"A" theoretical view
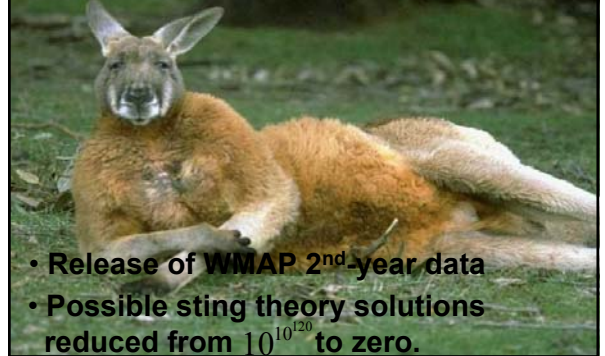
December 13–17, 2004

22nd TEXAS SYMPOSIUM

on Relativistic Astrophysics at

STANFORD UNIVERSITY

Rocky Kolb
Particle Astrophysics Center, Fermilab
& University of Chicago

Visions of the future
Melbourne 11–15 December 2006

- Release of WMAP 2nd-year data
- Possible sting theory solutions reduced from $10^{10^{120}}$ to zero.

---

via della Fisica

viale dell'Astronomia

ACS, ACT, AGASA, AGN, AMI, APEX, AXPs, BaBar, BLLac, CAST, CDMS, CELESTE, CIV, CMB, CON-X, CP, CPT, DAMA, DEEP2, EeV, EUSO, GALEX, GLAST, GOODS, GR, GRBs, GPB, GRB, HII, HESS, HETE, HST, IGM, JWST, KKLT, LIGO, LISA, LOPES, LLR, MHD, MSW, NICMOS, PBHs, PREX, QPOs, QUAD, RXTE, SALT, SGRs, SDSS, SNeIc, SPT, SNeIa, SZE, 2dFGRG, SNeII, UHCRs, VLA, VLBI, WIMPS, WMAP, XMM, …

WMAP cosmological parameters

$\Omega_{tot} = 1.02\,^{+0.02}_{-0.02}$ $n_s = 0.93\,^{+0.03}_{-0.03}$
$w < -0.78$ (95% CL) $dn/d\ln k = -0.031\,^{+0.016}_{-0.016}$

Greater accuracy if combine with other data
- CMB
- 2dFGRS
- SDSS
- Ly-α

Priors • Consult entrails of chickens, prophecies of Nostradamus, & the Kabbalah

$\sigma_8 = 0.84\,^{+0.04}_{-0.04}$ Mpc $a_A = 14.0\,^{+0.5}_{-0.3}$ Gpc
$\sigma_8 \Omega_m^{0.5} = 0.44\,^{+0.04}_{-0.05}$ $l_A = 301\,^{+1}_{-1}$
$A = 0.833\,^{+0.086}_{-0.083}$ $r_s = 147\,^{+2}_{-2}$ Mpc

What we "know": ΛCDM

Dark Energy 73%

Cold Dark Matter 23%

Atoms 4%

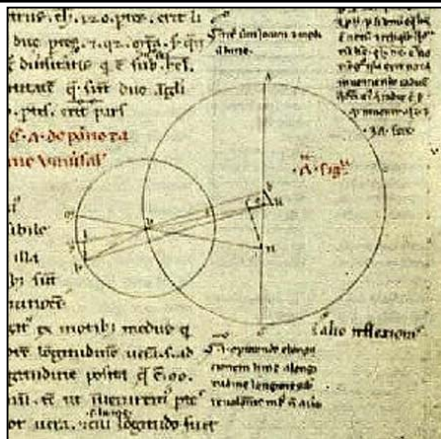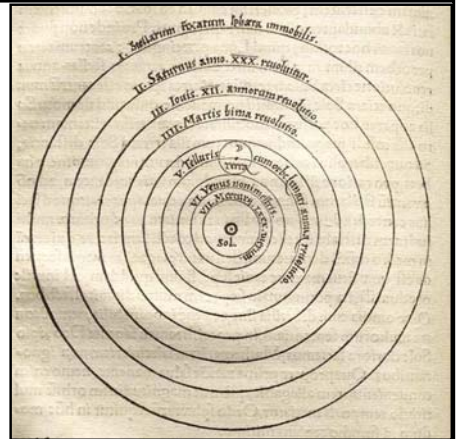## Mission accomplished …

… or premature jubilation?

