Title: Challenging the Alternative Perspectives in Dark Energy

Date: Mar 09, 2005 02:00 PM

URL: http://pirsa.org/05030102

Abstract: The existence, and enigmatic nature, of 'Dark Energy' is one of the biggest theoretical upsets of recent times. In this seminar we present ideas on alternative theoretical and phenomenological approaches to the Dark Energy problem, in particular the issue of whether dark energy is a matter or gravity-based phenomenon, and the ways in which such approaches can been constrained and guided by observation. We also focus on some of the exciting future approaches that could provide unprecedented insights into the fundamentals of Dark Energy

The key dark energy questions

- What is the underlying nature of dark energy?
- What dark energy properties can we measure observationally?

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- What is the underlying nature of dark energy?

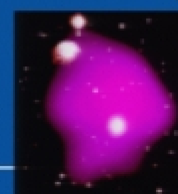
$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

Cosmological constant?

-Early phase transitions?

-Holographic?

-Anthropic?



Adjustment to matter?

-An 'exotic', dynamical matter component?

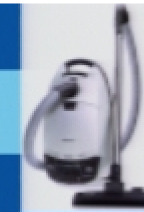
- 'Unified Dark Matter'?

Adjustment to gravity?

- Non-minimal couplings to gravity?

- Higher dimensional gravity?

- Inhomogeneous metric?

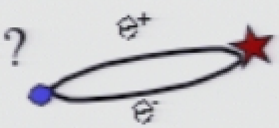


Λ - The problems with it

Why so small?

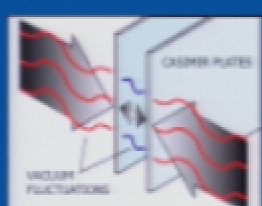
- UV divergences are the source of a dark energy fine-tuning problem

$$\Lambda \propto \int_0^\infty \sqrt{k^2+m^2}\,k^2 dk = ?$$



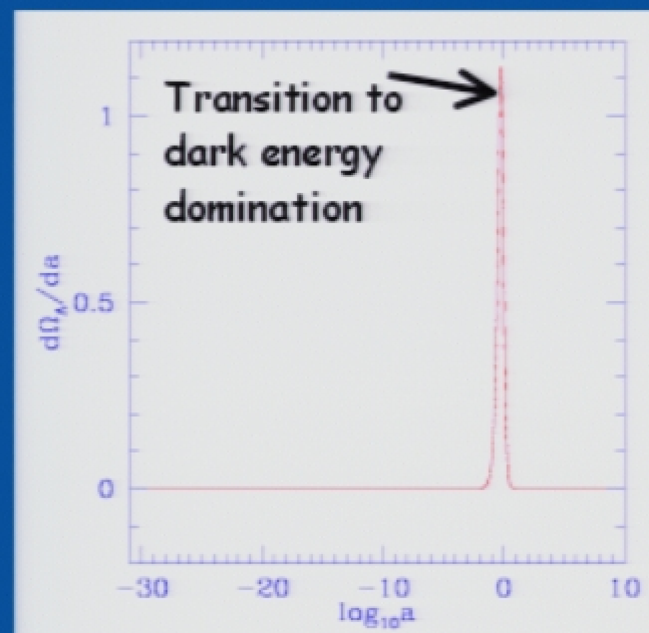
a) QFT	= ∞ ?
b) regularized at the Planck scale	= 10^{76} GeV^4?
c) regularized at the QCD scale	= 10^{-3} GeV^4?
d) 0 until SUSY breaking then	= 1 GeV^4?
e) all of the above	= 10^{-47} GeV^4?
f) none of the above	= 10^{-47} GeV^4?
g) none of the above	= 0 ?

- The cut off scale would have to be way below the scales currently in agreement with QFT (Casimir effect, Lamb shift)

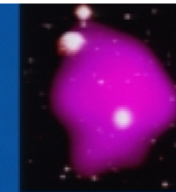


Why now?

- Coincidence problem
  - -Any later → Ω_Λ still negligible, we would infer a pure matter universe
  - - Any earlier → chronically affects structure formation; we wouldn't be here



- Inevitably led to anthropic arguments
  - -At most basic predict Ω_Λ/Ω_m<125



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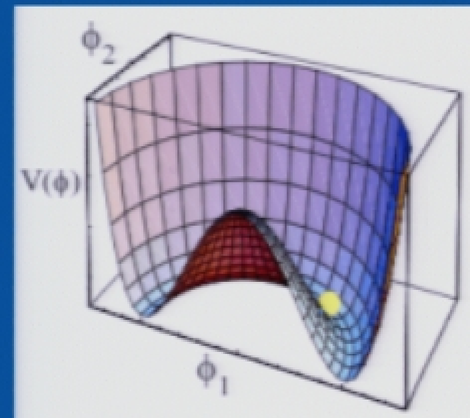
Scalar ϕ - spin 0 particle, like the Higgs

-with kinetic energy $\dot{\phi}^2/2$, Potential energy $V(\phi)$

-Accelerative expansion when potential dominates

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$



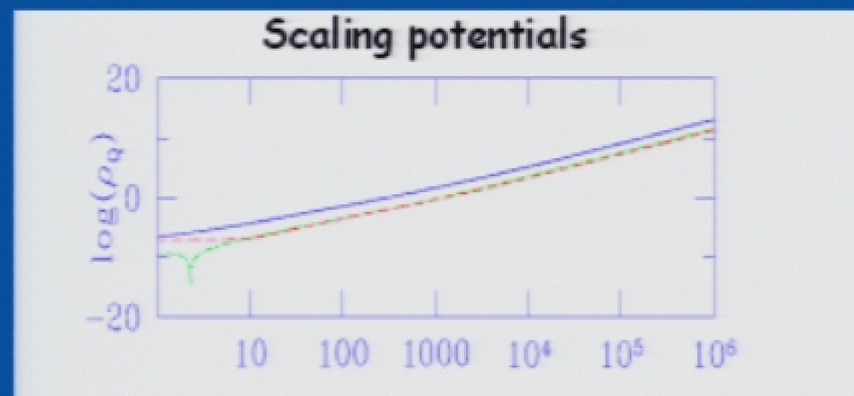
Scaling potentials

- Evolve as dominant background matter

$V \sim e^{-\lambda\phi}$

Wetterich 1988, Ferreira & Joyce 1998

- Need corrections to create eternal or transient acceleration Barrow, Bean, Magueijo 2000



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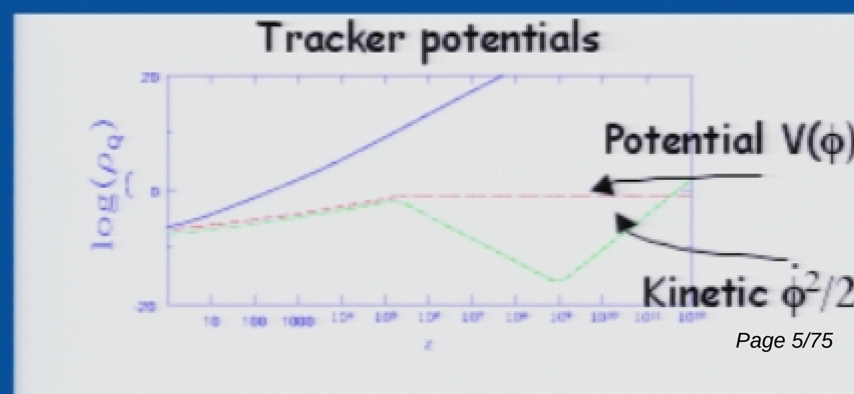

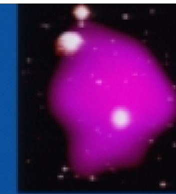

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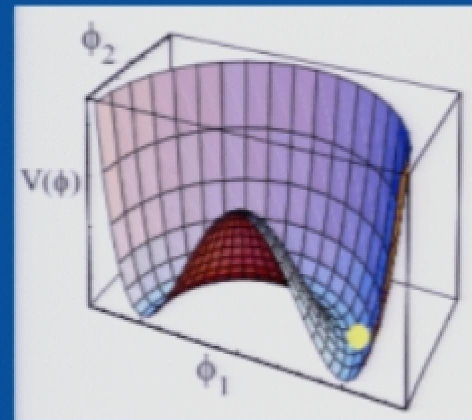

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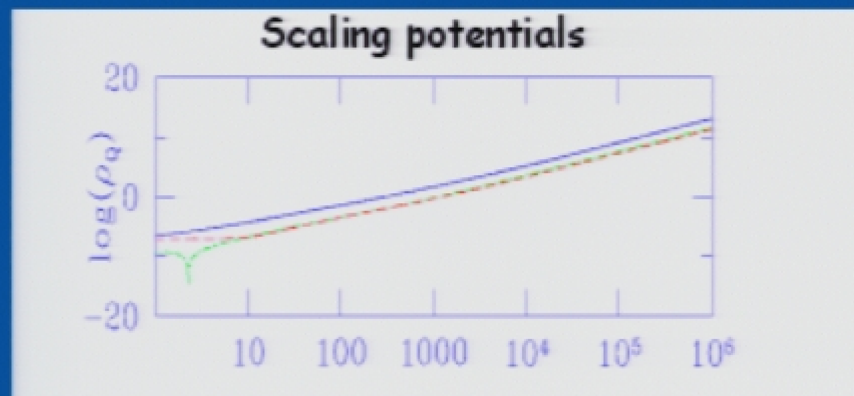

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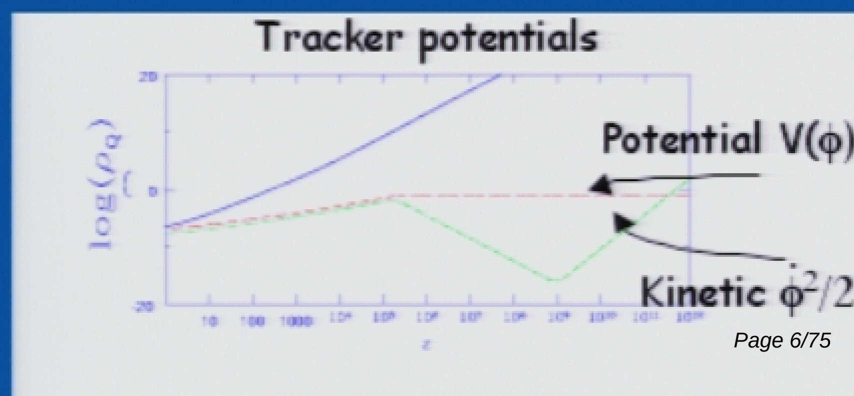

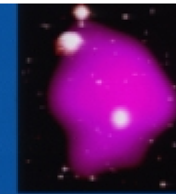

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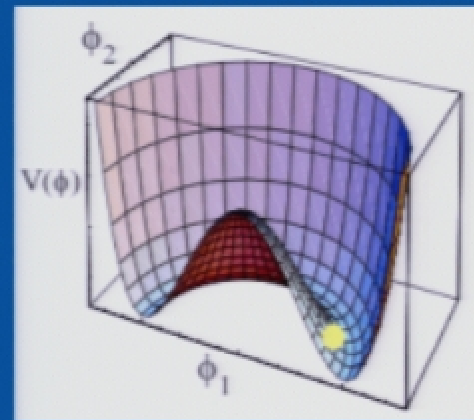

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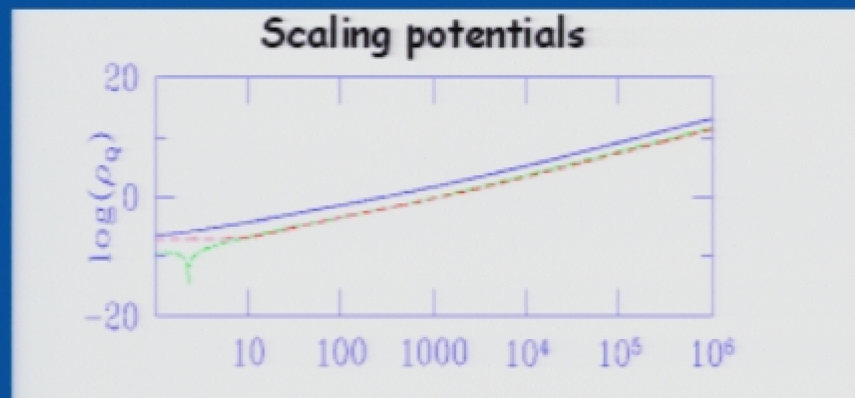

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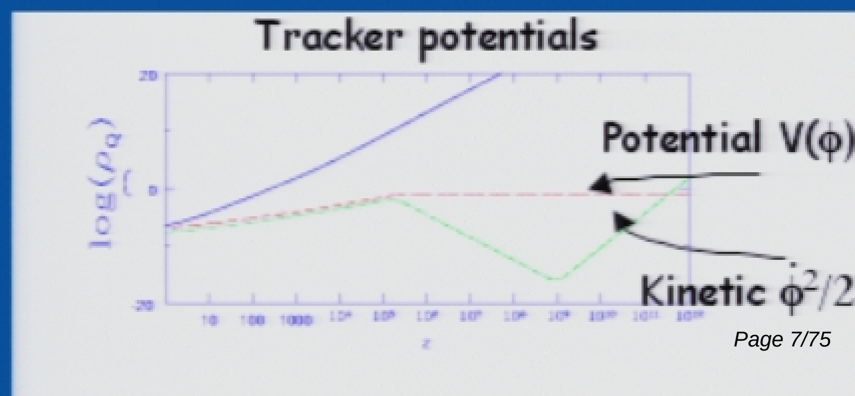

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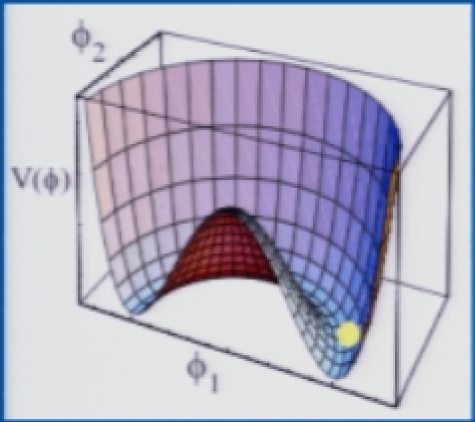

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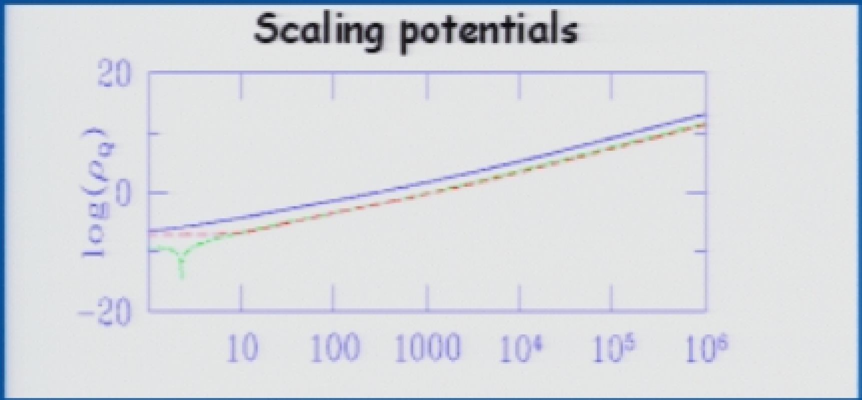

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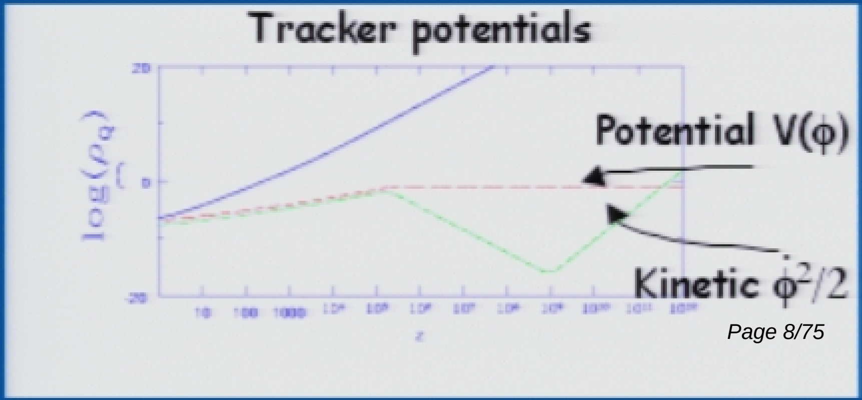

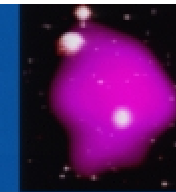

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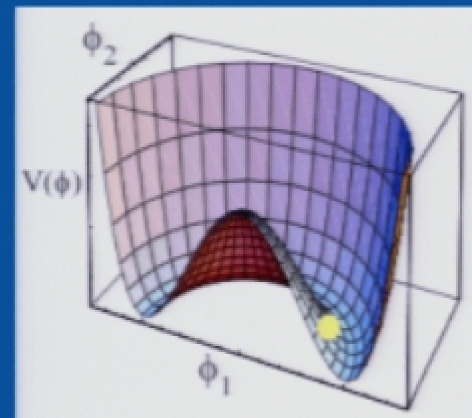

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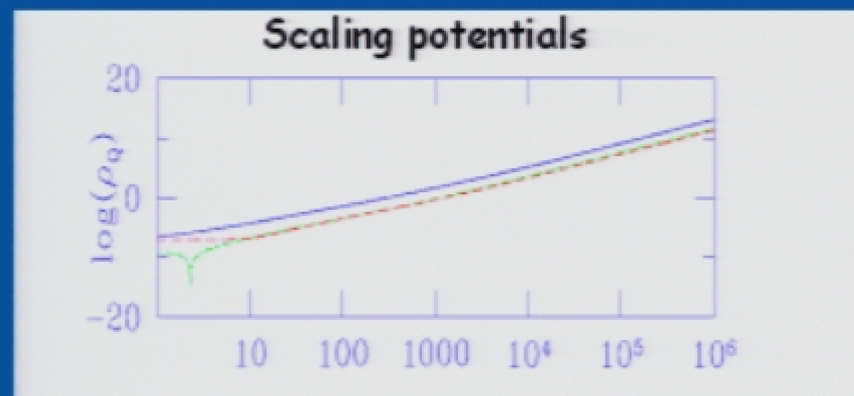

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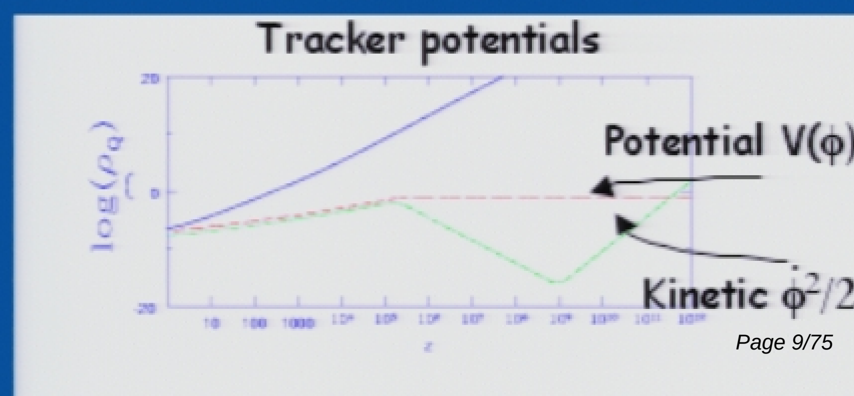

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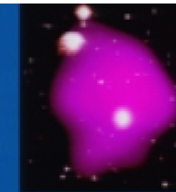

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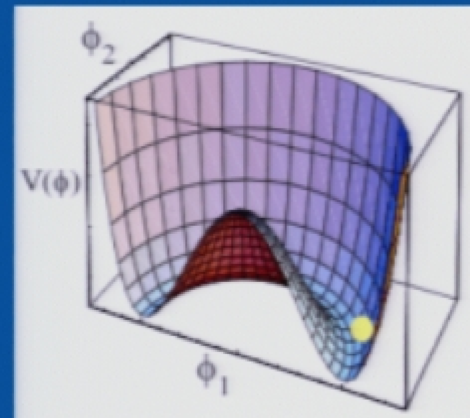

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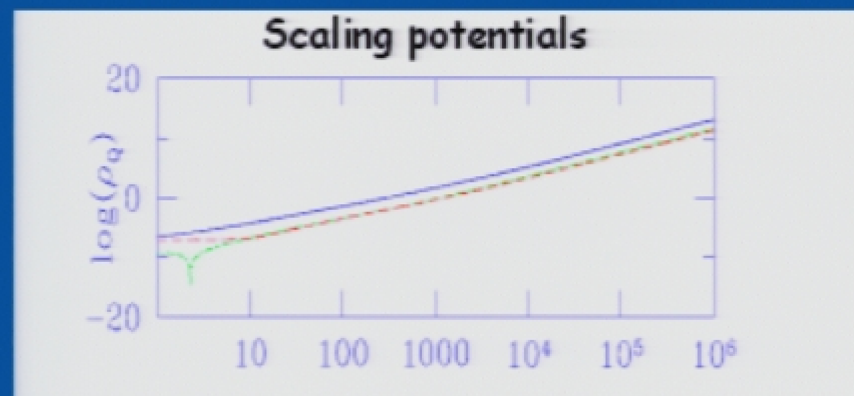

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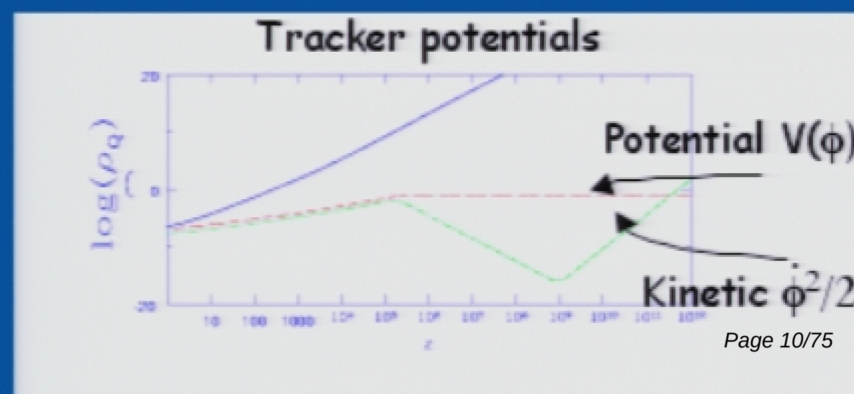

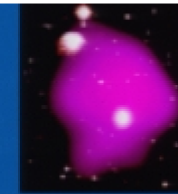

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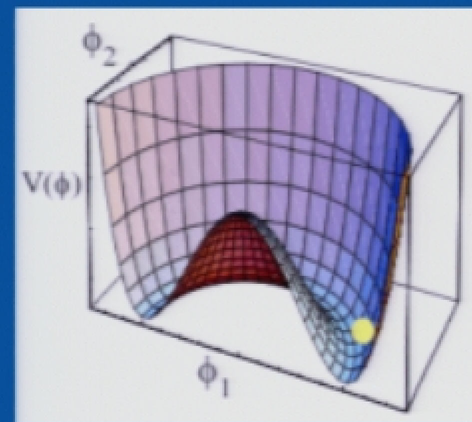

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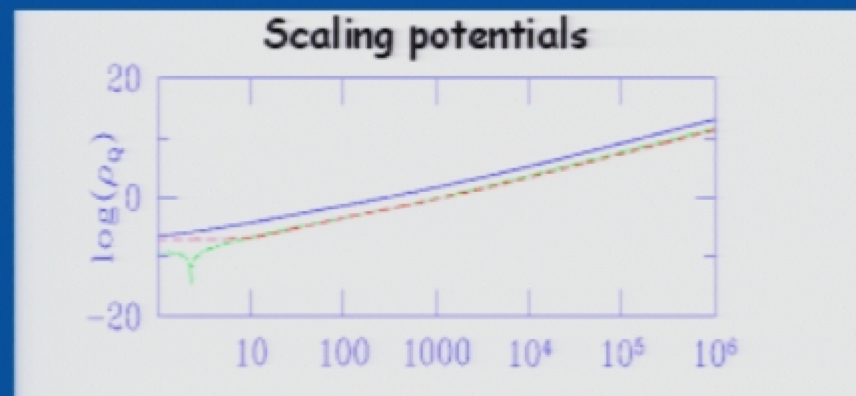

