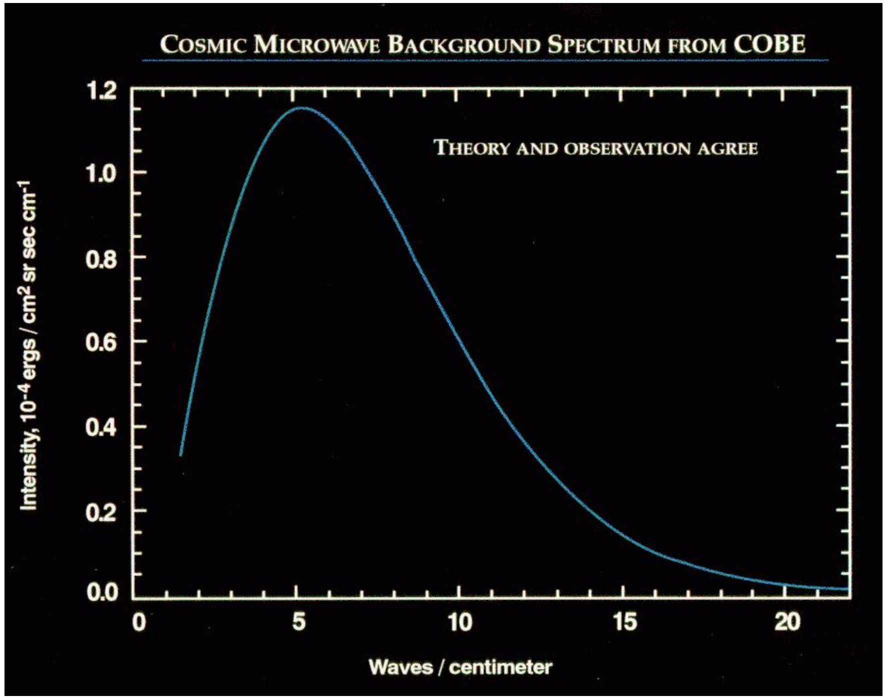


Courtesey: NASA/WMAP Science Team (2007)

So if we can look back far enough in time, we should see all matter dissolved in a hot, dense 'fireball' covering the sky

... and this is just what Penzias and Wilson discovered in 1965 when they looked at the sky at **microwave** wavelengths

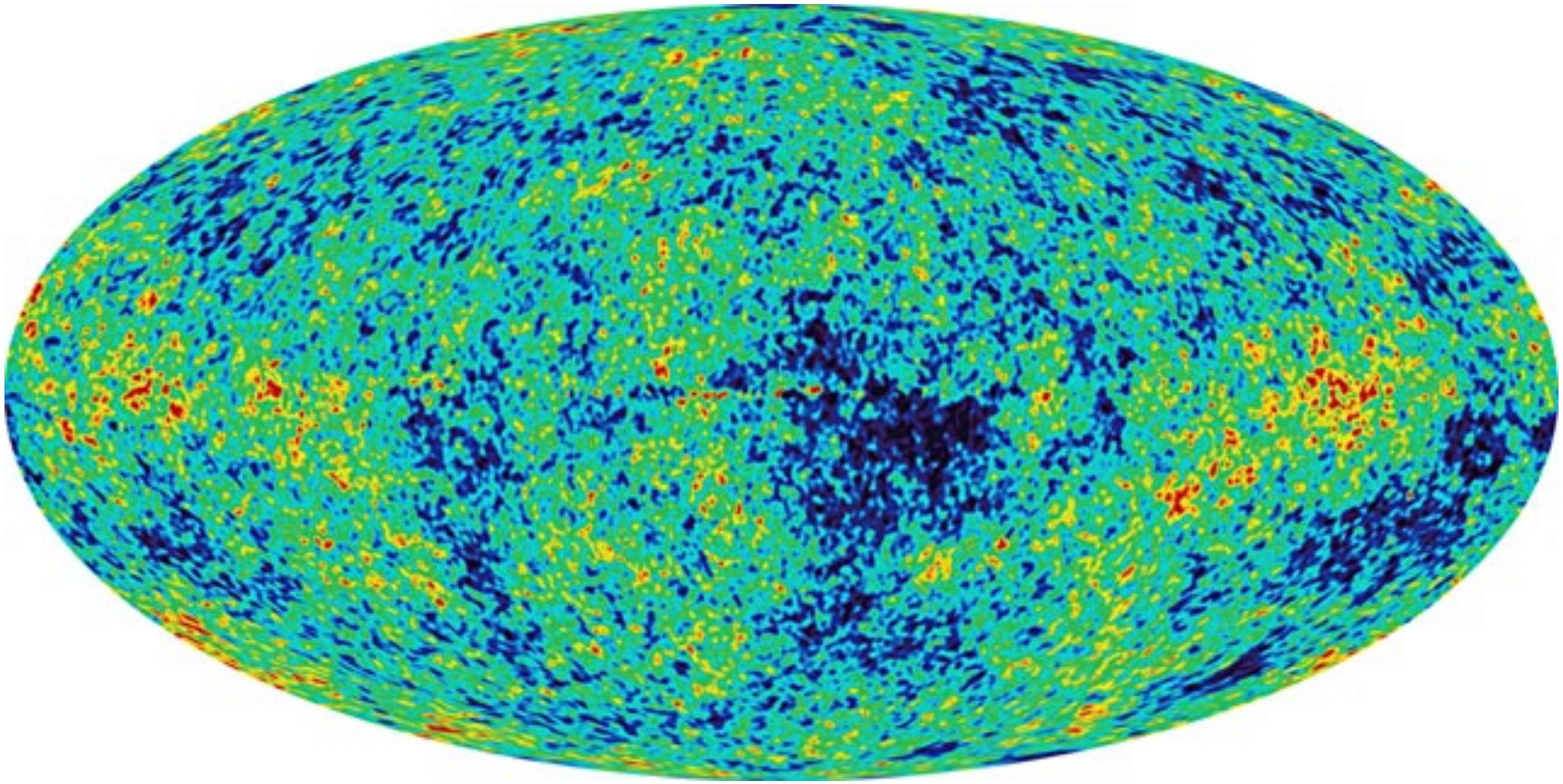




This 'bright sky' is the redshifted primordial light released from the hot plasma of the early universe 400,000 years after the Big Bang ...

The *Cosmic Background Explorer* (1992) showed that the spectrum is *exactly* that of a blackbody (ruling out the 'Steady State' model)

Wilkinson Microwave Anisotropy Probe (2003-)



Courtesey: NASA/WMAP Science Team (2007)

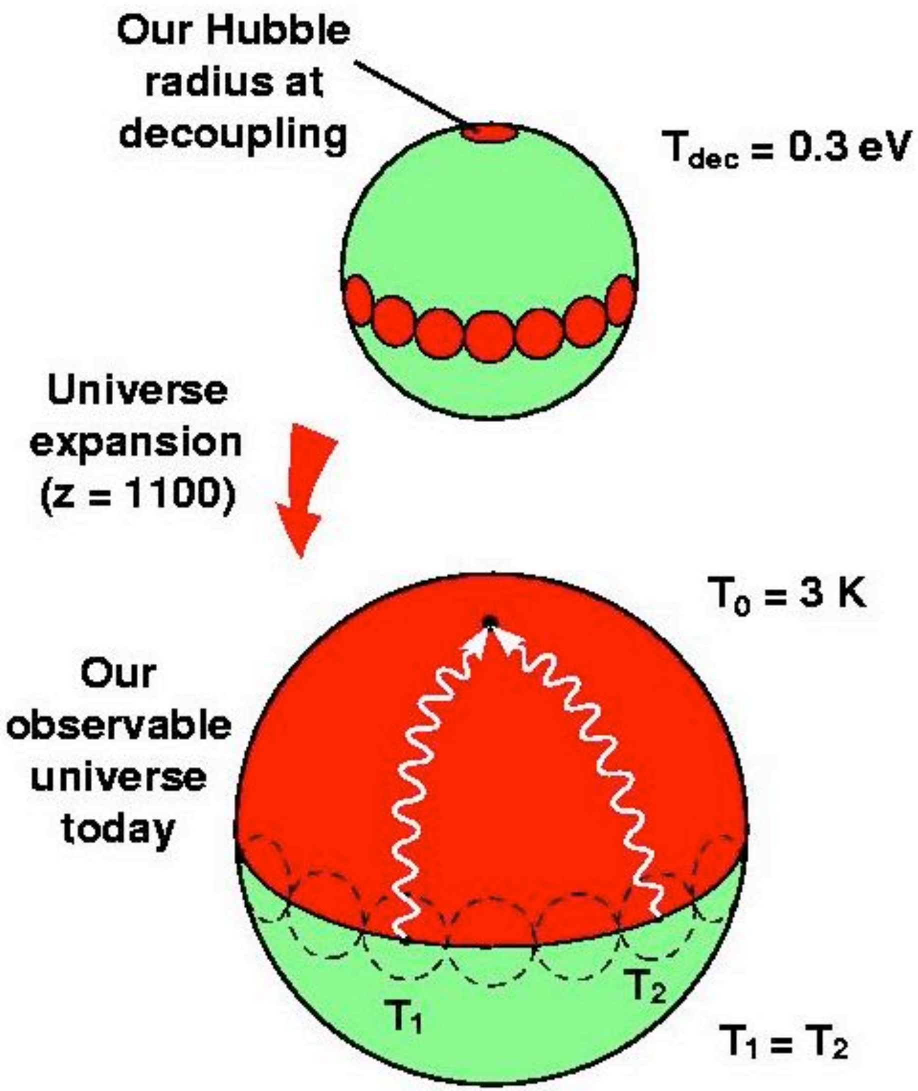
But on close inspection, the radiation is not *quite* uniform ...

these patches are hotter/colder than the average by just 1 part in ~10^3-10^5

→ believed to be due to quantum fluctuations generated during 'inflation'

... these density fluctuations excite sound waves in the plasma filling the early universe and provide the seeds for the formation of galaxies

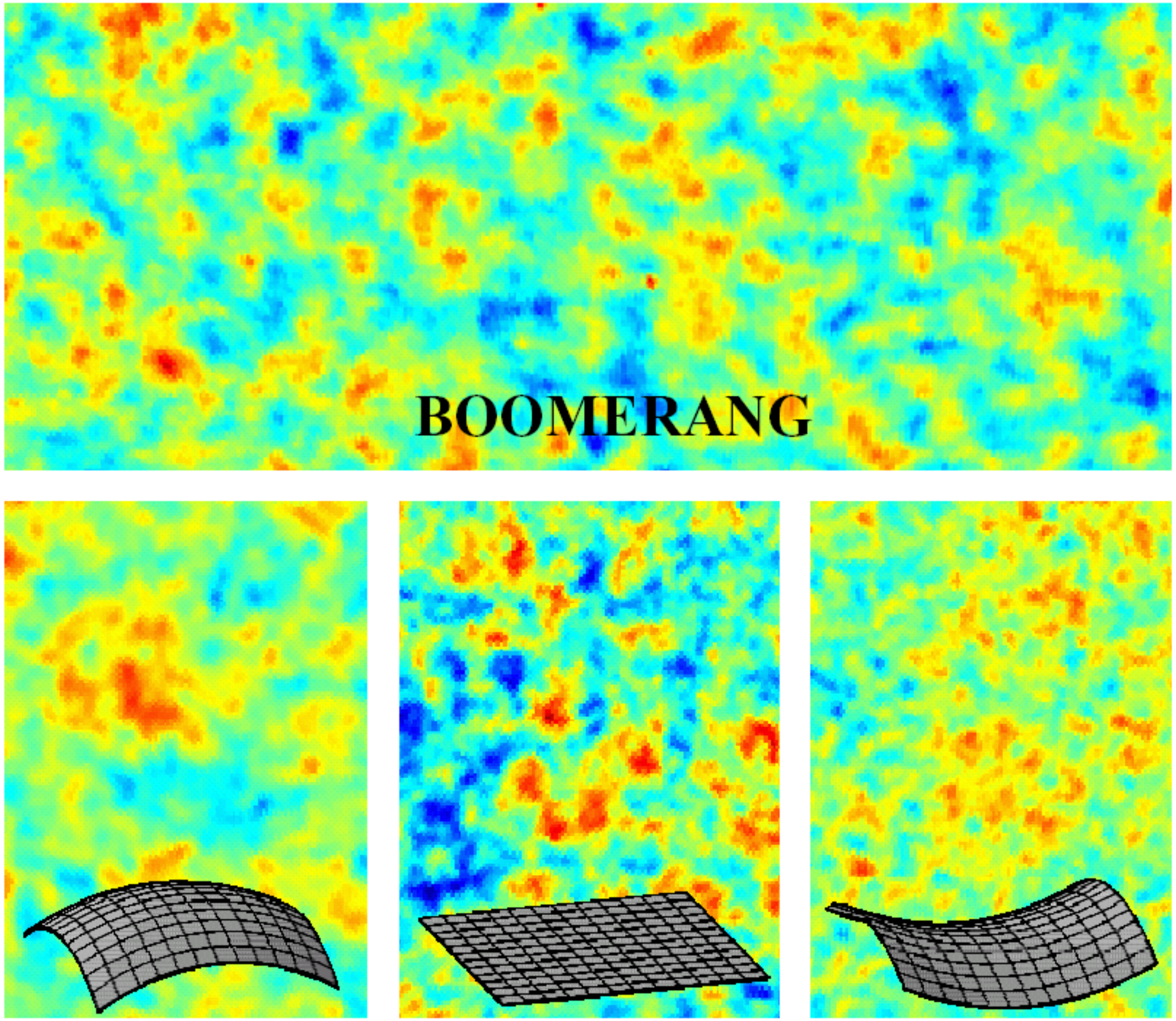
The characteristic scale of these hot/cold spots is thus determined by how far sound waves have propagated since the Big Bang



Courtesey: Wayne Hu

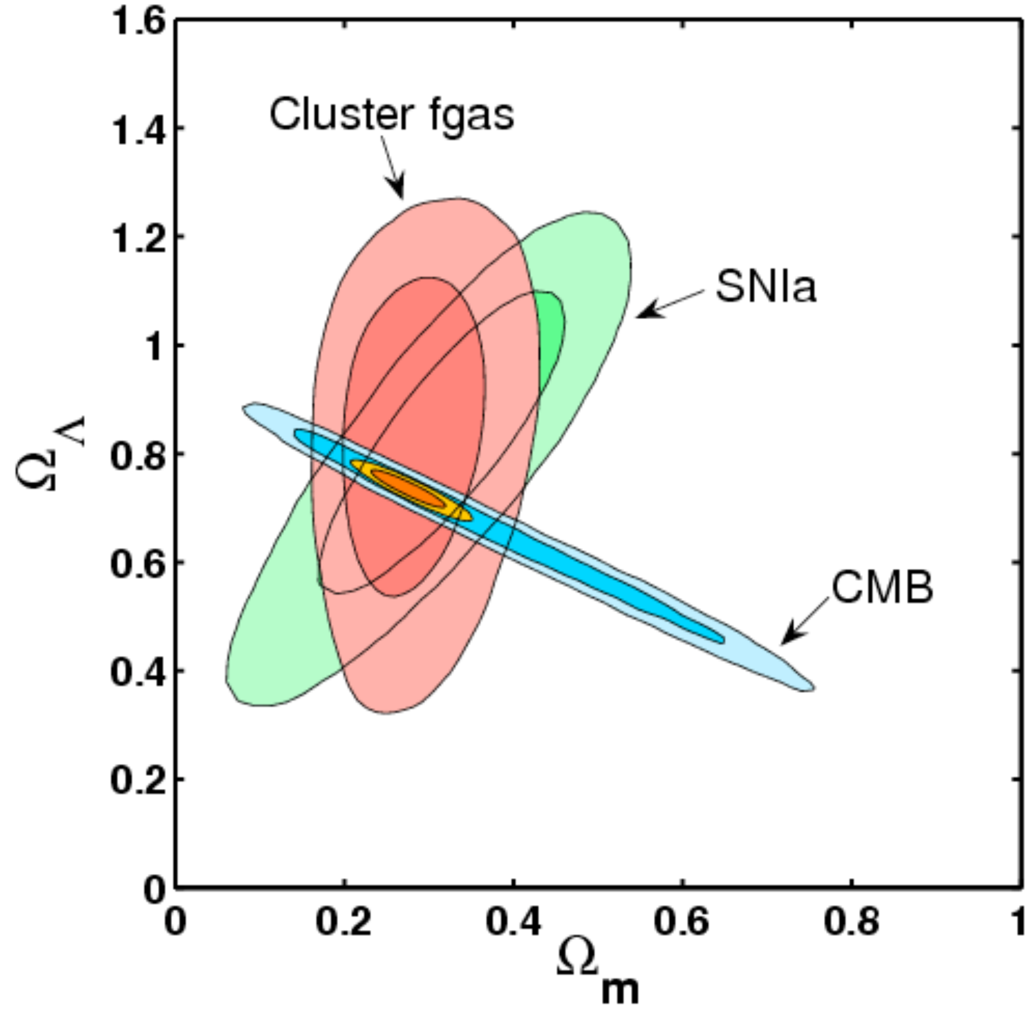
By measuring the size of hot/cold patches on the CMB sky we deduce that

the geometry of space is Euclidean – the universe is flat!



$$\Omega_m + \Omega_\Lambda = 1.0 \pm 0.03$$

CMB data indicate $\Omega_k \approx 0$ so the FRW model is simplified further, leaving only two free parameters (Ω_Λ and Ω_m) to be fitted to data



Allen *et al* (2008)

But if we *underestimate* Ω_m, or if there is a Ω_x ("back reaction") which the model does *not* account for, then we will *necessarily* infer $\Omega_\Lambda \neq 0$

Interpreting Λ as vacuum energy raises the coincidence problem: why is $\rho_\Lambda \approx \rho_m$ *today*?

An evolving ultralight scalar field (‘**quintessence**’) can display ‘tracking’ behaviour: this requires $V(\Phi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\varphi^2} \sim H_0 \sim 10^{-42}$ GeV to ensure slow-roll

… *i.e. just as much fine-tuning* as a bare cosmological constant

A similar comment applies to models (e.g. ‘**DGP brane-world**’) wherein gravity is modified on the scale of the present Hubble radius so as to mimic vacuum energy

… this scale is *unnatural in a fundamental theory* and is put in by hand

The only *natural* option is if $\Lambda \sim H^2$ *always*, but this is just a renormalisation of G_N !

(recall: $H^2 = 8\pi G_N\rho/3 + \Lambda/3$)

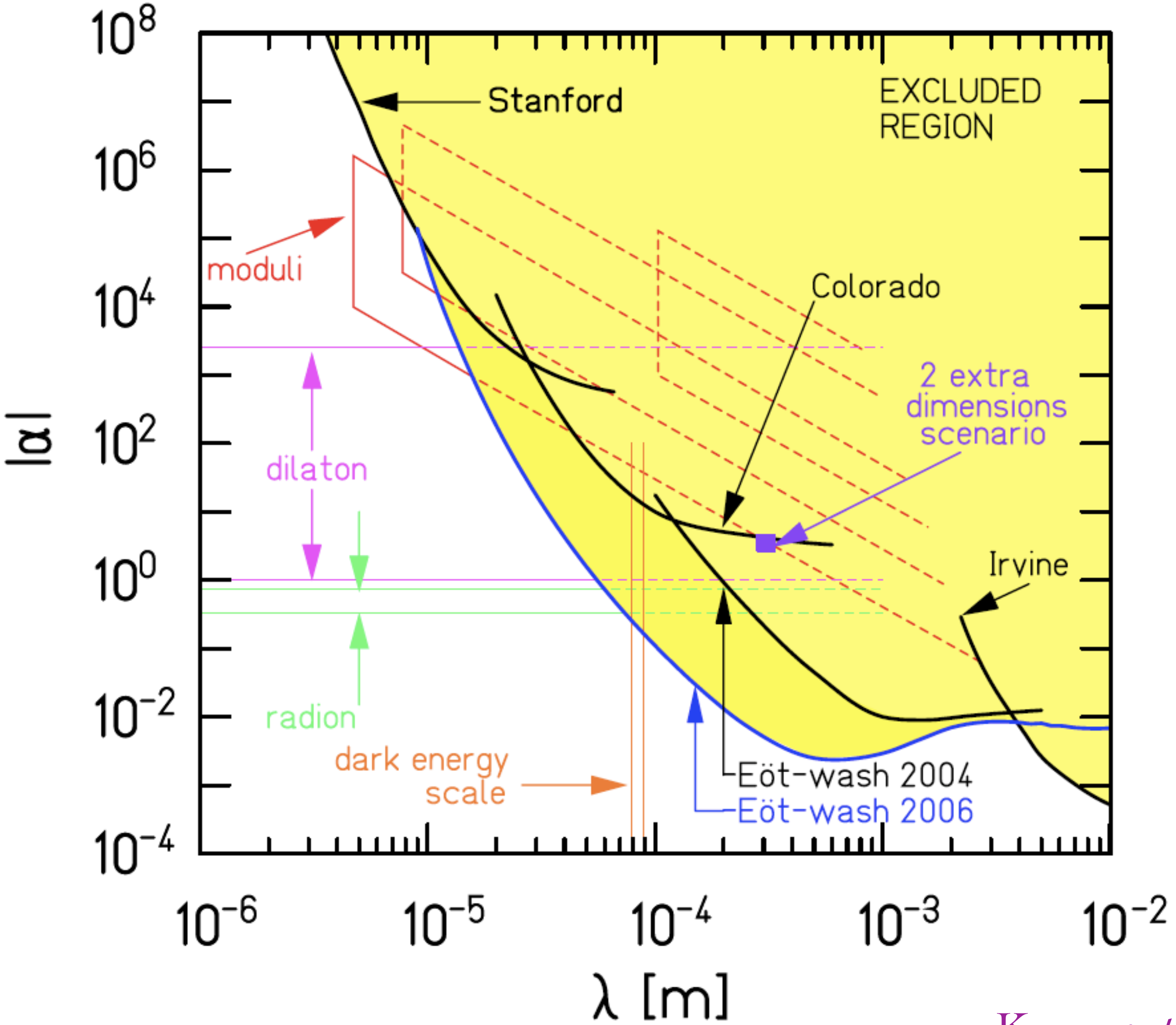
… *ruled out* by Big Bang nucleosynthesis (requires G_N to be within 5% of lab value)

There cannot be a *natural* explanation for the coincidence problem

Do we see $\Lambda \sim H_0^2$ because that is just the **observational sensitivity?**

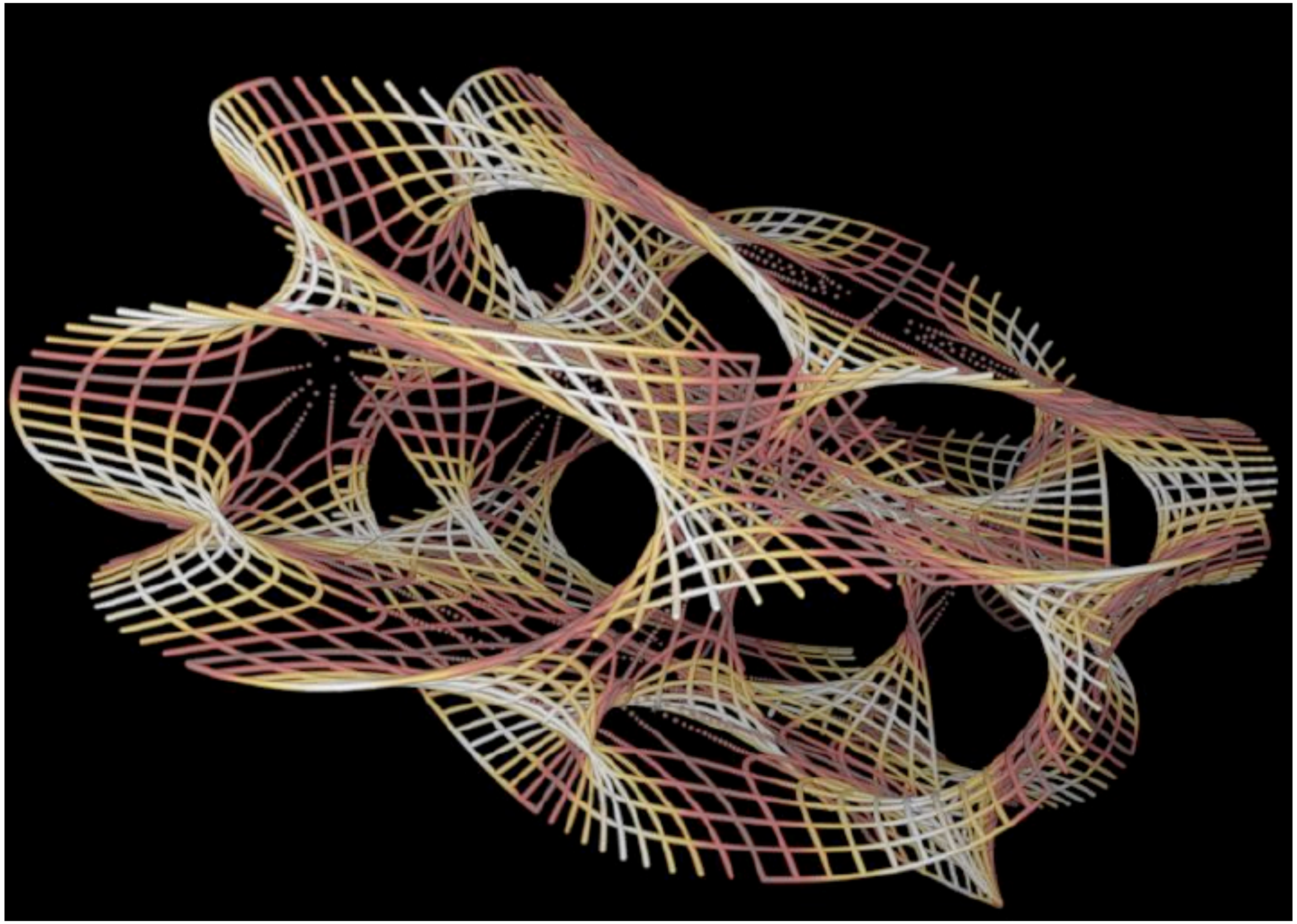
There is *no* evidence for a change in the inverse-square law at the **'dark energy' scale: $\rho_\Lambda^{-1/4} \sim (H_0 M_P)^{-1/2} \sim 0.1$ mm**

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$



Kapner *et al* (PRL 2007)

In string/M-theory, the sizes and shapes of the extra dimensions (‘moduli’) must be stabilised … e.g. by turning on background ‘fluxes’

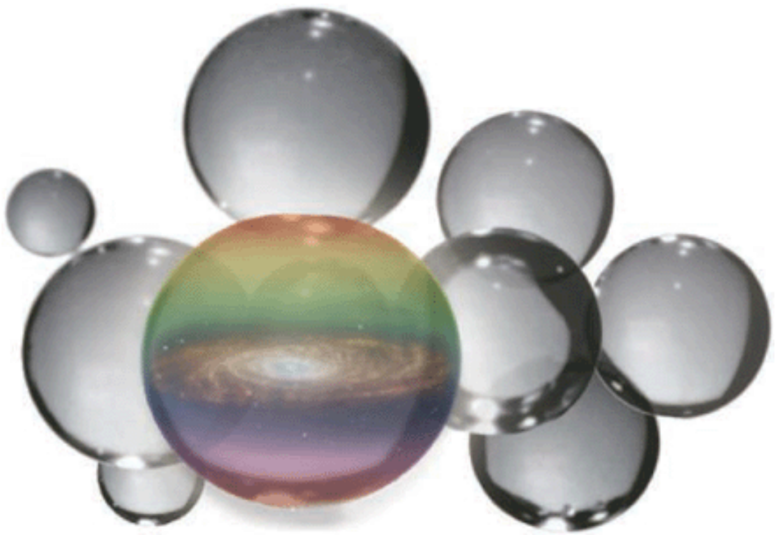


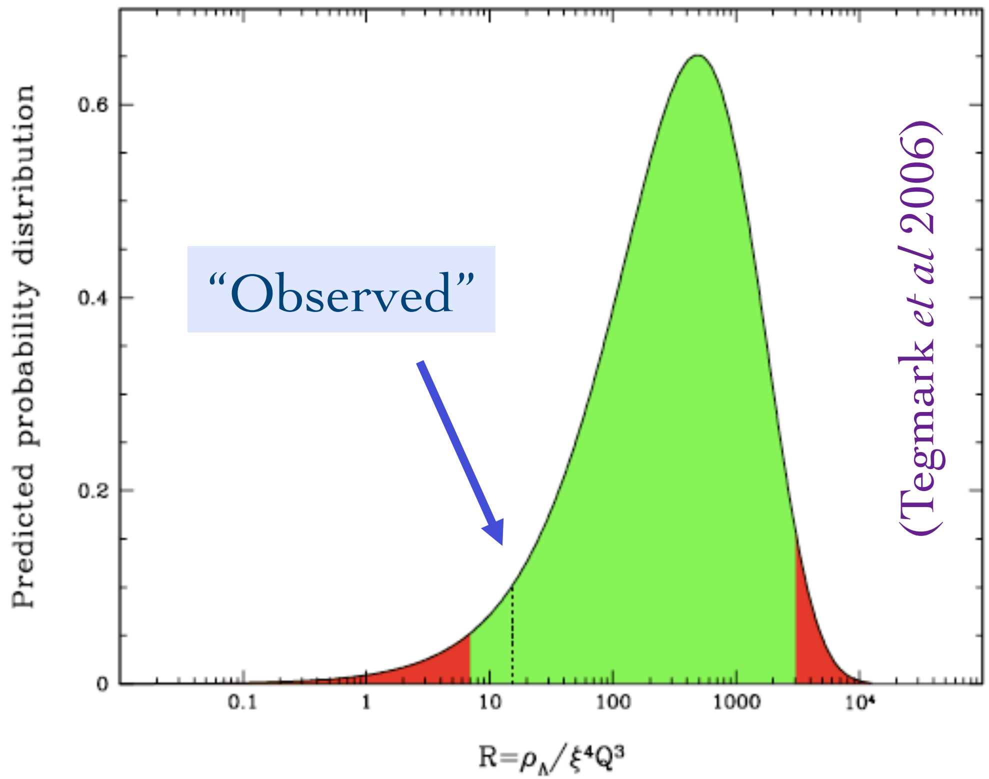
Given the variety of flux choices and the number of local minima in the flux potential, the total number of vacuua is *very* large - perhaps 10^{500}

The existence of the huge *landscape* of possible vacuua in string theory (with moduli stabilised through background fluxes) has remotivated **attempts at an 'anthropic' explanation for $\rho_{\Lambda} \sim \rho_m$**

Perhaps it is just "observer bias" … galaxies would not have formed if Λ had been much *higher* (Weinberg 1989, Efstathiou 1995, Martel, Shapiro, Weinberg 1998 …)

