The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1954-1

Summer School in Cosmology

21 July - 1 August, 2008

Dark Energy

R. Caldwell
Dartmouth College
U.S.A.

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

DARK ENERGY

ROBERT CALDWELL
DARTMOUTH COLLEGE, USA

"A HYPOTHETICAL FORM OF ENERGY THAT PRODUCES A FORCE THAT OPPOSES GRAVITY AND IS THOUGHT TO BE THE CAUSE OF THE ACCELERATING EXPANSION OF THE UNIVERSE."

DICTIONARY

PROBLEM : THE SIMPLEST, MOST SUCCESSFUL THEORY OF THE PHYSICS OF THE UNIVERSE IS THE HOT BIG BANG

EVIDENCE
- COSMIC EXPANSION
- B B NUCLEOSYNTHESIS
- COSMIC MICROWAVE BACKGROUND

THEORY
- COSMOLOGICAL PRINCIPLE
- GENERAL RELATIVITY
- QUANTUM PHYSICS

HOW SUCCESSFUL ? ANALOGY W/ QM

QM MAY NOT BE DEEPLY UNDERSTOOD
SOMEWHAT ENIGMATIC
(& QFT MAY BE DISTURBING!)

YET IT MAKES ACCURATE PREDICTIONS !

LIKEWISE, OUR THY. OF UNIVERSE ALLOWS US TO MAKE STUNNING PREDICTIONS — ACOUSTIC OSCILLATIONS IN THE CMB !

YET, WE HAVE GREAT CHALLENGES

~ 95% OF THE COSMIC ENERGY BUDGET APPEARS "DARK"

~ 1/4 APPEARS TO PLAY A DOMINANT ROLE
IN GALAXIES & CLUSTERS

DARK MATTER

~ 3/4 APPEARS TO BE V. NEARLY HOMOGENEOUS
& SUPPORTS NEGATIVE PRESSURE

DARK ENERGY

GOALS FOR COSMOLOGISTS:

IDENTIFY & EVALUATE TESTS OF DARK ENERGY, MATTER

TASK: MEASURE COSMOLOGICAL PARAMETERS

PURSUE THEORETICAL MODELS

OBTAIN A DEEPER UNDERSTANDING → MAKE PREDICTIONS

PHYSICS OF THE UNIVERSE

EVIDENCE – THREE MAIN LINES

1) LARGE SCALE STRUCTURE $\Omega_M < 1$

2) COSMIC MICROWAVE BACKGROUND $|\Omega_K| \ll 1$

3) SUPERNOVA HUBBLE DIAGRAM $q < 0$

CONCLUSION?

STATE OF THE ART :

* WMAP5 (KOMATSU et al, arXiv: 0803.0547)

$\Omega_M h^2 = 0.1369 \pm 0.0037$ } 1σ | CMB + OTHER DATA

$\Omega_\Lambda = 0.721 \pm 0.015$ }

$-1.11 < w < -0.86$ (2σ)

any viable dark energy model must satisfy these constraints!

* SCP UNION (KOWALSKI et al, arXiv: 0804.4142)

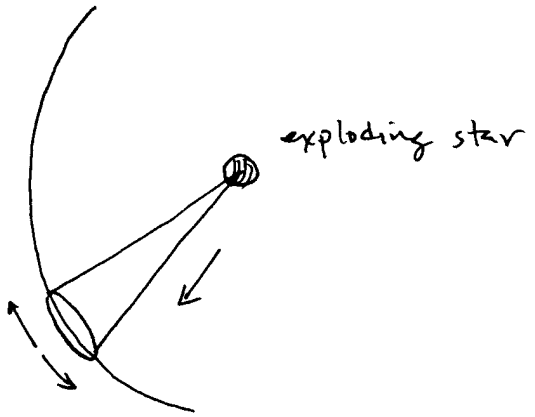
* SDSS & 2dFGRS BAO (Percival et al, MNRAS 381 1053(2007))

EXPANSION - THE MOST REMARKABLE PROPERTY OF THE UNIVERSE!

ACCELERATION !

evidence : distance vs. redshift

$$F = \frac{L}{4\pi R^2}$$



OBSERVED FLUX IS DILUTED BY DISTANCE & EXPANSION

IN AN EXPANDING UNIVERSE

$$R = d_L = (1+z) \int_0^z dz' / H(z')$$

DISCOVERY : RIESS et al, AJ 116 1009 (1998)
PERLMUTTER et al, ApJ 517 565 (1999)

WHO WAS FIRST?
SEE ARTICLE BY ROBERT CREASE IN JANUARY 2008 PHYSICS WORLD

HUBBLE DIAGRAM INDICATES GREATER DIMMING WITH REDSHIFT, CONSISTENT WITH ACCELERATED EXPANSION.

1917 Λ

1920's H

1930's DM

⋮

21ST CENTURY CHALLENGES

1. SYSTEMATIZE TESTS OF GRAVITATIONAL PHYSICS
2. TIGHTEN EVIDENCE FOR Λ (OR SOMETHING LIKE IT)
3. FIND THE PHYSICS OF VACUUM ENERGY
4. SORT OUT THE COSMIC COINCIDENCES
5. TEST THE PHYSICS OF THE DARK SECTOR
6. FIND THE PHYSICS OF HIGH REDSHIFT (EARLY UNIVERSE)

PEEBLES, astro-ph/0311435

NOTATION : GR

METRIC $-+++$

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} - \frac{\Lambda}{8\pi G} + L_M \right)$$

eg $L_{EM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

$$L_\phi = -\tfrac{1}{2} (\nabla\phi)^2 - V(\phi)$$

EE: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$

$$R_{\mu\nu} = \partial_\alpha \Gamma^\alpha_{\mu\nu} - \partial_\mu \Gamma^\alpha_{\nu\alpha} + \cdots$$

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\delta}{\delta g^{\mu\nu}} \left(\sqrt{-g} L \right)$$

ROBERTSON-WALKER COSMOLOGY

$$ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu + p g_{\mu\nu}$$

$$w \equiv p/\rho \quad \text{(HOMOGENEOUS) EQ'N OF STATE}$$

FRIEDMANN EQ'N: $3H^2 = 8\pi G \sum_i \rho_i \qquad i = r, m, DE$

CONSERVATION: $\nabla^\mu T_{\mu\nu} = 0$

$$\frac{d}{dt}\rho_i + 3H(\rho_i + p_i) = 0$$

LEMAÎTRE: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$

ACCELERATION: $q \equiv -\ddot{a}/H^2 \qquad q < 0 \rightarrow \sum_i (\rho_i + 3p_i) < 0$

DARK ENERGY ρ_{DE}, p_{DE}; w_{DE}

$$\rho_{DE}(a) = \rho_{DE}(a_0) \exp\left(-3 \int_a^{a_0} d\ln a' \,(1 + w_{DE}(a'))\right)$$

STD PERT'N EQ'NS — Ma & Bertschinger, ApJ 455 7 (1995)

METRIC: $ds^2 = a^2(\tau)\left[-(1+2\Psi)\,d\tau^2 + (1-2\phi)\,d\vec{x}^2\right]$ — LONGITUDINAL / CONFORMAL NEWTONIAN

$= a^2(\tau)\left[-d\tau^2 + (\delta_{ij} + h_{ij})\,dx^i dx^j\right]$ — SYNCHRONOUS

& $h_{ij}(\vec{k},t) = \hat{k}_i\hat{k}_j\,h + 6\left(\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij}\right)\eta$

VARIABLES: (Ψ, ϕ) or (h, η)

"t-t": $k^2\eta - \frac{1}{2}\mathcal{H}\dot{h} = -4\pi G a^2 \delta\rho$ $\qquad \mathcal{H} = \frac{\dot{a}}{a}$ $\qquad \cdot = \frac{d}{d\tau}$

"t-i": $k^2\dot{\eta} = 4\pi G a^2 (\rho + p)\,\theta$ $\qquad \theta = ik^j v_j$

"i-i": $\ddot{h} + 2\mathcal{H}\dot{h} - 2k^2\eta = -24\pi G a^2 \delta p$

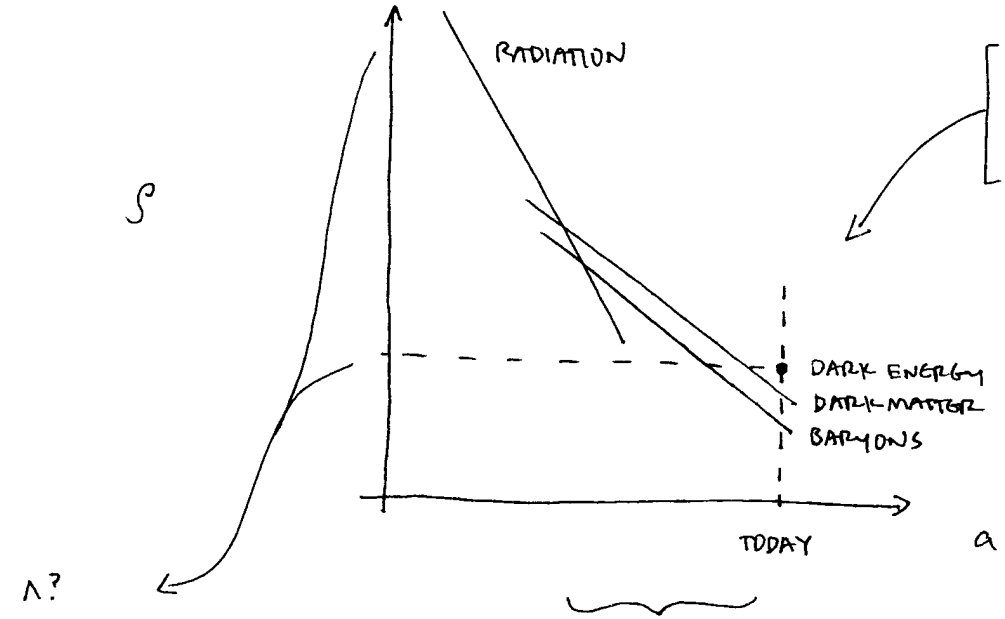
"i-j": $\ddot{h} + 6\ddot{\eta} + 2\mathcal{H}(\dot{h} + 6\dot{\eta}) - 2k^2\eta = -24\pi G a^2 (\rho + p)\sigma$

$\alpha = \frac{1}{2k^2}(\dot{h} + 6\dot{\eta})$ $\qquad \Psi = \dot{\alpha} + \mathcal{H}\alpha$, $\phi = \eta - \mathcal{H}\alpha$

$\delta = \frac{\delta\rho}{\rho} \rightarrow \dot{\delta} = -(1+w)\left(\theta + \frac{1}{2}\dot{h}\right) - 3\mathcal{H}\left(\frac{\delta p}{\delta\rho} - w\right)\delta$

$\dot{\theta} = -\mathcal{H}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{\delta p/\delta\rho}{1+w}k^2\delta - k^2\sigma$

COSMIC COINCIDENCES



WHY IS Ω_B SO CLOSE TO Ω_{CDM} ?

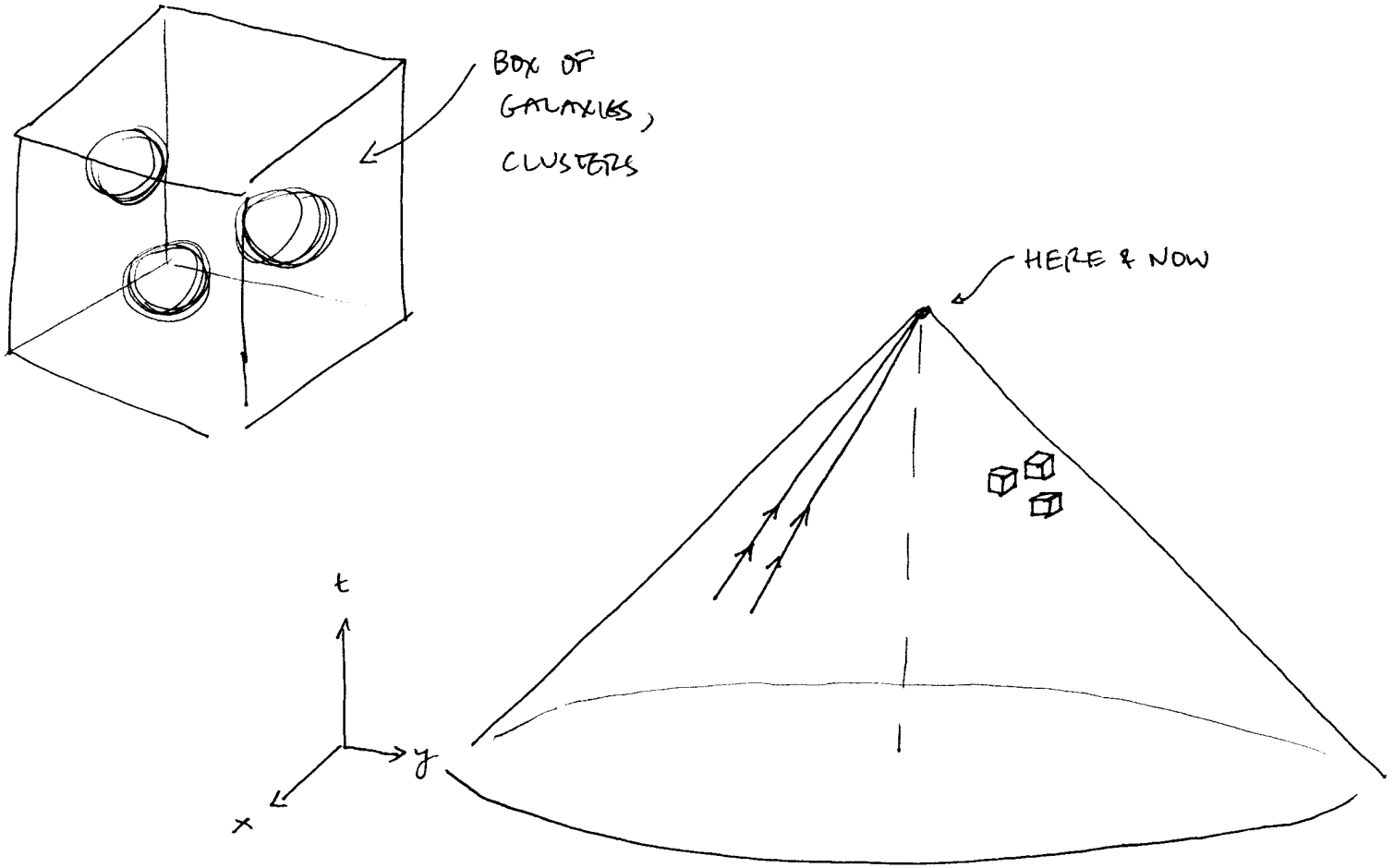
" Ω_{CDM} " Ω_{DE} ?

$$\rho_{DE} \sim (10^{-3}\ eV)^4$$

related to neutrino physics?