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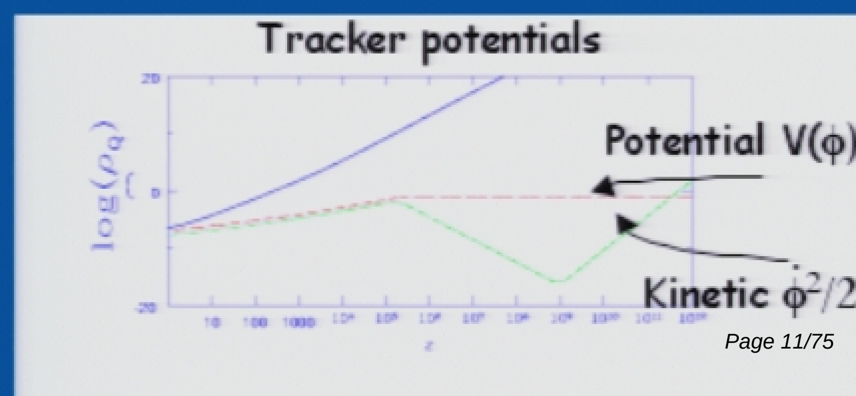

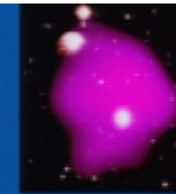

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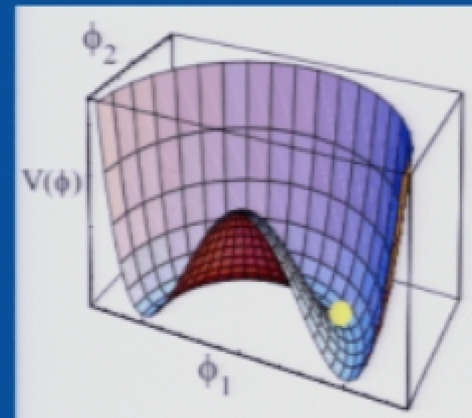

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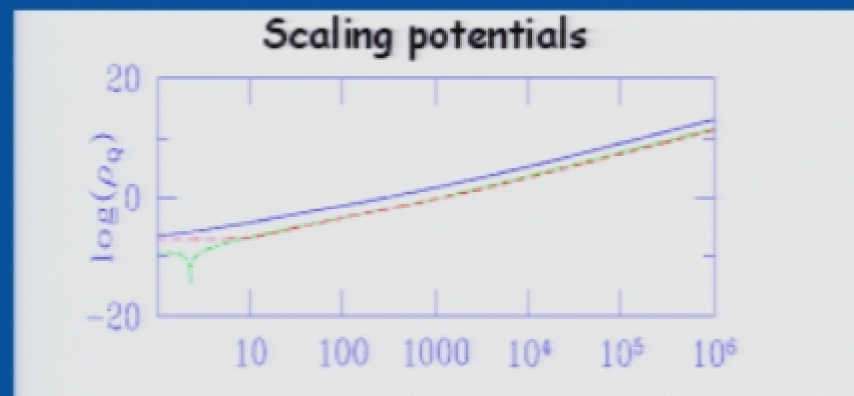

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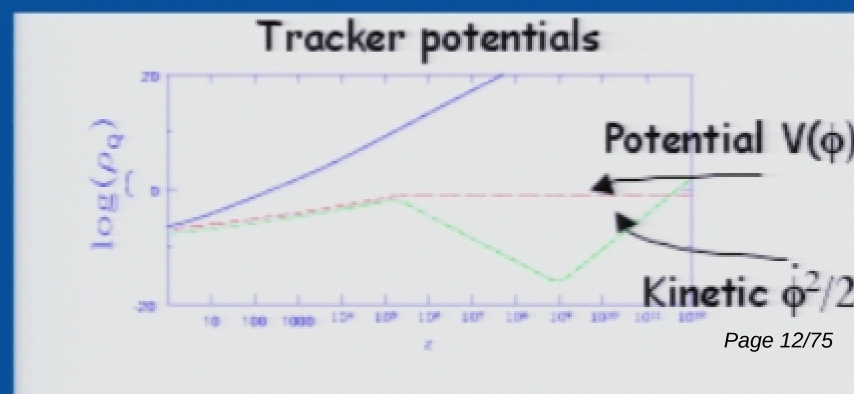

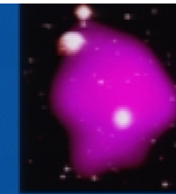

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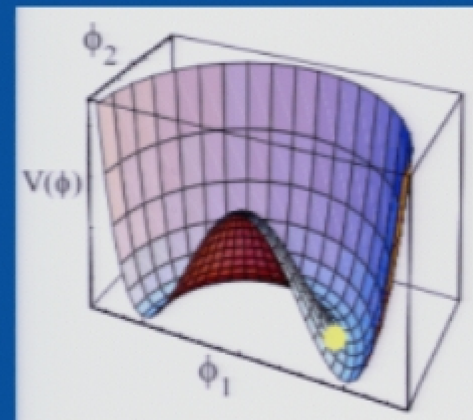

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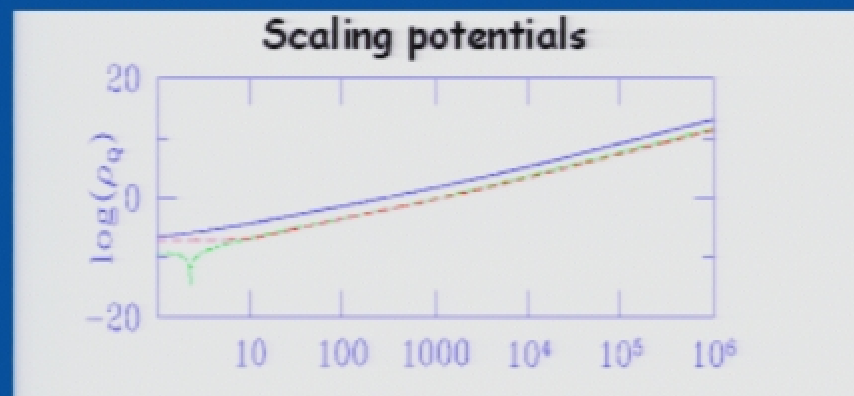

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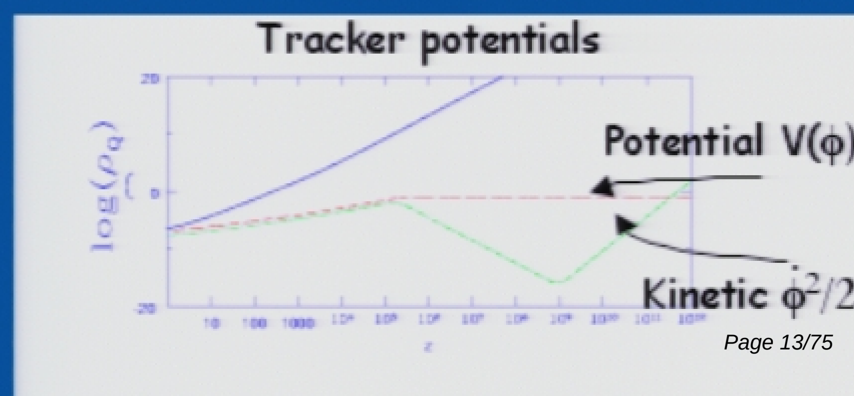

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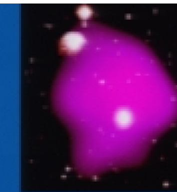

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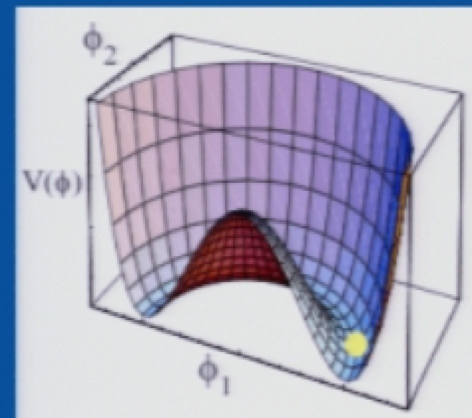

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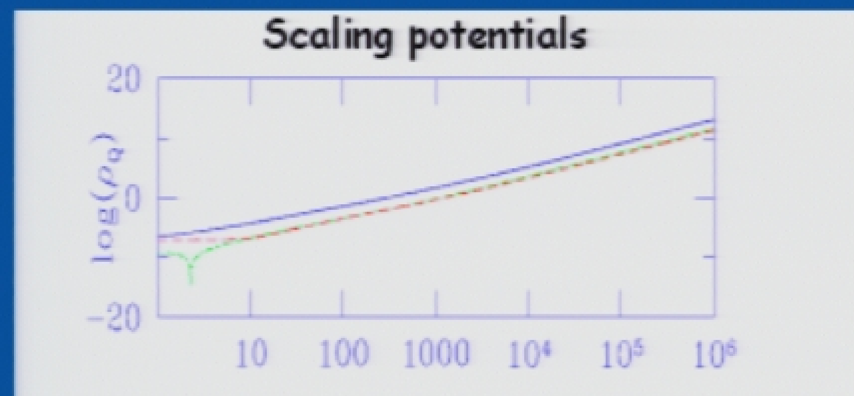

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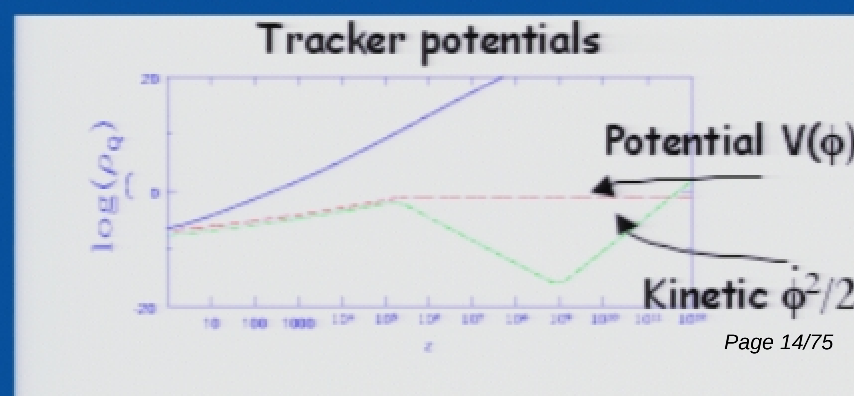

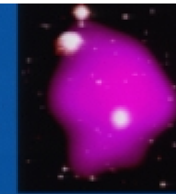

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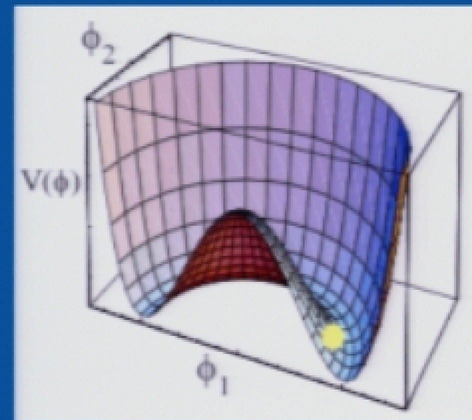

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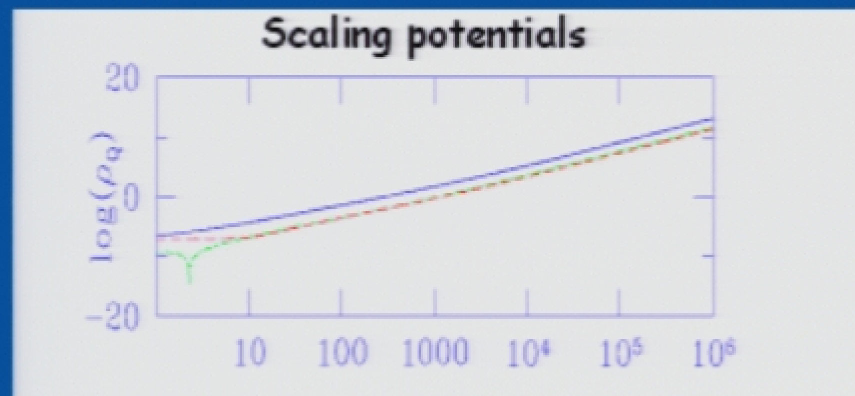

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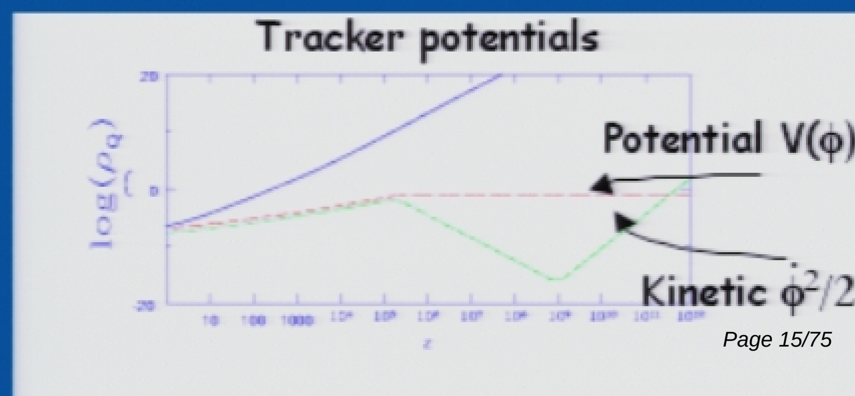

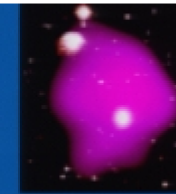

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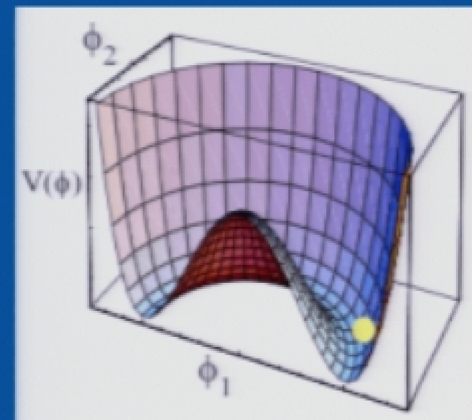

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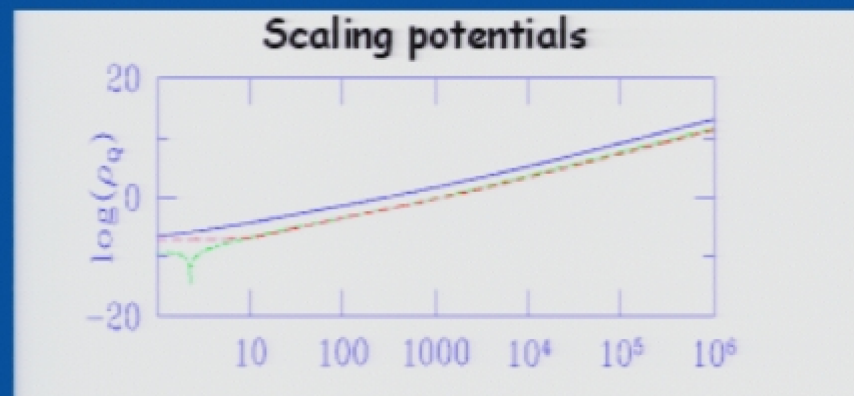

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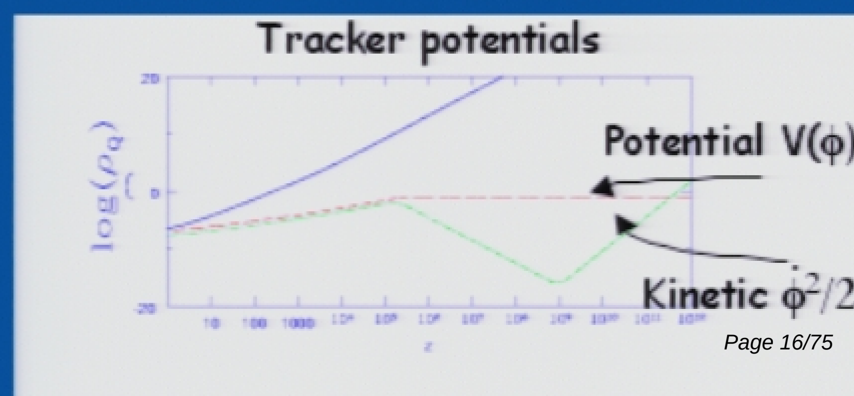

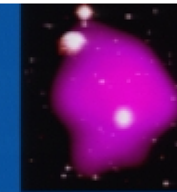

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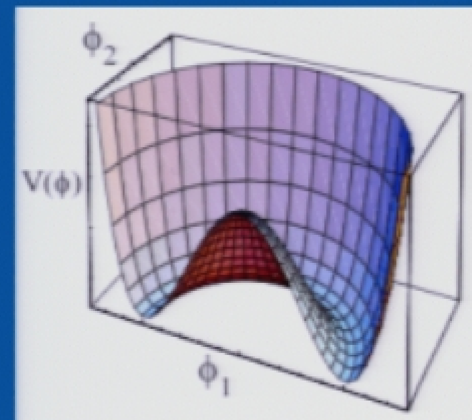

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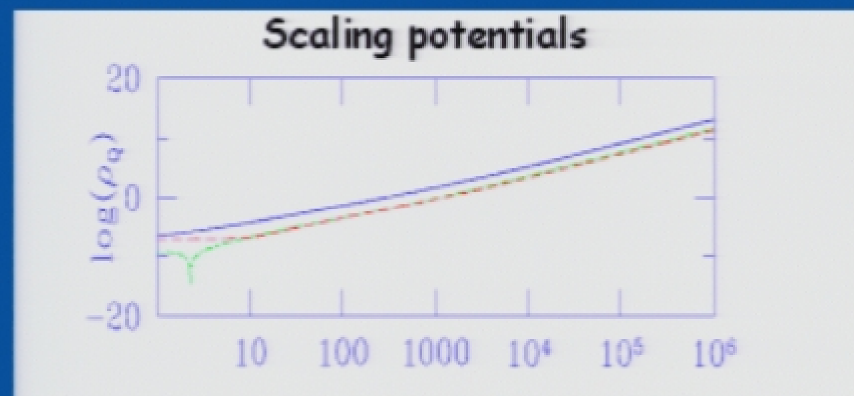

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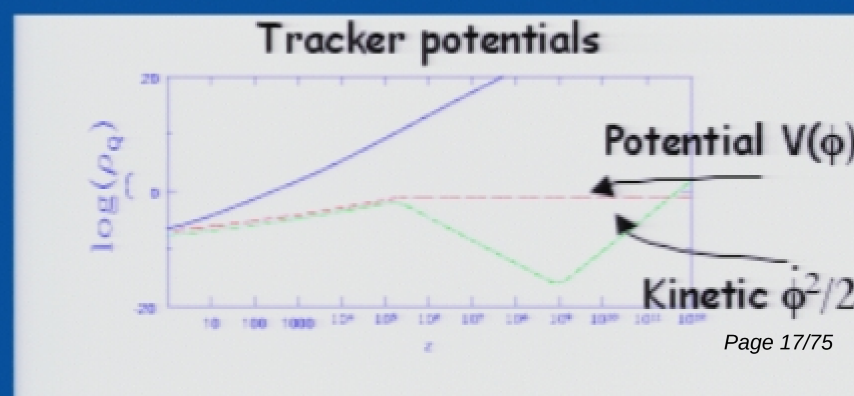

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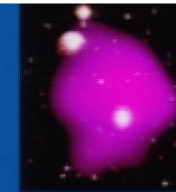

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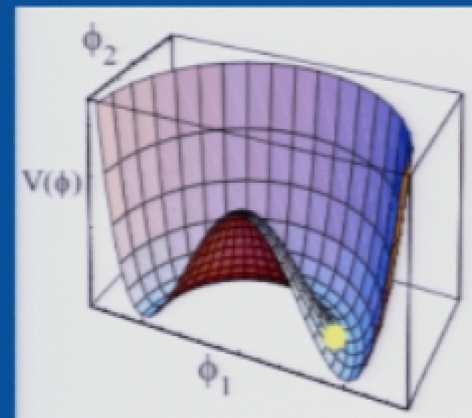

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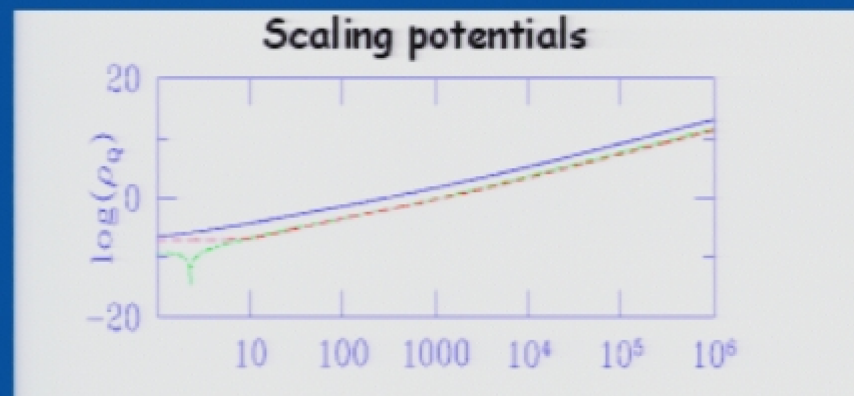

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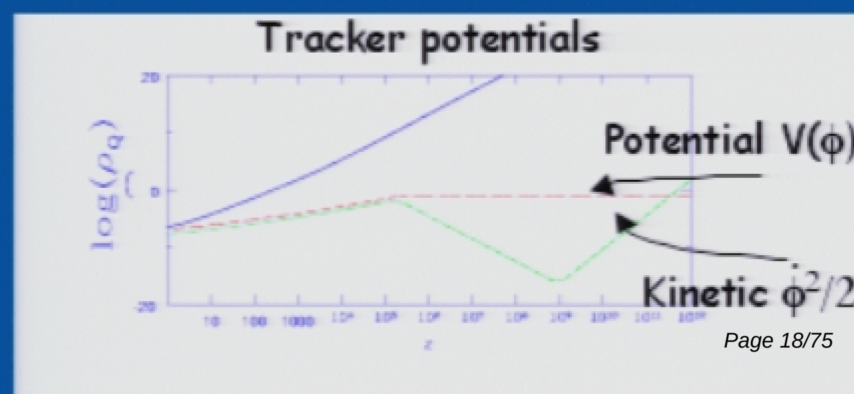

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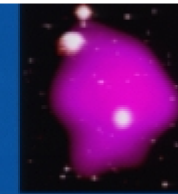

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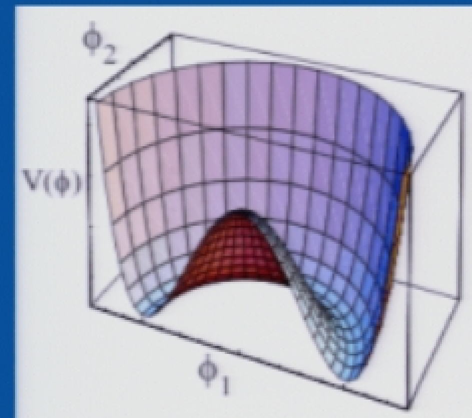

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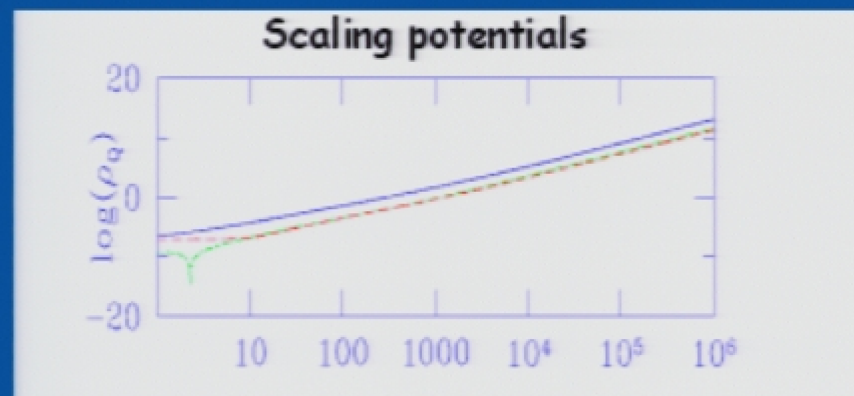