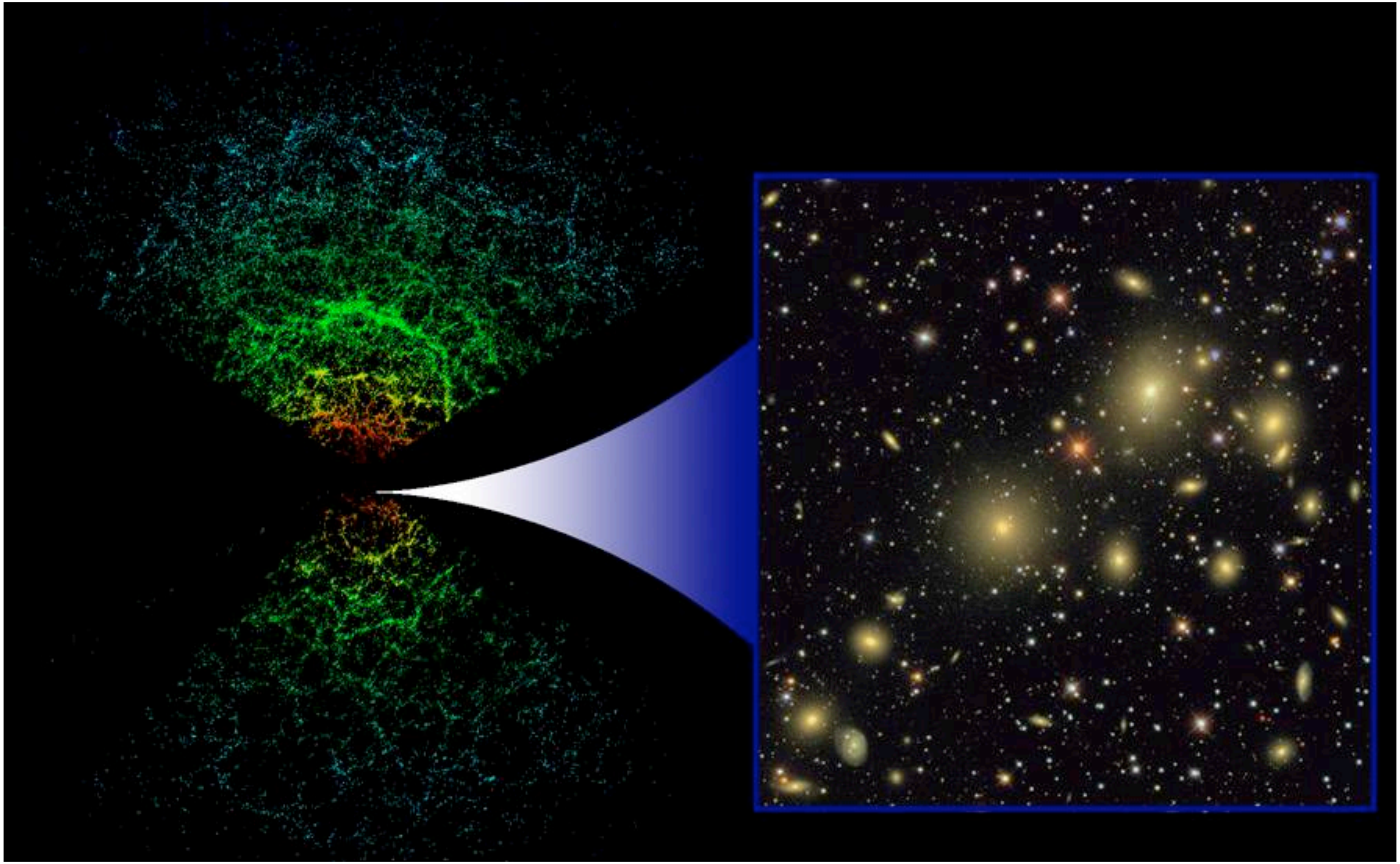
(Credit: K. Buckheit Krause/Science)



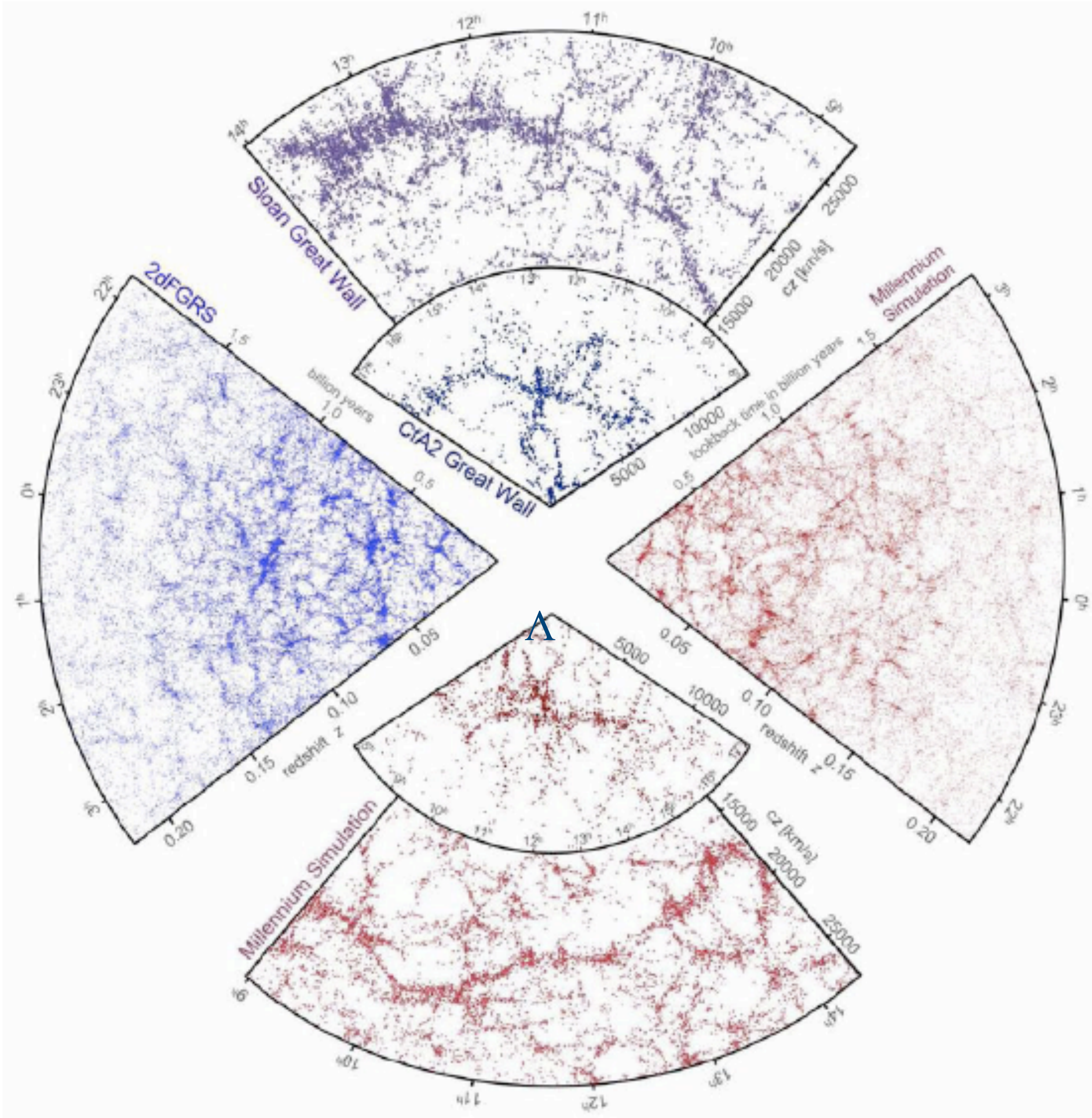


But the 'anthropic prediction' of $\mathbf{\Lambda}$ from considerations of galaxy formation is significantly *higher* than the observationally inferred value

Galaxies are *not* homogeneously distributed … they trace out a cosmic 'web' of filamentary structure (which is fractal on small scales)



Averaged on *large scales* the universe may well be homogeneous but how would it bias cosmological inferences if we are located in e.g. a void?



(Springel, Frenk, White 2007)

Numerical simulations of structure formation in the ΛCDM model claim to reproduce the observed large-scale clustering

Quantities averaged over a domain $\mathcal{D}$ obey modified Friedmann equations Buchert 1999:

$$
\begin{aligned}
3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} &= -4\pi G\langle\rho\rangle_{\mathcal{D}} + \mathcal{Q}_{\mathcal{D}} \ , \\
3\left(\frac{\dot{a}_{\mathcal{D}}}{a_{\mathcal{D}}}\right)^2 &= 8\pi G\langle\rho\rangle_{\mathcal{D}} - \frac{1}{2}\langle{}^{(3)}R\rangle_{\mathcal{D}} - \frac{1}{2}\mathcal{Q}_{\mathcal{D}} \ ,
\end{aligned}
$$

where $\mathcal{Q}_{\mathcal{D}}$ is the backreaction term,

$$
\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}\left(\langle\theta^2\rangle_{\mathcal{D}} - \langle\theta\rangle_{\mathcal{D}}^2\right) - \langle\sigma^{\mu\nu}\sigma_{\mu\nu}\rangle_{\mathcal{D}} \ .
$$

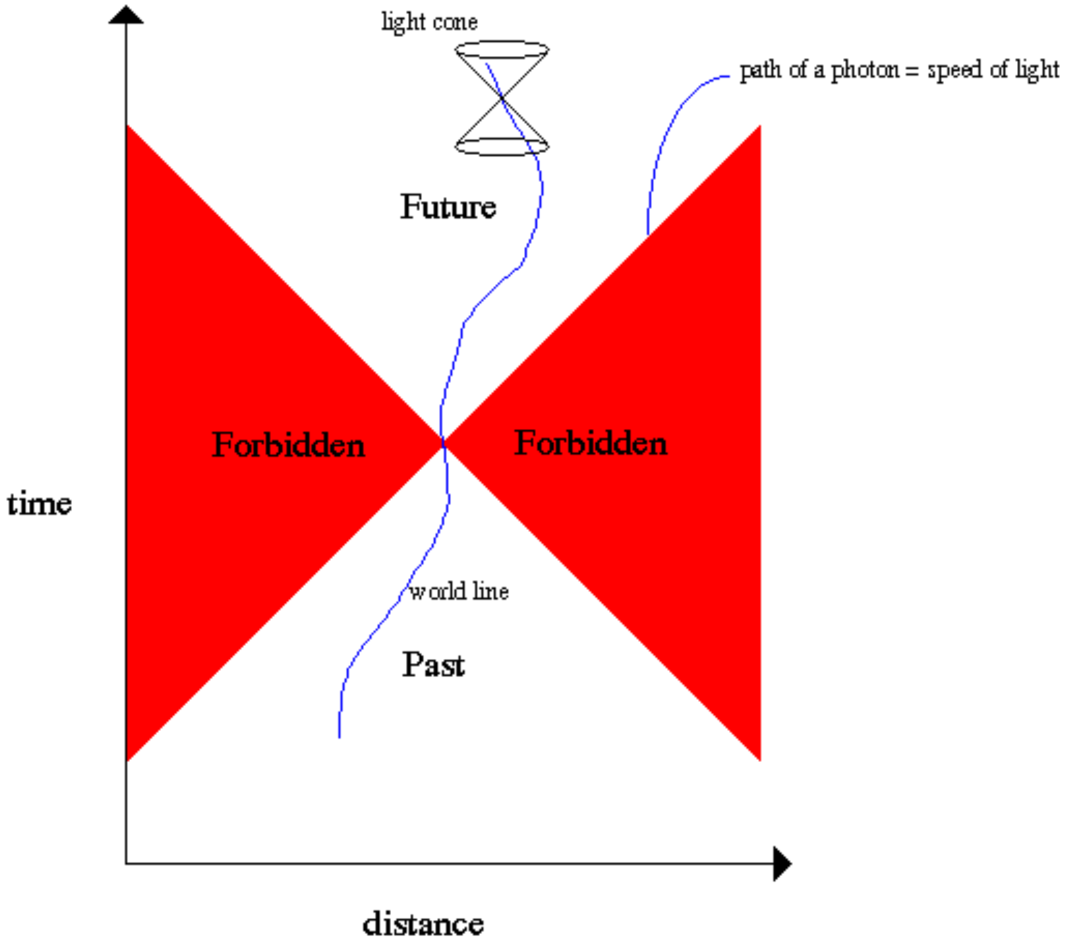
Variance of the expansion rate. Average shear.

If $\mathcal{Q}_{\mathcal{D}} > 4\pi G\langle\rho\rangle_{\mathcal{D}}$ then $a_{\mathcal{D}}$ accelerates.

Can mimic a cosmological constant if $\mathcal{Q}_{\mathcal{D}} = -\frac{1}{3}\langle{}^{(3)}R\rangle_{\mathcal{D}} = \Lambda_{\rm eff}$.

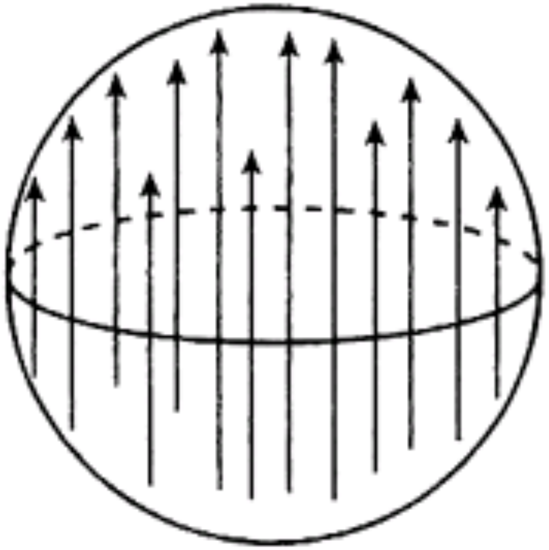
Whether the backreaction can be sufficiently large is an ***open question***

All we can ever learn about the universe is contained within our past light cone

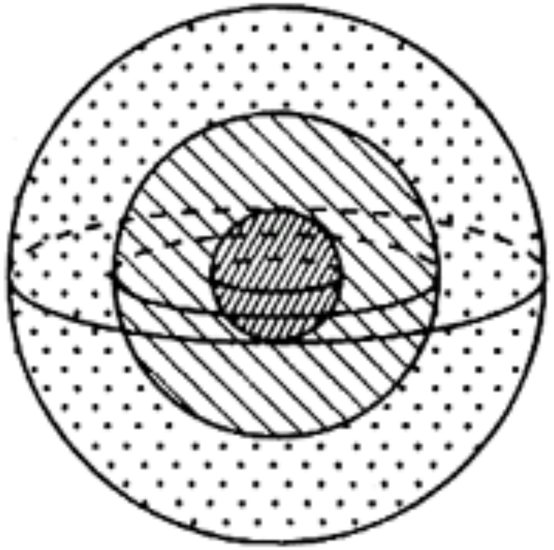


We *cannot* move over cosmological distances and check that the universe looks the same from 'over there' as it does from here … so there are ***fundamental limits* to what we can know about the universe**

That the universe looks isotropic around our position does *not* imply that it is homogeneous



Homogeneous
Not isotropic



Isotropic
Not homogeneous

… unless it is so about *every* point in space

But we cannot move (very far) in space so must *assume* that our position is typical - "The Cosmological Principle" (Milne 1935)

New H-band Galaxy Number Counts

Are we located in an underdense region in the galaxy distribution?

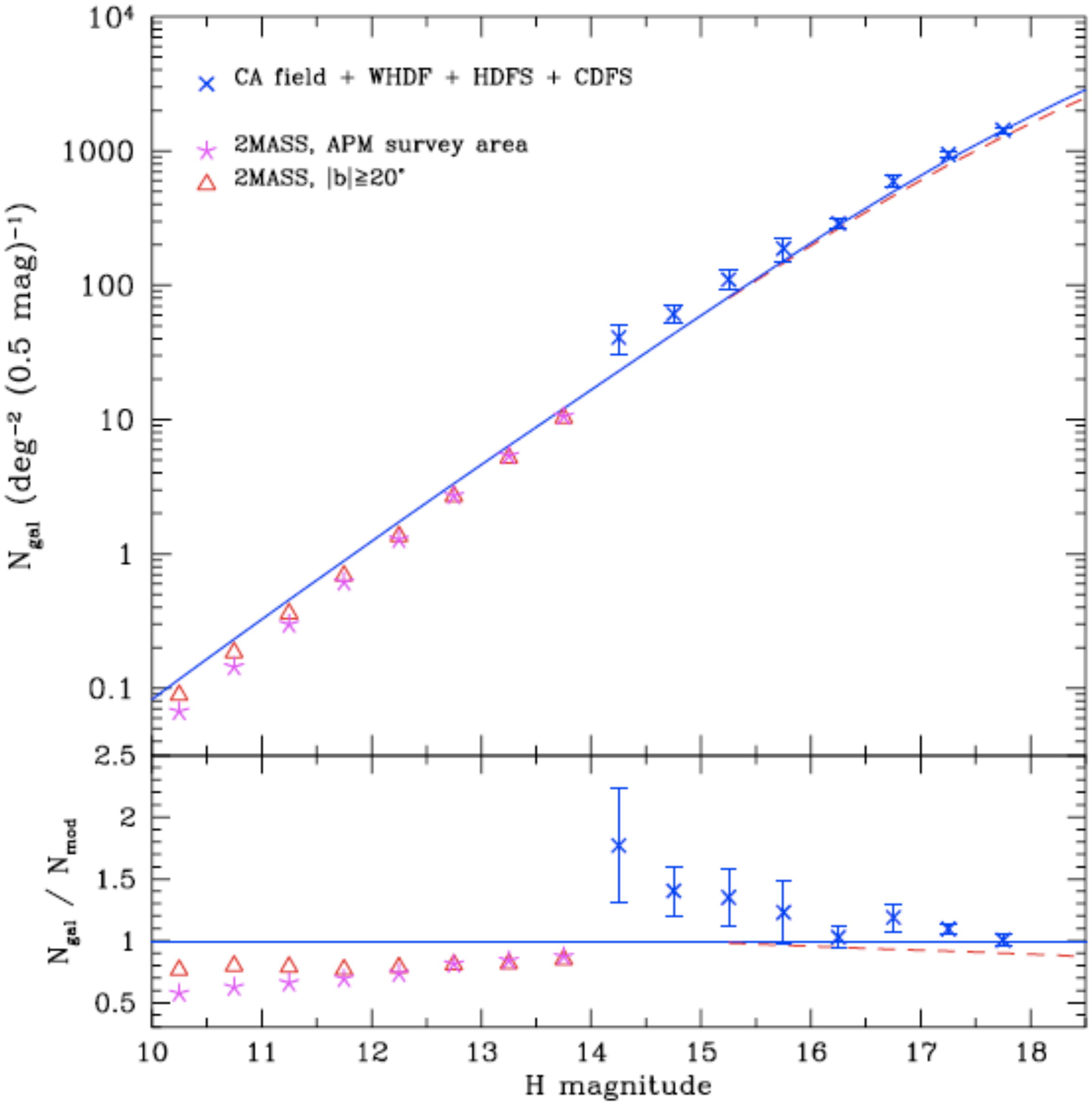
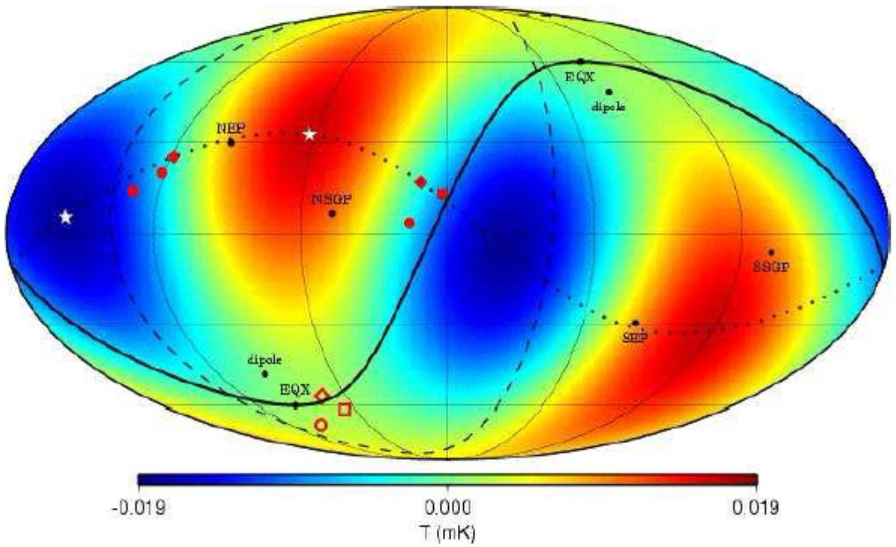


Figure 8. Here we show the faint H-band data from the two fields presented in this work (CA field and WHDF) and the two fields published by the LCIRS (HDFS and CDFS; Chen et al. 2002) applying a zeropoint to the LCIRS data consistent with the bright H-band 2MASS data (and hence the CA field and WHDF also), as shown in Fig. *7*. The errorbars at faint magnitudes indicate the field-to-field error, weighted in order to account for the different solid angles of each field. Bright H-band counts extracted from 2MASS for the APM survey area and for |b| >20° are shown as previously. In the lower panel, the counts are divided through by the pure luminosity evolution homogeneous prediction as before.

Frith, Metcalfe, Shanks (2006)



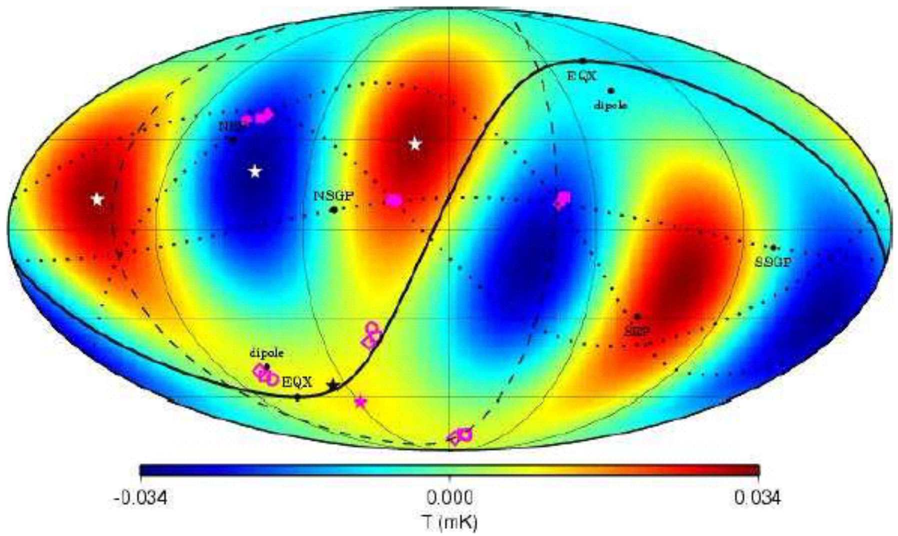
The local void need not be exactly spherical … nor would we expect to be *exactly* at its centre

So might expect (low *l*) CMB anisotropies to be generated by the **'Rees-Sciama effect'** (must be within 10% of centre to *not* generate excessive dipole)

Inoue & Silk (2006)

The CMB quadrupole and octupole are indeed very well-aligned!

Such large voids would be *very unlikely* in a **gaussian density field** … but do seem to be present elsewhere in the universe, as revealed by their CMB imprint



Many large voids are seen in the SDSS luminous red galaxy sample (through the 'cold spots' they create on the CMB)

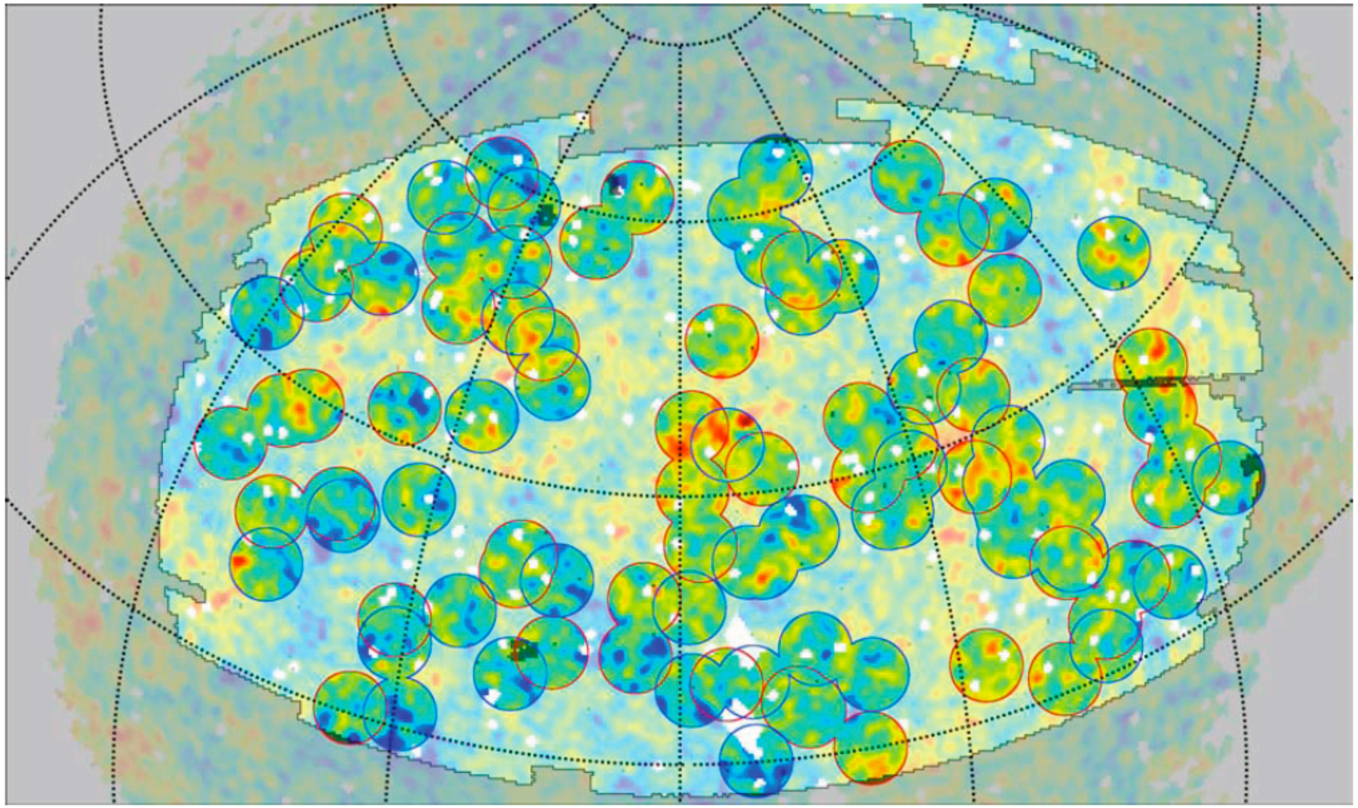
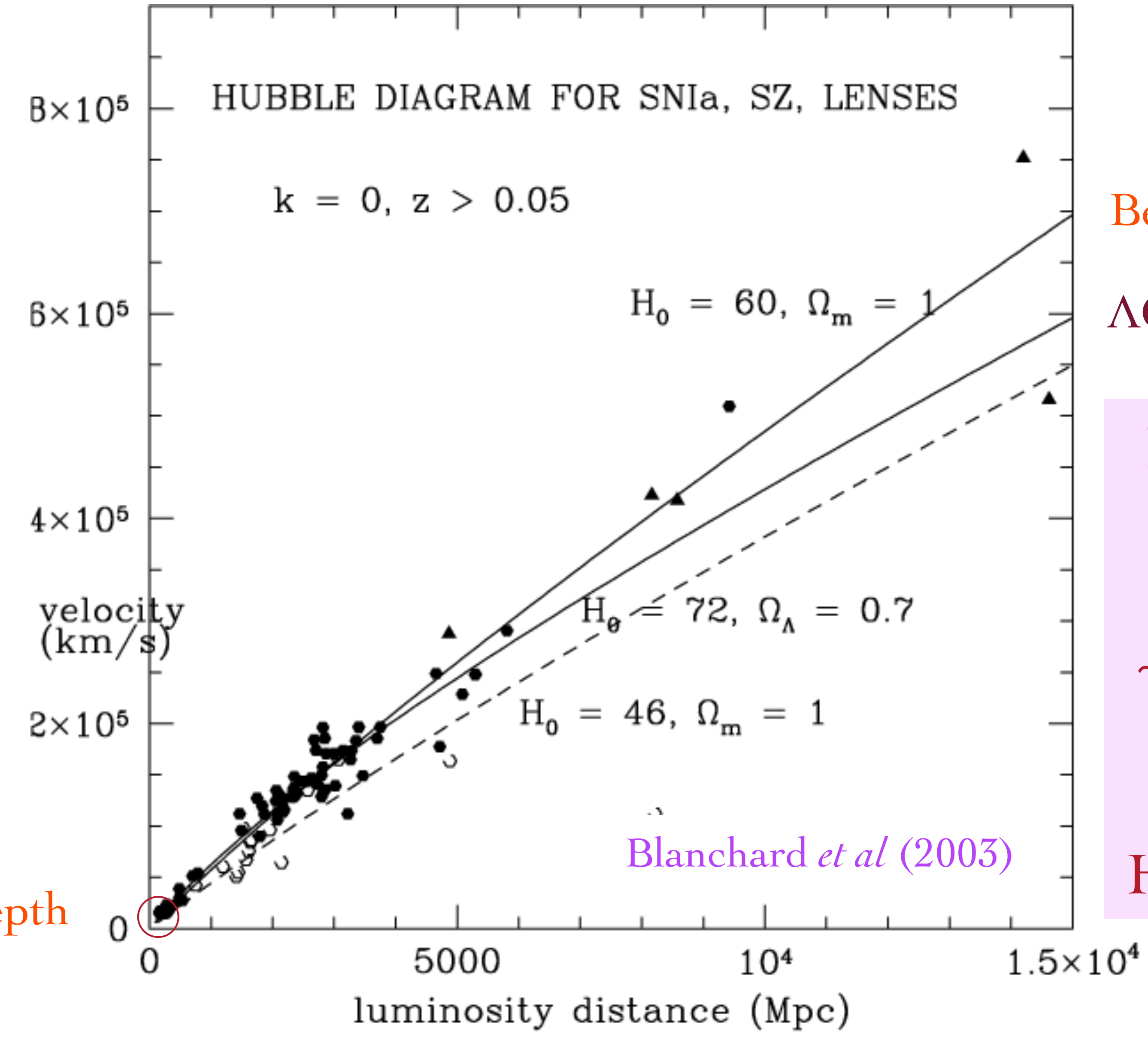


Figure 1: A map of the microwave sky over the SDSS area. The supervoids and superclusters used in our analysis are highlighted and outlined at a radius of 4°, blue for supervoids and red for superclusters. The compensated filter we use in our analysis approximately corrects for the large-angular-scale temperature variations that are visible across the map. The SDSS DR6 coverage footprint is outlined. Holes in the survey, *e.g.* due to bright stars, are displayed in black. Additionally, the WMAP Galactic foreground and point source mask is plotted (white holes). The disk of the Milky Way, which extends around the left and right border of the figure, is also masked. The map is in a Lambert azimuthal equal-area projection, centred at right ascension 180 and declination 35. The longitude and latitude lines are spaced at 30° intervals.