A standard cosmological model

- Visible Baryons
- Radiation
- Dark baryons
- Neutrinos
- Dark matter
- Dark energy
- Inflation
- Baryogenesis
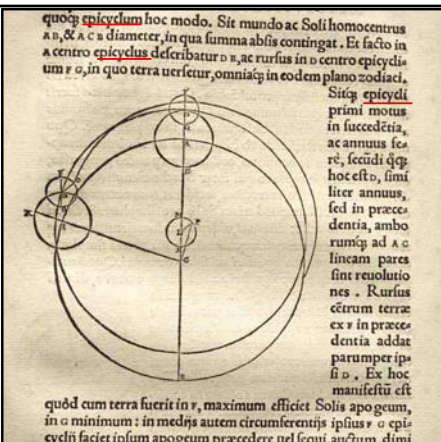
- Hypotheses?
- Saving the appearances?
- Epicycles?

Ptolemaic System from The Almagest

From Book I of De Revolutionibus

From Book III of De Revolutionibus

What Copernicus "Knew"

"First of all, we must note that the universe is spherical."
Elliptical orbits!

Motions are centered on the sun
Sun at a focus!

Uniform velocities
Equal areas in equal times!

What Kepler "Knew"

Gravity is an inverse-square force
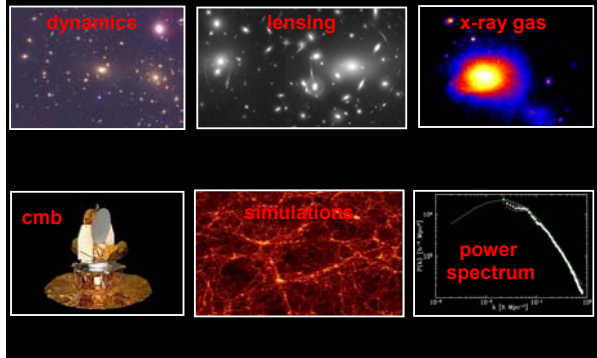*Kepler thought it was repulsive!*

…

…

…

What We "Know"

1) The baryon asymmetry arises in the GUT or EWK era through B, CP, and nonequilibrium (Sakharov)
   EWK doesn't seem to work….GUT scenarios not simple!

2) The matter density is dominated by cold dark matter …
   which we know nothing about!

3) The perturbations arise from inflationary dynamics, which depends on particle physics at high energies …
   which we know nothing about!

4) The universe is dominated by a cosmological term (dark energy, phantom energy, quintessence, polenta, cosmological constant, cosmo-illogical constant, ….) …
   which we know less than nothing about!
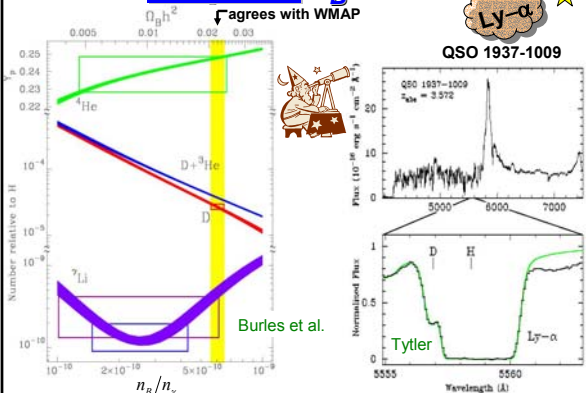

Dark matter Epicycle
What is dark matter?

