The Gravity of Dark Energy

Gravity in the Quantum World and the Cosmos

XXXIII SLAC Summer Institute, August 2005

Rocky Kolb, Fermilab & Chicago

Precision cosmology

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}\ \mathrm{cm}^{-3}$

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_\nu h^2 < 0.0076$ (95%CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_\gamma = 410.4^{+0.9}_{-0.9}\ \mathrm{cm}^{-3}$

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0.°598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc

WMAP

What is the nature of dark energy?

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

-- Virginia Woolf

A Room of Ones Own

Big-Bang

Robertson-Walker metric

$a(t) = \text{cosmic scale factor}$

$k = 0, \pm 1$

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

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

Perfect-fluid stress tensor

$\rho =$ energy density

$p =$ pressure

$T^{\mu}{}_{\nu} = \text{diag}(\rho, p, p, p)$

Field equations

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad H \equiv \frac{\dot{a}}{a} = \text{expansion rate}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \qquad q \equiv -\frac{\ddot{a}}{a}\frac{1}{H^2} = \text{deceleration parameter}$$

$$T^{\mu\nu}{}_{;\nu} = 0 \qquad \rho \propto a^{-3(1+w)} \qquad w = p/\rho$$

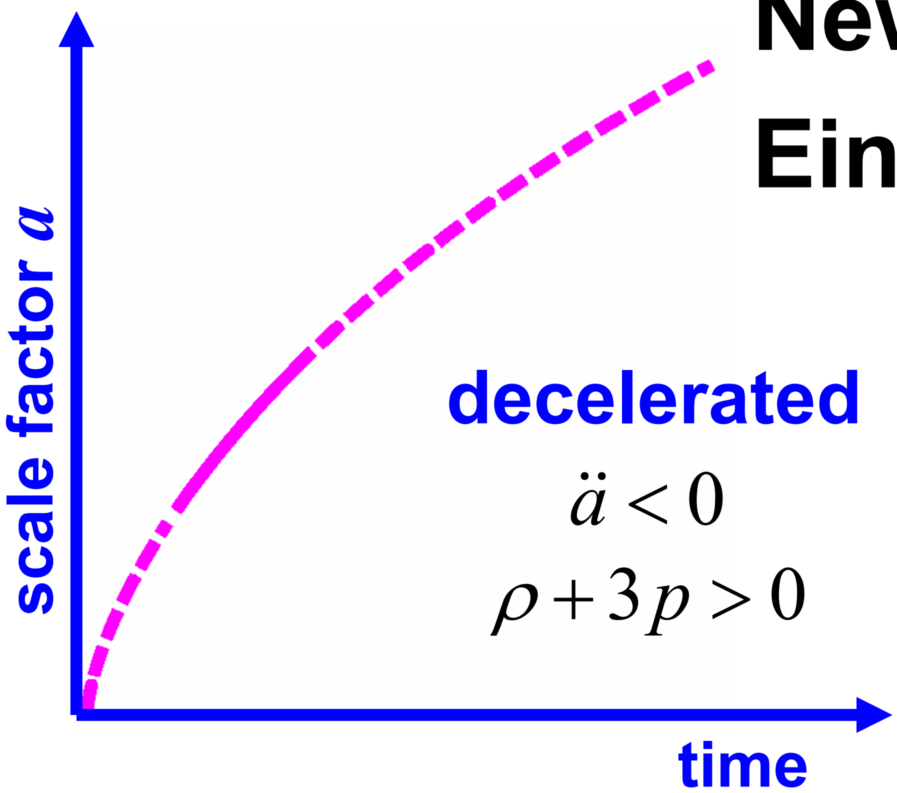
$T^{\mu\nu}$: fluids with different w

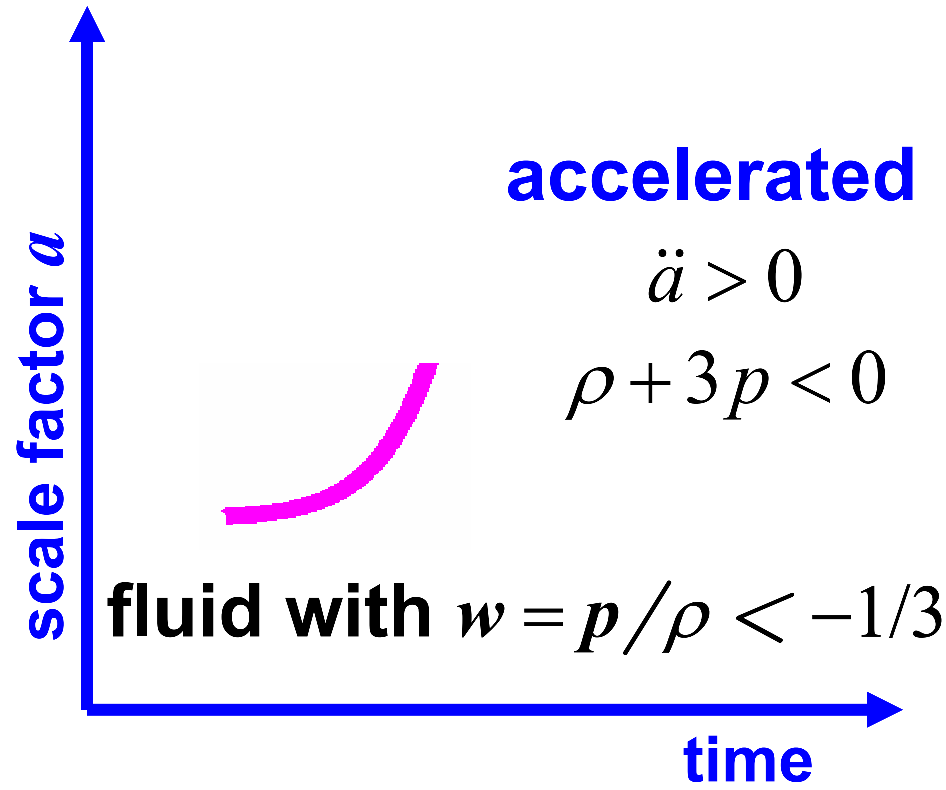
radiation:	$p_R = \rho_R/3$	$w = 1/3$	$\rho_R \propto a^{-4}$
matter:	$p_M = 0$	$w = 0$	$\rho_M \propto a^{-3}$
vacuum:	$p_\Lambda = -\rho_\Lambda$	$w = -1$	$\rho_\Lambda \propto a^0$

Newton

Einstein

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

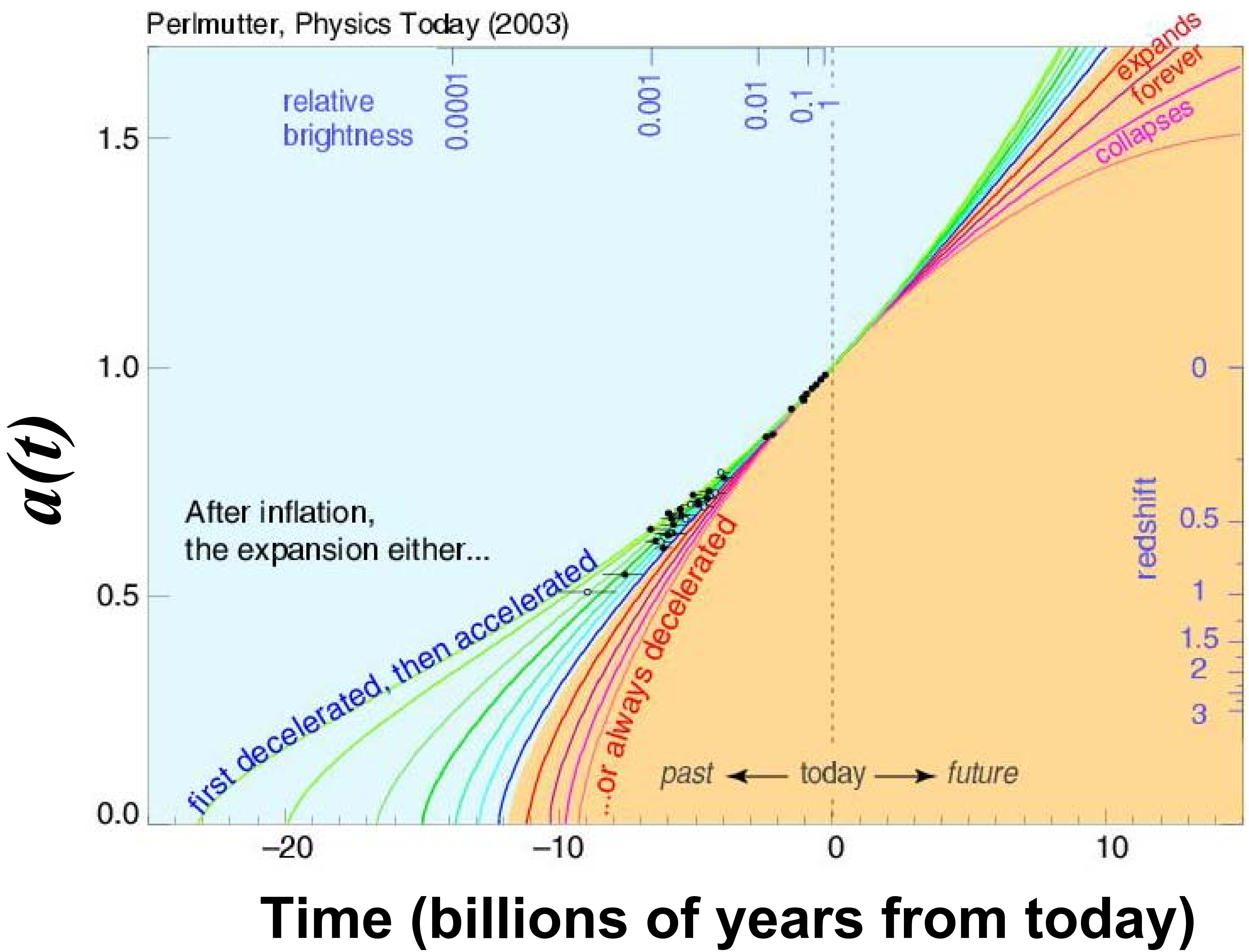




Dynamics → Evolution

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad \rho = \rho_M(a) + \rho_R(a) + \rho_\Lambda(a) + \ldots$$

- ***a(t)*, *H(t)*, depend on matter/energy content**
- ***a(t)* measurable via redshift** $1 + z \equiv a(0)/a(t)$
- **Redshift** z **is a proxy for time or scale factor**



Perlmutter, Physics Today (2003)
relative brightness
0.0001
0.001
0.01
0.1
1
expands
forever
collapses
1.5
1.0
0.5
0.0
0
0.5
1
1.5
2
3
redshift
a(t)
After inflation, the expansion either...
first decelerated, then accelerated
...or always decelerated
past
today
future
−20
−10
0
10
Time (billions of years from today)

Evolution of $H(z)$ is a key quantity

Many observables based on the comoving distance r

$$\left.\begin{array}{l}\sin^{-1} r(z) \\ r(z) \\ \sinh^{-1} r(z)\end{array}\right\} = \int_0^z \frac{dz'}{H(z')} \equiv R(z)$$

