# The Hunting of the Dark Energy

and

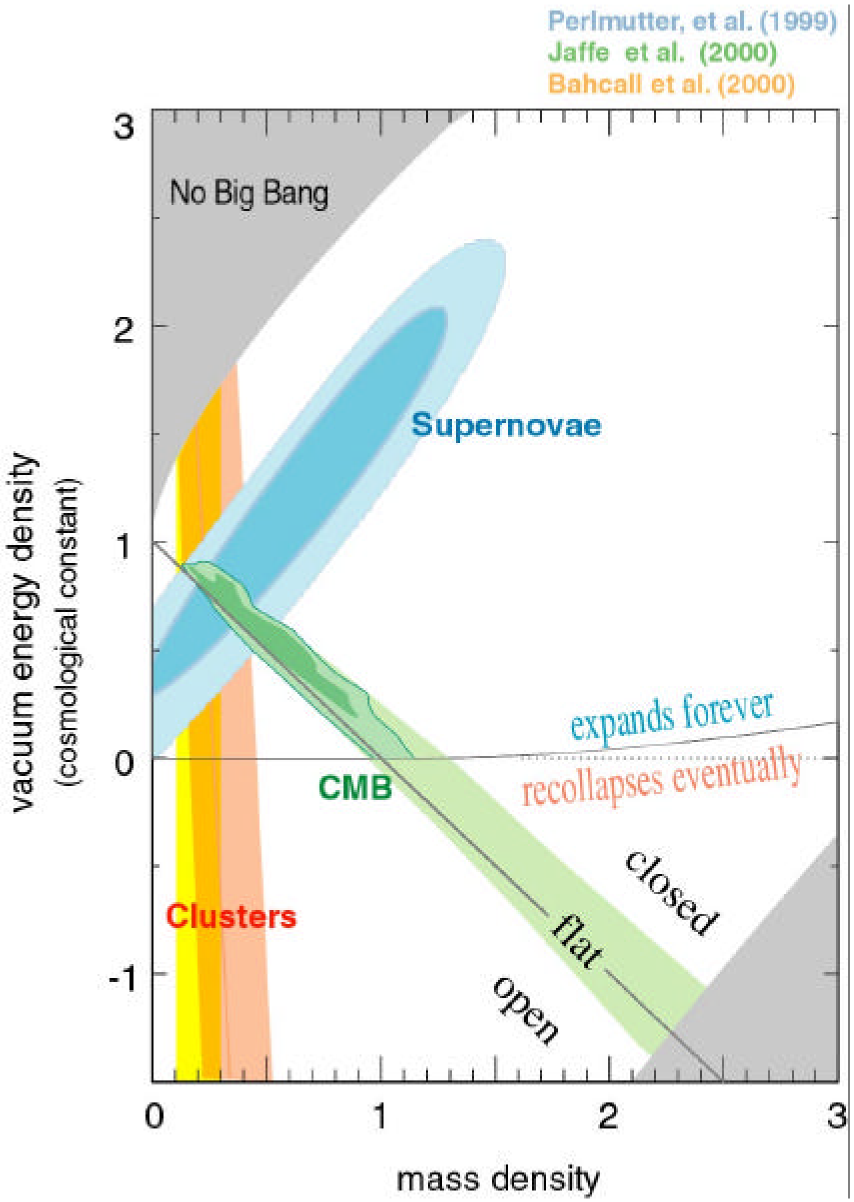
# On Beyond Lambda


Eric Linder


Cosmology Teach-In

26 June 2003

# Cosmic Concordance




- *Supernovae alone*