"In questions like this, truth is only to be had by laying together many variations of error."
— Virginia Woolf

Matter $\Omega_M \sim 0.3$

dynamics   lensing   x-ray gas

cmb   simulations   power spectrum

Baryons $\Omega_B \sim 0.04$

agrees with WMAP

$\Omega_B h^2$

Ly–α

QSO 1937-1009

^{4}He

$D+^3$He

D

^{7}Li

Burles et al.

n_B / n_γ

Tytler

Modified Newtonian dynamics

Velocity = Mass x Acceleration

Top left panel:

Sadoulet
Witten

Top down
(string inspired)

Dark Matter Workshop

Bottom up
(phenomenology
perspired)

Top right panel:

Cold thermal relics

Relative abundance

10^0
10^{-5}
10^{-10}
10^{-15}
10^{-20}

freeze out

actual

Ω_X

equilibrium
$e^{-M/T}$

1 10^{-1} 10^{-2} 10^{-3}

T/M_X

$\Omega_X \propto \sigma_A^{-1}$ *(independent of mass)*

Middle left panel:

Cold thermal relics $\Omega_X \propto \langle \sigma_A v \rangle^{-1}$

$\Omega_X \Rightarrow \sigma_A$

$X + \bar{X} \rightarrow q + \bar{q}$

$\Omega_X \Rightarrow \sigma_S$

$X + q \rightarrow X + q$

$\Omega_X \Rightarrow \sigma_P$

$q + \bar{q} \rightarrow X + \bar{X}$

Goodman & Witten

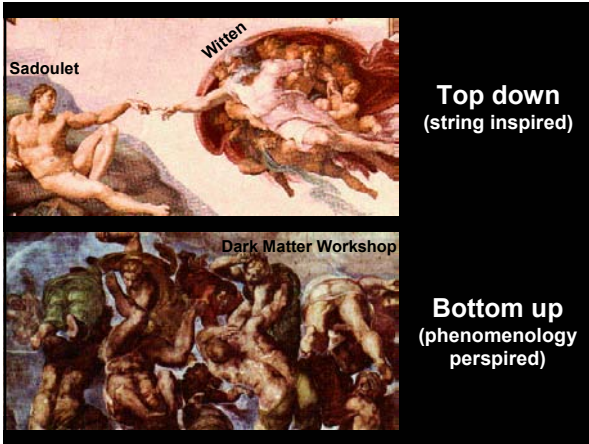**Middle right panel:**

Cold thermal relics

- **SUSY LSP (neutralino)**
- **Direct detection (σ_S)**
  More than a dozen experiments
- **Indirect detection (σ_A)**
  Annihilation in sun, Earth, galactic center, subclumps, . . .
  Neutrinos, positrons, antiprotons, γ rays, . . .
  (Role of halo substructure?)
- **Production at accelerators (σ_P)**

Bottom left panel:

The nature of dark matter is a complex natural phenomenon.

The neutralino is a simple, elegant, compelling explanation.

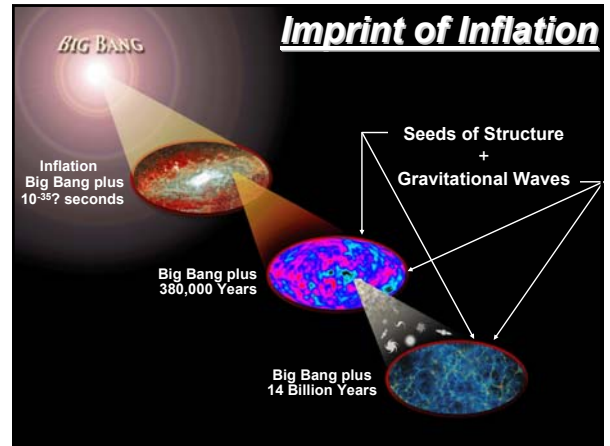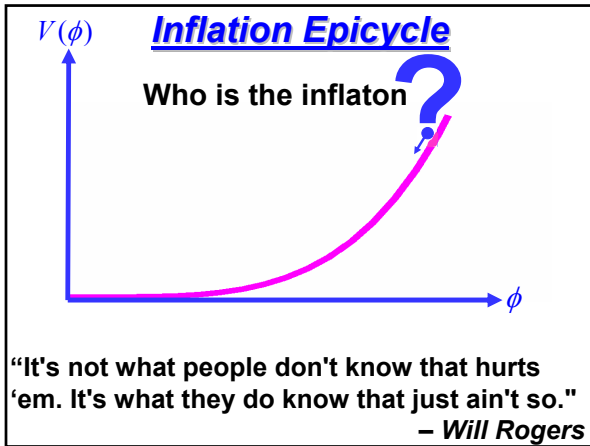**"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."**