Granett *et al* [arXiv:0805.2974]

Deep determinations of the Hubble constant e.g. gravitational lens time delays yield $h = 0.48 \pm 0.03$ (Kochanek & Schechter 2004) - much smaller than the *local* measurement by the Hubble Key Project ($h = 0.72 \pm 0.08$)



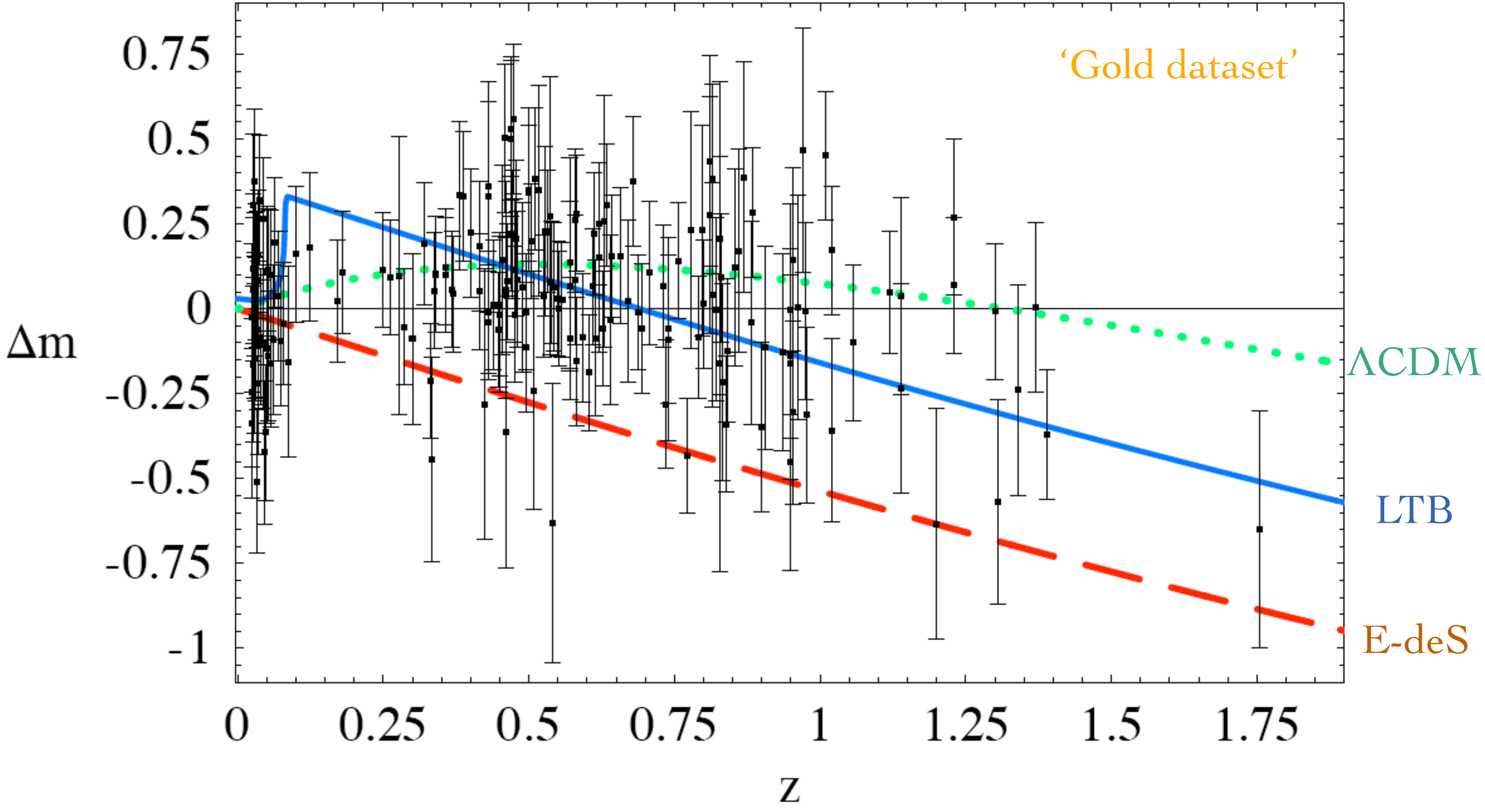
Best fit E-deS

ΛCDM

HKP depth

Is our local void expanding ~30% faster than the global Hubble rate?

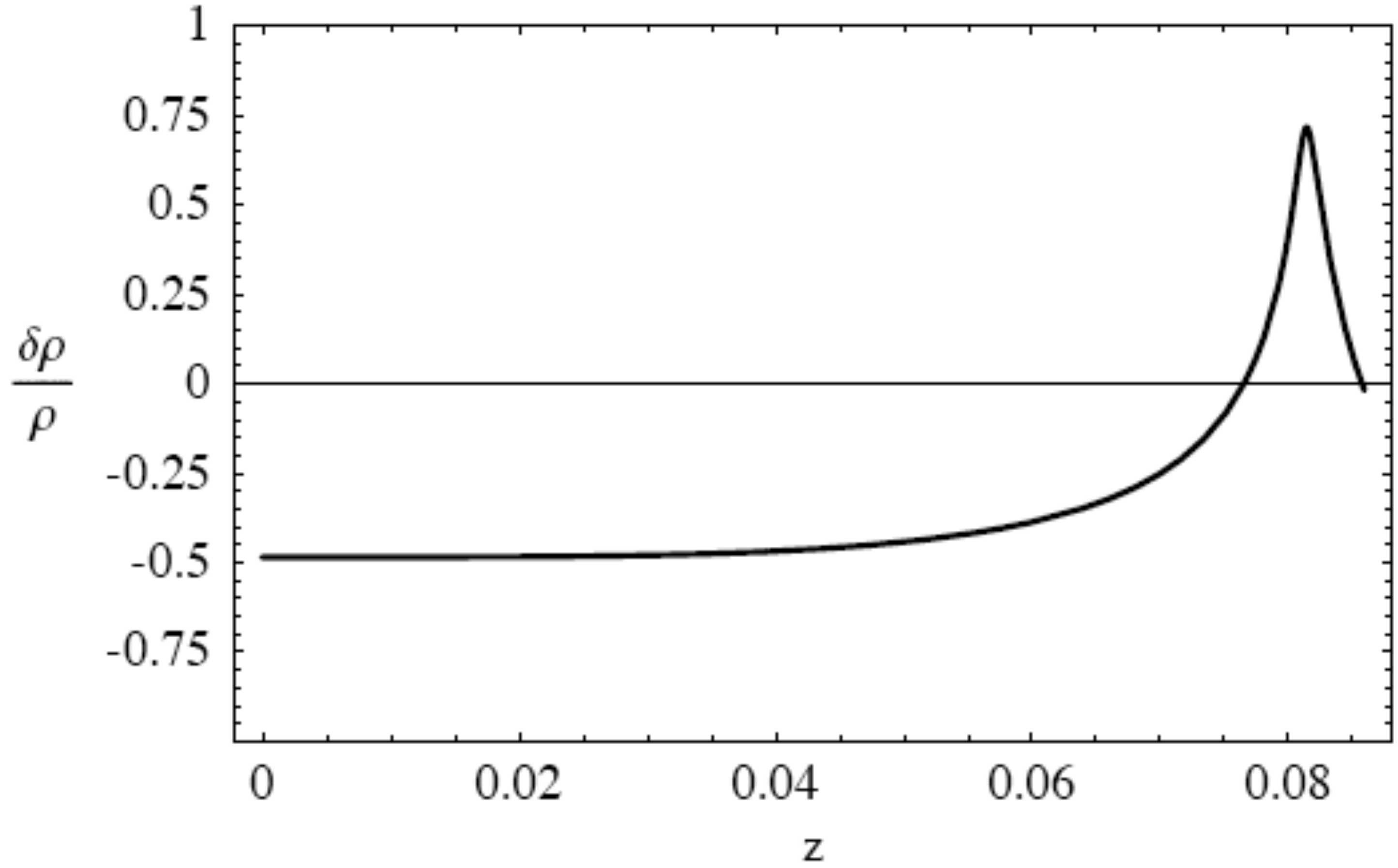
If so, the SN Ia Hubble diagram may be explained *without invoking acceleration*, since distant supernovae would be in a *slower* Hubble flow than the nearby ones within the local void (**Lemaitré-Tolman-Bondi inhomogeneous model**)



Alexander, Biswas, Notari & Vaid (2007)

The LTB metric is essentially a radially varying FRW metric:

$$ds^2 = -dt^2 + a^2 \left[\left(1 + \frac{r}{a}\frac{\partial a}{\partial r}\right)^2 \frac{dr^2}{1 - k(r)r^2} + r^2 d\Omega_2^2 \right] .$$

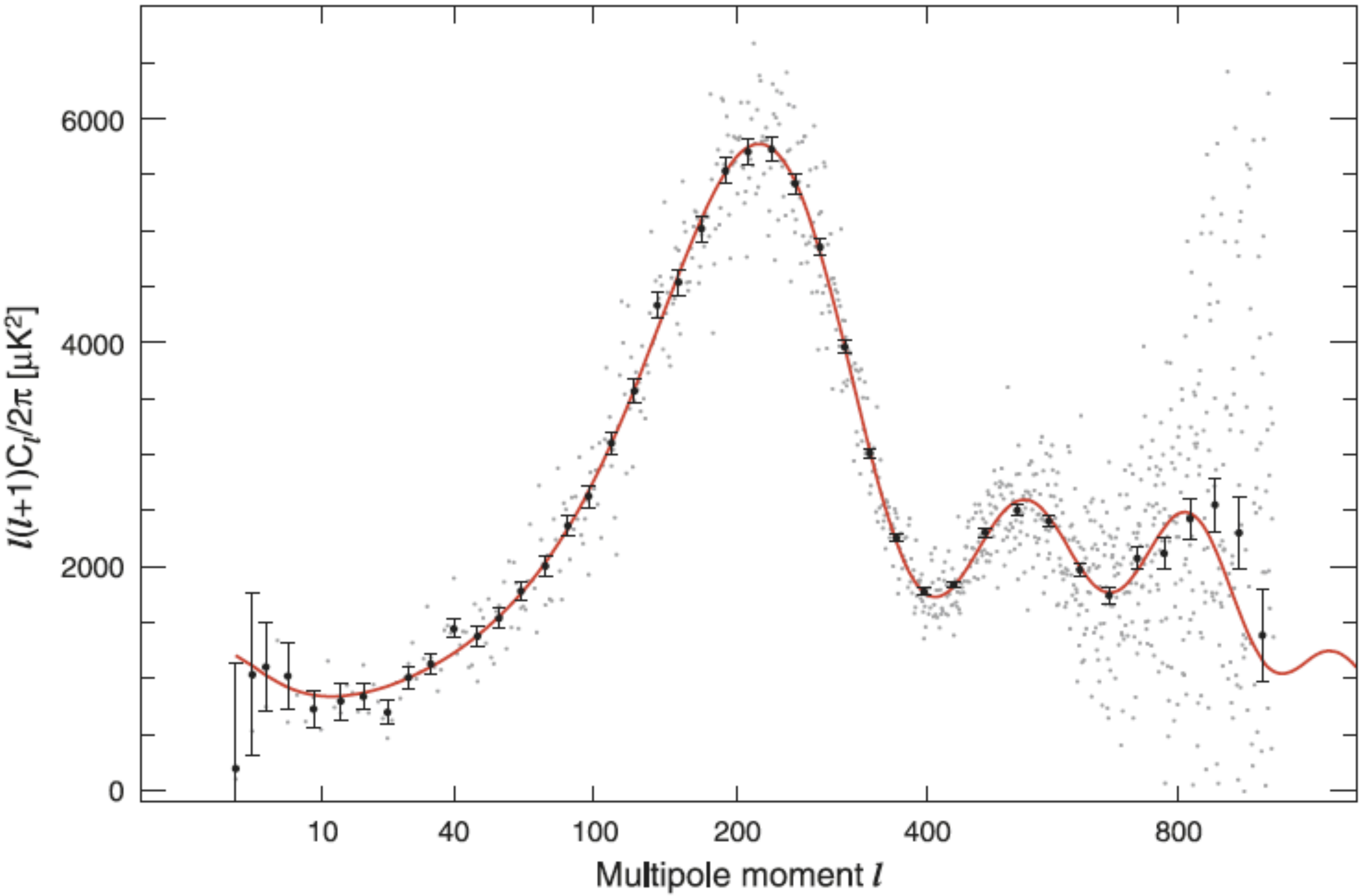


Alexander, Biswas, Notari & Vaid [0712:0370]

Fits the SN data with $h_{out} \sim 0.45$, $0.51 < h_{in} < 0.59$, void radius ~ 150-250 Mpc h_{in}^{-1}

The 'power-law ΛCDM model' is believed to be *confirmed* by *WMAP*

Best-fit: $\Omega_m h^2 = 0.11 \pm 0.01$, $\Omega_b h^2 = 0.023 \pm 0.001$, $h = 0.73 \pm 0.05$, $n = 0.96 \pm 0.02$

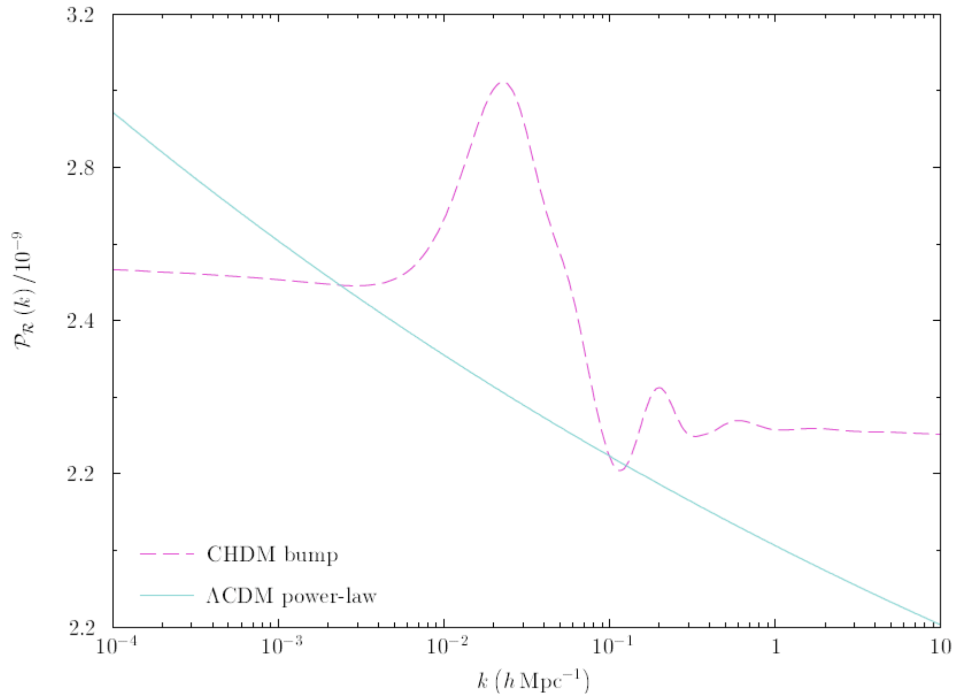


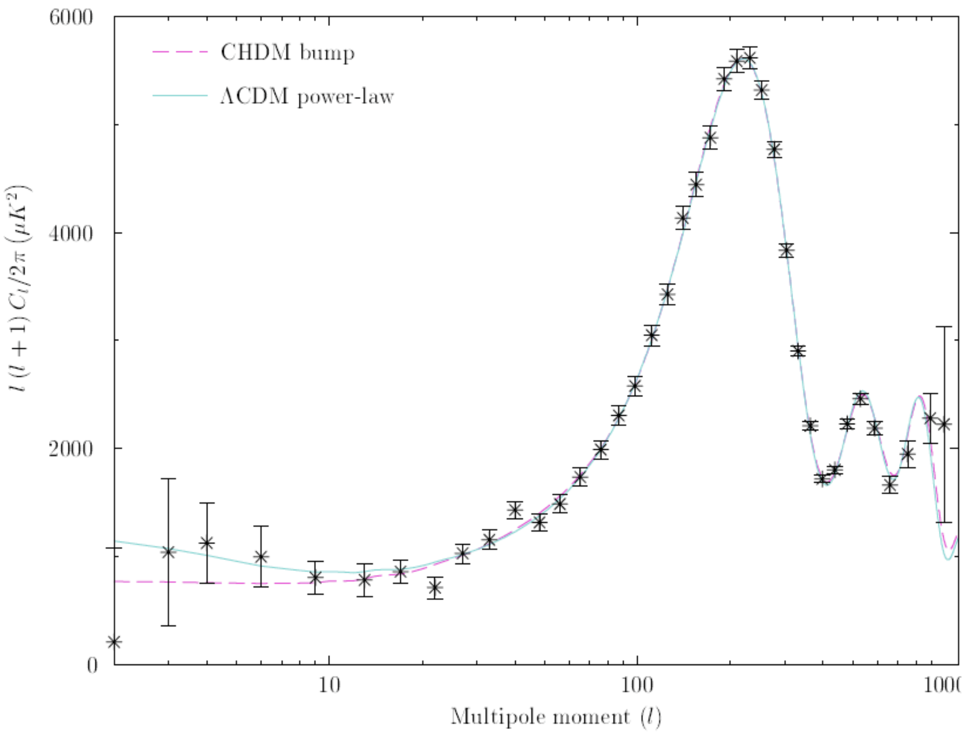
But the χ^2/dof of this fit is not very good … because there are outliers ("glitches")

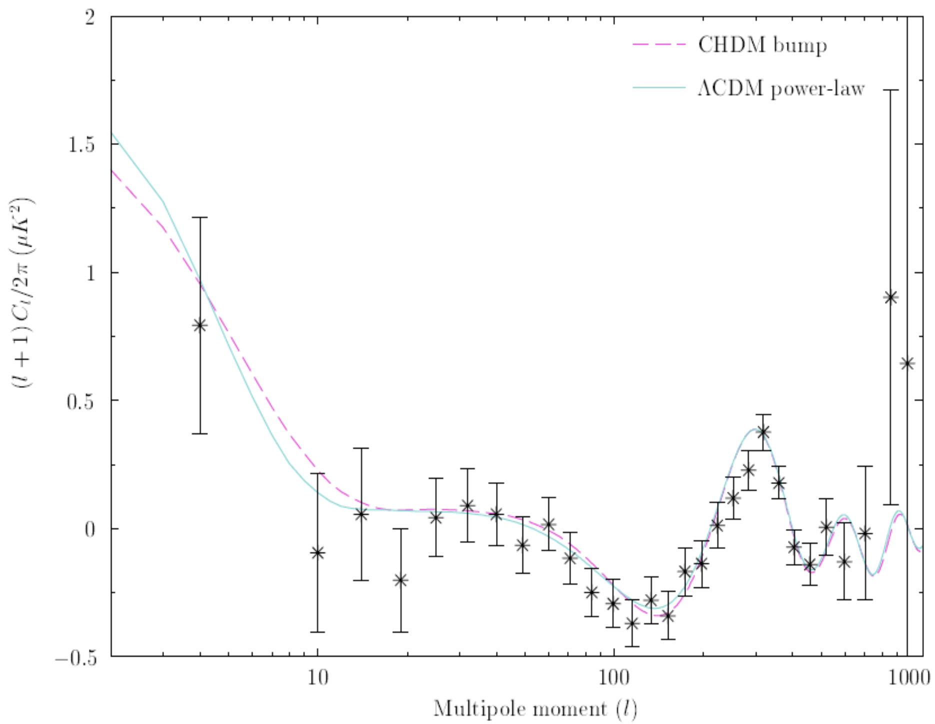
This suggests the primordial perturbation spectrum is not scale-free as is commonly *assumed*

If there is a small 'bump' in the spectrum, the data can be equally well fitted with *no* dark energy ($\Omega_m = 1$, $\Omega_\Lambda = 0$) if h ~ 0.44

(Hunt & Sarkar 2007, 2009)



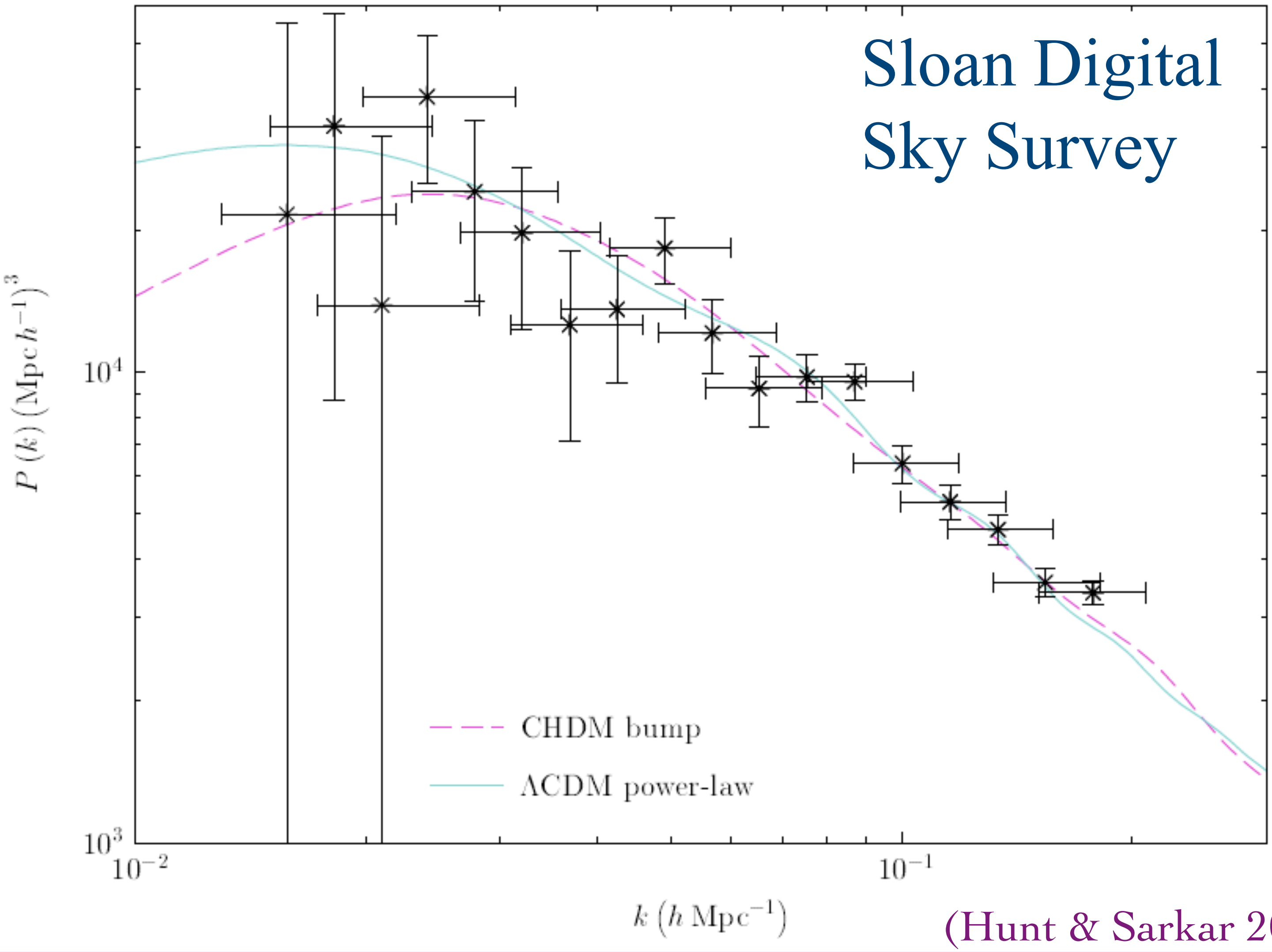




There is supposedly *independent* evidence for dark energy from the clustering of galaxies

But this assumes the dark matter is 'cold' and ignores neutrinos – which are *known* to have mass – as a 'hot' component of the dark matter

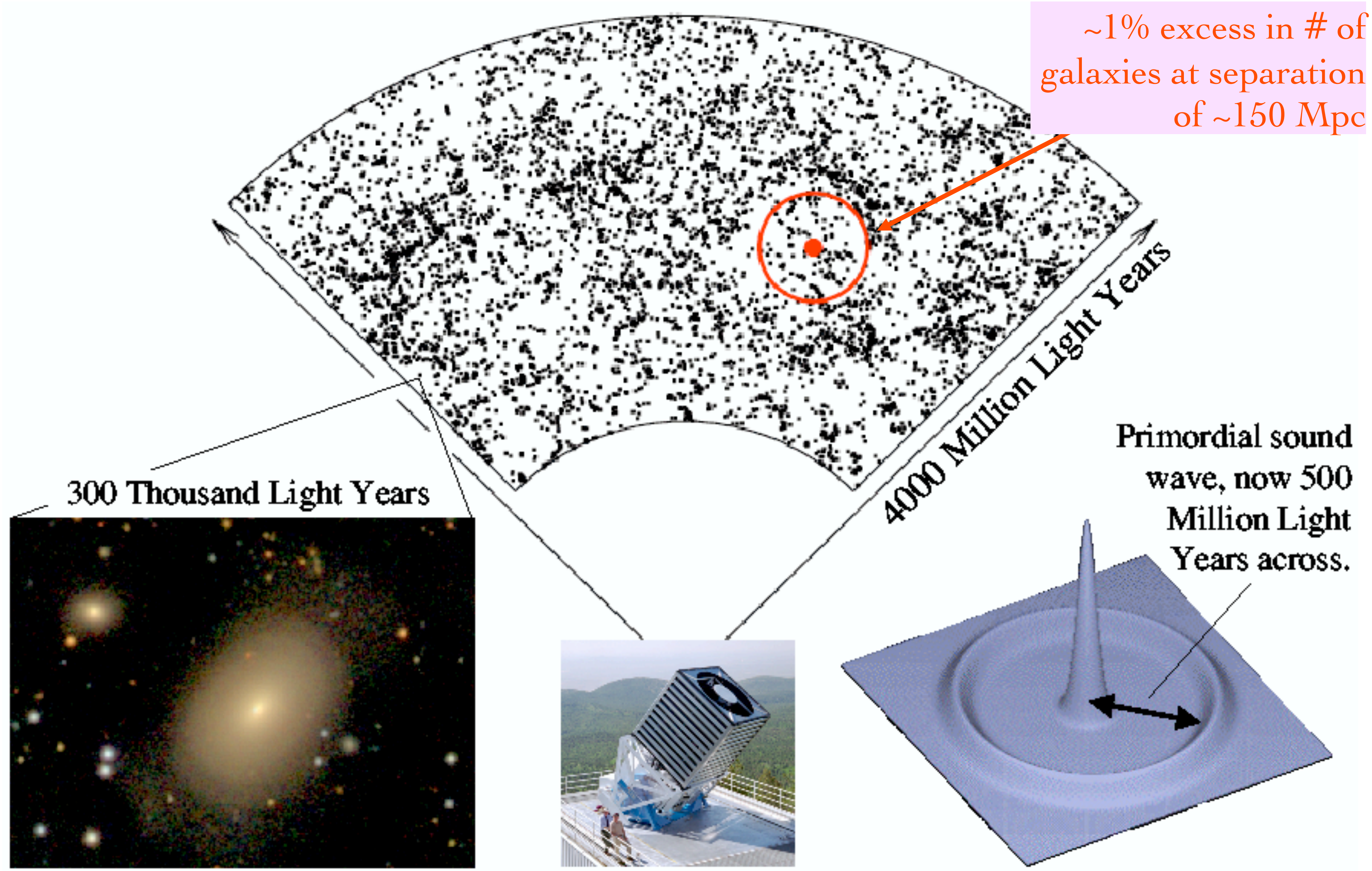
If this mass is ~0.5 eV ($\Rightarrow \Omega_\nu \sim 0.1$) then get *good match* to observations *without dark energy*



(Hunt & Sarkar 2007, 2009)

Fit gives $\Omega_b h^2 \approx 0.018 \rightarrow$ nucleosynthesis √ $\Rightarrow$ cluster baryon fraction ~10% √

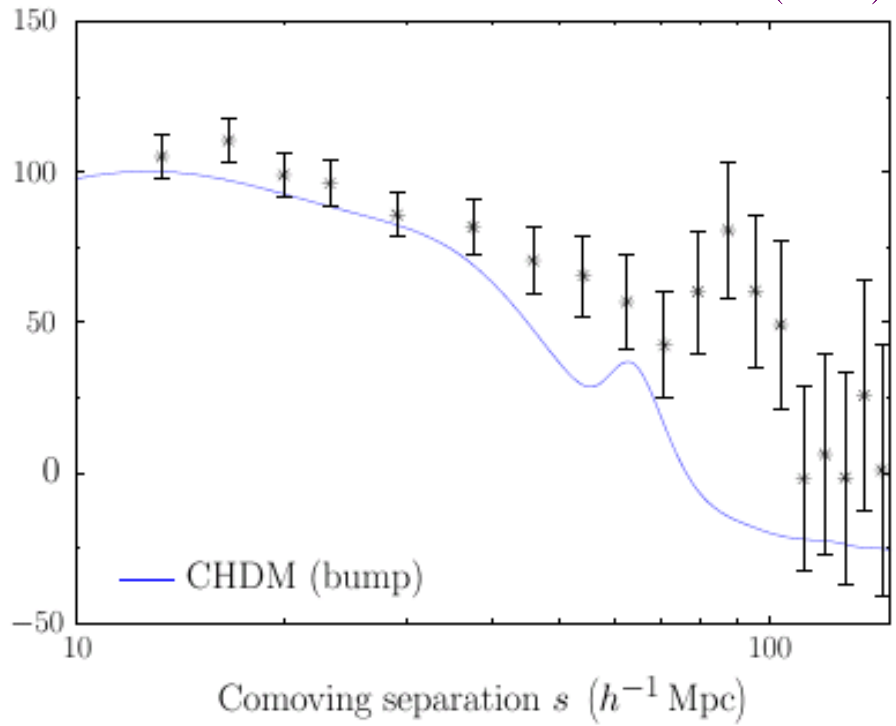
New Test: Baryon Acoustic Peak in the Large-Scale Correlation Function of *SDSS* Luminous Red Galaxies



Eisenstein (2005)

However the E-deS model ($\Omega_m = 1, \Omega_\Lambda = 0$) is *ruled out* by the 'baryon acoustic peak' (present at the ~same *physical* scale, but displaced in redshift space)

Blanchard *et al* (2006)



But can get angular diameter distance @ z = 0.35 similar to ΛCDM with a large enough void - so crucial to measure *z dependence* of BAO!