þ **Accelerating expansion**

⇒ L **> 0**

- *CMB alone*

þ **Flat universe**

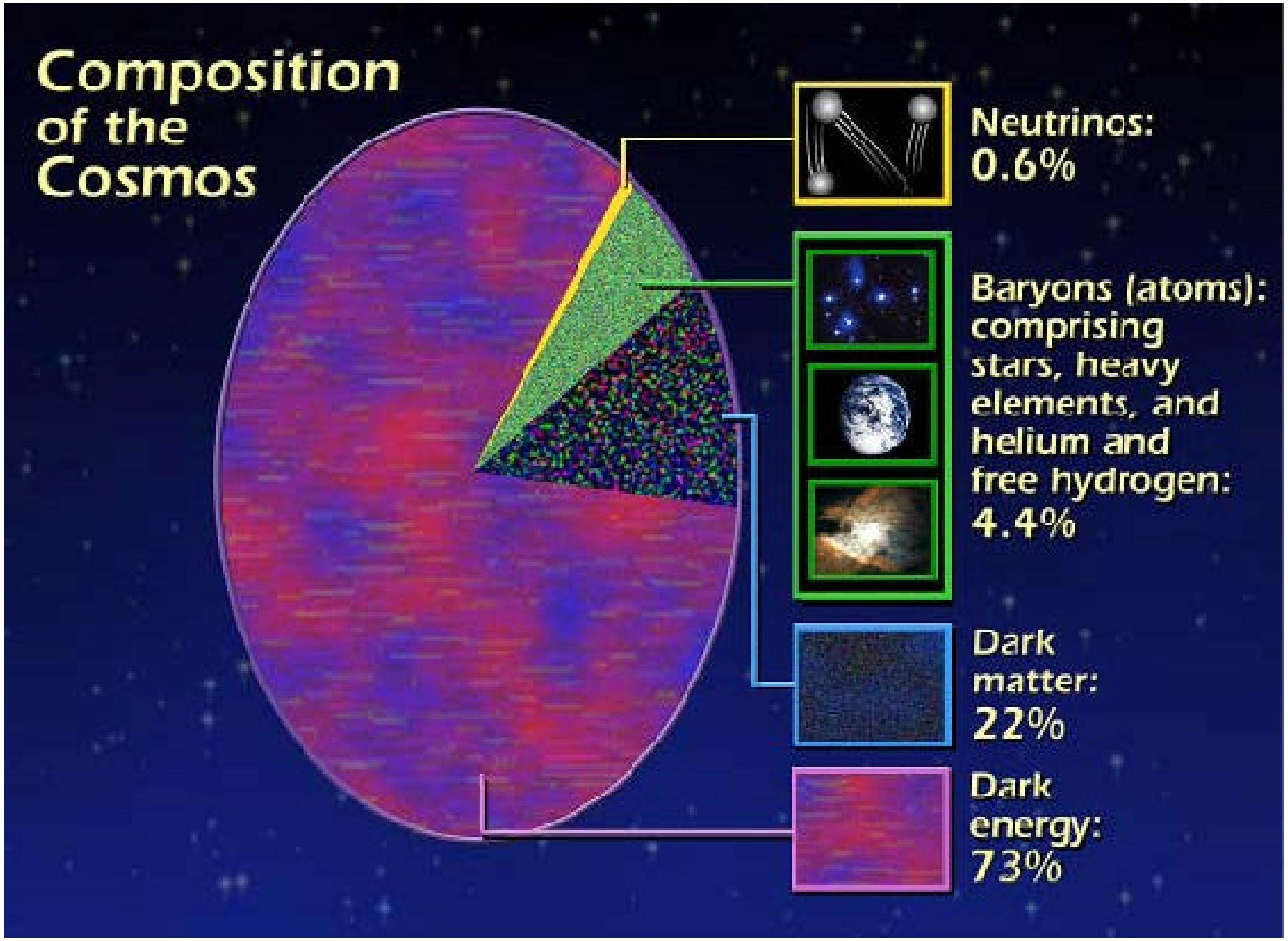
þ L **> 0**

- *Any two of SN, CMB, LSS*

þ **Dark energy ~70%**

