Cosmology beyond the Standard Model

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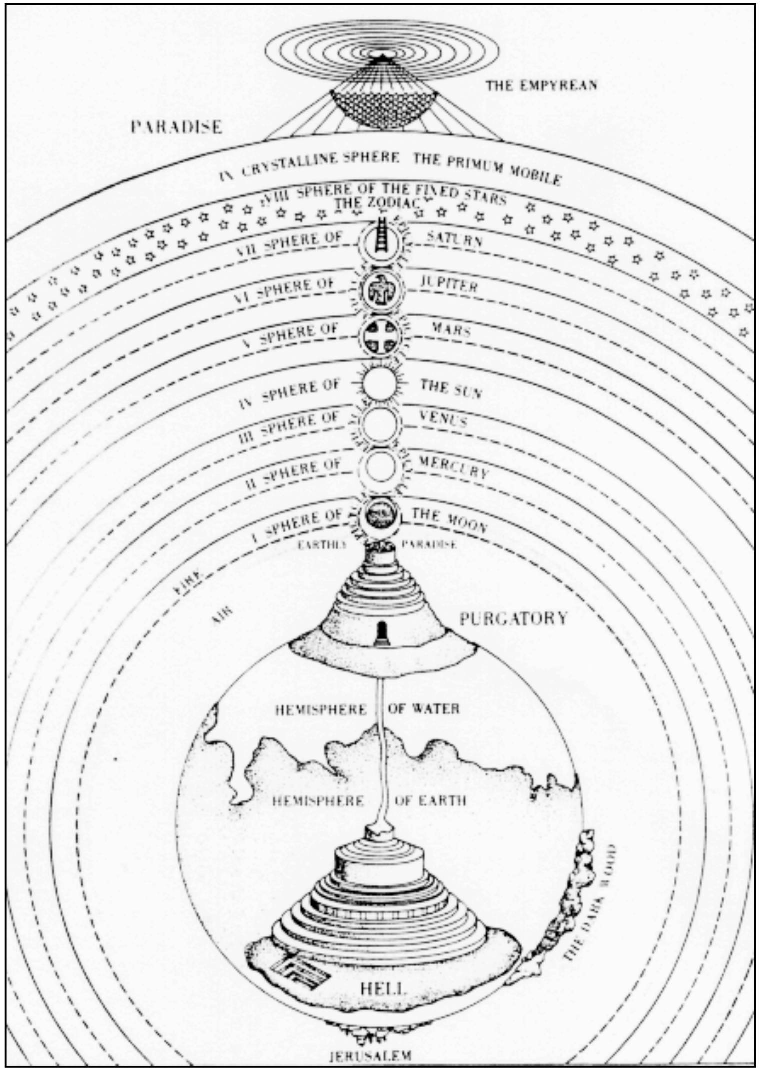
COSMO 07 AT SUSSEX

In the Aristotlean 'standard model' of cosmology (circa 350 BC) the universe was *static* and *finite* and *centred on the Earth*

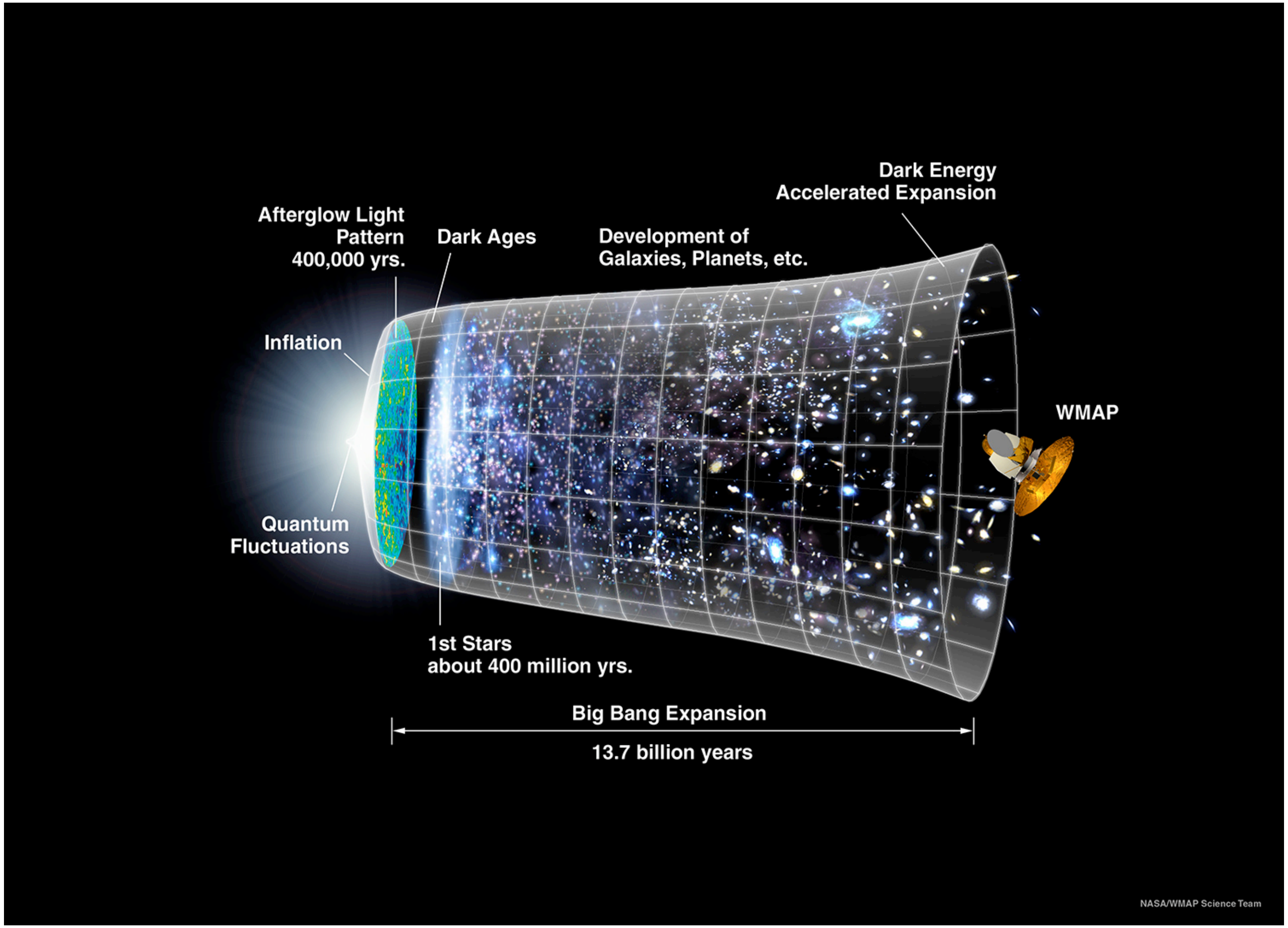


The Divine Comedy, Dante Allighieri (1321)

This was a 'simple' model and fitted all the observational data but the underlying dynamical principle was not physical

Today we have a new 'standard model' of the universe …

dominated by dark energy and undergoing accelerated expansion



It too is 'simple' and fits all the observational data but has no underlying dynamical physical principle

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

$$\begin{aligned}\mathcal{L}_{\rm eff} &= M^4 + M^2\Phi^2 \quad \textit{Higgs mass correction} && \textbf{super-renormalisable}\\ &+ (D\Phi)^2 + \bar{\Psi}\, \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2 && \textbf{renormalisable}\\ &+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots && \textbf{non-renormalisable}\end{aligned}$$

The effects of new physics beyond the SM (neutrino mass, nucleon decay, FCNC ...) $\Rightarrow$ Non-renormalisable operators suppressed by M^n … so 'decouple' as $M \rightarrow M_P$

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 (100 new parameters)

This immediately provides possible sources for **dark matter**, **baryogenesis**, **inflation** (as do other proposed extensions of the SM, e.g. new dimensions @ TeV scale)

The 1st term has *no* effect on microphysics - undetectable in the laboratory

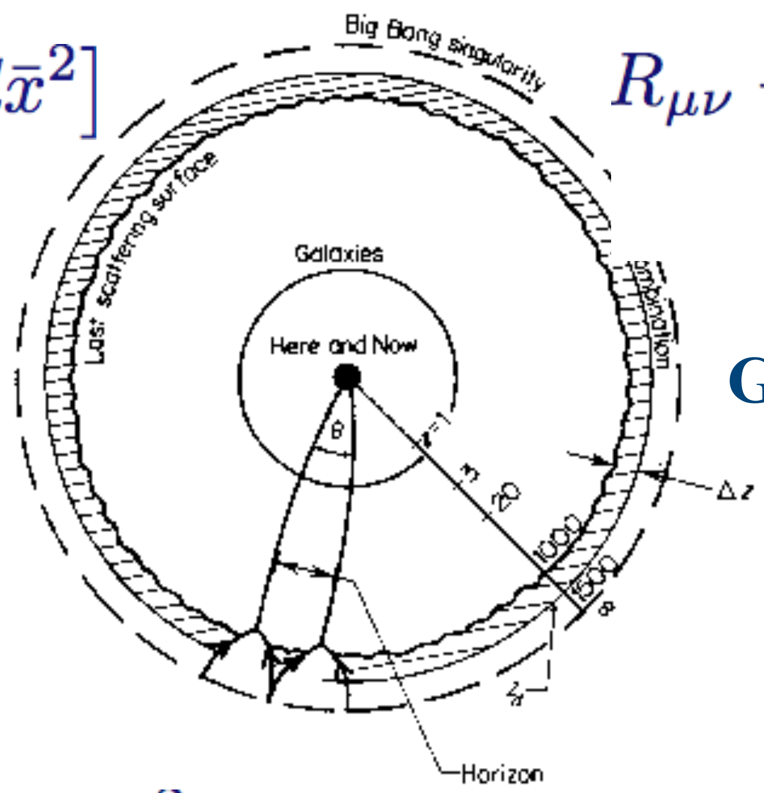
However it does *couple to gravity* so the SM makes a disastrous prediction:
ρ_Λ ~1 TeV^4 … i.e. at least 10^{60} x the cosmologically allowed value!

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



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

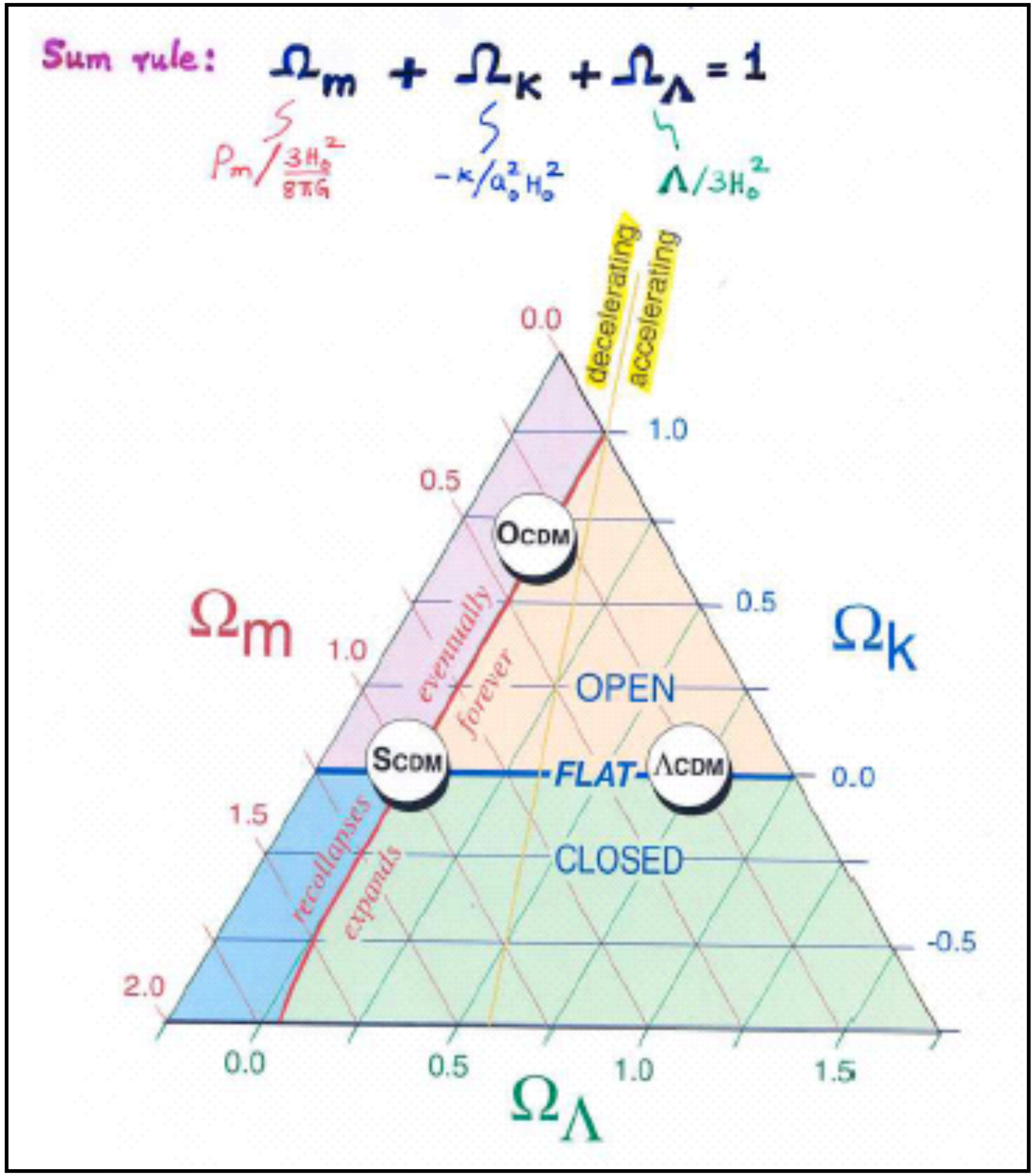
Geometrodynamics:
Einstein

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

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

… so *naturally* exhibits dark energy (and curvature) at late times!