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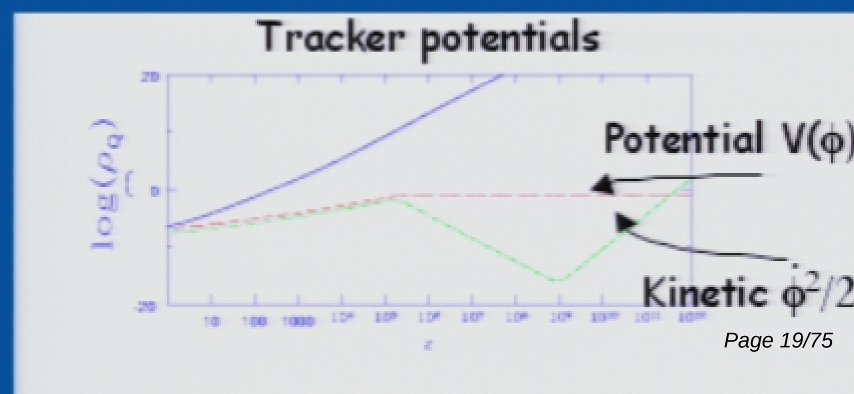

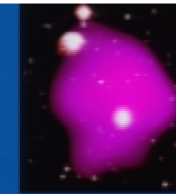

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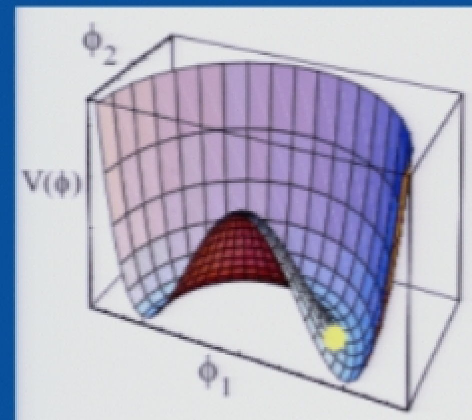

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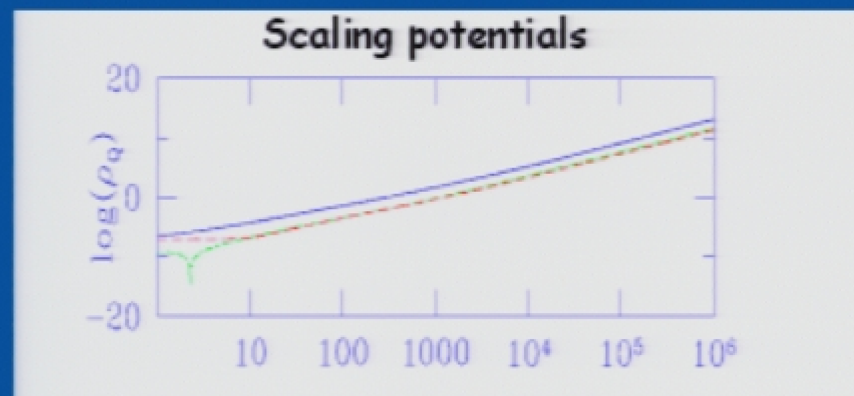

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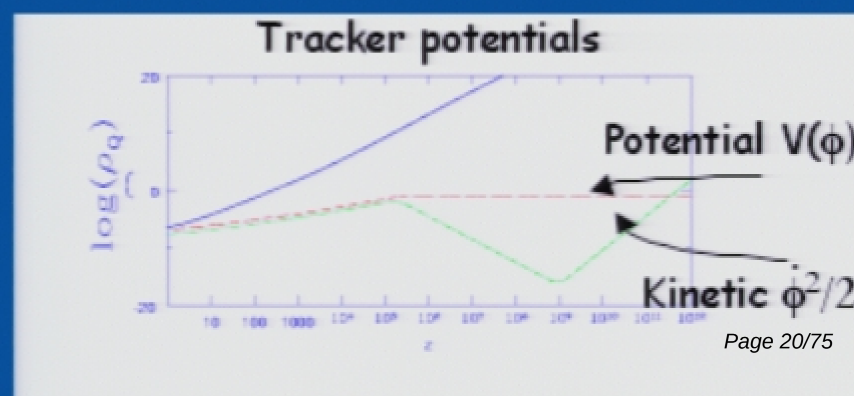

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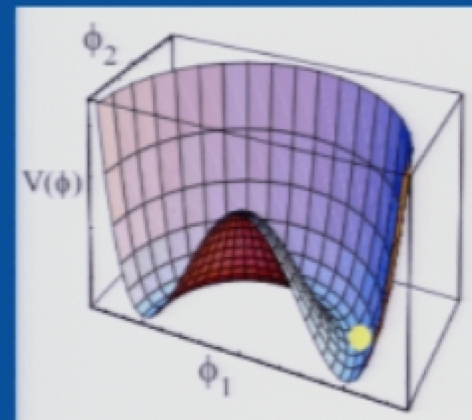

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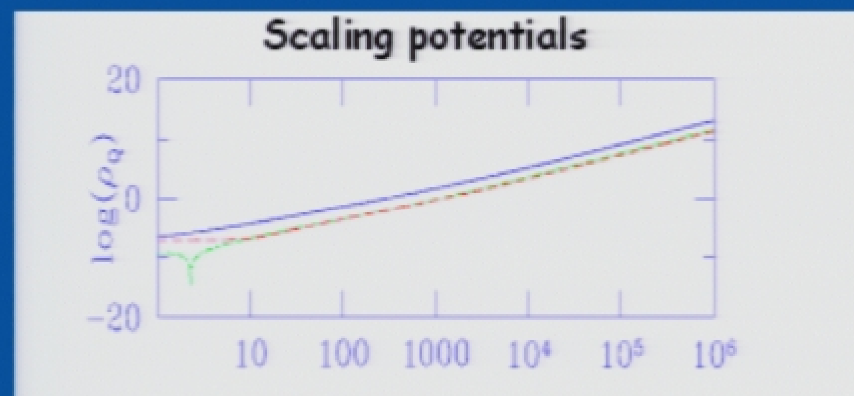

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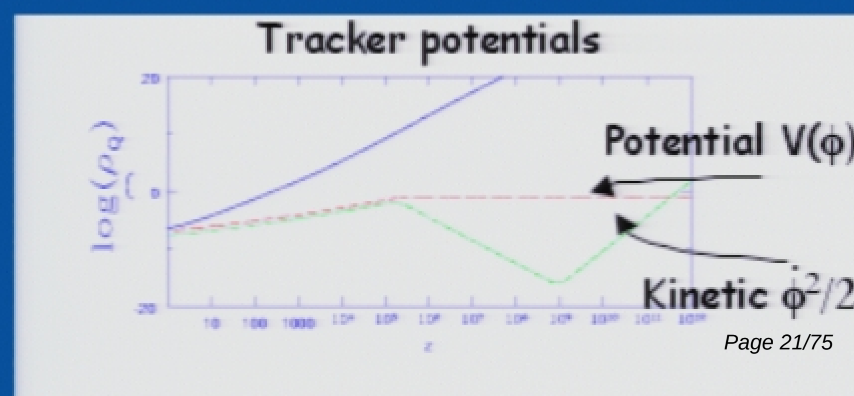

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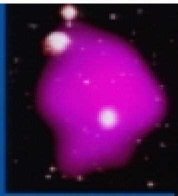

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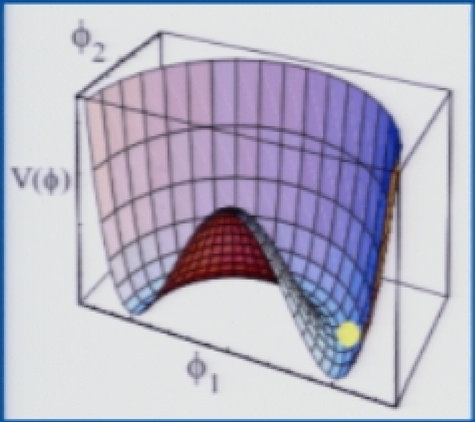

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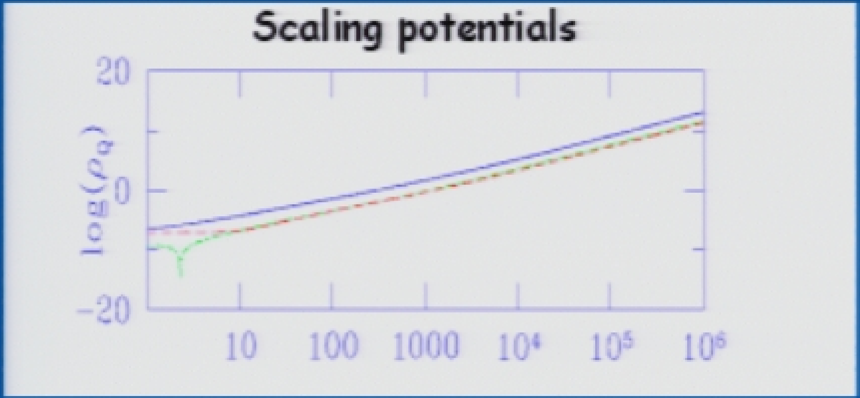

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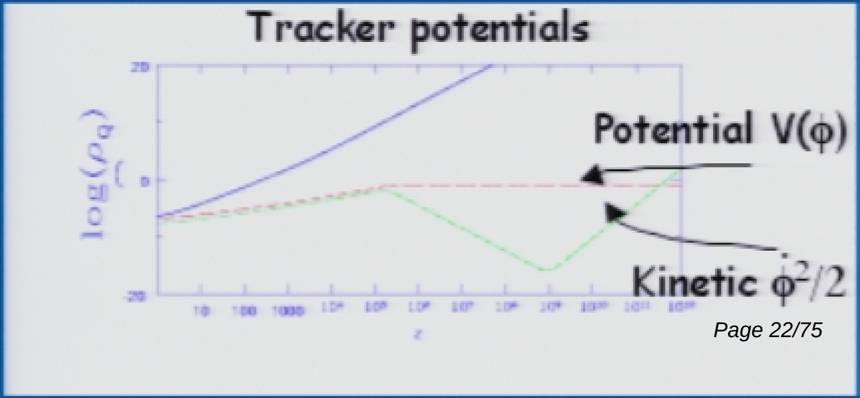

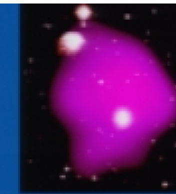

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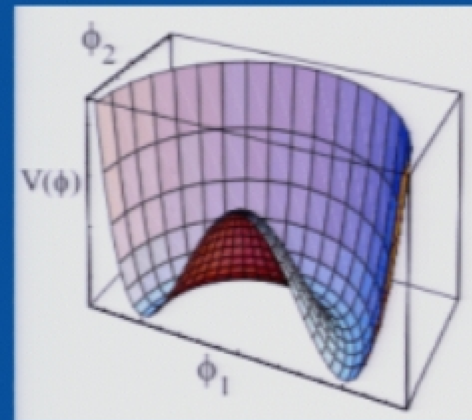

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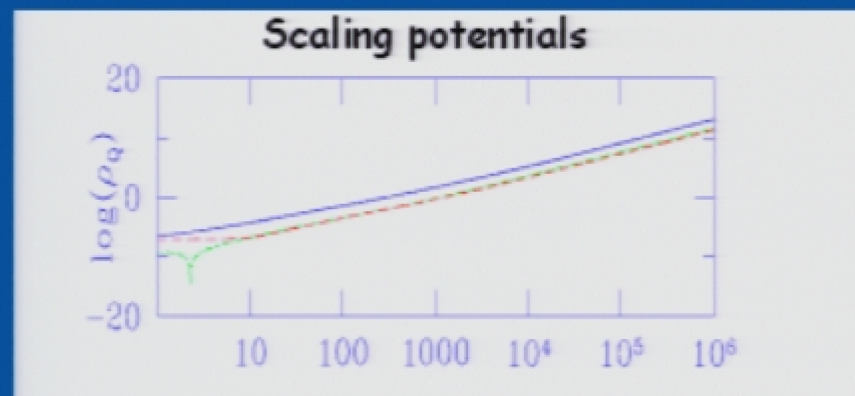

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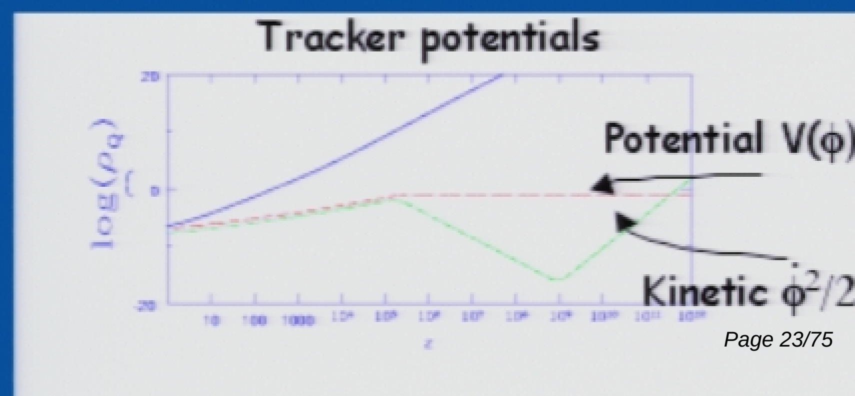

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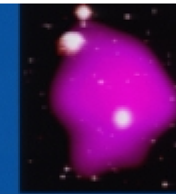

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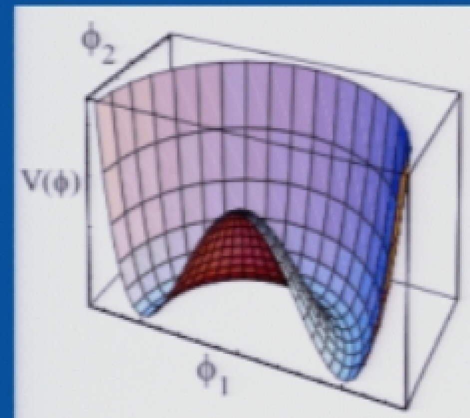

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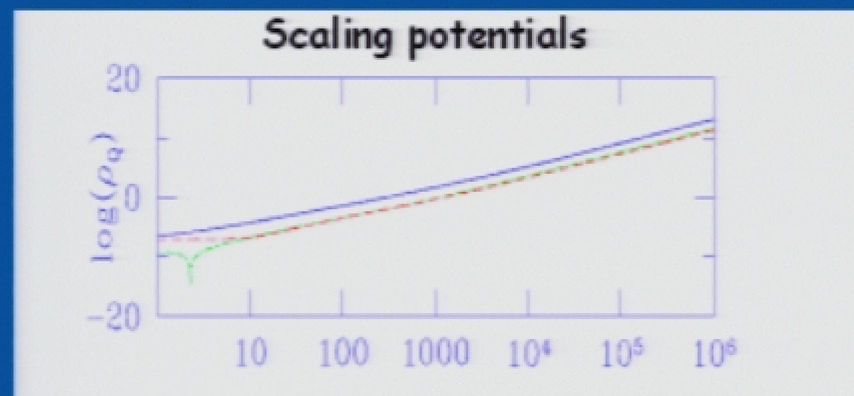

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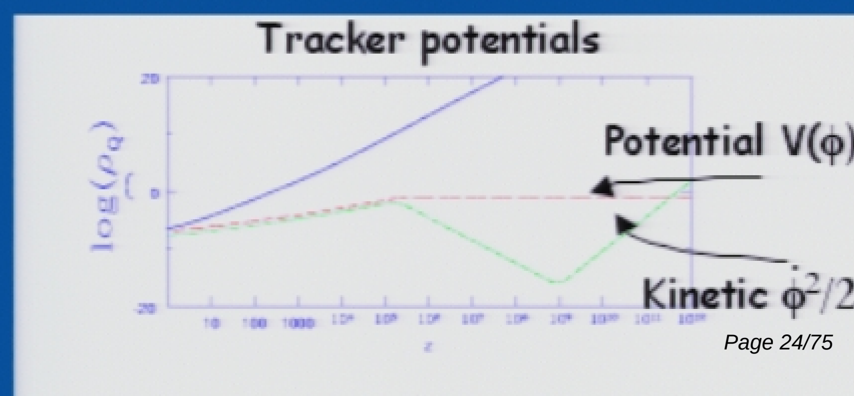
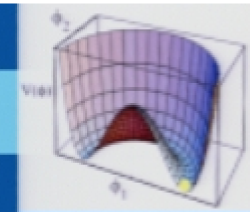
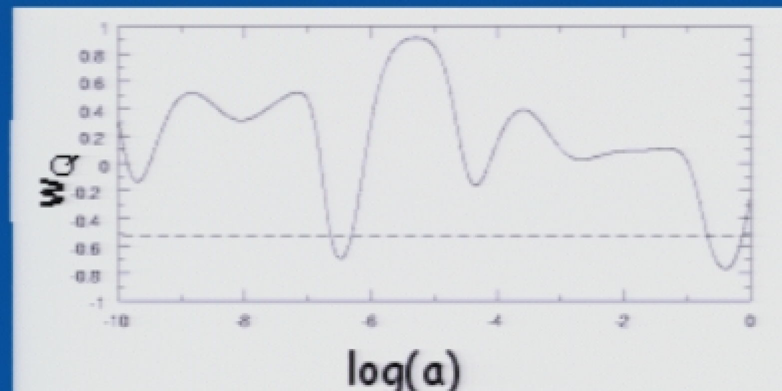


Tackling the coincidence problem: are we special?



- We're not special: universe sees periodic epochs of acceleration

$V \sim M^4 e^{-\lambda Q}(1+A\sin \nu Q)$ Dodelson , Kaplinghat, Stewart 2000



Oscillatory potential

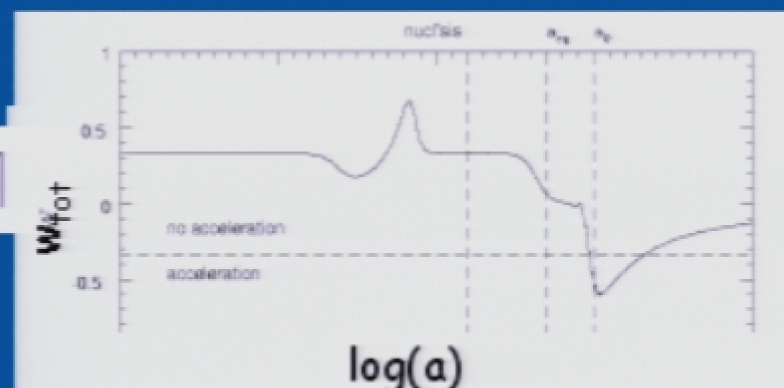
Dodelson , Kaplinghat, Stewart 2000

- We are special: the key is our proximity to the matter/ radiation equality

-Non-minimal coupling to matter (Bean & Magueijo 2001, Bean 2002)

$$= \int d^4x \sqrt{-\bar{g}}\,[B_g(\phi)\bar{R} + B_\phi(\phi)\bar{g}_{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{\alpha'}{4}B_F(\phi)\bar{F}^2 \ldots]$$

$$\mathcal{L} = -\frac{R}{2} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - f(\phi)\mathcal{L}_c + \mathcal{L}_v$$

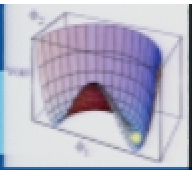


Non-minimal coupling to dark matter

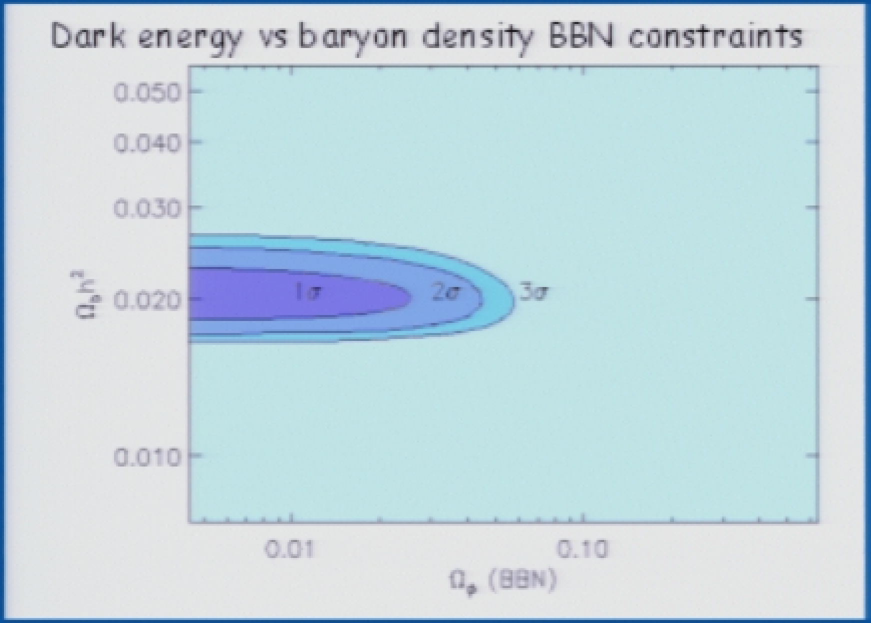
-k-essence : A dynamical push after z_{eq} with non-trivial kinetic Lagrangian term (Armendariz-Picon, et al 2000)

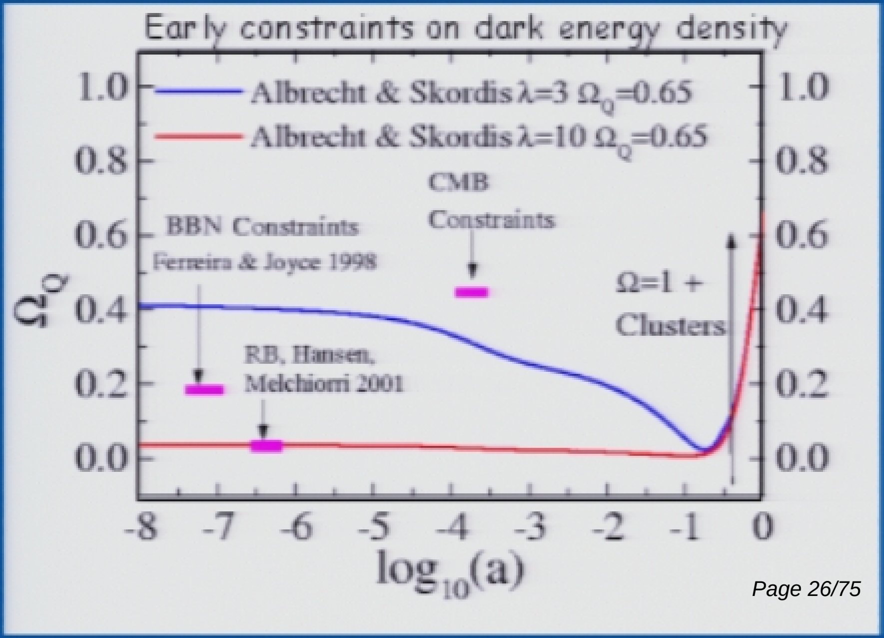
Bean & Magueijo 2001

Tackling the Λ problems: implications for BBN



- Scaling potentials can predict significant dark energy at earlier times treating Ω_Q as ΔN_{rel}. Bean, Hansen, Melchiorri 2001
- Bounds on Helium mass fraction, Y_{He}
  - $Y_{He}=0.234\pm0.003 \rightarrow 0.244\pm0.002$ (used higher value as more relaxed bound) Olive et al. (1995), Isotov et al (1998)
  - But more recently $Y_{He}=0.243\pm0.0009$ Olive et al. (2004)
- Relative Deuterium abundance D/H
  - $D/H=(3.0\pm0.4).10^{-5}$ Burles et al (1998)
  - But collated more recent value D/H = 2.6 $\pm0.4).10^{-5}$ Kirkman et al (2003)
- Abundance limits correspond to $\Delta N_{rel}<0.2$
  - This translates into Ω_Q (MeV)<0.05 (2σ)





Bean, Hansen, Melchiorri 2001

Tackling the Λ problems: implications for primordial black holes

Early dark energy could be source for feeding primordial black holes (Bean and Magueijo 2002)

-can lead to alternative structure formation model where PBHs form the seeds for structure

Assuming gravitational field from scalar << BH so that we can impose a Schwarzchild metric around PBH

-flux of scalar into BH ~ $\dot{\phi}^2$ determined in cosmological sol^n

Scalar field will be accreted into a black hole and can have a significant effect.

$$\frac{dM}{dt} = -\frac{\alpha}{M^2} + \kappa\frac{M^2}{t^2}$$

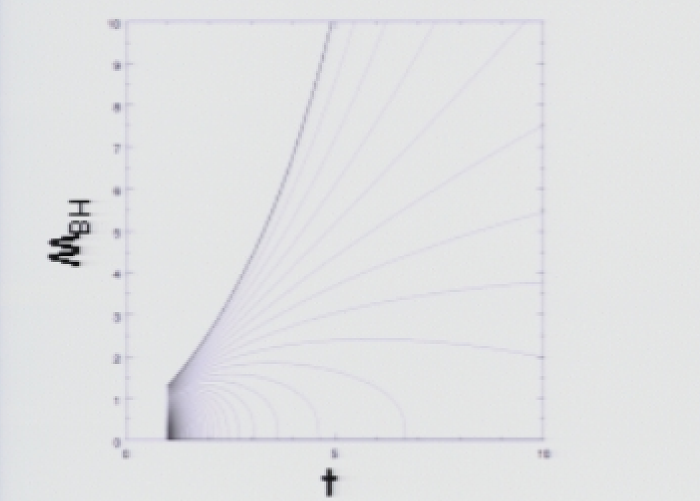
Evaporation Independent of Q

Accretion dependent on $\Omega_Q(z)$.