# Revolutions in Physics

## Lord Kelvin (1900): Two clouds on the horizon

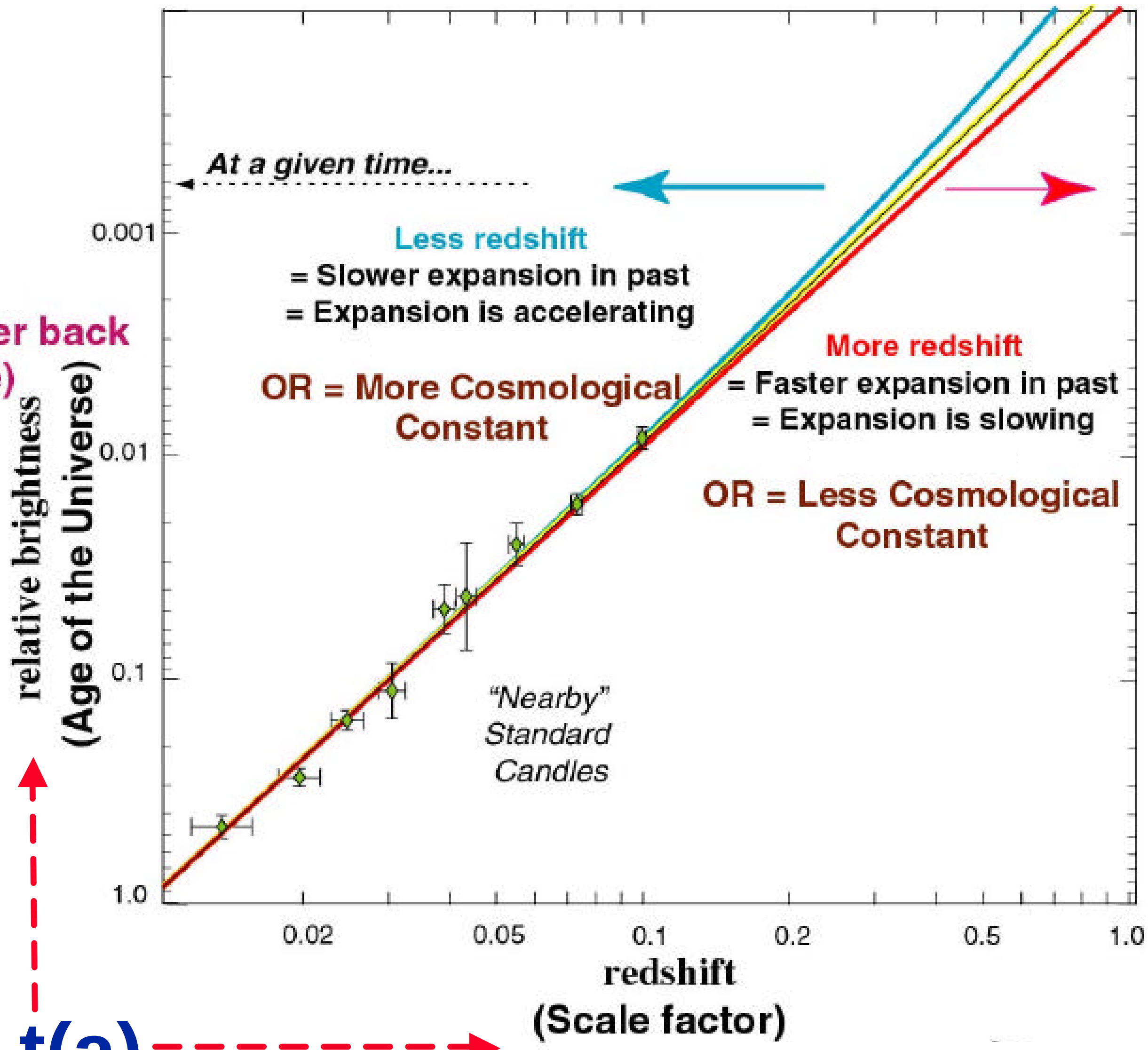



STScI

**The horizon is 95% cloudy!**

# Supernovae map expansion

(Further back in time)




