

# *Dark Matter and Dark Energy*

**Rocky I:** Evidence for dark matter and dark energy

**Rocky II:** Dark matter candidates

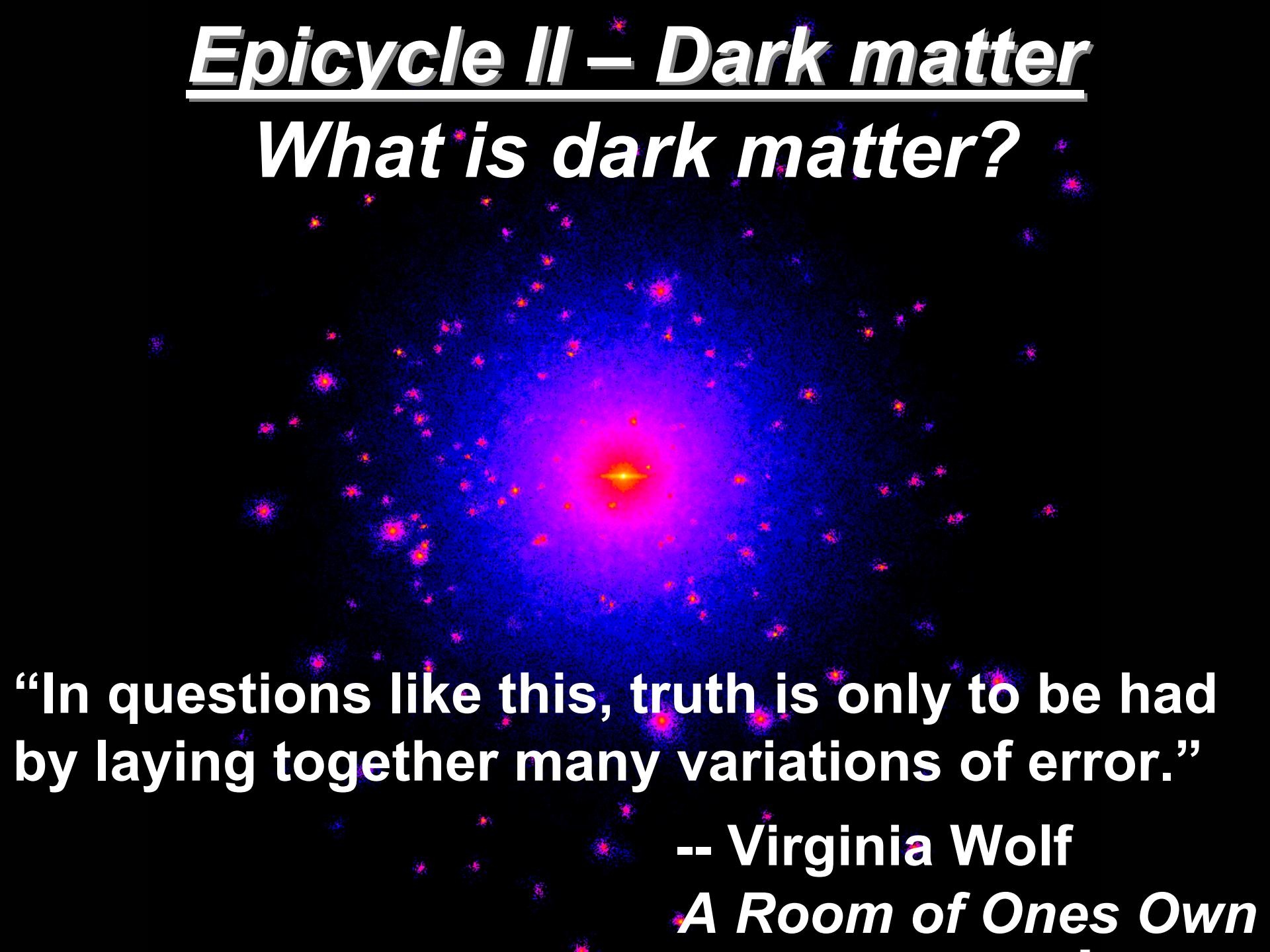
**Rocky III:** Dark energy ideas

SLAC Summer Institute, August 2003

*Rocky Kolb, Fermilab & The University of Chicago*

# Epicycle II – Dark matter

## *What is dark matter?*

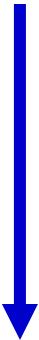


**“In questions like this, truth is only to be had  
by laying together many variations of error.”**

-- Virginia Wolf  
*A Room of One's Own*

# Particle Dark Matter Candidates

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, sneutrino, ...) (cold dark matter)
- LKP (lightest Kaluza-Klein particle)
- axions, axion clusters
- solitons (B-balls; Q-balls; Odd-balls,...)
- supermassive relics
  - 
  - 
  -



# **Supermassive relics** **(Nonthermal dark matter)**

## Production Mechanisms:

- Reheating Chung, Kolb, Riotto
- Preheating Chung
- Bubble collisions Chung, Kolb, Riotto
- Gravitational Chung, Kolb, Riotto; Kuzmin & Tkachev

# Expanding universe → particle creation

Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Lukash, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel'dovich,...

**It's not a bug, it's a feature!**

first application: { density perturbations from inflation  
gravitational waves from inflation

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

new application: dark matter

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- require (super)massive particle “X”
- stable (or at least long lived)
- initial inflationary era followed by radiation/matter

# Scalar field $X$ of mass $M_X$

Fourier modes [ $a(\tau)$  = expansion scale factor]

$$X(\vec{x}, \tau) = \int \frac{d^3x}{(2\pi)^{3/2} a(\tau)} \left[ a_k h_k(\tau) e^{i\vec{k} \cdot \vec{x}} + a_k^\dagger h_k^*(\tau) e^{-i\vec{k} \cdot \vec{x}} \right]$$

Mode equation ( $\tau$  = conformal time)

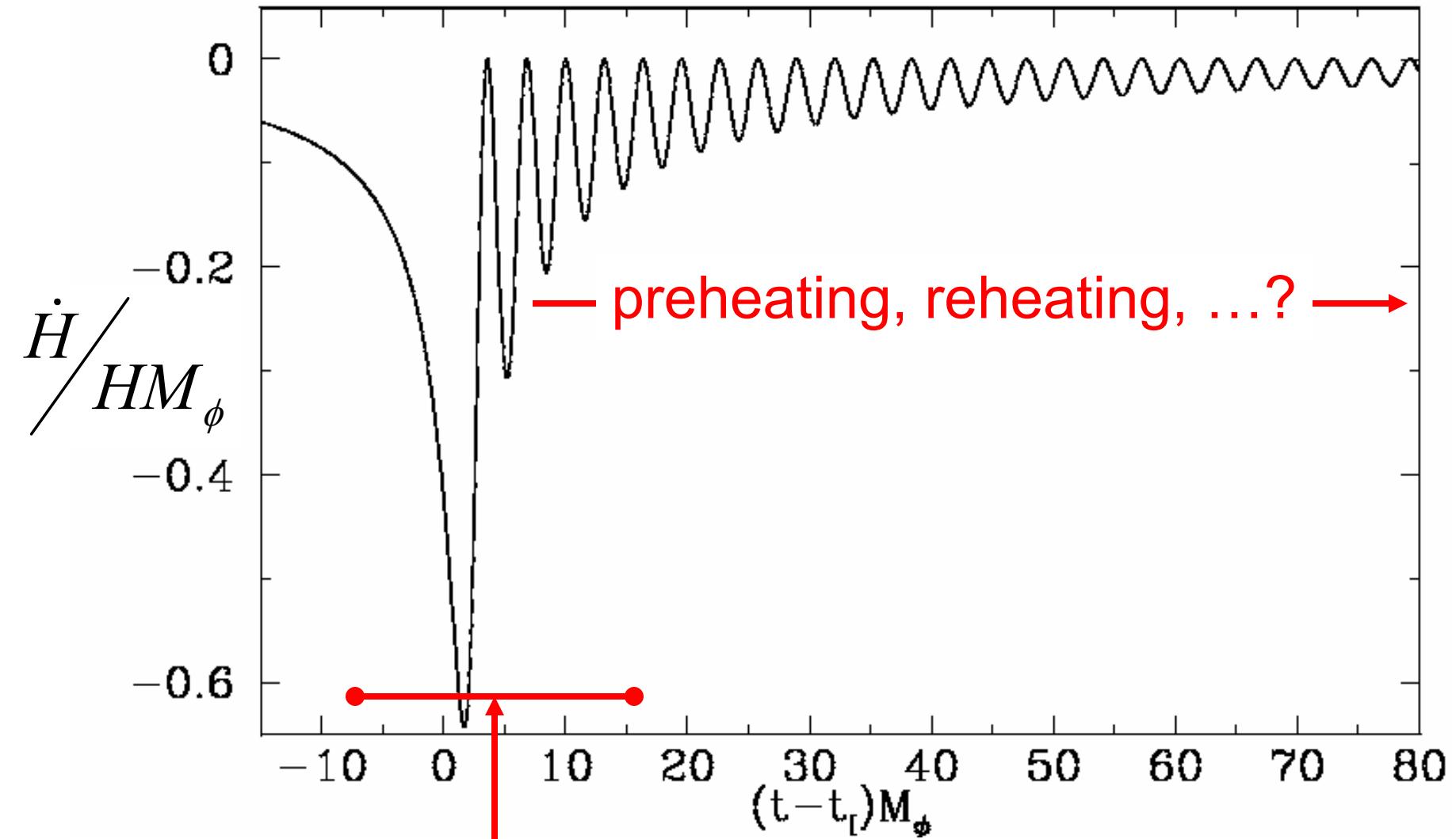
$$h_k''(\tau) + \left[ k^2 + M_X^2 a^2 + (6\xi - 1) \overset{\text{0}}{\cancel{a''/a}} \right] h_k(\tau) = 0$$