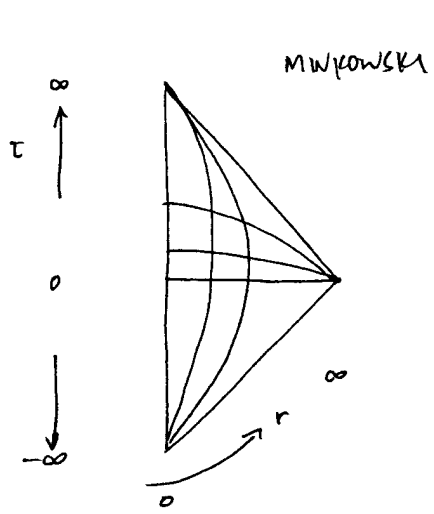
$\Delta m \sim 10^{-2} - 10^{-3}$ eV

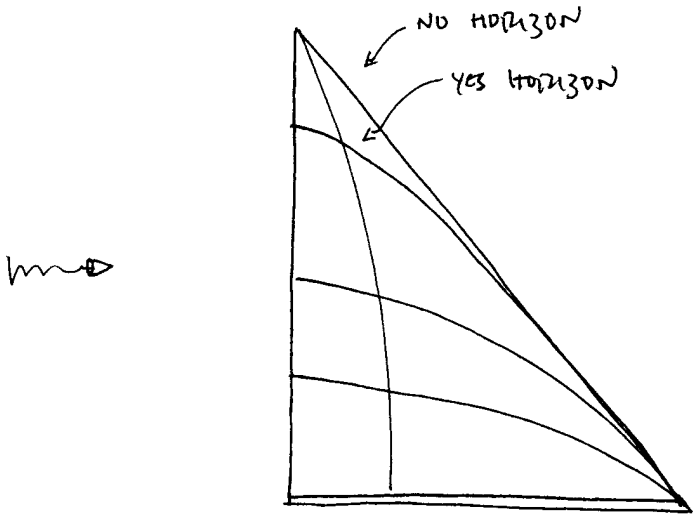
WHERE IS DARK ENERGY?



DARK ENERGY COSMOLOGY

CONFORMAL DIAGRAM





MORE DIAGRAMS : CHIBA et al CQG 22 3745 (2005)

INFLATION vs. DARK ENERGY

INFLATION	DARK ENERGY	
$\|1+w\| \ll 1$	$\|1+w\| \lesssim 1$	"STRENGTH"
$E > TeV$	$E \sim 10^{-3}\,eV$	"ENERGY"
$N = \ln \frac{a_f}{a_i} > 60$	$N \sim 1$?	"DURATION"
$\delta\phi \rightarrow$ SCALE-FREE SPECTRUM OF DENSITY PERTS	?	

$\longleftarrow$ SCALAR FIELD? $\longrightarrow$

QFT ORIGIN OF Λ

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} - \frac{\Lambda}{8\pi G} + L_M \right)$$

$$\Lambda_{eff} = \Lambda + 8\pi G \langle \rho \rangle$$

Λ → BARE CONSTANT

$8\pi G\langle\rho\rangle$ → VACUUM ENERGY $\int d^3k \, \frac{1}{2}\hbar\omega_k$

Zeldovich (1967) showed $\langle p \rangle = -\langle \rho \rangle$

→ QFT origin of Λ.

COMPLEMENTARY VIEWPOINT: ONE-LOOP EFFECTIVE ACTION INCLUDES TERMS THAT RENORMALIZE Λ, G, ...

(SEE BIRRELL & DAVIES, CH 6.)

NO SATISFACTORY METHOD TO "TAME" Λ_{eff} !

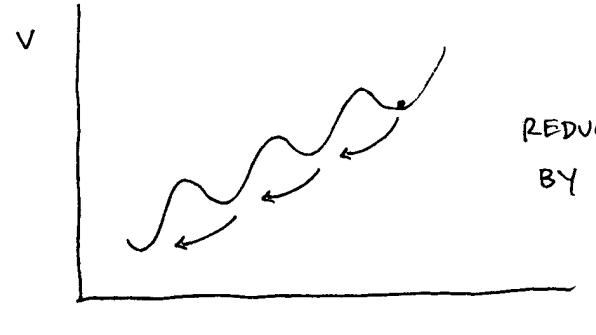
DON'T FORGET CONTRIBUTION FROM POTENTIAL MINIMA — CONDENSATES OF INTERACTING FIELDS.

ADJUSTING Λ

ABBOTT, PLB 150 427 (1985)

SCALAR FIELD: B

$$V(B) = V_0 + \epsilon \frac{B}{f_B} - \Lambda_0^4 \cos \frac{B}{f_B}$$



REDUCE VACUUM ENERGY BY ROLLING, TUNNELING

FOR $\epsilon \ll \Lambda_0^4$, MINIMA AT $B \simeq 2\pi N f_B$

$\Delta V \simeq 2\pi\epsilon$ NEED $\epsilon \lesssim (0.003\ \text{eV})^4$ FOR SUCCESS

STABILITY? LOWER VACUA ARE LONGER LIVED.

WHAT ABOUT $V(B) < 0$? COLD UNIVERSE?

(SIMILAR TO SCHWINGER MECHANISM TO REDUCE ELECTRIC FIELD...)

MOTIVATION FOR NUMEROUS RELATED SCHEMES

See BOUSSO + POLCHINSKI, JHEP 0006:006 (2000)

MORE TO SAY ABOUT Λ?

EXCELLENT REVIEWS: NOBBENHUIS, FOUND. PHYS. 36 613 (2006)

CARROLL, LIVING REV. REL. 4 1 (2001)

WEINBERG, REV. MOD. PHYS. 61 1 (1989)

OUR LACK OF UNDERSTANDING SOREM NEEDS GUIDANCE FROM OBS / EXPT!

COSMOLOGICAL IMPACT IS ENTIRELY THROUGH THE COSMIC EXPANSION

LARGE SCALE STRUCTURE Ω_m AVAILABLE, δ_m GROWTH

COSMIC MICROWAVE BACKGROUND ANGULAR SCALE, ISW

DISTANCES, VOLUMES, AGE

QUINTESSENCE – A DYNAMICAL SCALAR FIELD AS DARK ENERGY

TIME VARYING, NEARLY SMOOTH, NEGATIVE PRESSURE

$$L = -\frac{1}{2}(\partial\phi)^2 - V(\phi)$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V \quad , \quad p = \frac{1}{2}\dot{\phi}^2 - V$$

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V} \qquad -1 \leq w \leq 1$$

ZELDOVICH: "MOST IMPORTANT FIELD FOR COSMOLOGY"

Q: WHY CONSIDER ANYTHING OTHER THAN Λ?

A: THE PHYSICS OF Λ IS UNKNOWN – UNTIL WE GAIN A DEEPER UNDERSTANDING, REGARD Λ OR DARK ENERGY, OR QUINTESSENCE AS PLACE HOLDERS!

IF OBSERVATIONS CONVERGE ON $w = -1$ THEN NO NEED FOR DYNAMICS!?

REQUIRE A MODEL IN ORDER TO TEST FOR PHYSICS OF DARK ENERGY.

SCALAR FIELD

$$L = -\tfrac{1}{2}(\nabla\phi)^2 - V(\phi) \quad \rightarrow \quad \Box\phi = V'$$

$$T_{\mu\nu} = \nabla_\mu\phi\,\nabla_\nu\phi - g_{\mu\nu}\left(\tfrac{1}{2}(\nabla\phi)^2 + V(\phi)\right)$$

REQUIREMENTS $\quad w < 0 \quad$ SO $\quad V \gg \tfrac{1}{2}\dot{\phi}^2$

CONSEQUENTLY $\quad \rho \sim V$

DOMINANT $\quad \Omega_{DE} = \dfrac{8\pi G}{3}\dfrac{V}{H^2} \sim 1$

NEARLY SMOOTH $\quad V'' \sim H^2$

FOR $V = \tfrac{1}{2}m^2\phi^2$ THEN $\quad m \simeq 10^{-42}\ \text{GeV}$

$$\phi \simeq M_{PL}$$

INITIAL CONDITIONS? SET $\phi, \dot{\phi}$ TO GET w, Ω_{DE}

DIFFICULTIES

POTENTIAL MUST BE "FLAT"

IN ORDER TO KEEP $\dot{\phi}$ SMALL S.T. $w < 0$

" V " " $m \simeq H$

IN VIEW OF $\phi \sim M_{PL}$?

QFT LOOP CORRECTIONS TO V WILL SPOIL SMOOTHNESS

UNLESS A SYMMETRY PROTECTS V!

KOLDA & LYTH, PLB 458 197 (1999)

FIELD MUST STAY "DARK"

HOW TO PREVENT COUPLINGS TO THE STANDARD MODEL?

eg $\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$, $\frac{\phi}{M} F_{\mu\nu} \tilde{F}^{\mu\nu}$

CARROLL, PRL 81 3067 (1998)

* THE PNGB MODEL APPEARS TO BE THE BEST-MOTIVATED SCALAR FIELD DARK ENERGY MODEL, IN VIEW OF THESE CHALLENGES SEE KALOPER & SORBO, JCAP 0604:007 (2006)

QUINTESSENCE : PSEUDO NAMBU GOLDSTONE BOSON

PNGB

FRIEMAN et al,
PRL 75 2077 (1995)

$$V(\phi) = M^4 \left(1 + \cos \frac{\phi}{f}\right)$$

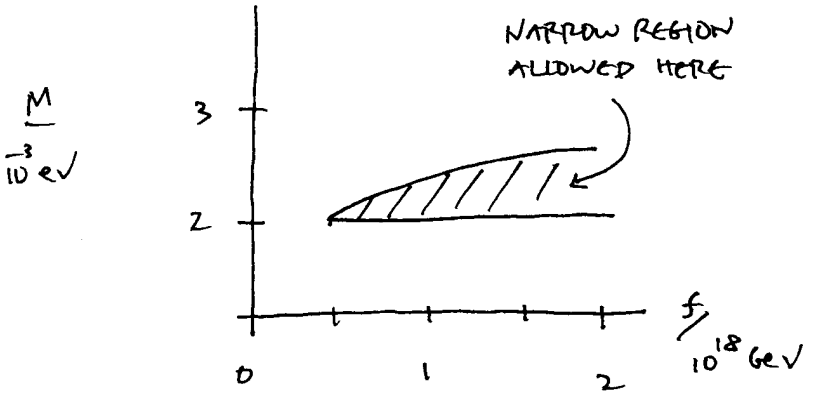
$f \sim M_{PL}$

$M \sim 10^{-3}$ eV

SHIFT SYMMETRY PROHIBITS COUPLINGS THAT LEAD TO LONG-RANGE FORCES; FORM OF POTENTIAL IS STABLE AGAINST CORRECTIONS

RECENT ANALYSIS OF OBS. CONSTRAINTS:

DUTTA & SORBO, PRD 75 063514 (2007)



$\dot{\phi}_i = 0$, $\phi \sim f$ TODAY.

HOW TO ADDRESS COINCIDENCES?
FINE TUNING?

"SCALING FIELDS"

FERREIRA & JOYCE,
PRL 79 4740 (1997)

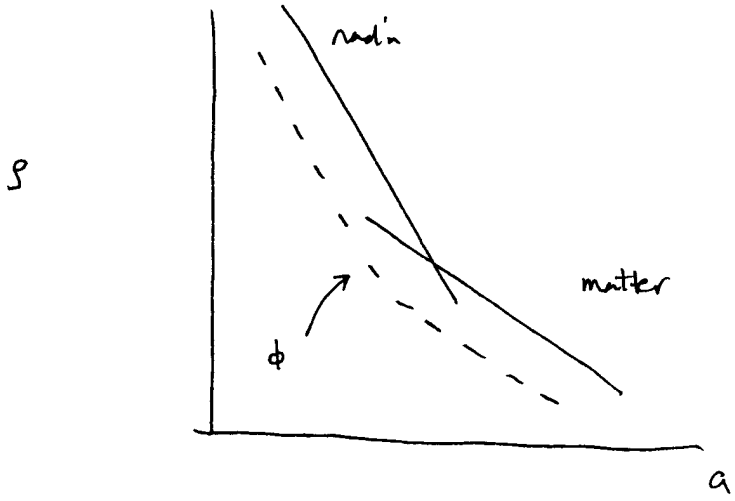
$V(\phi) = M^4 e^{-\lambda\phi/M_{PL}}$ UBIQUITOUS POTENTIAL!