– Tommy Gold

Bottom right panel:

Many variations of error

- **neutrinos** — **(hot dark matter)**
- **sterile neutrinos, gravitinos** — **(warm dark matter)**
- **LSP (neutralino, axino, …)** — **(cold dark matter)**
- **LKP (lightest Kaluza–Klein particle)**
- **axions, axion clusters**
- **solitons (Q–balls; B–balls; Odd–balls, Screw balls….)**
- **supermassive wimpzillas**

Mass range	Interaction strength range
10^{-6} eV $(10^{-40}$ g$)$ axions	Noninteracting: wimpzillas
10^{-8} $M_\odot$ $(10^{25}$ g$)$ axion clusters	Strongly interacting: B balls

Inflation Epicycle

$V(\phi)$

Who is the inflaton?

ϕ

"It's not what people don't know that hurts 'em. It's what they do know that just ain't so."
– Will Rogers

Imprint of Inflation

BIG BANG

Inflation
Big Bang plus
10^{-35}? seconds

Big Bang plus
380,000 Years

Seeds of Structure
+
Gravitational Waves

Big Bang plus
14 Billion Years

Comparison to observation:

1. a (<u>nearly</u> exact) *power-law*
2. spectrum of *gaussian*
3. *super-Hubble-radius*
4. *scalar* perturbations (seeds of structure) &
5. *tensor* perturbations (gravitational waves)
6. related by a *consistency relation*
7. in their *growing mode*
8. in a *spatially flat* universe.

Models of inflation

old, new, pre-owned,
chaotic, quixotic, ergodic,
ekpyrotic, autoerotic,
brane gas, bran gas, brain-less
faith-based, free-based,
supersymmetric, supercilious,
natural, supernatural, *au natural,*
hybrid, low-bred, white bread,
one-field, two-field, left-field,
eternal, internal, infernal,
self-reproducing, self-promoting,
dilaton, dilettante, …….

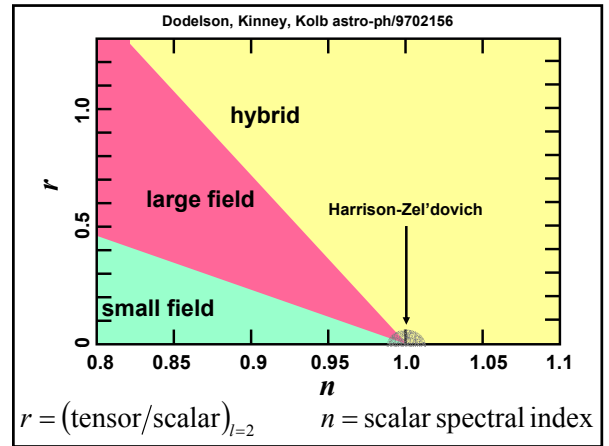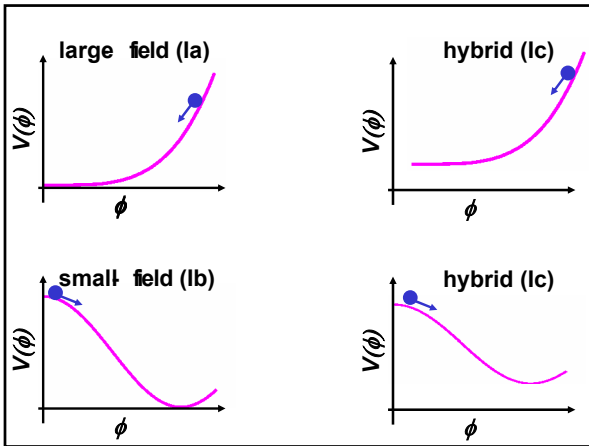## Complete list of known fundamental scalar fields (from Particle Data Book):

Model Classification*

Type I: single-field, slow-roll models
(or models that can be expressed as such)

   Type Ia: large-field models
   Type Ib: small-field models
   Type Ic: hybrid models

Type II: anything else
(pre-big bang, ekpyrotic, warm,
branes, brane gas, bran gas, etc.)