$$h_k''(\tau) + \omega_k^2(\tau) h_k(\tau) = 0$$

Particle creation in nonadiabatic region

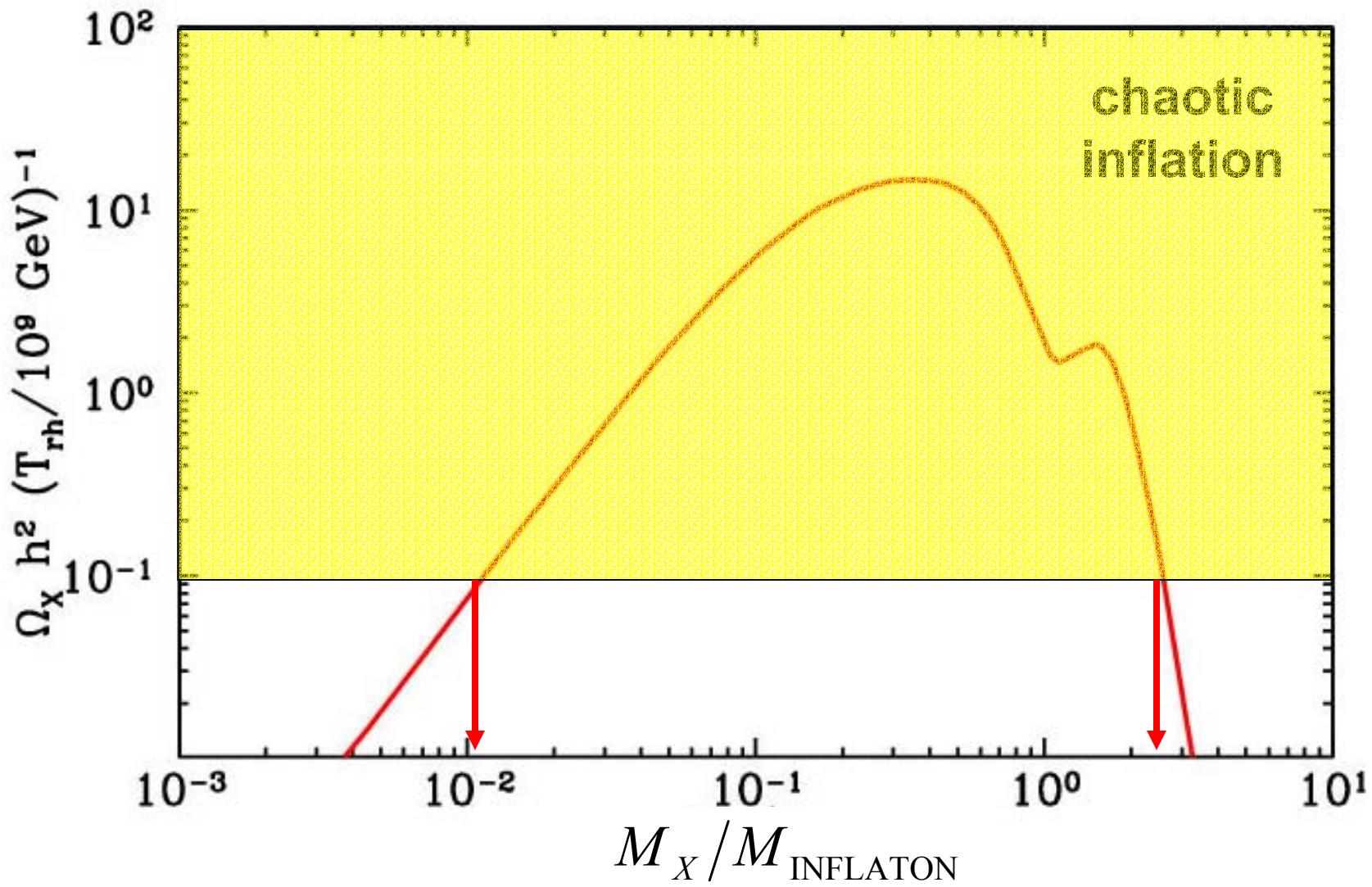
measure of nonadiabaticity  $\propto \frac{\omega'_k}{\omega_k}$  or  $\frac{\dot{H}}{H^2}$

# **Background fields in chaotic inflation**



# Particle production

Chung, Kolb& Riotto; Kuzmin & Tkachev



$$\Omega_X \approx 1 \quad \text{for} \quad M_X/M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{ GeV}$$

# Superheavy particles

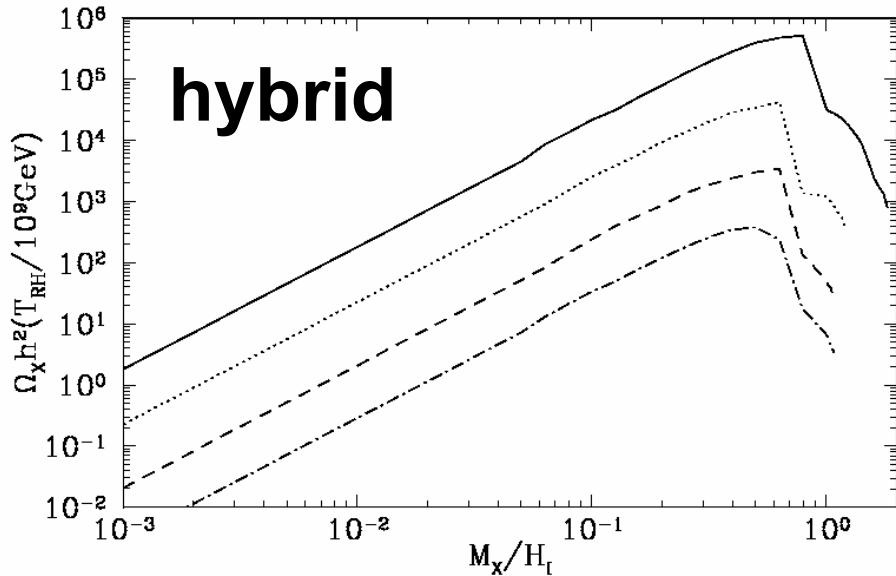
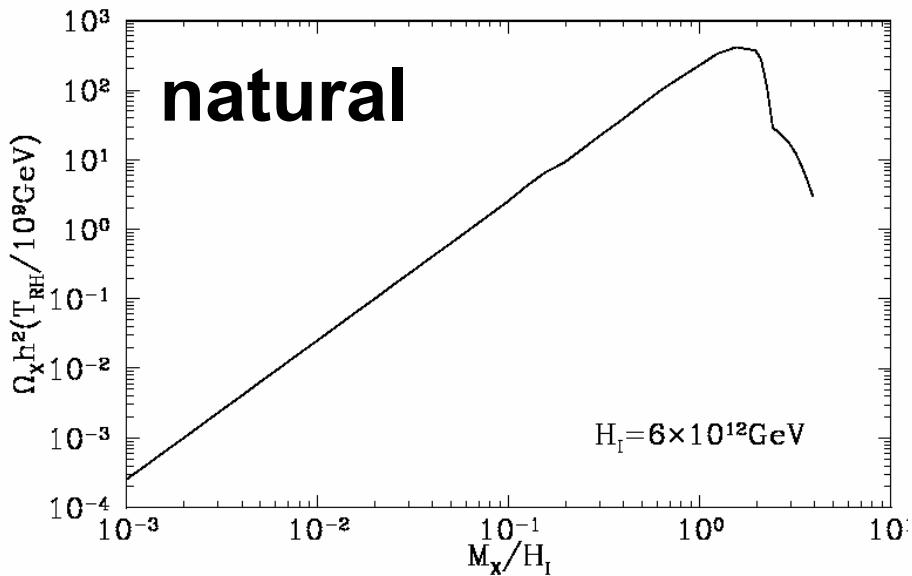
- Inflaton mass (in principle measurable from gravitational wave background, guess  $10^{12}$  GeV ) may signal a new mass scale in nature.
- Other particles may exist with mass comparable to the inflaton mass.
- Conserved quantum numbers may render the particle stable.

# Model exploration

## Gravitational Production:

- Fermions Kuzmin & Tkachev
- Non-conformal couplings Kuzmin & Tkachev
- Small-field models Crotty, Chung, Kolb, Riotto
- Hybrid models Crotty, Chung, Kolb, Riotto

# Model exploration



$$M_X \leq H_I \rightarrow \Omega_X h^2 \approx \left( \frac{M_X}{10^{11} \text{ GeV}} \right)^2 \left( \frac{T_{RH}}{10^9 \text{ GeV}} \right)$$

$$M_X \geq H_I \rightarrow \Omega_X h^2 \propto \exp(-M_X/H_I)$$

# **Wimpzilla characteristics:**

- supermassive:  $10^9 - 10^{15}$  GeV ( $\sim 10^{12}$  GeV ?)
- abundance may depend only on mass
- abundance may be independent of interactions
  - sterile?
  - electrically charged?
  - strong interactions?
  - weak interactions?
- unstable (lifetime > age of the universe)?

# **Gravitino production**

Giudice, Riotto, Tkachev

Linde, Kallosh, Kofman, Van Proeyen

Nilles, Peloso, Sorbo

Nilles, Olive, Peloso

.....

(perhaps it is a bug after all...)