Such a large void will however distort the CMB spectrum (Caldwell, Stebbins 2008) … also constrained by kinetic Sunyaev-Zeldovich effect (Haugboelle, Garcia-Bellido 2008)

Summary - dark energy

There has been a renaissance in cosmology but modern data is still interpreted in terms of an *idealised* model whose basic assumptions have not been rigorously tested

The standard FRLW model naturally admits $\Lambda \sim H_0^2$
… and this is being *interpreted* as dark energy: $\Omega_\Lambda \sim H_0^2 M_P^2$

More realistic models of our *inhomogeneous* universe may account for the SN Ia Hubble diagram without acceleration

The CMB and LSS data can be equally well fitted if the primordial perturbations are *not* scale-free and $m_\nu \sim 0.5$ eV

Dark energy may just be an artifact of an oversimplified cosmological model

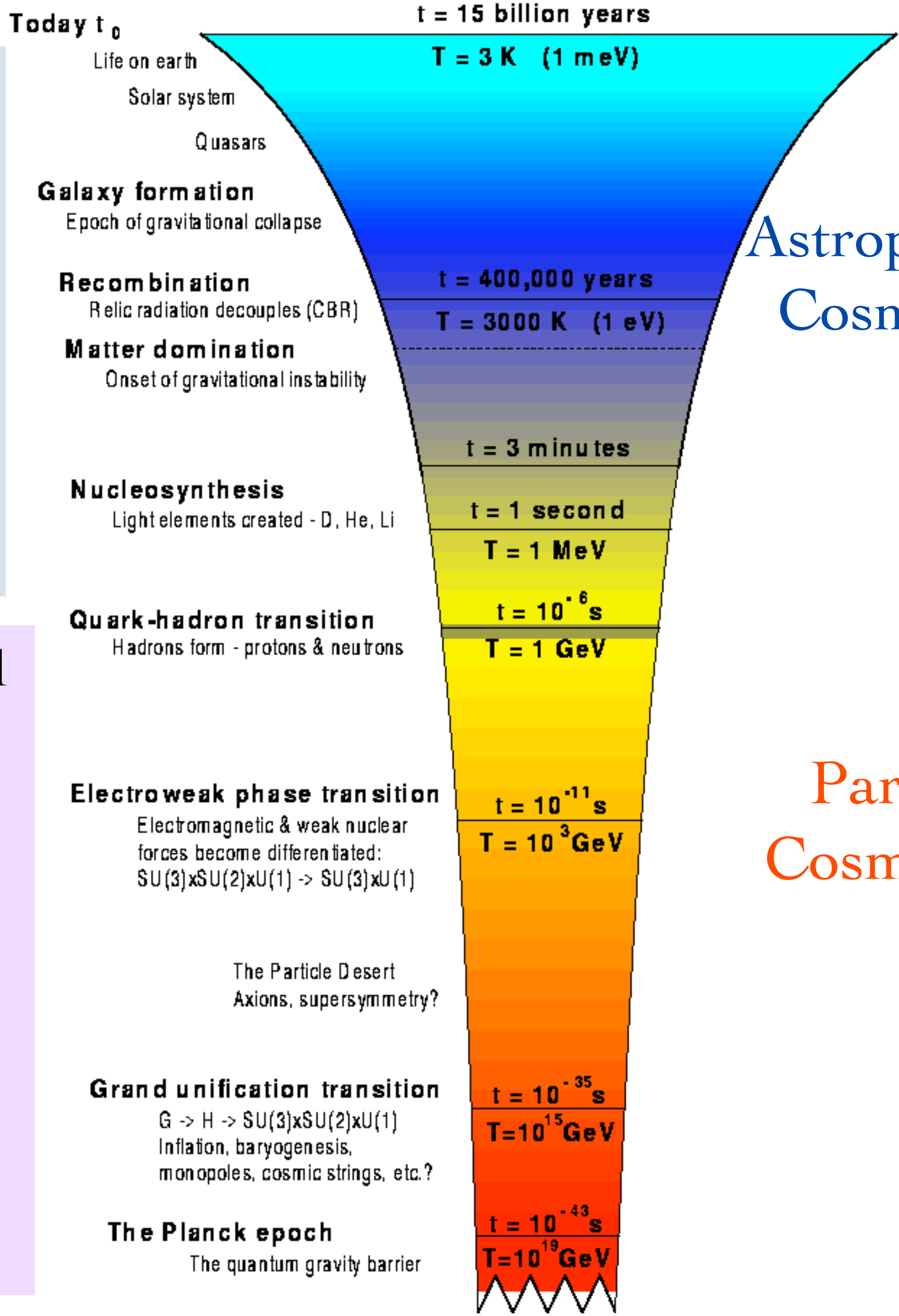
On the basis of SM physics, the evolution of the universe can be extrapolated into our past, fairly reliably up to the **big bang nucleosyntheis** era and (with some caveats) back through the **quark-hadron transition,** up to the **electroweak unification era**

However, *new* physics beyond the SM is required to:

(a) account for the observed **baryon asymmetry,**

(b) provide **dark matter,**

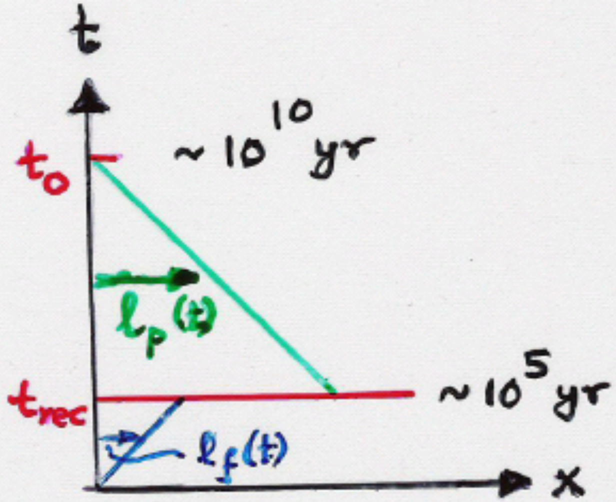
(c) generate primordial **density fluctuations** which seeded the growth of large-scale structure



Astrophysical Cosmology

Particle Cosmology

The cosmological horizon problem (Misner '68)



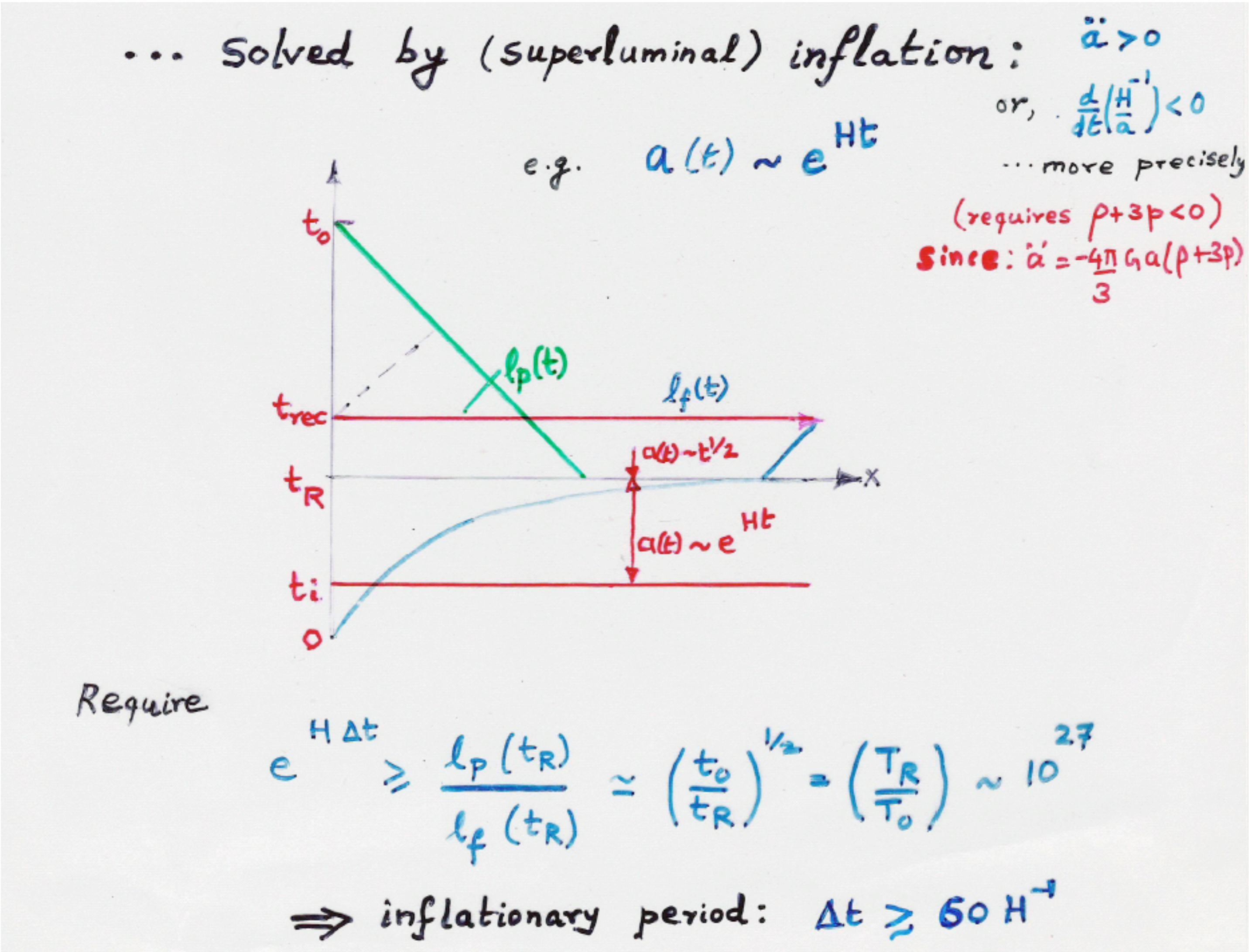
$$\ell_p(t) = \int_t^{t_0} \frac{dt'}{a(t')} = 3t_0\left[1 - \left(\frac{t}{t_0}\right)^{1/3}\right] \gg \ell_f(t) = \int_0^t \frac{dt'}{a(t')} \simeq 3t_0\left(\frac{t}{t_0}\right)^{1/3}$$

for $a \propto t^{2/3}$ with $a(t_0) \equiv 1$ for $t = t_{rec}$

Why is the relic radiation so uniform (to within ~1 part in 10^5) over regions which were apparently *causally disconnected*?

But note that the integral over the light cone has to go back to t = 0 … does a metric description of space-time hold at the Planck epoch?!

The solution is to invoke a period of *accelerated expansion* at early times



But for inflation to *start* we need a flat patch of space-time at least as big as $3H^{-1}$ (Vachaspati & Trodden 1999) so it is not clear if it really 'solves' the horizon problem … initial conditions are *very* improbable (Penrose 1989)

The flatness problem

(Dicke & Peebles '79)

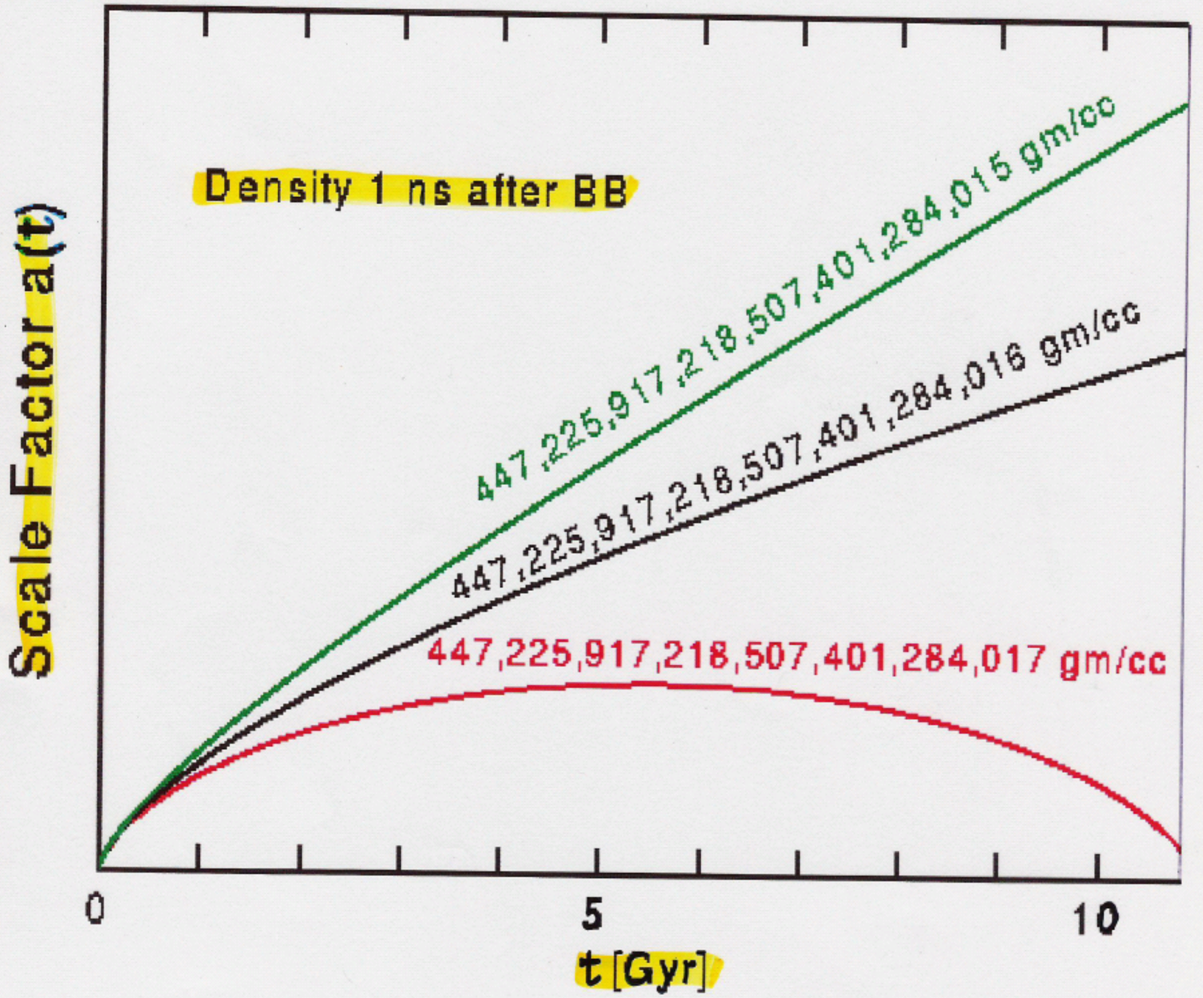
$$\Omega \equiv \frac{\rho}{\rho_{crit}} \quad , \quad \dot{\Omega} \propto 2\beta\,\Omega^{3/2\beta}(\Omega-1)^{\beta-1}$$

where $\beta \equiv \frac{\rho+3p}{2\rho} = \begin{cases} -1 & \text{... vacuum energy} \\ 1/2 & \text{... 'dust'} \\ 1 & \text{... 'radiation'} \end{cases}$

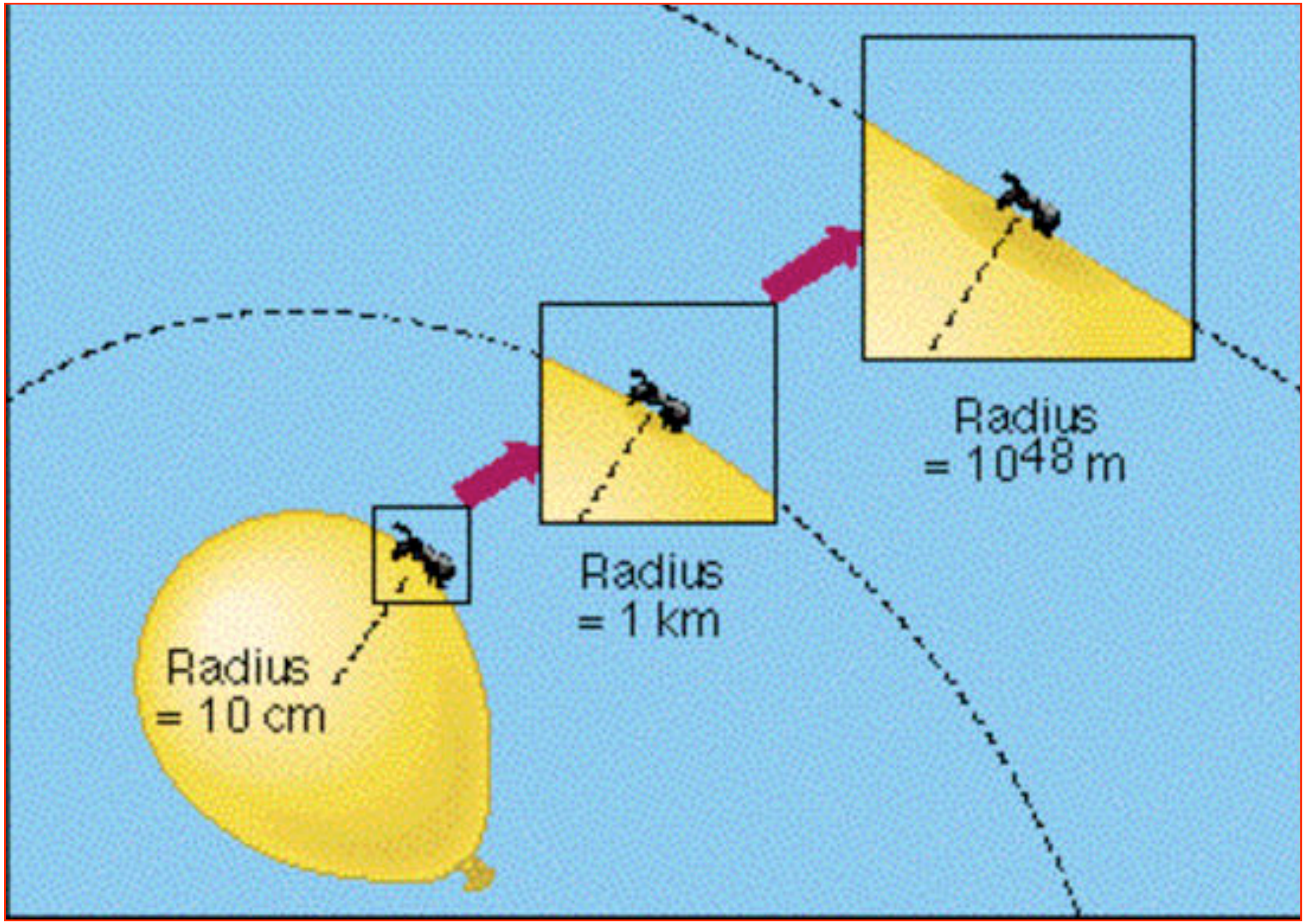
$$\rho_{crit} = \frac{3H^2}{8\pi G_N}$$

e.g. $\Omega = \dfrac{1}{1+\frac{t}{t_0}(\Omega_0^{-1/2}-1)^2}$, for $\beta = 1$

$$\boxed{\Omega - 1 = \frac{k}{a^2H^2}}$$

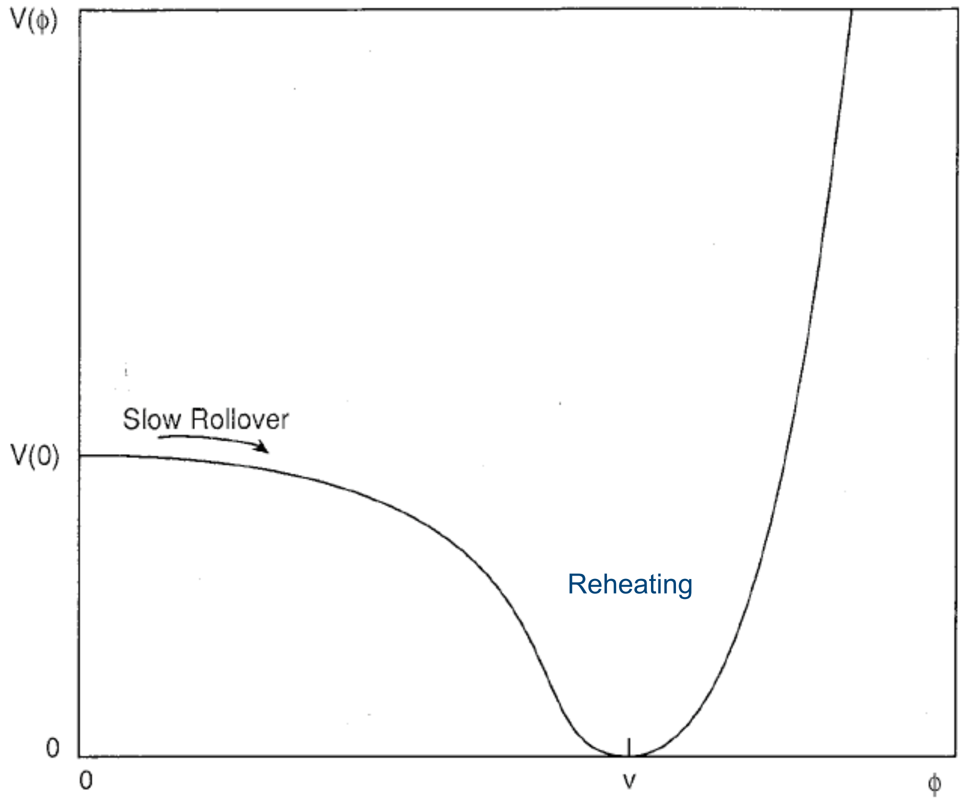


The solution is inflation … which flattens the curvature of space

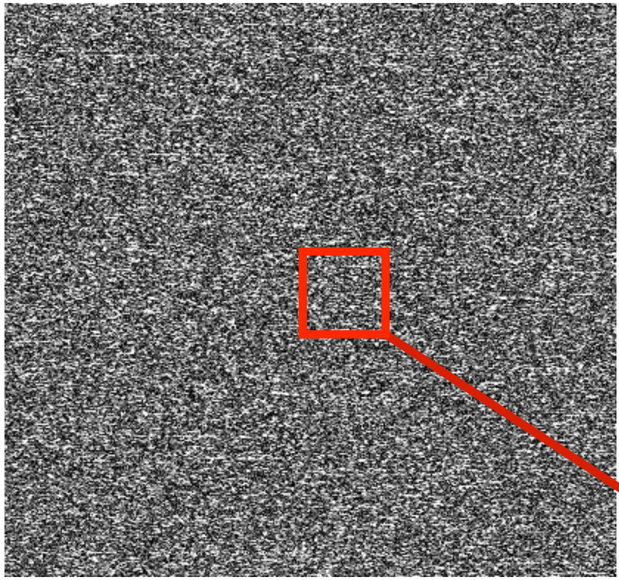


~30-60 e-folds of inflation suffices to solve the flatness problem
(Note there may have been several episodes of inflation)

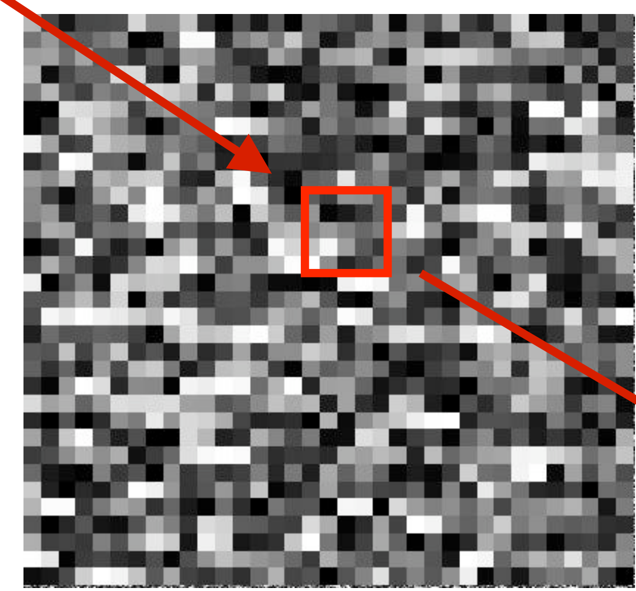
Inflation would have occurred if e.g. the early universe had become dominated temporarily by the vacuum energy of a scalar 'inflaton' field, which is displaced from the true minimum of its potential and evolves slowly towards it (while driving *exponentially* fast expansion)

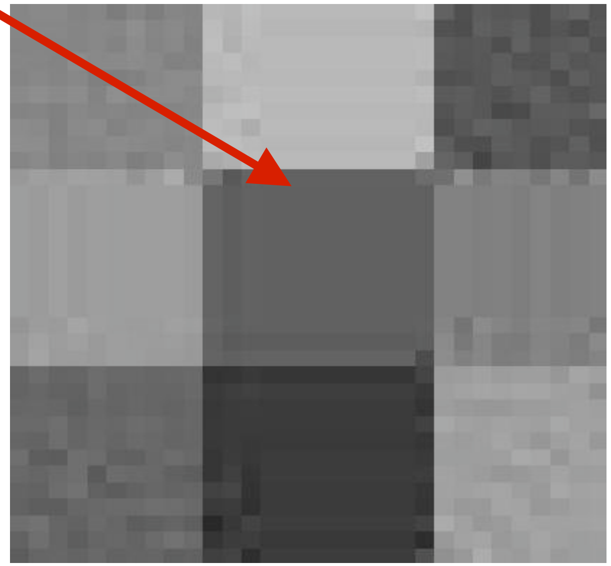


If the potential is sufficiently flat, the required number of e-folds of expansion can happen before the inflaton reaches its minimum … and converts its energy density into relativistic particles, starting off the **hot radiation-dominated era**



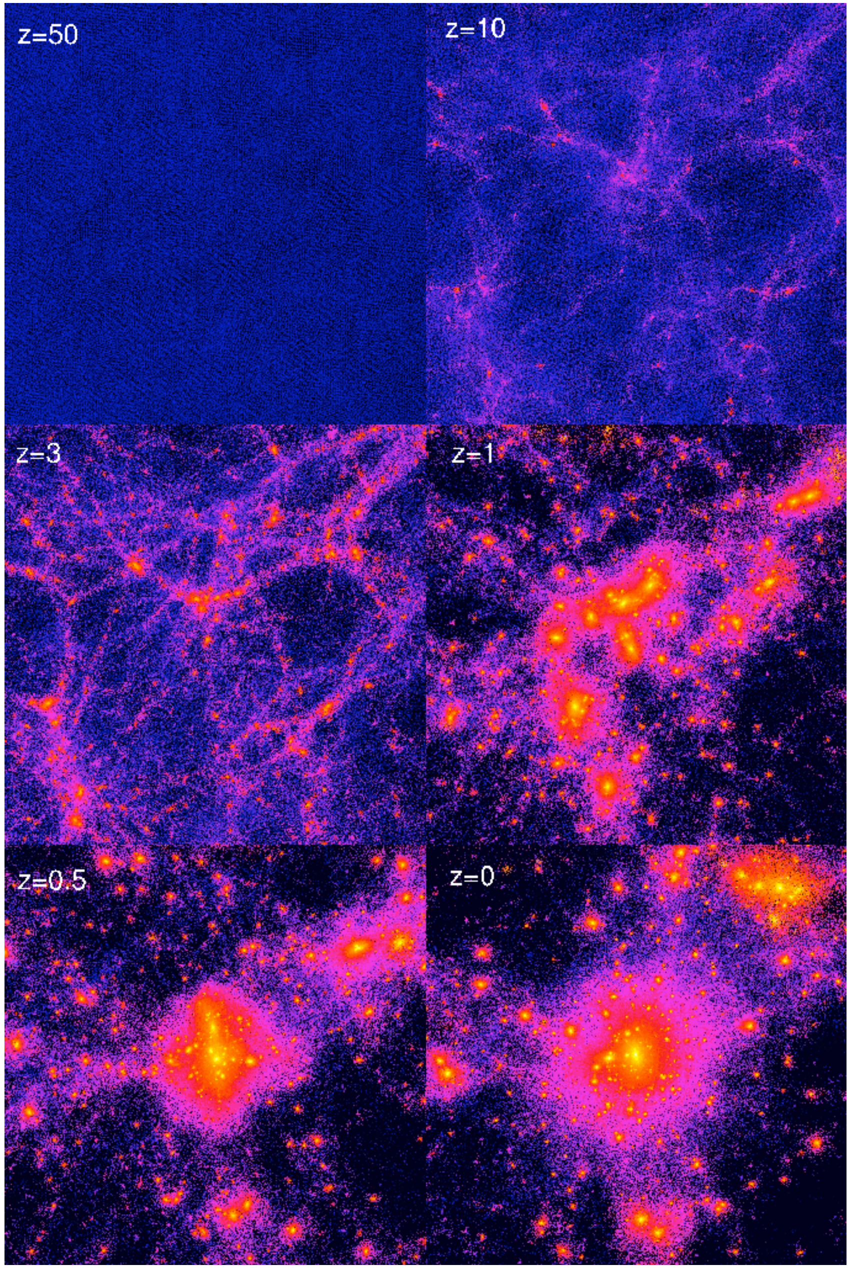
The quantum fluctuations of the (hypothetical) scalar ‘inflaton’ field - the energy density of which drives the inflationary expansion - are stretched out to *macroscopic scales* bigger than the horizon … and turn into classical density perturbations with an **approximately *scale-invariant* power spectrum**



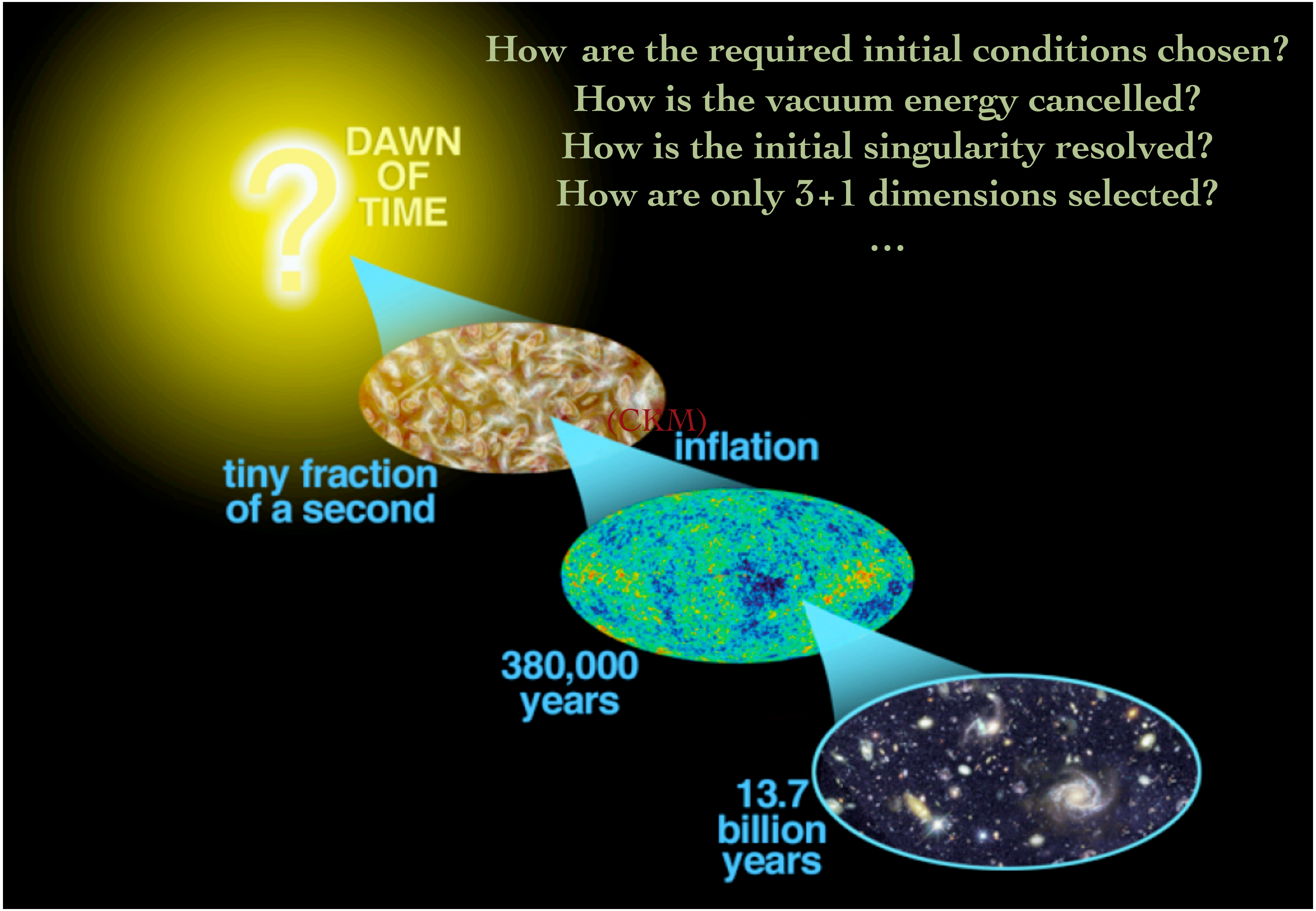


These density perturbations act as ‘seeds’ for the growth of **large-scale structure** through **gravitational instability** in the **dark matter** … baryonic matter traces these potential wells

Numerical simulations of the formation of structure through gravitational instability in cold dark matter *match* the observations



But we do not yet know the physics behind inflation or what came before it …



Discovering dark matter

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 been taken notice of by the British Astromer Royal!