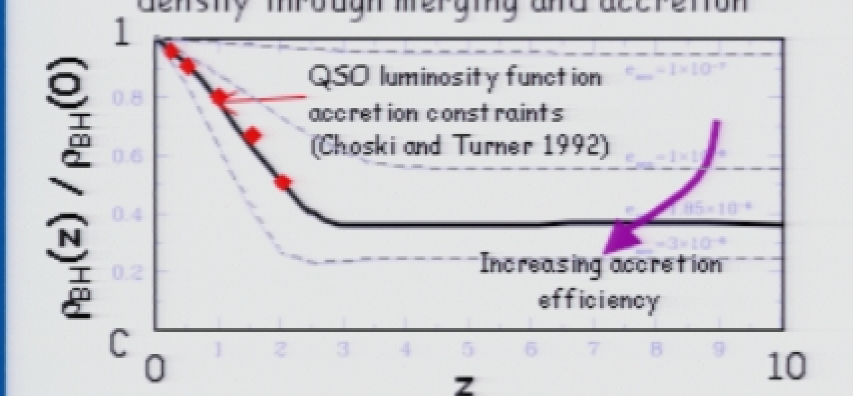
Merger history + halo accretion follow PBH accretion

-Give number density and SMBH/halo mass relation consistent with observations

Evolution of BH mass with quintessence accretion and evaporation



Late-time evolution of cosmological BH energy density through merging and accretion



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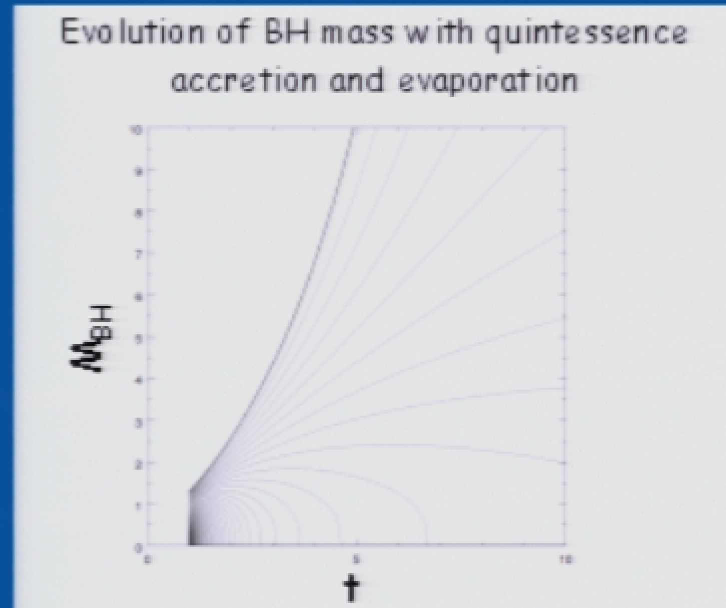

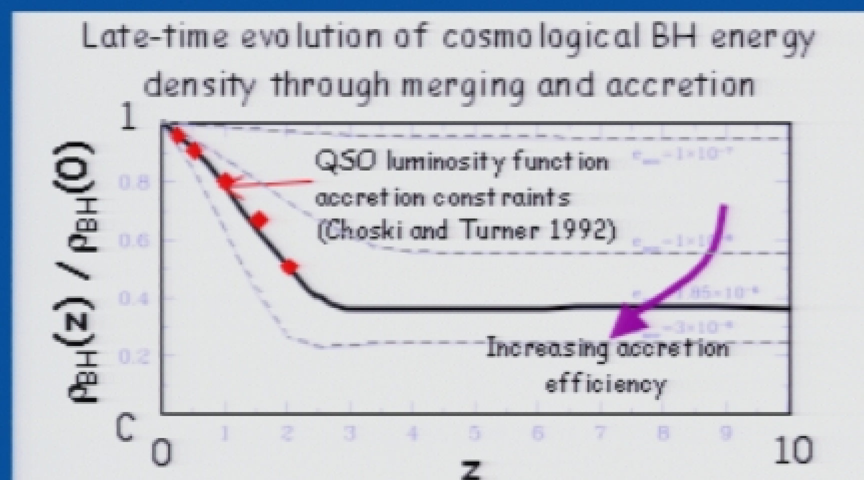

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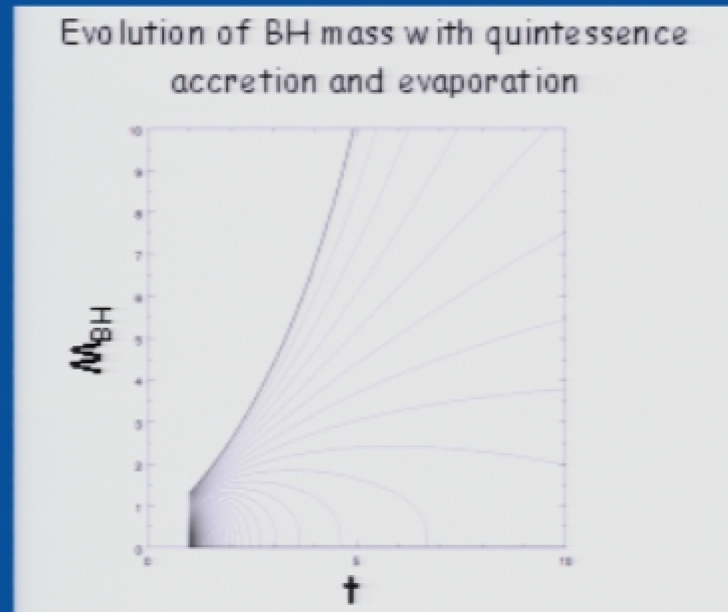

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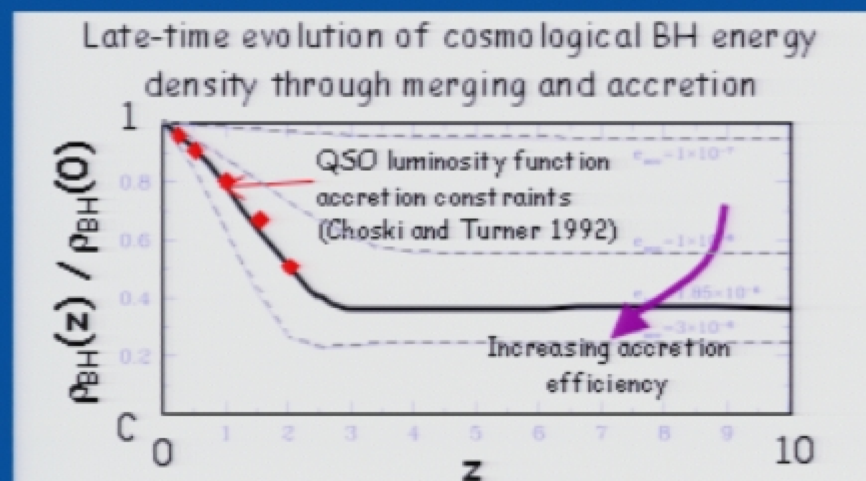
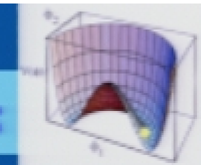


Merger history + halo accretion follow PBH accretion

-Give number density and SMBH/halo mass relation consistent with observations

Bean and Magueijo 2002

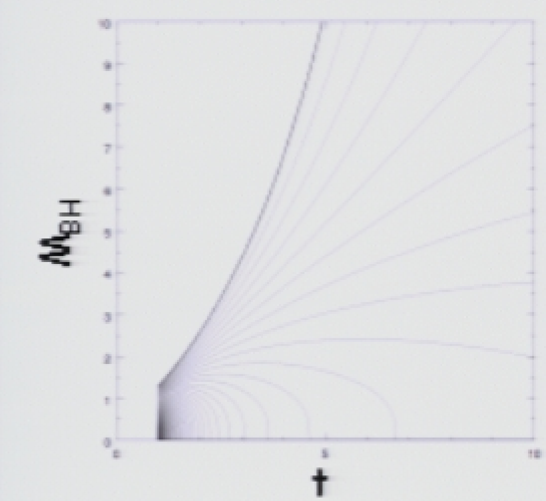


Tackling the Λ problems: implications for primordial black holes

Early dark energy could be source for feeding primordial black holes (Bean and Magueijo 2002)

-can lead to alternative structure formation model where PBHs form the seeds for structure

Evolution of BH mass with quintessence accretion and evaporation



Assuming gravitational field from scalar << BH so that we can impose a Schwarzchild metric around PBH

-flux of scalar into BH ~ $\dot{\phi}^2$ determined in cosmological sol^n

Scalar field will be accreted into a black hole and can have a significant effect.

$$\frac{dM}{dt} = -\frac{\alpha}{M^2} + \kappa\frac{M^2}{t^2}$$

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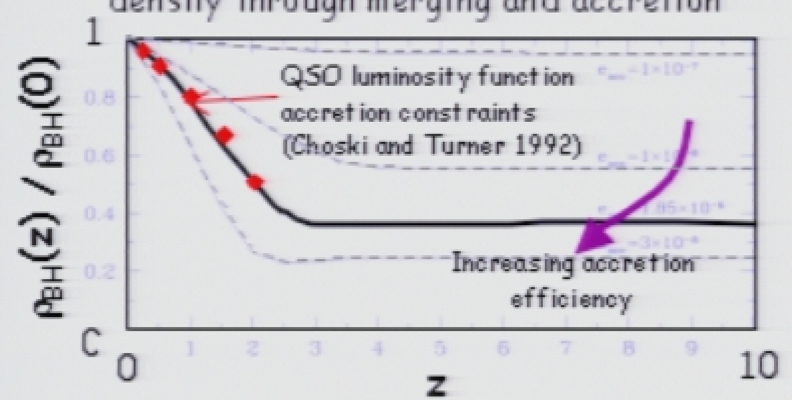
Late-time evolution of cosmological BH energy density through merging and accretion



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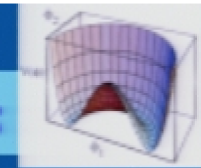

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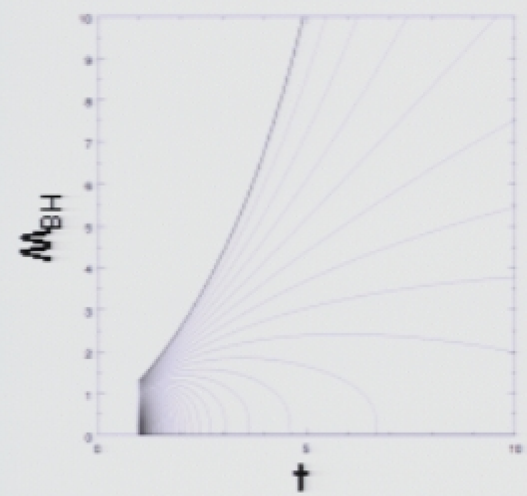

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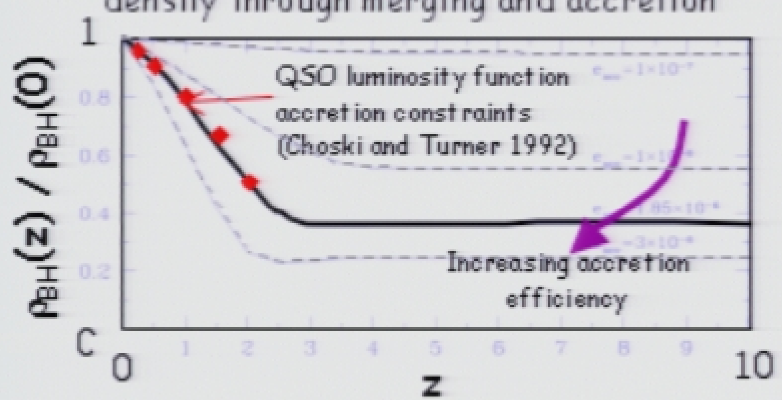
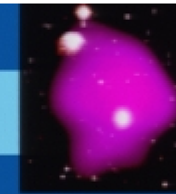
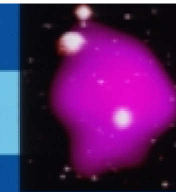


Bean and Magueijo 2002

Dark energy perturbations: an important discriminator?



- Natural extension to looking for w≠-1 ,dw/dz≠0
- To distinguish between theories ...
  - only effecting the background (Λ, alterations to FRW cosmology)
  - with negligible clustering...(minimally coupled quintessence)
  - that could contribute to structure formation (non-minimally coupled DE, k-essence)
- To test if dark matter and dark energy are intertwined?
  - unified dark matter?
- From a theorist's perspective, to decipher the dark energy action
  - probing the dark energy external and self-interactions (or lack of) bound up in an effective potential
- From an observational perspective, to check that a prior assuming no perturbations is fair
  - Does it effect the combination of perturbation independent (SN) and potentially dependent (CMB/LSS/WL) observations?



Expect little, but not necessarily no, clustering of dark energy

- Clustering properties determined by Jeans length and speed of sound
  - maximize clustering by having low c_s^2 and large Jean's length

$$\ddot{\delta} + 3H\dot{\delta} = -(k^2 c_s^2 - \lambda_J^2)\delta$$

- Consider from a scalar field perspective......
  - Perturbing the continuity equation we get an expression like that for conventional matter but with little clustering .....

$$\ddot{\varphi} + 3H\dot{\varphi} = -(k^2 + V'')\varphi + \dot{\delta}_c\dot{\phi}$$

Notice that $c_s^2=1$ for scalar field theories disfavoring clustering

Simple scalar field Jean's length imaginary: scalar doesn't cluster on its own

but it can cluster for large scales through gravitational feedback from a growing CDM mode...

General clustering properties influenced by speed of sound

- Perfect fluids specified adiabatic speed of sound, c_a^2
  - Purely determined by background (gauge independent)
  - e.g. Particulate, elastic interactions γ and CDM

$$c_a^2 = \frac{\dot{p}}{\dot{\rho}} = w - \frac{\dot{w}}{3H(1+w)}$$

- For imperfect fluids, intrinsic entropy perturbations Γ_{int} are also important
  - $\Gamma \neq 0$ means dissipative self-interactions (bundled up in effective potential)

$$w\Gamma_{int} = 3H(1+w)c_a^2\left[\frac{\delta\rho}{\dot{\rho}} - \frac{\delta p}{\dot{p}}\right]$$

Internal isocurvature mode

  - Gauge dependent speed of sound

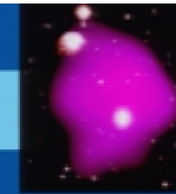
$$c_s^2 = \frac{\partial p}{\partial \rho}$$

$$w\Gamma_{int} = [c_s^2(k,t) - c_a^2(t)]\delta(k,t)$$

Any frame: Gauge dependent c_s^2 and density fluctuation

Rest-frame: Gauge independent c_s^2 and density fluctuation

1998



c_s^2 in scalar field theories

- For a scalar field , minimally coupled to gravity with a simple kinetic term $c_s^2=1$

- Consider a homogenous scalar field ,simply coupled to gravity, with kinetic variable $X=(\partial_\mu\phi)^2/2$

$$\mathcal{L}(\phi, X) = \sqrt{-g}\,[f_1(X) + f_2(X,\phi) - V(\phi) + f_3(\phi)\mathcal{L}_m]$$

- General speed of sound,

$$\frac{\delta p}{\delta \rho} = \frac{\mathcal{L}_{,X}\delta X + \mathcal{L}_{,\phi}\delta\phi}{(2X\mathcal{L}_{,XX}+\mathcal{L}_{,X})\delta X + (2X\mathcal{L}_{,\phi X}-\mathcal{L}_{,\phi})\delta\phi}$$

- In the rest frame v=0 -> $\delta\phi=0$, only kinetic terms determine speed sound

$$\delta T^0_j = (1+w)\rho v_j = \frac{k}{a^2}\dot{\phi}\delta\phi Y_j$$

$$c_s^2 = \frac{\mathcal{L}_{,X}}{2X\mathcal{L}_{,XX}+\mathcal{L}_{,X}}$$

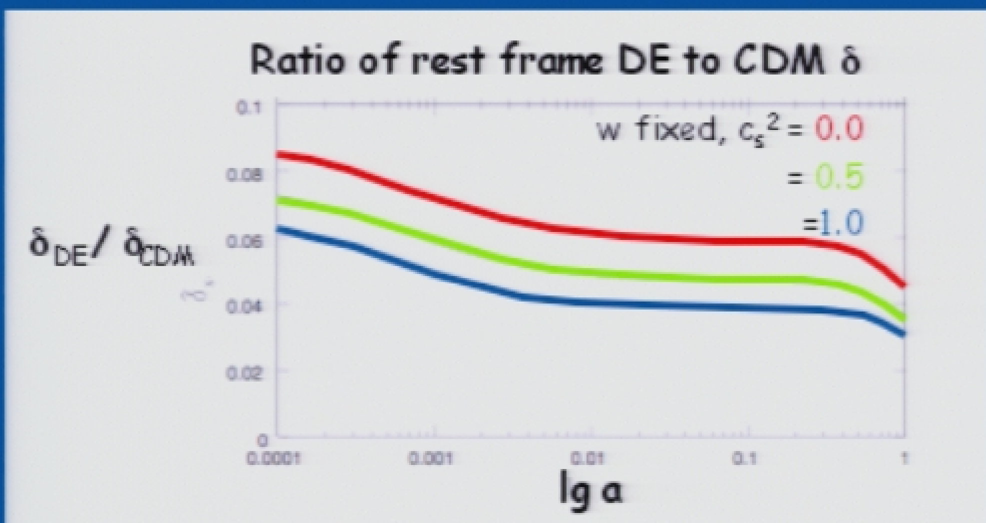
- For general scalar field actions c_s^2 can be less than 1 (encouraging clustering), if
  - have a non-trivial kinetic term
  - have a non-minimal coupling to gravity or matter other than CDM

Dark energy clustering and its affects structure formation

- Sound horizon associated with rest frame c_s^2

$$s_{eff}(\tau) = \int_0^\tau d\tau' c_s$$

-outside horizon DE perturbations have growing mode driven by dominant background component.

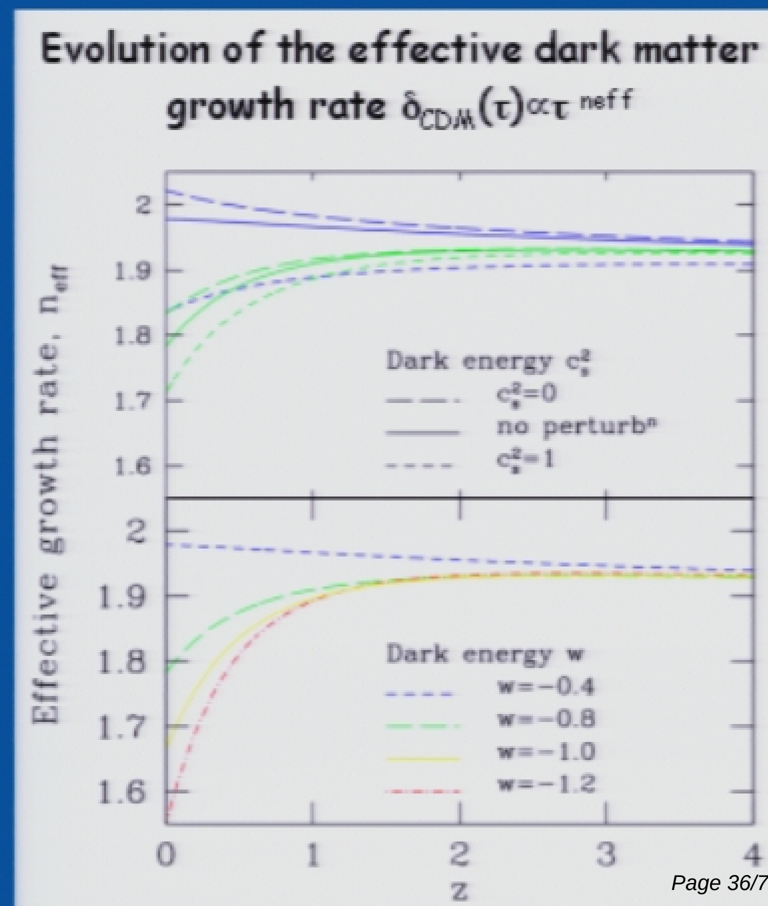


Bean and Dore PRD 69 2003

$$\delta_{DE} \approx A(c_s^2, w)(1+w)\delta_{CDM}$$

-inside horizon perturbations decay, and dark energy component is smoothed on these scales

- DE perturbations only affect structure at times when $\Omega_x > \Omega_c$ (at late times)
- Including DE perturbations has an effect on dark matter growth



c_s^2 in scalar field theories : k-essence

- Explain coincidence problem using attractor properties of scalar field action

- Non trivial kinetic term drives dark energy evolution

$$\mathcal{L}(\phi, X) = \sqrt{-g}\,[f_1(X) + f_2(X, \phi)]$$

$$c_s^2 = \frac{\mathcal{L}_{,X}}{2X\mathcal{L}_{,XX}+\mathcal{L}_{,X}}$$

- Recently been applied to "ghost condensates" (e.g. Piazza and Tsujikawa 2004)

-Start with a general action

$$= \int d^4x\sqrt{-\bar{g}}\,\left[B_g(\phi)\bar{R} + B_\phi(\phi)\bar{g}_{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{\alpha'}{4}B_F(\phi)\bar{F}^2 \ldots\right]$$

-Taylor expansion ...

$$\int d^4x\sqrt{-g}\,\left[\frac{M_p^2}{2}R \pm \frac{1}{2}(\partial\varphi)^2 - V(\varphi) + HOTs\right] + S_m[\varphi, g_{mu\nu}, \Phi_i]$$