# WIMPZILLA footprints:



**Isocurvature modes:**

CMB, Large-scale structure

**Decay:**

Ultra High Energy Cosmic Rays

**Annihilate:**

Galactic Center, Sun

**Direct Detection:**

Bulk, Underground Searches

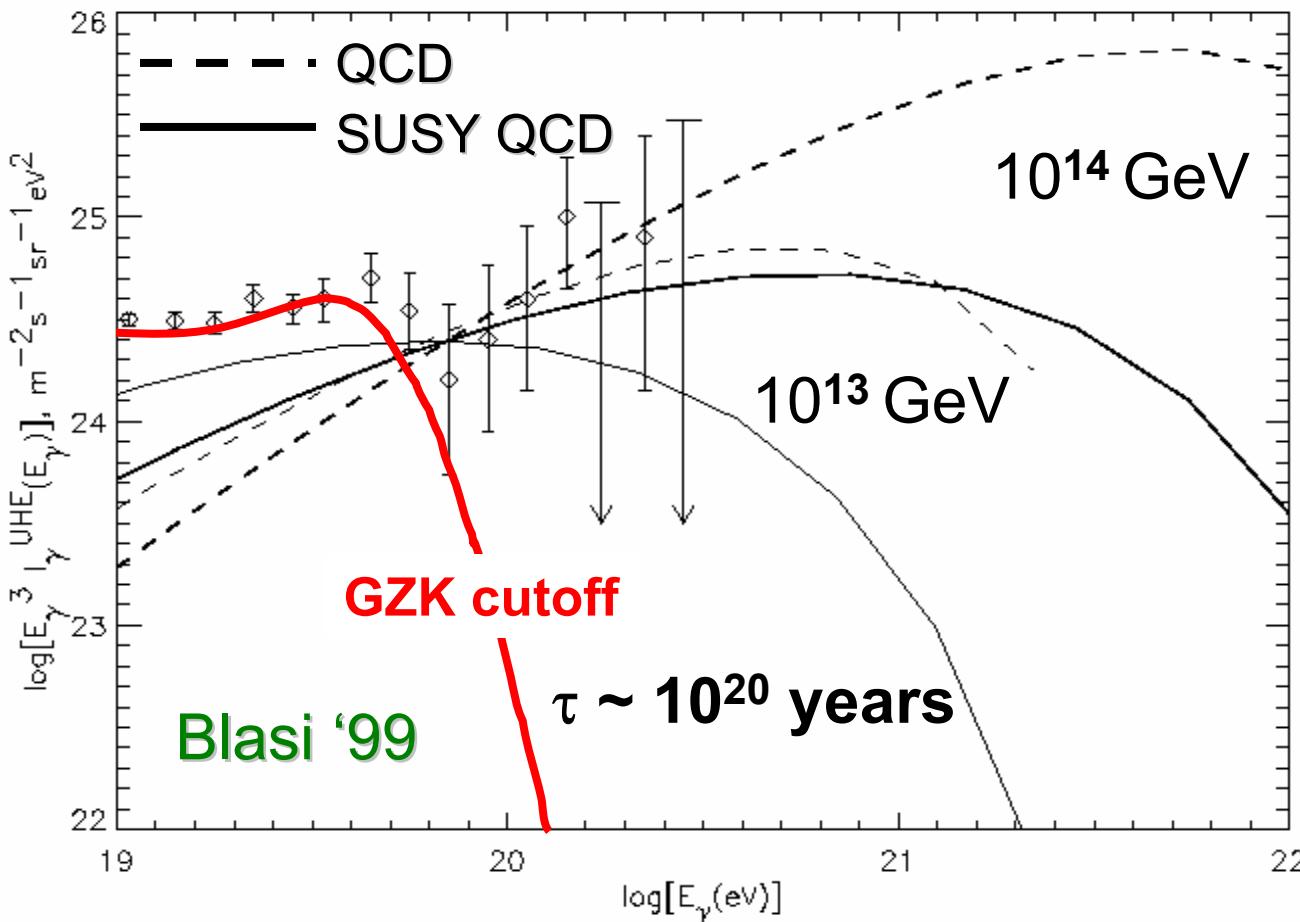
# **WIMPZILLA decay**

**X → UHE cosmic rays**

$$10^{13} \text{ GeV} = 10^{22} \text{ eV}$$

Kuzmin & Rubakov; Birkel & Sarkar;  
Ellis, Gelmini, Lopez, Nanopoulos & Sarkar;  
Berezinsky, Kachelriess, & Vilenkin;  
Benakli, Ellis, & Nanopoulos; Berezinsky, Blasi, & Vilenkin;  
Blasi; Berezinsky & Mikhaliou; Dubovsky & Tinyakov; Medina-Tanco & Watson;  
Blasi & Seth; Ziaeepour; Crooks, Dunn, & Frampton

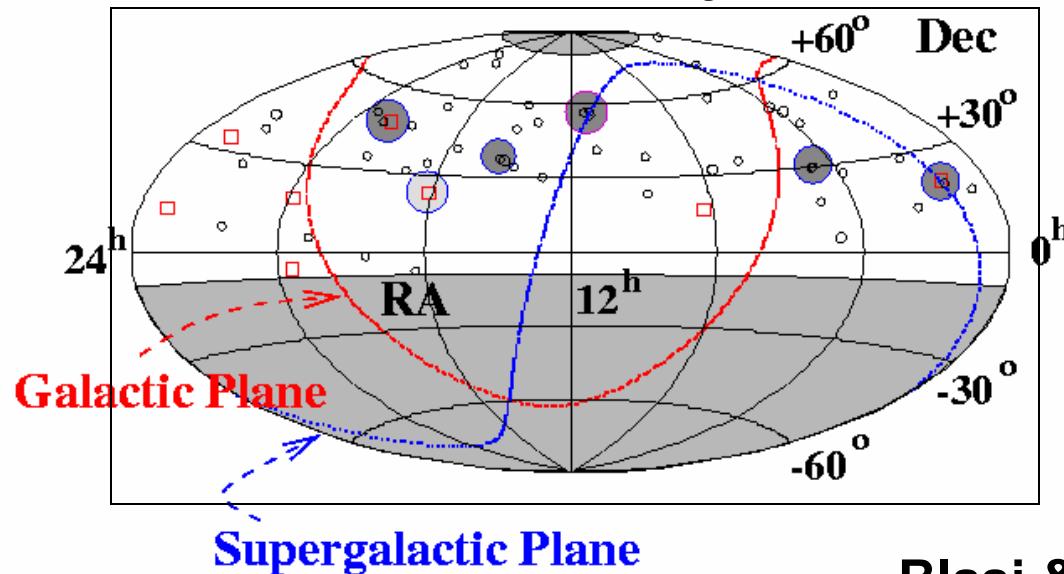
# WIMPZILLA decay



UHE cosmic rays mostly photons; characteristic spectrum;  
UHE neutrinos; lower-energy crud;  
clumping → anisotropies