Discovery of dark matter ➔ new (astro)physics

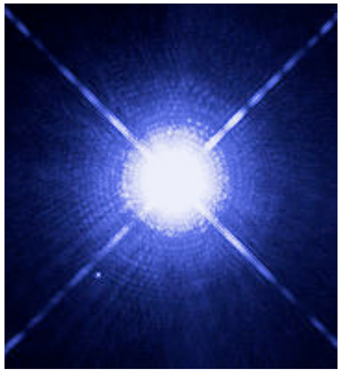
Friedrich Wilhelm Bessel (1832) finds the position of *Sirius* to be oscillating, indicating the presence of an unseen companion

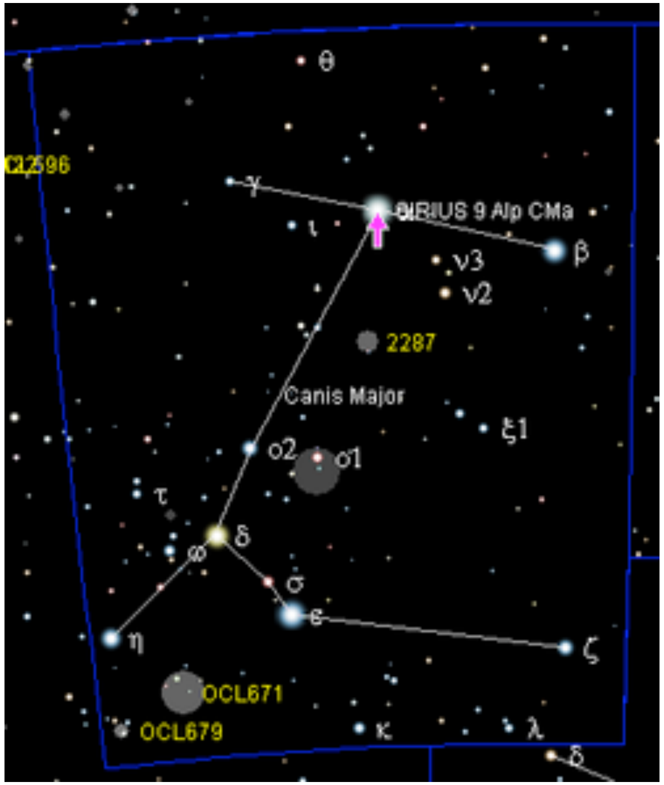
Ivan Clark (1862) discovers *Sirius B* visually

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

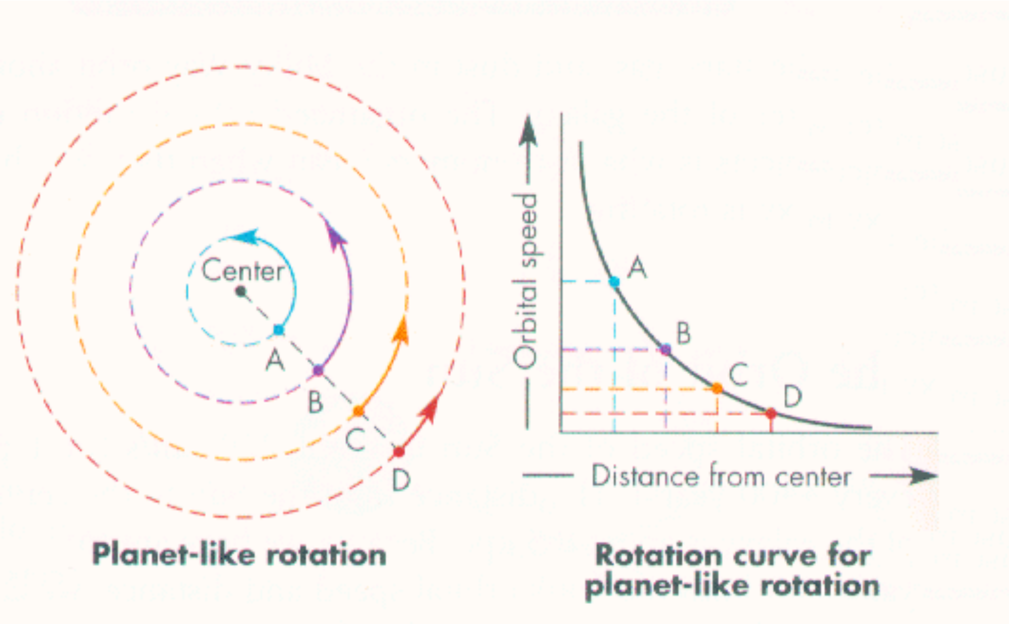
Subrahmanyan Chandrasekhar (1930) applies quantum ideas to stellar structure … infers that when the Sun exhausts its nuclear fuel it will collapse under gravity until held up by Pauli exclusion principle (electron degeneracy pressure)

… but stars heavier than $1.4M_0$ will continue to collapse and "… *one is left speculating on other possibilities*" (neutron stars and black holes!)





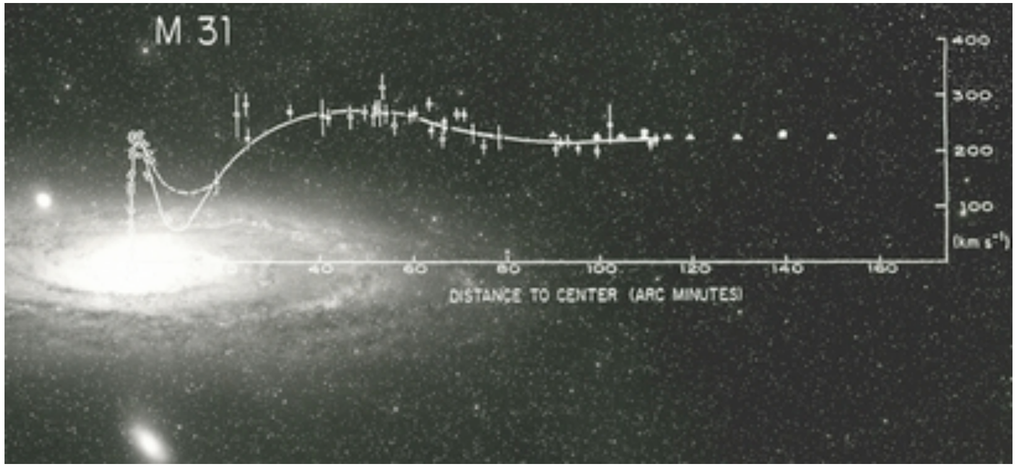
The modern saga of dark matter starts with the rotation curves of spiral galaxies …



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

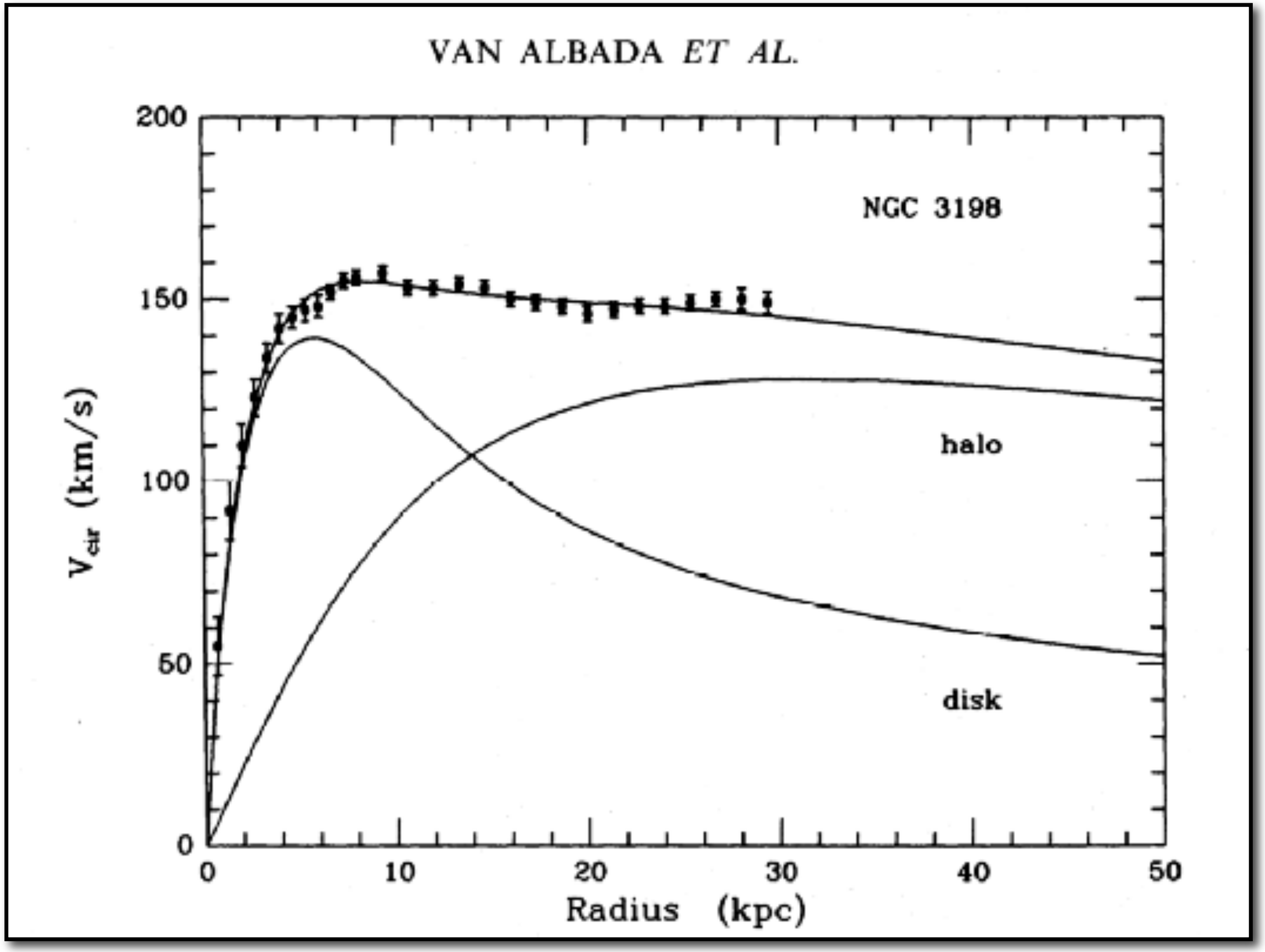
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

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

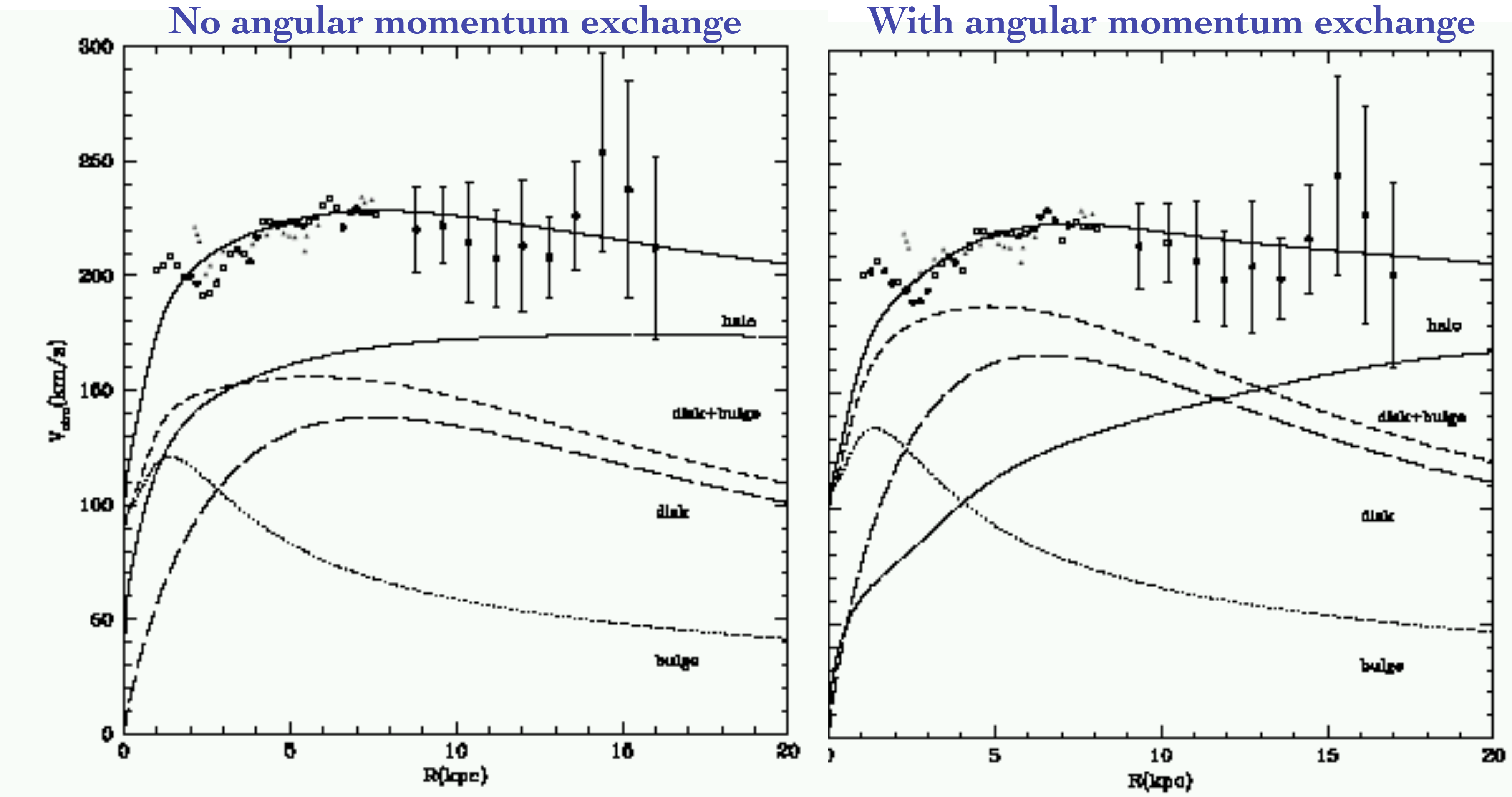


$$v_{\rm circ} \sim \text{constant} \quad \Rightarrow \quad M(<r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

The *really* compelling evidence for extended galactic **halos of dark matter** came in the 1980's from 21 cm observations of neutral hydrogen – found to be orbiting at ~constant velocity *well beyond* the extent of the visible disk



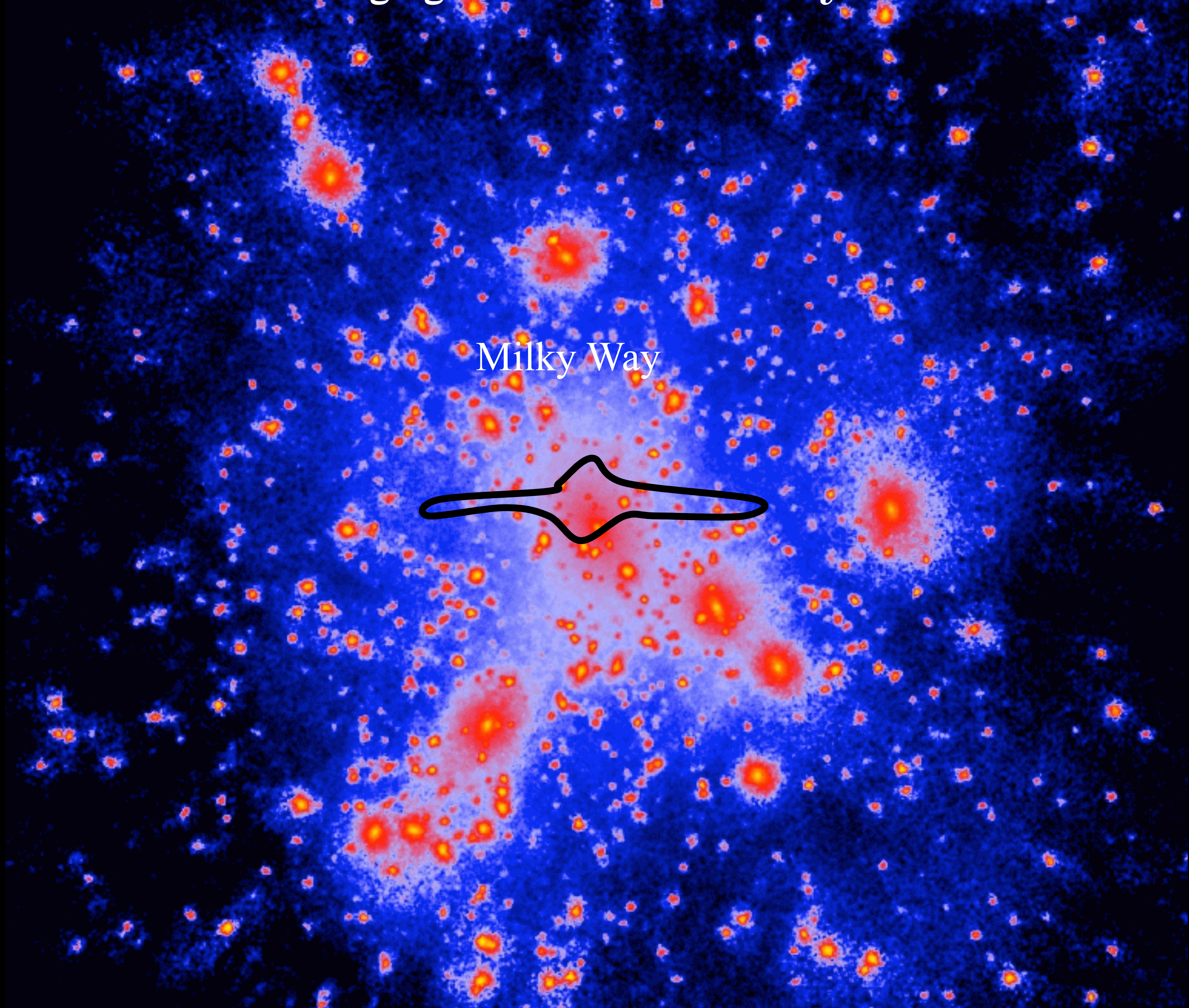
More sophisticated modelling needs to account for multiple components and the coupling between baryonic & dark matter



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

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

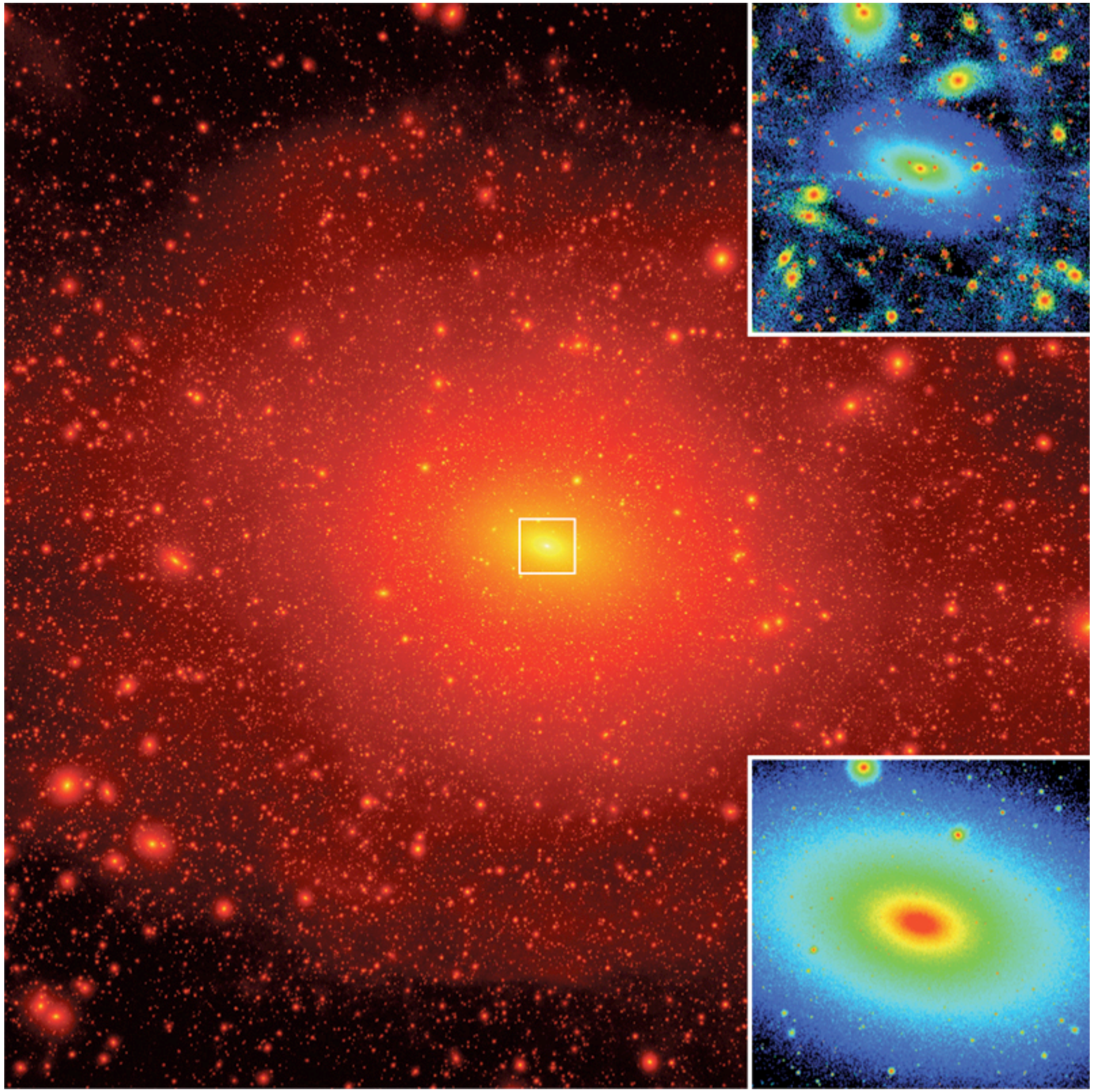
We can get an idea of what the Milky Way halo looks like from numerical simulations of **structure formation through gravitational instability in cold dark matter**



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

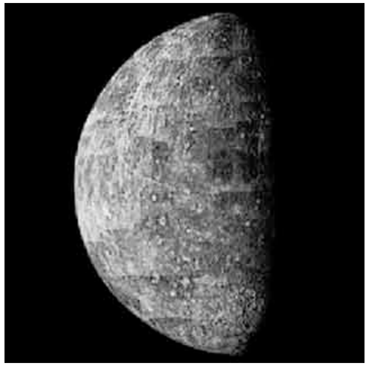
real space

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

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

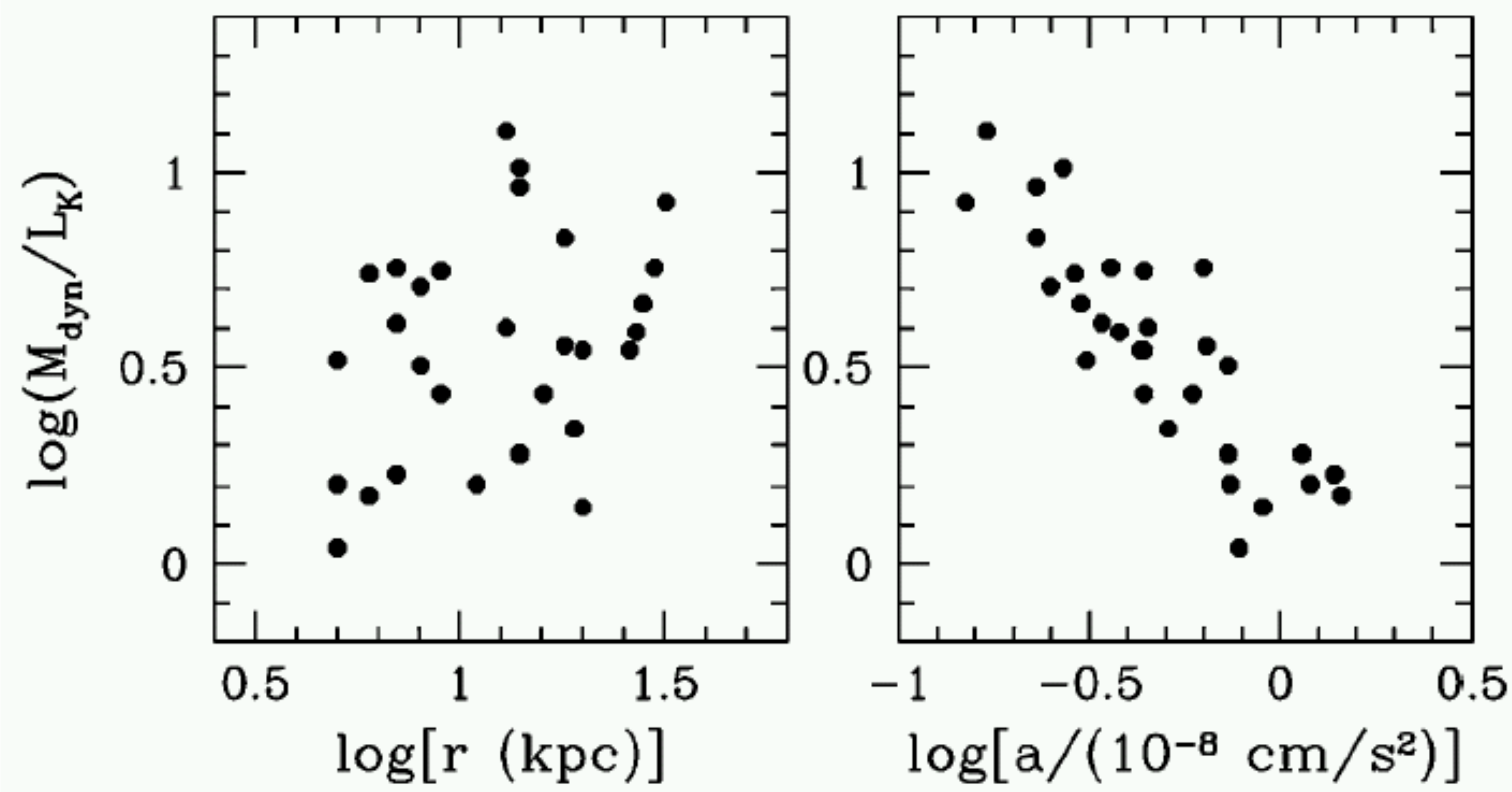
2 Jan 1860: *"Gentlemen, I Give You the Planet Vulcan"*
French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris.

Some astronomers even see 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?