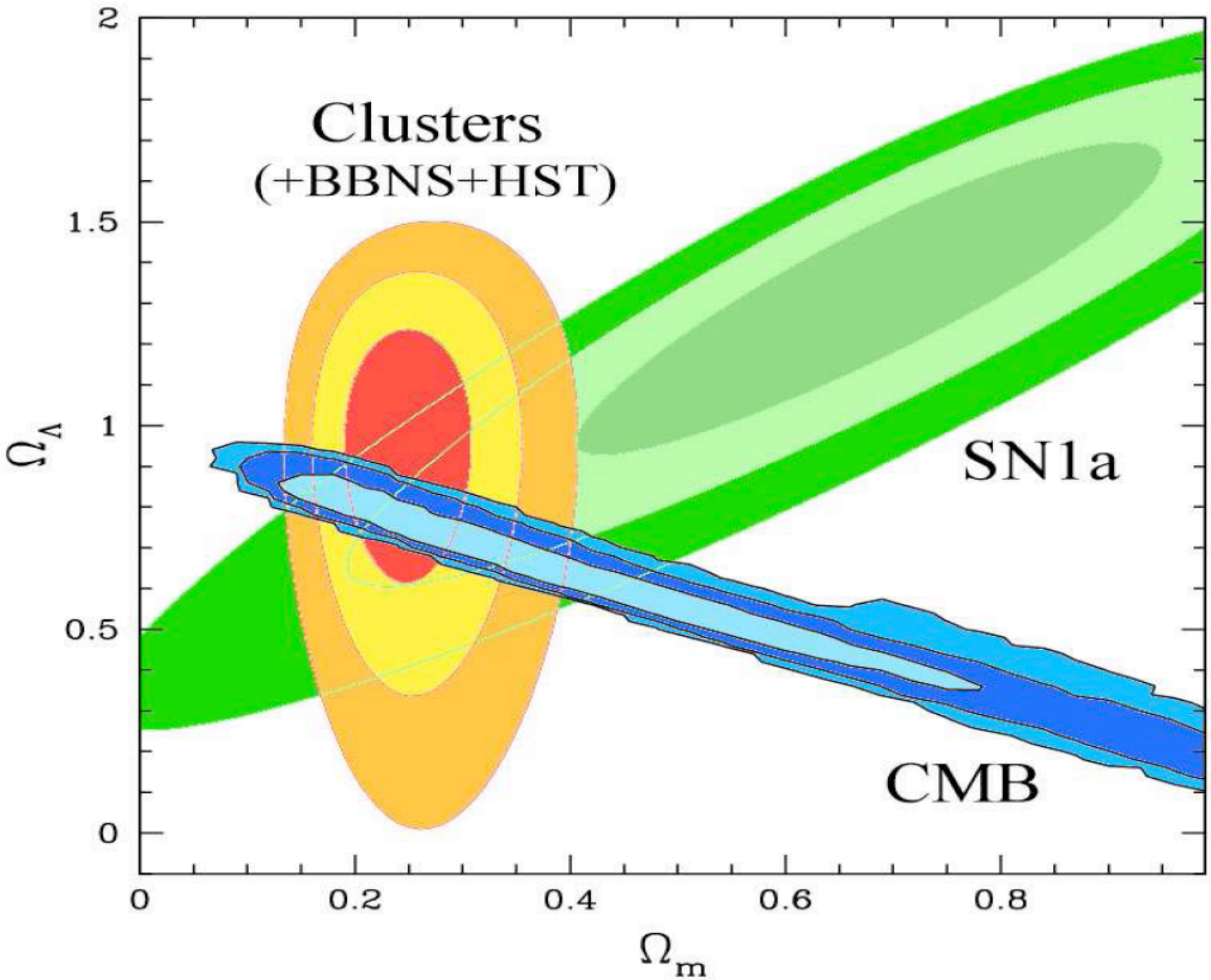
Hence interpretation of data in this framework is *likely* to yield $\Lambda \sim H_0^2$



e.g. if Ω_Λ ($= \Lambda/3H_0^2$) is inferred from the **cosmic sum rule** …
given the inevitable uncertainties in measuring Ω_m and Ω_k

We believe now that $\Omega_k = 0$ is natural because of dynamics (inflation)

but there is no plausible dynamical reason for $\Omega_\Lambda = 0$



Then 'cosmic concordance' *requires* dark energy: $\Omega_\Lambda \sim 0.75$, $\Omega_m \sim 0.25$

If it is just a cosmological *constant*, 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 $\sqrt{d^2V/d\Phi^2} \sim H_0 \sim 10^{-42}$ GeV to ensure slow-roll

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

(But might it be possible to have a technically natural solution if new large *supersymmetric* dimensions open up at the scale $\rho_\Lambda^{-1/4} \sim 0.1$ mm?)

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 simply *put in by hand* !

Would seem natural to have $\Lambda \sim H^2$ *always*, but this just means a redefinition of G_N

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

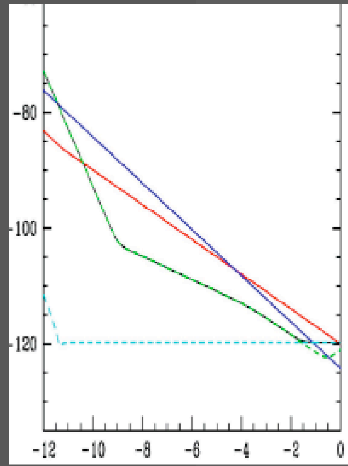
Thus there can be no *natural* explanation for the coincidence problem

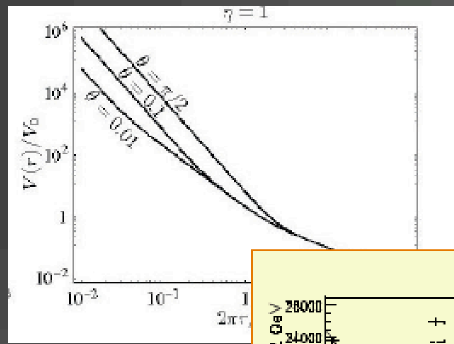
Do we see $\Lambda \sim H_0^2$ because that is just the **observational sensitivity**?

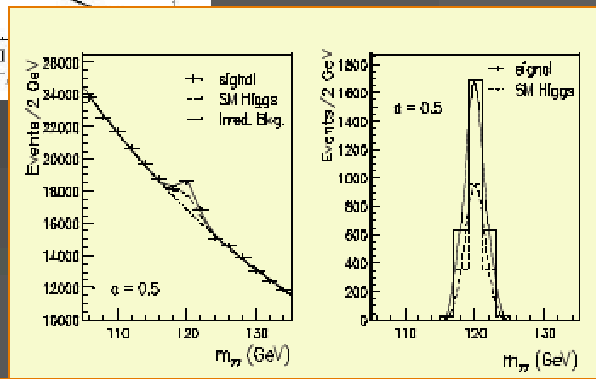
Observational Consequences

- Quintessence cosmology
- Modifications to gravity
- *Collider physics*
- Neutrino physics?
- And more!

SUSY broken at the TeV scale, but not the MSSM!







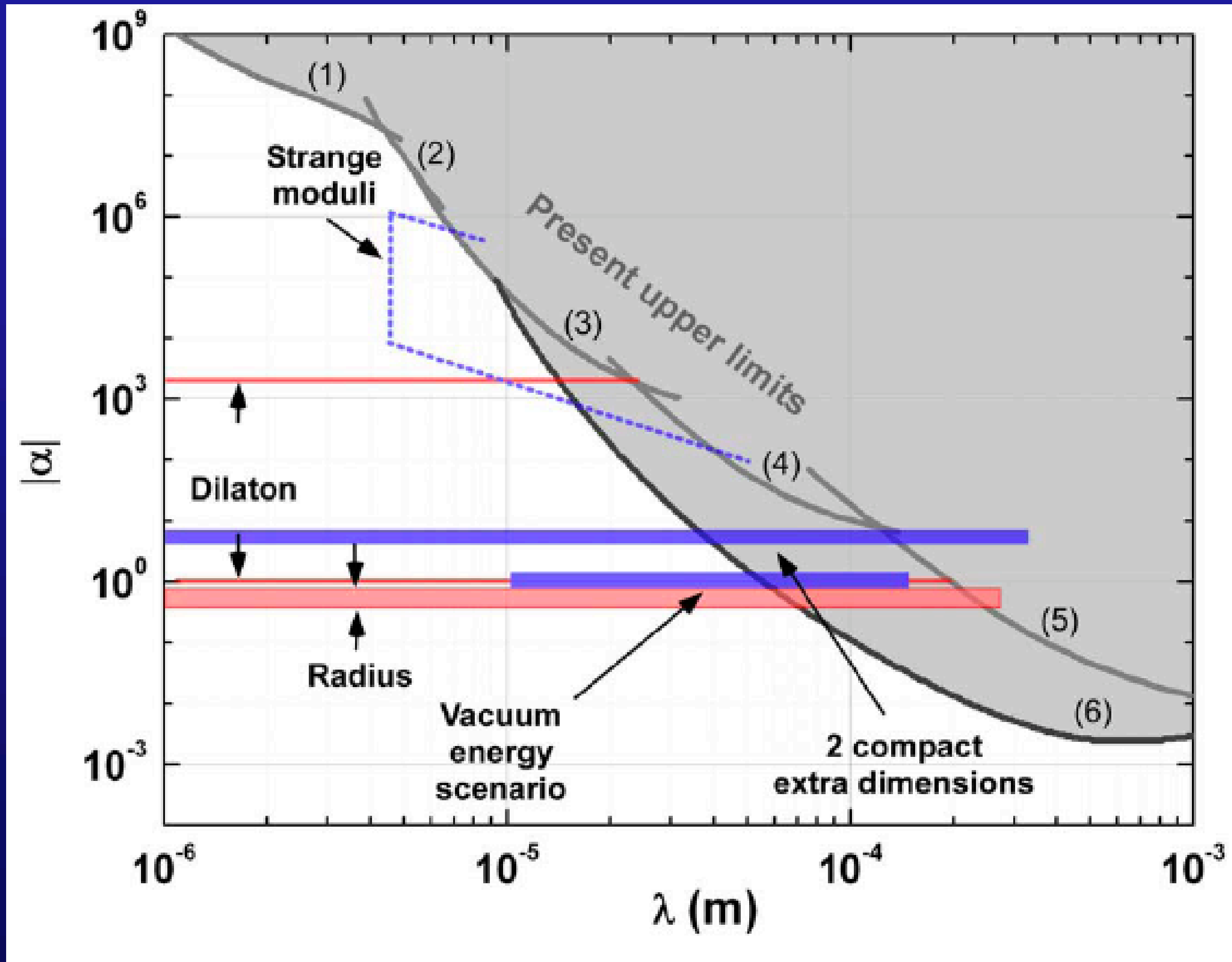
$$U \approx \begin{pmatrix} c_s(-1/\sqrt{2} - \delta/4) & c_s(1/\sqrt{2} - \delta/4) & 0 \\ c_s(1/2 - \delta/4\sqrt{2}) & c_s(1/2 + \delta/4\sqrt{2}) & 1/\sqrt{2} \\ c_s(1/2 - \delta/4\sqrt{2}) & c_s(1/2 + \delta/4\sqrt{2}) & -1/\sqrt{2} \end{pmatrix}$$

Cosmo 07

Comment: The SLED hypothesis is well motivated and falsifiable!

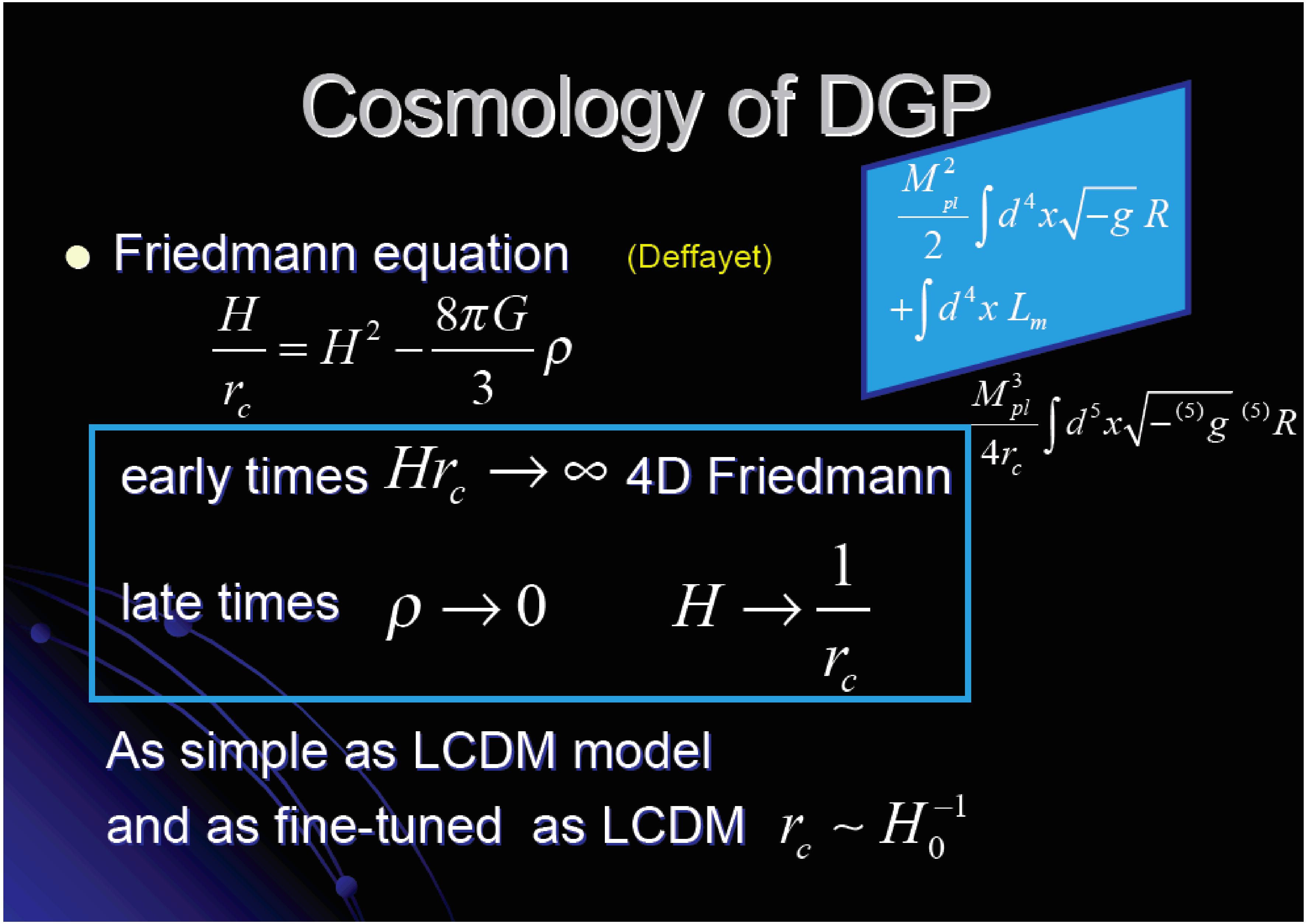
Clive Speake: *Tests of gravitation in the laboratory*