Used for superstrings, supernovae, superconductors, …

large field (Ia)

$V(\phi)$

ϕ

hybrid (Ic)

$V(\phi)$

ϕ

small field (Ib)

$V(\phi)$

ϕ

hybrid (Ic)

$V(\phi)$

ϕ

Dodelson, Kinney, Kolb astro-ph/9702156

hybrid

large field

Harrison-Zel'dovich

small field

r

n

$r = (\text{tensor/scalar})_{l=2}$ $n = \text{scalar spectral index}$

Harrison-Zel'dovich Spectrum ?

$n=1?, \ n'=0?, \ r=0?$

• Combine CMB, LSS, Ly α
• Tensor modes?
• What about beyond the horizon?

Issues

1. Who is the inflaton?
   • models of inflation, reconstruction?
2. Transplanckian physics?
   • probe of short-distance physics?
3. Defrosting?
   • preheating, reheating, ….?
4. Extra dimensions, brane, bulk, etc.?
   • new dynamics?
5. Other particle production?
   • WIMPZILLAS, gravitons, ….?
6. Are perturbations from the inflaton fluctuations?
   • curvaton, modulon, …

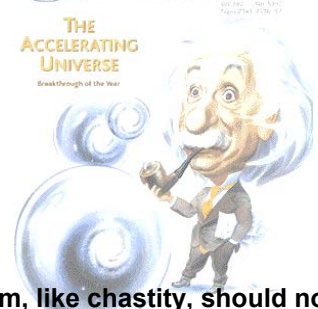The nature of inflation is a complex natural phenomenon.

Single-field, slow-roll inflation is a simple, elegant, compelling explanation.

"For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation."
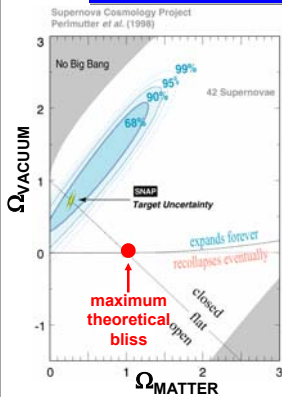
- Tommy Gold

Dark Energy Epicycle

Is there dark energy?

THE ACCELERATING UNIVERSE
Breakthrough of the Year

"Skepticism, like chastity, should not be relinquished too readily." – *G. Santayana*

Reason #3: dark energy

Supernova Cosmology Project
Perlmutter et al. (1998)

High-z SNeIa are fainter than expected in an Einstein-deSitter model

… a cosmological constant

… or some changing non-zero vacuum energy,

… or some unaccounted for systematic effect(s)

Six reasons I hate observers

Issue, Mystery, or Problem?

The Dark Energy *Issue*

The Dark Energy *Mystery*

The Dark Energy *Problem*

Problem: the magnitude of Λ:

The unbearable lightness of nothing:

$$\rho_\Lambda \simeq 10^{-30}\,\text{g cm}^{-3} \simeq \left(10^{-4}\ \text{eV}\right)^4 = \left(10^{-3}\ \text{cm}\right)^{-4}$$

$$\Lambda = 8\pi G\rho_\Lambda = \left(10^{29}\ \text{cm}\right)^{-2} = \left(10^{-33}\ \text{eV}\right)^2$$

Cosmo-illogical constant?