↓

HAS AN ATTRACTOR SOL'N $\phi \propto \ln t$

LEADS TO $\Omega_\phi = \frac{3(1+w_B)}{\lambda^2}$ $w_\phi = w_B$

FOR $\lambda > \sqrt{6}$



INTERESTING BEHAVIOR!

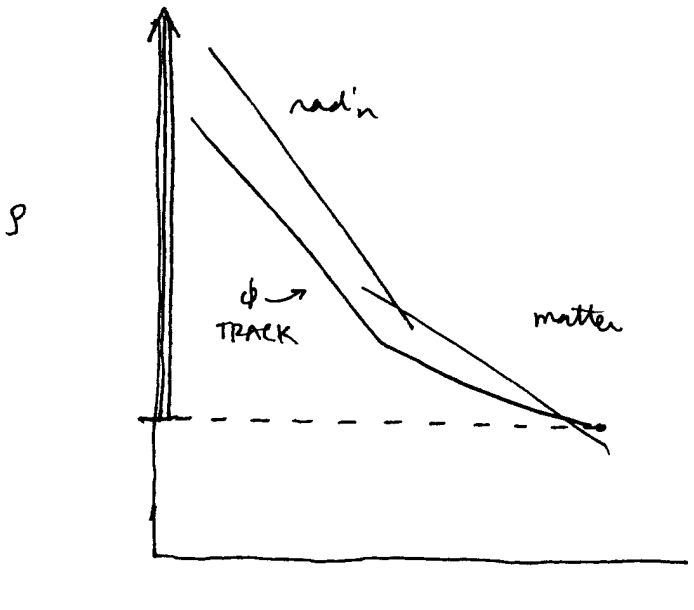
BUT NO COSMIC ACCELERATION

Ω_ϕ NON-NEGLIGIBLE DURING MATTER ERA? SLOWS δ_M GROWTH!

BBN LIMITS $\Omega_\phi \lesssim 0.1$ IN RAD'N ERA.

QUINTESSENCE "TRACKER"

A CLASS OF SCALAR FIELD MODELS THAT SOLVES A PROBLEM OF FINE-TUNING INITIAL CONDITIONS



eg $V(\phi) = \frac{M^{4+N}}{\phi^N}$

PHYSICS?
VACUUMLESS OR "RACETRACK" POTENTIAL

BINETRUY, PRD 60 063502 (1999)
MASIERO & PRD 61 023504 (2000)

ATTRACTOR SOL'N

$w_\phi = \frac{\frac{N}{2} w_B - 1}{\frac{N}{2} + 1}$ FOR $\Omega_\phi < 1$

$w_\phi \to -1$ FOR $\Omega_\phi \sim 1$

ZLATEV et al, PRL 82 896 (1999)

LOWER BOUND ON w_ϕ IS SET BY N & Ω_ϕ

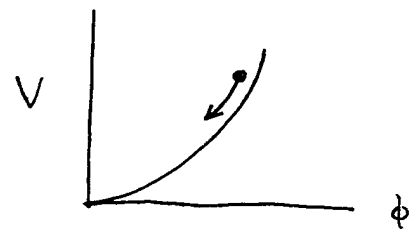
IF $N \geq 1$ THEN $w_\phi \gtrsim -0.75$ — RULED OUT!

STEINHARDT et al, PRD 59 123504 (1999)

QUALITATIVE BEHAVIOR

"FREEZING" & "THAWING"

THAWING

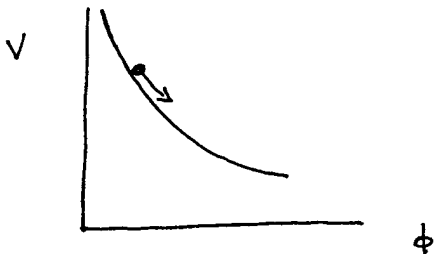


EARLY: FIELD IS FROZEN BY HUBBLE FRICTION $w \approx -1$

LATE: BEGINS TO RELAX $w \to 0$

EXAMPLE: $V = \frac{1}{2} m^2 \phi^2$, PNGB

FREEZING



EARLY: FIELD ROLLS AT A RATE SET BY HUBBLE FRICTION AND CURVATURE OF V

LATE: FIELD SLOWS, BUT V IS VACUUMLESS ($V_{MIN} \neq 0$) $w \to -1$

OBSERVATIONALLY, MUST HAVE $w \approx -1$ TODAY

BUT $\frac{dw}{dt}$ IS POORLY CONSTRAINED.

FREEZING & THAWING

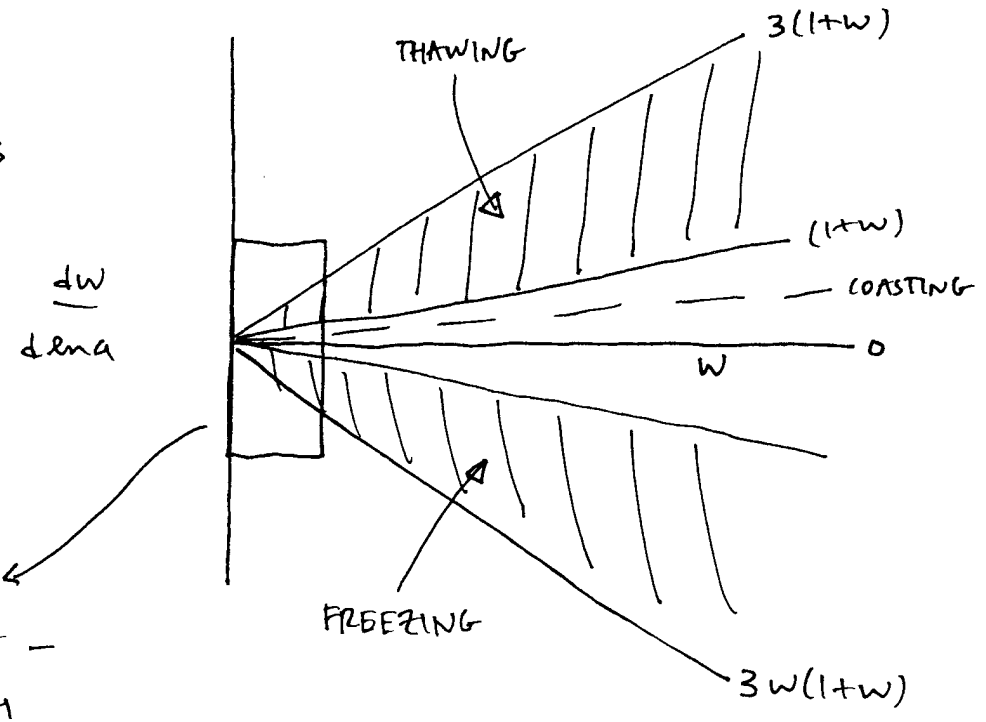
RC + LINDER, PRL 95 141301 (2005)

A GUIDE TO THE SIZE OF

$\frac{dw}{d\ln a}$ FOR QUINTESSENCE

BASED ON AN EMPIRICAL ANALYSIS

OF MODELS, PHASE SPACE.



RESOLUTION OF A

HYPOTHETICAL EXP'T —

CAN IT DISTINGUISH

THAWING VS. FREEZING?

HOW CLOSE TO $w = -1$?

IF OBSERVATIONS CONVERGE ON $w = -1 + \epsilon$, $|\epsilon| \ll 1$

THEN AT WHAT POINT DO WE DECLARE "Λ" ?

GUIDANCE FROM THEORY ?

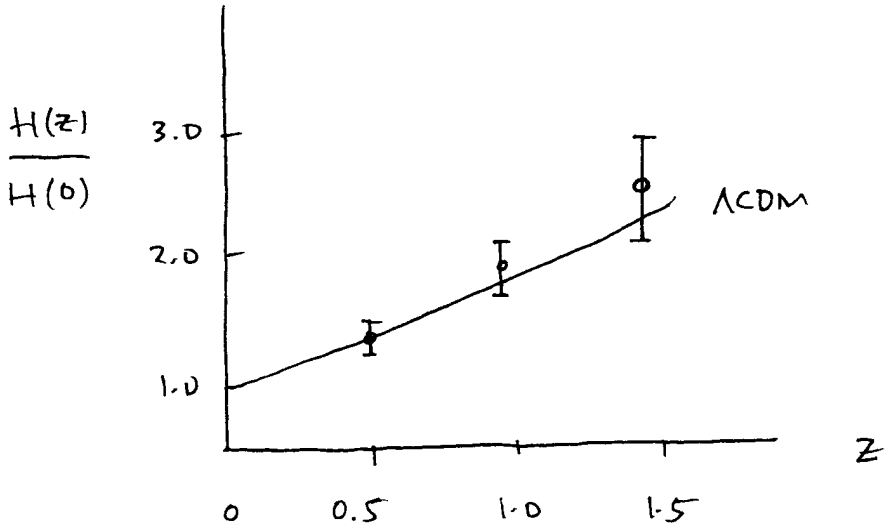
MANY SCALAR FIELD MODELS AT $|\epsilon| \ll 1$ ...

EXP'T ?

WHAT'S THE SMALLEST $|\epsilon|$ THAT CAN BE DISTINGUISHED?

OBSERVATIONAL CONSTRAINTS

EVOLUTION OF $H(z)$



DATA: WMAP 3 DISTANCES

SDSS BAO

SNLS SNe

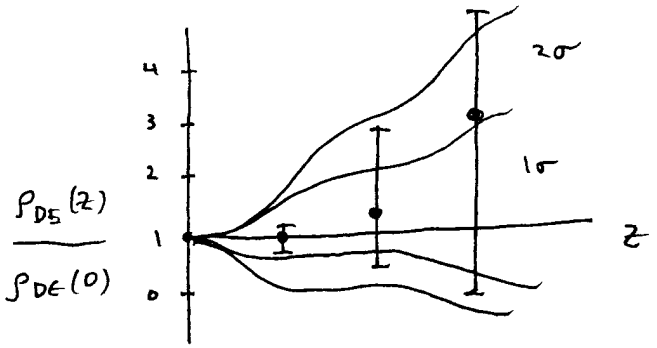
WANG & TEGMARK

PRD 71 103513 (2005)

WANG & MUKHERJEE

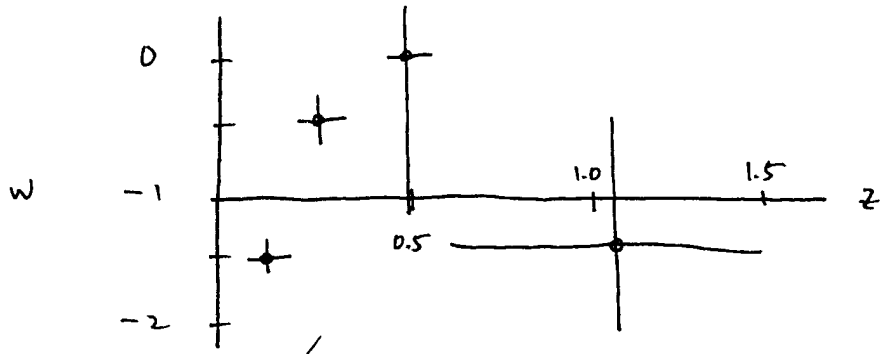
PRD 76 103533 (2007)

VIEW OF ρ_{DE} IS SOMEWHAT DIFFERENT



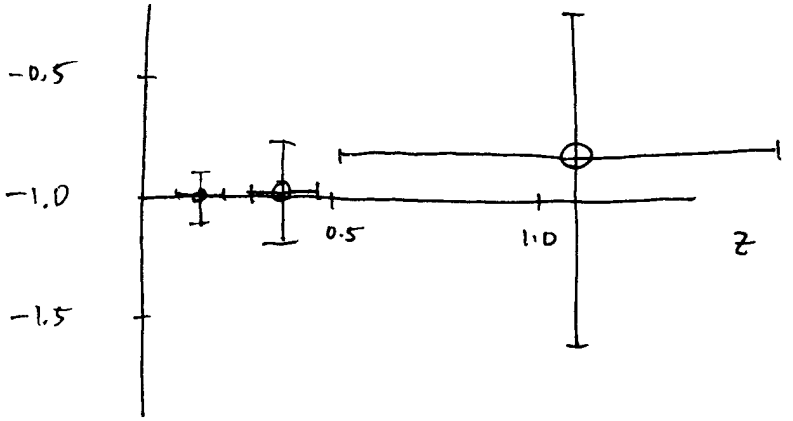
UNCORRELATED ESTIMATES OF w

HUTERER & KNOX
PRD 71 023506 (2006)



BANDPOWER ESTIMATES OF w
w/ INDEPENDENT z-BINS

SULLIVAN et al
JCAP, 0709:004 (2007)



IMPROVEMENT IN QUALITY, QUANTITY OF DATA.

DARK ENERGY PHENOMENOLOGY

SIMPLIFY DESCRIPTION : REPLACE SCALAR FIELD BY $w(a)$

EQUIVALENCE $V(\phi)$ VS. $w(a)$

$$\rho(a) = \rho(a_0) \exp\left(3 \int_a^{a_0} (1+w)\, d\ln a \right)$$

$$\phi' = a\sqrt{\rho(1+w)}$$

$$V = \tfrac{1}{2}\rho(1-w)$$

FLUCTUATIONS ?

$$\phi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)$$

$$\frac{d^2}{d\tau^2}\delta\phi + 2\mathcal{H}\frac{d\delta\phi}{d\tau} + (k^2 + a^2 V_{,\phi\phi})\,\delta\phi = -\frac{1}{2}\frac{dh}{d\tau}\frac{d\phi}{d\tau}$$

[JEANS SCALE FOR SLOWLY-VARYING ϕ (or w) IS HUBBLE SCALE!]