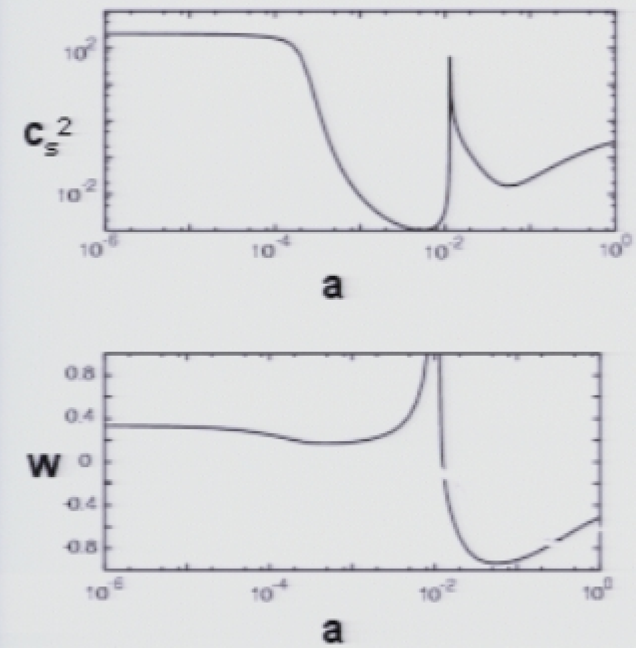
$$\frac{A}{m^4}\,(\partial\varphi)^4\, e^{\lambda\varphi/M_p}$$

-K-essence like action

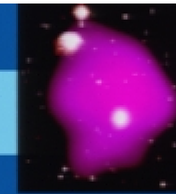
$$\mathcal{L} = p(\phi, X) + \mathcal{L}_m[\phi, \Psi_i, g_{\mu\nu}]$$

$$p(\phi, X) = -X + c_1 e^{\lambda\phi}X^2 - c_2 e^{-\lambda\phi}$$

Example of redshift evolution of w and c_s^2 for a k-essence model



Erickson et. al astro-ph/0112438
Steinhardt et. al. astro-ph/0004134



c_s^2 in scalar field theories : "extended quintessence"

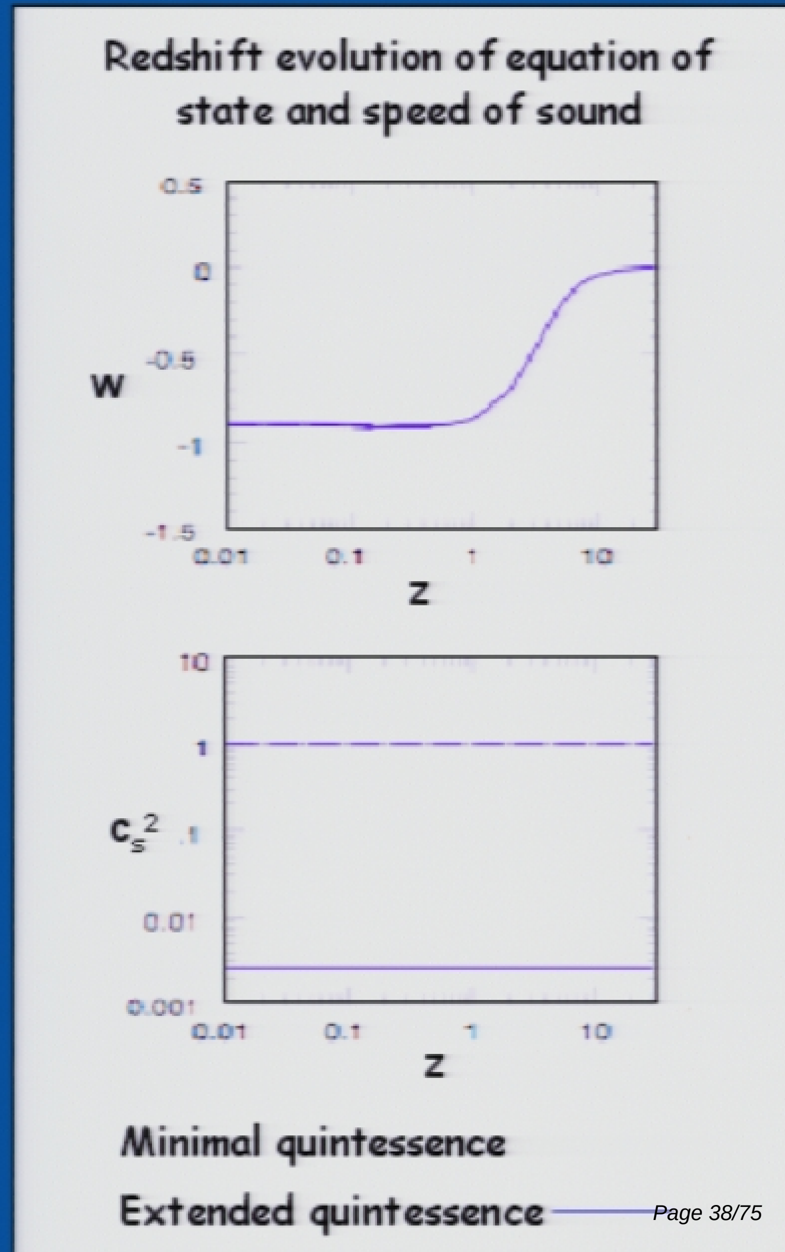
- Late time acceleration and varying Newton's constant produced by same scalar field

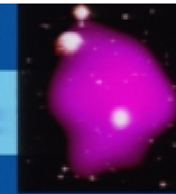
$$\mathcal{L}(\phi, X) = \sqrt{-g}\left(\frac{f(\phi,\mathcal{R})}{2\kappa} - \omega(\phi)X - V(\phi)\right)$$

$$f(\phi, R) = (1 - \xi\phi^2)R$$

- At early times an R-boost generates gravitational dragging which results in scalar tracking dominant matter component ($w \sim 0$ and $c_s^2 \sim 0$).
  - -constraints from CMB experiments
  - -limits on gravitational coupling from local gravitation experiments

- Could lead to non-linear ϕ and $\delta\phi$ over-densities and cavities on sub-horizon scales
  - -Detectable large scale structure /lensing signature?





Tackling the dark matter and dark energy problems as one

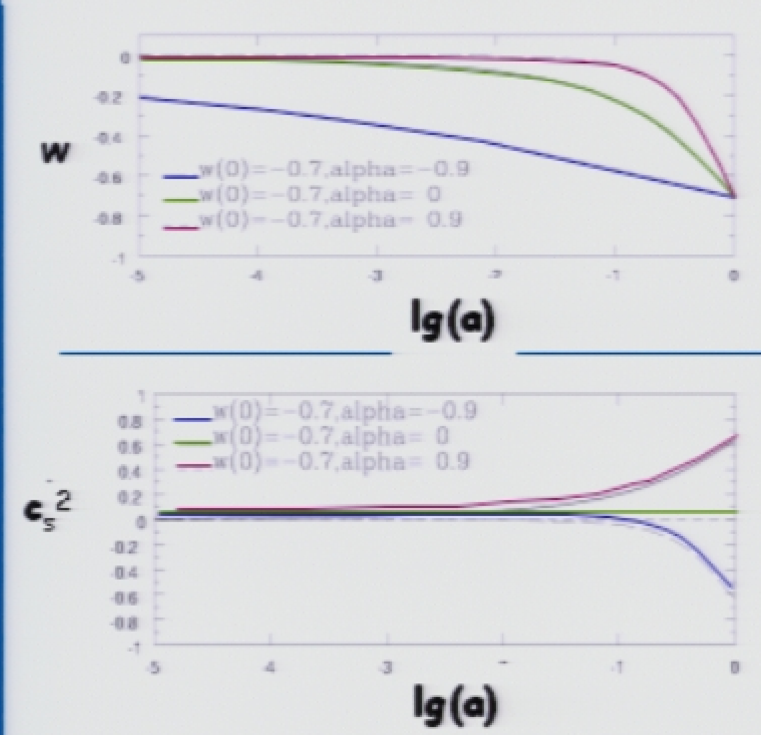
- 'Unified' dark matter / dark energy
  - Clustering at early times like CDM $w \sim 0$, $c_s^2 \sim 0$
  - Accelerating expansion at late times like Λ $w < 0$
- Phenomenology: Chaplygin gases (Bean and Dore PRD 68 2003)
  - an adiabatic fluid, parameters w_0, α

$$p = -\frac{|w_0|}{\rho^\alpha}$$
$$c_s^2 = \alpha |w|$$

- Particle physics interpretation? Condensates with low Compton wavelength (Bassett et al 2002)
- Strings interpretation? Born-Infeld action is of this form with $\alpha = 1$ (e.g. Gibbons astro-ph/0204008)

$$\mathcal{L}(\phi, X) = \sqrt{-g} V(\phi) (1 + X)^{\frac{1}{2}}$$
$$V(\phi) = \frac{\lambda}{\cosh(\phi/\phi_0)}$$

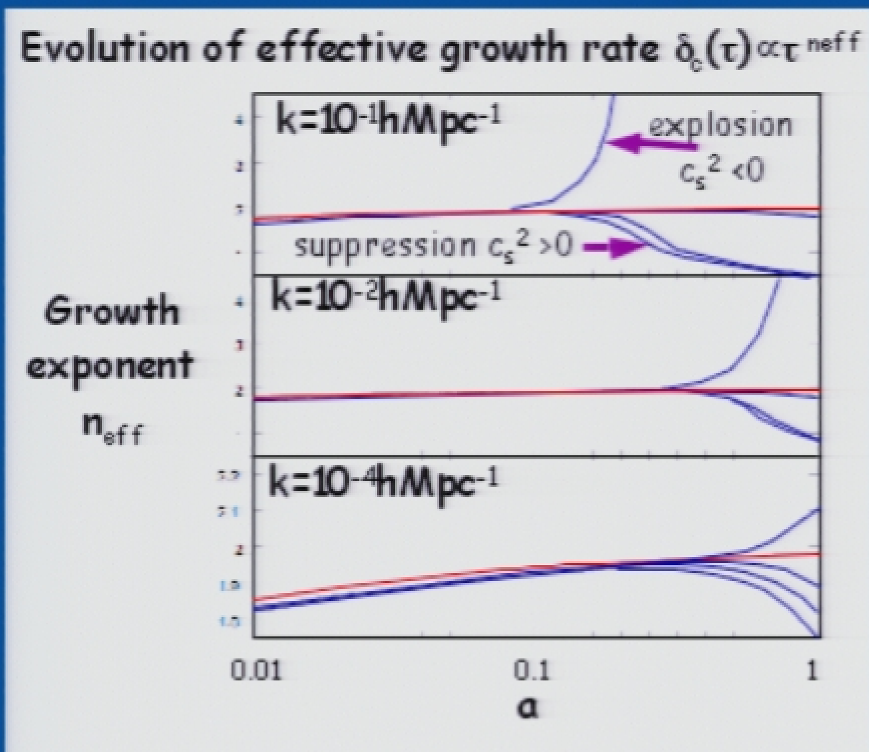
Evolution of equation of state and speed of sound for Chaplygin Gas

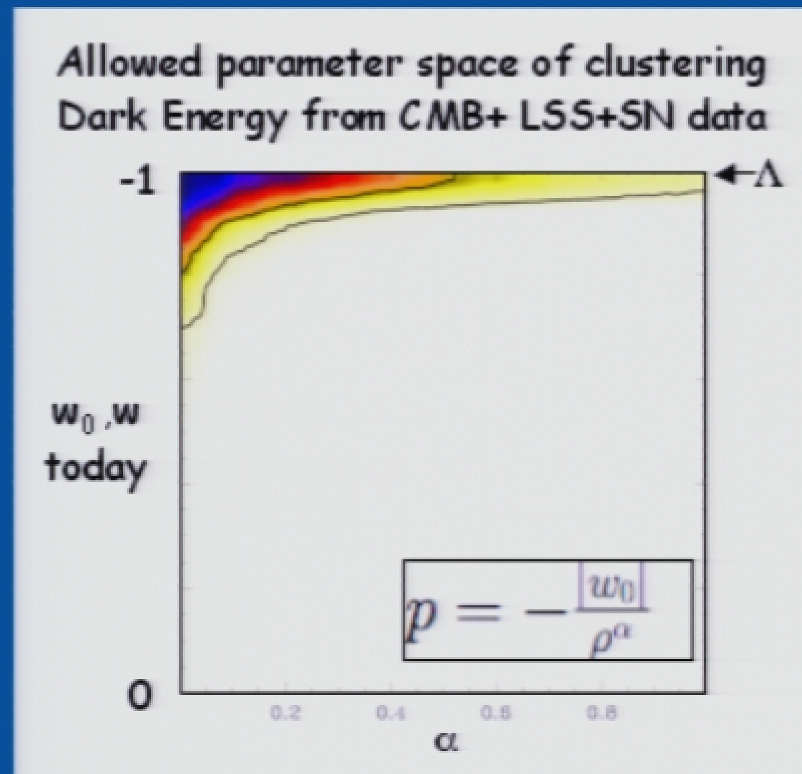


Bean and Dore PRD 68 2003

Tight bounds on unified dark matter candidates

- Evolution of dark energy perturbations highly sensitive to c_s^2 - can lead to chronic suppression or explosion of clustering





Bean & Dore PRD 68 2003

- Entropy perturbations ensuring $c_s^2=0$ could stabilise DE perturbations and reinvigorate Chaplygin gases as a unified dark matter approach (Reis et al astro-ph/0306004)

Modifications to gravity rather than matter

- Quintessential inflation (e.g. Copeland et al 2000)
  - Randall Sundrum scenario
  - ρ^2 term increases the damping of ϕ as rolls down potential at early (inflationary) times
  - inflation possible with V (ϕ) usually too steep to produce slow-roll

$$H^2 = \frac{8\pi G_4}{3}\left(\rho + \frac{\rho^2}{2\sigma}\right) + \frac{\Lambda_4}{3} + \frac{\mathcal{E}}{a^4}$$

$$\epsilon \approx 4\epsilon_{FRW} \left(\frac{V}{\sigma}\right)^{-1} \quad \eta \approx 2\eta_{FRW} \left(\frac{V}{\sigma}\right)^{-1}$$

- Curvature on the brane (Dvali ,Gabadadze Porrati 2001)
  - Gravity 5D (Minkowski) on large scales $l > l_c \sim H_0^{-1}$ i.e. only visible at late times
  - Although 4D on small scales not Einstein gravity
  - Potential implications for solar system tests as well as horizon scales ...

$$H = \sqrt{\frac{8\pi G}{3}\rho + \frac{1}{l_c^2}} + \frac{1}{l_c}$$

- Inhomogeneous metric (Moffat 2005)
  - Local kinematics are observer position dependent
  - Intrinsic cosmic variance in observables
  - Broader implications for perturbation evolution e.g. CMB, LSS

$$ds^2 = dt^2 - R'^2(t,r) f^{-2}(r) dr^2 - R^2(t,r) d\Omega^2$$

$$H_{eff}^2 = \frac{1}{3}\left(H_\perp^2 + 2H_\perp H_r\right) = \frac{8\pi G}{3}\rho$$

Many outstanding issues

- Perturbation evolution in modified gravity theories

  - Currently often using spherical collapse prescriptions but would be useful to have general, covariant approach

  -How do the CMB and structure power spectra look in these scenarios with a theoretical precision to match measured errors?

  -Extend formalism in presence of inhomogeneous metric

- Are the modifications from the standard LCDM scenario large enough that they might be detected in upcoming experiments?

- What does the non-linear structure formation regime look like in clustering dark energy models/ modified gravity theories?

  - Weak lensing occurs in the mildly non-linear regime, if we hope to detect dark energy properties need to understand this!

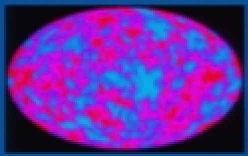
- Unified dark matter/dark energy from a scalar field (imperfect fluid) still a possibility?

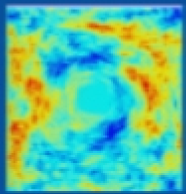
The key dark energy questions

- What is the underlying nature of dark energy?

- What dark energy properties can we measure observationally?

  - Overview
  - Prospective constraints from the CMB
  - Prospective constraints from cluster number counts
  - Prospective constraints from weak lensing





What are the different dark energy constraints?

- Late time probes of w(z)
  - Luminosity distance vs. z ← SN 1a HST Legacy, Essence, DES, SNAP
  - Angular diameter distance vs. z ← Alcock-Paczynski test, Baryon Oscillations SDSS
- Probes of w_{eff}
  - Angular diameter distance to last scattering ← CMB WMAP

    Bean & Melchiorri PRD 65 (2002)
  - Age of the universe ← CMB / Globular cluster

Tests probing background evolution only

What are the different dark energy constraints?

- Late time probes of w(z)
  - Luminosity distance vs. z
  - Angular diameter distance vs. z

Tests probing perturbations and background

- Probes of w_{eff}
  - Angular diameter distance to last scattering Bean & Melchiorri PRD 65 (2002)
  - Age of the universe

- Late time probes of w(z) and $c_s^2(z)$
  - Comoving volume * no. density vs. z Bean and Dore, PRD 68(2003)
  - Shear convergence
  - Late time ISW Bean & Dore PRD 69 (2003)

Galaxy /cluster surveys, SZ and X-rays from ICM
SDSS, ACT, APEX, DES, SPT

Weak lensing CFHTLS, SNAP, DES, LSST

CMB and cross correlation
WMAP, PLANCK, with SNAP, LSST, SDSS

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  - Late time ISW Bean & Dore PRD 69 (2003)
- Early time probes of $\Omega_Q(z)$
  - N_{eff} Bean, Hansen, Melchiorri (2001)

BBN/ CMB WMAP

Tests probing early behavior of dark energy

What are the different dark energy constraints?

- Late time probes of w(z)
  - Luminosity distance vs. z
  - Angular diameter distance vs. z

- Probes of w_{eff}
  - Angular diameter distance to last scattering Bean & Melchiorri PRD 65 (2002)
  - Age of the universe

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  - Late time ISW Bean & Dore PRD 69 (2003)

- Early time probes of $\Omega_Q(z)$
  - N_{eff} Bean, Hansen, Melchiorri (2001)

- Alternate probes of non-minimal couplings between dark energy and R/ matter or deviations from Einstein gravity
  - Varying alpha tests Martins et al (2002), Rocha et al (2004)
  - Equivalence principle tests
  - Deviation of solar system orbits

Tests probing wacky nature of dark energy

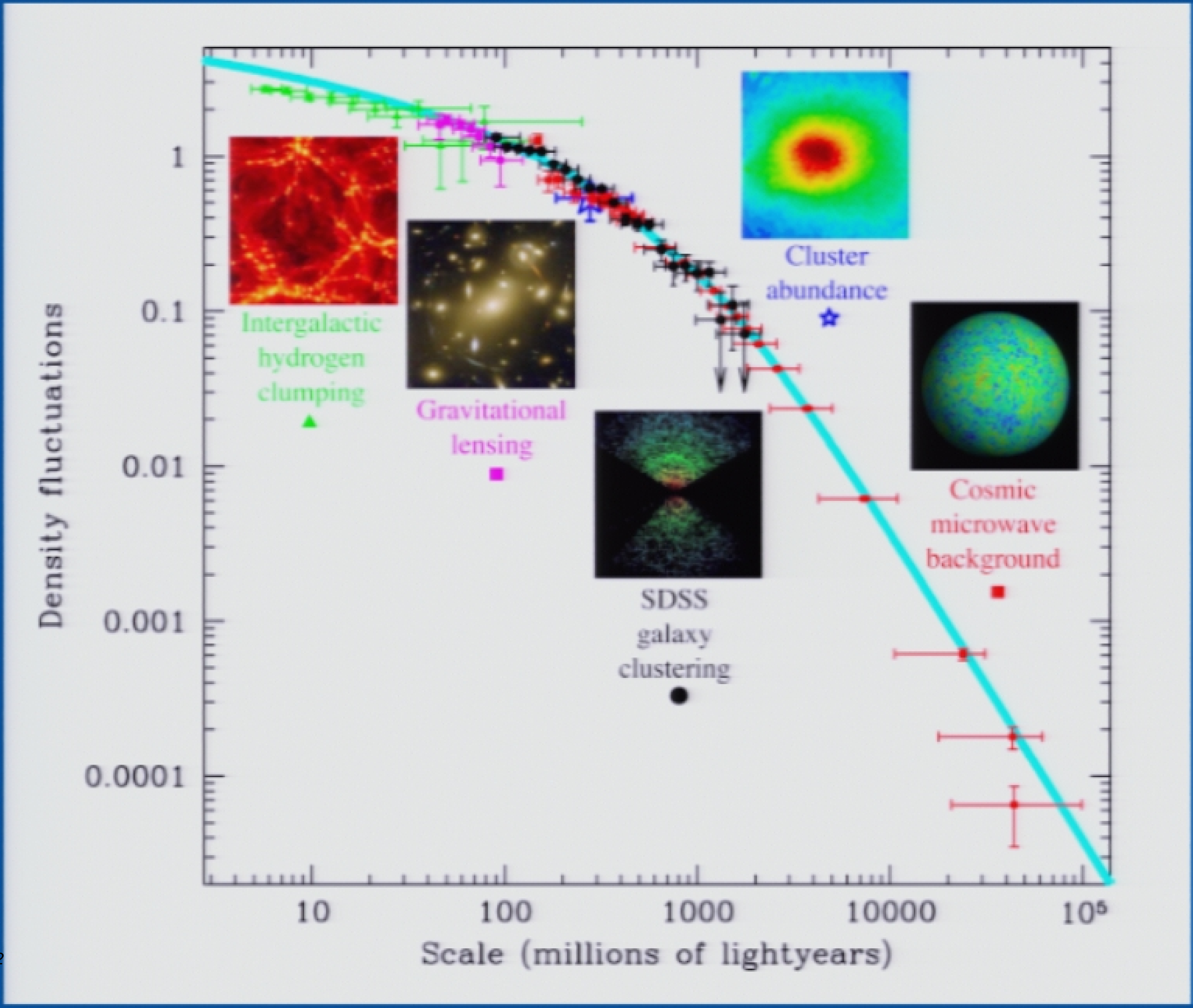
Evolution of H(z) is the primary observable

- In a flat universe, many measures based on the comoving distance — $r(z) = \int_0^z dz' / H(z')$
- Luminosity distance — $d_L(z) = r(z)\,(1+z)$
- Angular diameter distance — $d_A(z) = r(z) / (1+z)$
- Comoving volume element — $dV/dzd\Omega(z) = r^2(z) / H(z)$

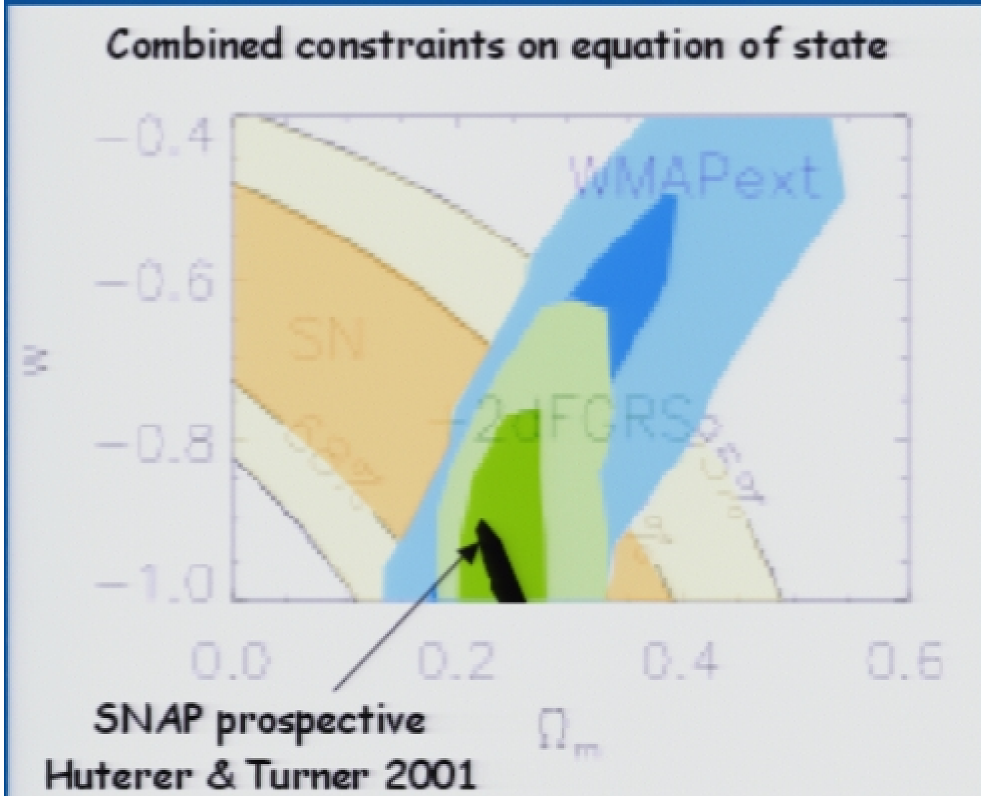
- Age of universe — $t(z) = \int_z^\infty dz/[(1+z)H(z)]$

But effect of fluctuations promises to be significant ....