# Clustering of UHE events

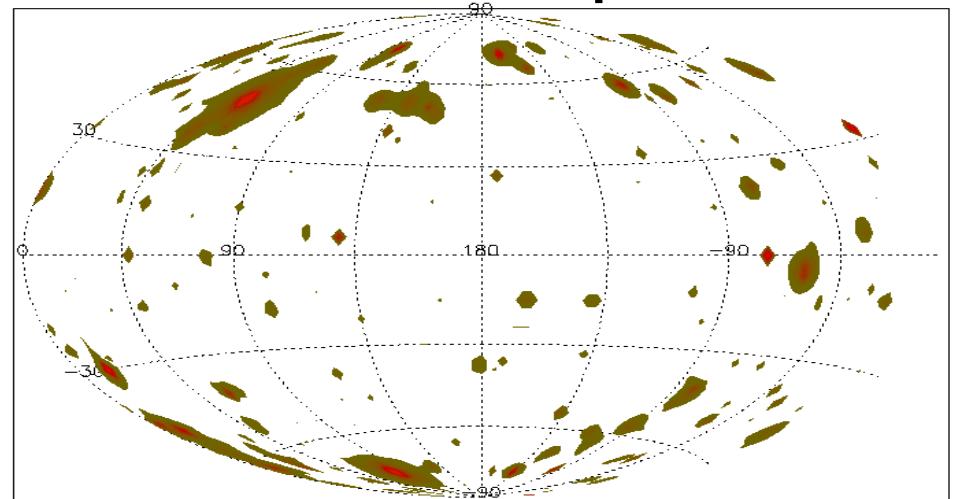
UHE cosmic rays



probability from  
isotropic distribution:  
 $<1\%$

model follows Navarro,  
Frenk, White dark matter  
distribution

Blasi & Sheth astro-ph/0006316



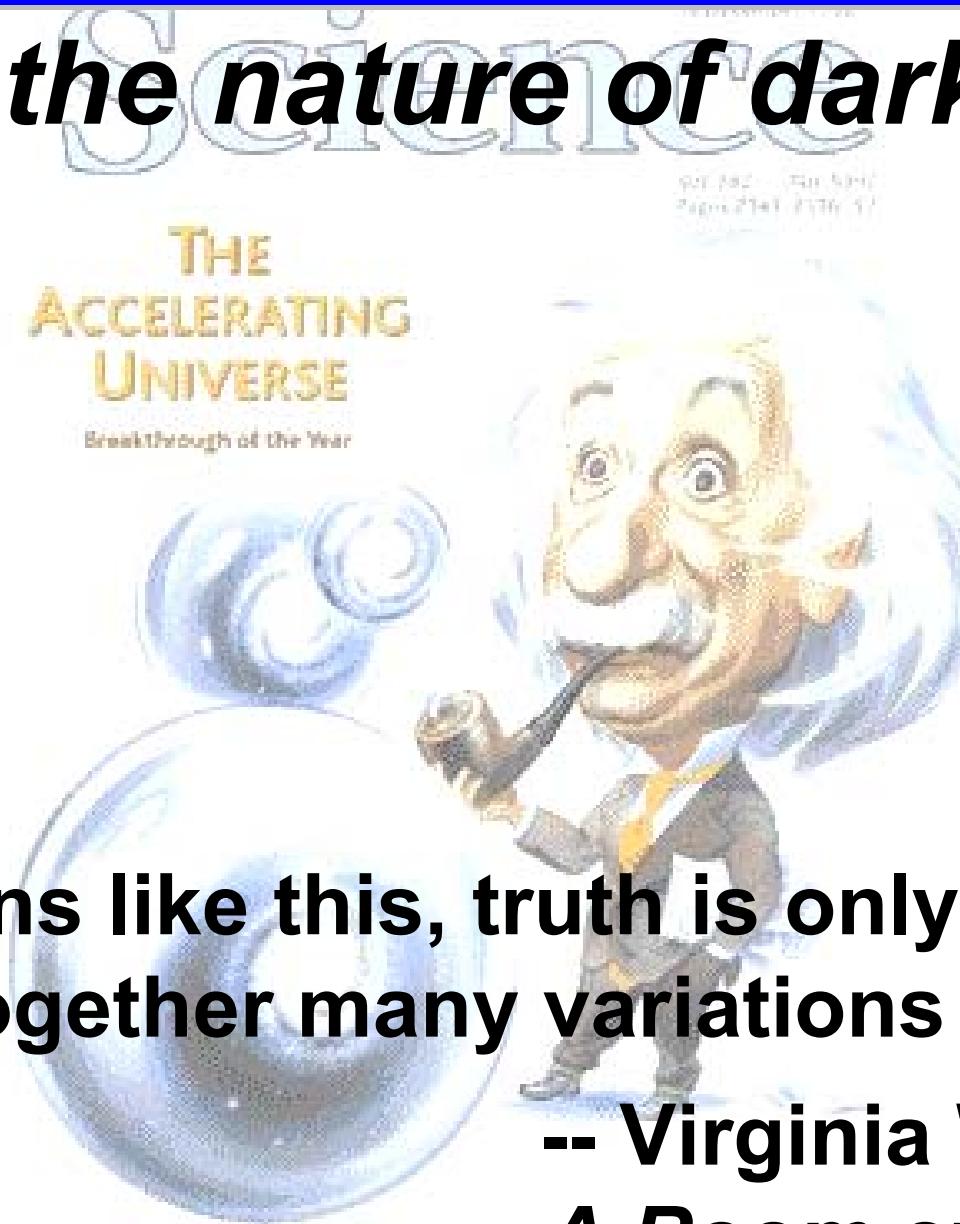
# Dark Energy RELOADED

SSI

2009

# Epicycle III – Dark Energy

*What is the nature of dark energy*



THE  
ACCELERATING  
UNIVERSE  
Breakthrough of the Year

“In questions like this, truth is only to be had  
by laying together many variations of error.”  
-- Virginia Wolf  
*A Room of Ones Own*

# Cosmological constant

## Mass density of space:

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

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

The unbearable lightness of nothing!

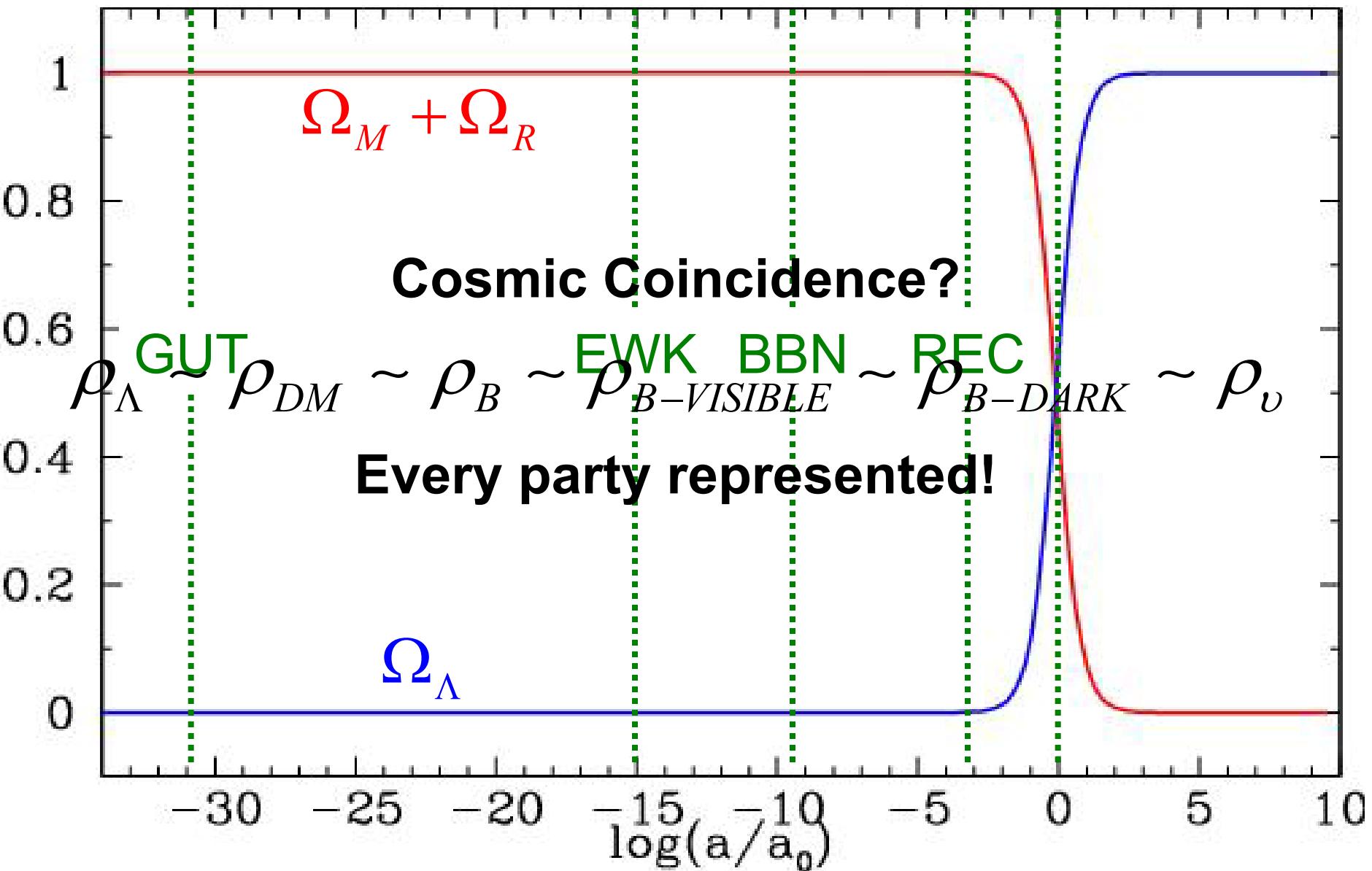
## Cosmo-illogical constant?

## Numerology:

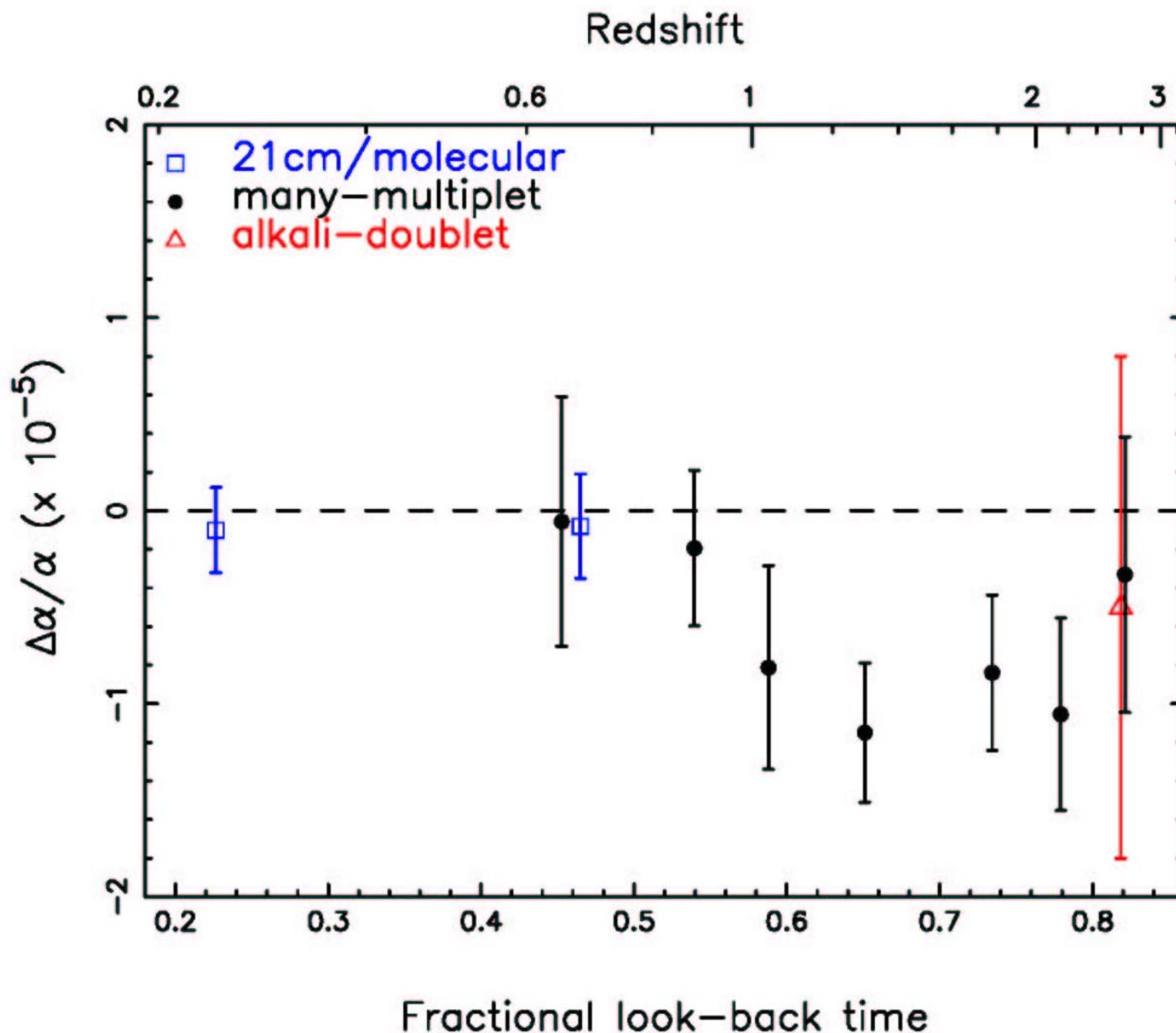
$$\rho_V = M_W^4 \exp(-2/\alpha) \quad \rho_V = M_{\text{SUSY}}^8 / M_{Pl}^4$$

$$m_\nu = 10^{-3} \text{ eV} \quad R_5 = 10^{-4} \text{ cm}$$

# Cosmic coincidence



# Anything interesting at $z \sim 1$ ?



Webb et al.