- Luminosity distance

  $\text{Flux} = \text{Luminosity}/4\pi d_L^2$

  $$d_L(z) \propto R(z)(1+z)$$

- Angular diameter distance

  $\text{Angular diameter} = \text{Physical size}/d_A$

  $$d_A(z) \propto \frac{R(z)}{(1+z)}$$

- Comoving volume element

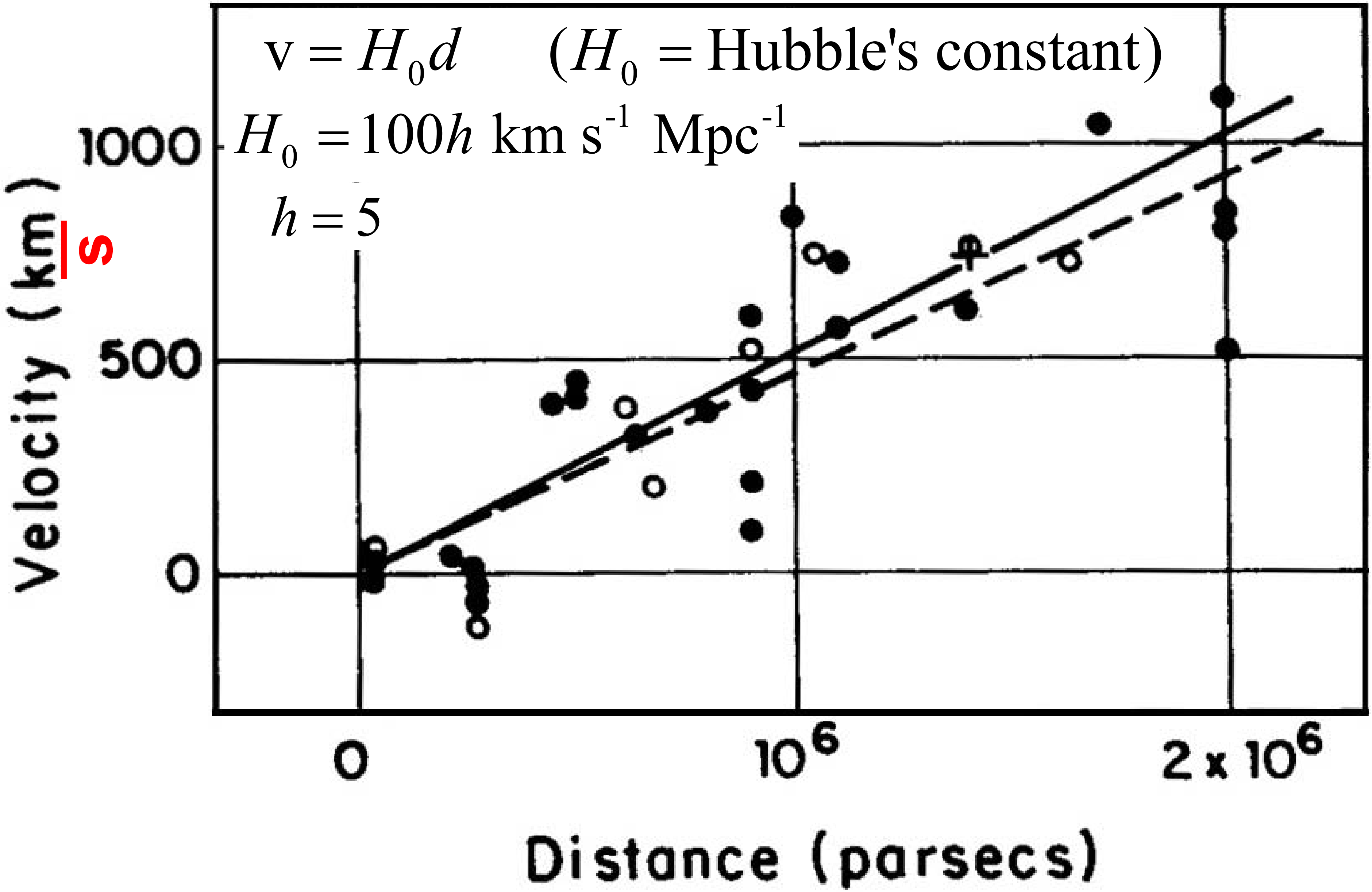
  $N \propto V^{-1}(z)$

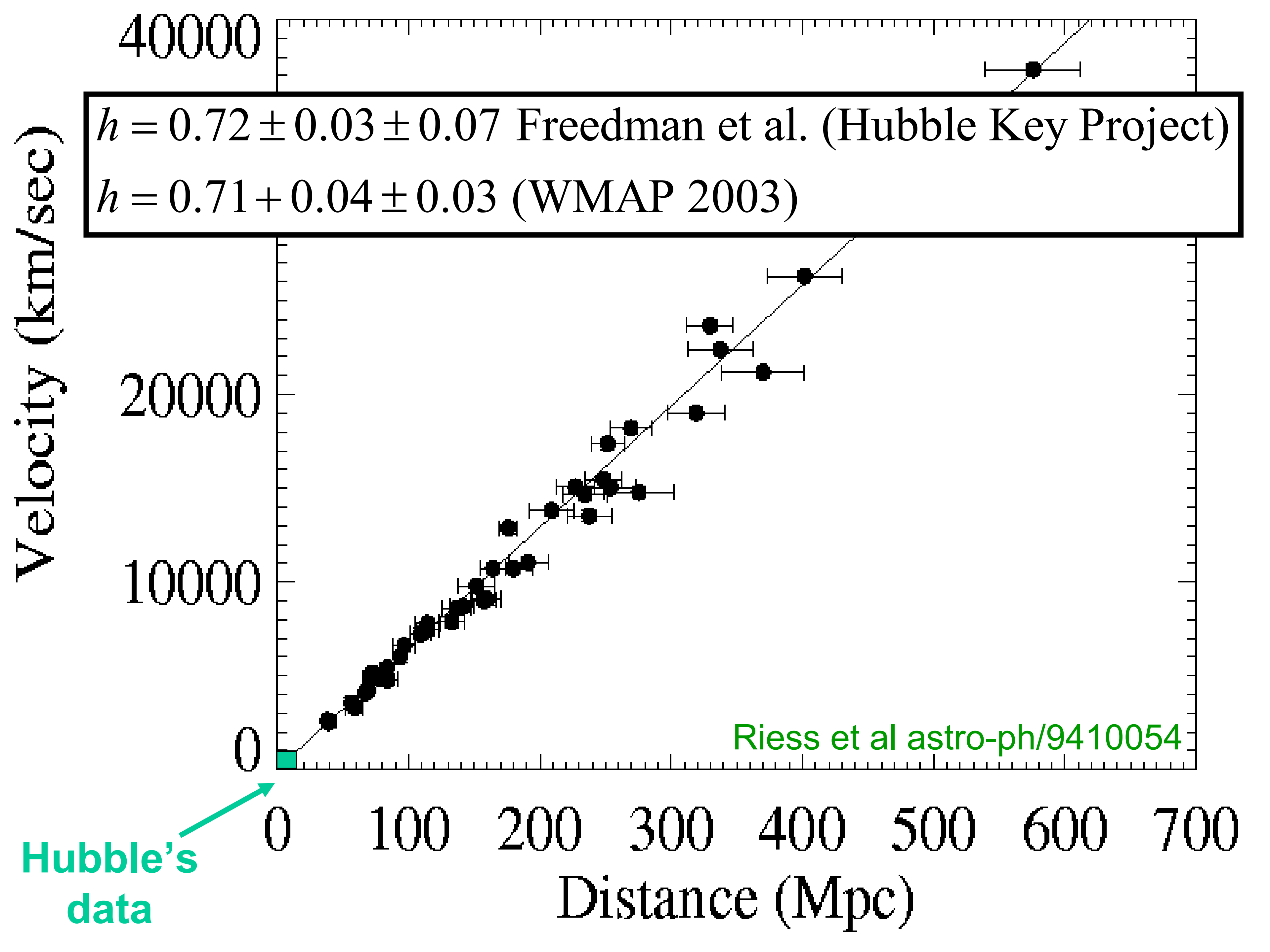
  $$\frac{dV(z)}{dz\,d\Omega} \propto \frac{R^2(z)}{H(z)}$$