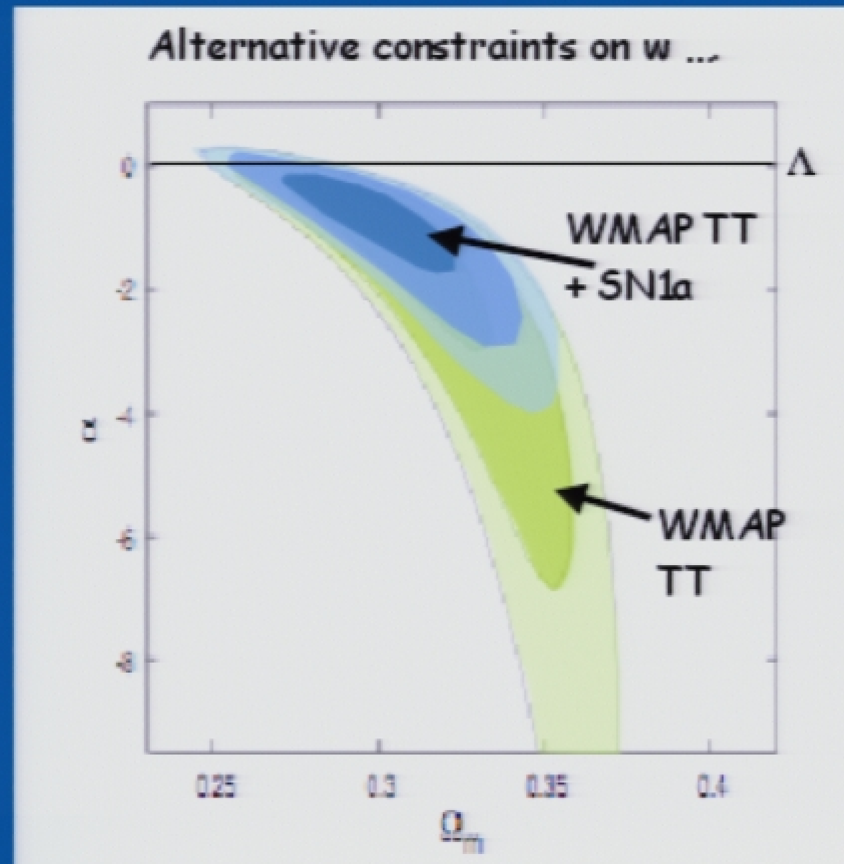
... And leveraging evolution on different spatial scales



But could equally signal deviations from FRW



Spergel et al. 2003



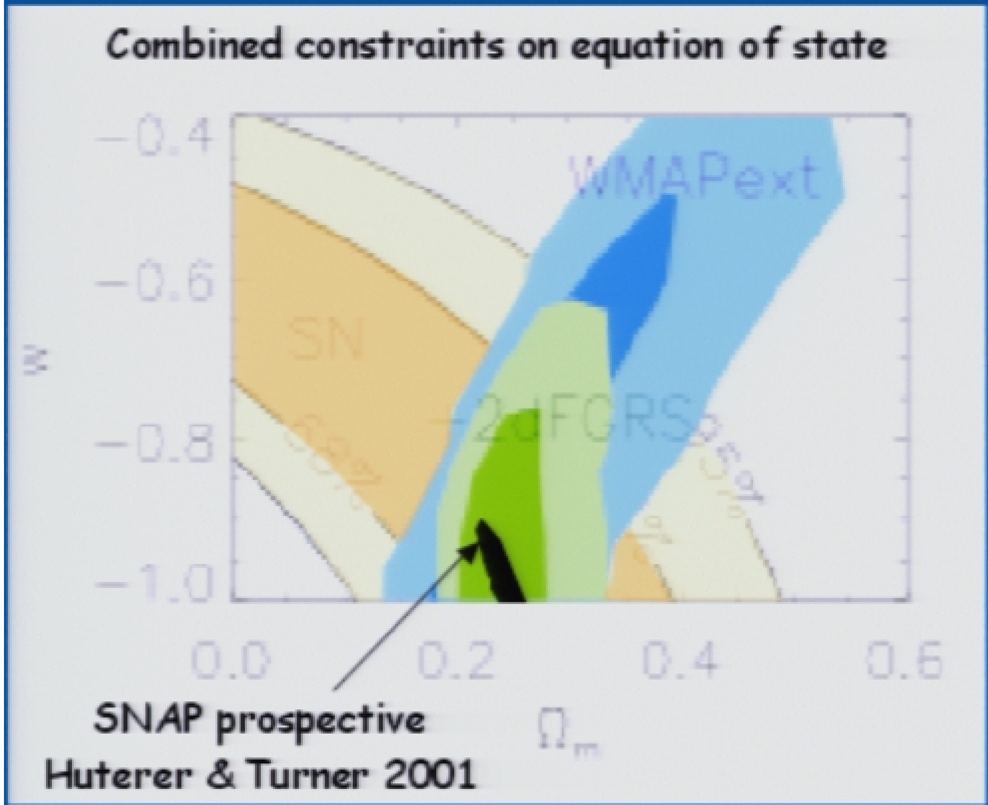
$$\left(\frac{H}{H_0}\right)^2 = \Omega_m(1+z)^3 + (1-\Omega_m)\left(\frac{H}{H_0}\right)^\alpha$$

Elgarøy and Multimäki 2004

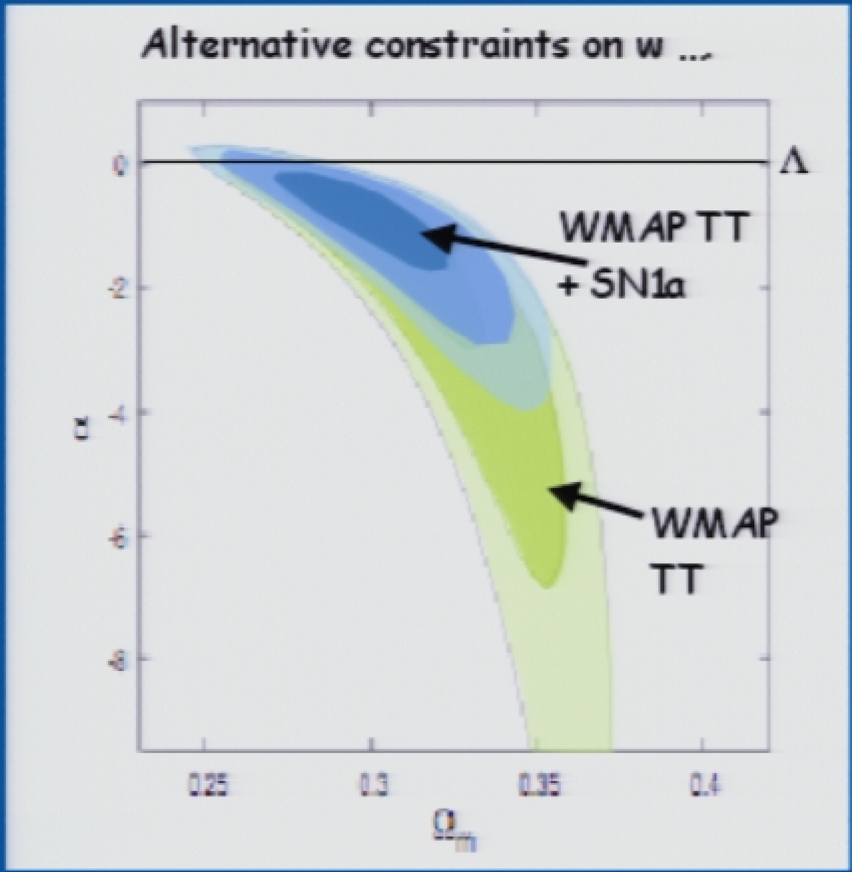
- But, implicit priors in this 'consistent' picture:
  - -Assuming a constant w
  - -Assuming no dark energy clustering
  - -Assuming Einstein gravity

- How can we test for different properties of dark energy rather than making implicit assumptions?

But could equally signal deviations from FRW



Spergel et al. 2003



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Reconstructing dark energy : a cautionary note

- Ansatz for H(z), $d_l(z)$ or w(z)
- w(z) applies well to scalar fields as well as many extensions to gravity Linder 2003

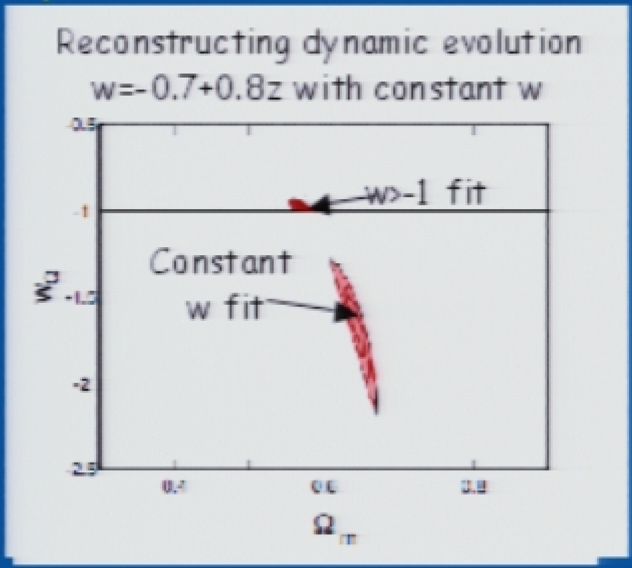
$$\Delta = H^2 - \frac{8\pi G}{3}\rho_m$$
$$w(z) = -1 + \frac{1}{3}\frac{d\ln(\Delta/H_0^2)}{d\ln(1+z)}$$

-Taylor expansions robust for low-z

$$w(z) = w_0 + w_a(1-a)$$

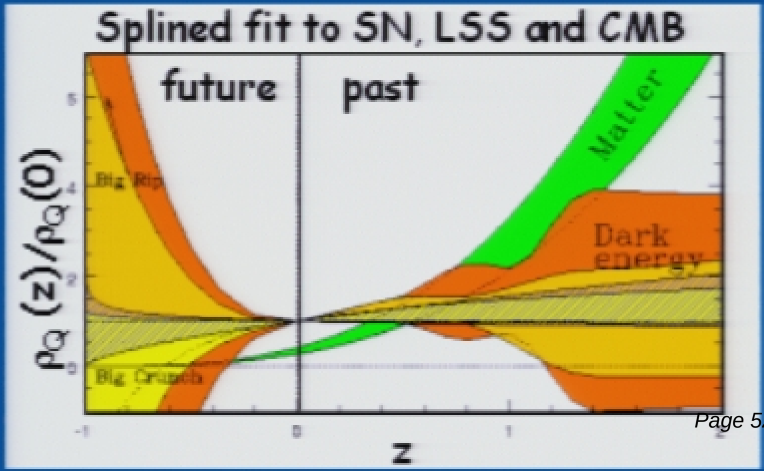
- But remember we are just parameterizing our ignorance, any number of options
  - Statefinder parameters (Sahni et al 2003)
  - expansions in H^n
  - as matter with w=p/ρ, and $c_s^2 = \delta p/\delta\rho$ ...

- But, parameterizations can mislead



Maor et al 2002

- Can reconstruct making minimal assumptions, but ultimately want to connect to a theory



Dark energy domination induces signature in CMB photons

- When dark energy dominates it acts to suppress growth in the CDM and gravitational potential wells , Ψ

$$\nabla^2 \Phi = 4\pi G a^2 \rho\delta$$

- late time Integrated Sach's Wolfe effect (ISW) in CMB photons results

  = Net blue shifting of photons as they traverse gravitational potential well of baryonic and dark matter on way.

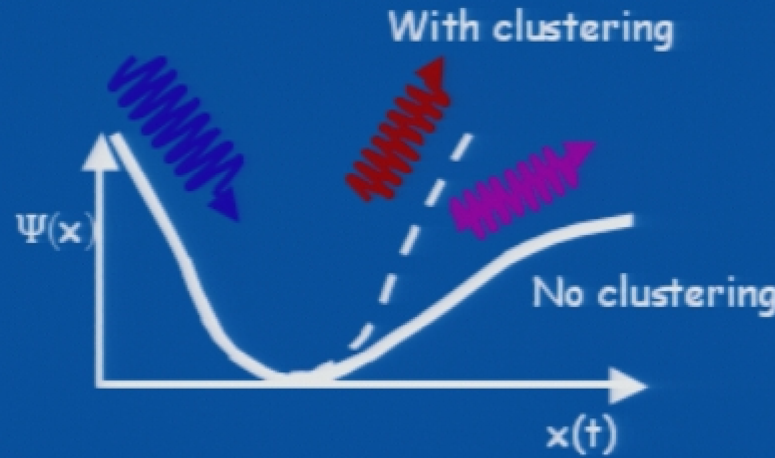
- ISW important at large scales

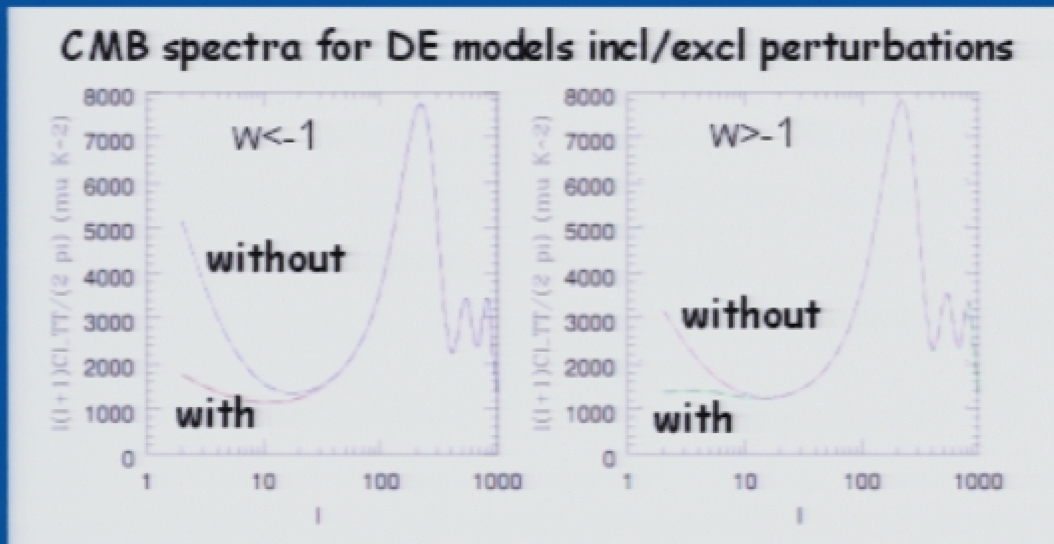
  -Cancellation of effects on small scales

  -At scales of key importance for DE perturbations

- Dark energy clustering counters suppression due to accelerative expansion

  -Decreases ISW signature



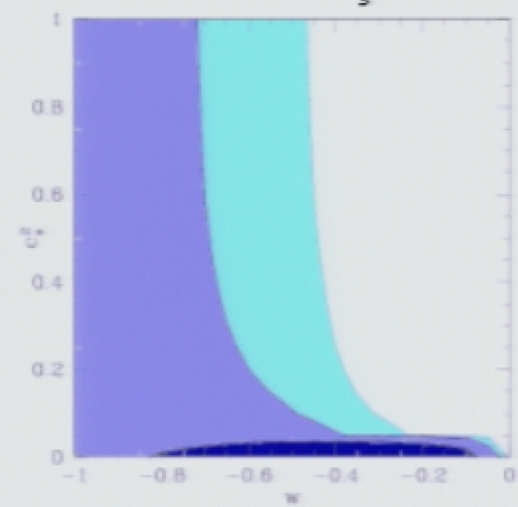


Bean & Dore PRD 69 2003

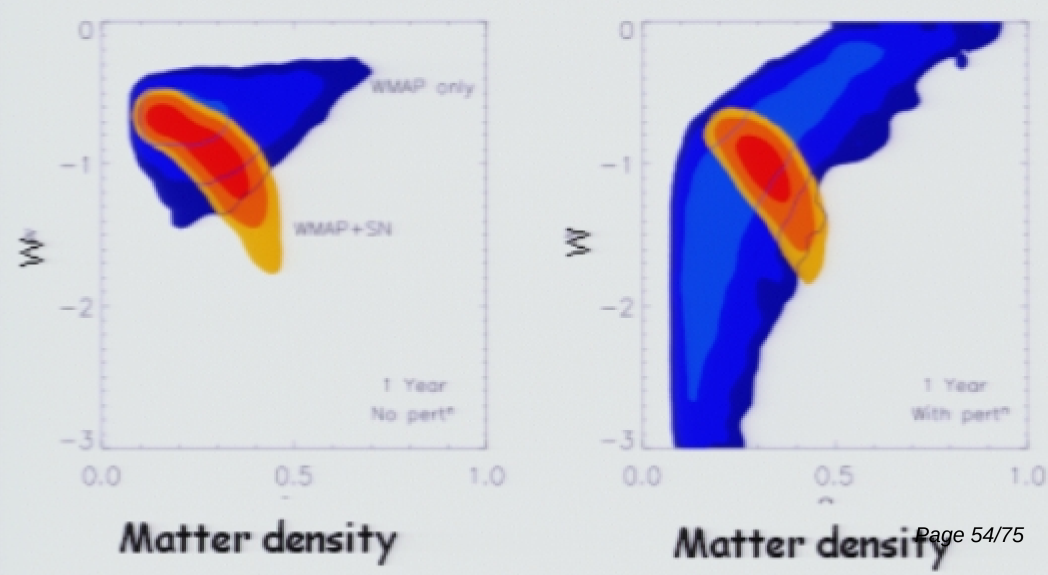
Dark energy perturbations can affect CMB and LSS predictions

- Degeneracies & cosmic variance prevent constraints on clustering itself
  - -Large scale anisotropies also altered by spectral tilt, running in the tilt and tensor modes
- Dark energy clustering <u>will</u> be factor in combining future high precision CMB with supernova data.
- Avoid degeneracies by cross correlating ISW with other observables ...
  - galaxy number counts
  - Radio source counts
  - Weak lensing of galaxies or CMB ...

'Constraints' on w and c_s^2 from WMAP



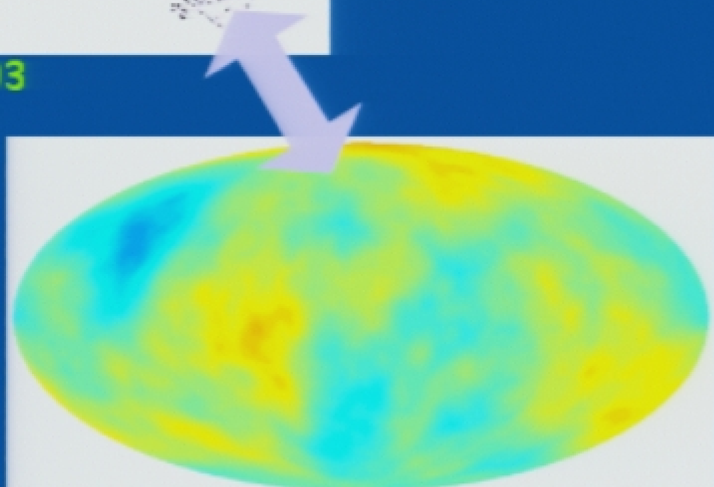
Constraints on w from CMB+ SN1a incl/excl perturbations

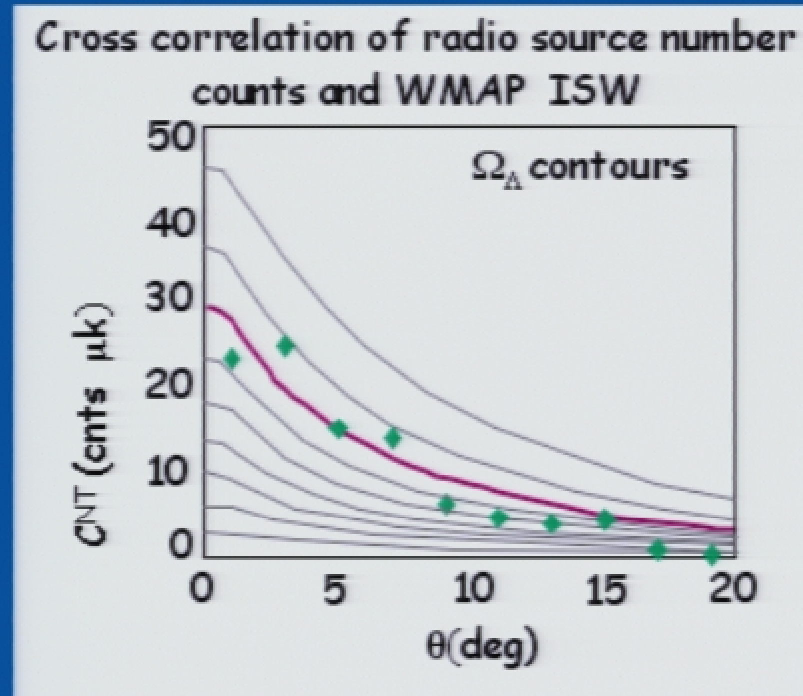


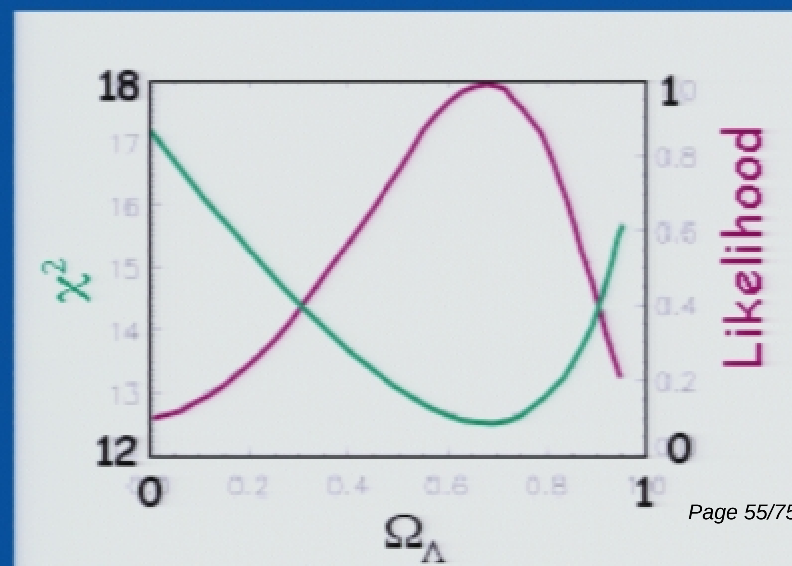
Dark energy prospects : CMB cross correlation

- ISW intimately related to matter distribution

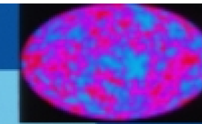
olless/2dF 2003







- Should see cross-correlation of CMB ISW with LSS. e.g. NVSS radio source survey (Boughn & Crittenden 2003 Nolta et al 2003, Scranton et al 2003)