$k^2 \gg a^2 V_{,\phi\phi}$ FLUCTUATIONS DECAY

$k^2 \ll a^2 V_{,\phi\phi}$ " GROW

SEE:

$$a^2 V_{,\phi\phi} = -\frac{3}{2}(1-w)\left[\mathcal{H}' - \mathcal{H}^2\left(\frac{5}{2} + \frac{3}{2}w\right)\right] + w' \text{ TERMS}$$

SCALAR FIELDS FLUCTUATE

$$\phi(\vec{x},t) \to \phi(t) + \delta\phi(\vec{x},t)$$

$$\text{FT} \quad \delta\phi(\vec{k},t)$$

$$' = \frac{d}{d\tau} \qquad \delta\phi'' + 2\mathcal{H}\delta\phi' + (k^2 + a^2 V_{,\phi\phi})\delta\phi = -\tfrac{1}{2}h'\phi'$$

CHANGE VARIABLES: $\delta\psi = \delta\phi/\sqrt{1+w}$, $\psi' = \phi'/\sqrt{1+w}$

$$\delta\psi'' + \left(2\mathcal{H} + \frac{w'}{1+w}\right)\delta\psi' + \left(k^2 - \tfrac{3}{2}(1-w)\left(\mathcal{H}' - \mathcal{H}^2\left(\tfrac{5}{2} + \tfrac{3}{2}w\right)\right) + 3w'\mathcal{H}\right)\delta\psi$$

$$= -\tfrac{1}{2}h'\psi' \qquad \text{SYNCHRONOUS GAUGE}$$

$$\delta\rho = \frac{1}{a^2}\psi'\left((1+w)\delta\psi' - \tfrac{3}{2}\mathcal{H}(1-w^2)\delta\psi\right)$$

$$\delta p = \frac{1}{a^2}\psi'\left((1+w)\delta\psi' + w'\delta\psi + \tfrac{3}{2}\mathcal{H}(1-w^2)\delta\psi\right)$$

$$\rho = \frac{(\psi')^2}{a^2} \qquad \text{so} \qquad \delta \equiv \frac{\delta\rho}{\rho} = \frac{1}{\psi'}\left((1+w)\delta\psi' - \tfrac{3}{2}\mathcal{H}(1-w^2)\delta\psi\right)$$

$$\Theta = k^2\frac{\delta\psi}{\psi'}$$

CONSTANT w — DAVE et al, PRD 66 023516 (2002)

ϕ IN BKGD

$$\frac{d^2}{d\ln a^2}\delta\Psi + V\frac{d}{d\ln a}\delta\Psi + (k^2+m^2)\delta\Psi = -\frac{1}{2}\frac{dh}{d\ln a}\frac{d\Psi}{d\ln a}$$

$$V = \frac{3}{2}(1-w_B)$$

$$m = \frac{3}{2}\sqrt{(1-w)(2+w+w_B)}$$

SOURCE TERMS

$$\frac{d\Psi}{d\ln a} = \sqrt{\Omega_{DE}\frac{3}{8\pi G}H_0^2}\;\frac{a^2}{a'}\left(\frac{1}{a}\right)^{\frac{3}{2}(1+w)}$$

$$\frac{d^2h}{d\ln a^2} + \frac{1-3w_B}{2}\frac{dh}{d\ln a} = -3\frac{\delta\rho+\delta p}{\rho} \simeq -3\delta_B(1+w_B)$$

$$\delta_B = D_B\left(\frac{a}{a_H}\right)^{p/2} \qquad p = \begin{cases} 4 & \text{RAD'N ERA} \\ 2 & \text{MATTER ERA} \end{cases}$$

a_H → HORIZON RE-ENTRY

D_B → k-INDEP. FOR H-Z SPECTRUM

USE THESE TOOLS TO SHOW

$k \ll k_J$ (JEANS SCALE) $\qquad \delta\phi = -C_I D_B a_H^{-2} a^{M/2}$

$M = p + 3(w_B - w) > 0$

so $\delta\phi$ GROWS!

BUT AT EARLY TIMES, $\delta\phi$ IS NEGLIGIBLE!

AS FOR THE HOMOGENEOUS SOL'N

$$\delta\phi = C_H a^{-\frac{1}{2}\nu} \Theta(a, k, m, \nu)$$

Θ → HARMONIC OSCILLATOR

$\nu > 0$ → SO ENVELOPE DECAYS

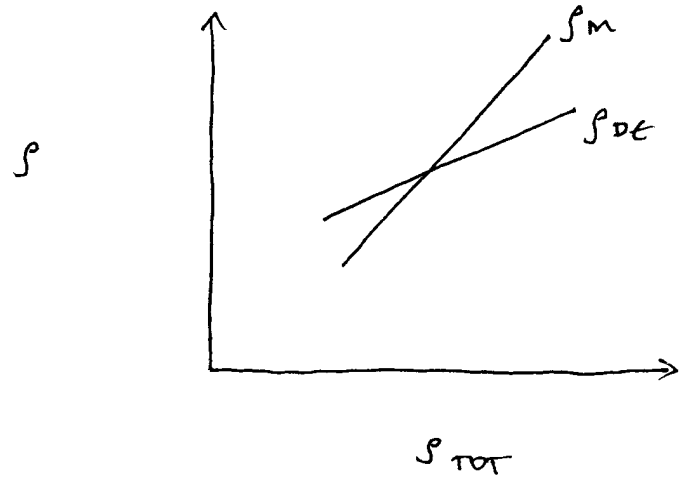
C_H → IF C_H IS SET $\delta\rho_\phi \leq \delta\rho_{r,m}$

THEN $\delta\phi$ DECAYS BY PRESENT

AND INITIAL CONDITIONS ARE NEGLIGIBLE!

ANOTHER LOOK AT CLUSTERING IN SCALAR FIELD DARK ENERGY

SEE DUTTA & MAOR PRD 75 063507 (2007)



HOMOGENEOUS / COSMIC SCALES

- UNIVERSE EXPANDS
- ρ_{TOT} DECREASES
- ρ_{DE} SURPASSES ρ_M

INHOMOGENEOUS / CLUSTER SCALES

- SPHERICAL OVERDENSITY OF MATTER COLLAPSES
- ρ_M INCREASES
- ρ_{DE} DECREASES

EXPECT A (SLIGHT) VOID IN DARK ENERGY NEAR CLUSTER

δ_p vs. δ_ρ ?

$$\delta_p - \delta_\rho = \frac{1}{a^2}\psi'\delta\psi\left(w' + 3\mathcal{H}(1-w^2)\right)$$

$$= \frac{\theta\rho}{k^2}\left(w' + 3\mathcal{H}(1-w^2)\right)$$

SOUND SPEED? $\quad \frac{\delta P}{\delta\rho} \neq w, 1$ or anything simple.

PHASE VELOCITY : $\quad \delta\phi'' + 2\mathcal{H}\delta\phi' + (k^2 + a^2 V_{,\phi\phi})\delta\phi = -\frac{1}{2}h'\phi'$

$(k^2 + a^2 V_{,\phi\phi})$ ↑ PHASE SPEED = 1 (IN UNITS OF c)

AND $\dot\delta$, $\dot\theta$ YIELD

$$\dot\delta = -(1+w)\left(\theta + \tfrac{1}{2}\dot h\right) - 3\mathcal{H}\left(\frac{\delta P}{\delta\rho} - w\right)\delta$$

$$\dot\theta = -\mathcal{H}(1-3w)\theta - \frac{\dot w}{1+w}\theta + \frac{\delta P/\delta\rho}{1+w}k^2\delta$$

JUST AS FOR A FLUID, BUT $\delta P/\delta\rho$ GIVEN AS ABOVE.

PROCEED TO STUDY SCALAR FIELD DARK ENERGY COSMOLOGY

1. EXPANSION, DISTANCES, AGES DEPEND ON V or $w(a)$

2. DM, BARYONS, PHOTONS AFFECTED

$$\delta_M'' + \mathcal{H}\delta_M' = 4\pi G a^2 \delta\rho_M$$

$$\frac{d\ln\delta_M}{d\ln a} \approx \left[\Omega_M(a)\right]^\gamma$$

$$\gamma \approx \frac{3}{5 - \frac{w}{1+w}} + \text{CORRECTIONS}$$

EVALUATE EXACTLY! OR SEE WANG & STEINHARDT ApJ 508 483 (1998)

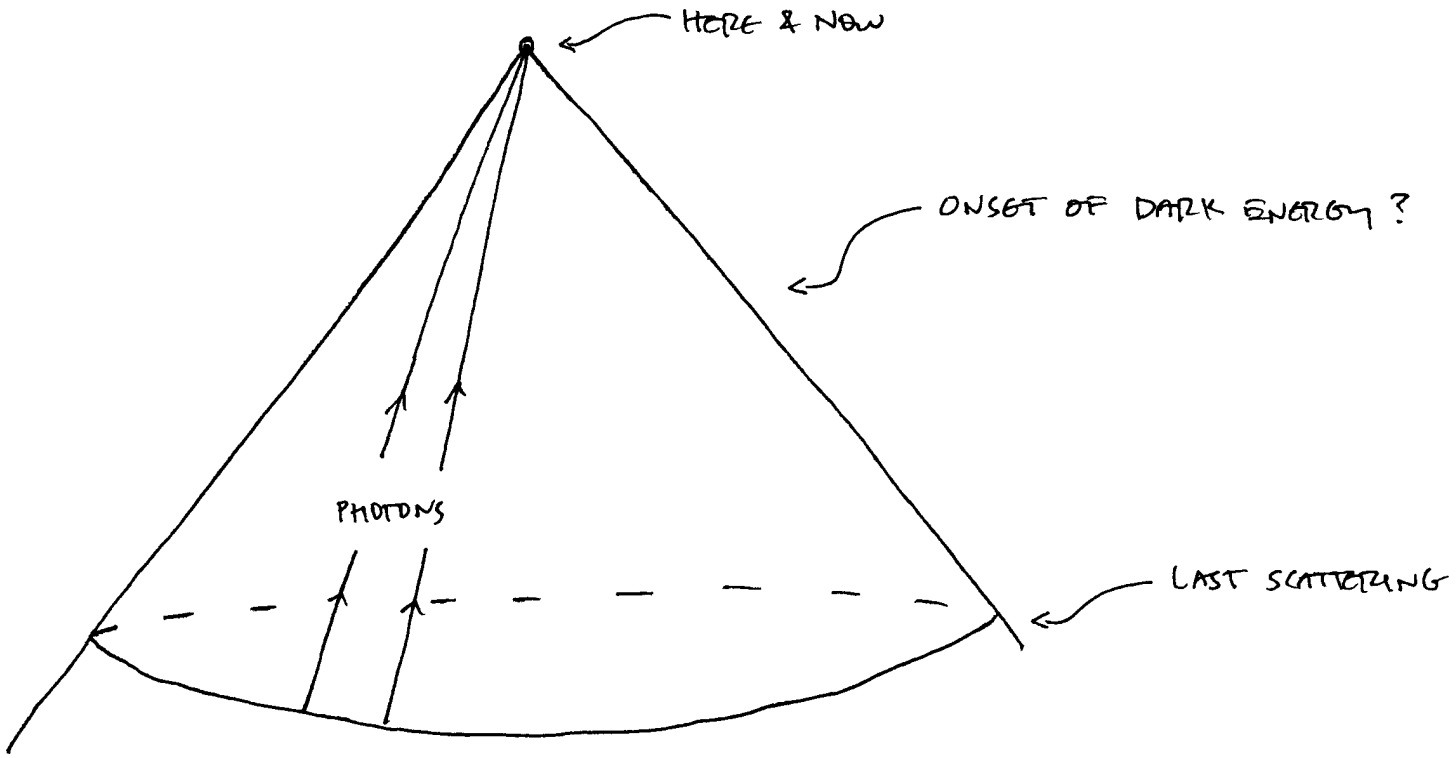
RATE OF GROWTH OF δ_M SLOWS AS $w \to -1$, $\Omega_M \to 0$