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

Milgrom (1983)

Bekenstein – Milgrom Equation

Suppose $\mathbf{F} = -\nabla\phi$ where

$\nabla^2\phi_\mathrm{N} = 4\pi G\rho \quad \rightarrow \quad \nabla \cdot [\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$

where

$$\mu(x) \rightarrow \begin{cases} 1 & \text{for } x \gg 1 \\ x & \text{for } x \ll 1 \end{cases}$$

Then

$$0 = \nabla \cdot [\mu(|\nabla\phi|/a_0)\nabla\phi - \nabla\phi_\mathrm{N}]$$

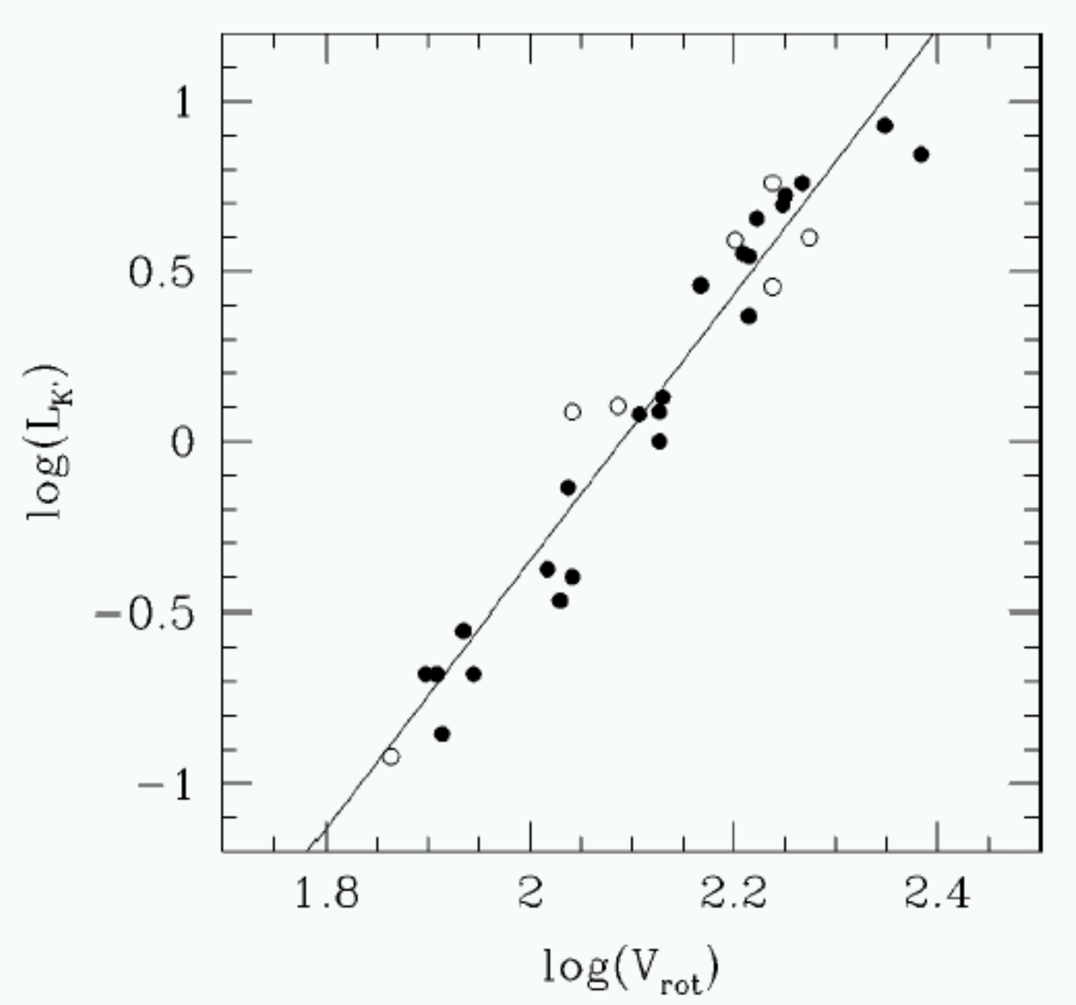
implies

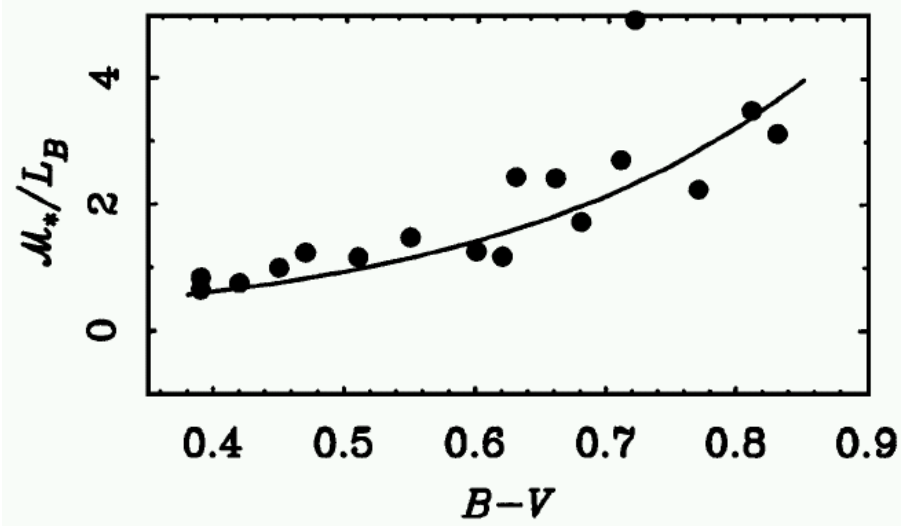
$$\mu(|\nabla\phi|/a_0)\nabla\phi = \nabla\phi_\mathrm{N} + \nabla \times \mathbf{A}$$

so when $\mathbf{A} \simeq 0$ and $|\nabla\phi| \ll 1$

$$\frac{|\nabla\phi|^2}{a_0} = |\nabla\phi_\mathrm{N}|$$

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





… 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

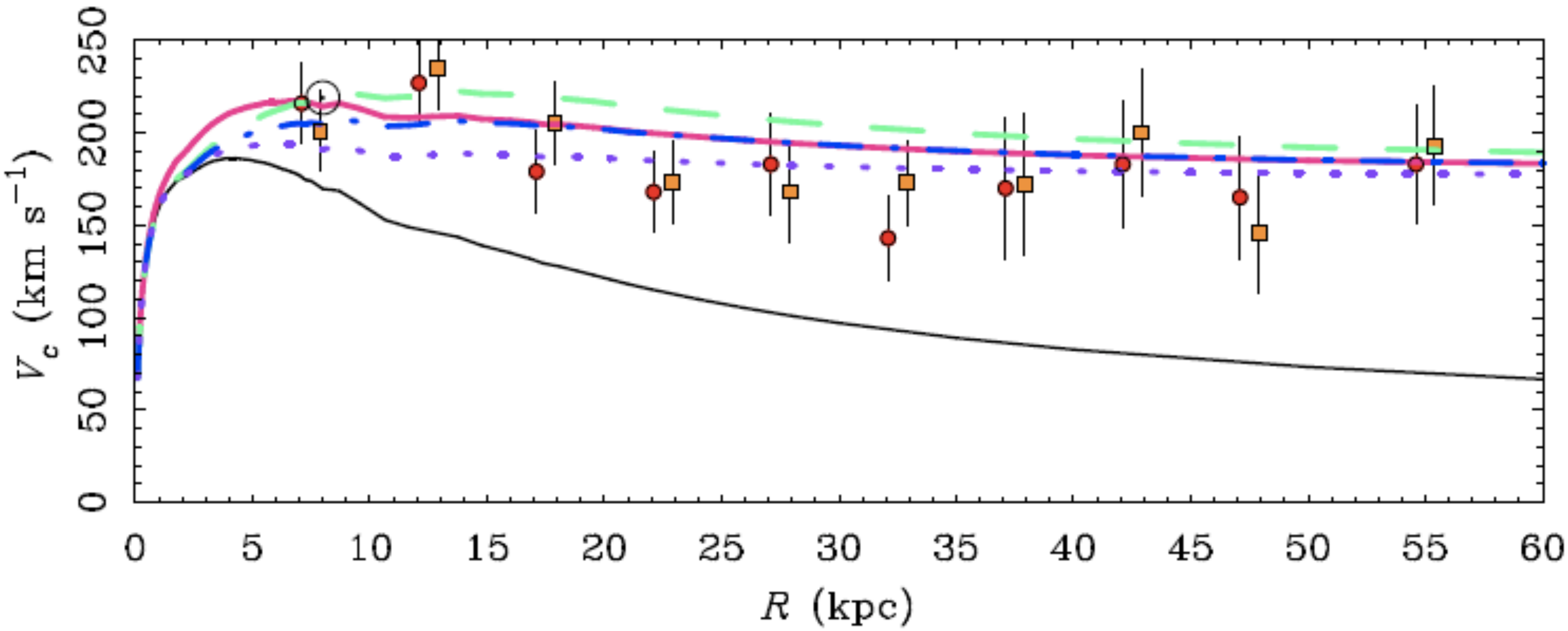
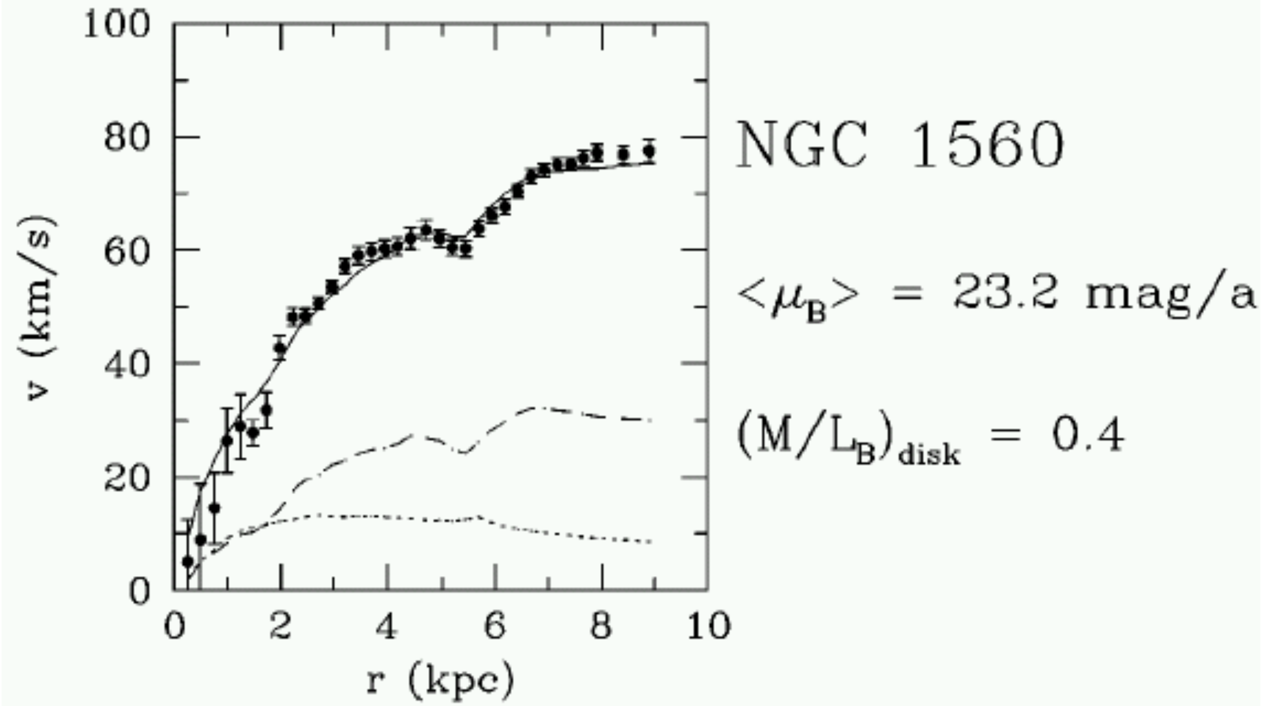
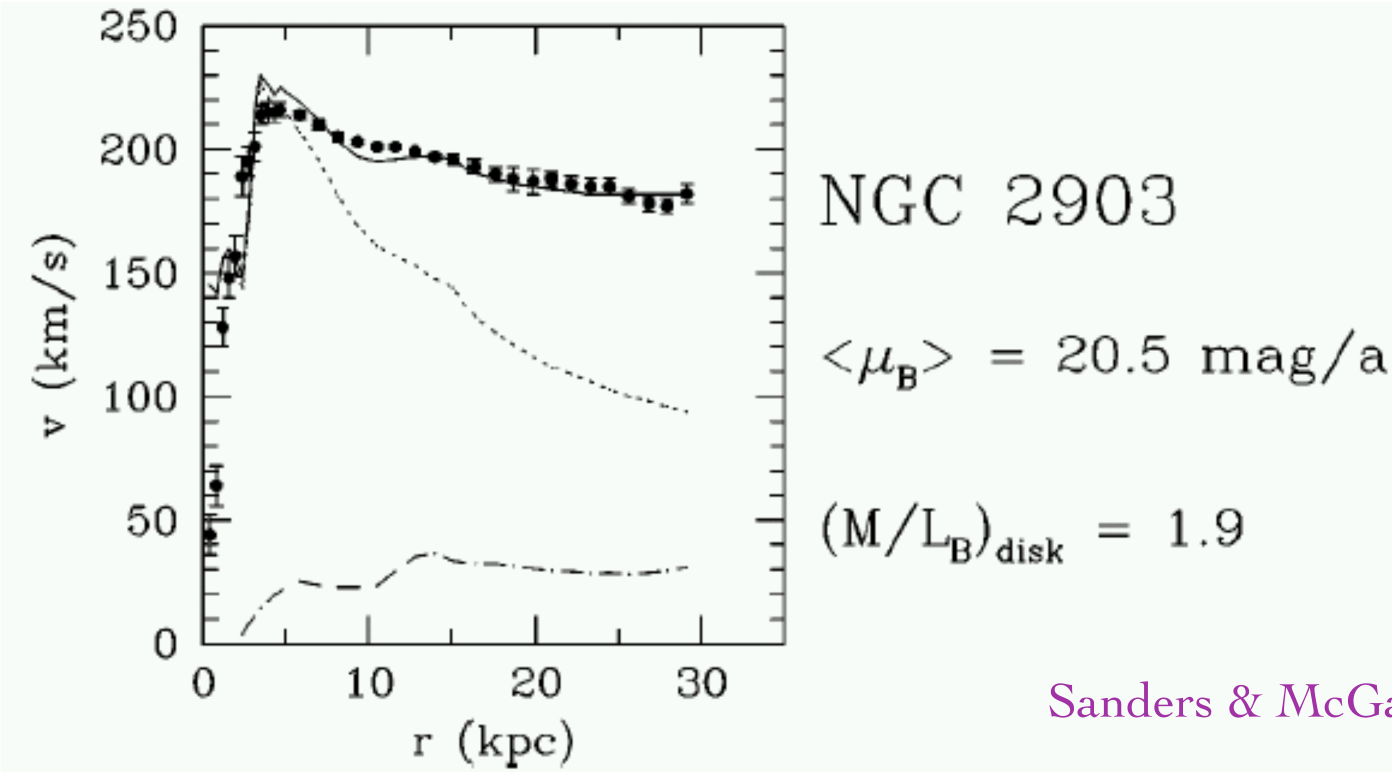


Fig. 7.— The outer rotation curve predicted by MOND for the Milky Way compared to the two realizations of the Blue Horizontal Branch stars in the SDSS data reported by Xue et al. (2008). The data points from the two realizations have been offset slightly from each other in radius for clarity; lines as 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]

Excellent fits to galactic rotation curves with $a_0 = 1.2\times10^{-8}$ cm s^{-2}

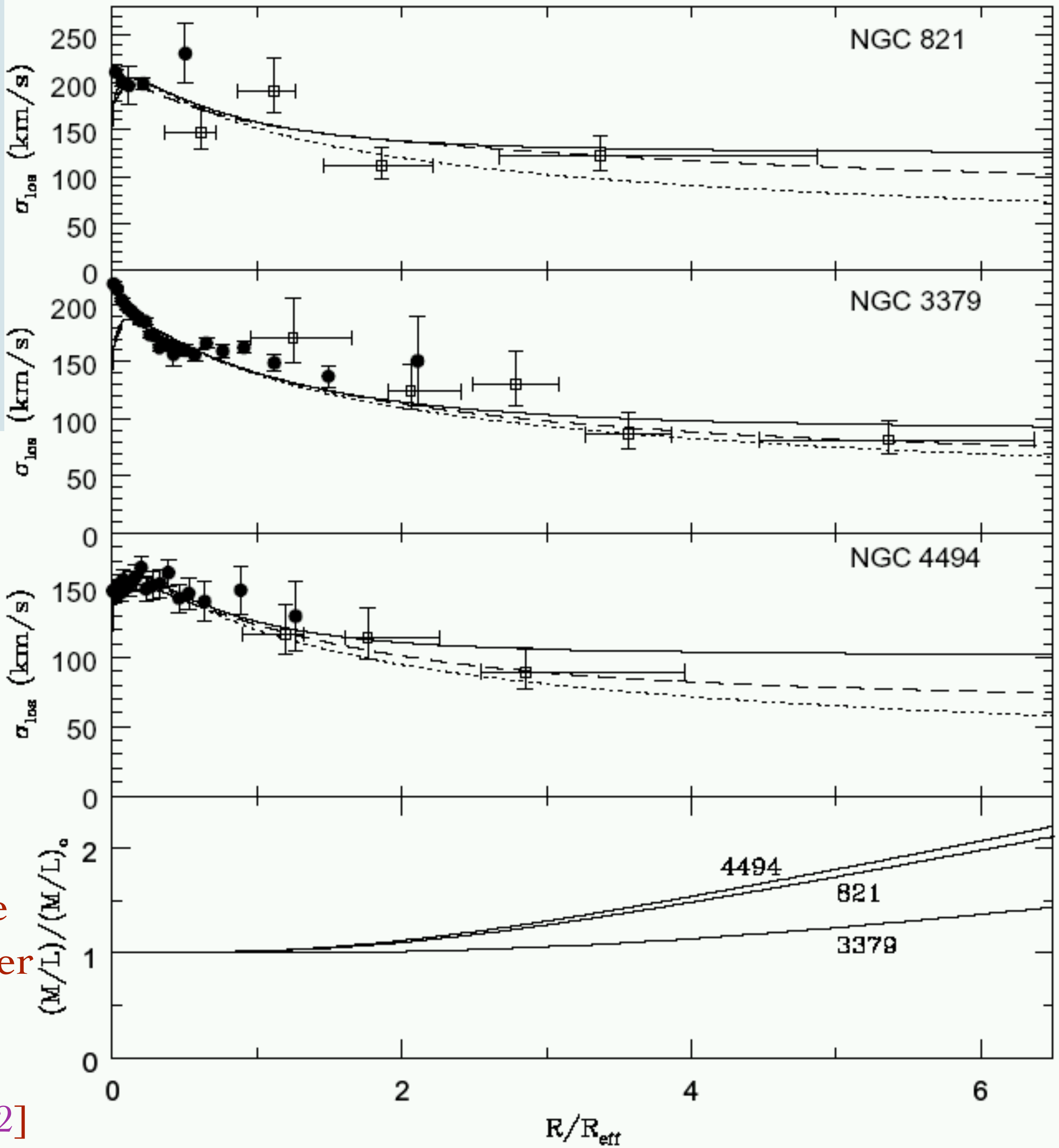




Features in the *baryonic* disc are clearly reproduced

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!



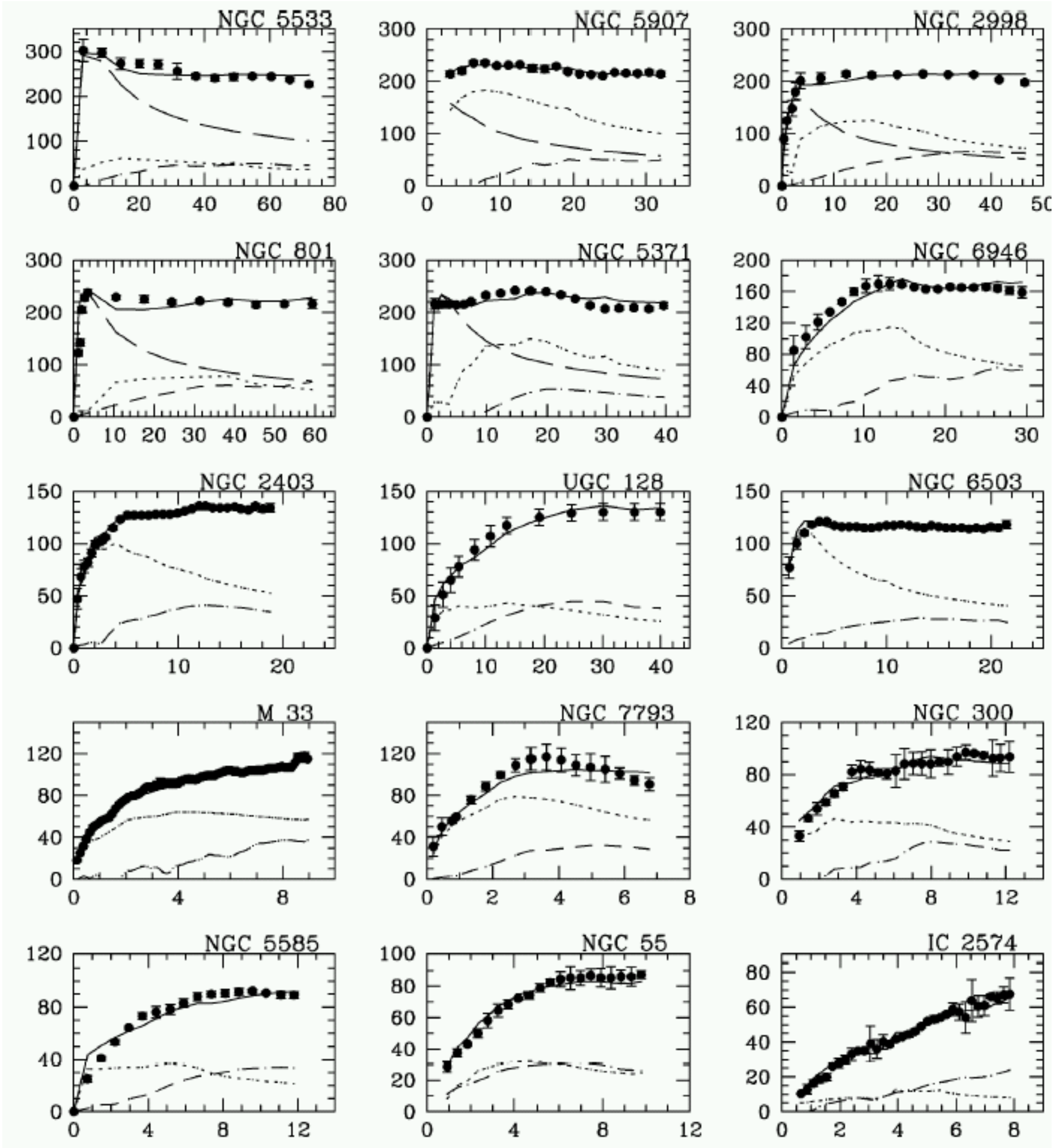
Data:
Romanowsky *et al* [astro-ph/0308518]

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

However this can also be explained in a dark matter model if the stars are on very elliptical orbits …
Dekel *et al* [astro-ph/0501622]

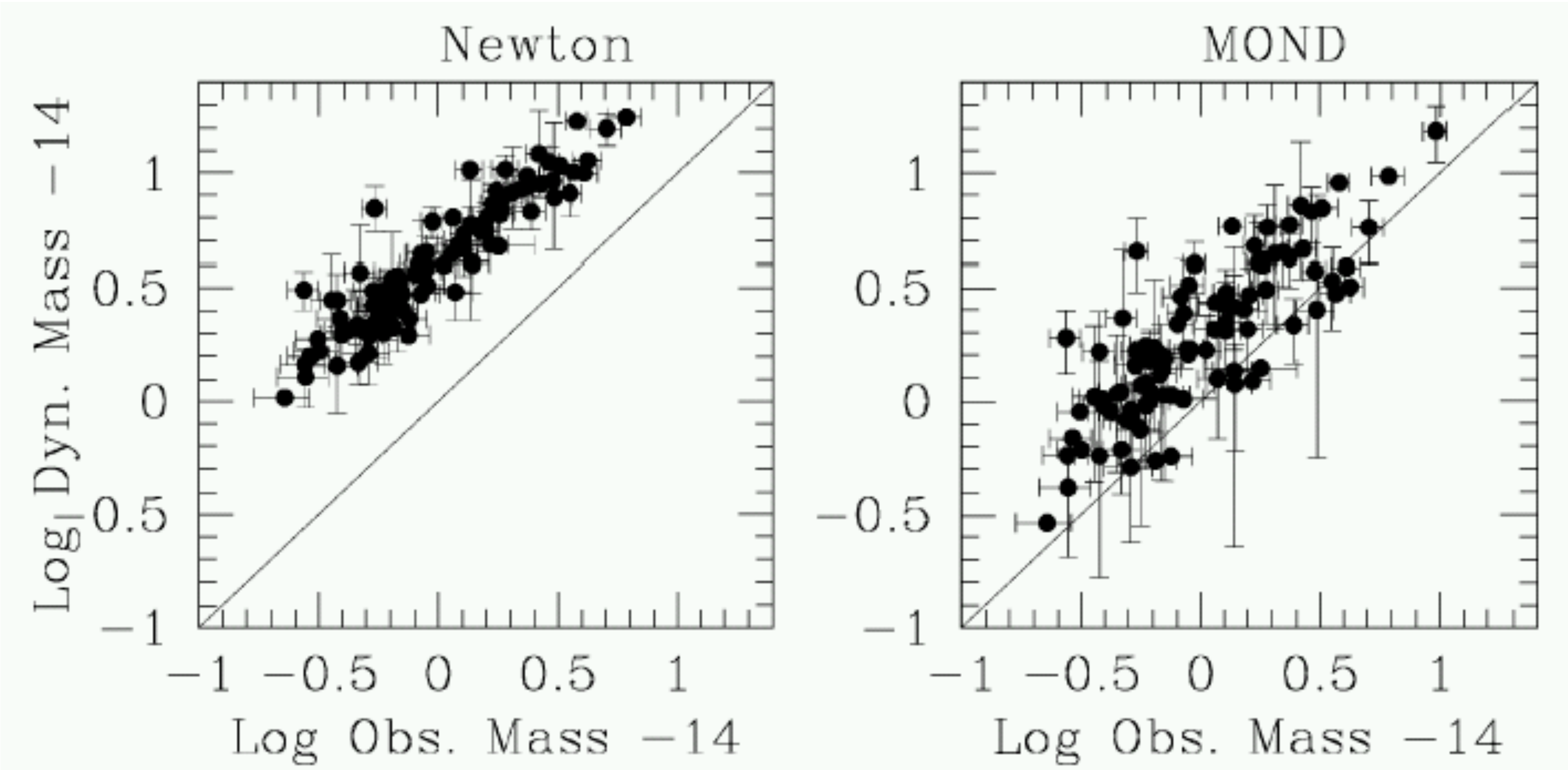
A huge variety of rotation curves is well fitted by MOND

… with fewer parameters than is required by the dark matter model

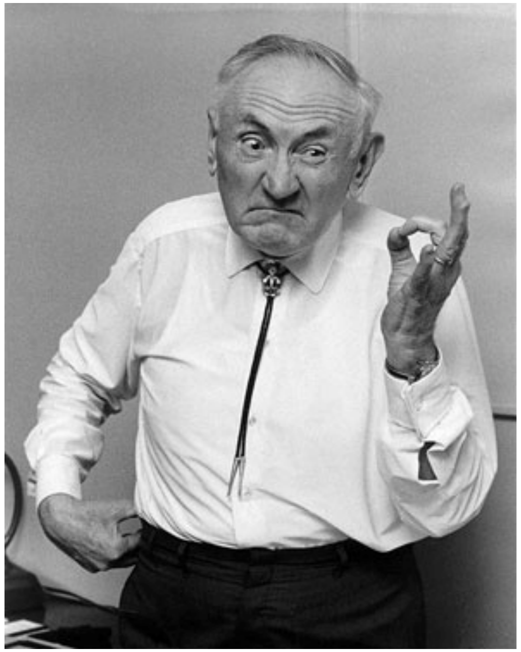


Sanders & Verheijen [astro-ph/9802240]

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)



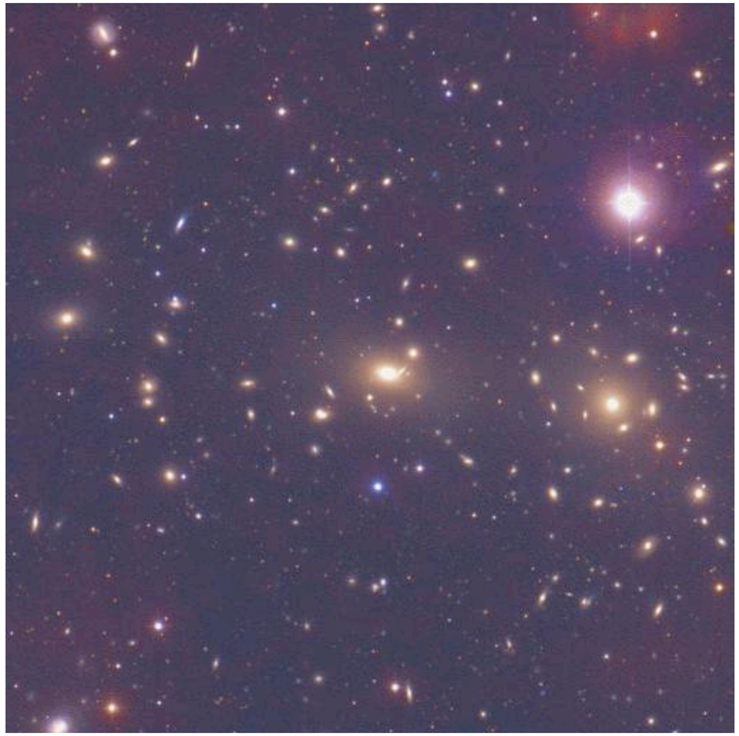
Fritz Zwicky (1933) measured velocity dispersion in the Coma cluster to be ~1000 km/s ➔ M/L ~O(100) Mo/Lo

"… 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"

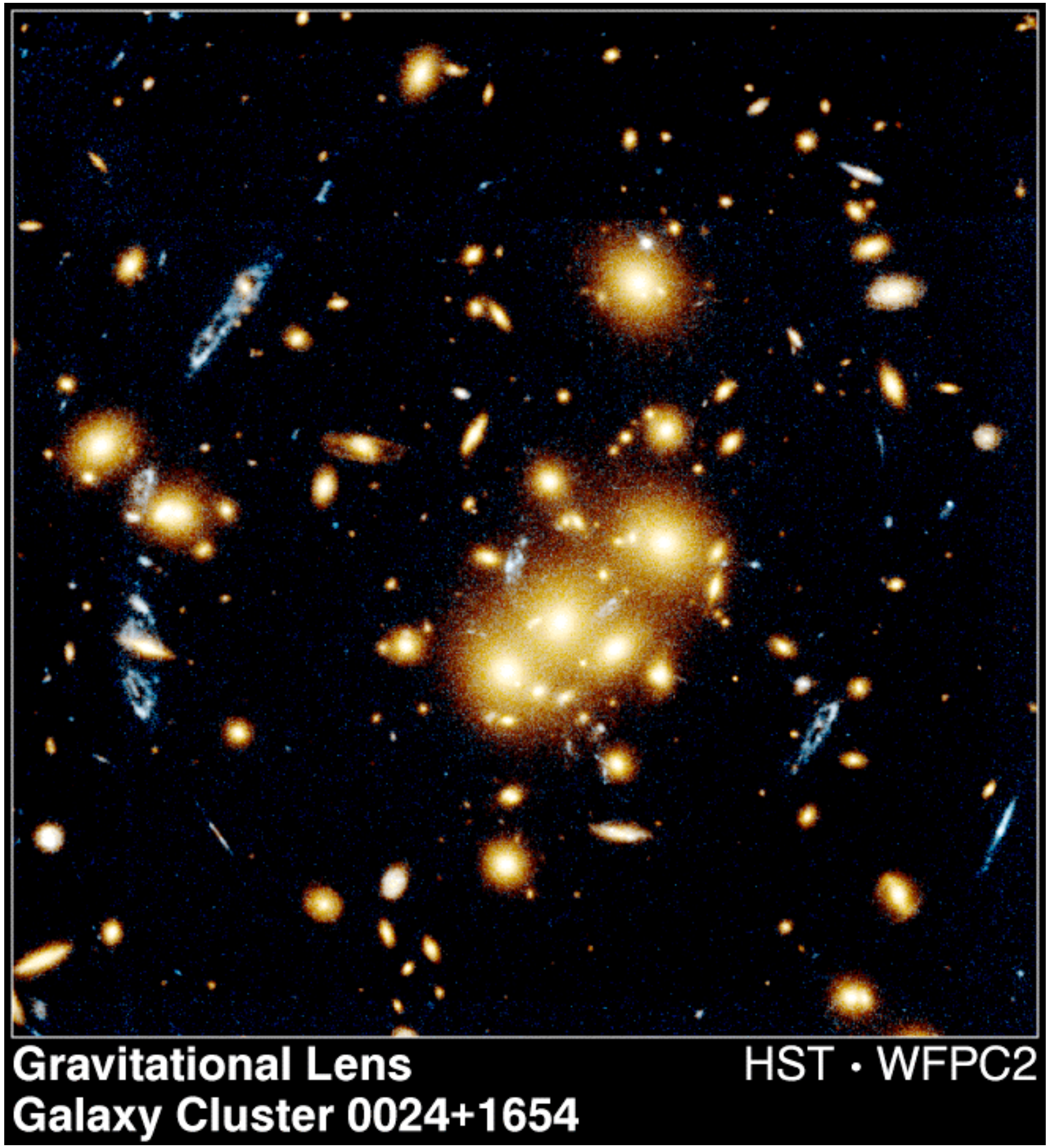
Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