# $\Lambda$ : the uninvited guest

1. No unbroken symmetry demands  $\Lambda=0$
2. Nothing sets the scale
3. Scale seems unrelated to any other energy scale
  - . . . seems to require  $m \sim 10^{-33}$  eV
  - . . . fifth-force experiments?

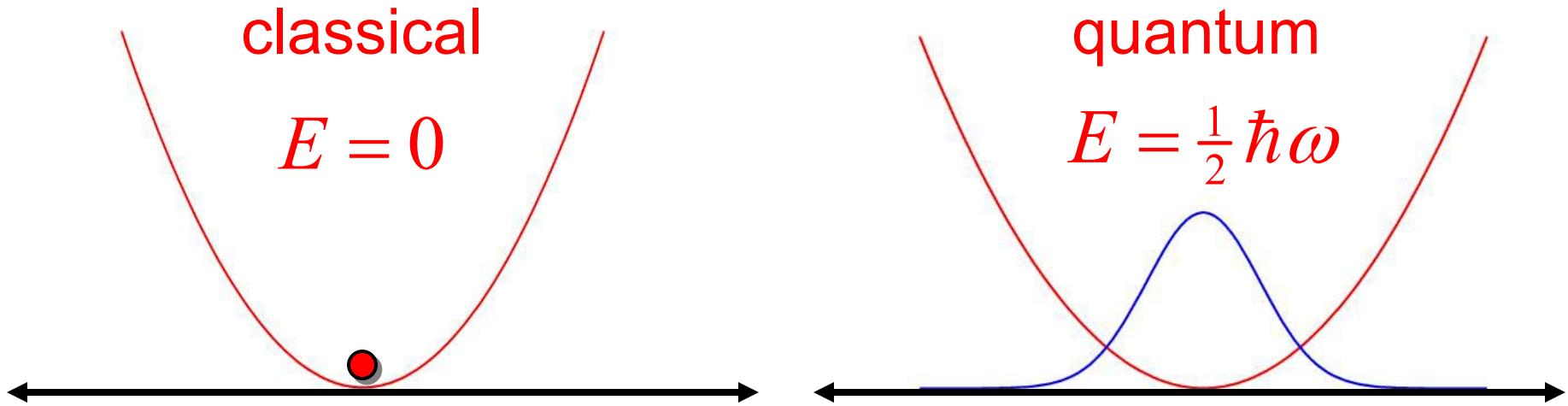
Non l'avrei giammai creduto;  
Ma farò quel che potrò.

*Mozart/Da Ponte,  
Don Giovanni, Act II*

4. *Deal with it!*

# Quantum uncertainty

Fourier modes of all fields are harmonic oscillators with a zero-point energy



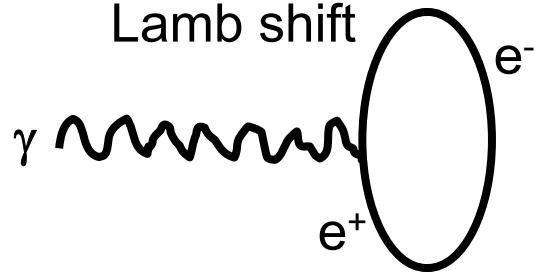
$$\rho = \sum_{all\ particles} \pm \int d^3k \sqrt{k^2 + m^2}$$

# Quantum uncertainty

$$\rho = \sum_{\text{all particles}} \pm \int d^3k \sqrt{k^2 + m^2} \simeq \sum_{\text{all particles}} \pm \int d^3k k^4$$

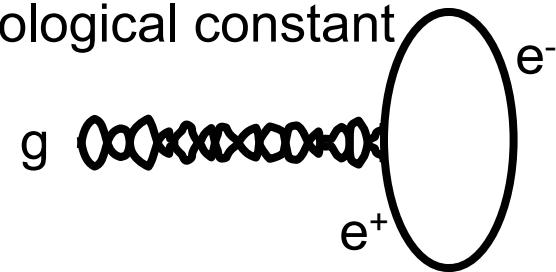
Photons couple to virtual particles

Lamb shift



Gravitons couple to virtual particles

Cosmological constant



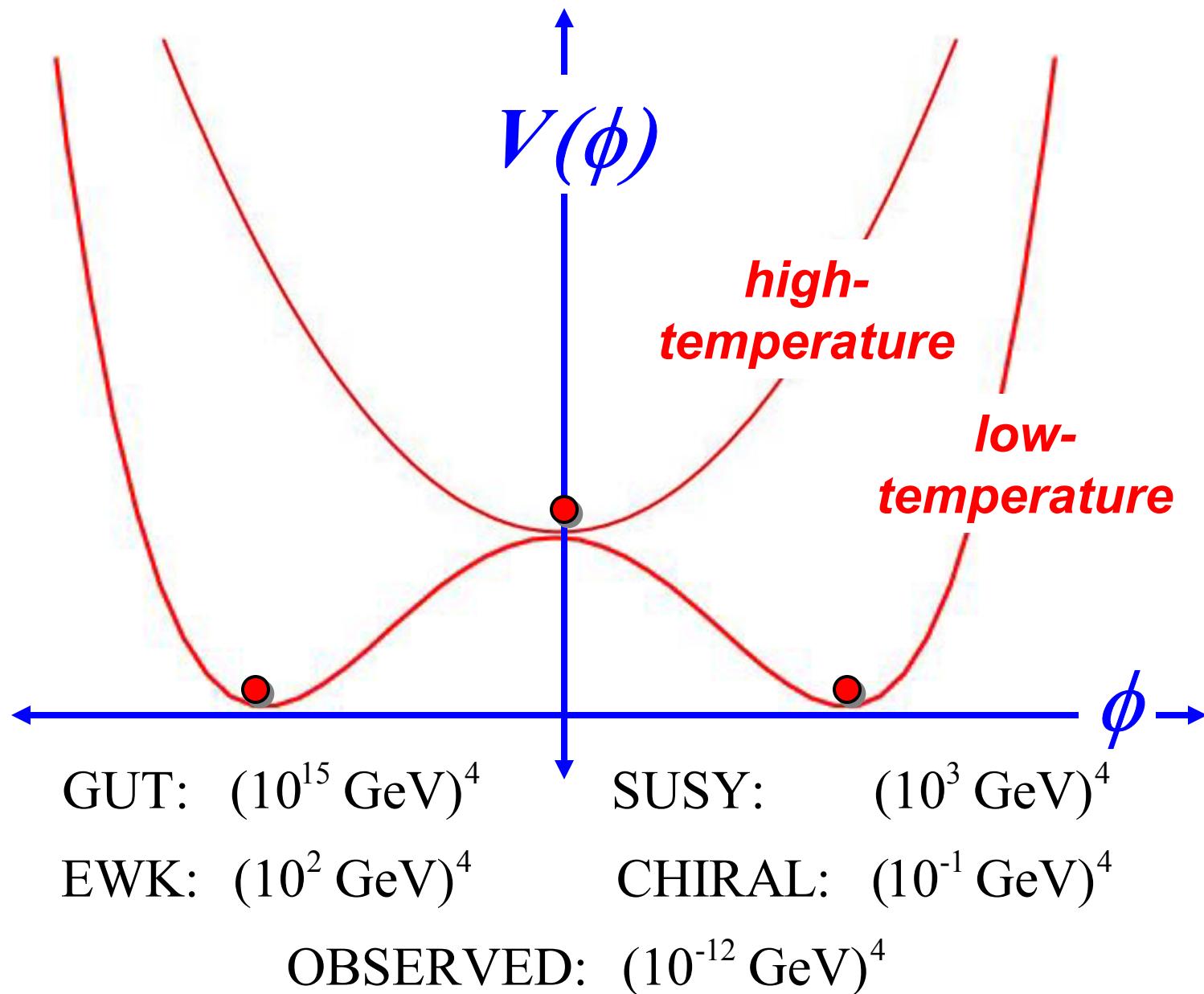
$$\Lambda_C = \infty : \quad \rho_\Lambda = \infty^4 \quad = \text{bad prediction}$$

$$\Lambda_C = M_{Pl} : \quad \rho_\Lambda = M_{Pl}^4 = (10^{28} \text{ eV})^4$$

$$\Lambda_C = M_{SUSY} : \quad \rho_\Lambda = M_{SUSY}^4 = (10^{12} \text{ eV})^4$$