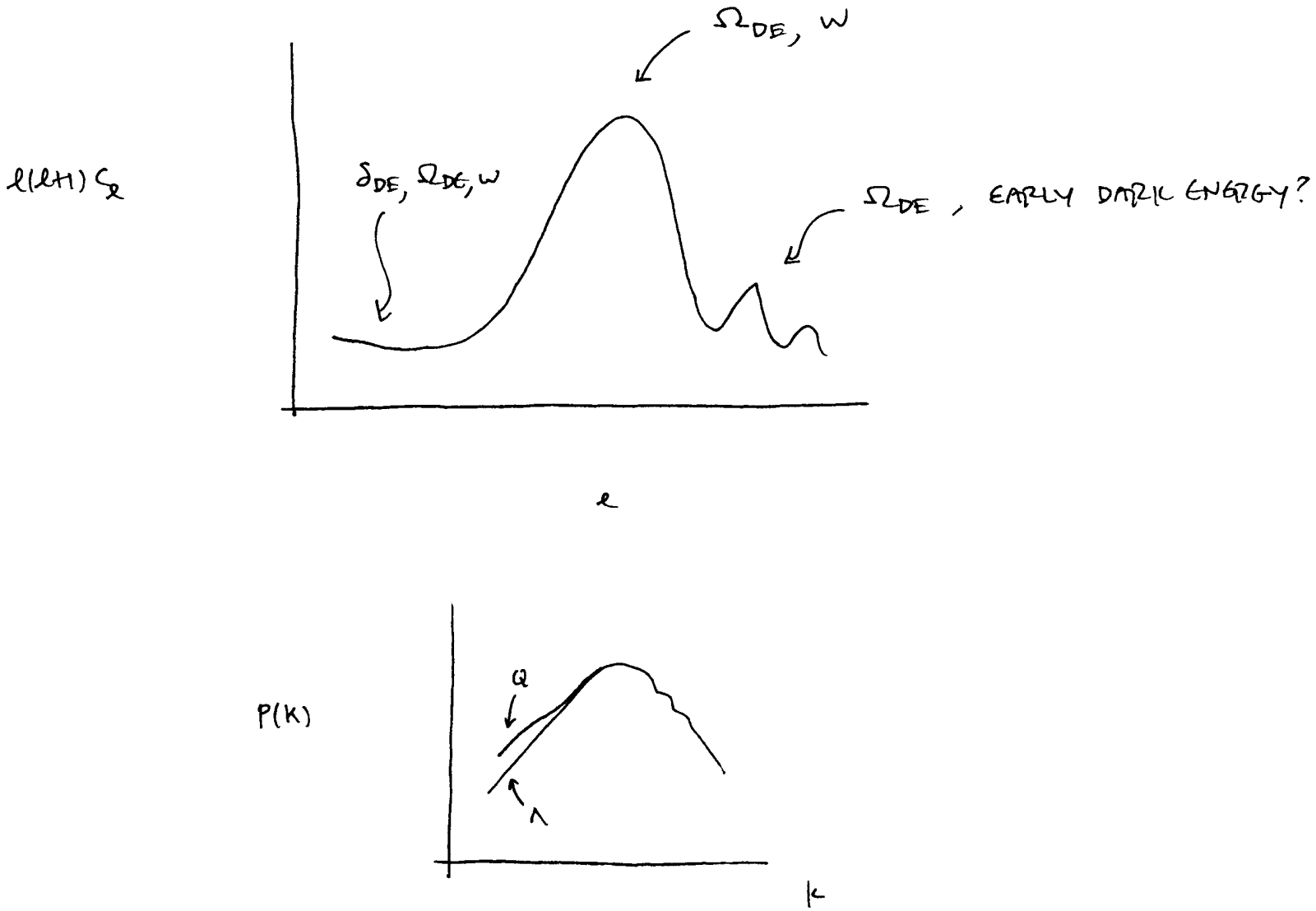
3. δ_{DE}

CMB !

$$\frac{\delta T}{T}(\hat{n}) = \left[\left(\frac{1}{4}\frac{\delta\rho}{\rho} + \Phi\right) - \hat{n}\cdot\vec{V}_e\right]_{\substack{\vec{r}=r_{LS}\hat{n} \\ \tau=\tau_{LS}}} + \int_0^{r_{LS}} d\lambda\,(\dot{\Phi}+\dot{\Psi})[\lambda\hat{n}, \tau_0-\lambda]$$

SW OSCILLATIONS ISW




Ω_{DE}, w
δ_{DE}, Ω_{DE}, w
Ω_{DE} , EARLY DARK ENERGY?
$\ell(\ell+1)C_\ell$
ℓ
P(k)
Q
Λ
k

DARK ENERGY & CMB

GEOMETRIC DEGENERACY

BOND + EFSTATHIOU
MNRAS 304 75 (1999)

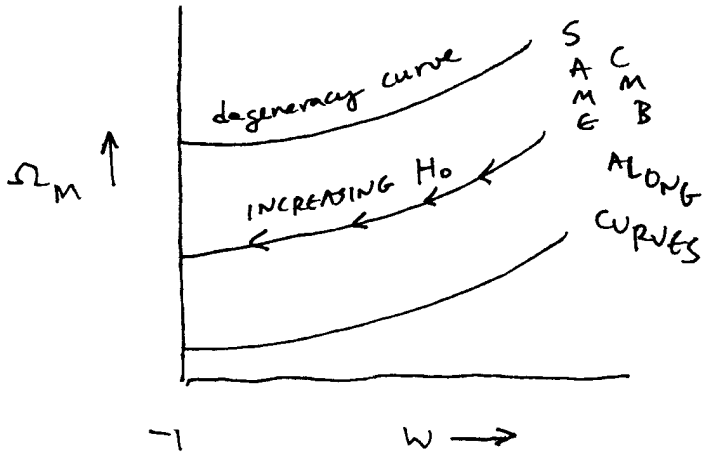
HUEY et al
PRD 59 063005 (1999)

COSMOLOGICAL MODELS WITH SAME

$\Omega_M + \Omega_{DE} = 1$	GEOMETRY
$\Omega_M h^2$	MATTER
$\Omega_B h^2$	BARYONS
n_s	SPECTRAL INDEX
ℓ_{CMB}	ANGULAR DISTANCE TO LAST SCATTERING

HAVE IDENTICAL CMB ANISOTROPY PATTERN,

WITHIN COSMIC VARIANCE



ALSO – EARLY APPEARANCE OF DARK ENERGY?

QUINTESSENTIAL INFLATION? PEEBLES & VILENKIN, PRD59 063505 (1999)

INTERMITTENT PERIODS OF DARK ENERGY DOMINANCE?
DODELSON et al, PRL 85 5276 (2000)

OR K-NATION?
eg SALATI, PLB571 121 (2003)

AT LAST SCATTERING?
eg DORAN et al, PRD64 123520 (2001)

K-ESSENCE

SCALAR FIELD DARK ENERGY WITH NON-CANONICAL KINETIC ENERGY

$$X \equiv -\tfrac{1}{2}(\nabla\phi)^2$$

$$L = p(\phi, X)$$

$$\rho = 2X p_{,X} - p$$

example: $p = f(\phi)(X - X^2)$, $f(\phi) \propto \phi^{-n}$

$$\rightarrow \rho = f(\phi)(X - 3X^2)$$

$$w = -1 + \frac{n}{2}(1 + w_B)$$

IF $n < 2$ THEN K-ESSENCE IS A "TRACKER"

CHIBA et al,
PRD 62 023511 (2000)

ARMENDARIZ-PICON et al,
PRL 85 4438 (2000);
PRD 63 103510 (2001)

ADVANTAGE? THERE EXIST ATTRACTORS
radiation-like
de Sitter ($w = -1$)-like

SO THE BACKGROUND MATTER & RADIATION PUSHES K-ESSENCE FROM ONE ATTRACTOR TO THE OTHER. HELP SOLVE COINCIDENCES?

K-ESSENCE PERTURBATIONS

$$\delta\ddot{\phi} + \ldots + c_s^2 k^2 \delta\phi = \text{SOURCE TERMS}$$

$$\downarrow$$

$$c_s^2 = \frac{P_{,X}}{\rho_{,X}}$$

IN TERMS OF FLUID VARIABLES δ, θ FOR K-ESSENCE

$$\dot{\delta} = -(1+w)\left(\theta + \tfrac{1}{2}\dot{h}\right) - 3\mathcal{H}\left(\frac{\delta P}{\delta\rho} - w\right)\delta$$

$$\dot{\theta} = -\mathcal{H}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{\delta P/\delta\rho}{1+w}k^2\delta$$

$$\delta p = c_s^2 \delta\rho + \rho\frac{\theta}{k^2}\left[3\mathcal{H}(1+w)(c_s^2 - w) + \dot{w}\right]$$

$$= \qquad\qquad\qquad\qquad\qquad\qquad =$$

FOR CANONICAL SCALAR, $c_s^2 = 1$.

K-ESSENCE

SOUND SPEED $c_s^2 = \dfrac{P_{,X}}{\rho_{,X}} > 1$ IS FEASIBLE !

THIS IS BAD NEWS,

AND IT OCCURS FOR THE MODELS OF INTEREST

SEE BONVIN et al, PRL 97 081303 (2006)

LAGRANGIAN $L = K(\phi)\, F(X)$

DEFINE $y = Y\sqrt{X}$, $g(y) = F(X)/\sqrt{X}$

SO $w = -\dfrac{g}{y g'}$, $c_s^2 = \dfrac{g - y g'}{y^2 g''}$

AS P, ρ DECAY IN TIME, y INCREASES

NEXT $w' = -\dfrac{(1+w)(c_s^2 - w)}{c_s^2\, y}$

SO IF $w > 1$ & $w' < 0$

THEN $c_s^2 > 1$

DOES THIS OCCUR?

THESE K-ESSENCE MODELS HAVE FIXED POINTS

$$r = \frac{3}{2\sqrt{2}}(1+w)\sqrt{-g'}\,y = \text{CONSTANT}$$

$$= \sqrt{\Omega_K}$$

ONE FIXED POINT IS RADIATION-LIKE

THE OTHER IS deSITTER-LIKE

DESIRE FOR THE MODEL TO START IN RAD'N-LIKE PHASE, AND THEN DRIFT INTO THE dS or ACCELERATION PHASE.

SO $r(\text{RAD}) < r(\text{ACC})$, $y(\text{RAD}) < y(\text{ACC})$, $g(\text{RAD}) > 0$, $g(\text{ACC}) < 0$

SO r MUST INCREASE, BUT $\frac{dr}{dy} = \frac{3}{2\sqrt{8}} \frac{g'' y}{\sqrt{-g'}}(w-1)$

$g'' > 0$ IN ORDER THAT $c_s^2 > 0$ (ELSE INSTABILITY!)

SO THEN $w - 1 > 0$ ✓ AND $w' < 0$

$c_s^2 > 1$ NECESSARILY OCCURS!

"CHAPLYGIN GAS"

CONSIDER A COSMIC FLUID FOR WHICH

$$p = -A/\rho^{\gamma}$$

SEE KAMENSHCHIK ET AL,
PLB 511 265 (2001)

BENTO ET AL,
PRD 66 043507 (2002)

[A SIMILAR E.O.S. OCCURS IN SPECIAL HYDRODYNAMIC SITUATIONS

$A>0$, $\gamma>0$

NEGLIGIBLE PRESSURE AT EARLY TIMES

STRONG NEGATIVE PRESSURE TODAY?

INTERESTING COSMOLOGY?

BACKGROUND EVOLUTION OF DARK ENERGY MAY BE ACCEPTABLE – BUT FLUCTUATIONS?

EQUIVALENT SCALAR FIELD: $V(\phi) = \frac{1}{2}\sqrt{A}\,(\cosh 3\phi + \operatorname{sech} 3\phi)$ $(\gamma=1)$

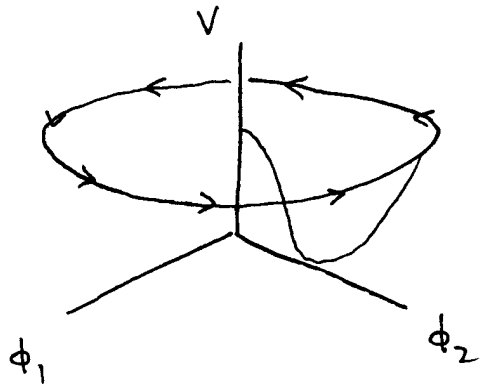
REPLACE (SOME) DARK MATTER?

PROBLEMS WITH SOUND SPEED, AS SCALAR FIELD OR $c_s^2 = \frac{dp}{d\rho} = -\alpha w$?

SEE SANDVIK et al, PRD 69 123524 (2004)

SPINTESSENCE !

COMPLEX SCALAR FIELD DARK ENERGY — BOYLE et al, PLB 545 17 (2002)



FIELD SPINS IN POTENTIAL

KEEPS UP POTENTIAL ENERGY?

$$\phi = R e^{i\theta}$$

If $\dot{\theta} \gg H$ Then $w \approx \frac{RV' - 2V}{RV' + 2V}$

EXAMPLE: $V = V_0 \left(\frac{R}{R_0}\right)^N$ GIVES $w = \frac{(N-2)}{(N+2)}$

DARK ENERGY REQUIRES $w < -\frac{1}{3}$ SO $N < 2$

(IN)STABILITY: JEANS WAVENUMBER $K_J^2 \propto GV' < 0$

UNSTABLE!

SO FLUCTUATIONS RAPIDLY GROW

FORM "Q-BALLS"

SEE COLEMAN, NPB 262 263 (1985)

DARK ENERGY & VARIATION OF CONSTANTS?

WEBB et al, PRL 87 091301 (2001)

review: UZAN, REV. MOD. PHYS. 75 403 (2003)

$$L = -\tfrac{1}{2}(\nabla\phi)^2 - V(\phi) - \tfrac{1}{4}\left(1+\epsilon\tfrac{\phi}{M}\right)F^2$$

CLASSICAL PROBLEM: MUST STABILIZE ϕ : SLOWLY VARYING DARK ENERGY?

AND KEEP $\left|\frac{\Delta\alpha}{\alpha}\right| \ll 1$

WATCH OUT FOR EARLY UNIVERSE CONSTRAINTS FROM BBN, CMB IF α VARIES.

QUANTUM PROBLEM: DARK ENERGY NOT SO DARK?

LONG RANGE FORCE?

BUT $\delta\Lambda = \left(\frac{\delta\alpha}{\alpha}\right)^n \Lambda$ VARIATION OF VACUUM?

WOULD SPOIL ANY CANCELLATION SCHEME

$\Lambda_{EFF} = \Lambda_B + \Lambda = 0$

$\rightarrow \Lambda_B + \Lambda\left(1+\left(\frac{\delta\alpha}{\alpha}\right)^n\right) \neq 0$

[BANKS et al, PRL 88, 131301 (2002)]

$w < -1$? PHANTOM DARK ENERGY, "BIG RIP"

OBSERVATIONS SEEM TO INDICATE $w<-1$ IS ALLOWED

CALDWELL, PLB 545 23 (2002)

WHAT DOES IT MEAN?