- Age of the universe

  $$t(z) \propto \int_0^z \frac{dz'}{(1+z')H(z')}$$

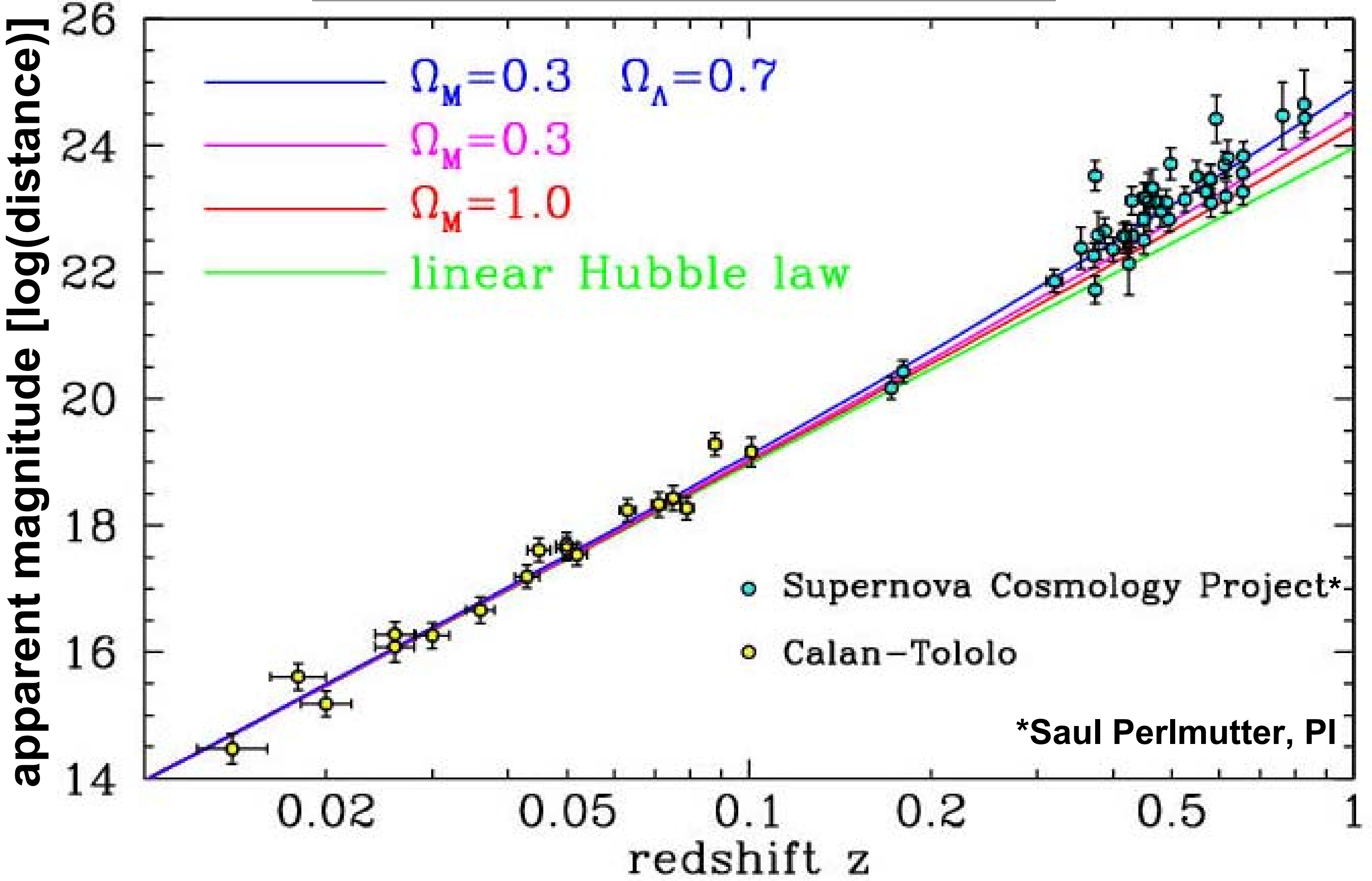
Hubble's Discovery Paper - 1929



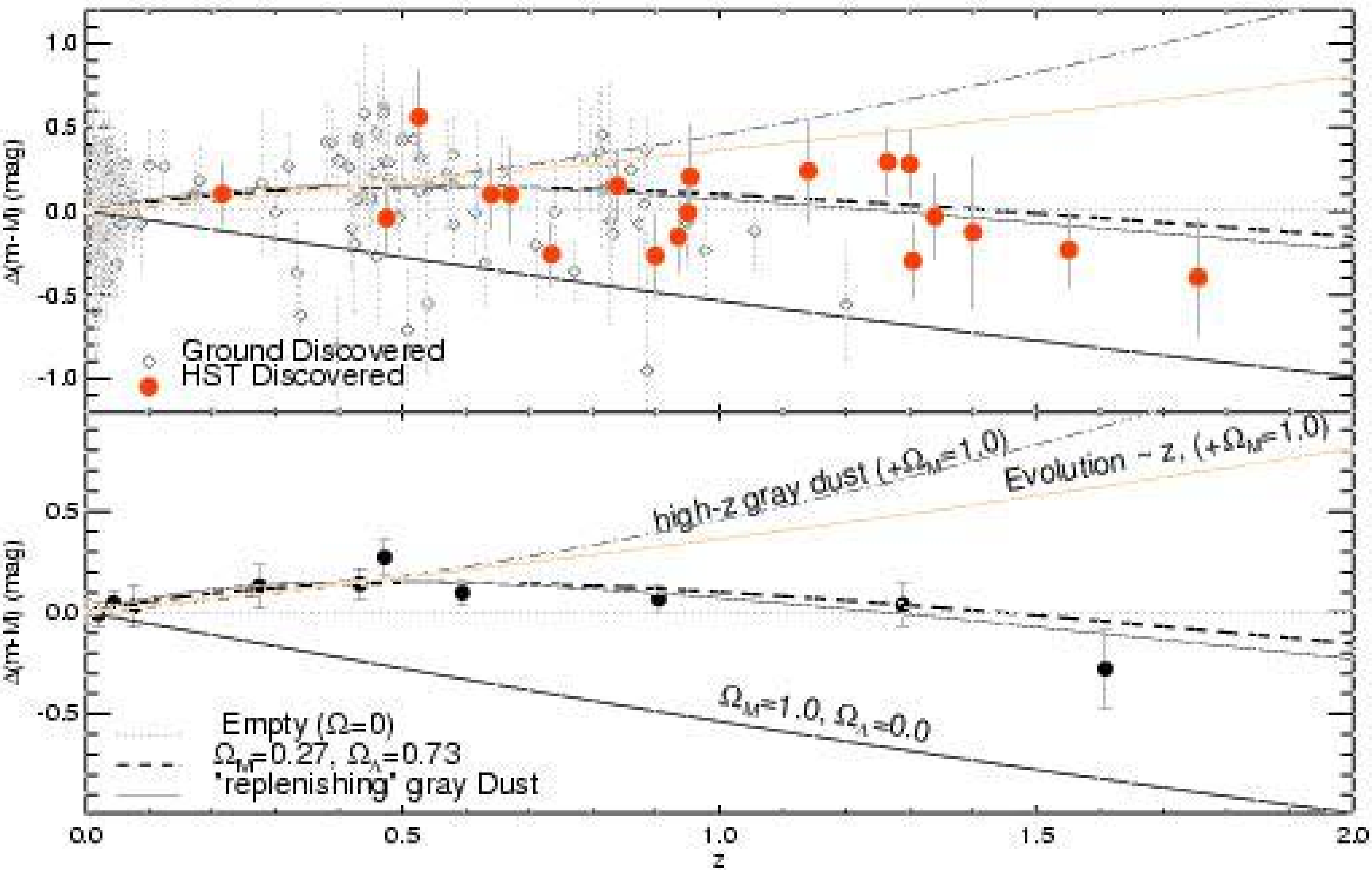


$h = 0.72 \pm 0.03 \pm 0.07$ Freedman et al. (Hubble Key Project)
$h = 0.71 + 0.04 \pm 0.03$ (WMAP 2003)
Velocity (km/sec)
40000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)
Riess et al astro-ph/9410054
Hubble's data

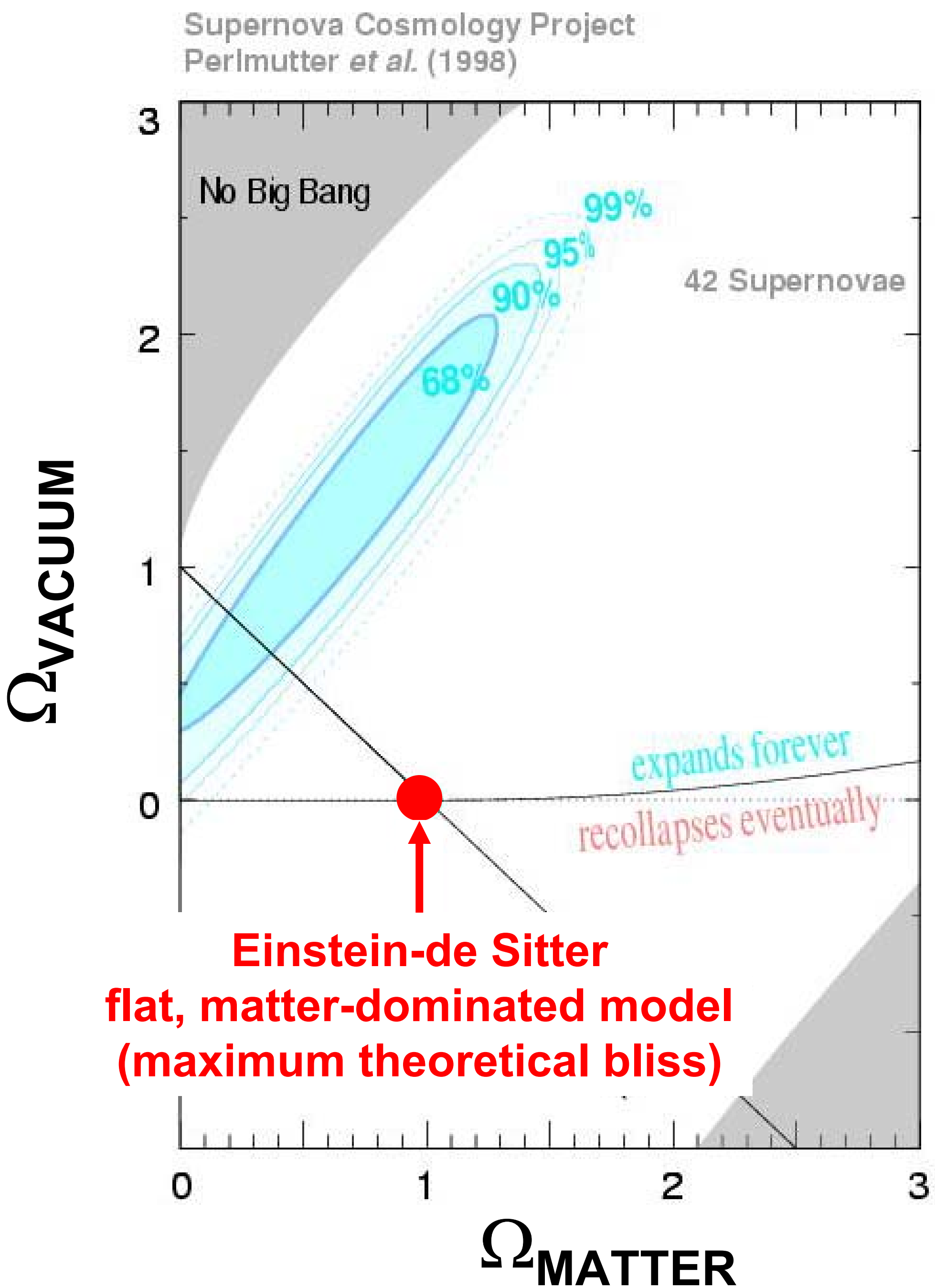
Type Ia supernova



deceleration ⇔ acceleration transition at $z = 0.46 \pm 0.13$



Riess et al. **Astrophys.J.607:665-687,2004**



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

cosmological constant, or
…some changing non-zero vacuum energy, or
… or some unknown systematic effect(s)