Cross correlation of CMB with large scale structure

- Although current observations cannot distinguish dark energy features (Bean and Dore PRD 69 2003) , future large scale surveys which are deep, ~z=2, and were weak lensing can avoid bias uncertainties such as LSST might well be able to

$$C_{NT}(\theta) = \frac{1}{4\pi}\sum_{l=2}^{\infty}(2l+1)C_l^{NT}P_l(cos\theta)$$

$$\propto \delta_c(c_s^2, w, z=0)$$

Dark energy clustering w, c_s^2 dependence

$$C_l^{NT} = 4\pi\int_0^\infty \frac{dk}{k}\Delta^2(k)f_l^N(k)f_l^T(k)$$

Purely background (w) dependent

$$b_r \int_0^z \frac{d\tilde{N}}{dz}\, D(z)\, j_l(k\eta)dz$$

$$\frac{3H_0^2\Omega_m^0}{c^2k^2}\int_0^z \frac{d[D(z)(1+z)]}{dz}\, j_l(k\eta)dz$$

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Dark energy prospects : Galaxy / cluster number counts

- Volume element has better sensitivity to w and w′ than luminosity distance

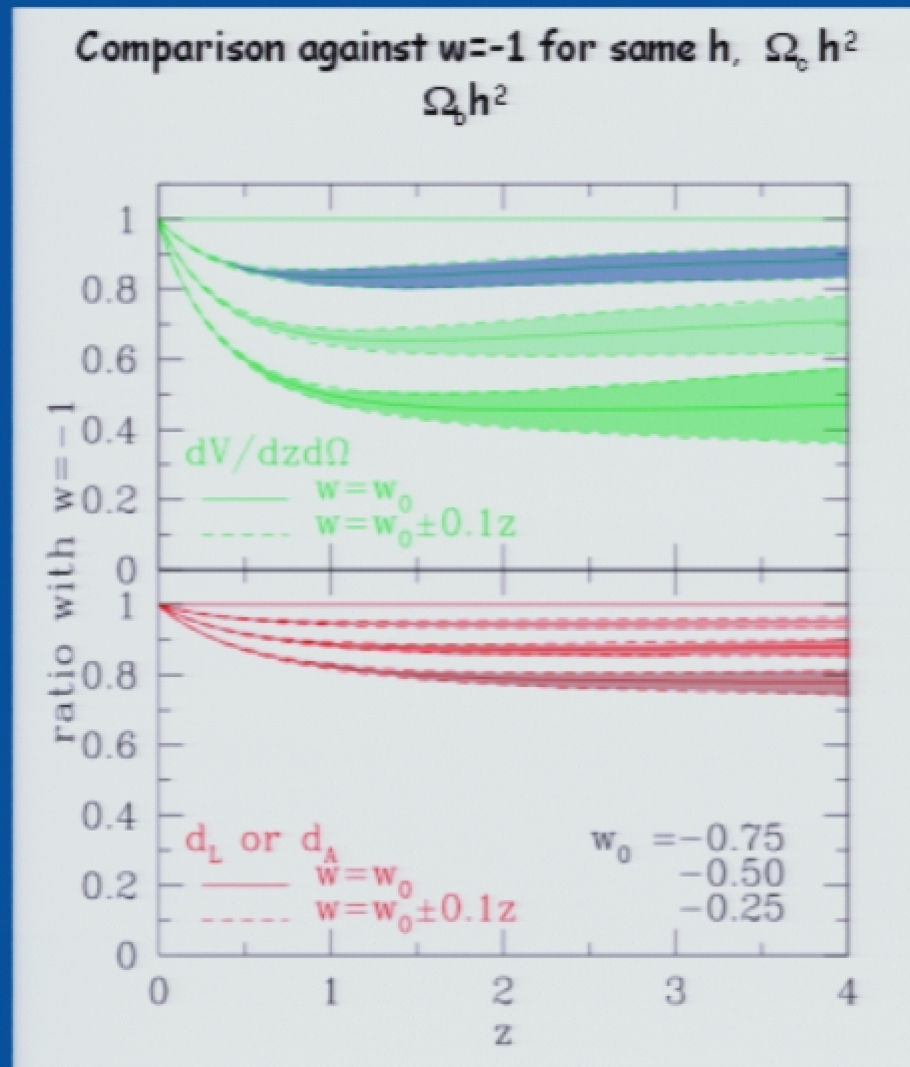
$$dV/dzd\Omega\ (z) = r^2(z) / H(z)$$

- Number counts related to underlying matter distribution and $\delta_c(z)$
  - inherent modeling sensitivity

$$\frac{dN}{dzd\Omega} = \frac{dV}{dzd\Omega} \int_{m_{lim}(z)}^{\infty} dM \frac{dn(M,z)}{dM}$$

e.g. cluster mass function Jenkins et. al 2000

$$\frac{dn(M,z)}{dM} \propto exp\left\{ -|0.61 - log\left(\frac{\delta_c(z)\sigma_M}{\delta_c(0)}\right)|^{3.8}\right\}$$



Dark energy prospects : cluster number counts from SZ

- **Advantages:**

-Degeneracy directions complementary to CMB, SN1a

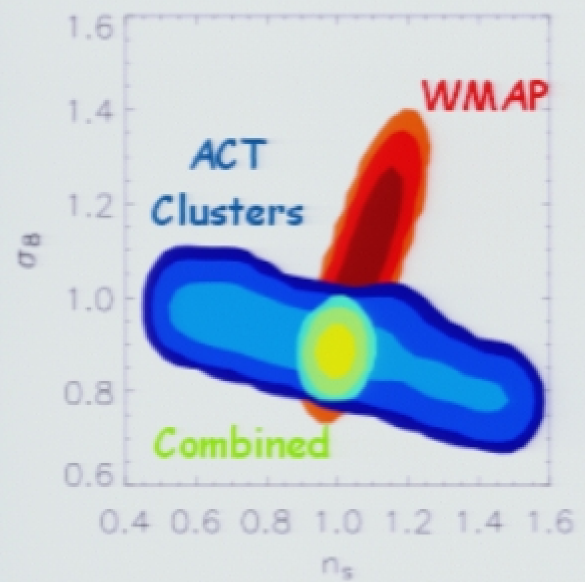
-Clusters exponentially sensitive to growth factor

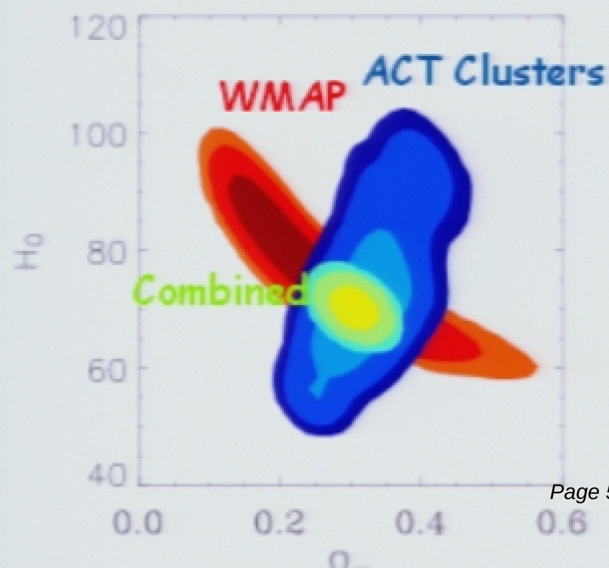
- e.g. sensitive to suppressions due to dark energy or neutrinos

-Multiple mass estimates

- Velocity dispersion of cluster galaxies
- Gravitational lensing of background galaxies
- X rays temperature from intracluster medium
- Weak lensing

Parameter degeneracies for CMB and clusters





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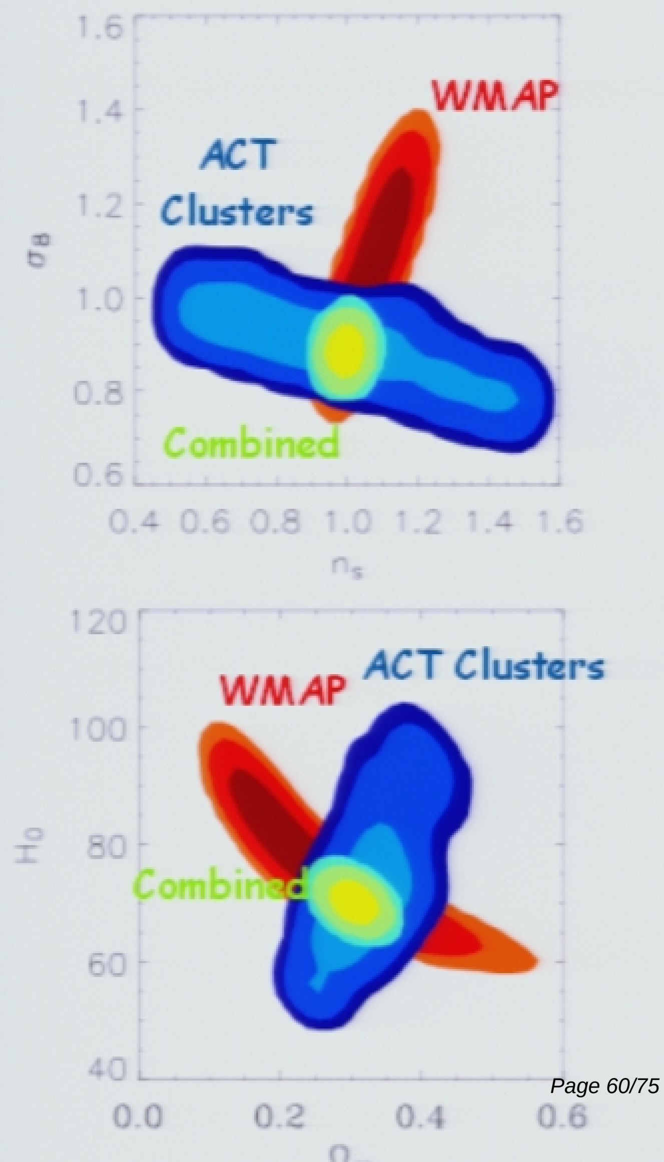

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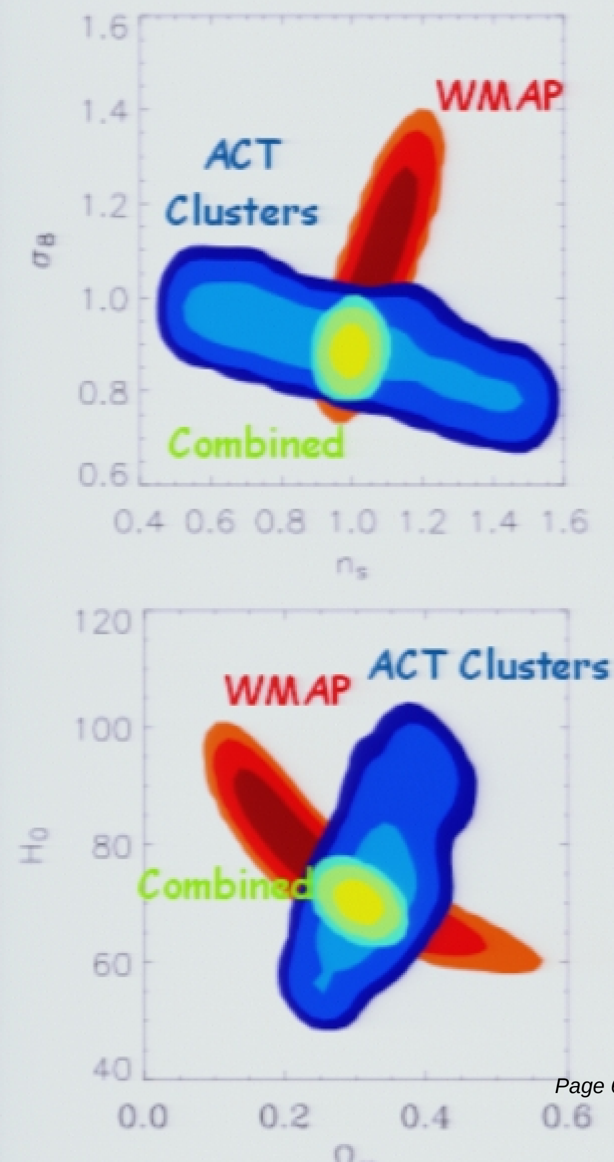

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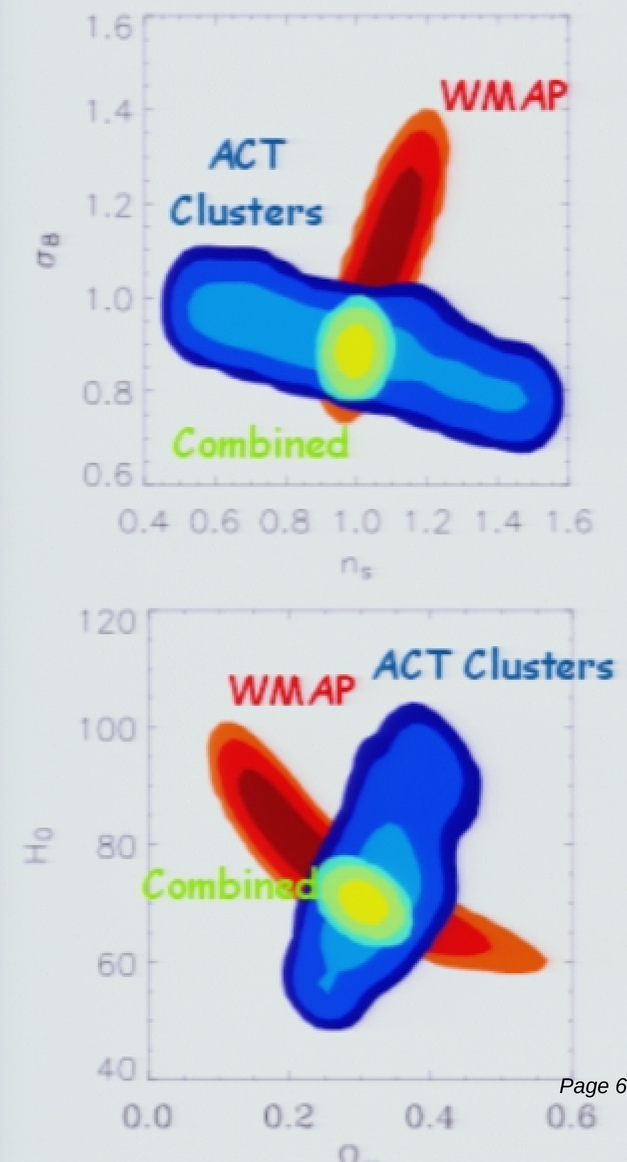

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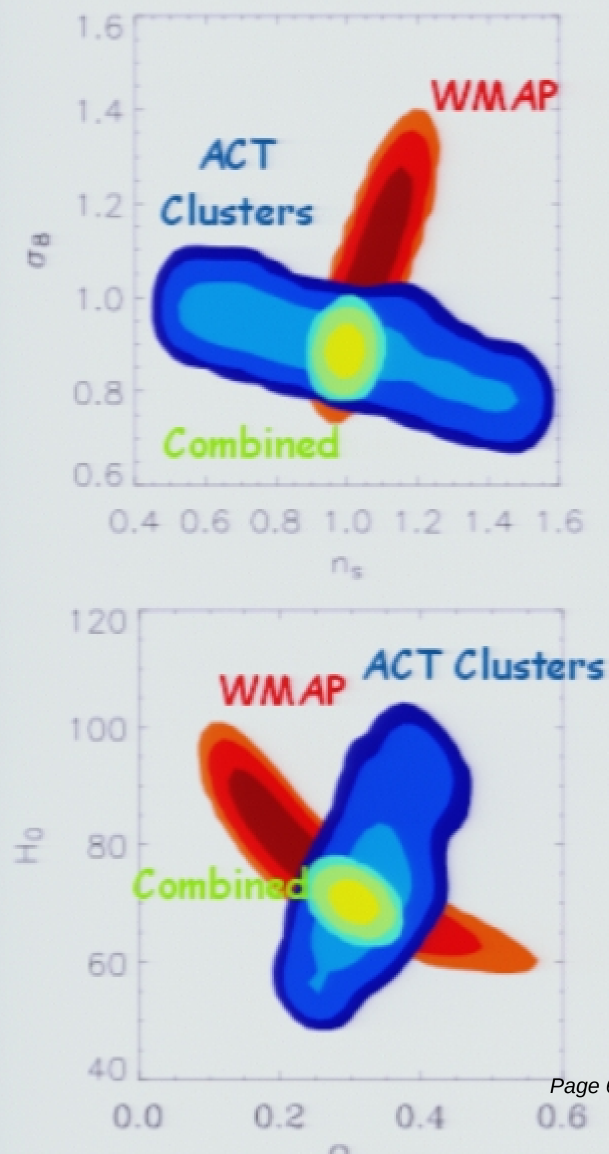

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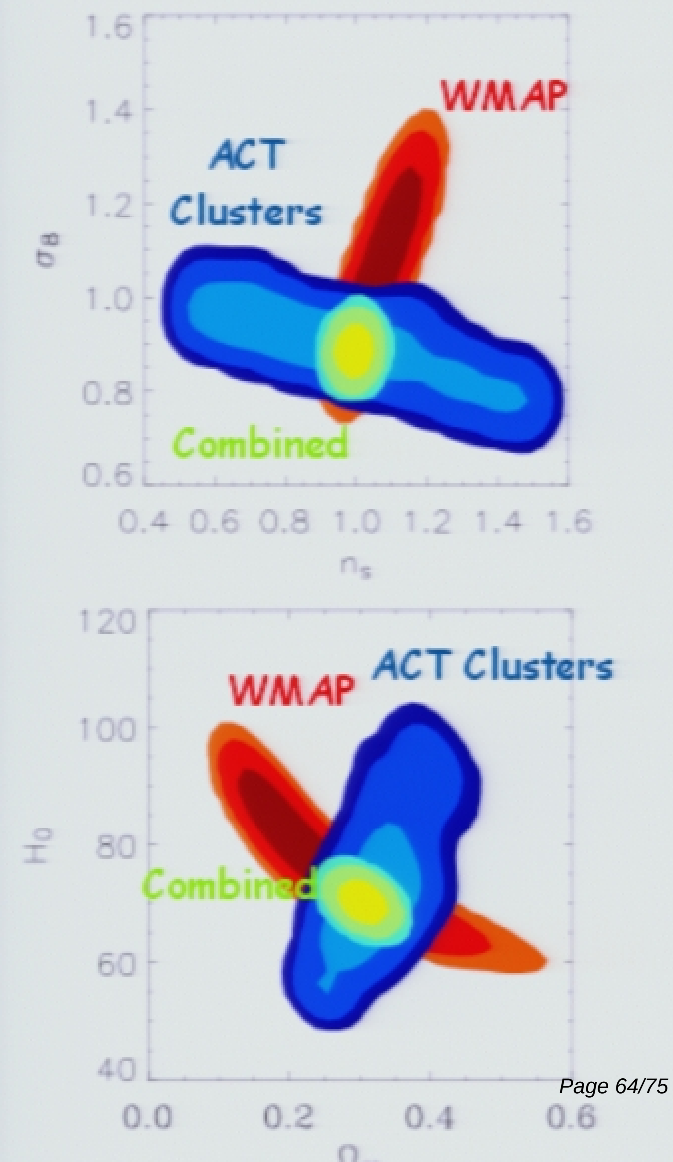


Dark Energy Prospects : Cluster counts from SZ

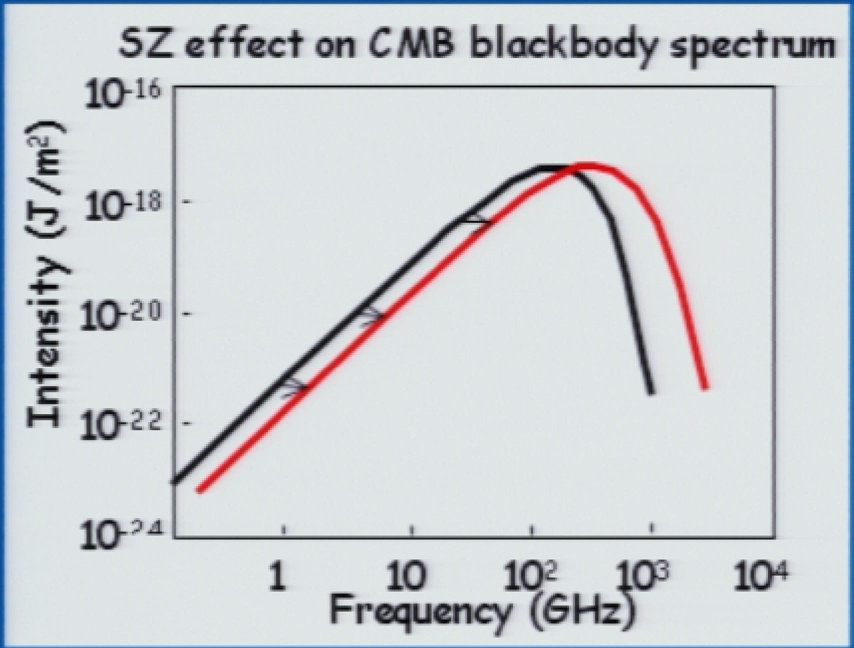
The passage of the CMB through a hot e- cloud distorts the spectrum of the γ_{CMB} due to Compton interactions

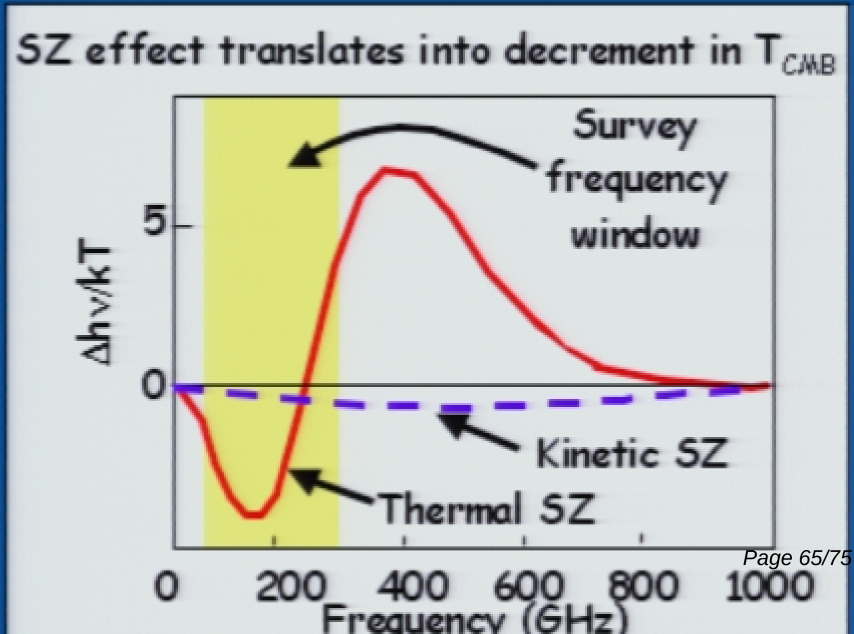
Due to the high energy of the e-'s, and the homogeneity and isotropy of the CMB, the γ gain energy.

- Rayleigh-Jeans regime (at low ν) the change can also be produced with a lower temperature of the radiation.
- In the Wien part of the spectrum (at high ν) one can interpret the change with a higher radiation temperature.

If one measures T_{CMB} towards a region containing hot e- one expects a decrement of this temperature at low ν and an increment at high ν compared to the normal brightness temperature (2.73 Kelvin).