Current constraints to violations of the ISL



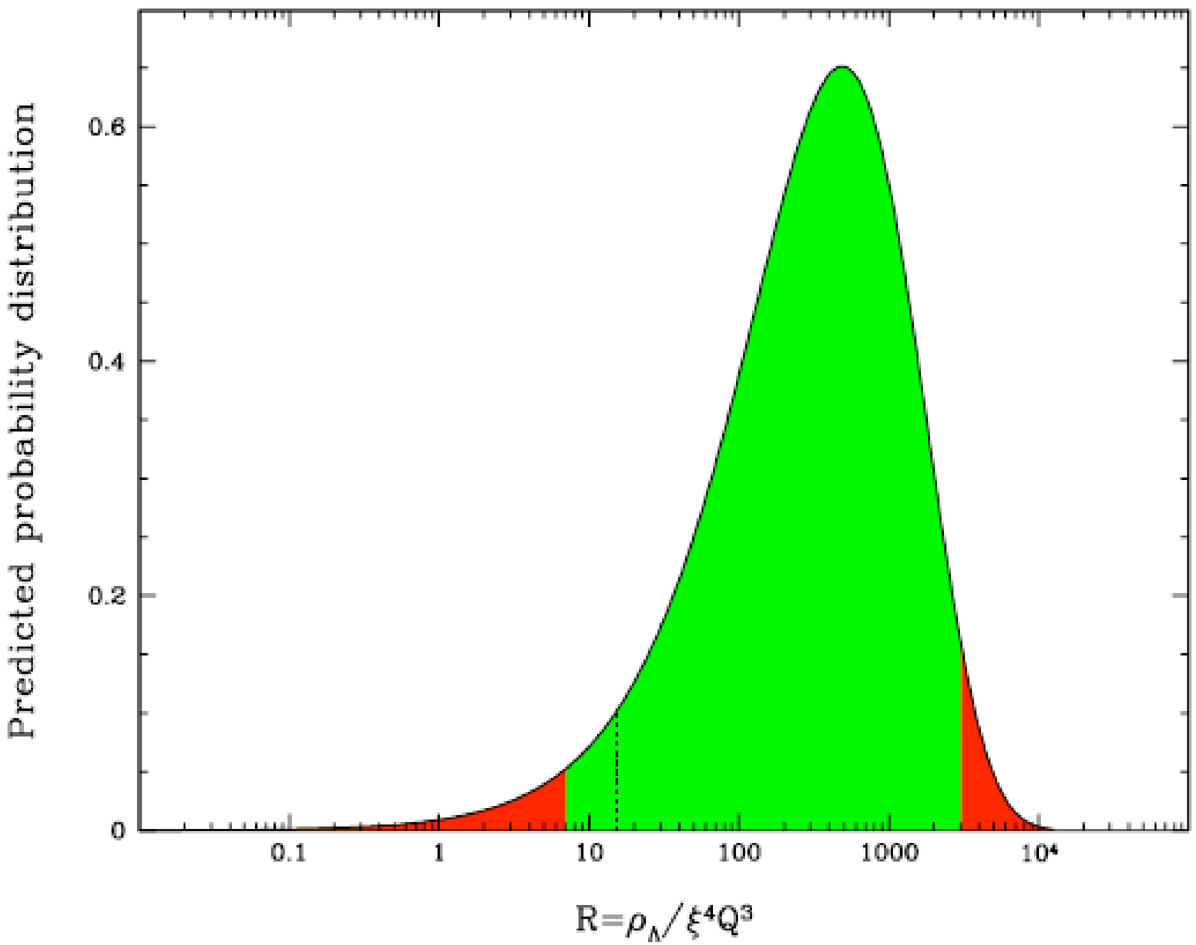
Comment: Begining to probe the interesting scale $\rho_\Lambda^{-1/4} \sim (H_0 M_P)^{-1/2} \sim 0.1$ mm !

Kazuya Koyama: *Braneworlds*



Comment: *Model is also sick* ("ghosts") but still under study!

'Anthropic prediction' of Λ from considerations of galaxy formation



But this *assumes* the prior distribution of ρ_Λ is *flat* in the range $0 \rightarrow 10^{-120} M_P{}^4$

Since we have no physical understanding of Λ this may not be reasonable

If the relevant physical variable is in fact *log* ρ_Λ, then $\rho_\Lambda = 0$ would be the favoured possibility!

(Efstathiou 1995, Martel, Shapiro & Weinberg 1998, … Tegmark, Aguirre, Rees & Wilczek 2006)

FIG. 11: Probability distribution for the quantity $R \equiv \rho_\Lambda/\xi^4 Q^3$ measured from a random $10^{12} M_\odot$ halo, using a uniform prior for R and ignoring other selection effects. This is equivalent to treating ξ and Q as fixed. Green/light shading indicates the 95% confidence interval, the dotted line indicates the observed value $R \approx 15$.

New H-band Galaxy Number Counts

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

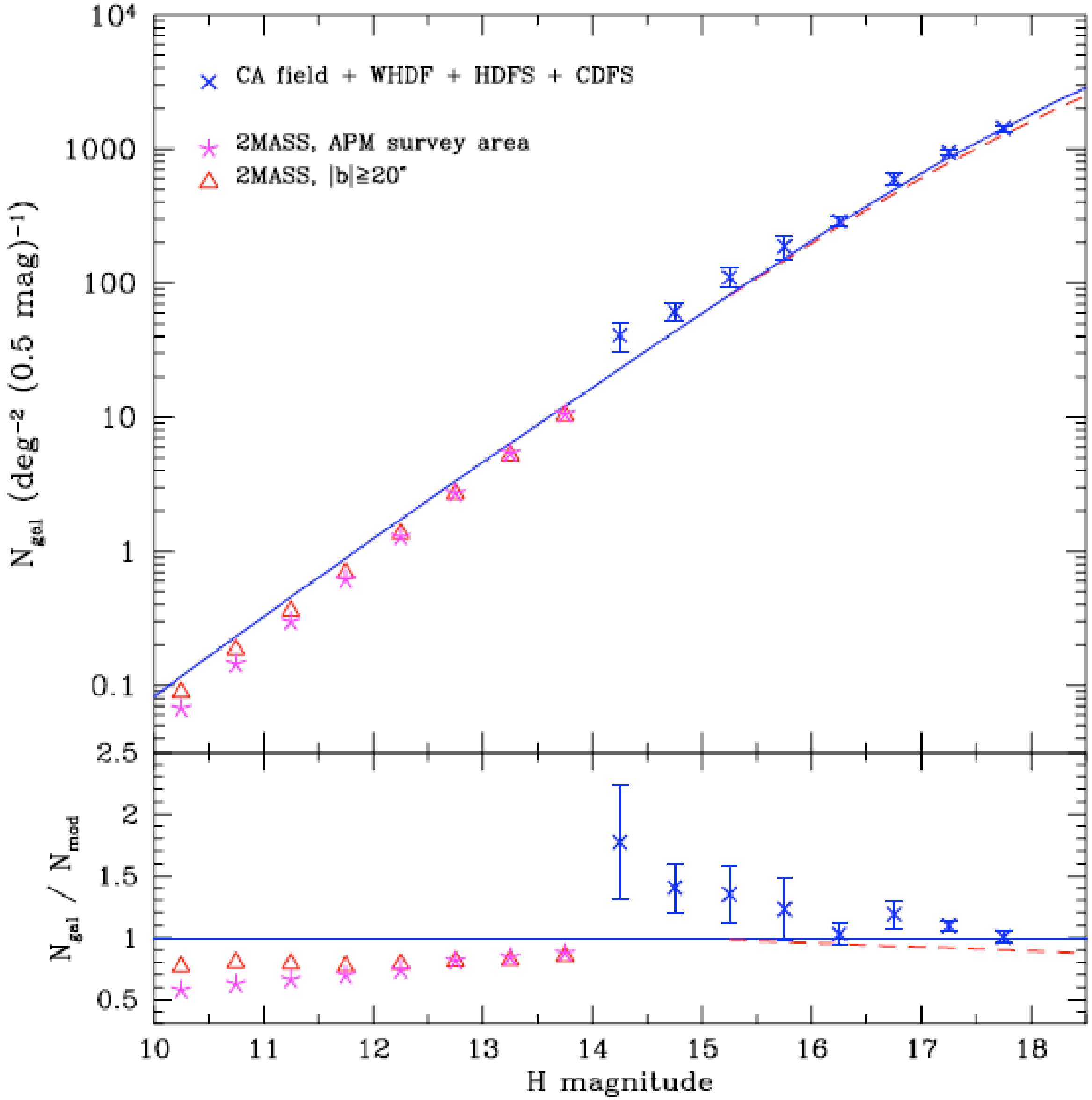
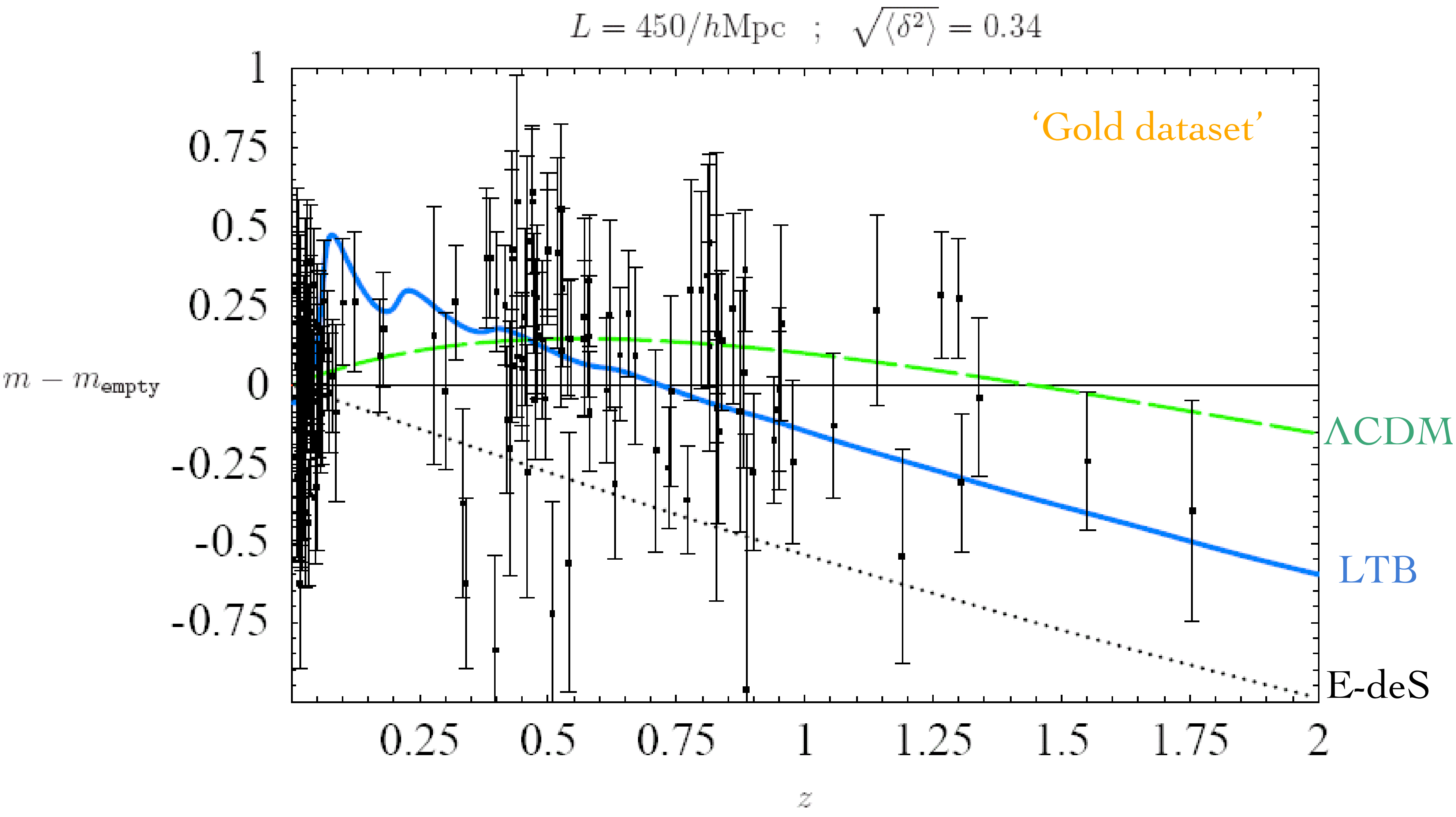


Figure 8. Here we show the faint H-band data from the two fields presented in this work (CA field and WHDF) and the two fields published by the LCIRS (HDFS and CDFS; Chen et al. 2002) applying a zeropoint to the LCIRS data consistent with the bright H-band 2MASS data (and hence the CA field and WHDF 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)

If so the SN Ia Hubble diagram may be explained *without* invoking acceleration, in a Lemaitré-Tolman-Bondi model



Biswas, Mansouri & Notari (2006)

is the acceleration apparent?

maybe the expansion of the universe is not accelerating, but the light-path is affected by the growth of inhomogeneities?

→ solves size problem (effect expected to be small)

→ solves coincidence problem (we appear after structure forms)

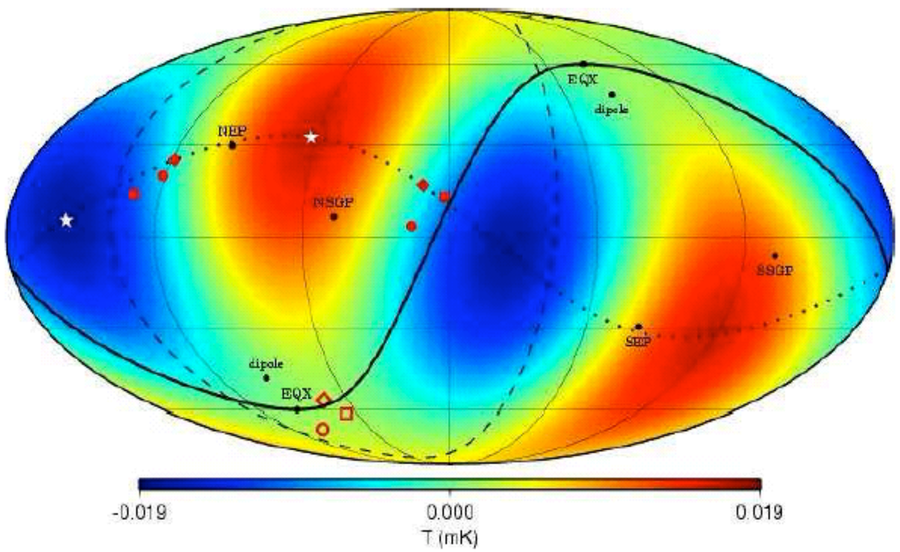
Working toy models exist (e.g. with Lemaitre-Tolman-Bondi metric) and exact smoothed dust solutions ("Buchert equations") contain an apparent acceleration term.

However, the CMB is very isotropic, 1st order perturbation theory is very successful and the gravitational potentials appear to be small. Also some theoretical arguments say that the backreaction effect is expected to be present, but too small without finetuning.