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

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



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



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

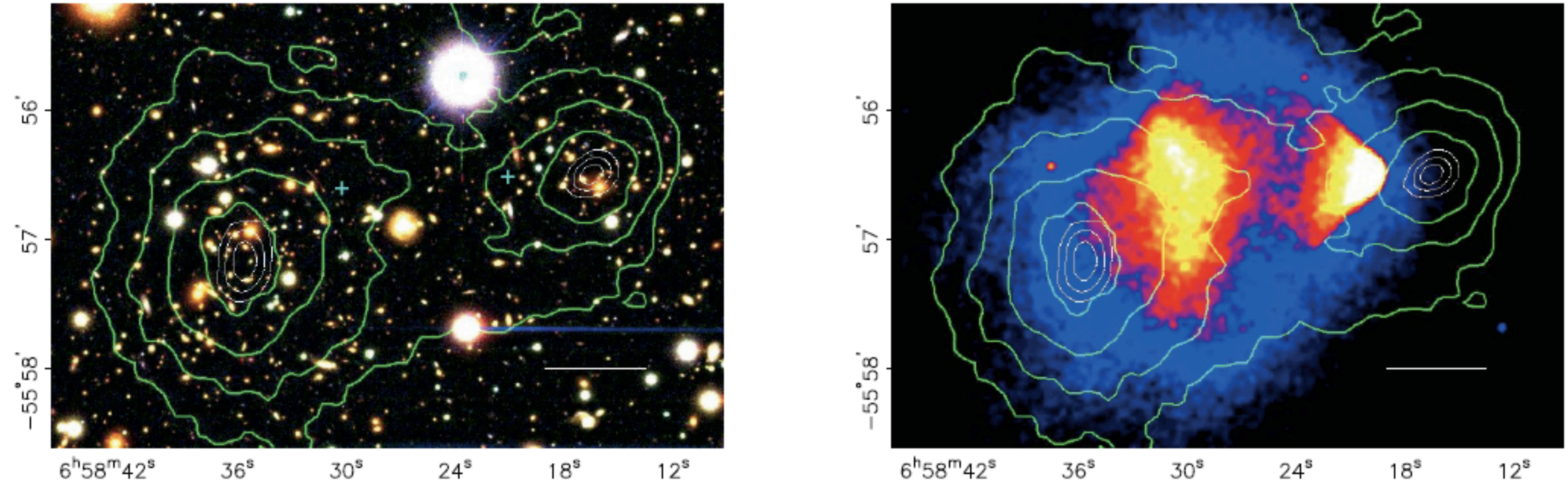


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at κ = 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]

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

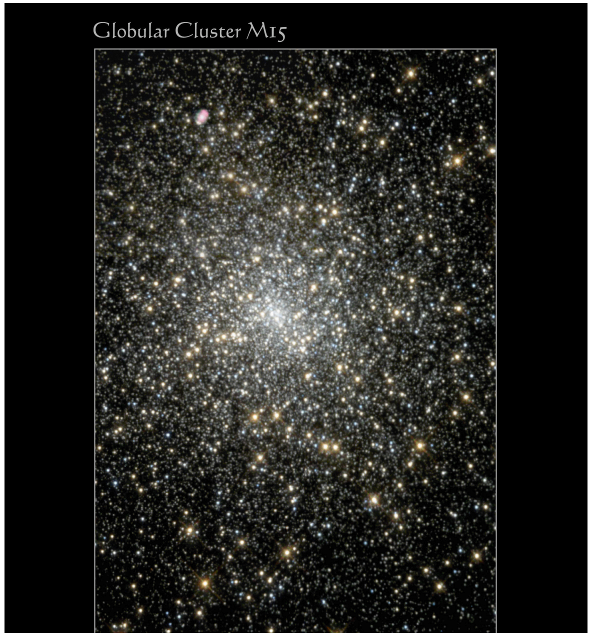
$\Omega \sim 0.005$

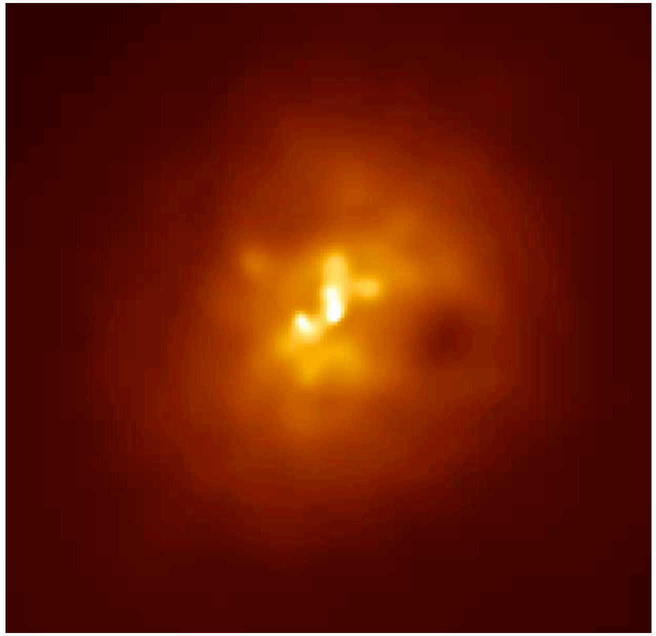
Interstellar gas

$\Omega \sim 0.005$

Hot gas in clusters

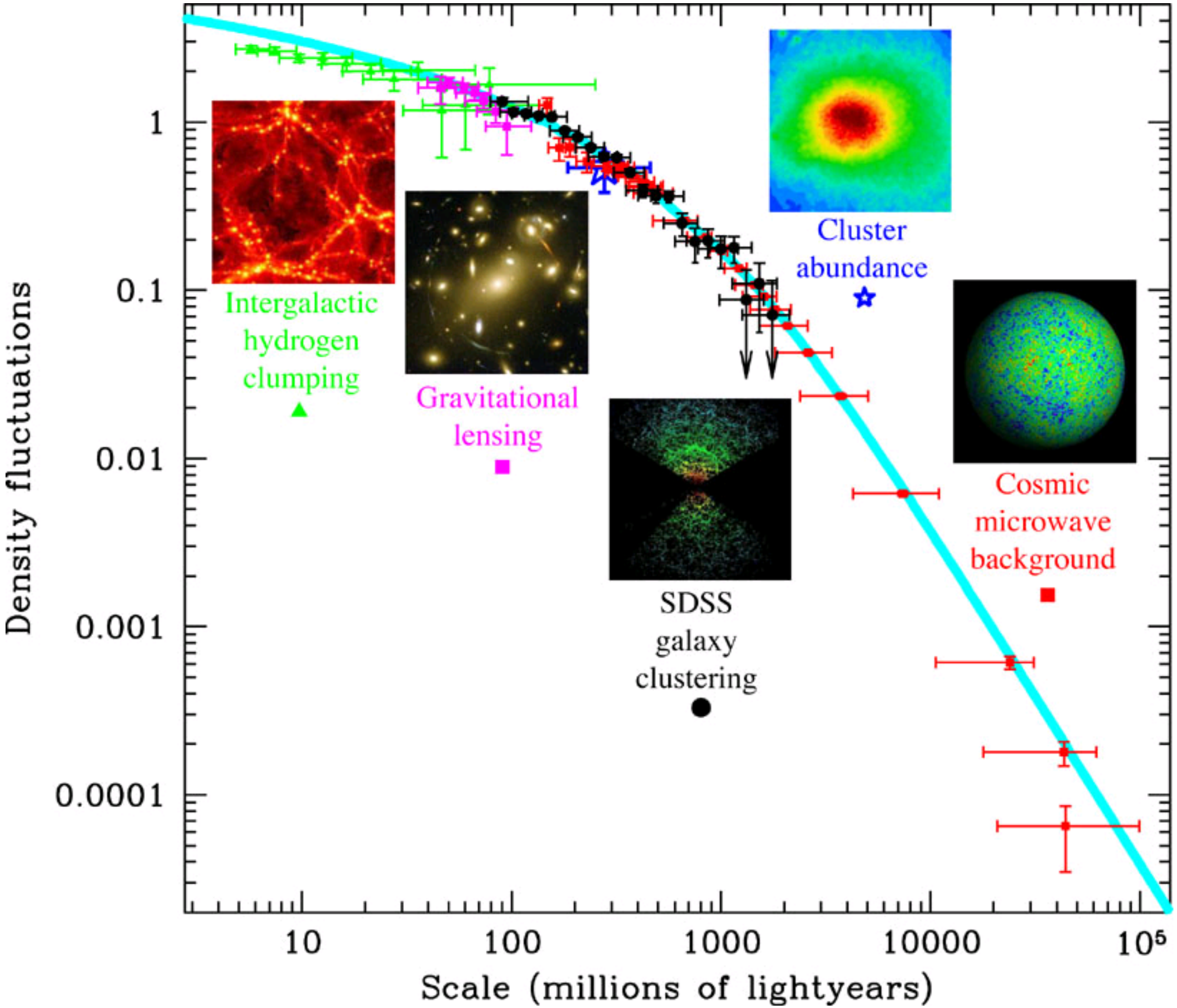
$\Omega \sim 0.03$





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

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



Courtesy: Max Tegmark

The large-scale structure (of the galaxy distribution) *requires* $\Omega_m >> \Omega_B$ if it has resulted from the growth under gravity of small initial density fluctuations - which left their imprint on the CMB at last scattering

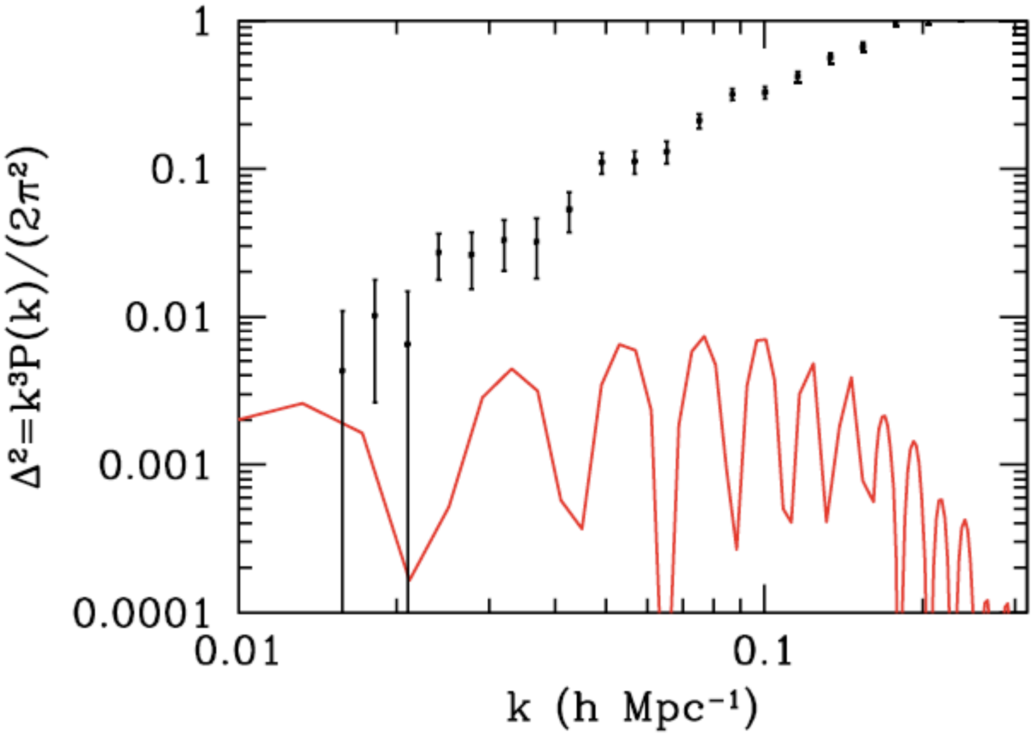


FIG. 1: Power spectrum of matter fluctuations in a theory without dark matter as compared to observations of the galaxy power spectrum. The observed spectrum [14] does not have the pronounced wiggles predicted by a baryon-only model, but it also has significantly higher power than does the model. In 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.

Detailed modelling of WMAP and 2dF/SDSS data gives: $\Omega_m \sim 0.3$, $\Omega_B \sim 0.05$

Dodelson & Liguori [astro-ph/0608602]

What *should* the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? $\tau \sim 10^{18}$ yr e^+ excess?!	'freeze-out' from thermal equilibrium Asymmetric (like the *observed* baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$
$\Lambda_{hidden\ sector} \sim (\Lambda_F M_P)^{1/2}$ $\Lambda_{see\text{-}saw} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$	Crypton? (hidden valley, sequestered) **Neutrinos**	Discrete (*very* model-dependent) Lepton number	$\tau > 10^{18}$ yr Stable.	Varying gravitational field during inflation Thermal (like CMB)	$\Omega_X \sim 0.3$? $\Omega_\nu > 0.003$
M_{string} M_{Planck}	Kaluza-Klein states? Axions	? Peccei-Quinn	? stable	? Field oscillations	? $\Omega_a \gg 1$!

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 $T \sim m_N/45$, 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* anti-baryons, so there must have been an **initial asymmetry**:

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

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

So the only form of matter we know exists was *not* born in thermal equilibrium

Sakharov conditions for baryogenesis:

1. Baryon number violation
2. C and CP violation
3. Departure for thermal equilibrium

B violation can occur even in the Standard Model through *non*-perturbative (sphaleron-mediated) processes down to $T \sim m_W$ … moreover out-of-equilibrium conditions are created if $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$ is a 1st order phase transition … however this is *not* the case for the SM and furthermore *CP*-violation is *too weak*

Thus the generation of the observed matter-antimatter asymmetry *requires* BSM physics (could be related to neutrino masses … if generated through violation of lepton number ➔ **leptogenesis**)

Alternatively, a TeV mass stable particle which *shares* in this asymmetry (e.g. a **techni-baryon**) would have the right abundance to be dark matter **… and explain the ratio of dark to baryonic matter**

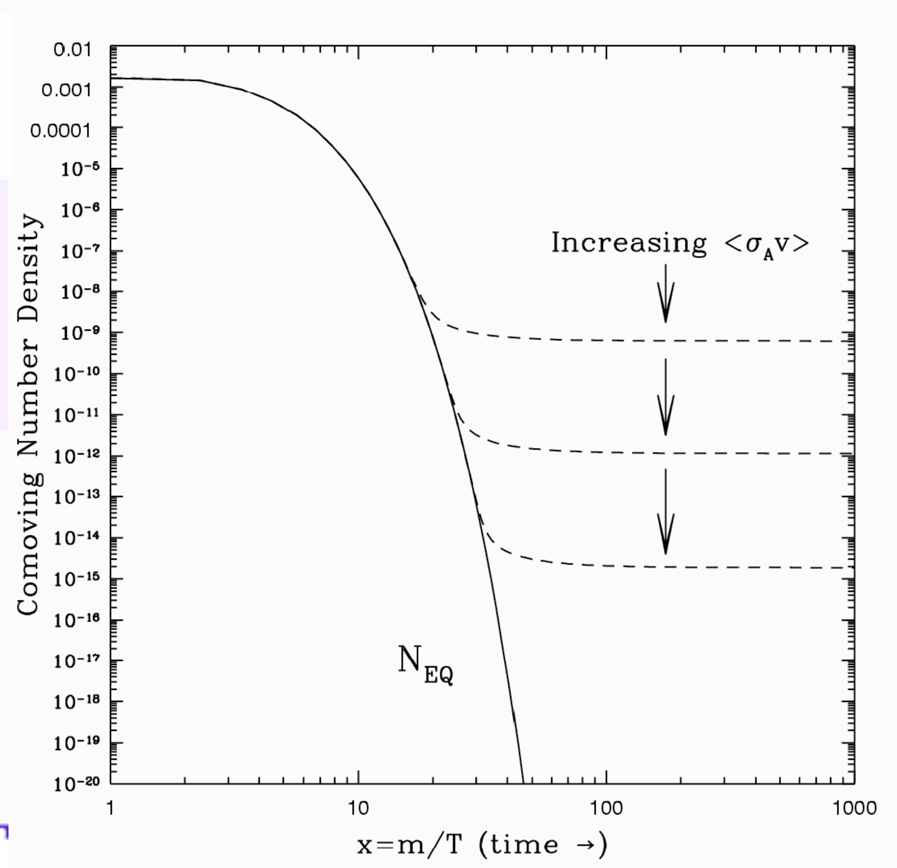
$$\frac{\rho_{\rm DM}}{\rho_{\rm B}} \simeq 6 \sim \frac{m_{\rm DM}}{m_{\rm B}} \left(\frac{m_{\rm DM}}{m_{\rm B}}\right)^{3/2} {\rm e}^{-m_{\rm DM}/T_{\rm dec|sphaleron}}$$

Thermal relics

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

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

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



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

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

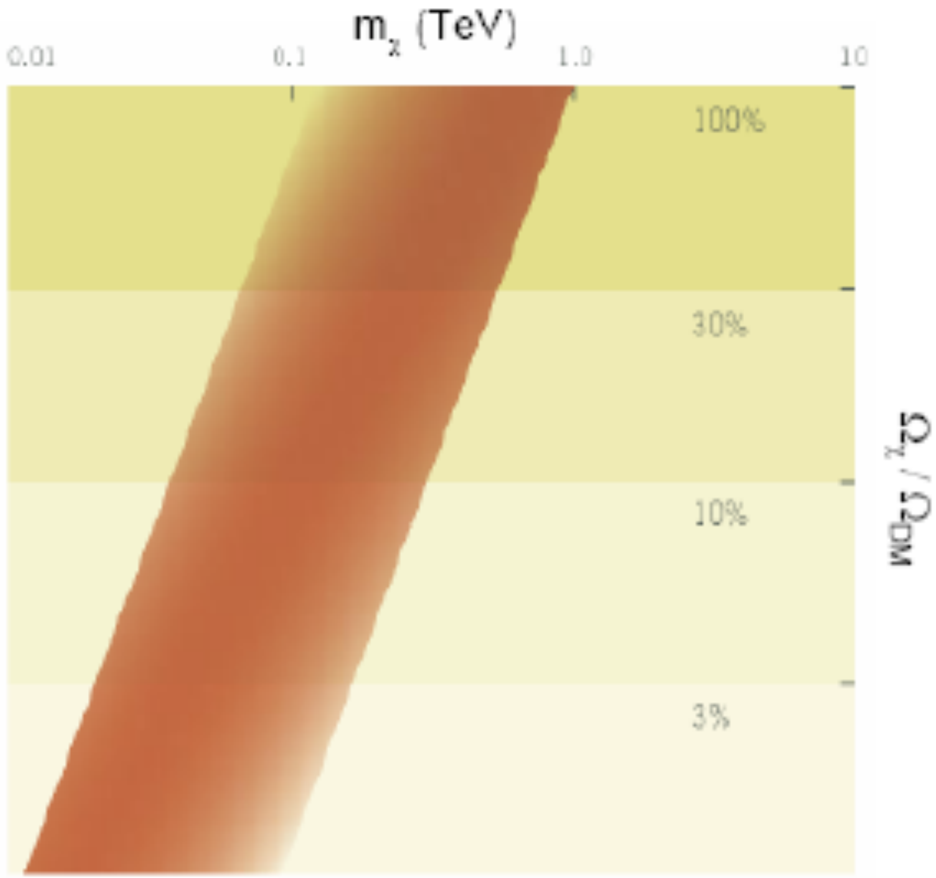
$$\text{Example 1 :} \quad \sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\mathrm{eV}$$

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

The lightest supersymmetric particle is typically neutral and stable through conservation of R-parity, thus a good candidate for **dark matter**

Its cosmlogical (thermal) relic abundance is naturally of the required order

$$\Omega_\chi \sim \langle\sigma_A v\rangle^{-1} \sim m_\chi^{\ 2}/(k\alpha^2)$$



(Courtesey: Lars Bergstorm)

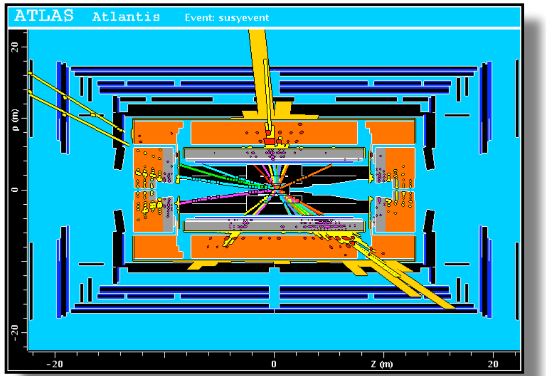
But is R-parity really *conserved* (matter-parity suffices to prevent nucleon decay)?!

The relic abundance of a **W**eakly **I**nteracting **M**assive **P**article matches that of the dark matter if the annihilation cross-section is ~1 TeV^{-2} … hence there are *many* candidates for WIMPS in extensions of physics beyond the Standard Model

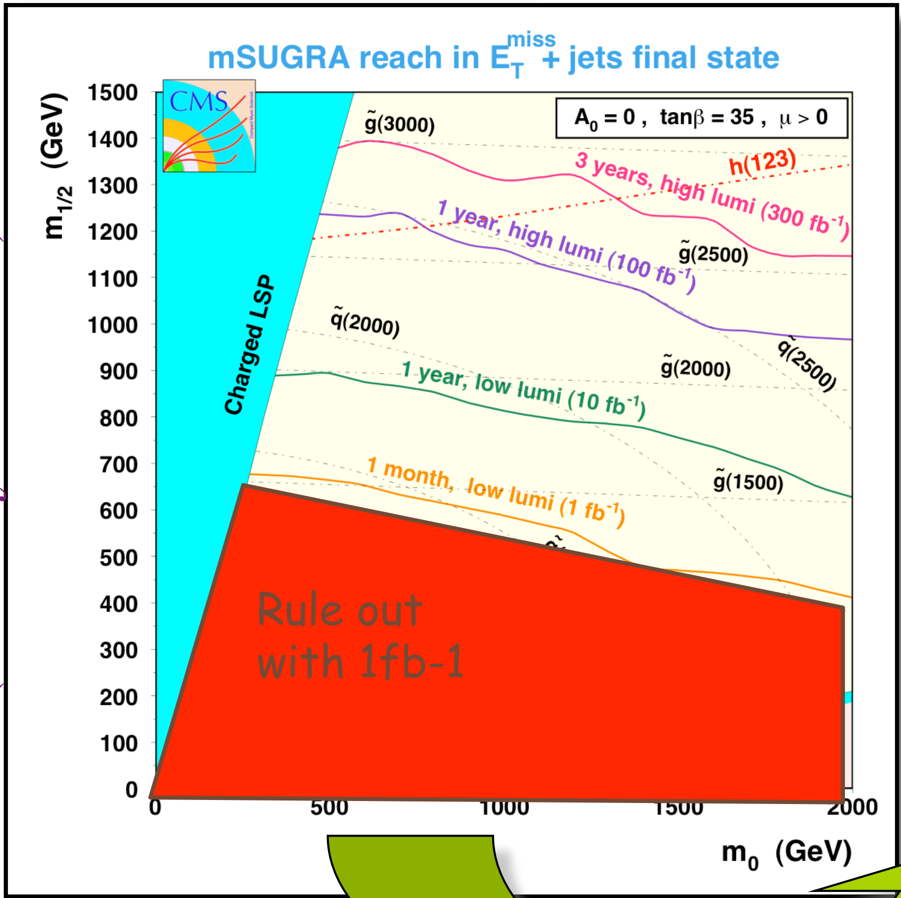
There must be a new conserved quantum number that ensures its stability (e.g. *R*-parity for the **L**ightest **S**upersymmetric **P**article) but the particle must *not* carry electric or colour charge (so it does not bind to ordinary nuclei and form unobserved anomalous isotopes) … thus dark matter might be made of e.g. relic **neutralinos** (if it is the LSP)

The LHC may directly produce the dark matter particles and complement searches that are being carried out using both *direct* means (underground nuclear recoil detectors) and *indirect* methods (looking for annihilation γ/ν or e^+/p^- from dark matter concentrations – Sun, dwarf satellites, Galactic Centre …)

LHC reach for SUSY dark matter

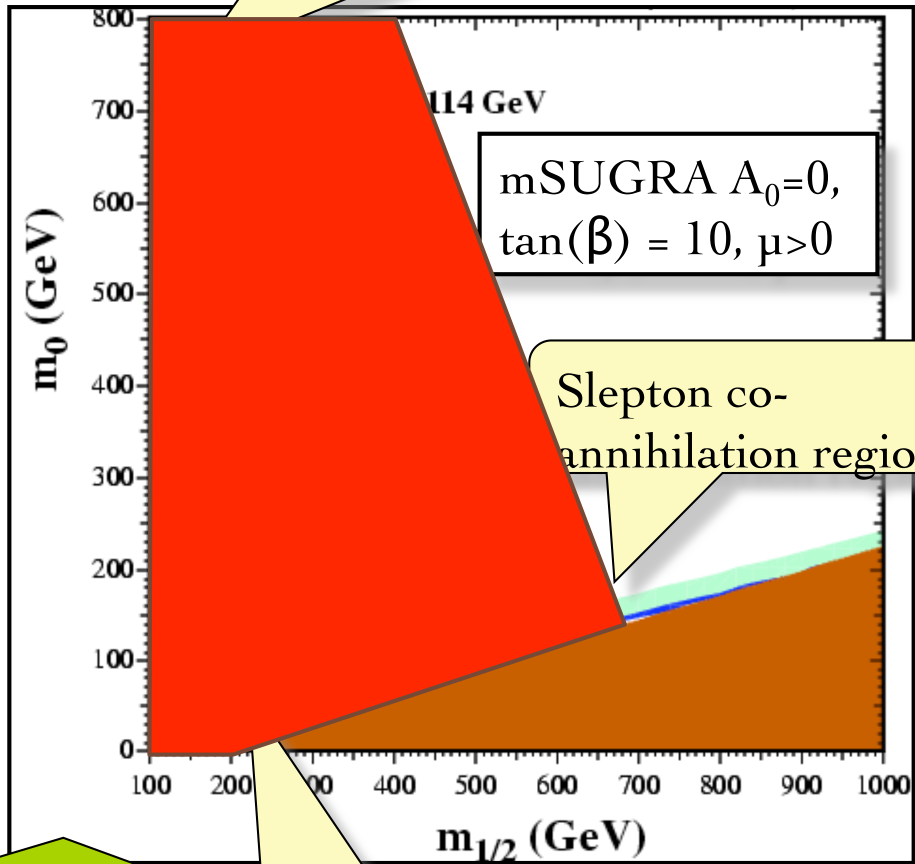


(Courtesey: Alan Barr)



WMAP constraints

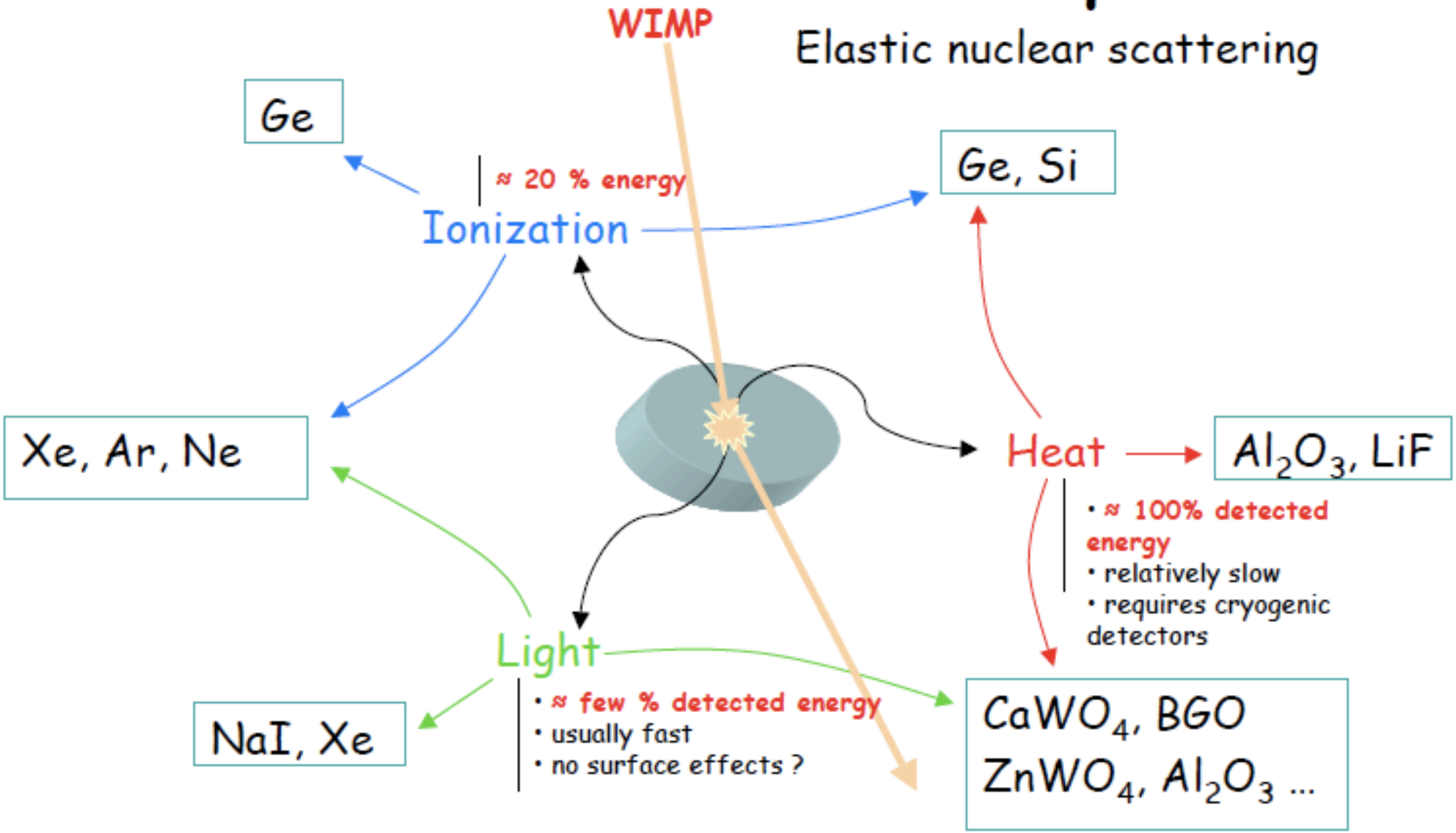
'Focus point' region: annihilation to gauge bosons