Numerology:

$$\rho_V = M_Z^4 \exp\left(-2/\alpha\right) \qquad \rho_V = M_{\text{SUSY}}^8 / M_{Pl}^4$$
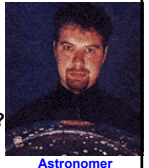
$$m_\nu = 10^{-3}\ \text{eV} \qquad R_5 = 10^{-4}\ \text{cm}$$

What do Martha Stewart and Adam Reiss have in common?

Martha Stewart

Adam Reiss

1. Convicted felons?
2. Standard candles?
3. Scented candles?
4. Organic herbs?
5. Relationship with Bob Kirshner?
6. Cosmic coincidence?

Homemaker

Astronomer

What do Martha Stewart and Adam Reiss have in common?

Martha Stewart

Adam Reiss

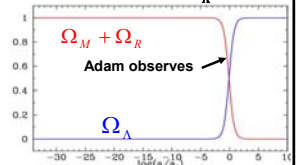**Cosmic coincidence!**

ImClone stock price

Evolution of Ω_Λ

$\Omega_M + \Omega_R$

Martha sells

Adam observes

Ω_Λ
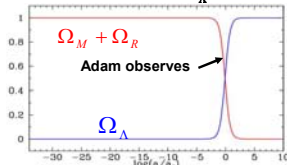
Cosmic Coincidences

• **Should be regarded with skepticism**
• **Require an explanation**
• **Must be investigated**
• **Prosecution of guilty parties (if wrongdoing)**
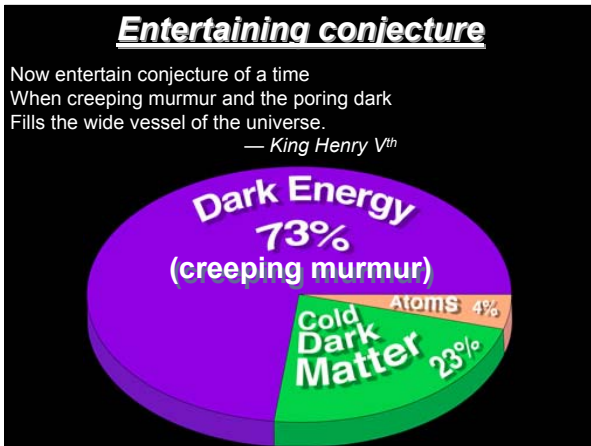
ImClone stock price

Evolution of Ω_Λ

$\Omega_M + \Omega_R$

Martha sells

Adam observes

Ω_Λ

Practical tools for dark energy

scalar fields

anthropic principle

Entertaining conjecture

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.
— *King Henry V[th]*

Dark Energy
73%
(creeping murmur)

Atoms 4%

Cold Dark Matter 23%

Do we know there is dark energy?

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.
— *King Henry V[th]*

All evidence for creeping murmur (dark energy) is indirect!

SNIa
Age   : $\int \dfrac{dz}{H(z)}$
LSS

• We infer dark energy from time evolution of H.
• Observed time evolution of H does not fit Einstein–de Sitter.
• Naïve cosmologists infer existence of dark energy!
• Could Friedmann equation be modified?

Do we know there is dark energy?

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.
— *King Henry V[th]*

All evidence for creeping murmur (dark energy) is indirect!

SNIa
Age   : $\int \dfrac{dz}{H(z)}$
LSS

• We infer dark energy from time evolution of H.
• Observed time evolution of H does not fit Einstein–de Sitter.
• Naïve cosmologists infer existence of dark energy!
• Could Friedmann equation be modified?

How do we sort it out?

- Something is established – ΛCDM too good to ignore
  - SNIa
  - Subtraction
  - Age
  - Large-scale structure ⎫ $H(z)$ not given by Einstein–de Sitter cosmological model
  - …
- Dark energy (rhs of Einstein equations)?
  - Is it "just" a cosmological constant?
  - If not cosmological constant, what is dynamics?
  - interpretation of w
- Gravity (lhs of Einstein equations)?
  - Beyond Einstein (non-GR: branes,etc.)
  - Just GR (inhomogeneities, etc.)