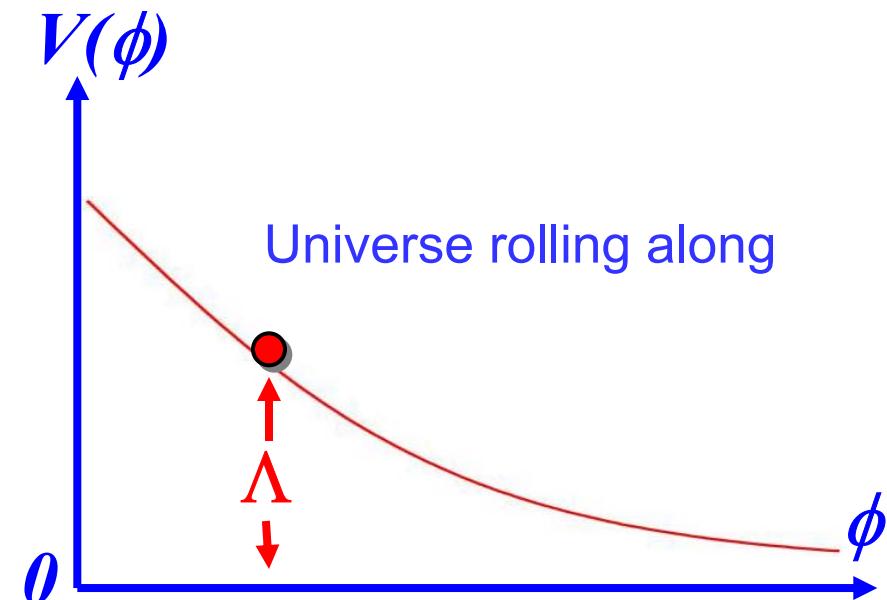
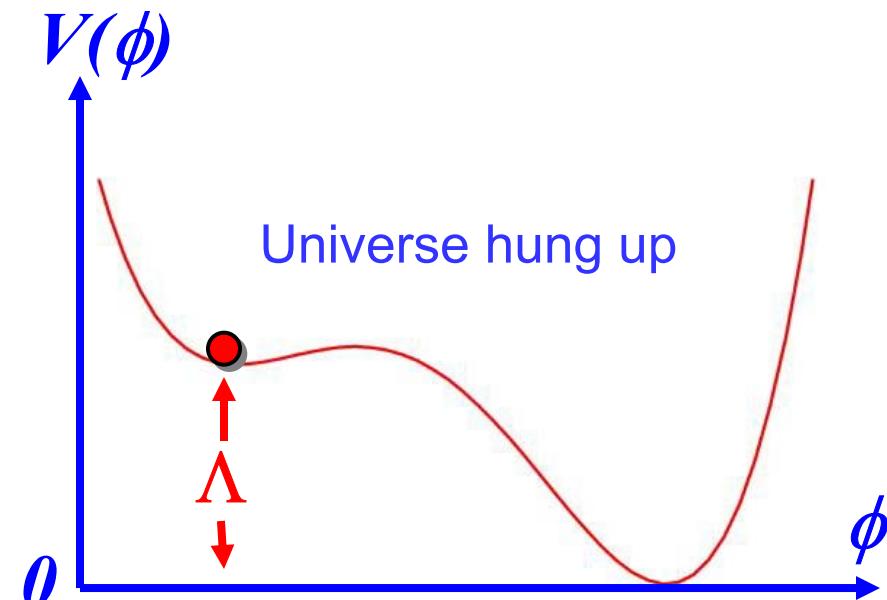
$$\Lambda_C = 10^{-3} \text{ eV} : \quad \rho_\Lambda = \text{Observed}$$

# Spontaneous symmetry breaking



# Balancing other contributions

- Many possible contributions.
- Why then is total so small?
- Perhaps unknown dynamics sets global vacuum energy equal to zero.....*but we're not there yet!*



# Balancing other contributions

- But *why now?*
- Tracker potentials,  $e^{-\phi}$ ,  $\phi^{-n}$ , ... relate dark energy to other contributions.\*      Wetterich; Ratra & Peebles; ...

Field equation for tracker:  $\ddot{\phi} + 3H\dot{\phi} + dV/d\phi = 0$

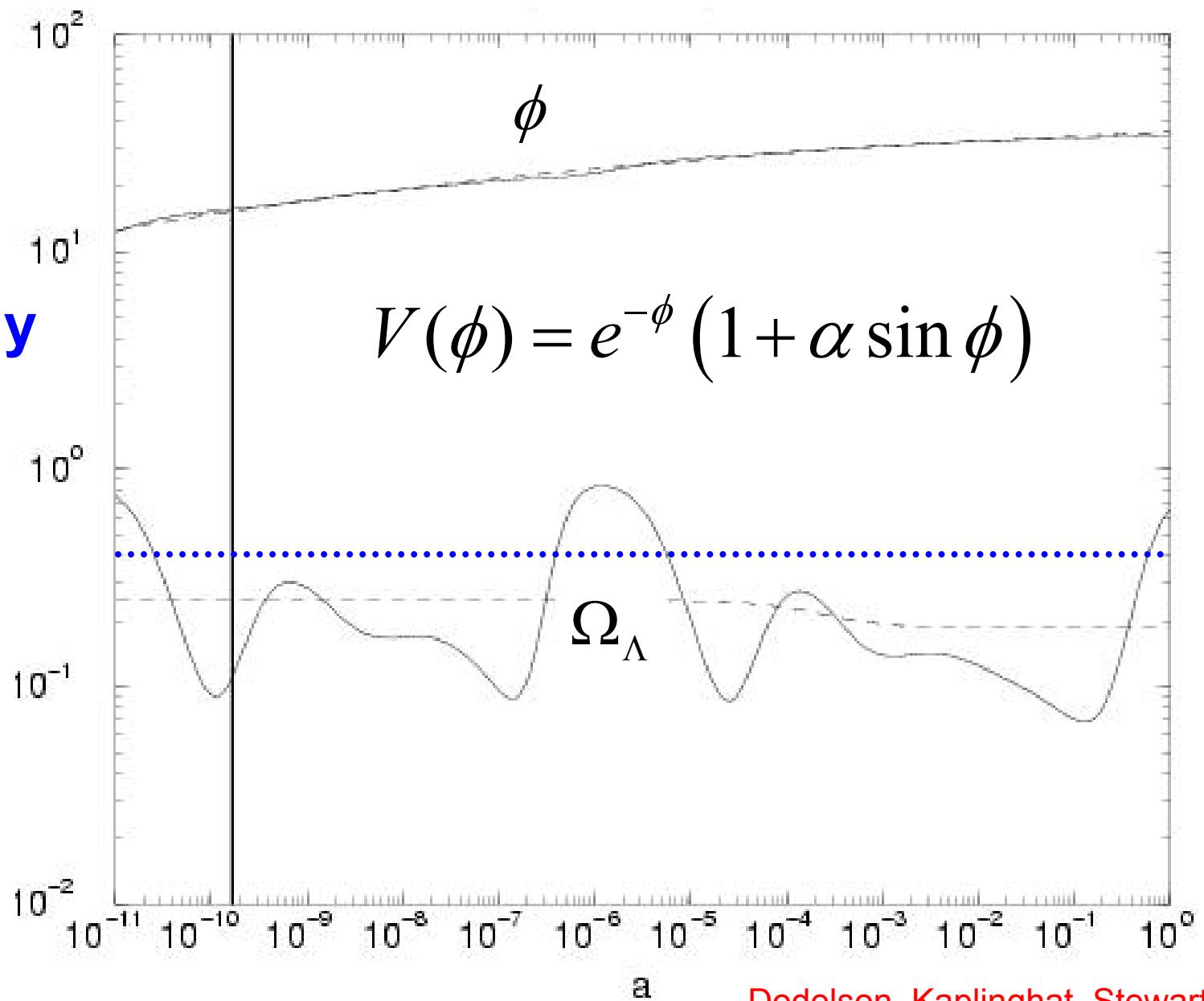
$$H^2 = \frac{8\pi G}{3} (\rho_\phi + \rho_M + \dots)$$

Can have  $\rho_\phi$  track (stalk)  $\rho_M$  - effective mass of the field decreases as  $H$ : close but no cigar

- *Why now?.... “close to matter domination”*
- *Why now?.... “it’s just that time”*