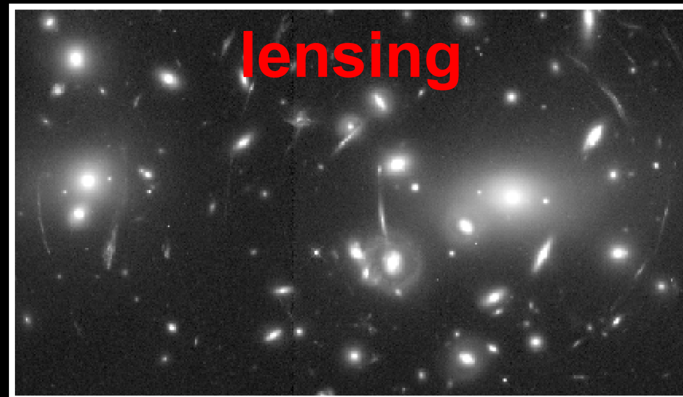
<u>The case for Λ:</u>

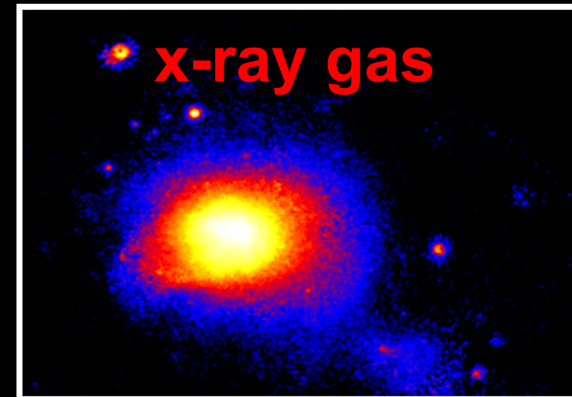
1) Hubble diagram $d_L(z)$

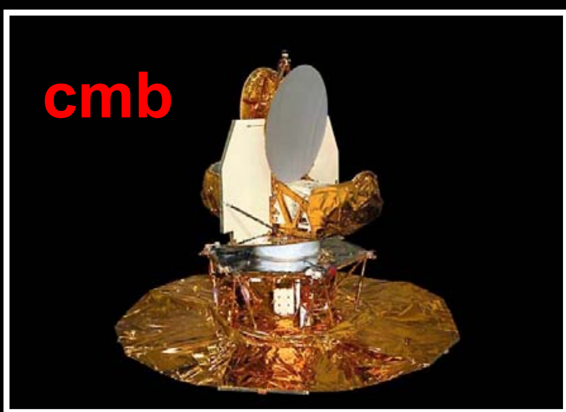
2) subtraction

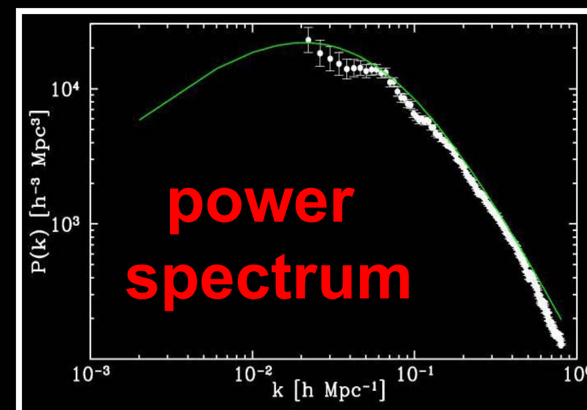
Subtraction

$\Omega_i \equiv \rho_i / \rho_C$ $\qquad$ $\rho_C \equiv 3H_0^2 / 8\pi G$

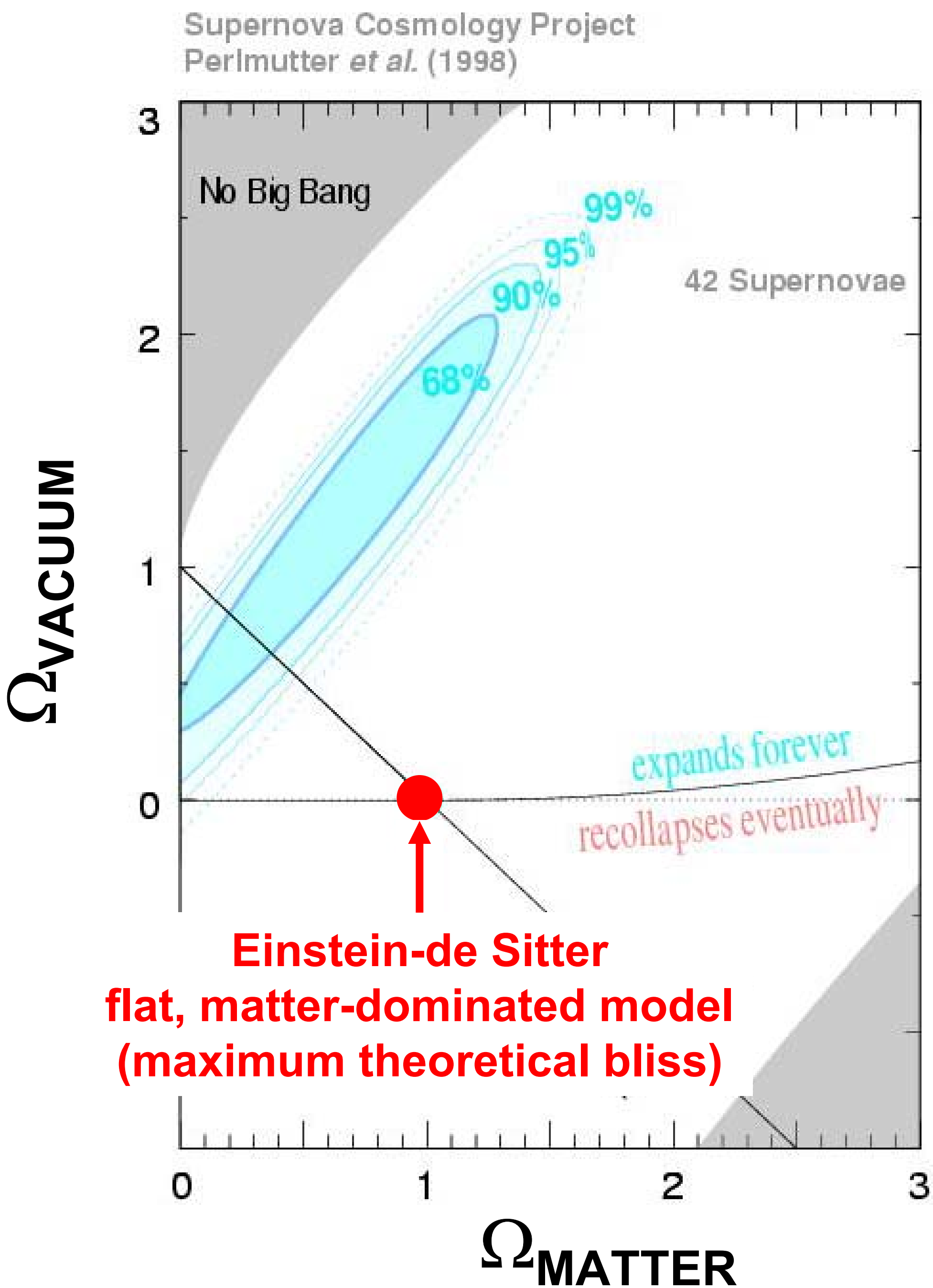








$\Omega_{\mathrm{TOTAL}} = 1$ **(CMB),** $\quad \Omega_M = 0.3, \quad 1 - 0.3 = 0.7$



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**cosmological constant, or
…some changing non-zero vacuum energy, or
… or some unknown systematic effect(s)**

<u>The case for Λ:</u>

1) Hubble diagram $d_L(z)$

2) subtraction

$\Omega_{TOTAL} = 1$
$\Omega_M = 0.3$
$1 - 0.3 = 0.7$

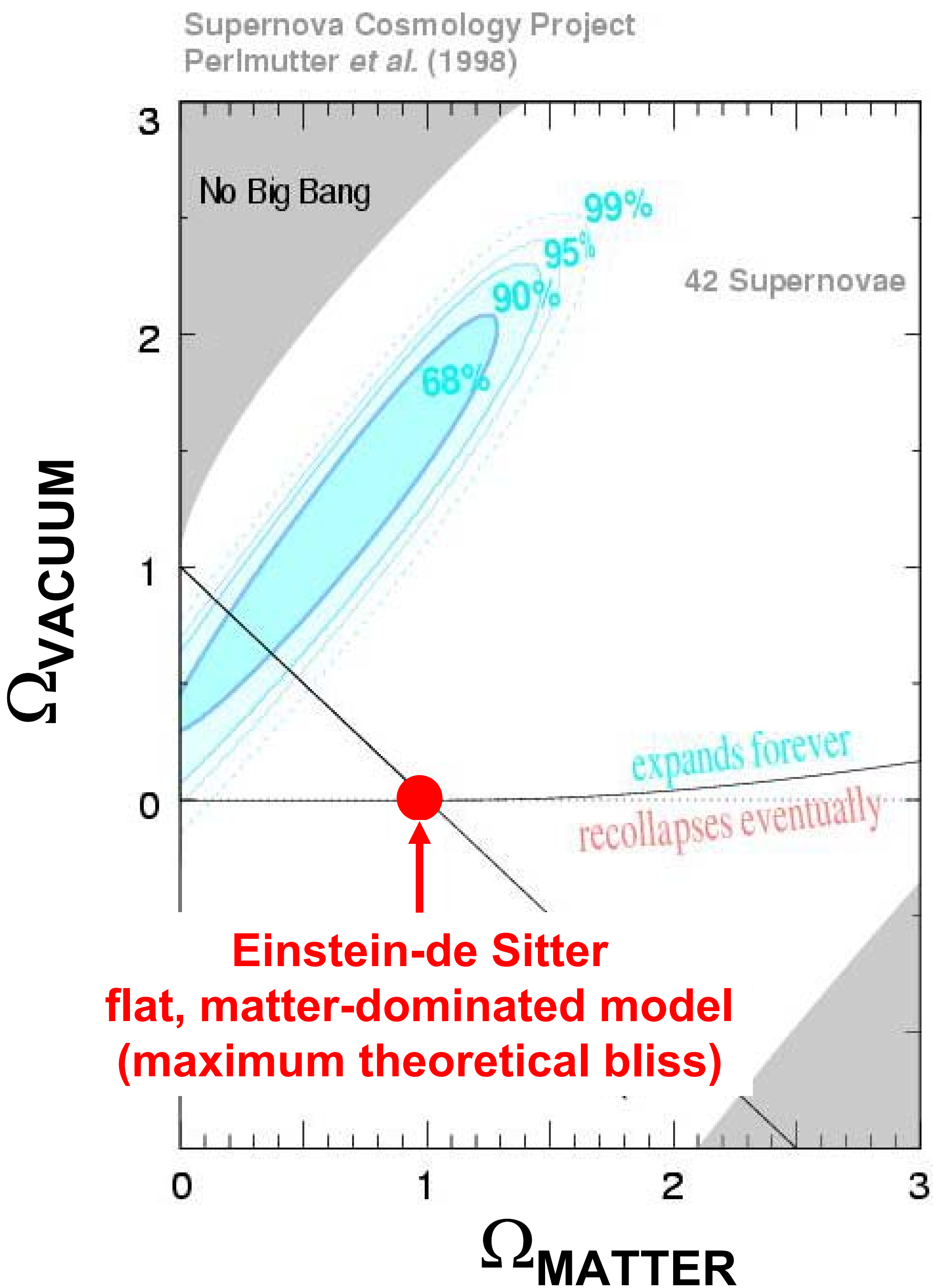
3) age of the universe

t_0 : age of the universe

size challenged star

- ~~white dwarf~~ star cooling 11 ± 2 Gyr
- nucleocosmochronology 12.6 ± 3 Gyr
- globular cluster evolution 13.5 ± 2 Gyr

H_0 =70	Ω_M	Ω_Λ	t_0 (Gyr)
Flat	1.0	0	9.3
Open	0.3	0	12
Open	0.2	0	14
Flat	0.3	0.7	13.5
Flat	0.2	0.8	15



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cosmological constant, or
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The case for Λ:

1) Hubble diagram $d_L(z)$

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$\Omega_{TOTAL} = 1$

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$1 - 0.3 = 0.7$

3) age of the universe

4) structure formation

Einstein's Biggest Blunder?

1917 Einstein proposes cosmological constant

1929 Hubble discovers Expansion of the universe

1934 Einstein calls it "my biggest blunder"

1998 Astronomers find evidence for it

Cosmological constant

Mass density of space:

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

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

The unbearable lightness of nothing!