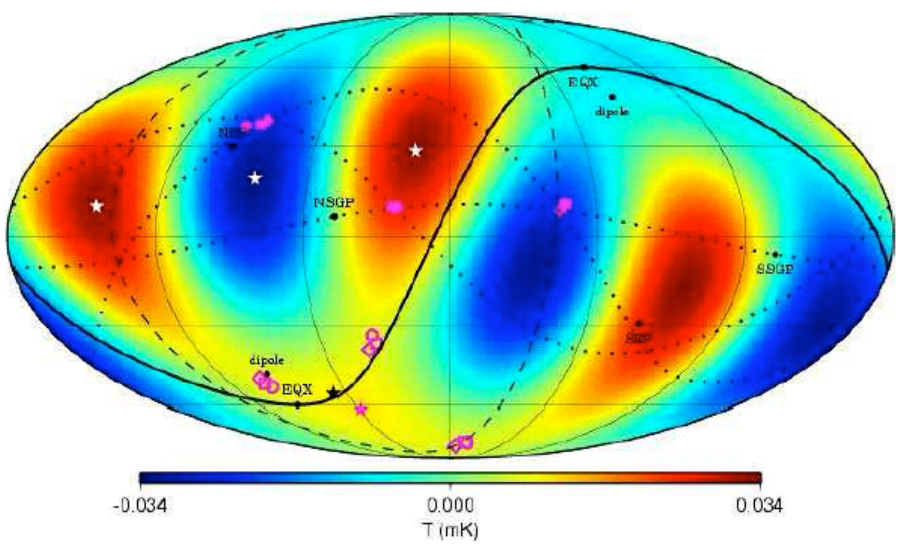
(and it still needs $\Lambda=0$)

(talk by I. Brown)

Comment: The LTB model does require us to be pretty close to the 'centre'

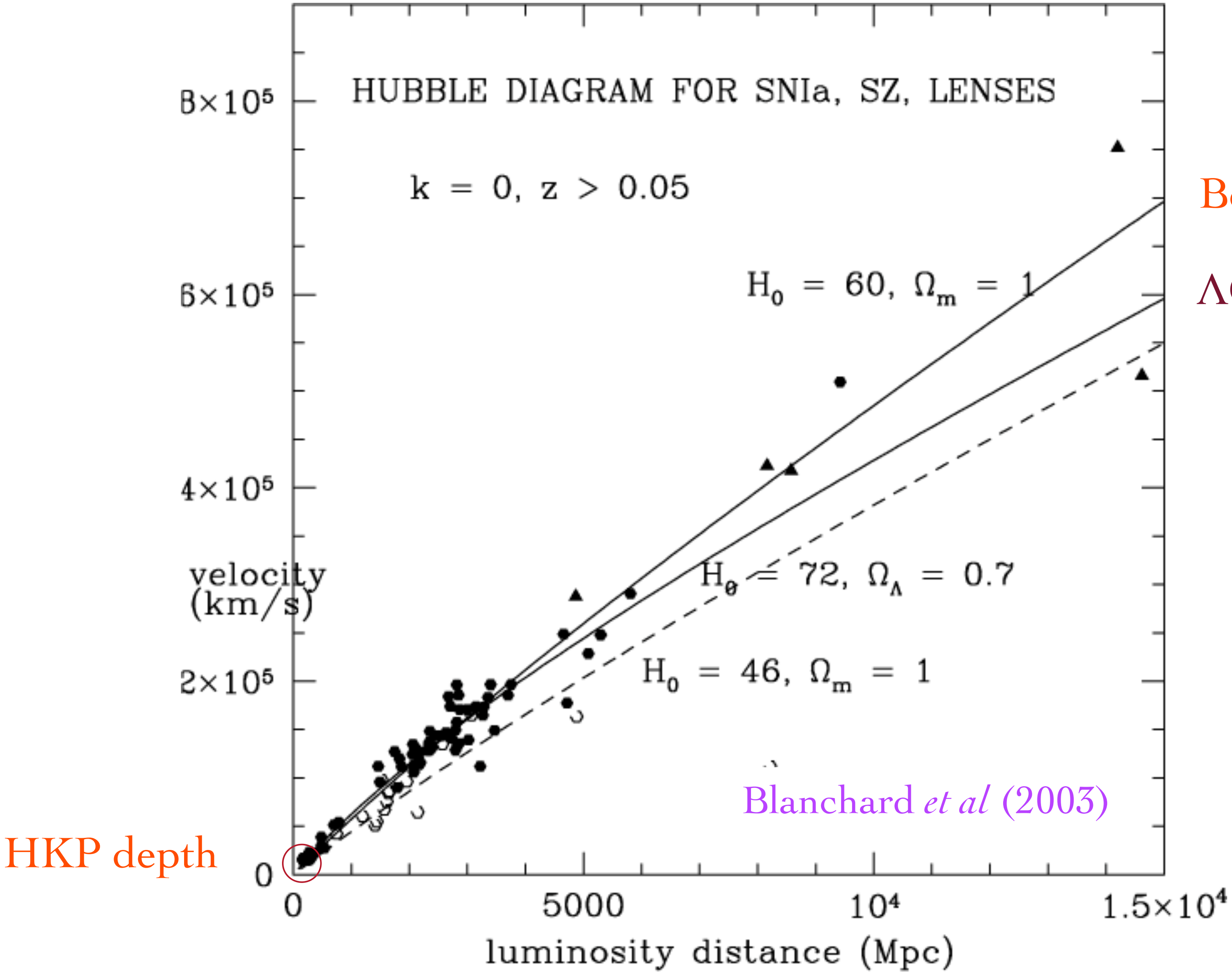


But there *is* a mysterious alignment of the quadrupole and octupole - could this be due to the Rees-Sciama effect?

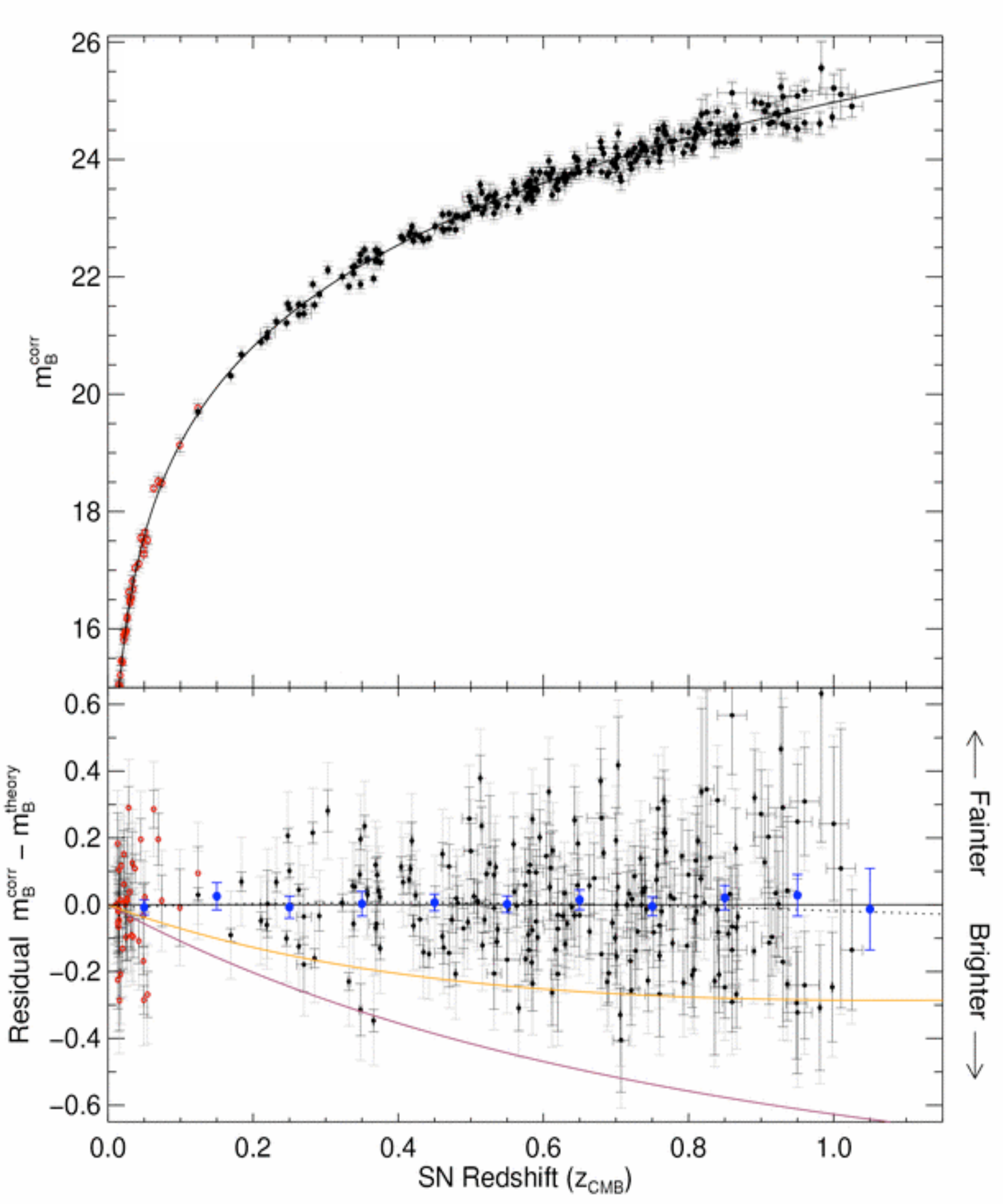


(Inoue & Silk 2006)

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



Perhaps the local void is expanding ~30% faster than the global rate?



"Third year" SNLS Hubble Diagram (**preliminary**)

3/5 years of SNLS

~240 distant SNe Ia

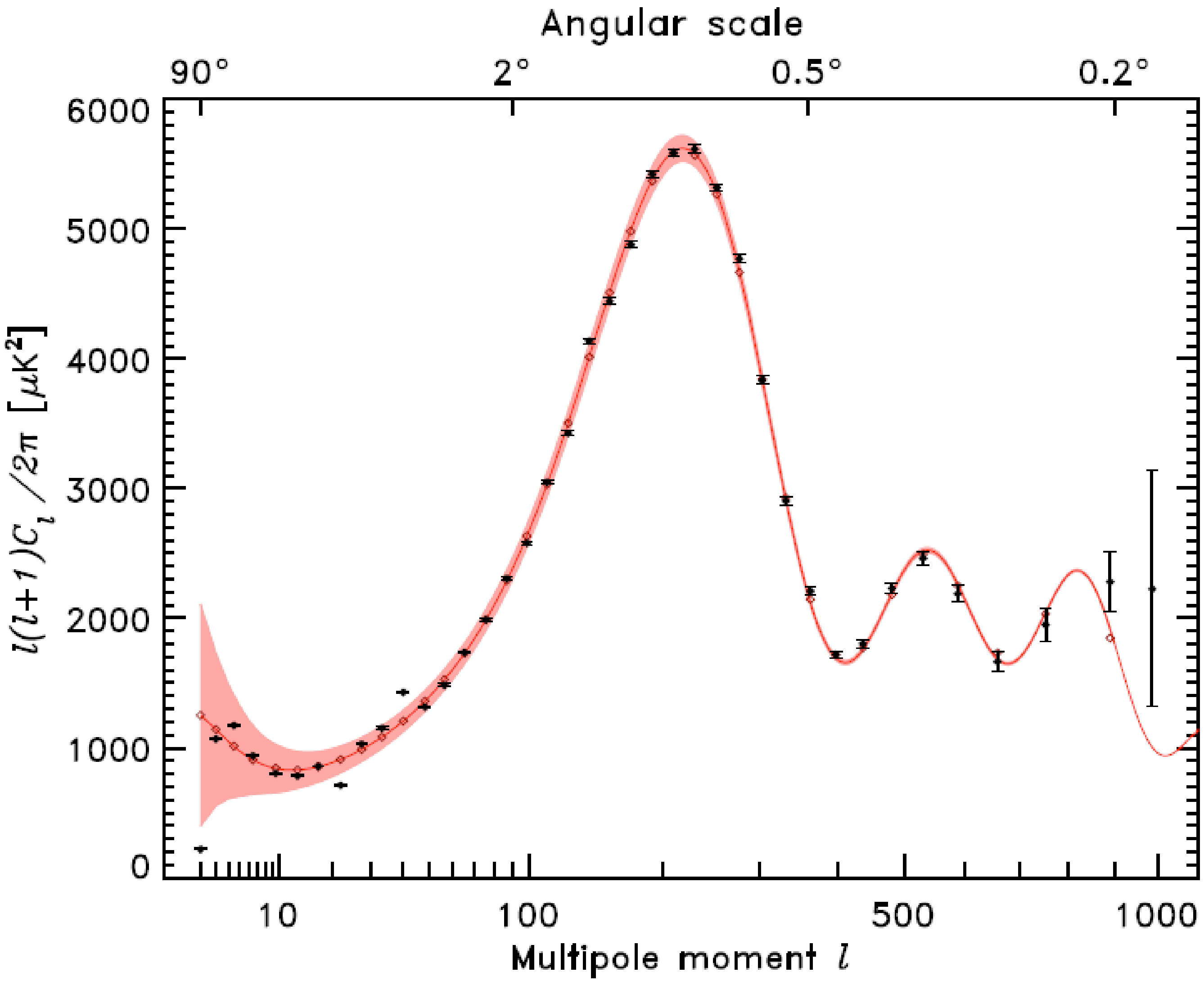
rms ~ 0.17mag

Credit: M.Sullivan

Comment: There is still a gap at z ~ 0.1- 0.3 (being filled in partially by SDSS)

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

Best-fit: $\Omega_m h^2 = 0.13 \pm 0.01$, $\Omega_b h^2 = 0.022 \pm 0.001$, $h = 0.73 \pm 0.05$, $n = 0.95 \pm 0.02$