Expansion history **t(a)**

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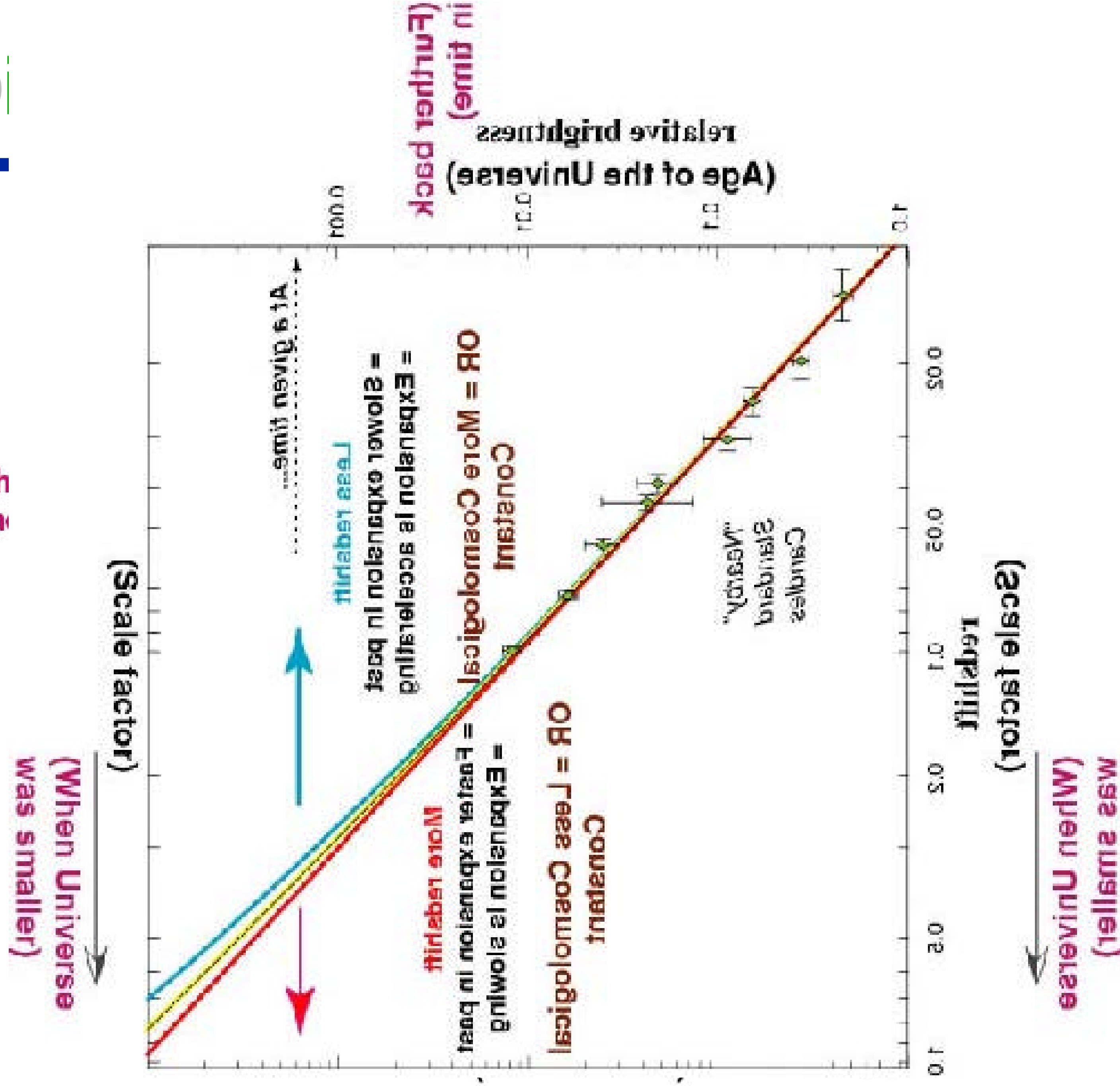