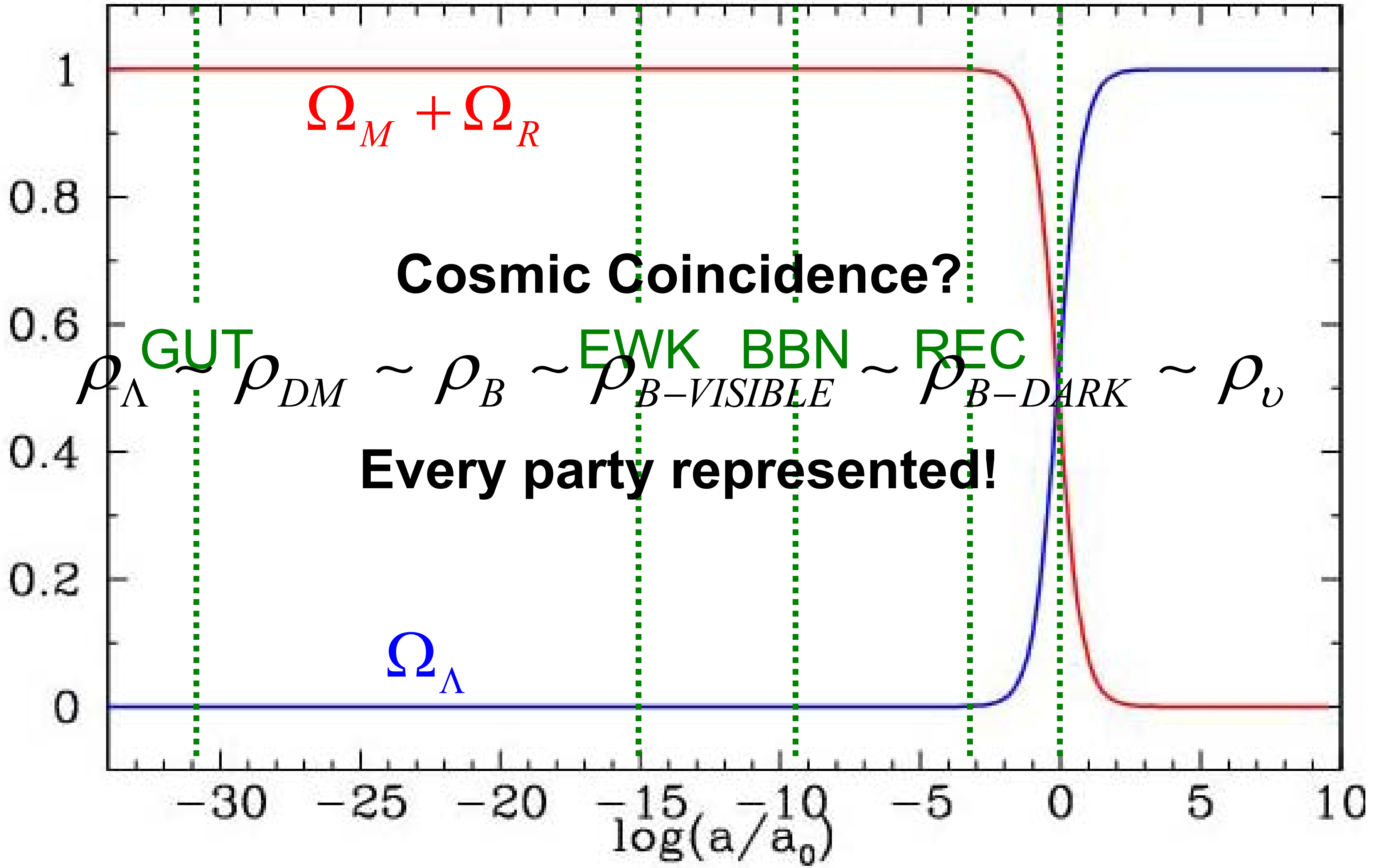
Cosmo-illogical constant?

Numerology:

$$\rho_V = M_W^4 \exp\left(-2/\alpha\right) \qquad \rho_V = M_{\mathrm{SUSY}}^8 \big/ M_{Pl}^4$$

$$m_\nu = 10^{-3}\ \mathrm{eV} \qquad R_5 = 10^{-4}\ \mathrm{cm}$$

Cosmic coincidence



Dark energy depression?

1. Alcohol*

2. Drugs*

3. Anthropic principle*

4. Creative theories

5. Hard experimental work

6. Observational direction

* Therapy, medication, and twelve-step programs available.

Take sides!

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

Perfect fluid stress tensor: $T^{\mu}{}_{\nu} = \mathrm{diag}\left(\rho, -p, -p, -p\right)$

"I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms connected by addition. About the justification of such feelings concerning logical simplicity it is difficult to argue. I cannot help to feel it strongly and I am unable to believe that such an ugly thing should be realized in nature."

Einstein in a letter to Lemaitre, Sept. 26, 1947

Modern view: "It belongs on the right-hand side, and has many contributions."

$$\tilde{T}^{\mu}{}_{\nu} = \mathrm{diag}\left(\rho_\Lambda, \rho_\Lambda, \rho_\Lambda, \rho_\Lambda\right) \qquad \rho_\Lambda = \Lambda/8\pi G$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\left(T_{\mu\nu} + \tilde{T}_{\mu\nu}\right)$$

Take sides!

- Something is established – ΛCDM too good to ignore
  - SNIa
  - Subtraction
  - Age
  - Large-scale structure
  - …

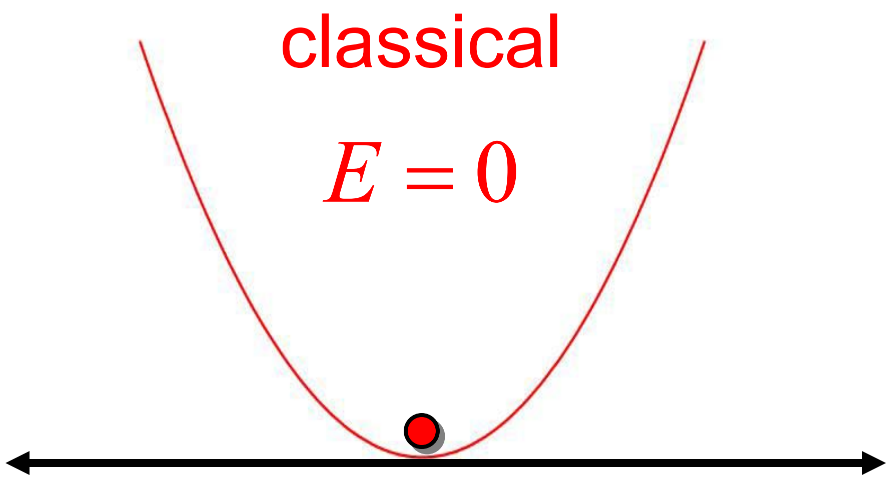
  } $H(z)$ not given by Einstein–de Sitter cosmological model

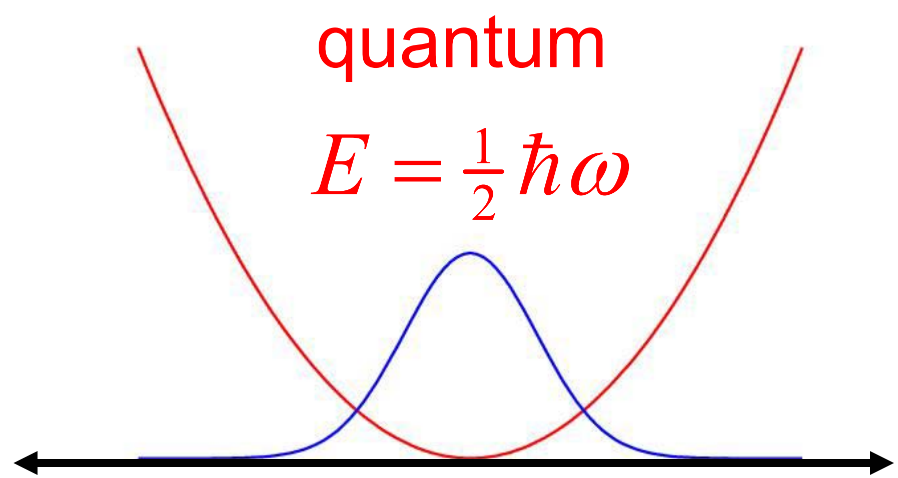
- Dark energy (right-hand side of Einstein equations)?
  - Is it "just" a cosmological constant?
  - If not cosmological constant, what is dynamics?
  - interpretation of $w = \rho/p$?

- Gravity (left-hand side of Einstein equations)?
  - Beyond Einstein (non-GR: branes,etc.)
  - (Just) Einstein (Back reaction of inhomogeneities)

Quantum uncertainty

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



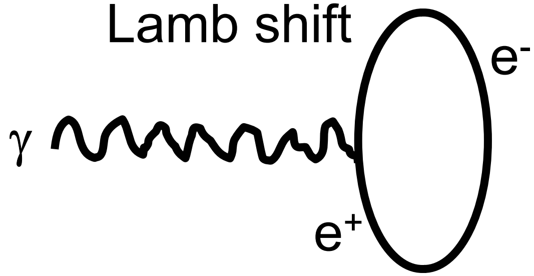


$$\rho = \sum_{all\ particles} \pm \int d^3k \sqrt{k^2 + m^2}$$

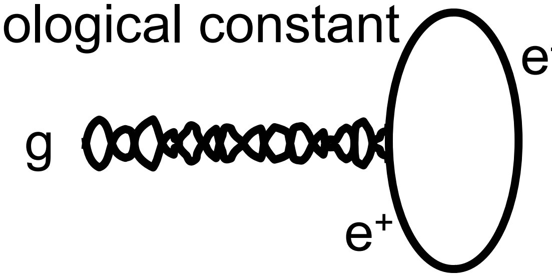
Quantum uncertainty

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

Photons couple to virtual particles
Lamb shift



Gravitons couple to virtual particles
Cosmological constant



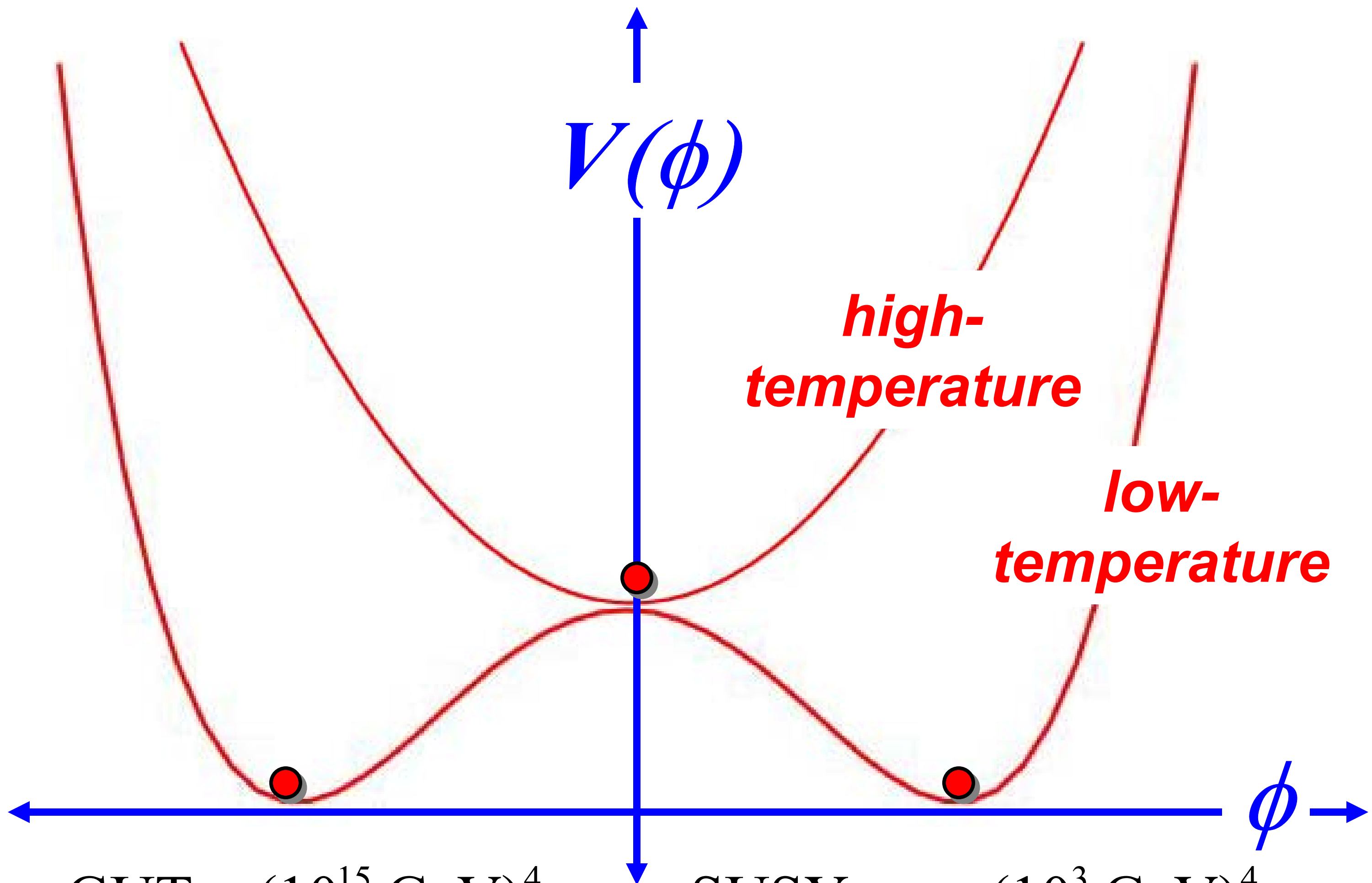
$$\Lambda_C = \infty : \quad \rho_\Lambda = \infty^4 \quad = \text{bad prediction}$$