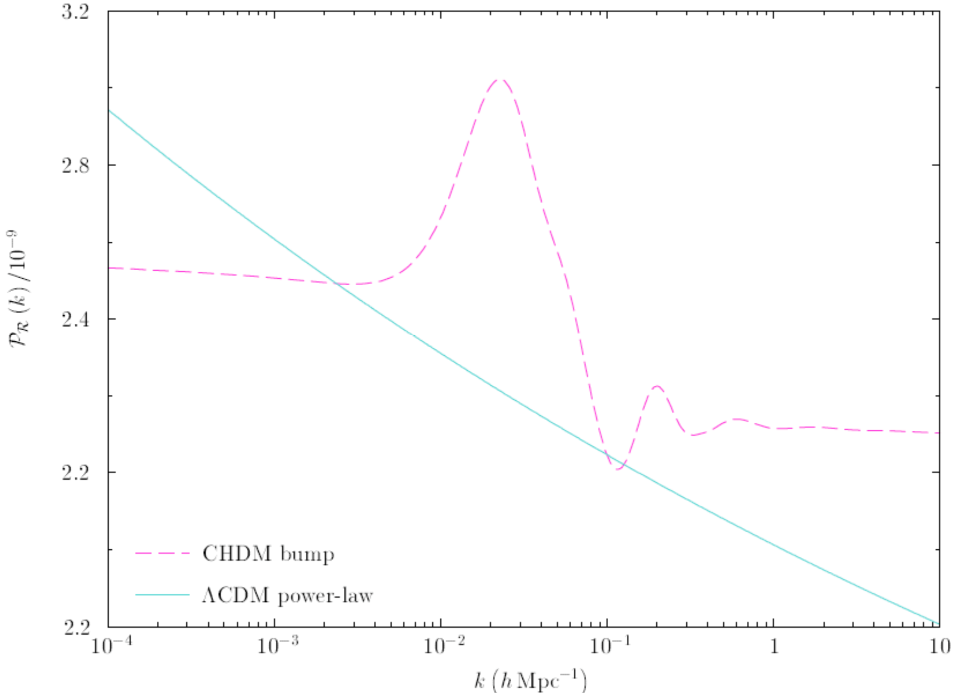


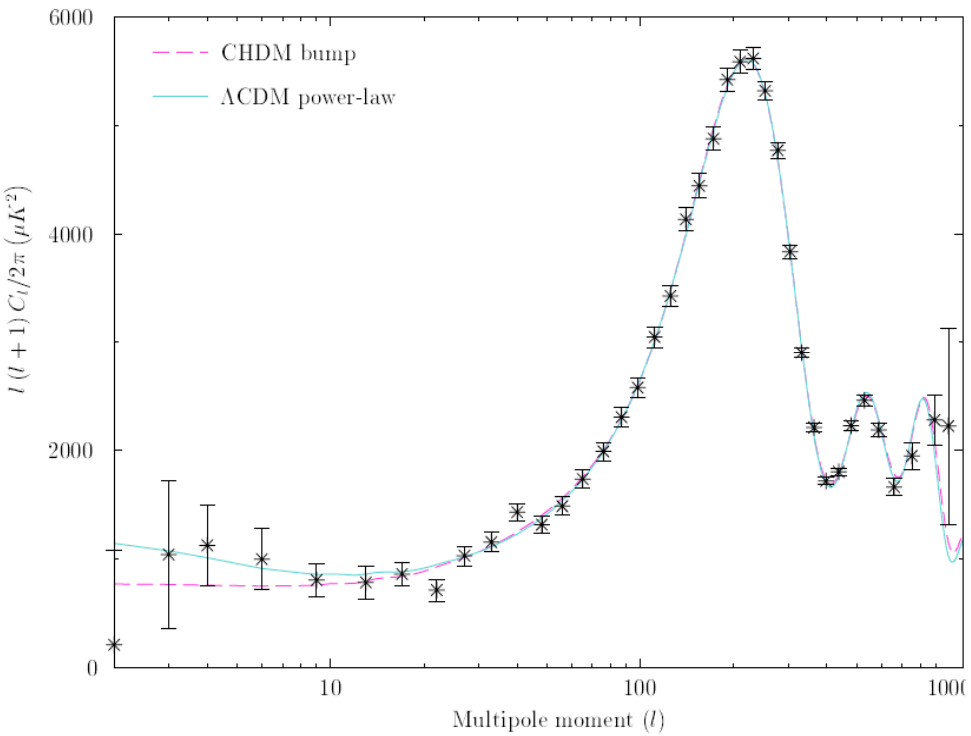
But the χ^2/dof = 1049/982 ⇒ probability of only ~7% that this model is correct!

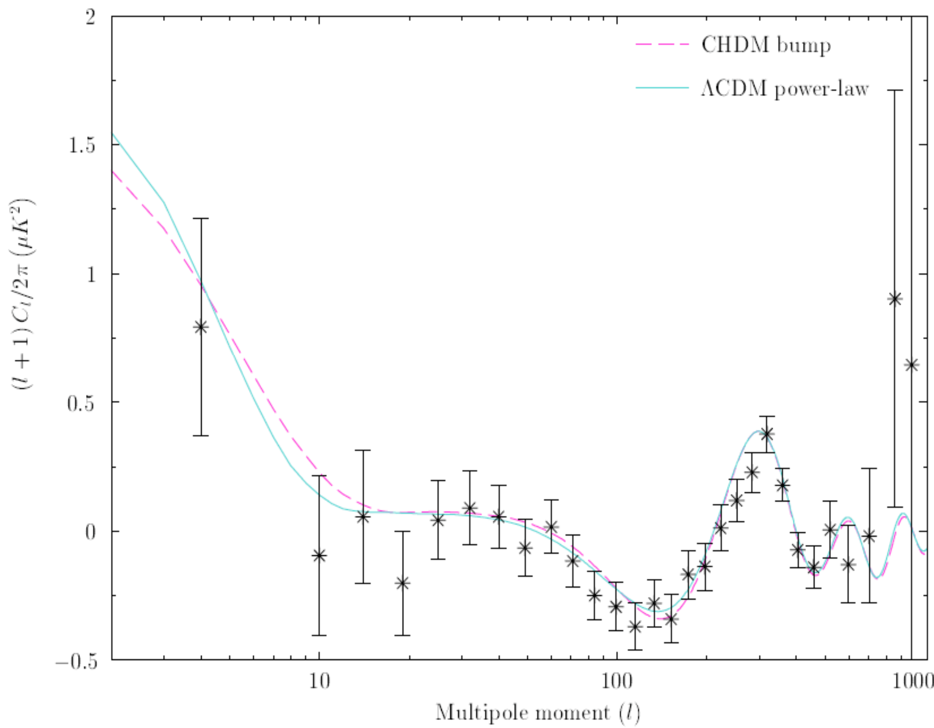
This suggests that the primordial density perturbation is not **scale-free**, as is usually *assumed*

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

(Hunt & Sarkar 2007)

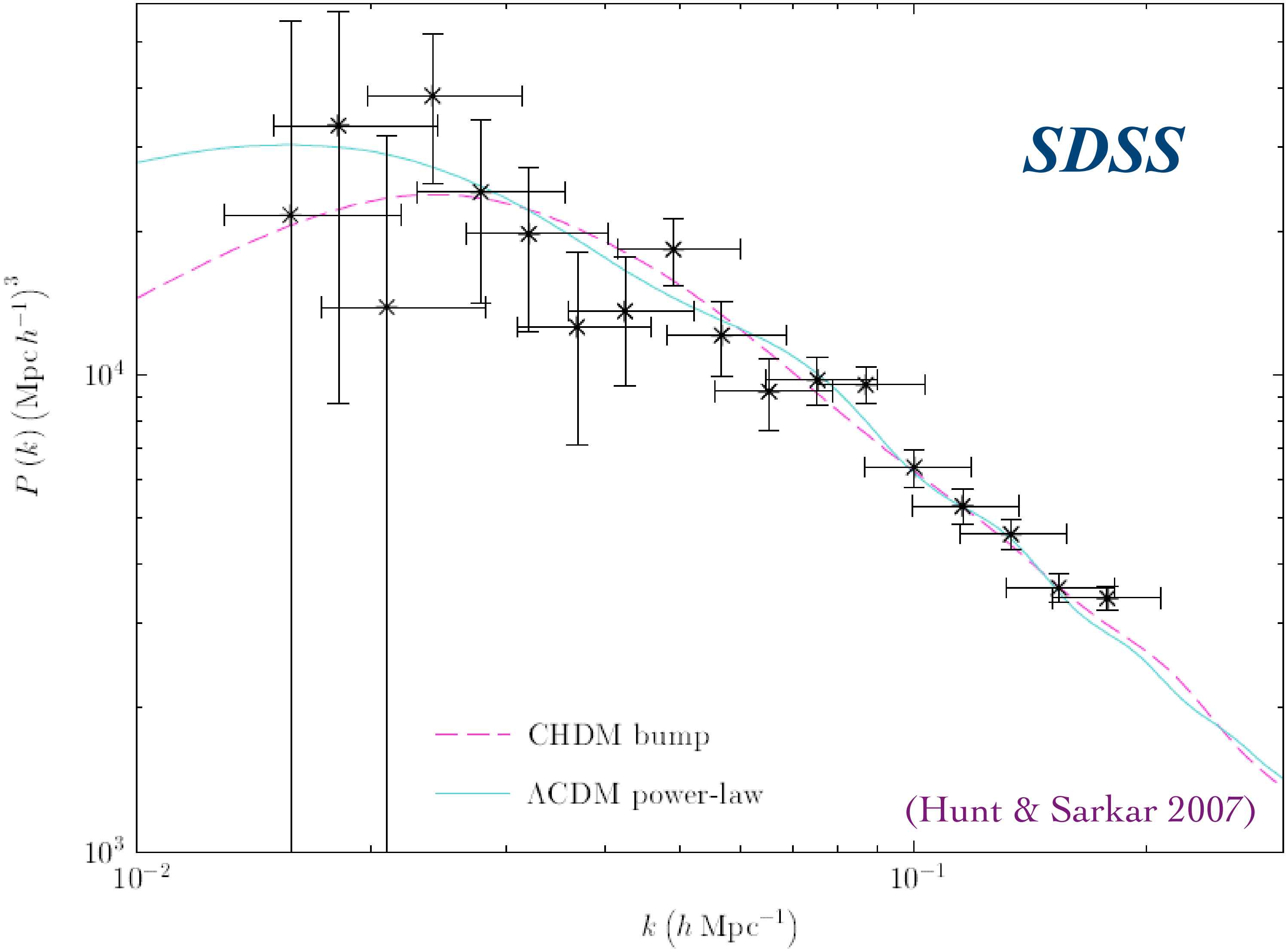






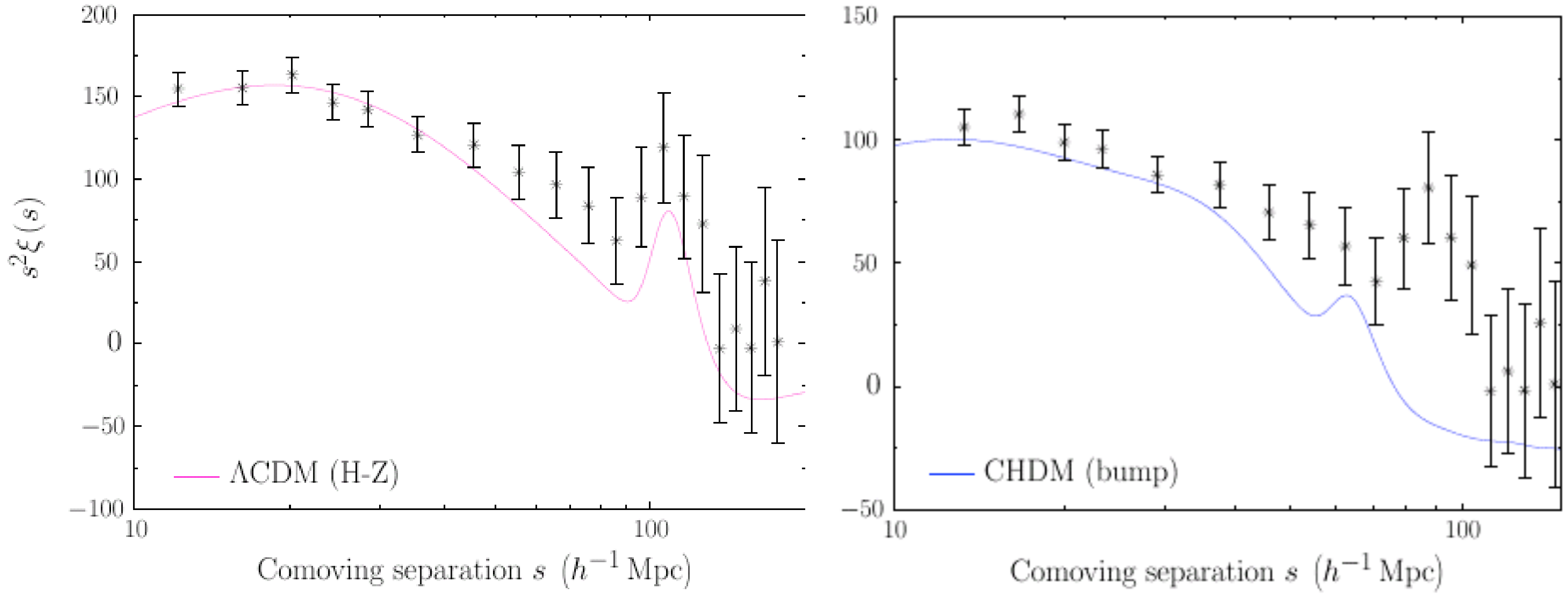
The small-scale power would be excessive unless damped by free-streaming

But adding 3 ν of mass 0.5 eV ($\Rightarrow \Omega_\nu \sim 0.1$) gives *good match* to large-scale structure



Fit gives $\Omega_b h^2 \approx 0.018 \rightarrow$ BBN √ ⇒ baryon fraction in clusters ~10% √

However the E-deS model is ruled out by the 'baryon acoustic peak' (present at the ~same *physical* scale, but displaced in redshift space)

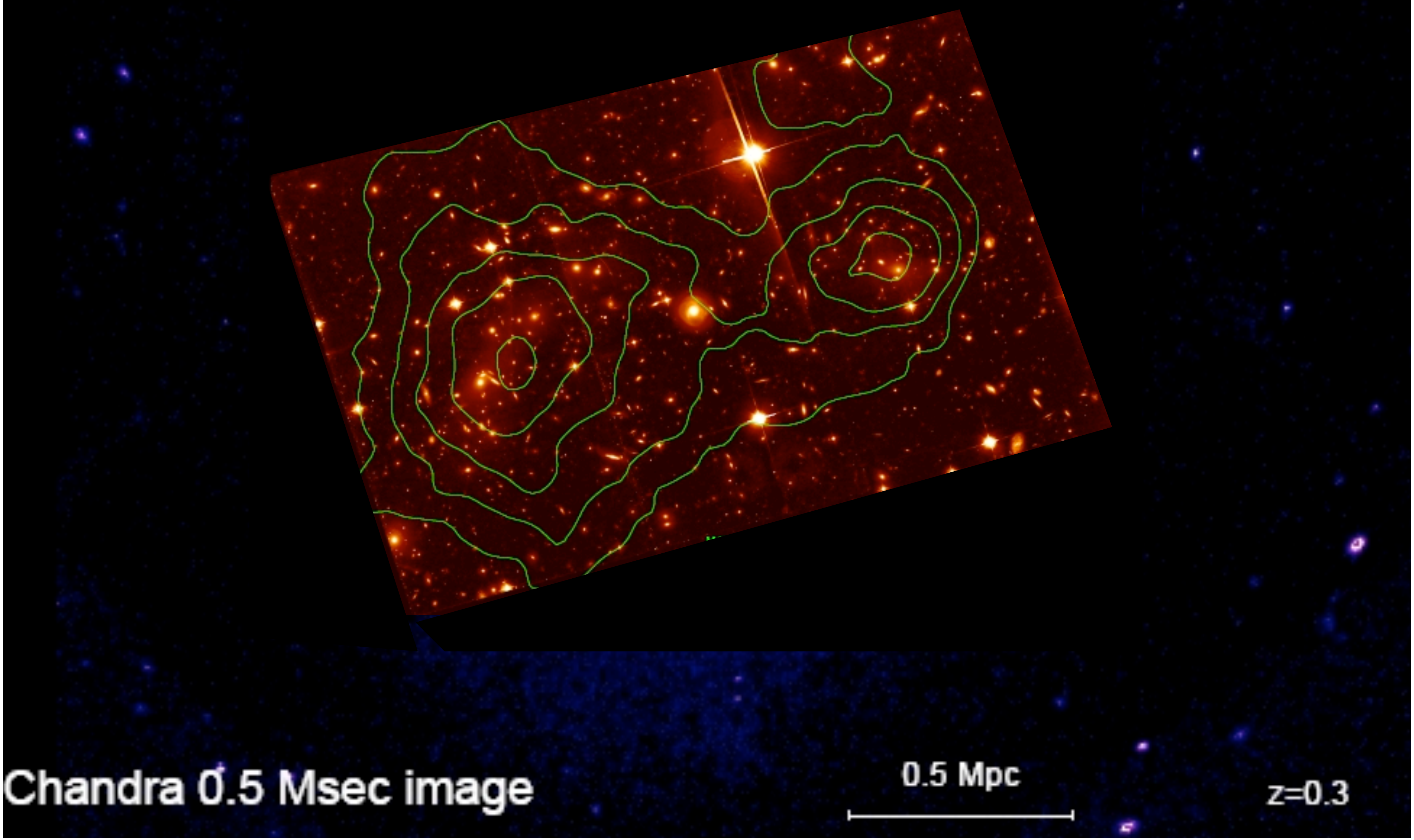


But can get angular diameter distance @ z = 0.35 similar to ΛCDM in inhomogeneous LTB model - so crucial to measure *z dependence of BAO*!