MISINTERPRETATION OF OBSERVATIONS

OR VIOLATION OF SACRED LAWS OF PHYSICS

eg GR NOT VALID ?

NEGATIVE ENERGIES ?

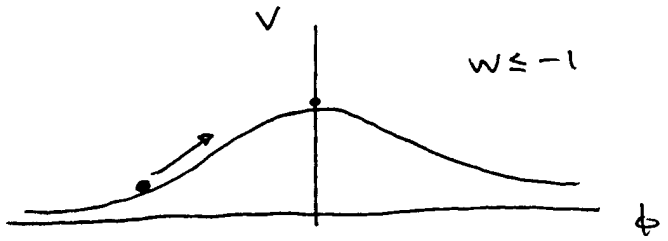
WHAT COULD PRODUCE $w<-1$?

SCALAR FIELD w/ WRONG-SIGN KINETIC ENERGY

$$L = +\tfrac{1}{2}(\nabla\phi)^2 - V(\phi)$$

SO FIELD ROLLS UP HILL!

THIS IS (CLASSICALLY) STABLE!



$w < -1$

ENERGY DENSITY GROWS

$w = \text{CONSTANT} \rightarrow \rho \propto a^{-3(1+w)}$

IF EXPANSION IS MATTER DOMINATED FOR $t < t_m$,

"PHANTOM" " $t > t_m$

$$a(t) = \begin{cases} a(t_m)\left(\frac{t}{t_m}\right)^{2/3} & t < t_m \\ a(t_m)\left[-w + (1+w)\frac{t}{t_m}\right]^{\frac{2}{3(1+w)}} & t > t_m \end{cases}$$

↙

SCALE FACTOR DIVERGES IN FINITE COSMIC TIME!

CURVATURE DIVERGES

THIS IS A FUTURE SINGULARITY.

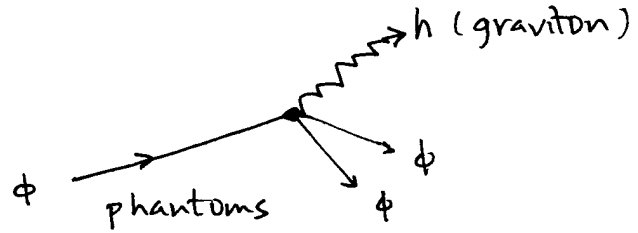
"BIG RIP"

FURTHER CONSIDERATIONS OF $w<-1$

CARROLL et al,
PRD 68 023509 (2003)

CLASSICALLY, NEGATIVE-KINETIC SCALAR FIELD WITHOUT COUPLINGS TO OTHER FIELDS, MATTER IS STABLE.

QFT, SUCH A FIELD IS UNSTABLE
AT LEAST TO THE SPONTANEOUS DECAY INTO GRAVITONS



DECAY RATE IS INFINITE
UNLESS ϕ or h is VALID
UP TO SOME SCALE, λ ?

$\Gamma \gg H_0$ REQUIRES $\lambda \lesssim 10^{-3}$ eV IF ϕ, h COUPLE
(UNCOMFORTABLY LOW)

$\lambda \lesssim 100$ MeV IF SYMMETRIES OF ϕ
RESTRICT COUPLINGS

SAFE FOR NOW?

NOVEL PHOTON INTERACTIONS IMPERSONATE $w<-1$?

SN LUMINOSITY - DISTANCE DIMINISHED

BY PHOTON - AXION CONVERSION $\gamma \to a$

$$L = \frac{a}{M} \vec{E} \cdot \vec{B}$$

in a magnetic field $B \sim 10^{-9}$ GAUSS

$M \sim 10^{11}$ GeV, $m_{axion} \sim 10^{-16}$ eV

(axion is not dark energy)

CSAKI et al, PRL 88 161302 (2002)

CAN THIS MECHANISM MAKE $w > -\frac{1}{3}$ LOOK LIKE $w \simeq -1$?

NO! SONG & HU, PRD 73 023003 (2006)

DIMMING PHOTON CONVERSION MUST EXPLAIN

BAD DISTANCES, AS WELL AS X-RAY, CMB RESULTS.

BUT IF TRUE $w \sim -1$, DIMMING CAN MAKE IT APPEAR $w \lesssim -1$.

$w < -1$? OTHER CONSIDERATIONS

IF DM DECAYS FASTER THAN $\rho_M \propto a^{-3}$

THEN D.E. WITH $w = -1$ CAN APPEAR TO HAVE $w < -1$.

eg DAS et al, PRD 73 083509 (2006)
HUEY et al, PRD 74 023519 (2006)

IF w EVOLVES RAPIDLY

BUT WE INTERPRET DATA AS $w =$ CONSTANT

CAN OBTAIN $w < -1$!

PRIORS ON w CAN GREATLY BIAS RESULTS

eg MADR et al, PRL 86 6 (2001)
PRD 65 123003 (2002)

EXAMPLE: $w(z) = -0.7 + 0.8z$ for $0 < z < 2$, $\Omega_m = 0.3$

LOOKS LIKE (SIMULATED DATA) $w = -1.75$
IF CONSTANT w IS ASSUMED !

MORE BIAS!

CONSIDER SN MAGNITUDES OR DISTANCES

AND CONSTANT-w DARK ENERGY

$$d_L = (1+z)\int_0^z dz'/H(z') \quad , \quad H(z') = H_0\left[\Omega_m(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)}\right]^{1/2}$$

$$\Omega_{DE} = (1-\Omega_m)$$

"NOT ALL w IS THE SAME"

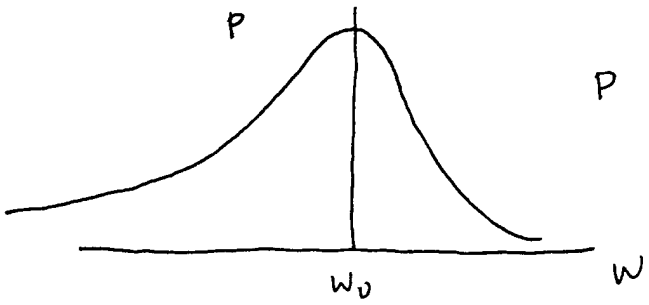
STARTING FROM A FIDUCIAL w_0

CHANGING w TOWARDS NEGATIVE PRODUCES

LESS CHANGE IN DISTANCES THAN

CHANGING w TOWARDS POSITIVE...

$$P(w,\Omega_m) = N\exp\left(-\tfrac{1}{2}\sum_i [m_{obs} - m_{thy}(w,\Omega_m)]^2/\sigma^2\right)$$



P IS SKEWED!

CROSSING $w = -1$

INDICATES INTERNAL DEGREES OF FREEDOM;

A SIMPLE SCALAR FIELD CANNOT CROSS

$$L = \pm \tfrac{1}{2}(\nabla\phi)^2 - V(\phi)$$

$$L = p(X, \phi)$$ generalized scalar has pathologies if it crosses

PRACTICAL APPROACH?

MODEL GENERAL BEHAVIOR USING 2+ FIELDS

ϕ_1 w/ $w > -1$, ϕ_2 w/ $w < -1$

TO ACCOMMODATE $w(a)$

SEE VIKMAN, PRD 71 023515 (2005)

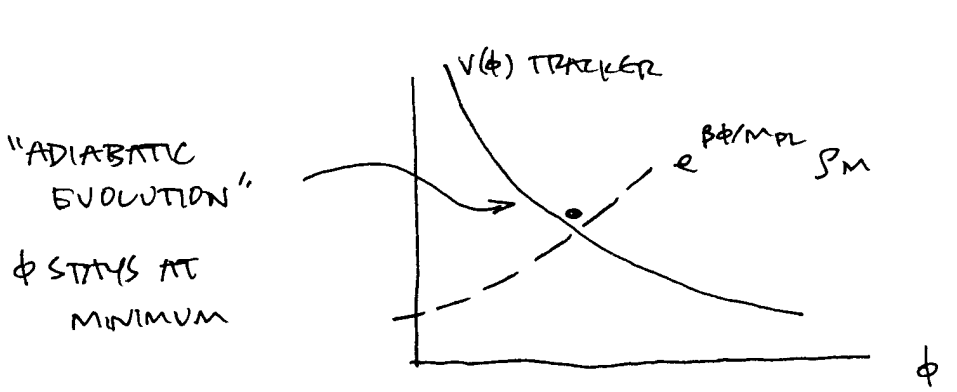
HU, PRD 71 047301 (2005)

CALDWELL + DORAN, PRD 72 043527 (2005)

CHAMELEON QUINTESSENCE

SCALAR FIELD GAINS DENSITY-DEPENDENT MASS

$$L = \frac{R}{16\pi G} - \tfrac{1}{2}(\nabla\phi)^2 - V(\phi) - e^{\beta\phi/M_{Pl}}\rho_M$$



COUPLINGS TO φ SEEM INEVITABLE

BUT LEAD TO LONG RANGE FORCES!

SEE

KHOURY & WELTMAN

PRL 93 171104 (2004)

PRD 69 044026 (2004)

UNLESS φ IS V. HEAVY,

COUPLING TO ρ_M KEEPS φ HEAVY

HERE IN THE GALAXY!

NEUTRINOS

$$(\Delta m_{21})^2 = 8.0^{+0.4}_{-0.3} \times 10^{-5}\ eV^2$$

$$(\Delta m_{23})^2 = 1.9 - 3.0 \times 10^{-3}\ eV^2$$

PDG 8/30/07

DARK ENERGY

?

$$\rho = \frac{3}{8\pi G} H_0^2 \Omega_{DE} = (0.0023\ eV)^4 = (5.5 \times 10^{-6}\ eV^2)^2$$

$h = 0.7$, $\Omega_{DE} = 0.75$

DO NEUTRINOS, OSCILLATIONS HAVE ANYTHING TO DO WITH DARK ENERGY ?

IDEA: MASS VARYING NEUTRINOS (MaVaNs) COUPLED TO QUINTESSENCE

FARDON et al
JCAP 0410:005 (2004)

COUPLED QUINTESSENCE

$$L = -\frac{1}{2}(\nabla\phi)^2 - V(\phi) - m(\phi)\bar{\Psi}\Psi + L_{\Psi,SM}$$

ex: $m(\phi) = m_0 e^{f(\phi)}$

PLENTY OF INVESTIGATIONS: WETTERICH, A&A 301 321 (1995)

AMENDOLA, PRD 62 043521 (2000)

↓

DISTINGUISH $m(\phi)$ FROM GRAVITATIONAL COUPLING

IF $f(\phi)$ DECAYS

THEN CDM DECAYS FASTER THAN Ya^3

WATCH OUT FOR CMB, LSS,

LONG RANGE FORCES

INSTABILITY

NEUTRINOS: AFSHORDI et al, PRD 72 065024 (2005)

CHAMELEON: KOIVISTO, PRD 72 043516 (2005)

BEAN et al, 0709:1128

DE & DM UNCOUPLED LEADS TO SUPPRESSED DM GROWTH

COUPLED " STRONGLY ENHANCED "

WHAT HAPPENS: DARK FLUID

$$\ddot{\delta} + A(w, c_s)\dot{\delta} + \left(B(w, c_s) + k^2 \frac{\delta p}{\delta \rho} \right) \delta = \text{SOURCES}$$

$\frac{\delta p}{\delta \rho} \propto V'$ ON SMALL SCALES

$V' < 0$ RUNAWAY!

GENERALLY, ENERGY FLOWS FROM DE INTO DM

DE'S NEGATIVE EQN OF STATE MEANS IT CAN REDUCE ENERGY FASTEST BY TRANSFER TO DM

COSMIC BULK PRESSURE

ZIMDAHL et al, PRD 64 063501 (2001)

IMPERFECT FLUID $\quad T_{\mu\nu} = (\rho + p_T) u_\mu u_\nu + p_T g_{\mu\nu}$

TOTAL PRESSURE $\quad p_T = p + \Pi$

NON-EQUILIBRIUM PRESSURE: $\quad \Pi < 0$?

CONSIDER NUMBER DENSITY OF PARTICLES

$$\dot{n} + 3Hn = n\Gamma \qquad n = N/V, \quad \Gamma = \dot{N}/N$$

$$\dot{\rho} + 3H(\rho + p_T) = 0$$

$$T\dot{S} = -3H\Pi - (\rho + p)\Gamma$$

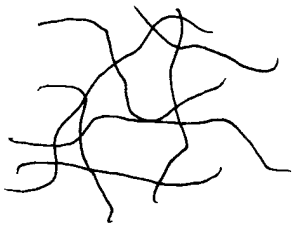
$$\dot{S} = 0 \rightarrow \Pi = -(\rho + p)\frac{\Gamma}{3H}$$

$\Gamma > 0$ (PARTICLE CREATION)

LEADS TO NEGATIVE PRESSURE

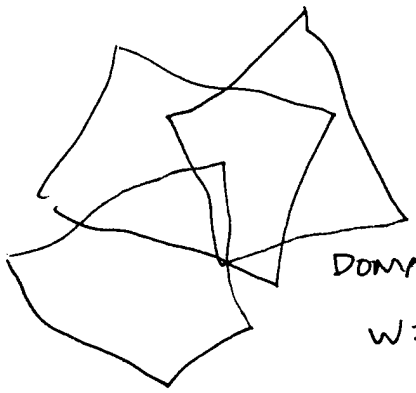
IS THE DARK ENERGY A SOLID?