Slepton co-annihilation region

'Bulk' region: t-channel slepton exchange

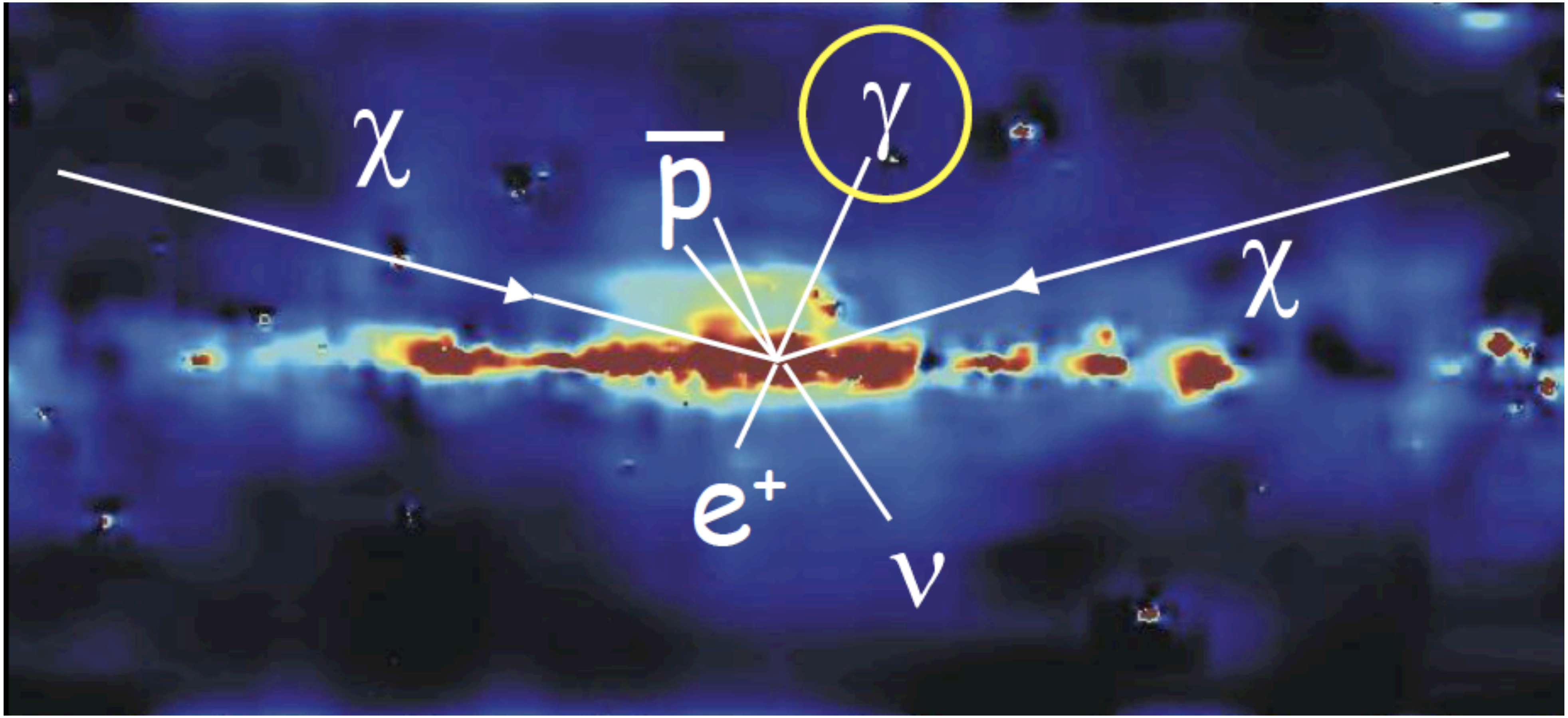
Direct detection techniques



(Drukier & Stodolsky 1984; Goodman & Witten 1985)

No detection so far … stringent upper limits (~10^{-43} cm^2) on eastic scattering cross-section, *assuming* local halo dark matter density ~ 0.3 GeV cm^{-3}

Many techniques for indirect detection … and many claims!



The WMAP 'haze' (radio), PAMELA 'excess' (e^+) … have been ascribed to dark matter annihilations (but may well be of astrophysical origin)

Nevertheless these offer probes of DM distribution at other locations in the Galaxy so usefully complement direct detection experiments

The *PAMELA* anomaly

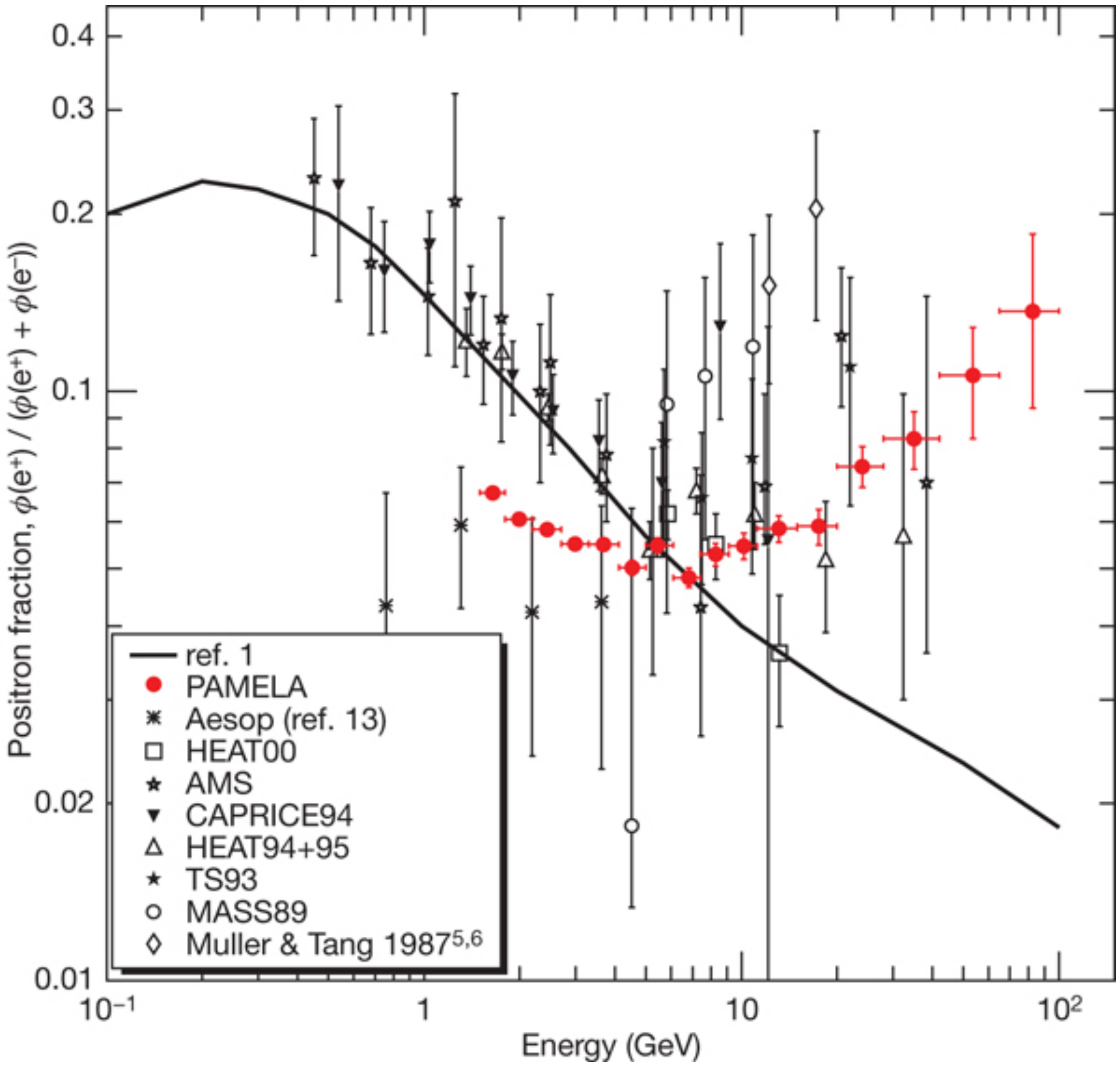
PAMELA has measured the positron fraction:

$$\frac{\phi_{e+}}{\phi_{e+} + \phi_{e-}}$$

Anomaly $\Rightarrow$ excess above 'astrophysical background'

Source of anomaly:

- DM decay/ annihilation?
- Pulsars?
- Nearby SNRs?



Nature 458:607,2009

… 200 papers and counting!

Dark matter as source of $e^{\pm}$

Dark matter annihilation

Annihilation rate $\propto n_{\rm DM}^2$

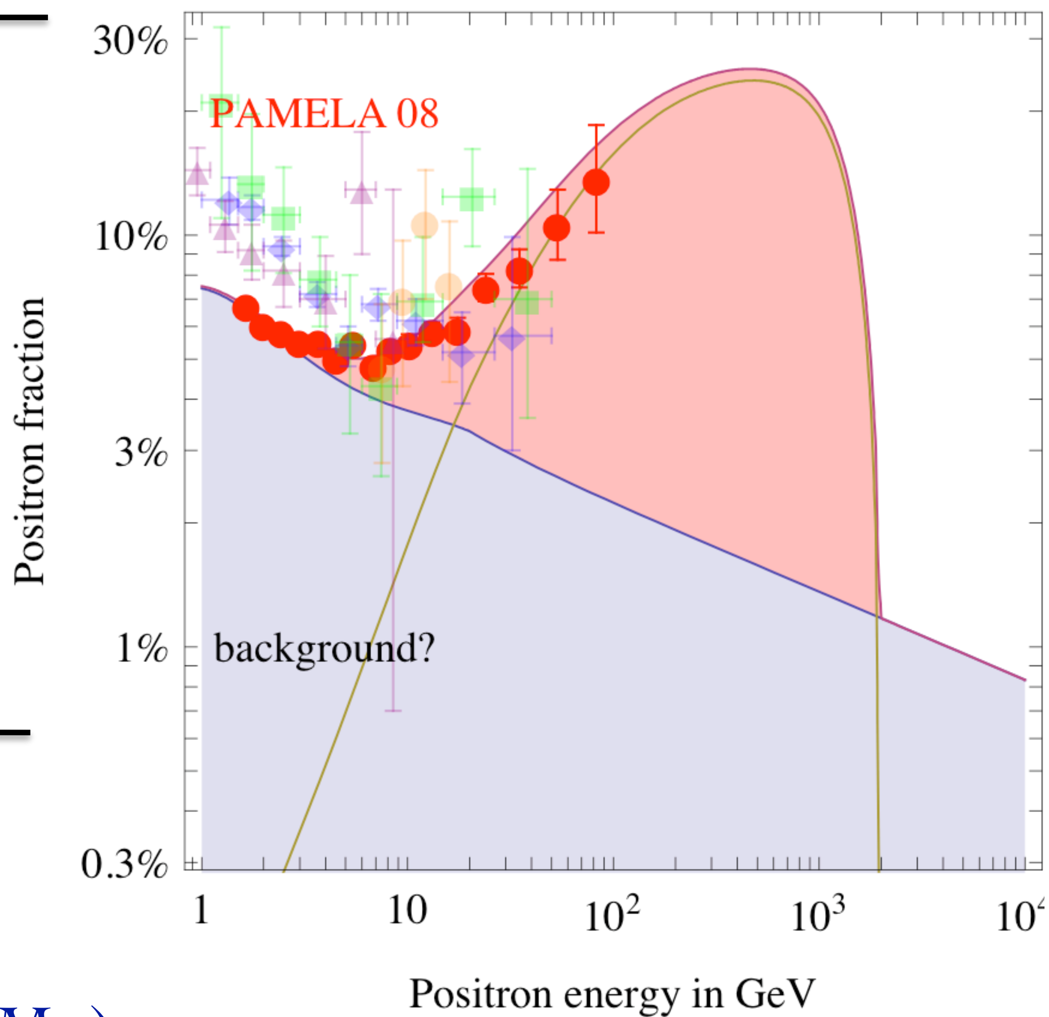
Leads eventually to SM particles

If WIMPs produced thermally, need astrophysical (clumping) or particle physics (Sommerfeld) enhancement to yield 'boost factor' of $\mathcal{O}(100)$

Dark matter decay

Similar, but decay rate $\propto n_{\rm DM}$

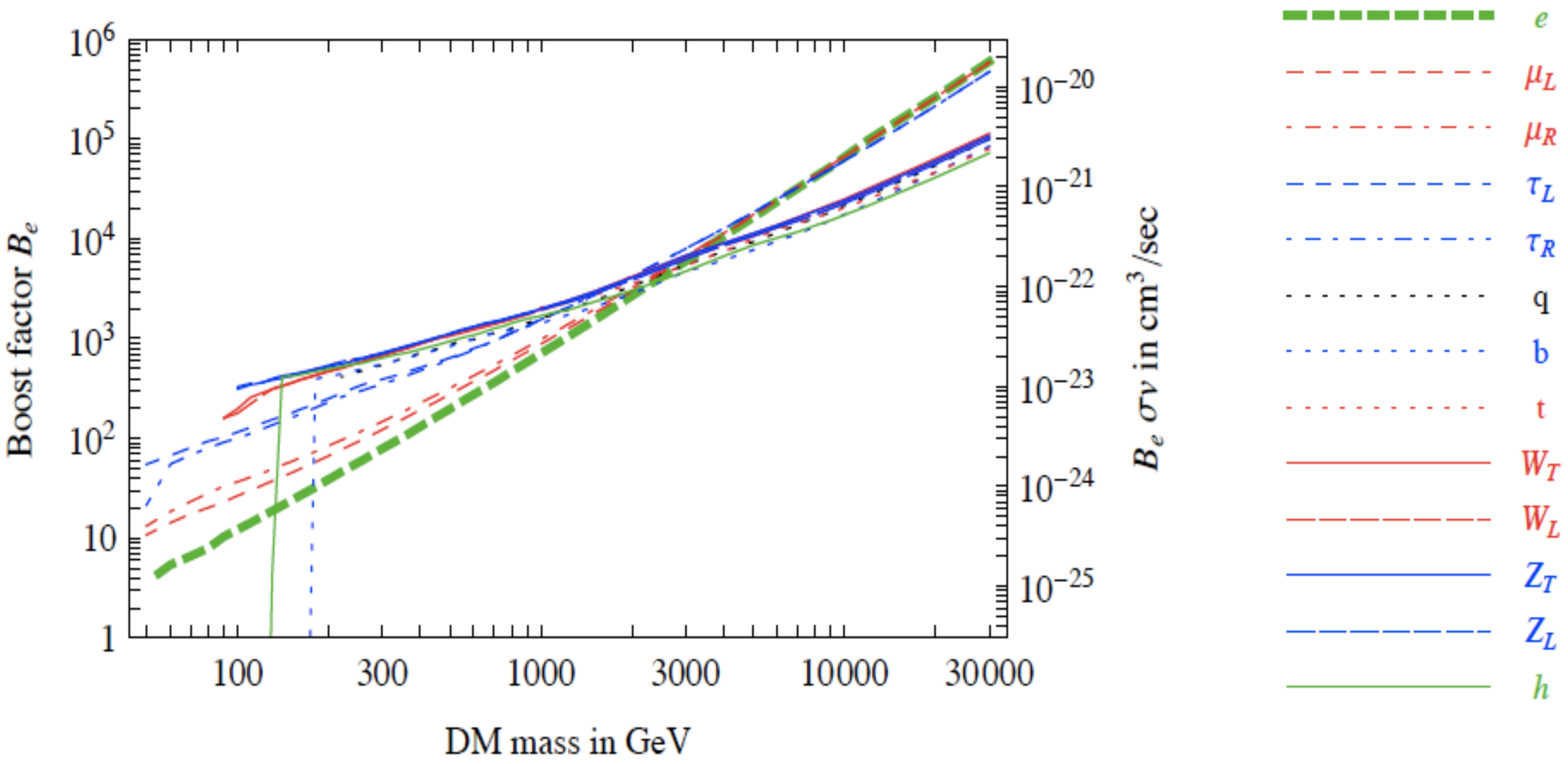
Lifetime ~ 10^9 x age of universe (dim-6 operator suppressed by $M_{\rm pl}$)



Nardi, Sannino & Strumia, JCAP 0901:043,2009

… but requires huge 'boost factor' of annihilation rate to match flux

➔ would imply in general negligible relic abundance unless strong velocity dependence (e.g. 'Sommerfeld enhancement') of annihilation #-section is invoked

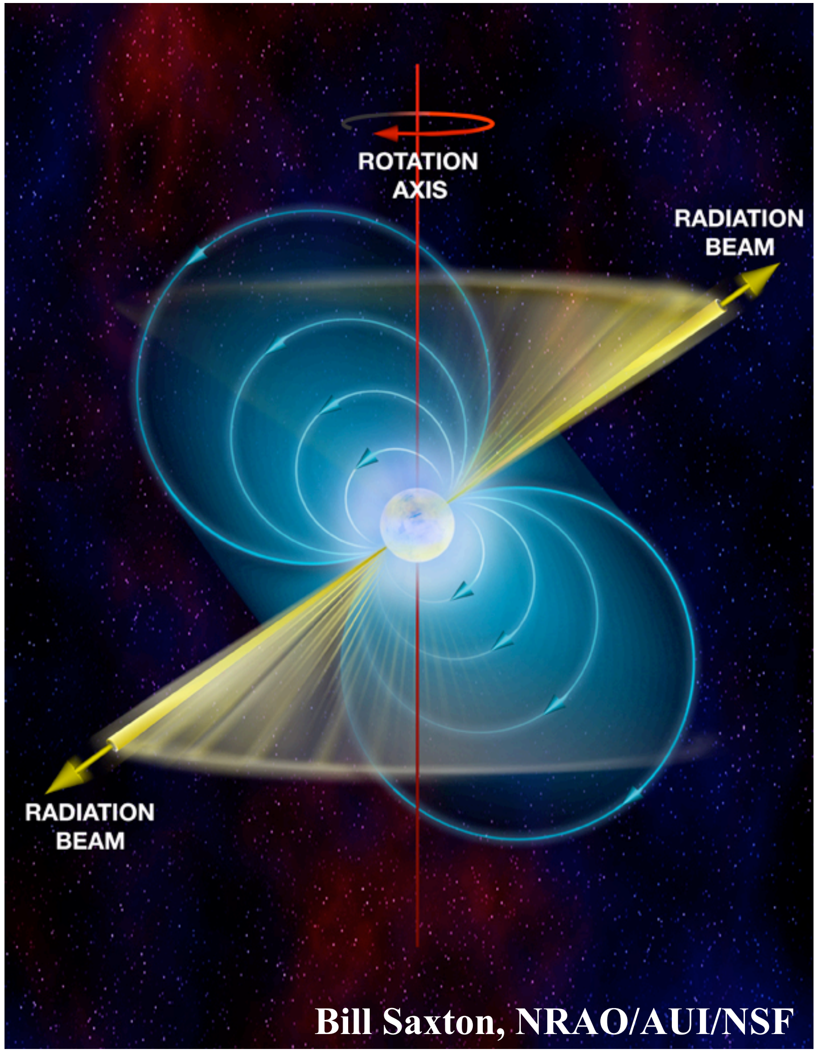


Cirelli, Kadastik, Raidal & Strumia Nucl.Phys.B813:1,2009

Nearby pulsars as source of $e^{\pm}$?

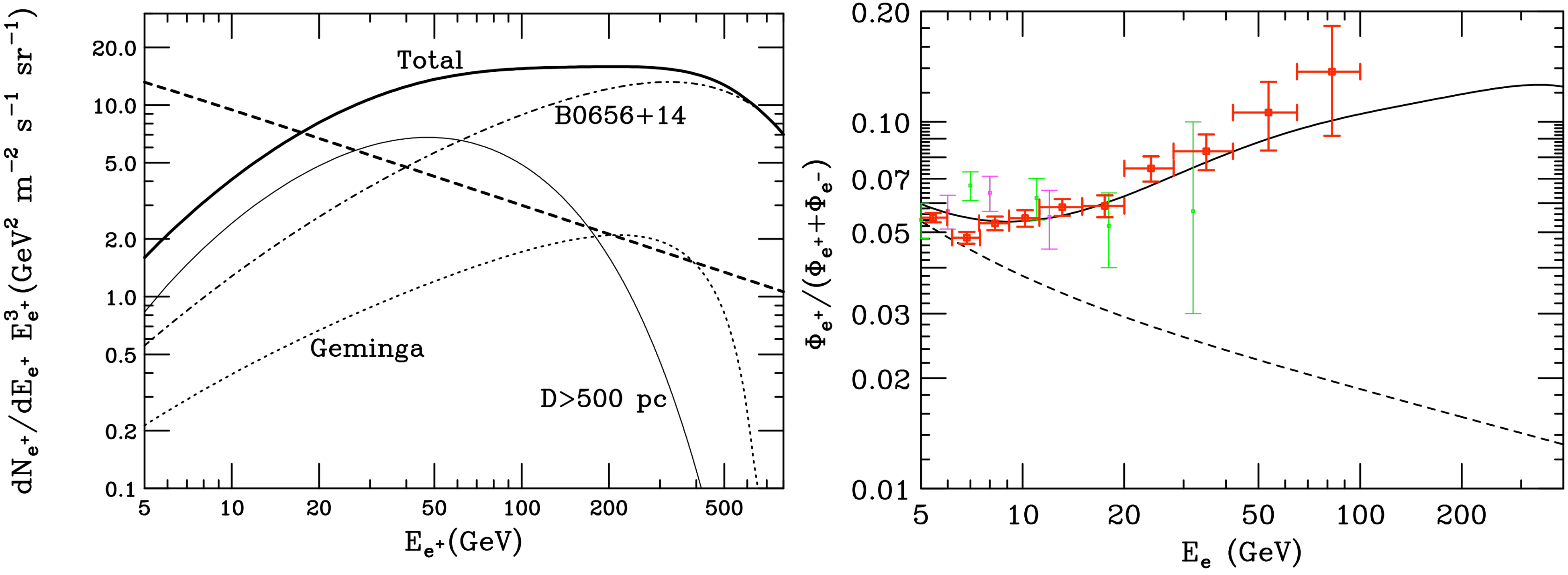
- Highly magnetized, fast spinning neutron stars
- γ rays and electron/ positron pairs produced along the magnetic axis
- Spectrum expected to be harder than background from propagation, *viz.*

$$N \propto E_e^{\pm -1.6} e^{-E_e^{\pm}/100\,\mathrm{GeV}}$$



Combination of galactic contribution and two nearby mature pulsars, **Geminga** (157 pc) and **B0656+14** (290 pc), *can* fit ***PAMELA*** excess

Hooper, Blasi & Serpico, JCAP 0901:025,2009



Parameters of pulsars are however not well known …

<u>Possible test</u>: ***FERMI*** may be able to detect expected anisotropy towards B0656+14 within 5 years

Nearby cosmic ray accelerator?

Rise in e^+ fraction could be due to secondaries being produced *during* acceleration … which are then accelerated along with the primaries

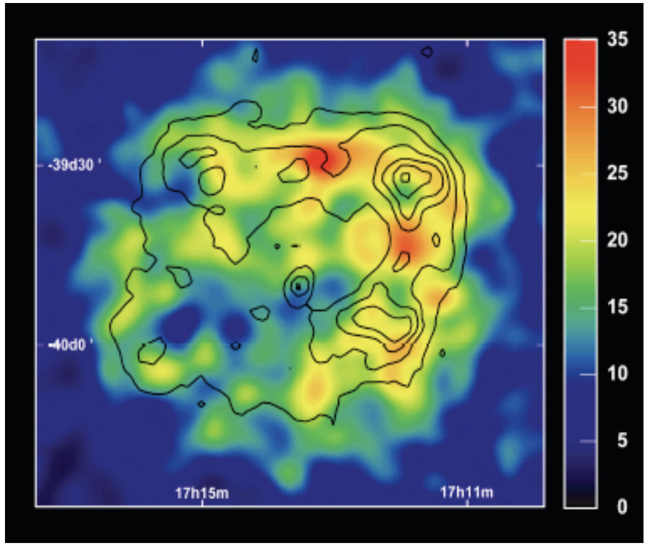
Blasi, arXiv:0903.2794

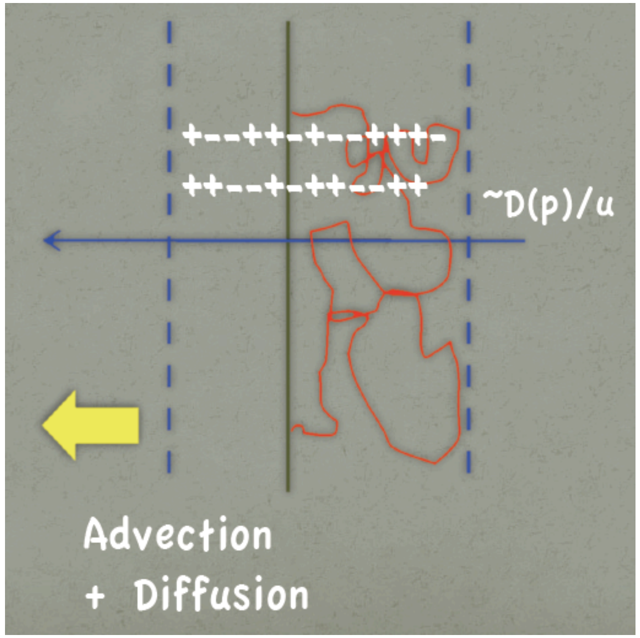
… assuming the sources of galactic cosmic rays are SNR, the ***PAMELA*** positron fraction can be well fitted

This is a generic feature of any *stochastic* acceleration process, if

$$\tau_{\rm acc} > \tau_{1\to 2}$$

(Cowsik 1979, Eichler 1979)

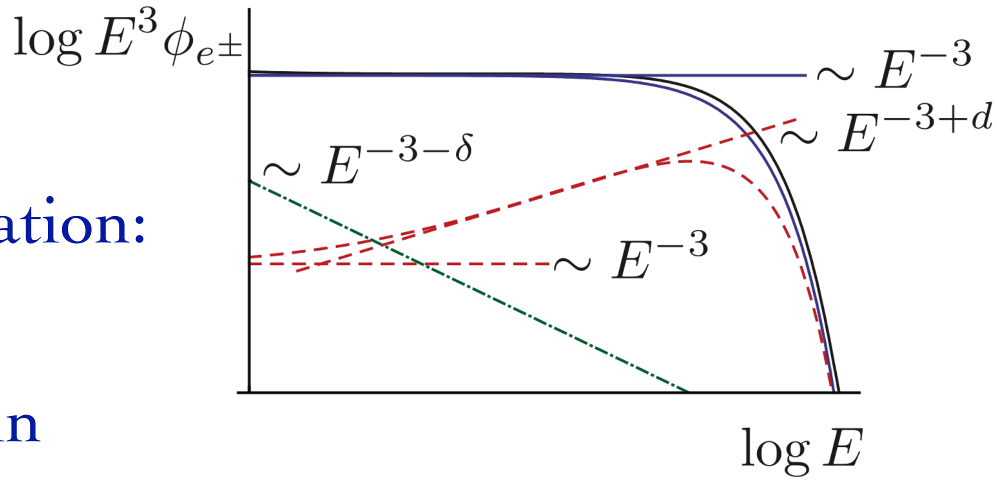




Acceleration of secondary $e^{\pm}$

Blasi, arXiv:0903.2794

Total electron + positron flux:

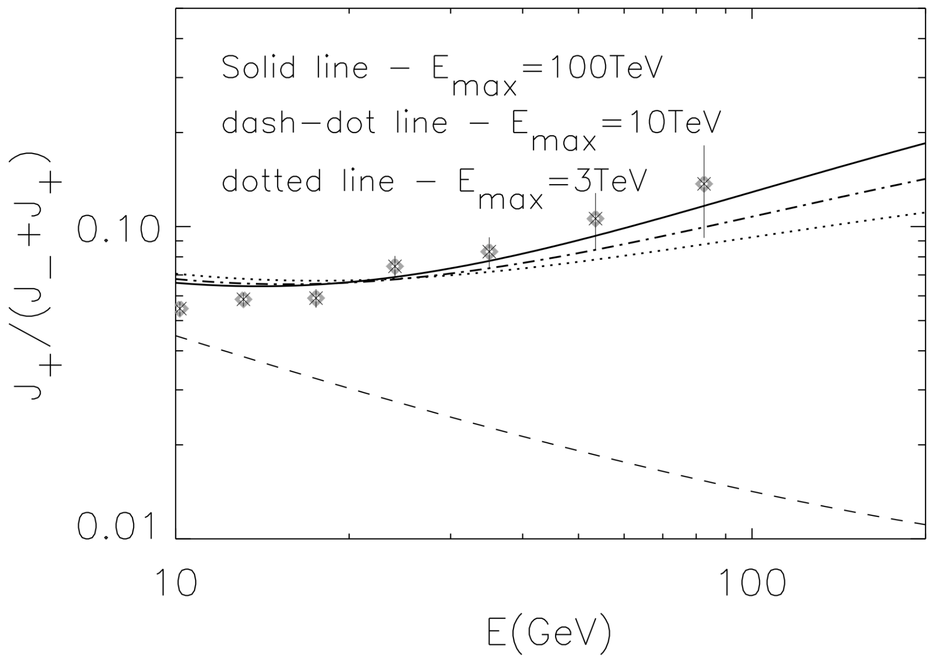


- primary electrons: $\sim E^{-3}$
- secondary $e^{\pm}$ from propagation: $\sim E^{-3-\delta}$
- secondary $e^{\pm}$, accelerated in source: $\sim E^{-\delta} + E^{d}$

Positron ratio:

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}} \simeq \frac{\phi_{e^+}}{\phi_{e^-}}$$

$$\sim \frac{E^{-3-\delta} + E^{-3+d}}{E^{-3}} \sim E^{-\delta} + E^{d}$$



Summary – dark matter

Experimental situation reminiscent of search for temperature fluctuations in the CMB in the '80s … there were 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

keep an open mind!