Modifying the left-hand side

- Friedmann equation modified <u>today</u> *Freese & Lewis*
$$H^2 = A\rho\left[1+\left(\rho/\rho_{\text{cutoff}}\right)^{n-1}\right]$$
- Gravitational force law modified at large distance *Deffayet, Dvali & Gabadadze*
  Five-dimensional at cosmic distances
- Tired gravitons *Gregory, Rubakov & Sibiryakov Dvali, Gabadadze & Porrati*
  Gravitons metastable - leak into bulk
- Gravity repulsive at distance $R \approx$ Gpc *Csaki, Erlich, Hollowood & Terning*
- $n=1$ KK graviton mode very light, $m \approx$ (Gpc)$^{-1}$ *Kogan, Mouslopoulos, Papazoglou, Ross & Santiago*
- 3+1 Lorentz invariance broken in the IR *Chung, Kolb & Riotto*
- ultraviolet modes of perturbations *Räsänen*
- Infrared modes of inhomogeneities *Kolb, Matarrese, Notari & Riotto*

Braneless cosmology
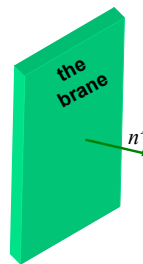
- Old Friedmann law

$$G_{00} = M_{Pl}^{-2}\, T_{00}$$
$$3H^2 = M_{Pl}^{-2}\, \rho$$
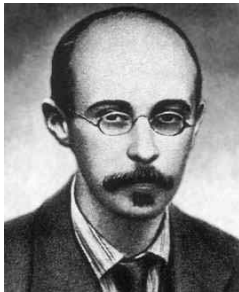
Friedmann (1921)

Brane cosmology

- Israel junction condition (Israel 1966)

  the brane

  n^A

  - n^A : unit vector normal to the brane
  - $h_{AB} = g_{AB} - n_A n_B$: the induced metric
  - $\kappa_{AB} = h_A{}^C \nabla_C n_B$: the extrinsic curvature

  $$\left[\kappa_{\mu\nu}\right] = -M_*^{-3} T_{\mu\nu}^{BRANE}$$

  $[....] = $ discontinuity across the brane

  $$a'' = \langle a''\rangle + [a']\delta(y)$$

  discontinuity in second derivative of scale factor

Brane cosmology

- New Friedmann law *Binetruy, Deffayet, Langlois (2000)*

$$H^2 = \frac{\Lambda}{6} + \frac{M_*^{-6}}{36}\rho^2 + \frac{c}{a^4(t, y=0)}$$

- Possible solution *Randall & Sundrum (2000)*

  Introduce a tension σ on the brane $\rho \to \rho + \sigma$

$$H^2 = \underbrace{\left(\frac{\Lambda}{6} + \frac{M_*^{-6}}{36}\sigma^2\right)}_{\substack{\text{cosmological}\\\text{constant}\\\text{(cancels?)}}} + \underbrace{\frac{M_*^{-6}}{18}\sigma\rho}_{\substack{\frac{M_*^{-6}}{18}\sigma = \frac{8\pi G}{3}\\\text{Friedmann}\\\text{equation}}} + \underbrace{\frac{M_*^{-6}}{36}\rho^2 + \frac{c}{a^4(t,y=0)}}_{\substack{\text{unconventional}\\\text{corrections}}}$$