BUCHER + SPERGEL
PRD 60 043505 (1999)



TANGLED WEB OF
NON-ABELIAN
COSMIC STRINGS

$w = -1/3$



DOMAIN WALLS

$w = -2/3$

ADOPT A CONTINUUM DESCRIPTION

$-1 < w < -1/3$

MATERIAL IS <u>ELASTIC</u>, SUPPORTS SCALAR, VECTOR, TENSOR PERTNS

IMPACT ON CMB, LSS — SEE BATTYE + MOSS, JCAP 0508:001 (2005)

& <u>ANISOTROPIC</u> ⇝ DAMPS PERTURBATION GROWTH

CAUSES SLIP BETWEEN ϕ & ψ

A CLOSER LOOK AT ANISOTROPIC DARK ENERGY

$$\dot{\delta} = -(1+w)(\theta + \tfrac{1}{2}\dot{h}) - 3\mathcal{H}\left(\frac{\delta p}{\delta \rho} - w\right)\delta$$

$$\dot{\theta} = -\mathcal{H}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{\delta p}{\delta \rho}\frac{k^2\delta}{1+w} - k^2\sigma$$

REQUIRE INPUT: δp, σ IN TERMS OF $\delta\rho$, θ, h, η.

PHENOMENOLOGICAL MODEL

$$\frac{\delta p}{\delta \rho} = c_s^2 \quad , \qquad \dot{\sigma} + 3\mathcal{H}\sigma = \frac{8}{3}\frac{c_v^2}{1+w}\left(\theta + \tfrac{1}{2}\dot{h} + 3\dot{\eta}\right)$$

SET $c_v^2 = 0$ FOR PERFECT FLUID

$c_v^2 = 1/3$ FOR APPROXIMATE DESCRIPTION OF RELATIVISTIC SPECIES

SEE HU, ApJ 506 485 (1998) ⟩

MOTA et al, 0708.0830

BATTYE & MOSS ⟩

$$\sigma = \frac{c_s^2 - w}{1+w}\left[-\delta + 3(1+w)(\eta - \eta_I)\right]$$

WHAT HAPPENS IN THE $w \to -1$ LIMIT ?

DEFINE $V \equiv (1+w)\theta$ AS PHYSICAL VARIABLE

SO $\dot{\delta} = -V - 3\mathcal{H}\left(\frac{\delta P}{\delta \rho} + 1\right)\delta$

$$\dot{V} = -\mathcal{H}(1-3w)V + \frac{\delta P}{\delta \rho}k^2\delta - k^2(1+w)\sigma$$

(A) SOLID DARK ENERGY

$$(1+w)\sigma = (c_s^2 - w)\left(-\delta + 3(1+w)(n-n_I)\right)$$

$w \to -1$ $\quad \dot{V} = -4\mathcal{H}V + \frac{\delta P}{\delta \rho}k^2\delta + k^2(c_s^2+1)\delta$

METRIC PERT'NS DROP OUT!

HOMOGENEOUS EQ'N FOR δ HAS ONLY DECAYING SOL'NS

SO STRANGE "WRINKLES" IN "Λ" STRAIGHTEN OUT!

(B) HU'S MODEL $\quad \dot{\sigma} + 3\mathcal{H}\sigma = \frac{c_V^2}{Hw}\left(\theta + \frac{1}{2}\dot{h} + 3\dot{\eta}\right)$

$$\to (1+w)\sigma \simeq \frac{1}{a^3}\int d\tau\, a^3 c_V^2 \left(\theta + \tfrac{1}{2}(\dot{h} + 6\dot{\eta})\right)$$

METRIC PERT'NS PERSIST ↵ TO DRIVE δ ?

GENERAL LINE OF INQUIRY — CONSTRAIN DARK ENERGY SOUND SPEED

IMPRINT : LARGE ANGLE CMB

V. LARGE SCALE POWER

↳ LENSING ?

SOME REFS. ERIKSON ET AL, PRL 88 121301 (2002)

DEDEO ET AL, PRD 67 103509 (2003)

BEAN & DORÉ, PRD 69 083503 (2004)

HANNESTAD, PRD 71 103519 (2005)

HARD TO CONSTRAIN !

CURVED SPACE QFT

MODELS OF DARK ENERGY

PARKER & RAVAL, PRD 60 063512 (1999)

NON-PERTURBATIVE EFFECTS DUE TO RENORMALIZED STRESS-ENERGY TENSOR OF A MASSIVE SCALAR FIELD

$$W = \int d^4x \sqrt{-g} \left[\kappa_0 R - 2\kappa_0 \Lambda + (\alpha_1 R^2 + \alpha_2 R_{\mu\nu} R^{\mu\nu} + \alpha_3 R_{\alpha\beta\gamma\delta} R^{\alpha\beta\gamma\delta}) - \frac{1}{64\pi^2} R_2 \ln\left(\frac{M^4 + \epsilon^2}{m^4} \right) \right]$$

m = SCALAR FIELD MASS

$M^2 = m^2 + \xi R$, $\xi = \zeta - \frac{1}{6}$

$\Box\phi = (m^2 + \zeta R)\phi$

R_2 QUADRATIC FUNCTION OF CURVATURE R^2, $R_{\mu\nu}^2$, $R_{\mu\nu\alpha\beta}^2$, $\Box R$, etc

PARKER & RAVAL :

EQ'NS OF MOTION HAVE A POLE AT $R = m^2$ —

CURVATURE IS FORCED TO A CONSTANT (à la dS)

HOWEVER, $w_{TOTAL} = -1$ SO $w_{eff} \to -1$ FROM BELOW!

& $\left|\frac{dw}{da}\right|$ IS BIG (TOO BIG TO MATCH OBS.)

SEE CALDWELL et al, PRD 73 023513 (2006)

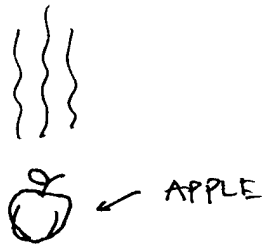
OTHER CS QFT MODELS?

ONEMLI & WOODARD, PRD 70 107301 (2004)

ANTONIADIS, MAZUR, MOTTOLA, NEW JOURNAL PHYS., 9, 11 (2007)

GRAVITY ?

PERHAPS DARK ENERGY PHENOMENA
IS DUE TO A DEPARTURE FROM GR?



FRIEDMANN EQ'N : $3H^2 = 8\pi G(\rho_{M,R} + \rho_{DE})$

① SLOWING DECAY OF H^2, DUE TO ACCELERATION

② MAY NOT BE CAUSED BY THE ONSET OF A NEW FLUID COMPONENT.

③ BUT IS CAUSED BY AN INCREASE IN NEWTON'S CONSTANT, AS IT APPEARS IN THE ENERGY DENSITY EQUATION.

④ WHAT ABOUT Λ?

⑤ AND CAN'T I ALWAYS FORCE OBSERVATIONS TO FIT THE FRIEDMANN EQ'N WITH SOME DARK ENERGY?

SPECULATE : $G = G(\phi)$
DYNAMICS OF ϕ (OR OTHER FIELDS)
CAUSE THE NEW GRAVITATIONAL PHENOMENA

PERHAPS GR IS JUST AN INTERMEDIATE THEORY!

SCALAR-TENSOR GRAVITY

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} f(\phi) - \tfrac{1}{2}(\nabla\phi)^2 - V(\phi) + L_M(g_{\mu\nu}, \Psi)\right]$$

BEWARE OF CONFORMAL TRANSFORMATIONS

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

$$S = \int d^4x\sqrt{-\tilde{g}}\left[\frac{\tilde{R}}{16\pi G} - \tfrac{1}{2}(\nabla\tilde{\phi})^2 - V(\tilde{\phi}) + L_M(\tilde{g}_{\mu\nu}, \Psi, \tilde{\phi})\right]$$

VARIATION WITH RESPECT TO $g_{\mu\nu} \neq \Gamma^\alpha_{\mu\nu}$ { see Li et al, arXiv: 0805.3428 or FLANAGAN, PRL 92 071101 (2004)

TWO WIDELY-STUDIED CLASSES OF MODELS

A) "EXTENDED QUINTESSENCE"

$$S = \int d^4x\sqrt{-g}\left[f(R,\phi) - \tfrac{1}{2}\omega(\phi)(\nabla\phi)^2 - V(\phi) + L_M(g_{\mu\nu}, \Psi)\right]$$

PERROTTA et al, PRD 61 023507 (2000) and MANY MORE!

INVESTIGATE: SOLAR SYSTEM CONSTRAINTS

SNe vs. $G(\phi)$

CMB, LSS, ...

MUST LOOK A LOT LIKE GR+Λ !?

B) "$f(R)$" KICKOFF: CARROLL et al, PRD 70 043528 (2004)

$$S = \int d^4x \sqrt{-g} \left[f(R) + L_M \right]$$

1) THIS IS EQUIVALENT TO BRANS-DICKE THY. WITH $\omega_{BD} = 0$

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} F(\phi) + \omega_{BD} (\nabla\phi)^2 - V(\phi) + L_M \right]$$

ω_{BD} → ZERO

ϕ IS JUST A CONSTRAINT, $\phi = \phi(R)$.

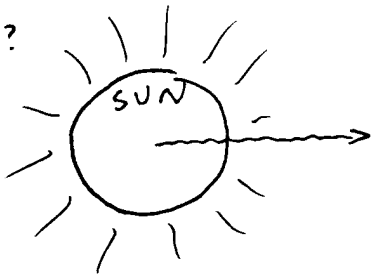
2) $\omega_{BD} = 0$ MEANS $\gamma_{PPN} = \frac{1}{2}$ WHICH IS RULED OUT!

SEE CHIBA, PLB 575 1 (2003)

CONSTRAINTS, EVASION! CHIBA et al, PRD 75 124014 (2007)

ERICKCEK et al, PRD 74 121501 (2006)

SCHWARZSCHILD IN $f(R)$?



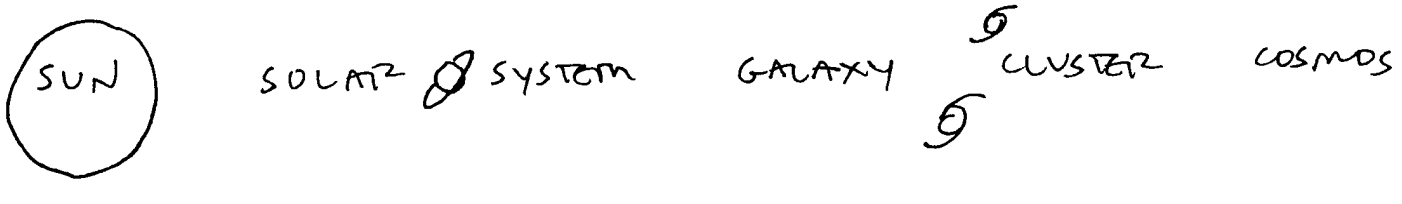
$R=0$?

(JUST LIKE E&M!)

EXTERIOR GEOMETRY MUST MATCH ONTO INTERIOR SOLN, S.T. $R \neq 0$ OUTSIDE SUN!

NEW $f(R)$ – GRAVITY FIELD EQNS INCLUDE GAIN FOR R.

R(SOLAR SYSTEM) $\neq$ R(COSMOLOGY)



HU & SAWICKI, PRD 76 064004 (2007)

3) EXCITEMENT? $f(R) = \frac{1}{16\pi G}(R - M/R^n)$

SMALL R → NOVEL BEHAVIOR

$n > 0$ ATTRACTOR BEHAVIOR: ACCELERATION

UNFORTUNATELY, DURING MATTER-DOMINATED ERA

PRIOR TO ACCELERATION

$a(t) \propto t^{1/2}$ NOT $t^{2/3}$ RUINS CMB, LSS!

AMENDOLA et al, PRL 98 131302 (2007)

DEPARTURE FROM GR : PHENOMENOLOGY

1. REMOVE DARK ENERGY (DISREGARD CCP)
2. MODIFY G, POTENTIALS ϕ, Ψ

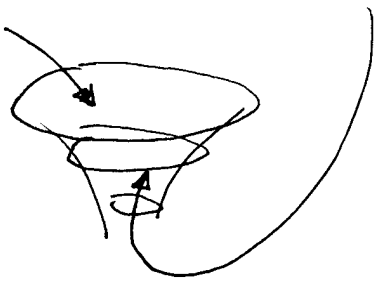
   SATISFY SOLAR SYSTEM CONSTRAINTS, $|\phi/\Psi - 1| \ll 1$

   DOES COSMOLOGY FIT?

REMARK - MANY SCALAR-TENSOR THEORIES PREDICT $\phi \neq \Psi$ IN THE PRESENCE OF N.R. MATTER

$$ds^2 = a^2(\tau)\left[-(1+2\Psi)\,d\tau^2 + (1-2\phi)\,d\vec{x}^2\right]$$

$$\vec{a}_g = -\vec{\nabla}\Psi \quad , \quad \nabla^2\phi = 4\pi G \delta\rho$$



VARIATION IN THE AMOUNT OF CURVATURE PER UNIT MASS

HOW TO BUILD A THEORY OF GRAVITY (WITHOUT A LAGRANGIAN)

1. ASSUME BKGD IS ΛCDM

   eg EFFECTS OF NON-GR GRAVITY MIMIC Λ.

2. IMPOSE $\phi \neq \Psi$ $\rightarrow$ $\Psi = (1+\tilde{w})\phi$

   NOT TOO DIFFERENT THAN QUINTESSENCE w,

   THIS NEW VARIABLE PARAMETERIZES OUR IGNORANCE!