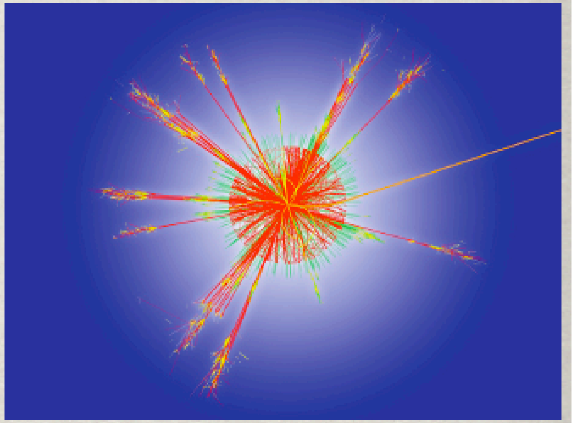
Must find direct *dynamical* evidence for Λ (e.g. late ISW effect @ 5σ) to establish that dark energy really exists

The Bullet Cluster: Proof of Dark Matter?

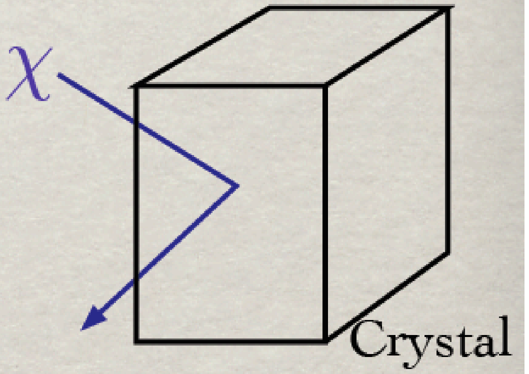
Clowes et al 2006



THE HOPE:
DETECT DM IN MORE WAYS !



- At future colliders like the LHC at CERN or the ILC somewhere in the world... If it is a neutralino it is possible !

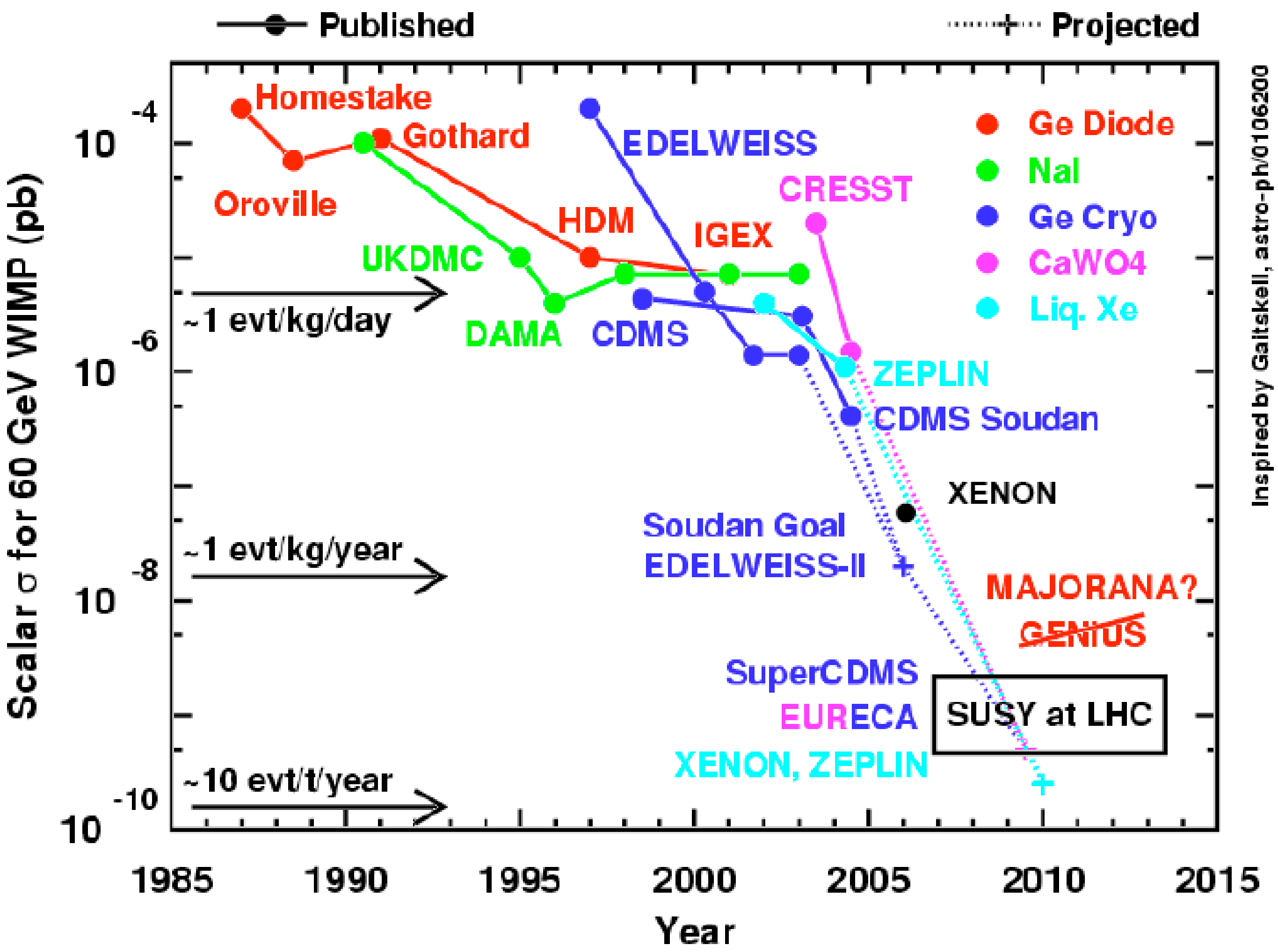


- In direct experimental searches in various underground laboratories or indirectly by looking at photons, cosmic rays or neutrinos

STAY TUNED: WE WILL KNOW MORE SOON...

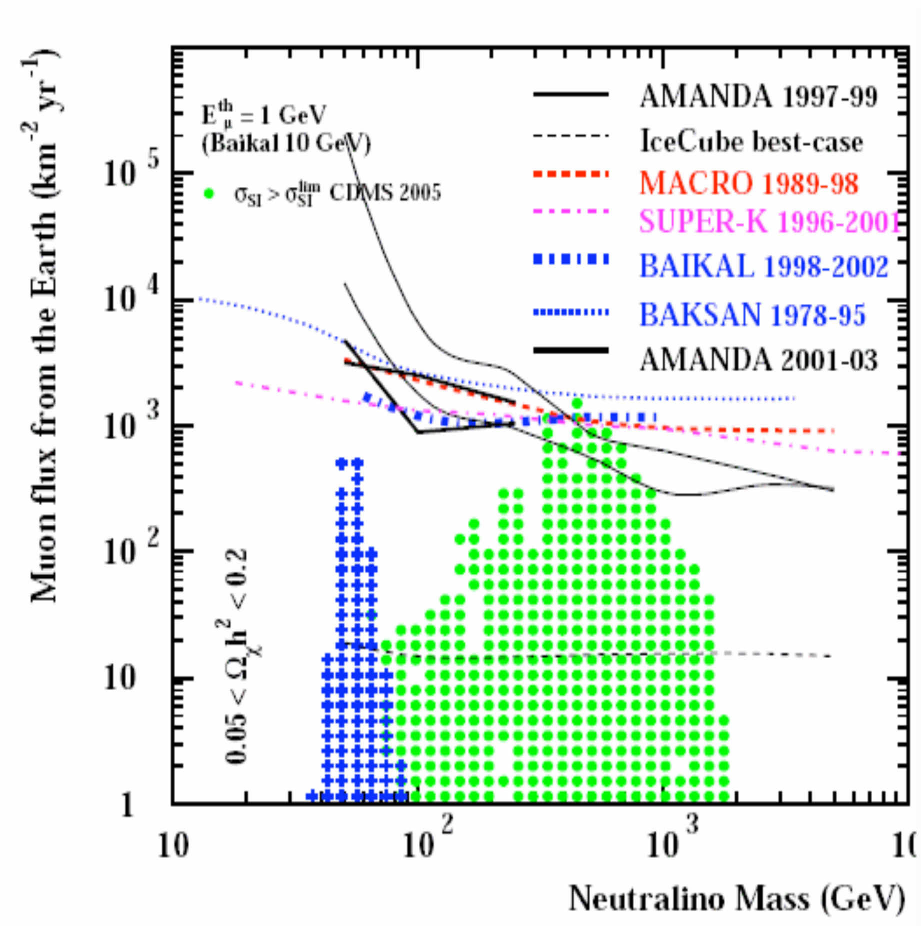
Comment:

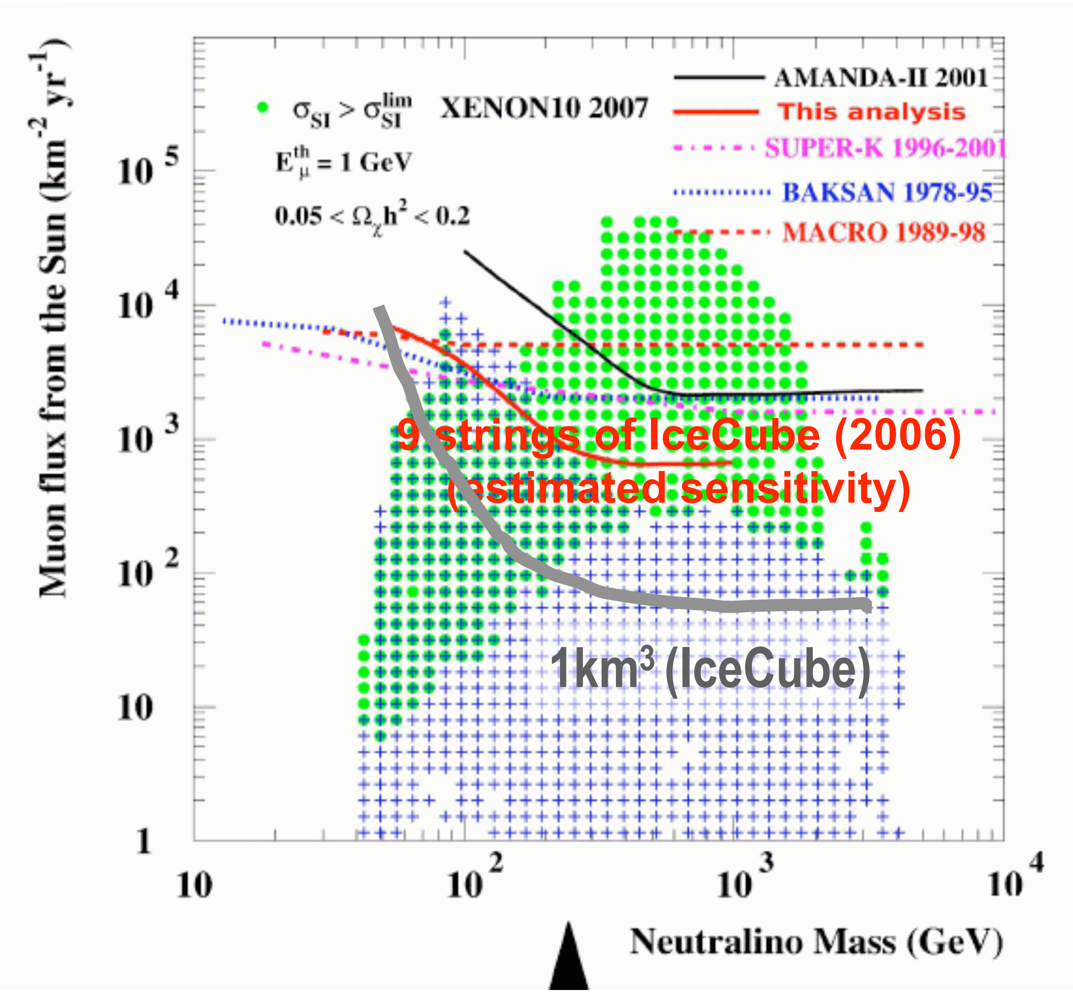
Status and Long-term Future



Comment:

WIMP search --- new results





Limits on muon flux from Earth **Limits on muon flux from Sun**

Comment: *Complementarity* between direct and indirect searches

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 baryogenesis?	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$!
$1/\sqrt{G_F}$	neutralino?	R-parity?	R_p violation?	freeze-out from thermal equilibrium	$\Omega_{LSP} \sim 1$
$\Lambda_{\text{hidden sector}}$ $\sim(M_{Pl}/\sqrt{G_F})^{1/2}$	'crypton'?	discrete (*very* model-dependent)	$\tau \sim 10^{10-18}$ yr for $m_x \sim \Lambda_{hs}$	not in thermal equilibrium … grav fluc during inflation →	$\Omega_X \sim 1$
M_{string} ; M_{Pl}	Kaluza-Klein states?	?	?	?	?