# Punctuated vacuum domination

dark energy  
 $\neq$  destiny



$a$

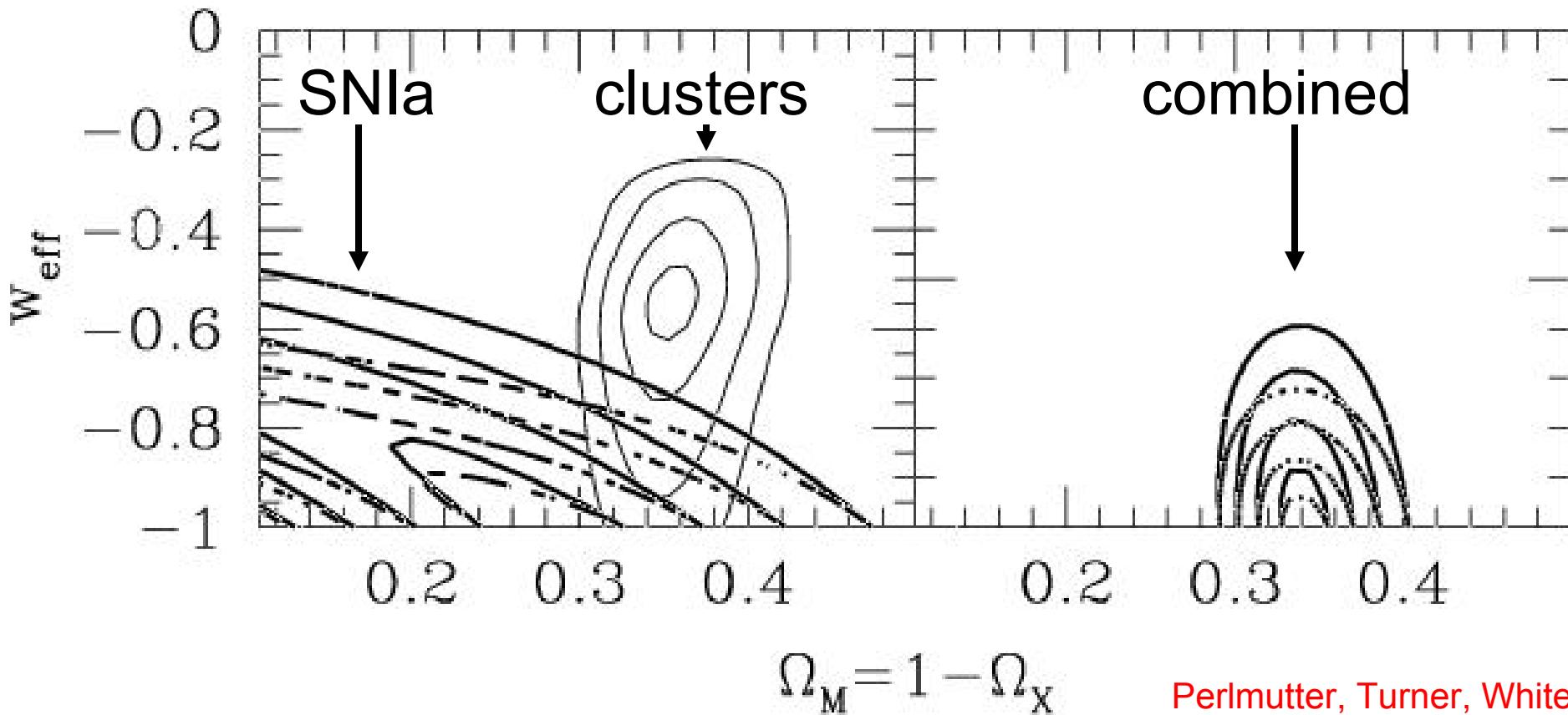
Dodelson, Kaplinghat, Stewart

# For now...parameterize

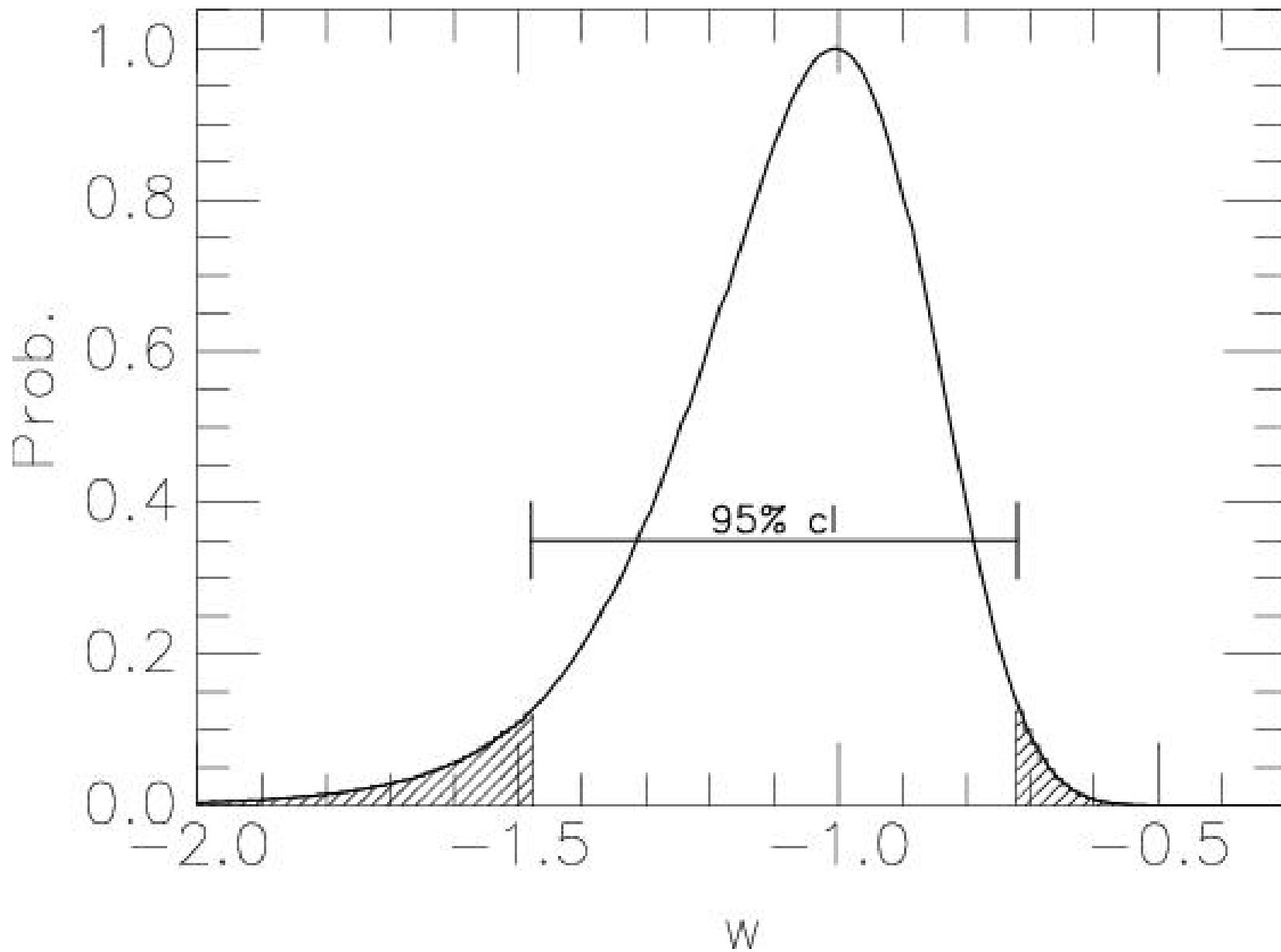
$$w = p_V / \rho_V$$

$w = -1$  for constant  $\Lambda$

$-1 < w \leq -1/3$  for dynamical dark energy



# For now...parameterize



High-z supernova team

# $w < -1 ?$

- **null dominant energy condition: energy doesn't propagate outside the light cone**

$$|p| \leq |\rho| \Rightarrow -\rho \leq p \leq \rho$$

- **model with  $w < -1$ : negative kinetic energy scalar field**

$$L = -\dot{\phi}^2 - \exp(-\phi^2)$$

- **instability cured with higher derivative terms?**

# Aether of the 21<sup>st</sup> century?

- It's an infrared issue!
- Scalars (quintessence, trackers, ....)?
- Tensors (gravity at large distances)?

# Braneless cosmology

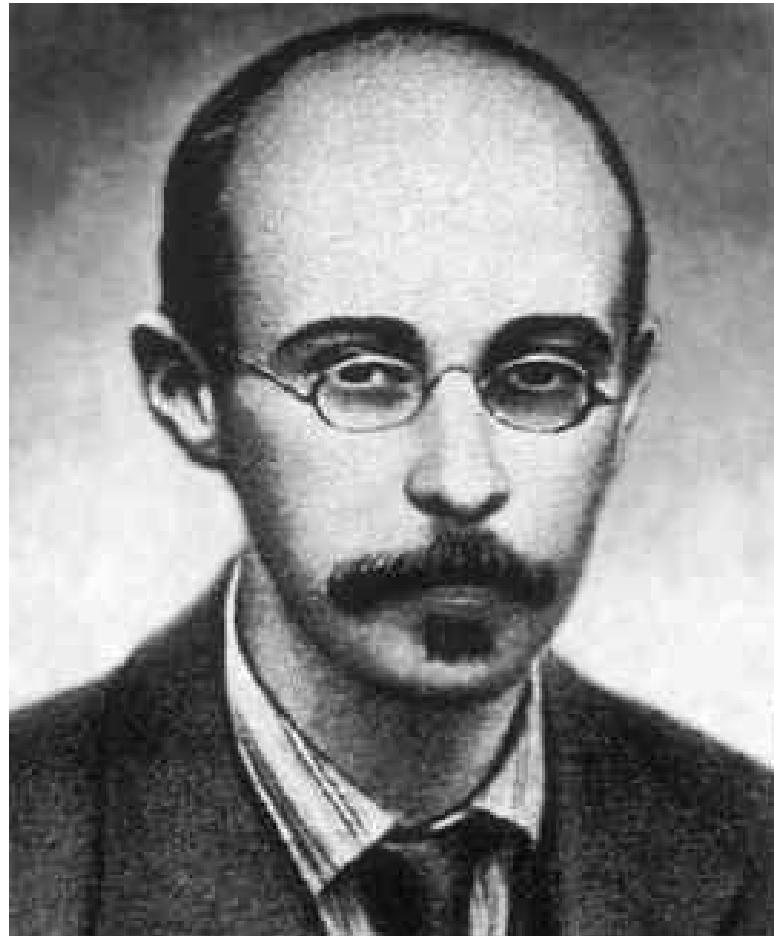
- Old Friedmann law

$$G_{00} = M_{Pl}^{-2} T_{00}$$

$$3H^2 = M_{Pl}^{-2} \rho$$

**SNIa evidence  
for dark energy:**

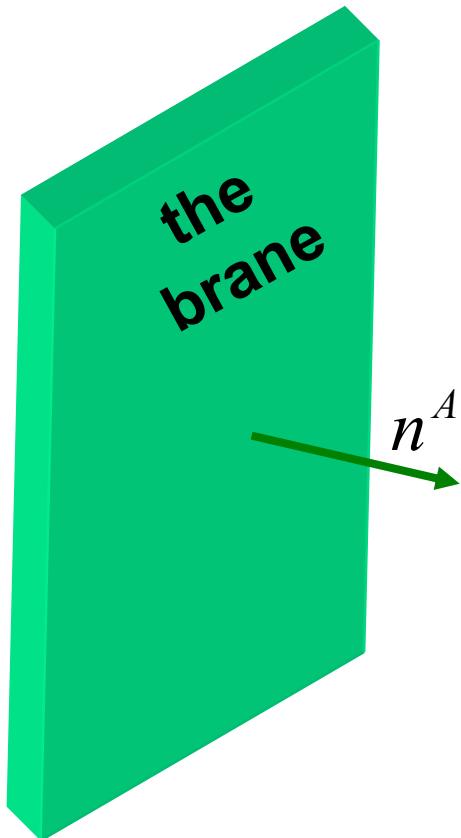
$$\int \frac{dz}{H(z)}$$



Friedmann (1921)

# Brane cosmology

- Israel junction condition (Israel 1966)



- $n^A$  : 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

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

[....] = 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  $\sigma$  on the brane  $\rho \rightarrow \rho + \sigma$*

$$H^2 = \left( \frac{\Lambda}{6} + \frac{M_*^{-6}}{36} \sigma^2 \right) + \frac{M_*^{-6}}{18} \sigma \rho + \frac{M_*^{-6}}{36} \rho^2 + \frac{c}{a^4(t, y=0)}$$

cosmological constant (cancels?)       $\frac{M_*^{-6}}{18} \sigma = \frac{8\pi G}{3}$       unconventional corrections  
Friedmann equation

# Brane cosmology

- Friedmann equation modified today

$$H^2 = A\rho \left[ 1 + \left( \rho / \rho_{\text{cutoff}} \right)^{n-1} \right]$$

Freese & Lewis

- Gravitational force law modified at large distance

Five-dimensional at cosmic distances

Deffayet, Dvali & Gabadadze

- Tired gravitons

Gravitons metastable - leak into bulk

Gregory, Rubakov & Sibiryakov  
Dvali, Gabadadze & Porrati

- Gravity repulsive at cosmological distance

$R \sim \text{Gpc}$

Csaki, Erlich, Hollowood & Terning

- $n=1$  KK graviton mode very light

$$m \sim (\text{Gpc})^{-1}$$

Kogan, Mouslopoulos, Papazoglou, Ross & Santiago

- 3+1 Lorentz invariance broken

In the IR!