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

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

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

Spontaneous symmetry breaking



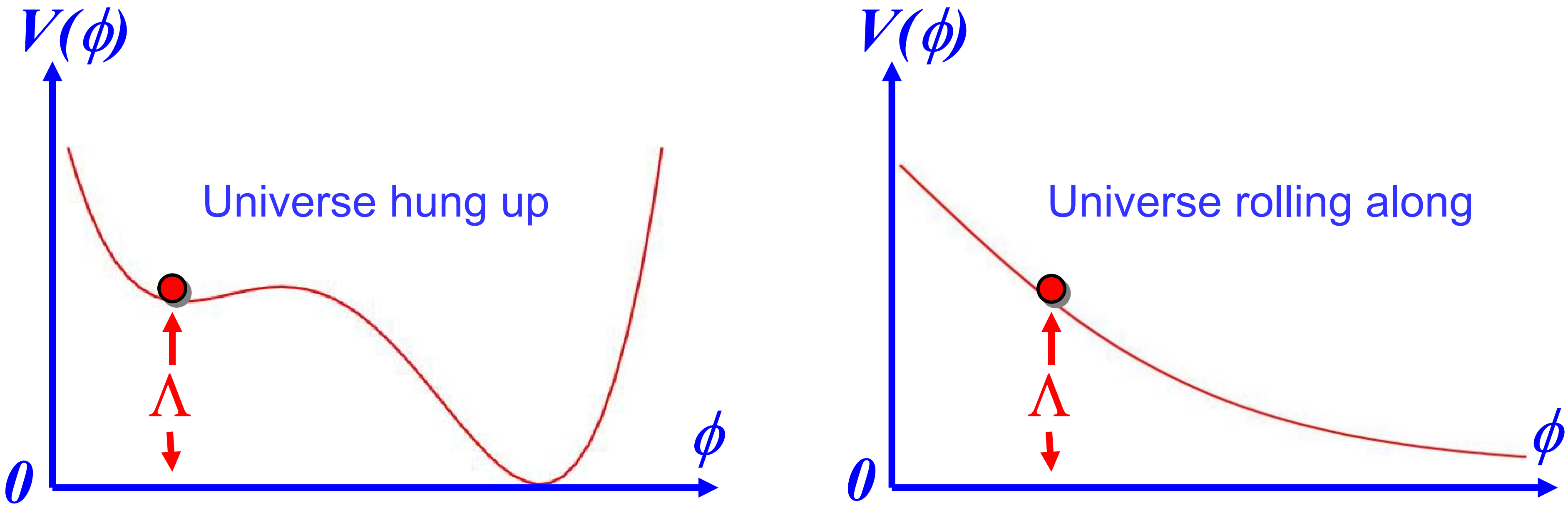
GUT: $(10^{15}\ \mathrm{GeV})^4$ SUSY: $(10^{3}\ \mathrm{GeV})^4$

EWK: $(10^{2}\ \mathrm{GeV})^4$ CHIRAL: $(10^{-1}\ \mathrm{GeV})^4$

OBSERVED: $(10^{-12}\ \mathrm{GeV})^4$

WD-40

- **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!***



Frieman, Freese, Hill, Olinto, …..

WD-40

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

Wetterich; Ratra & Peebles; …

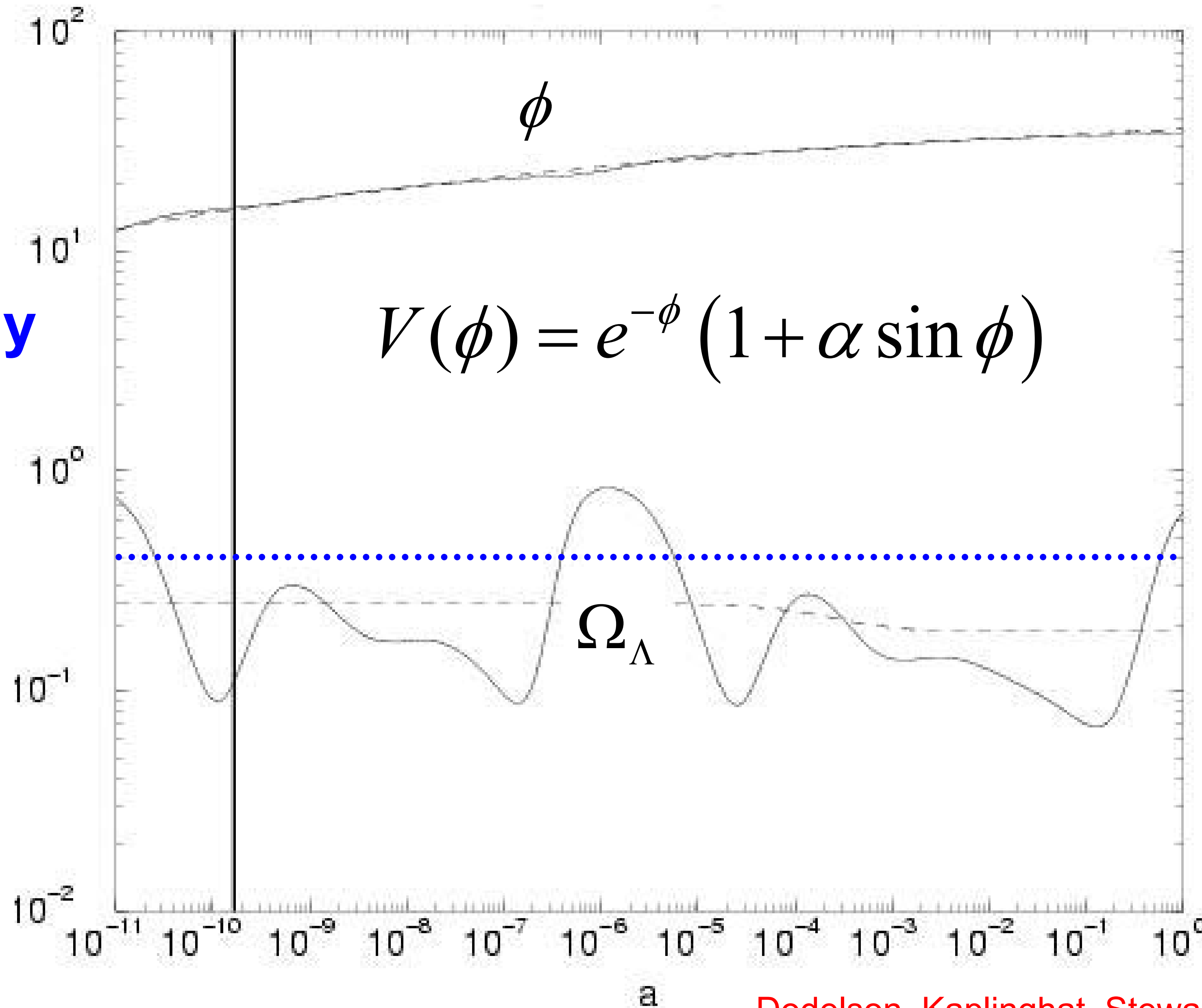
Field equation for tracker: $\ddot{\phi} + 3H\dot{\phi} + dV/d\phi = 0$

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

Can have ρ_ϕ track (stalk) ρ_M - effective mass of the field decreases as H: close but not final answer

- ***Why now?…..* "close to matter domination"**
- ***Why now?…..* "it's just that time"**

WD-40



dark energy
$\neq$ destiny

Dodelson, Kaplinghat, Stewart

WD-40

- **“Quintessence” models have very light scalar fields**
- **Long-range interactions?** Carroll 1998

Entertaining conjecture

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.

— *Shakespeare, King Henry V*th

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

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

- Observed time evolution of H does not fit Einstein–de Sitter.
- We *infer* the existence of dark energy!
- Could Friedmann equation be modified-and no dark energy?

Modifying the left-hand side

- Braneworld modifies Friedmann equation — Binetruy, Deffayet, Langlois
- Friedmann equation modified today — 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
- Einstein (Hilbert) got it wrong — Carroll, Duvvuri, Turner, Trodden

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

- Backreaction of inhomogeneities — Räsänan; Kolb, Matarrese, Notari & Riotto, Notari; Kolb, Matarrese & Riotto

Braneless cosmology

Old Friedmann law:

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

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

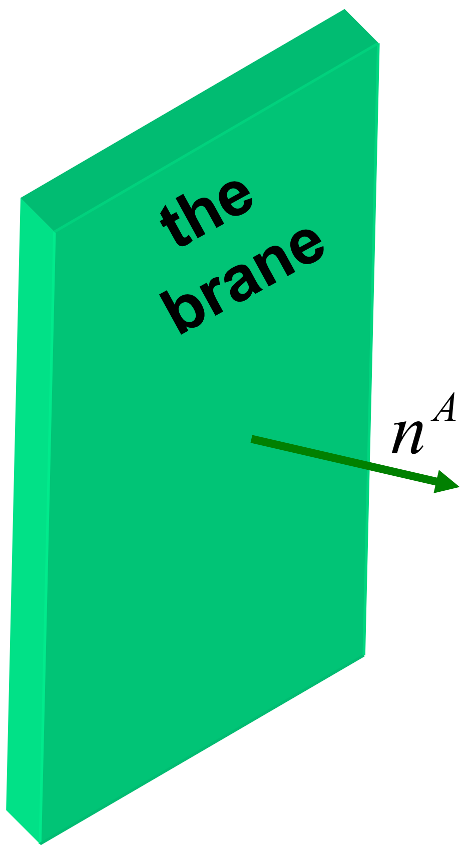
Friedmann (1921)

SNIa evidence for dark energy:

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

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

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

$$[....] = \text{discontinuity across the brane}$$

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

discontinuity in second derivative of scale factor

Braneless cosmology

Old Friedmann law:

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

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

Friedmann (1921)

SNIa evidence for dark energy:

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

Braneful cosmology

New Friedmann law:

Israel jump conditions

Binetruy, Deffayet, Langlois (2000)

$$3H^2 = \frac{\Lambda}{2} + \frac{M_*^{-6}}{12}\rho^2 + \frac{c}{a^4(t, y=0)}$$

Brane cosmology

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

$$3H^2 = \frac{\Lambda}{2} + \frac{M_*^{-6}}{12}\rho^2 + \frac{c}{a^4(t, y=0)}$$

- Possible solution Randall & Sundrum (2000)

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

$$3H^2 = \left(\frac{\Lambda}{2} + \frac{M_*^{-6}}{12}\sigma^2\right) + \frac{M_*^{-6}}{6}\sigma\rho + \frac{M_*^{-6}}{12}\rho^2 + \frac{c}{a^4(t, y=0)}$$

cosmological constant (cancels?)

$$\frac{M_*^{-6}}{18}\sigma = \frac{8\pi G}{3}$$

Friedmann equation

unconventional corrections

Inhomogeneities

Most conservative approach
(no new fields, gravity, extra dimensions)
Universe is inhomogeneous & anisotropic $\rightarrow$ smooth

- Matter smoothing is straightforward (particles $\rightarrow$ fluid), space-time metric smoothing not straightforward!
- Suppose Al's equations apply on some small inhomo/aniso scale
- Smooth on some larger scale
- Smoothing and evolution (going to field eqns.) do not commute
- Einstein tensor computed from smoothed metric is not the same as Einstein tensor computed from smoothed stress-energy
- Difference is a new term that enters Friedmann equation
- New term need not obey energy conditions!