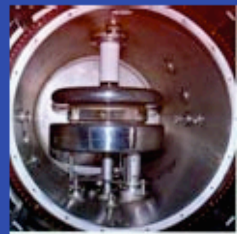
No definite indication from theory … must decide by experiment!

Stephan Huber: *Electroweak baryogenesis*

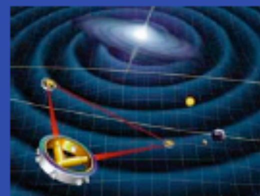
Why is it interesting?

There are testable consequences:

- New particles (scalars?!) at the LHC
  (Higgs sector is crucial!)



- New sources of CP violation which should show up soon in electric dipole experiments

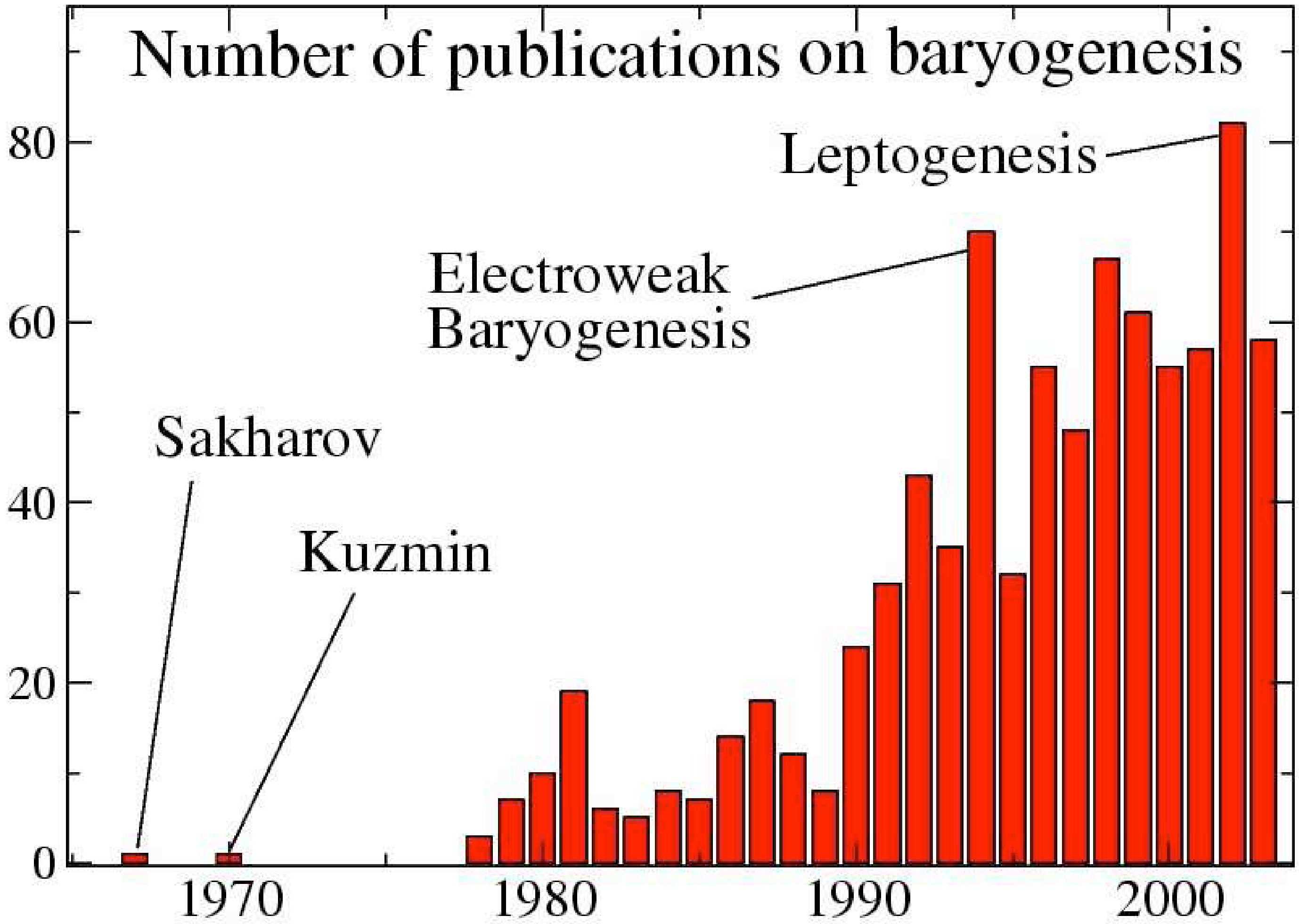


- Could the electroweak phase transition produce observable gravitational waves?

If confirmed, it would constrain the early universe up to T~100 GeV (nano sec.), like nucleosynthesis does for the MeV-scale (min.)

Comment: Perhaps the *only* mechanism which can be tested in the laboratory

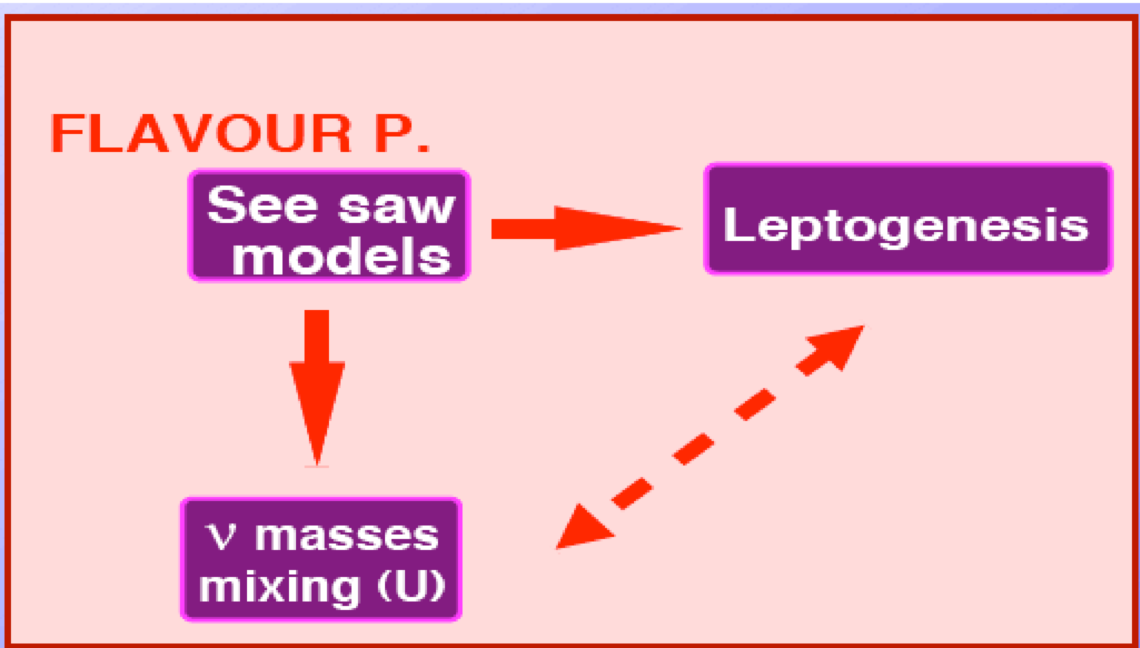
It has proved hard to realize *all* the three Sakharov conditions in a well motivated physical model



(Jim Cline hep-ph/0609145)

… but that hasn't stopped us trying!

Silvia Pascoli: *Leptgenesis and low energy neutrino physics*



In presence of flavour effects,

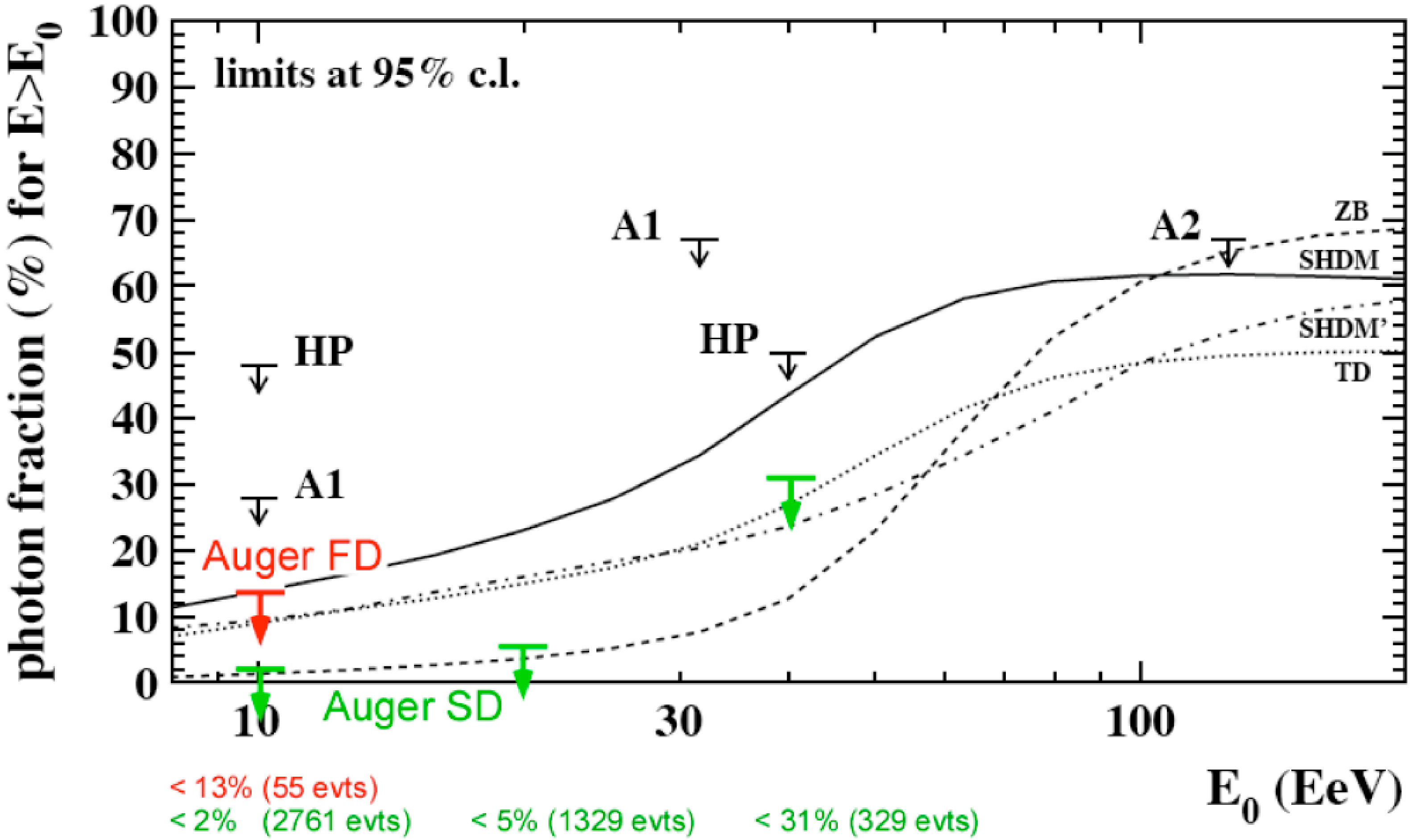
low energy phases enter directly leptogenesis.

The observation of L violation ($(\beta\beta)_{0\nu}$-decay)

and of CPV in the lepton sector (neutrino oscillations and/or $(\beta\beta)_{0\nu}$-decay)

would be a strong indication, even if not a proof, of leptogenesis.

Comment: But how would we know the thermal history back to ~10^{12} GeV?



most top-down models are ruled out

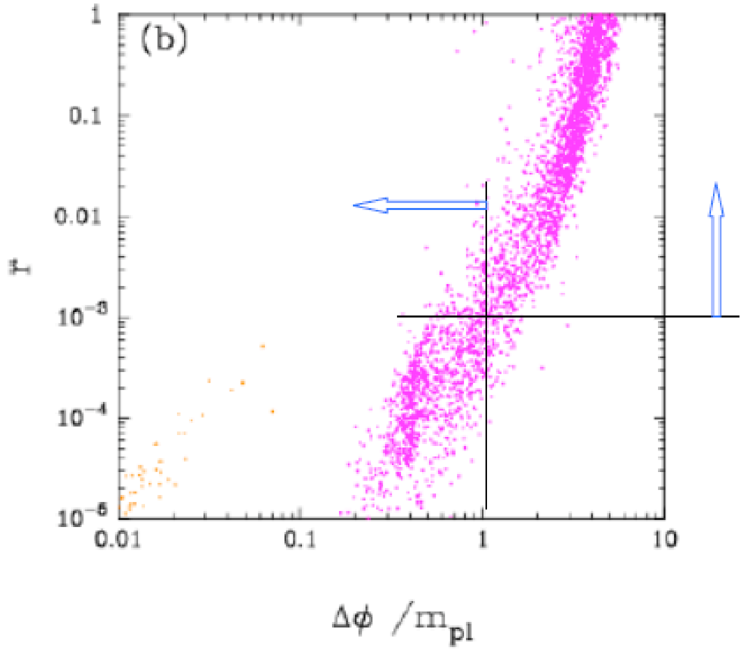
Auger Collaboration
Astrop. Phys. 27 (2007) 155
to be submitted to Astrop. Phys.

Comment: Excludes superheavy dark matter as the source of UHECRs

Lyth hep-ph/9606387

$$\Delta\phi \sim \frac{m_{\rm pl}}{8}\left(\frac{r}{\pi}\right)^{1/2}\Delta N$$

Efstathiou &Mack
astro-ph/0503360



Baumann&Mcallister
hep-th/0610285

for the brane inflation $\frac{\Delta\phi}{M_p} < \frac{2}{\sqrt{n}}$

$$r \leq 0.01(4/n)\left(\frac{60}{N}\right)^2$$

Comment: A detectable tensor signal expected only for *super-Planckian* field values

What we measure is the density perturbation, *not* the inflaton potential … so expand this around the field value φ^* when the perturbation just entering our present Hubble radius ($H_0^{-1} \sim 3000\ h^{-1}$ Mpc) was generated

$$V(\phi) = V(0) + V'(0)\phi + \frac{1}{2}V''(0)\phi^2 + \dots \qquad \boxed{\phi \equiv \phi^* - \phi^*_{\mathrm{I}}}$$

Then: $$\delta^2_{\mathrm{H}}(k) = \frac{1}{75\pi^2}\frac{V(\phi^* = \phi^*_{\mathrm{H}})^3}{V'(\phi^* = \phi^*_{\mathrm{H}})^2 M^6}$$

on the scale k which exits the horizon when $\varphi^* = \varphi^*_{\mathrm{H}}$:

$$\boxed{k = aH,\ H \equiv \dot{a}/a \simeq (V/3M^2)^{1/2},\ M \equiv M_{\mathrm{P}}/\sqrt{8\pi} \simeq 2.44 \times 10^{18}\ \mathrm{GeV}}$$

If the *linear* term in the expansion of $V(\varphi)$ dominates, then

$$V'(\phi^* = \phi^*_{\mathrm{H}}) = V'(0) + V''(0)\phi_{\mathrm{H}} + \dots, \qquad V'(0) = cV(0)/M$$

So the energy scale needed to generate $\delta_{\mathrm{H}} \sim 10^{-5}$ is $\sim M_{\mathrm{GUT}}$:

$$V^{1/4}(\phi = 0) \simeq (75\pi^2\delta^2_{\mathrm{H}})^{1/4} c^{1/2} M \sim 2 \times 10^{-2}\sqrt{c}M$$

Question: What sort of models exhibit "linear inflation"?