Chung, Kolb & Riotto

# Modify gravity

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( R + \alpha R^2 + \dots \right) + \int d^4x \sqrt{-g} L_M$$

Starobinski - inflation

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( R - \frac{\mu^4}{R} \right) + \int d^4x \sqrt{-g} L_M$$

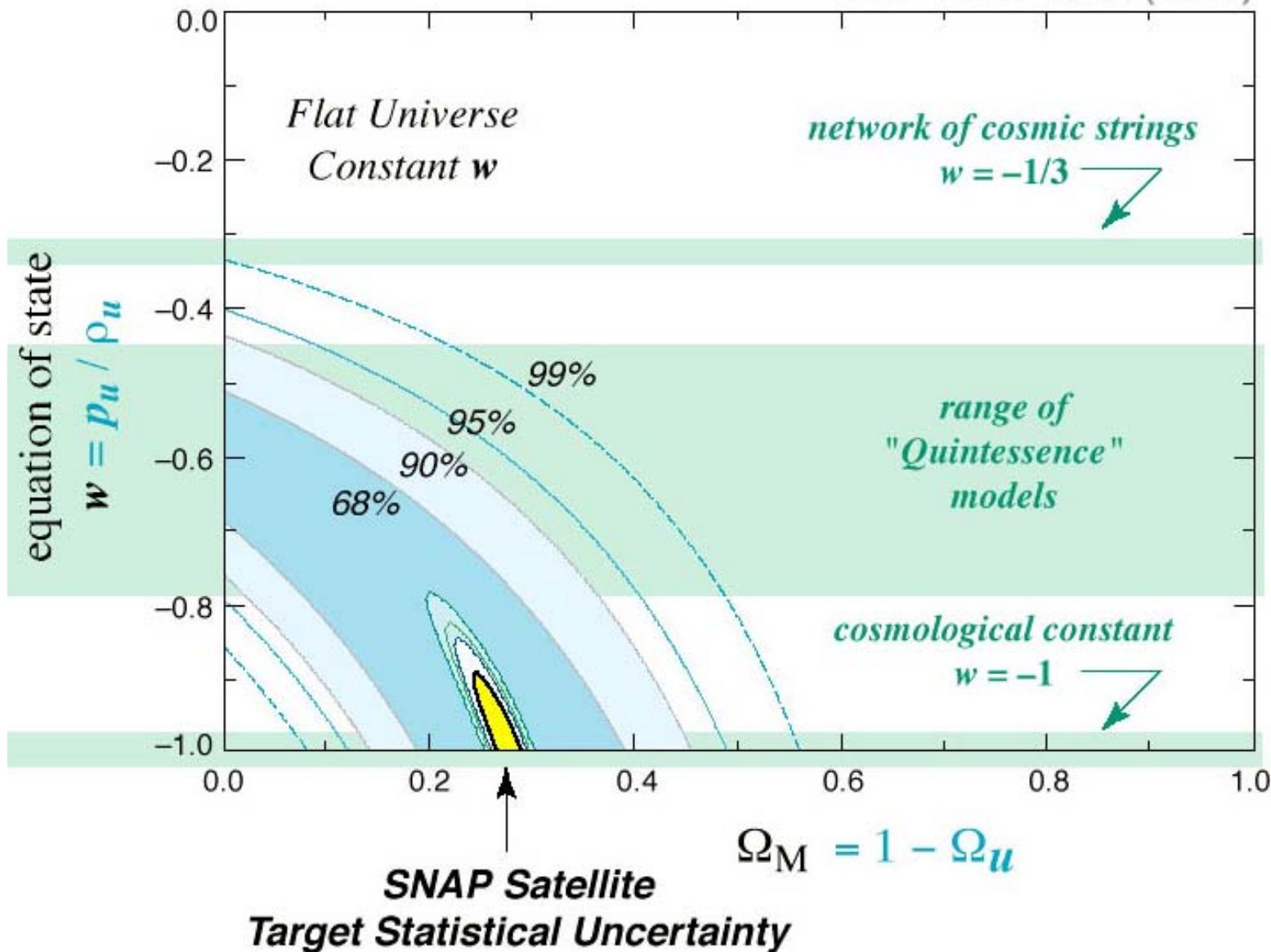
Carroll, Duvvuri, Turner, Trodden – dark energy

# How do we sort it out?

- Something is established- $\Lambda$ CDM too good to ignore  
SNIa  
Subtraction  
Age  
Large-scale structure  
.....
- Is it “just” a cosmological constant? Is  $w = -1$ ?
- If  $w \neq -1$  what is the dynamics?

# How do we sort it out?

Supernova Cosmology Project  
Perlmutter et al. (1998)

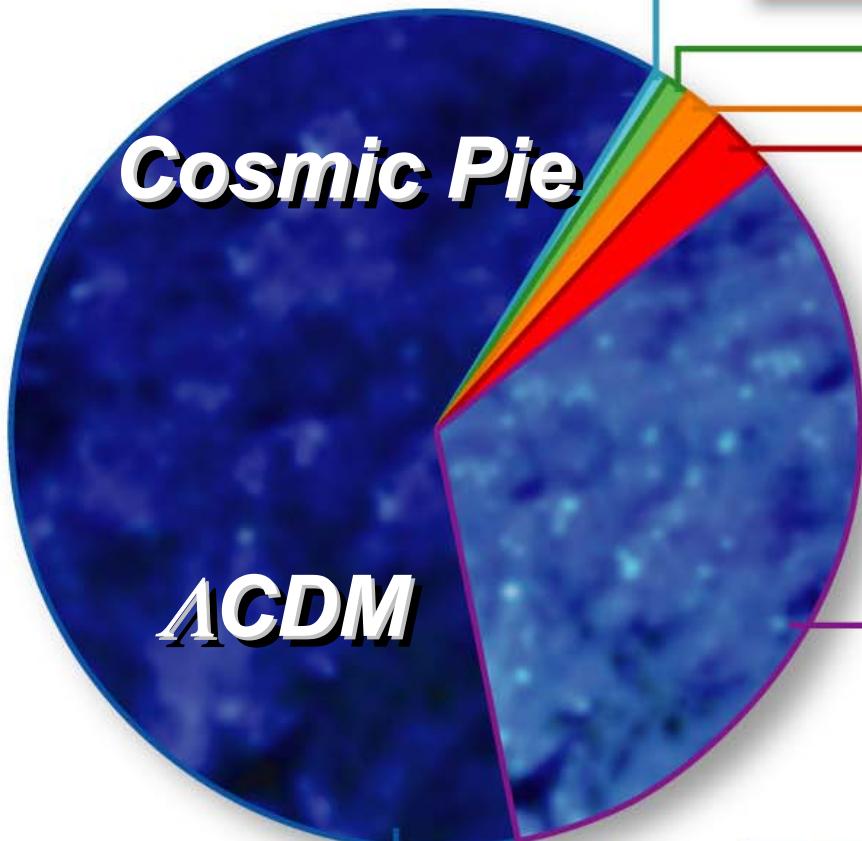


# Cosmology in the “precision” era

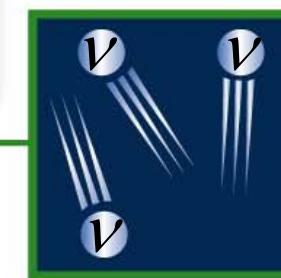
- $\Lambda$ CDM is a most predictive cosmological model
- Fundamental parts are a mystery
  - nature of dark matter
  - nature of dark energy
  - dynamics of inflation
- The best is yet to come!

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$



**Heavy Elements:**  
 $\Omega=0.0003$



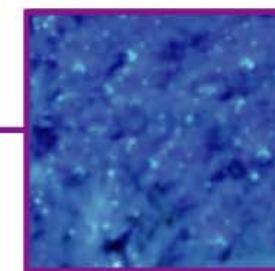
**Neutrinos ( $\nu$ ):**  
 $\Omega=0.0047$



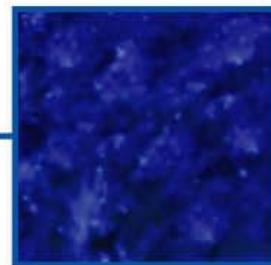
**Stars:**  
 $\Omega=0.005$



**Free H & He:**  
 $\Omega=0.04$



**Cold Dark Matter:**  
 $\Omega=0.25$



**Dark Energy ( $\Lambda$ ):**  
 $\Omega=0.70$