Ellis, Barausse, Buchert, Ellis, Kolb, Matarrese, Notari, Räsänan, Riotto, Schwarz

Inhomogeneities

- The Universe is inhomogeneous

- One can define an average density $\langle \rho \rangle$

- The expansion rate of an inhomogeneous universe of average density $\langle \rho \rangle$ is ***NOT!*** the same as the expansion rate of a homogeneous universe of average density $\langle \rho \rangle$!

- We deduce dark energy because we are comparing to the wrong model universe

- Acceleration is a pure GR effect

Inhomogeneities

Kolb, Matarrese, Notari & Riotto

- $H(z)$ in a perturbed FLRW model:

$$G_{\mu\nu}\left(\vec{x},t\right) = G_{\mu\nu}^{\mathrm{FLRW}}\left(t\right) + \delta G_{\mu\nu}\left(\vec{x},t\right)$$

$$G_{00}^{\mathrm{FLRW}}\left(t\right) + \delta G_{00}\left(\vec{x},t\right) = \kappa^2 T_{00}\left(\vec{x},t\right)$$

$$3\left(\dot{a}/a\right)^2 = \kappa^2\left(\left\langle\rho\right\rangle - \kappa^{-2}\left\langle\delta G_{00}\right\rangle\right)$$

- $(\dot{a}/a)^2$ *is not* $\kappa^2\langle\rho\rangle/3$.

- $\dot{a}/a$ *is not even the expansion rate.*

Inhomogeneities

- For a general fluid, four velocity $u^{\mu} = (1,\vec{0})$.
  (Local observer comoving with energy flow)

- For irrotational dust, work in synchronous and comoving gauge

$$ds^2 = -dt^2 + h_{ij}(\vec{x},t)dx^i dx^j$$

- Velocity gradient tensor

$$\Theta^i{}_j = u^i{}_{;j} = \tfrac{1}{2} h^{ik}\dot{h}_{kj} = \Theta\delta^i{}_j + \sigma^i{}_j$$

- Θ is the volume-expansion factor and $\sigma^i{}_j$ is the shear
  ($\Theta = 3H$ and $\sigma^i{}_j = 0$ in the homogeneous case)

Inhomogeneities

- Local deceleration parameter positive (no-go theorem):

$$q = -\frac{\left(3\dot{\Theta} + \Theta^2\right)}{\Theta^2} = 6\left(\sigma^2 + 2\pi G\rho\right) \geq 0$$

Hirata & Seljak; Flanagan; Giovannini; Alnes, Amarzguioui & Gron

- However must course-grain over some finite domain:

$$\left\langle F \right\rangle_D = \frac{\int_D \sqrt{h}\, F\, d^3x}{\int_D \sqrt{h}\ d^3x}$$

- Evolution and smoothing do not commute:

Buchert & Ellis

Kolb, Matarrese & Riotto astro-ph/0506534

$$\left\langle F \right\rangle_D^{\bullet} - \left\langle F^{\bullet} \right\rangle_D = \left\langle F\Theta \right\rangle_D - \left\langle \Theta \right\rangle_D \left\langle F \right\rangle_D$$

$$\left\langle \Theta \right\rangle_D^{\bullet} = \left\langle \Theta^{\bullet} \right\rangle_D + \left\langle \Theta^2 \right\rangle_D - \left\langle \Theta \right\rangle_D^2 \geq \left\langle \Theta^{\bullet} \right\rangle_D$$

- Invalidates *no-go* theorem

Inhomogeneities

- Define an effective scale factor:

Kolb, Matarrese & Riotto astro-ph/0506534

Buchert & Ellis

$$a_D \equiv \left(V_D / V_{D0}\right)^{1/3} \qquad V_D = \int_D d^3x \sqrt{h}$$

- Course-grained Hubble rate:

$$H_D = \frac{\dot{a}_D}{a_D} = \tfrac{1}{3}\langle \Theta \rangle_D$$

- Effective evolution equations:

$$\frac{\ddot{a}_D}{a_D} = -\frac{4\pi G}{3}\left(\rho_{\text{eff}} + 3p_{\text{eff}}\right) \qquad \rho_{\text{eff}} = \langle \rho \rangle_D - \frac{Q_D}{16\pi G} - \frac{\langle R \rangle_D}{16\pi G}$$

$$\left(\frac{\dot{a}_D}{a_D}\right)^2 = \frac{8\pi G}{3}\rho_{\text{eff}} \qquad p_{\text{eff}} = -\frac{Q_D}{16\pi G} + \frac{\langle R \rangle_D}{48\pi G}$$

not described by a simple $p = w\,\rho$

- Kinematical back reaction: $Q_D = \tfrac{2}{3}\left(\langle \Theta^2 \rangle_D - \langle \Theta \rangle_D^2\right) - 2\langle \sigma^2 \rangle_D$

Inhomogeneities

- Does this have anything to do with our universe?
- Have to go to non-perturbative limit
- Toy model proof of principle: Tolman-Bondi dust model
  (Nambu and Tanimoto (gr-qc/0507057)

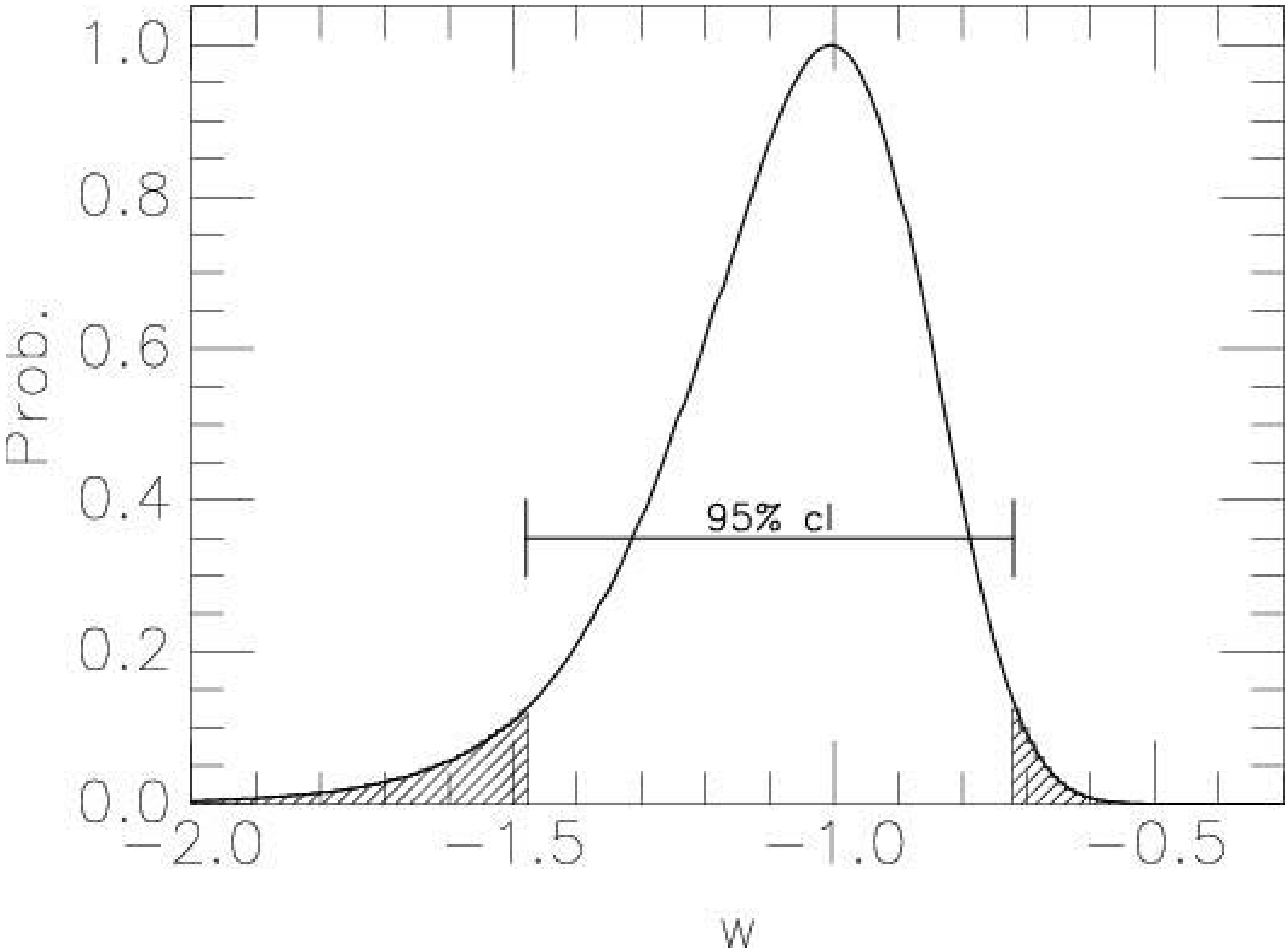
How do we sort it out?

- Something is established-ΛCDM too good to ignore
  SNIa
  Subtraction
  Age
  Large-scale structure
  .....
- Left-hand side or right-hand side?

Left-hand side:
- Growth of structure
- New gravity?
  solar-system effects
  short-range effects
  branes (accelerator effects)
- Inhomogreneities?

Right-hand side:
- $w = -1$
  "just" Λ?
- $w \neq -1$
  what is dynamics?
- Scalars
  long-range forces?

For now…parameterize



High-z supernova team

$w < -1$?