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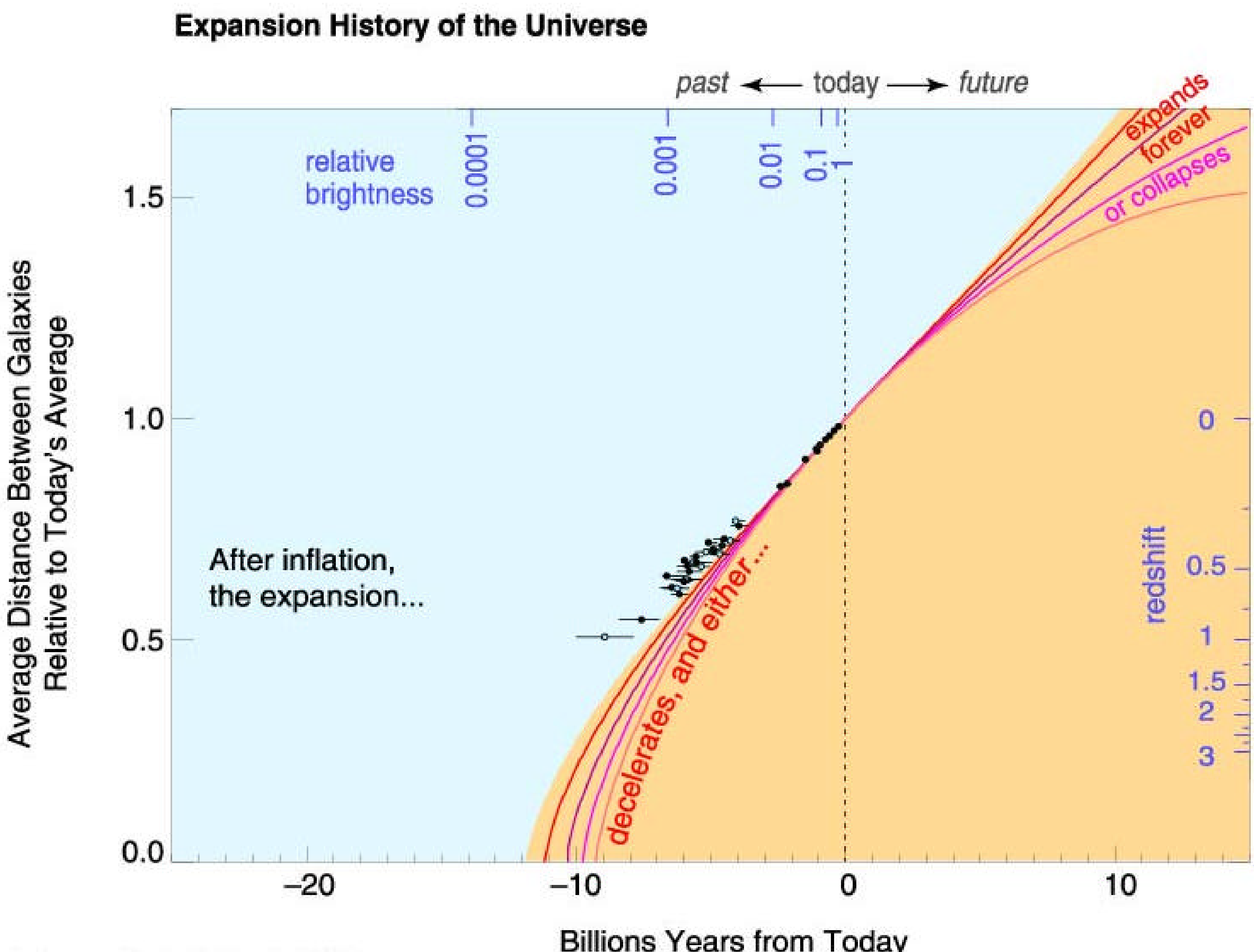