SZ signal not attenuated with z





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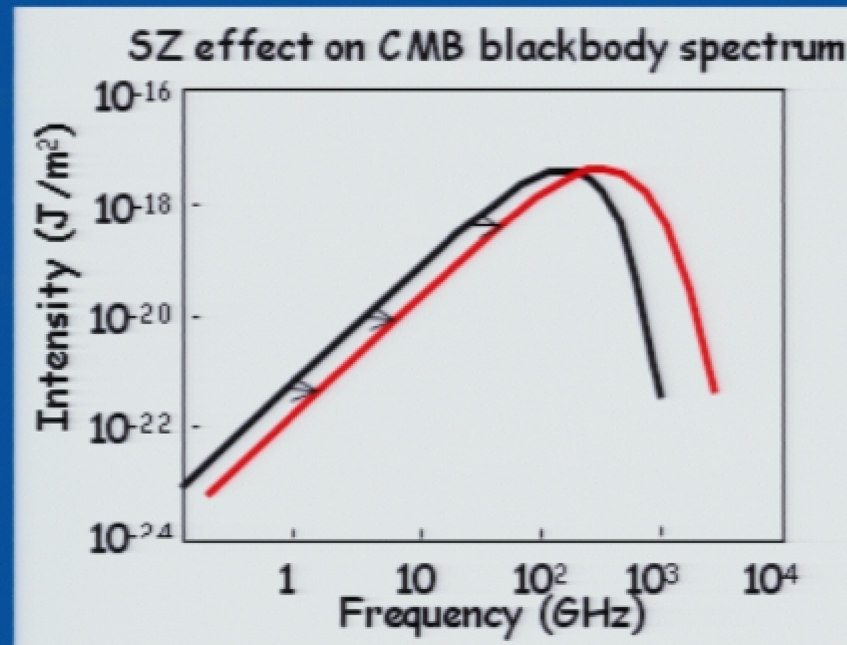

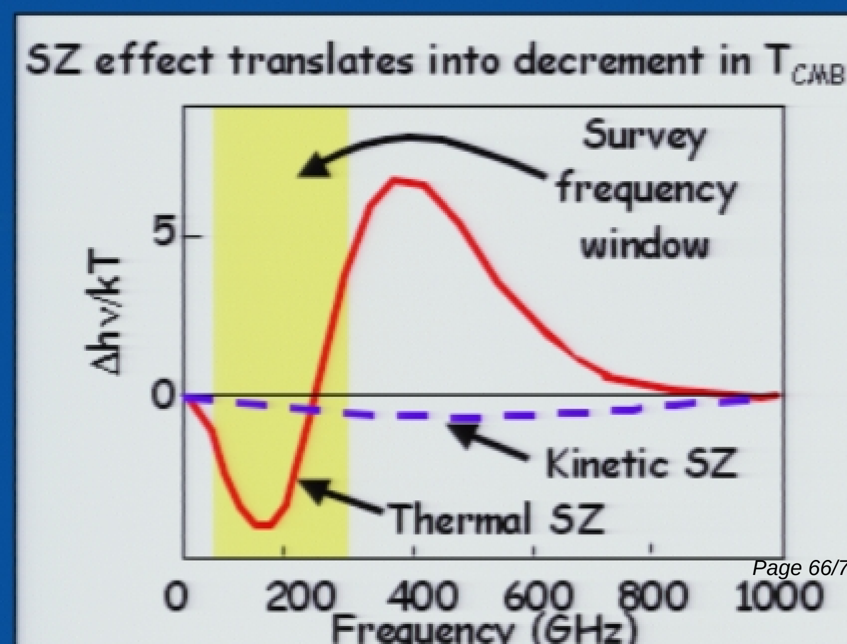

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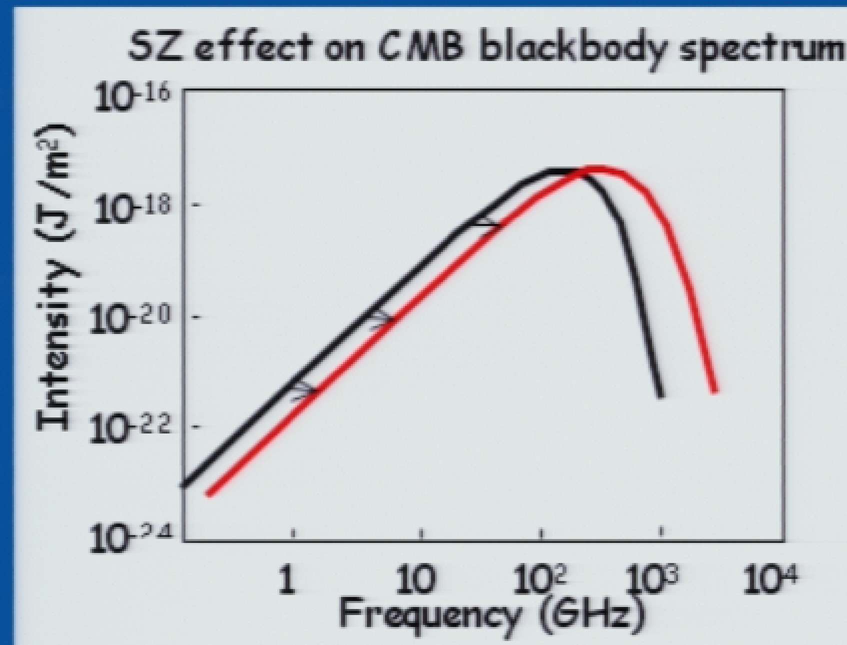
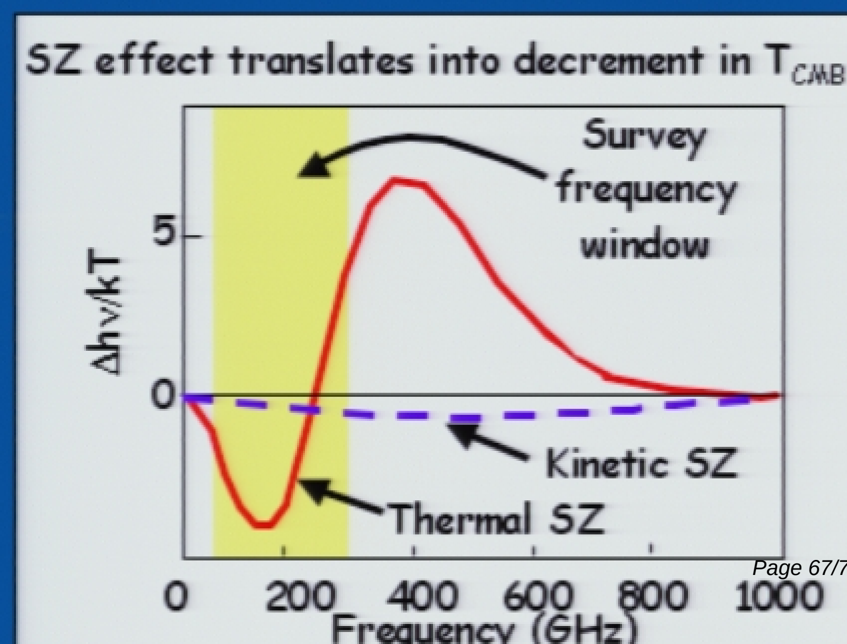
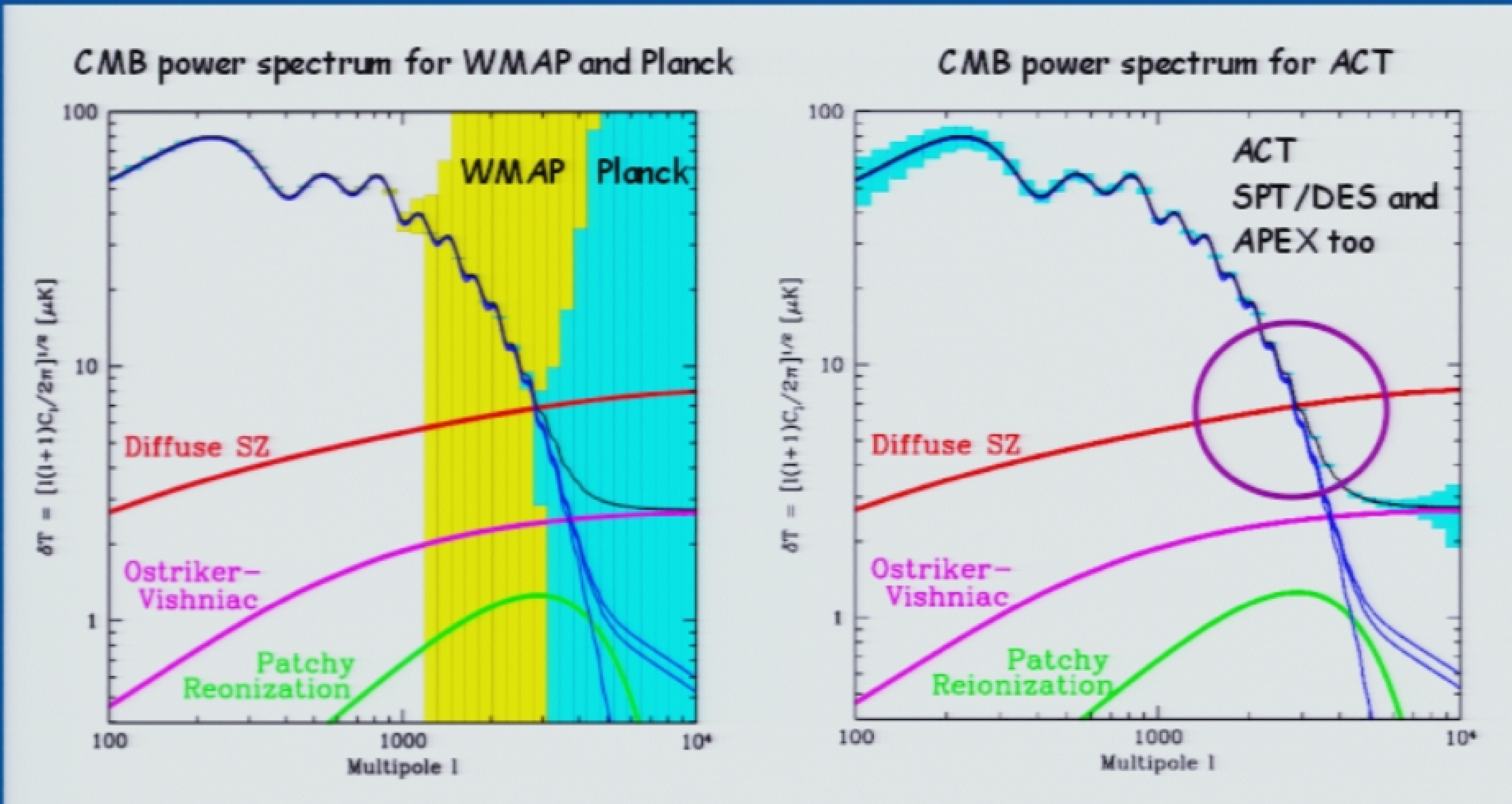




SZ surveys set up to probe entirely new regime of CMB

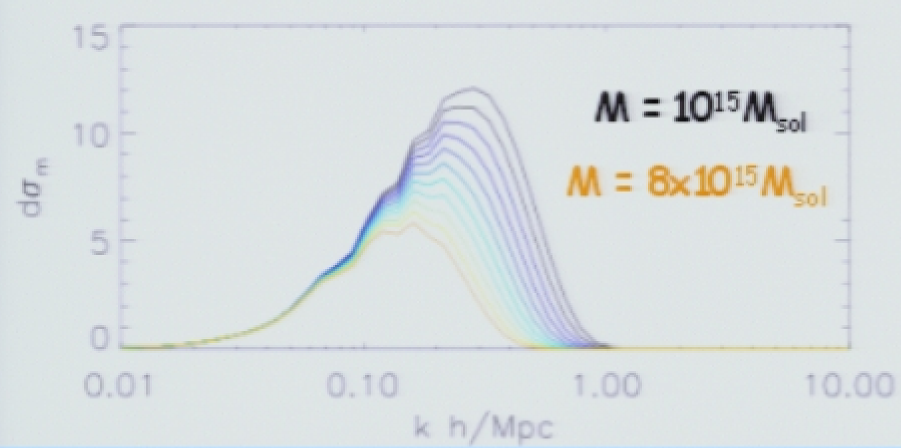


de Oliveira-Costa

Cluster number counts from SZ : ACT

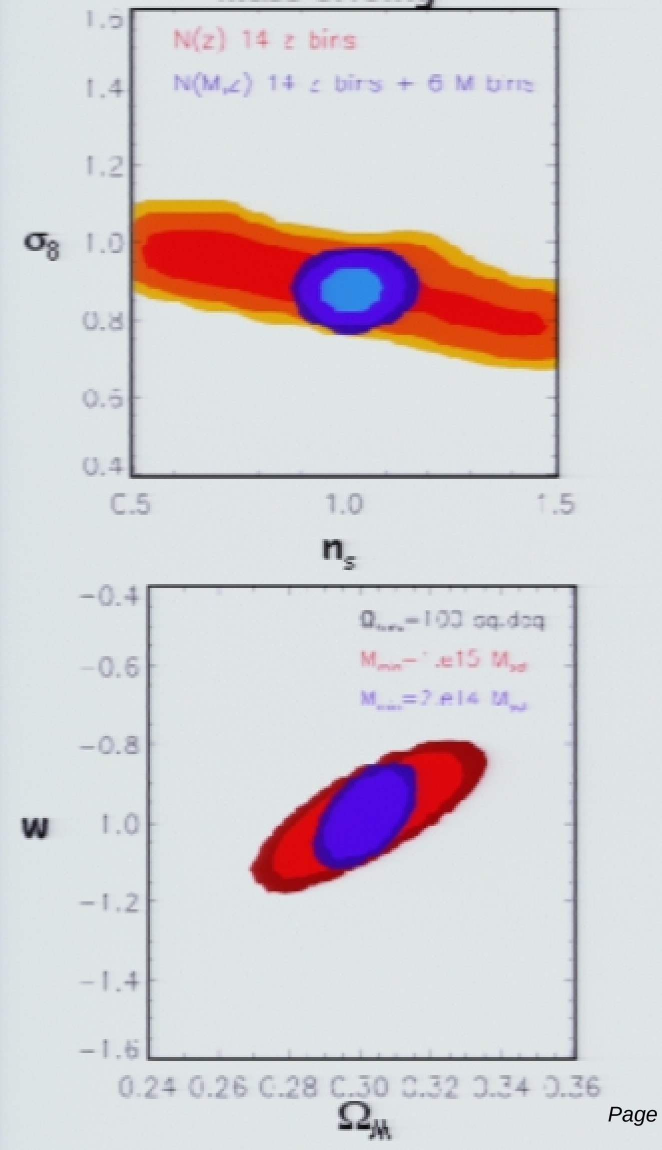
- **Investigating dark energy and neutrino constraints for ACT using redshift and mass slicing to increase information extracted**
  - mass weight functions for dN/dz peak at larger scales for more massive clusters, so able to separate out evolution at scales k~0.1-1 h/Mpc

Mass weight function spatial dependency



-Using z and mass slices breaks key degeneracies in SZ measurements

Cluster contour with and without mass slicing

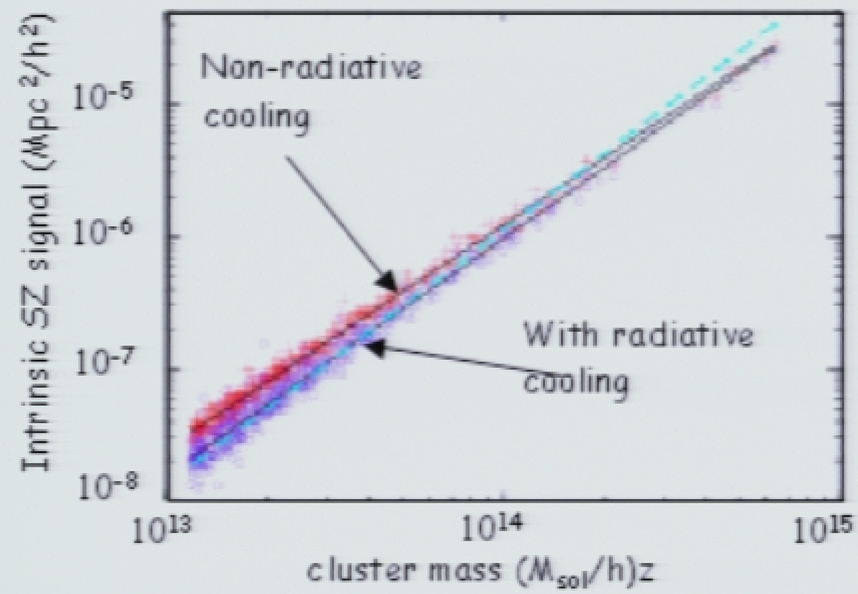


Bean, Francis and Kosowsky in prep

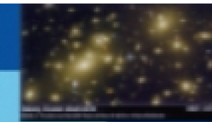
Cluster number counts from SZ : systematic uncertainties

- Uncertainty in mass-scaling relations from theoretical cluster physics modeling is an important systematic
- How do radiative cooling effects and pre-heating within the cluster affect mass - SZ/ Xray luminosities scaling relations?
- How does cluster evolution affect redshift evolution in mass-scaling relationship for SZ, X-ray?
- How can we combine/ parameterize these theoretical modelling uncertainties in the cosmological parameter estimation codes for future SZ surveys?

Cluster mass- SZ scaling relation dependency on cluster model



daSilva et al 2003



Small scale CMB : Many SZ surveys planned

- Ground based e.g.:
  - -SZA ~100 clusters, 12 sqdeg, z~1, 2004
  - -APEX ~1000, 200sqdeg, 2005
  - -ACT ~1000 clusters, 100 sqdeg, z~1.4, early 2006, photometric support from SALT
  - -SPT ~10,000 clusters, 40,000 sqdeg, z~1.2, 2007, photometric support from DES
- Satellite :
  - Planck, ~ 15,000 clusters, z~1, 2007
- And many others ... AmI, SuZIE, Polarbear I , QUIET, CLOVER, ALMA, BiCEP ...

Dark Energy Prospects : Weak lensing

CHFLT, SNAP and LSST offer promising prospects for WL

- -many millions of galaxies over hundreds of square degrees
- -Using all the mass information not just luminous matter

Tomography => bias independent z evolution of DE
Jain and Taylor 03, Zhang, Hui, Stebbins 03

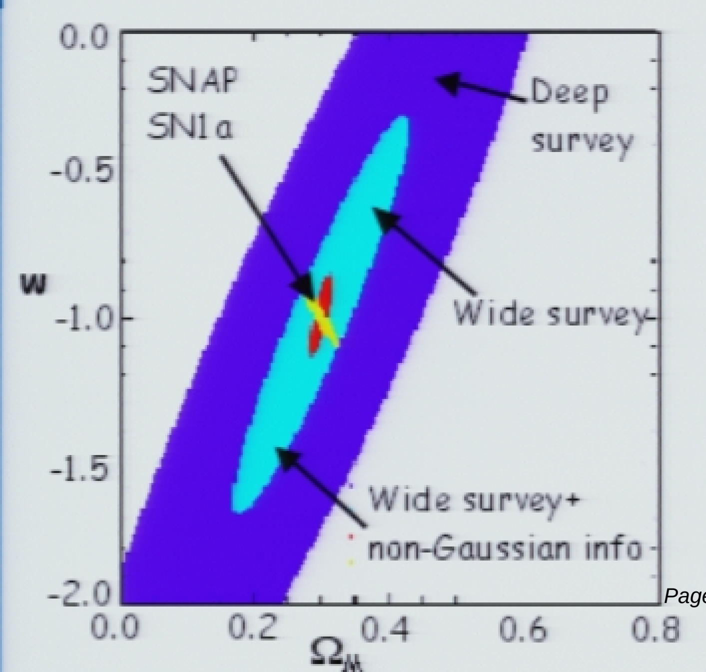
- -Ratios of growth factor (perturbation) dependent observables at different z give growth factor (perturbation) independent measurement of w, w′
- -e.g. tangential shear - galaxy cross correlation

Would like to see if technique could probe dark energy clustering in the SNAP wide survey or with LSST?

- -What kind of survey strategy would be best to test this?
- -What kind of statistical estimators would best

- Understanding theoretical and observational systematics key
  - -effect of non-linearities in power spectrum
  - -Accurately reconstructing anisotropic point spread function
  - - z-distribution of background sources and foreground halo
  - - inherent ellipticities ...

Prospective constraints on w from the SNAP SN1a + WL measurements



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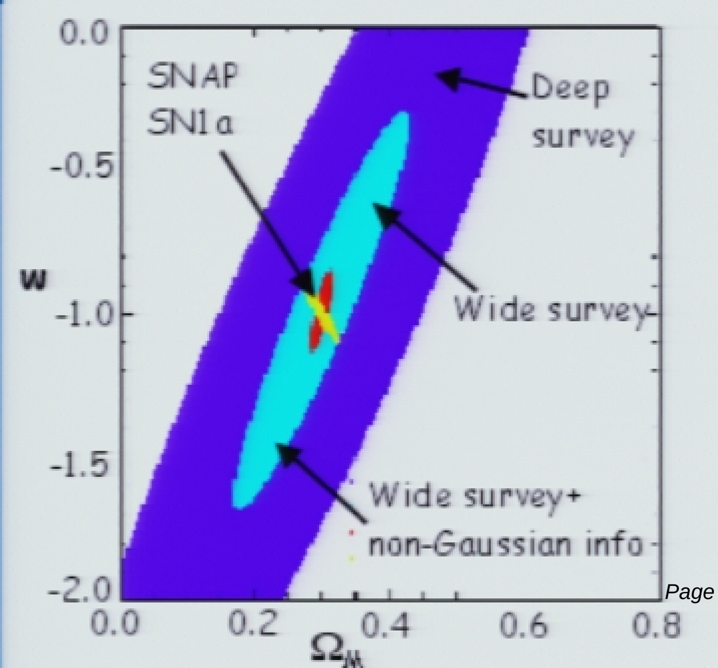

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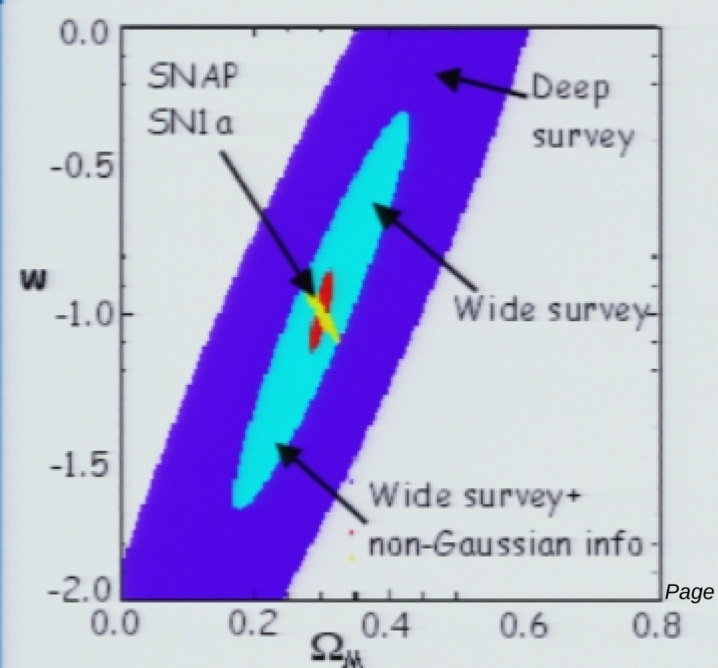


To conclude

- **A wealth of theoretical activity**

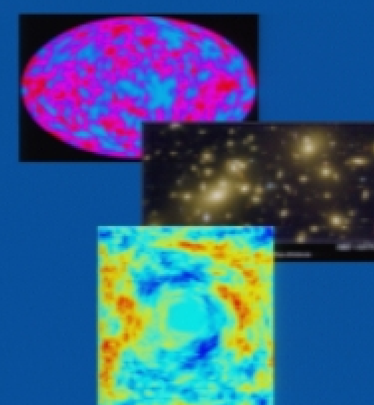
  -investigating dark energy explanations as a cosmological constant, an adjustment to gravity or a strange matter component.

- **Theories are making testable predictions**

  -from horizon scales (dark matter perturbations) down to solar system scales (modified gravity)

- **Observations are promising unprecedented precision in the next 5-10 years**

  -with a lever arm tying down both large (ISW) and small scale (SZ, weak lensing) anisotropies



- **We have a very exciting decade ahead of us both theoretically and experimentally!**