Infrared modes of inhomogeneities

- $H(z)$ in a perturbed FLRW model:
$$G_{\mu\nu}\left(\vec{x},t\right) = G_{\mu\nu}^{\text{FLRW}}\left(t\right) + \delta G_{\mu\nu}\left(\vec{x},t\right)$$
$$G_{00}^{\text{FLRW}}\left(t\right) + \delta G_{00}\left(\vec{x},t\right) = \kappa^2 T_{00}\left(\vec{x},t\right)$$
$$3\left(\dot{a}/a\right)^2 = \kappa^2\left(\langle\rho\rangle - \kappa^{-2}\langle\delta G_{00}\rangle\right)$$
- $(\dot{a}/a)^2$ <u>is not</u> $\kappa^2\langle\rho\rangle/3 \equiv H^2$.
- $G_{00} \propto \varphi\nabla^2\varphi$
- Inflation produces φ such that today in our Hubble volume:
  - $\langle\nabla^2\varphi\rangle/a^2H^2 = 10^{-5}$
  - $\langle\varphi\rangle = 10^5$
  - $\langle\delta H\rangle \propto \langle\varphi\nabla^2\varphi\rangle/a^2H^2 \sim \mathcal{O}(1)$
  - observed $H(z)$ explained by inhomogeneities
  - there is no "dark energy" – $\Omega_M = 0.3$ & flat universe
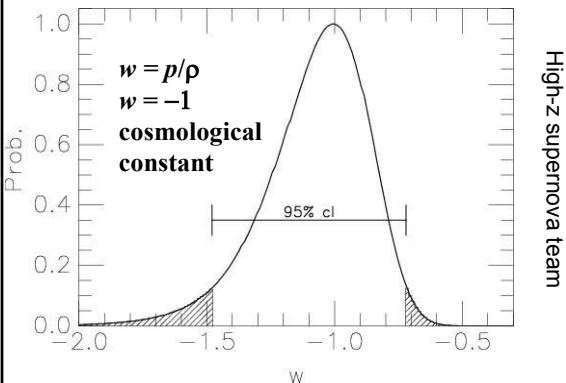
Advantages

- Proves anthropic principle is useless—even worse, it leads to wrong results.

- Just involves GR—no cosmo-illogical constant, extra dimensions, branes, quintessence, modified GR, 10^{-33} eV mass scalars, new long-range forces, Lorentz violation, or other such totally lame ideas.

- $\langle \delta\theta \rangle \sim \delta\rho/\rho$: accounts for cosmic coincidence:
  - modified $H(z)$ driven by $\delta\rho/\rho$

- In principle evolution of $\langle \delta\theta \rangle$ can be calculated in terms of inflation parameters that determine n and N_{TOTAL}:
  - *can see beyond the horizon!!*

- Can imagine a fixed point in modification of $H(z)$:
  - in matter era correction increases as $\delta\rho/\rho$ grows
  - increased expansion rate cuts off growth of $\delta\rho/\rho$
  - perhaps can even predict Ω_M

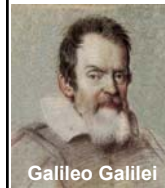## *Disadvantages*

- Not connected to microphysics.
- "Dark Energy" sounds really cool.

(But seeing beyond the horizon is way cool!)
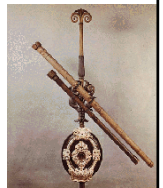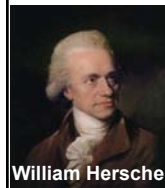
Dark energy parameter, w

$w = p/\rho$
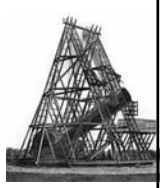$w = -1$
cosmological constant

95% cl

High-z supernova team

Medicean stars

Galileo Galilei + Cosimo II →

Georgium sidus

William Herschel + George III →

Dark energy parameter, w

Dubya

w + George II →

How do we sort it out?

Nature's nice	Nature's a bitch
• **Neutralino dark matter:**	• **Wimpzilla dark matter:**
Direct detection	*Only gravitational interactions*
Indirect detection	*No direct or indirect detection*
Accelerator production	*No accelerator production*
• **Inflation dynamics:**	• **Inflation dynamics:**
Departure from H-Z	*H-Z – no dynamics?*
Gravitational waves	*Mass scale too small for tensors*
• **Dark energy:**	• **Dark energy:**
w differs from -1	*w = -1 – it's just a number!*

How to test idea?

- Time evolution of H (in matter era, perturbative result $\rightarrow w = -5/6$).
  - Require nonperturbative results?
  - Need 3rd–order calculation?
  - Averaging and evolution do not commute.

- Other effects.
  - Only non-Newtonian?
  - Consistent cosmology?
  - Weak lensing?
  - Propagation of gravitational waves?

- Help!