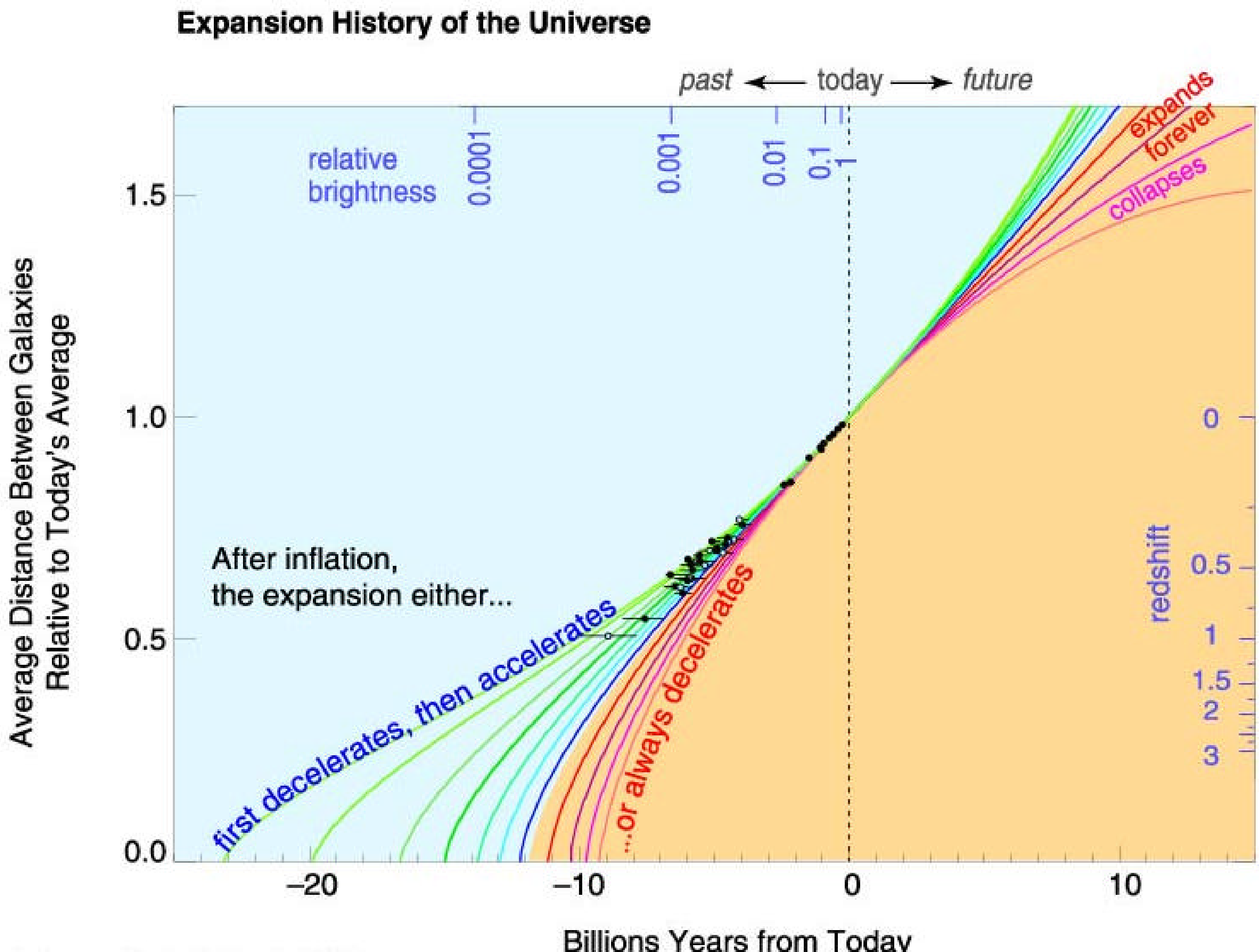
# Supernovae: Mapping Expansion