Answer: *All* "chaotic" (large-field) models with $\boxed{V \propto \phi^{*n}}$

because then: $V^{p+1}(\phi = 0)\phi^p / V'(\phi = 0) \simeq (\phi/\phi_{\mathrm{I}}^*)^p \ll 1$

so $V = m^2\varphi^2, \lambda\varphi^4$ are ***both equivalent*** to: $V \approx V(0) + \alpha\,\varphi$

German, Ross & Sarkar (2001)

But if φ transforms under a symmetry then *no* linear term

$\Rightarrow$ "new inflation" with $V''(0) = \tilde{c}V(0)/M^2$

$$\rightarrow \qquad \delta_{\mathrm{H}}^2 \simeq \frac{V(0)^3}{75\pi^2\tilde{c}^2V(0)^2\phi_{\mathrm{H}}^2M^2}$$

So the energy scale of inflation gets *smaller* as $\varphi_{\mathrm{H}} \rightarrow 0$:

$$V(\phi = 0)^{1/4} \simeq 2 \times 10^{-2}\sqrt{\tilde{c}}\,\phi_{\mathrm{H}}^{1/2}M^{1/2}$$

Amplitudeof GW and gravitino mass

$$r \sim 10^8 H^2$$ for inflationary perturbations

KKLT $$H \leq M_{3/2}$$

$$r \leq 10^8 M_{3/2}^2$$

Kallosh, Linde hepth/0704.0647

$$r \sim 10^{-2} \longrightarrow M_{3/2} \sim 10^{13} GeV$$ superheavy gravitino

$$M_{3/2} \sim 1 TeV \longrightarrow r \sim 10^{-24}$$ unobservable

A discovery or non-discovery of tensor modes would be a crucial test for string theory and particle phenomenology

Comment: It was known already in supergravity inflation that *H* must be low

- Primordial non-gaussianity: non-trivial correlation between Fourier components of curvature perturbation ζ
- Powerful discriminator between models for origin of ζ
- $-54 < f_{\rm NL} < 114$ (WMAP+SDSS)
- $\tau_{\rm NL} \lesssim 10^4$ (WMAP)
- $\boxed{\text{Eventual bounds}}$: $|f_{\rm NL}| \lesssim 1$ and $|\tau_{\rm NL}| \lesssim 300$
  - Or $|f_{\rm NL}| \sim 0.01$ from $21\,$cm anisotropy? (Cooray 06)
- $\boxed{\text{Theory}}$ gives $|f_{\rm NL}| \sim 0.01$ (standard paradigm)
  - Or $|f_{\rm NL}| \gtrsim 1$ (curvaton & inhomogeneous reheating paradigms)

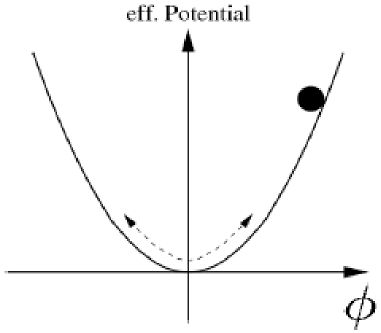
Comment: Bispectrum good target observationally - also easily calculable

Preheating dynamics

<u>*N*-component $\lambda\phi^4$, conformal time *t*</u>

Kofman, Linde, Starobinsky, PRL 73 (1994) 3195, …

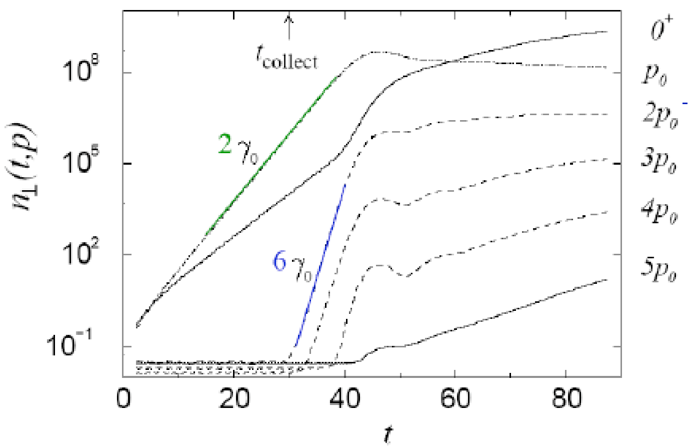
Berges, Serreau PRL91 (2003) 111601

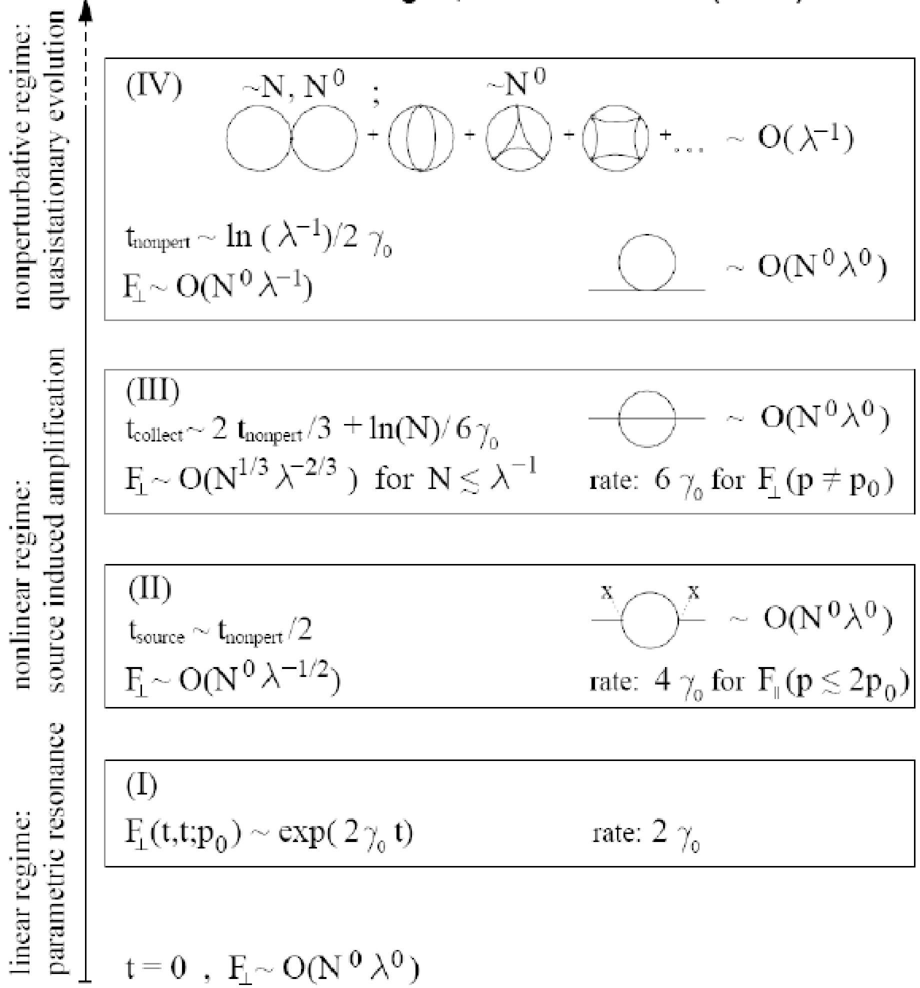


macroscopic field $\phi = \langle\Phi\rangle$

fluctuations $F \sim \langle\Phi\Phi\rangle - \langle\Phi\rangle^2$

Particle production:





Comment: Sophisticated treatment … but inflaton couplings to matter uncertain

- **WHY?** - obtain information about astrophysical events obtainable in no other way
- Fundamental Physics
  - test Einstein's quadrupole formula in the strong field regime using binary inspirals
  - test Einstein's theory from network measurements of polarisation
  - confirm the speed of gravitational waves with coincident EM/GW observations
- Astrophysics: (Advanced interferometers)
  - provide links to γ-ray bursts by detecting NS-NS, NS-BH binaries
  - take a census of BHs by detecting 100's of BBH from cosmological distances
  - detect radiation from LMXB's
  - Measure NS normal modes; probe glitches in pulsars
- Cosmology and Fundamental Physics (Advanced detectors +)
  - Inform studies of dark energy
    - obtain accurate luminosity-distance Vs. red-shift relationship from inspirals at $z \sim 1$ from GW/EM observations
  - Detect possible GW background at $\Omega \sim 10^{-9}$
- New Sources and Science:
  - Intermediate Mass Binary Black Holes?
  - Burst of radiation from cosmic strings?
  - Backgrounds predicted by Brane-world scenarios?

B. Sathyaprakash, 2006

Comment: Well defined programme to open up a new astronomy

Ruth Durrer: *Magnetic fields and gravitational waves*

- **Primordial magnetic fields leave an imprint on the CMB. Since $\Omega_B = 10^5\Omega_\gamma(B/10^{-8}G)^2$, this is only detectable if $B \sim 10^{-9}G$ on CMB scales.**

- **But if $n>-3$, this means that the magnetic fields on smaller scales are much larger and might be constrained better by other means, e.g. the induced gravity wave background.**

- **To generate the observed galactic or cluster magnetic fields by simple contraction, seed fields of $B \sim 10^{-9}G$ on about 1Mpc scale are needed. Dynamo amplification requires seed fields of at least $10^{-22}G$.**

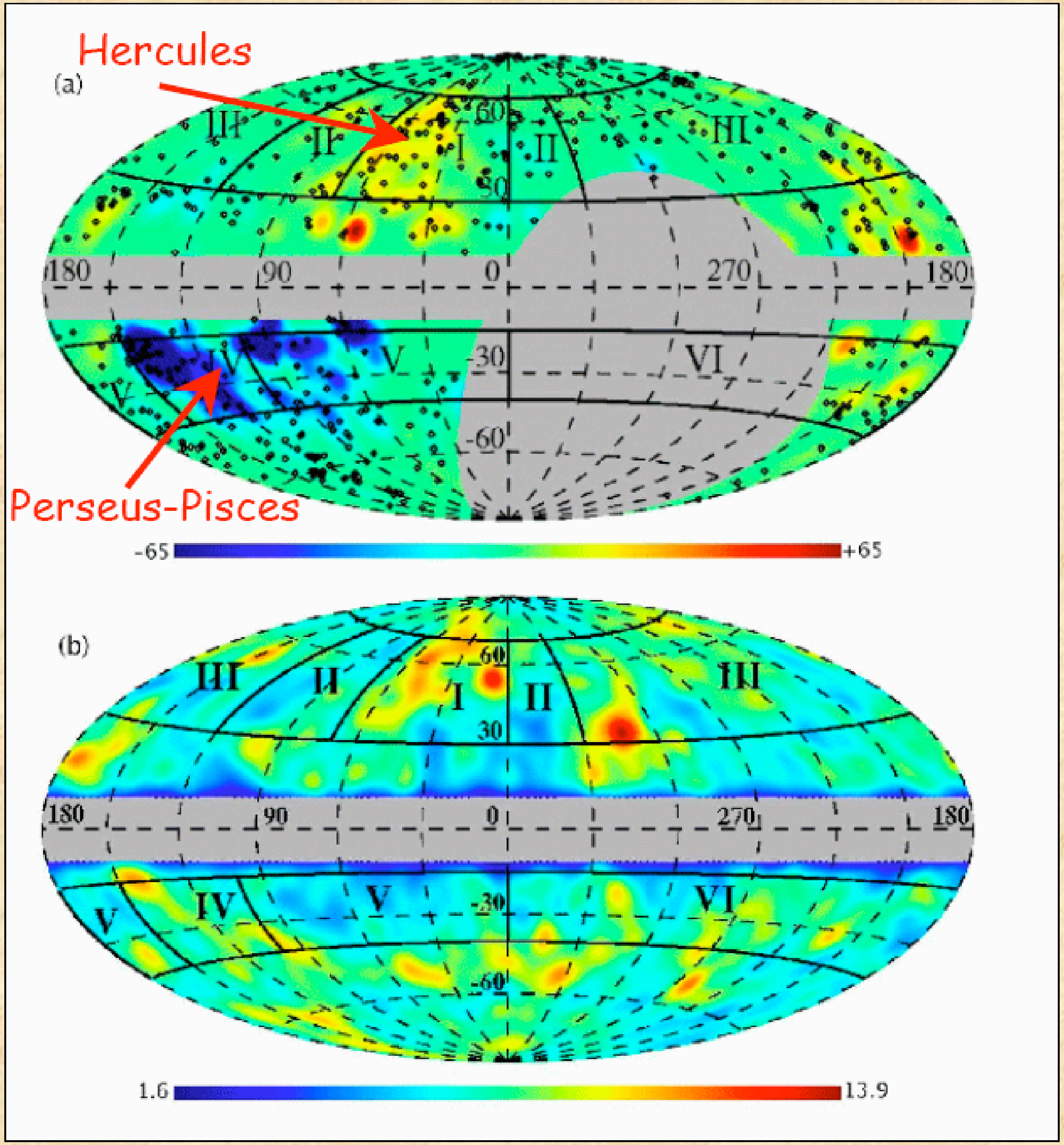
- **The induced gravity wave background limits causally produced (non-helical) fields to $B<10^{-30}G$ on 1Mpc scale and fields from inflation with spectral index $n \sim 0$ to $B<10^{-43}G$.**

- **Only scale invariant magnetic seed fields may be as large as $10^{-9}G$ and therefore leave a detectable imprint on the CMB.**

- **Helical fields might induce an inverse cascade leading to larger fields on large scales.**

- **Currents induced by charge separation (2nd order cosmological perturbation theory) may generate seed fields at much later times $(10^{-23}\text{-}10^{-16})G$ (Riotto et al. '05, Ichiki et al. '05).**

Comment: Would be very exciting to establish as a relic of the early universe!



Smoothed rotation measure:
Possible signatures of ~0.1μG level on super-cluster scales!

Theoretical motivations from the Weibel instability which tends to drive field to fraction of thermal energy density

But need much more data from radio astronomy, e.g. Lofar, SKA

2MASS galaxy column density

Xu et al., astro-ph/0509826

Comment: Complementary probes opening up study of cosmic magnetic fields

“Wir müssen wissen. Wir werden wissen”

(***We must know. We will know***)

David Hilbert: Speech in Königsberg, 1930

Thanks to Andrew, Kai and Mark for a superb conference!