   DESIRE $|\tilde{w}| \ll 1$ IN SOLAR SYSTEM

   BUT $|\tilde{w}| \sim \mathcal{O}(1)$ ON HUBBLE SCALE

WHAT TO EXPECT

IN GR $\quad k^2\phi \simeq -4\pi G \delta\rho$

$\frac{1}{3}k^2(\phi-\Psi) \simeq 4\pi G \delta\rho$

$$\frac{\Psi-\phi}{\phi} \simeq \frac{3\delta\rho}{\delta\rho} = \tilde{w}$$

EXPECT $\tilde{w} \sim \pm 3\Omega_{DE}$

3. PERTURBATION EQUATIONS

DISCARD LINEARIZED EINSTEIN EQNS

BUT CAN ASSUME NEW GRAVITY DOES NOT

MIMIC NEW MOMENTUM FLOW — MATTER (D, B)

SETS THE ONLY PREFERRED FRAMES!

SO KEEP "t-i" EQN

$$k^2(\dot{\phi} + \mathcal{H}\Psi) = 4\pi G a^2 (\rho + p)\theta$$

↳ DUE TO MATTER, RAD'N.

SLIP BETWEEN ϕ & Ψ CAN ALSO ARISE FROM SHEAR, σ

SO ALLOW

$$k^2(\phi - \Psi) = 12\pi G a^2 (\rho + p)\sigma - k^2 \bar{w}\phi$$

AND IMPLEMENT k, τ - DEPENDENCE FOR $\bar{w}$

SEE BERTSCHINGER, ApJ 648 797 (2006)
CALDWELL et al, PRD 76 023507 (2007)
DANIEL et al, PRD 77 103513 (2007)

VERSATILITY

SCALAR–TENSOR THY.

$$S = \int d^4x \sqrt{-g} \left[\frac{f(\varphi, R)}{16\pi G} - \frac{1}{2}\omega(\varphi)(\nabla\varphi)^2 - V(\varphi) + L_M \right]$$

$$\text{THEN} \quad \Psi - \phi = -\left(\frac{\partial f}{\partial R}\right)^{-1}\left[\frac{\partial^2 f}{\partial\varphi\,\partial R}\,\delta\varphi + \frac{\partial^2 f}{\partial R^2}\,\delta R\right]$$

$$= \omega\phi$$

SEE ACQUAVIVA et al, PRD 70 023515 (2004)

SCHIMD et al, PRD 71 083512 (2005)

DGP GRAVITY

DVALI et al, PLB 485 208 (2000)

$$S = \int d^5x \sqrt{-g} \left[\frac{{}^{(5)}R}{16\pi G_5} + \delta(\chi) \left(\frac{{}^{(4)}R}{16\pi G_4} + \mathcal{L}_M \right) \right]$$

$r_c = \frac{1}{2} \frac{G_5}{G_4}$ CHARACTERISTIC SCALE: COSMIC!

$\rightsquigarrow$ IN 4D $\quad H^2 - \frac{H}{r_c} = \frac{8\pi G_4}{3} \rho$

$H =$ CONSTANT IS A SOLUTION!

$w = \frac{2}{3\beta - 1}$, $\quad \beta = 1 - 2 r_c H \left(1 + \frac{\dot{H}}{3H^2} \right)$

(NOT ZERO!)

SEE LUE, PHYSICS REPORTS 423, 1 (2006)

SONG et al, PRD 75 064003 (2007)

MASSIVE GRAVITY

SEE DUBOVSKY, JHEP 0410:076 (2004)

LORENTZ-VIOLATING MASSIVE GRAVITY

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} + F(X, \phi) + \mathcal{L}_M \right]$$

"F" LEADS TO DM, DE-LIKE CONTRIBUTIONS TO FRIEDMANN EQ'N

PREDICTS $\phi - \psi = \theta(x)\, a^n$

a^n: PARAMETER OF THY

$\theta(x)$: SPATIAL FUNCTION SET BY INITIAL CONDITIONS

SEE BREBONNE & TINYAKOV, PRD 76 084011 (2007)

PHENOMENOLOGICAL MODEL

$$\Psi(k,t) = \Psi_0 \frac{\Omega_{DE}(t)}{\Omega_M(t)}$$

EXPECT $\Psi_0 \sim \pm 1$

ALT. MODEL?

$$1 + \Psi = \frac{1}{\gamma_{PPN}} a^{\beta}$$

BERTSCHINGER + ZUKIN, arXiv: 0801.2431

HU & SAWICKI, PRD 76 104043 (2007)

CONSEQUENCES: CMB — CHANGE ISW ($\dot{\phi} + \dot{\psi}$)

LSS — AMPLITUDE

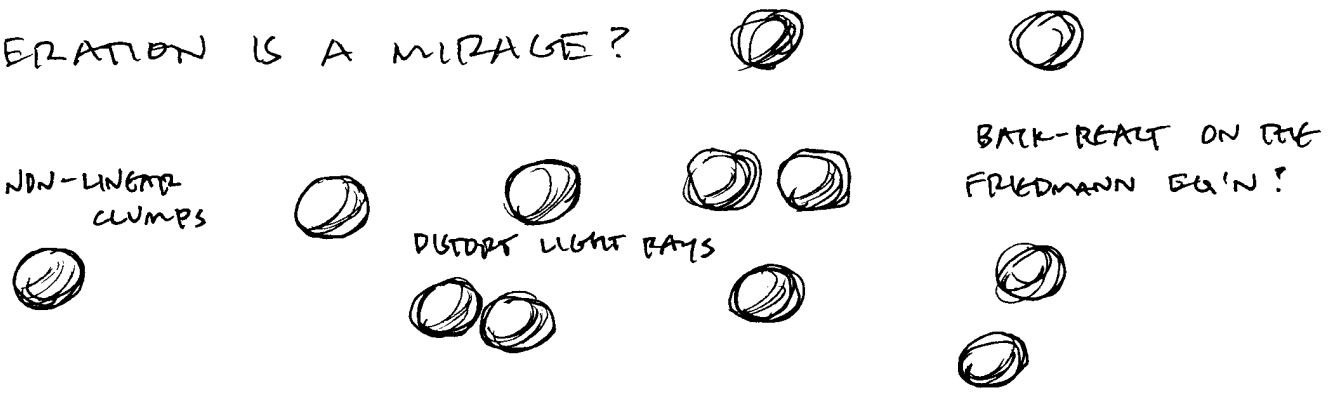
RATE OF GROWTH

LENSING ($\phi + \psi$)

CURRENT OBSERVATIONS: $-0.5 \leq \Psi_0 \leq 0.25$ ($\sim 2\sigma$)

IS DARK ENERGY REALLY THERE?

ACCELERATION IS A MIRAGE?



CAN SUPERHORIZON COSMOLOGICAL PERTURBATIONS EXPLAIN THE ACCELERATION?

BUT $\delta \sim 10^{-5}$ AT $k \sim H$ IN STD. INFLATIONARY MODEL

HIRATA & SELJAK, PRD 72 083501 (2005)

ISHIBASHI & WALD, CQG 23 235 (2006)

LARGE SCALE STRUCTURE DOES DISTORT LIGHT RAYS — LENSING DEFLECTION, MAGNIFICATION

FRIEMAN, astro-ph/9608068

BONVIN et al, PRD 73 023523 (2006)

DISTANCES & REDSHIFTS

INTEGRATE GEODESIC EQ'N: { SEE GARFINKLE, CQG 23 4811 (2006)
GARCIA-BELLIDO et al, JCAP 0804:003 (2008)

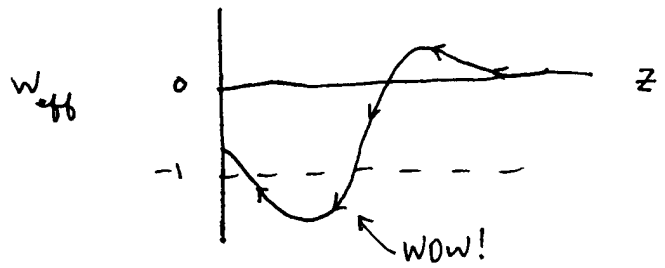
SAMPLE MODEL

INSIDE, AT CENTER $\Omega_M = 0.2$, $H_0 = 70$ km/s/Mpc

OUTSIDE, FAR AWAY $\Omega_M = 1$, $H_0 = 35$ km/s/Mpc

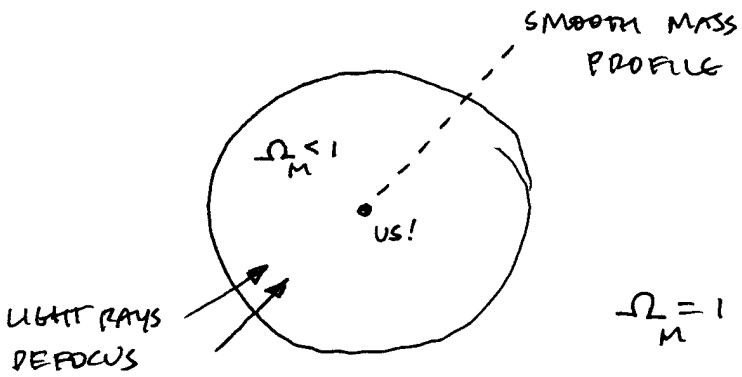
RECALL BARTLETT et al, SCIENCE 267 980 (1995)

NO ACCELERATION, BUT INTERPRET LUMINOSITY DISTANCE VS. REDSHIFT AS IF IN FRW W/ DARK ENERGY



ALTERNATIVE SCENARIO

WE RESIDE AT THE CENTER OF A DEEP VOID — COSMIC ACCELERATION IS A MIRAGE



NO DARK ENERGY

NO ROBERTSON–WALKER METRIC

LEMAITRE–TOLMAN–BONDI

$$ds^2 = -dt^2 + \frac{(\partial_r R)^2}{1 + K(r) r^2} dr^2 + R^2(t,r) d\Omega^2$$

$K(r) = K_0 / (1 + (r/r_0)^2)$ CURVATURE FCN

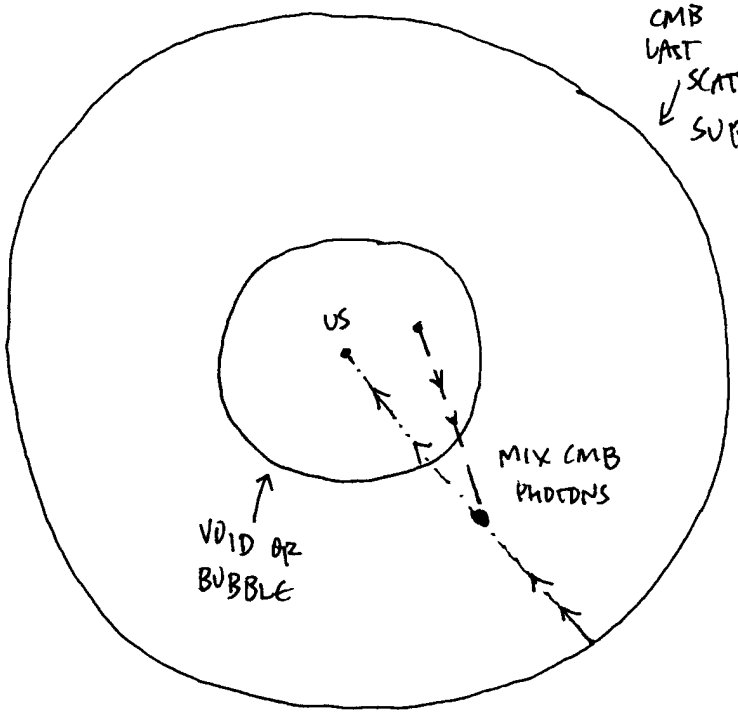
$R(t,r)$ radially-dependent scale factor

RATE OF EXPANSION ALONG RADIAL, TRANSVERSE DIRECTIONS IS DIFFERENT! H_R, H_T

"LTB" MODEL CAN SATISFY LUMINOSITY DISTANCE – REDSHIFT CONSTRAINTS FROM SNe, BAO, CMB ✓

CMB ANISOTROPY CANNOT "SEE" VOID

BUT CMB SPECTRUM WOULD BE DISTORTED FROM BLACKBODY



CALDWELL & STEBBINS,
PRL 100 191302 (2008)

SUFFICIENT TO RULE OUT THESE MODELS!

COBE FIRAS : $y < 15 \times 10^{-6}$ (95% CL)

FUTURE ? INTERPLAY BETWEEN THY & EXPT.

MANY EXPERIMENTS & OBSERVATIONAL PROGRAMS
AIMING AT DARK ENERGY

SOURCE : "DARK ENERGY TASK FORCE"
http://www.nsf.gov/mps/ast/detf.asp

OBSERVATIONAL METHODS : SNe, BAO, WEAK LENSING, CLUSTERS

WHICH IS BEST? ATTEMPT TO DISCRIMINATE WITH "FIGURE OF MERIT"

"STAGE III" SMALL, FAST, INEXPENSIVE, CURRENTLY PROPOSED

"STAGE IV" FUTURE, EXPENSIVE, AUTHORITATIVE

* LSST (MAP THE SKY EVERY NIGHT) YEAR: 2013?
~8m TELESCOPE W/ HUGE CAMERA

* JDEM dark energy satellite, eg SNAP
PROPOSALS IN 2008/9 ?

INTERESTING TOPICS NOT DISCUSSED

HOW TO BEST MEASURE COSMIC PARAMETERS

EXTRA DIMENSIONS, BRANE WORLDS

QUINTESSENTIAL INFLATION

QUANTUM COSMOLOGY, GRAVITY

HOLOGRAPHY & Λ

PRE-BIG BANG, CYCLIC, EKPYROTIC SCENARIOS