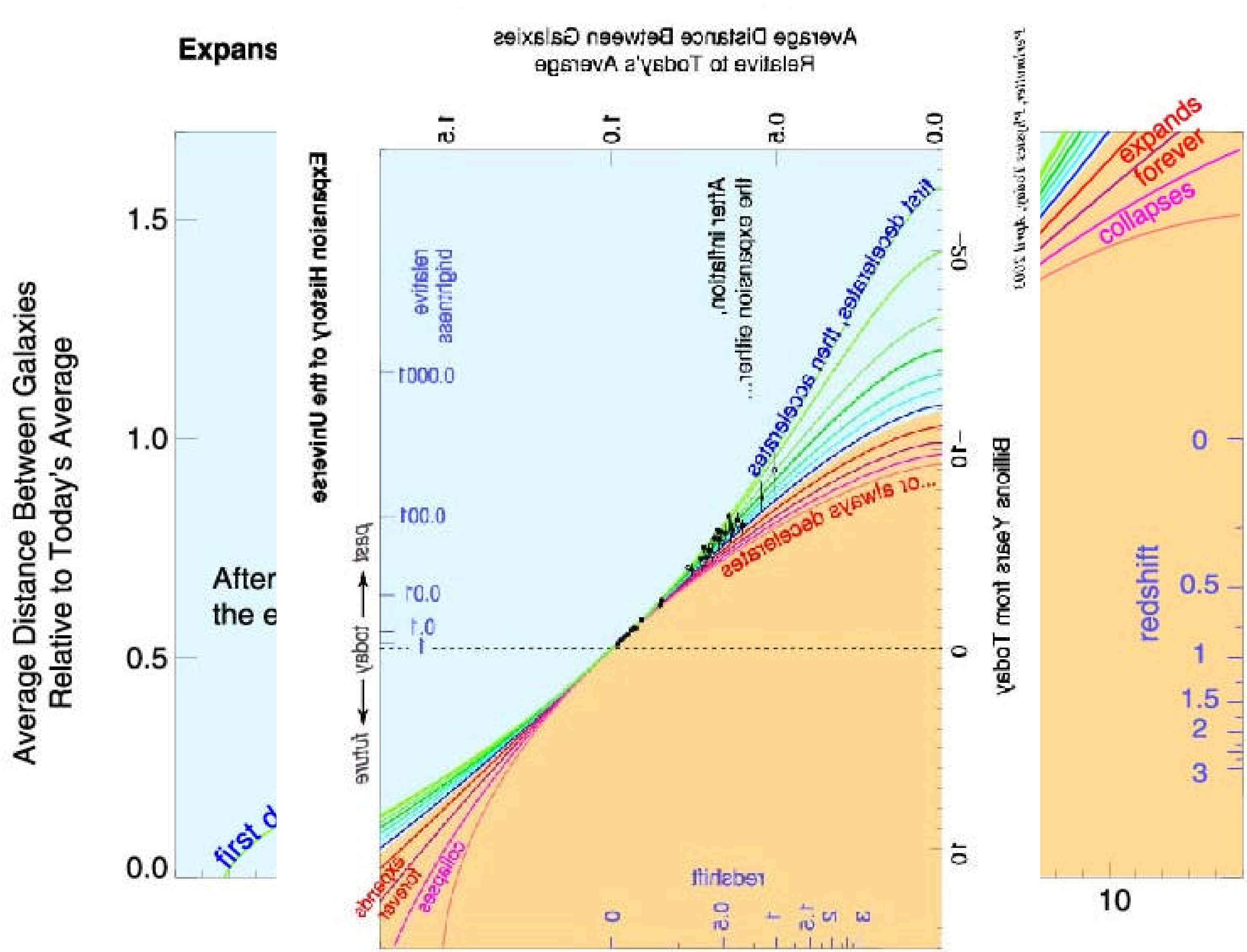

*Perlmutter, Physics Today, April 2003*

# Supernovae: Acceleration



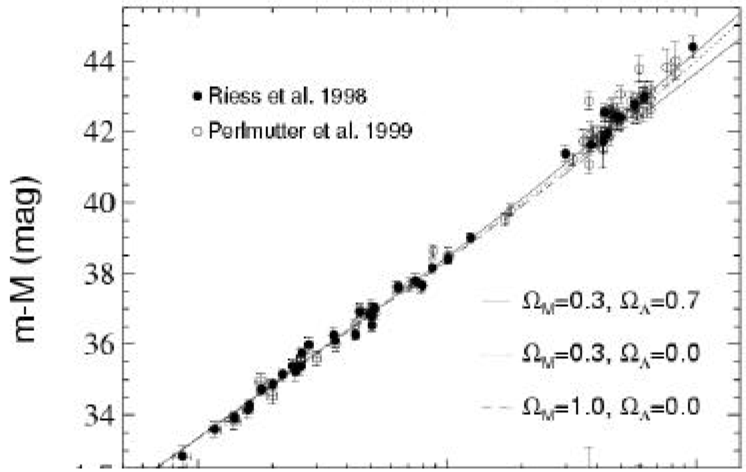

*Perlmutter, Physics Today, April 2003*

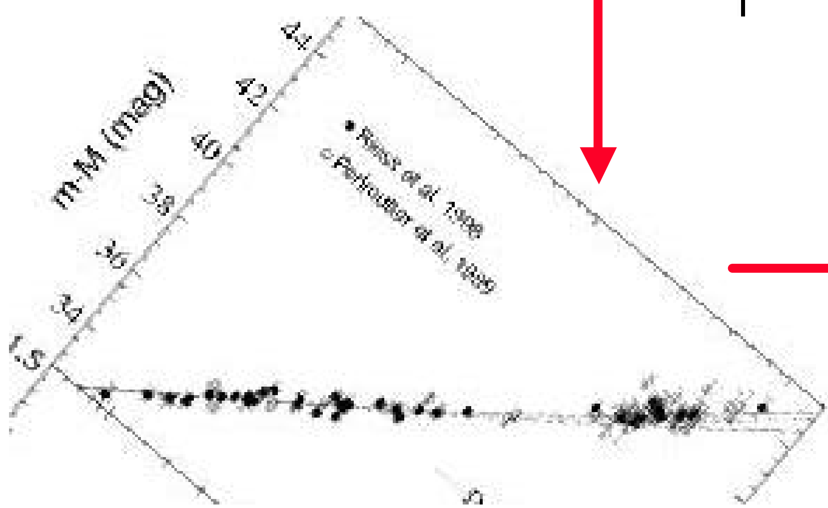
# Expansion map ® d(z)