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

$$|p| \le |\rho| \Rightarrow -\rho \le p \le \rho$$

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

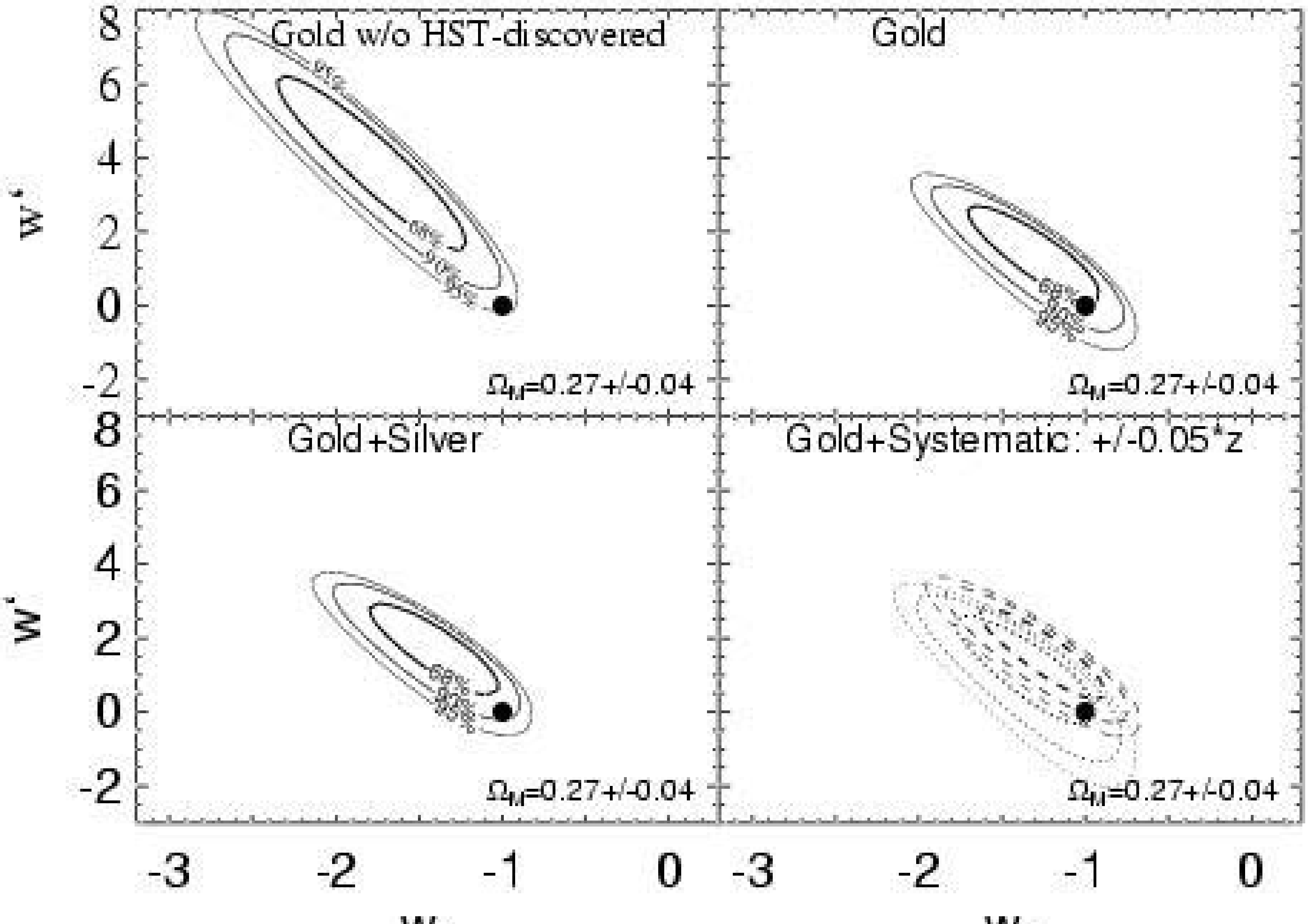
$$L = -\dot{\phi}^2 - \exp\left(-\phi^2\right)$$

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

Caution in interpretation

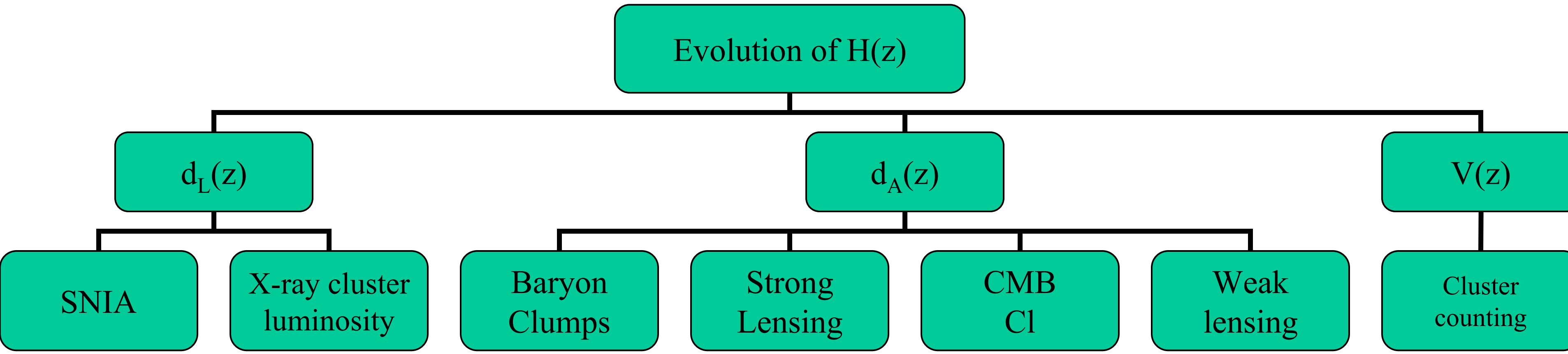
Always read the fine print:

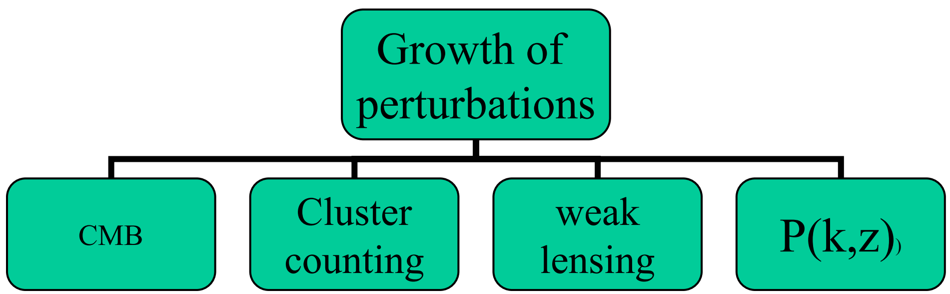
- **Astrophysical systematic errors**
- **What are the model assumptions?**
  - w = constant? w', w_a
  - assume Ω_Λ?
- **What are the priors?**
  - Ω_M, Ω_B, H_0, …

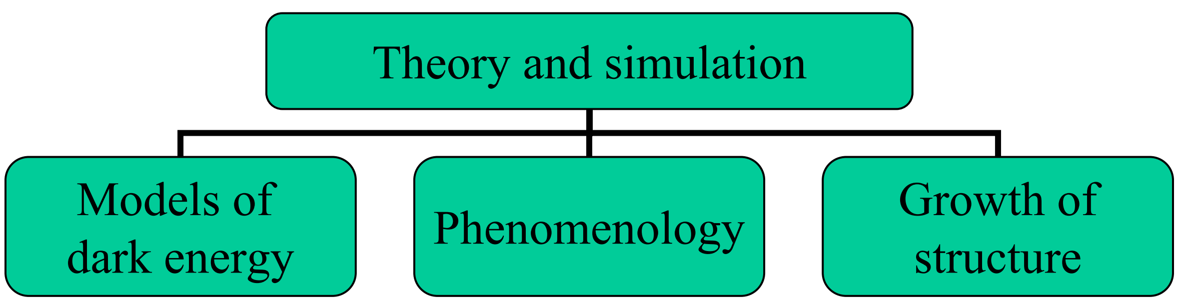


Gold w/o HST-discovered
Gold
Gold+Silver
Gold+Systematic: +/-0.05*z
68%
95%
99%
Ω_M=0.27+/-0.04
w'
w_o
8
6
4
2
0
-2
-3
-2
-1
0

Riess et al.

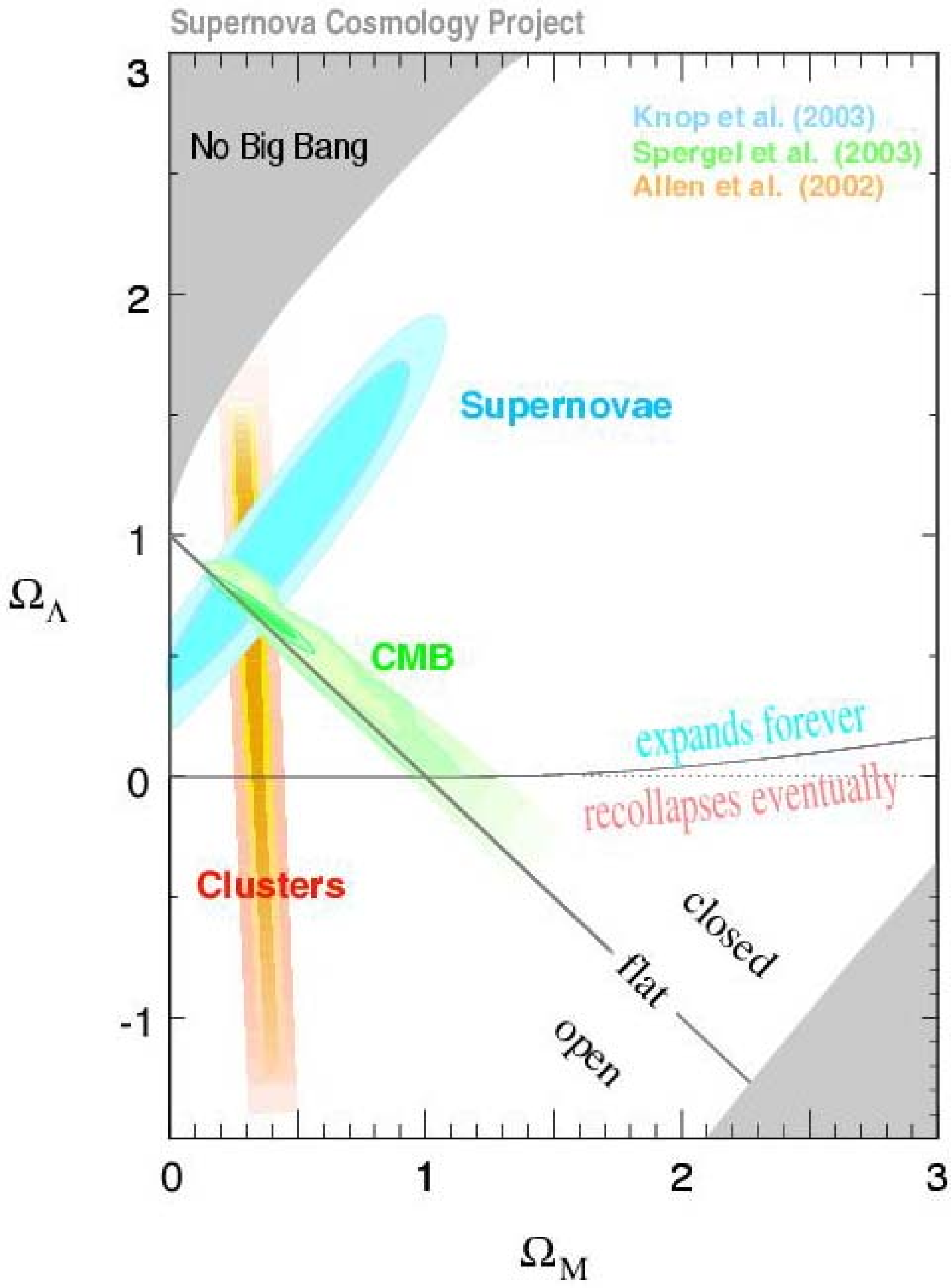

Evolution of H(z)
$d_L(z)$
$d_A(z)$
V(z)
SNIA
X-ray cluster luminosity
Baryon Clumps
Strong Lensing
CMB Cl
Weak lensing
Cluster counting


Growth of perturbations
CMB
Cluster counting
weak lensing
P(k,z)


Theory and simulation
Models of dark energy
Phenomenology
Growth of structure

• Don’t focus on any one particular error contour

• Focus on fact that error contours for different methods are not parallel



Aether of the 21st century?

- It’s an infrared issue!

- It’s an ultraviolet issue!

The Gravity of

Dark Energy

Gravity in the Quantum World and the Cosmos

XXXIII SLAC Summer Institute, August 2005

Rocky Kolb, Fermilab & Chicago