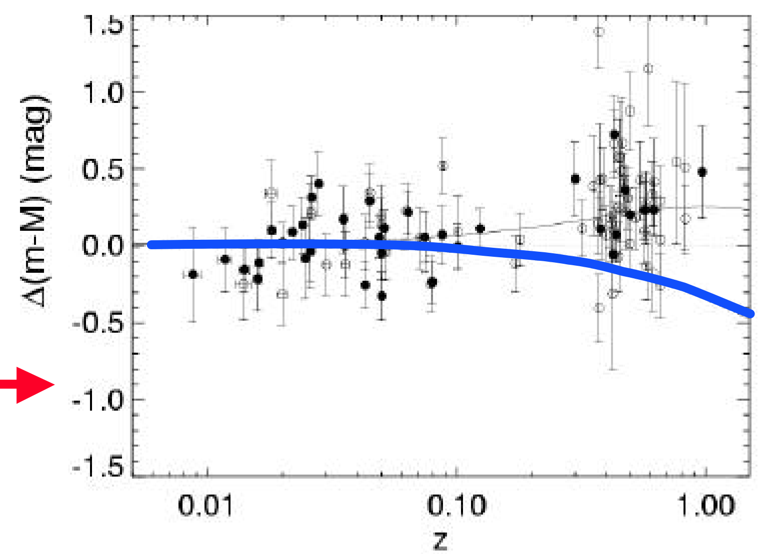



Perlmutter, Physics Today, A

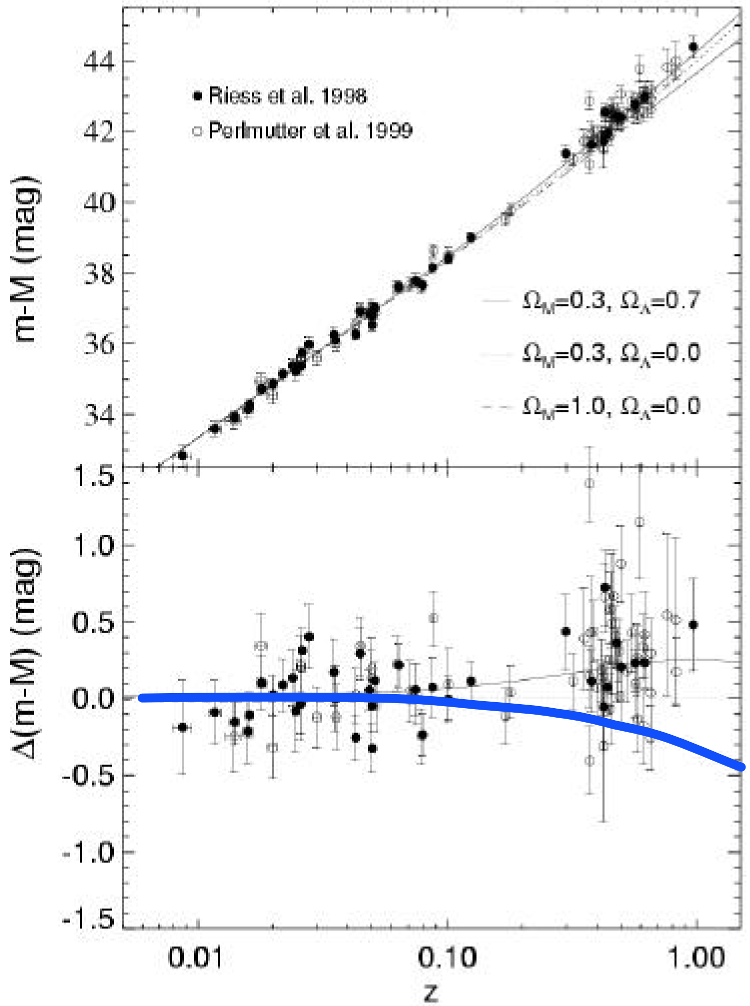
# Supernova Cosmology 1

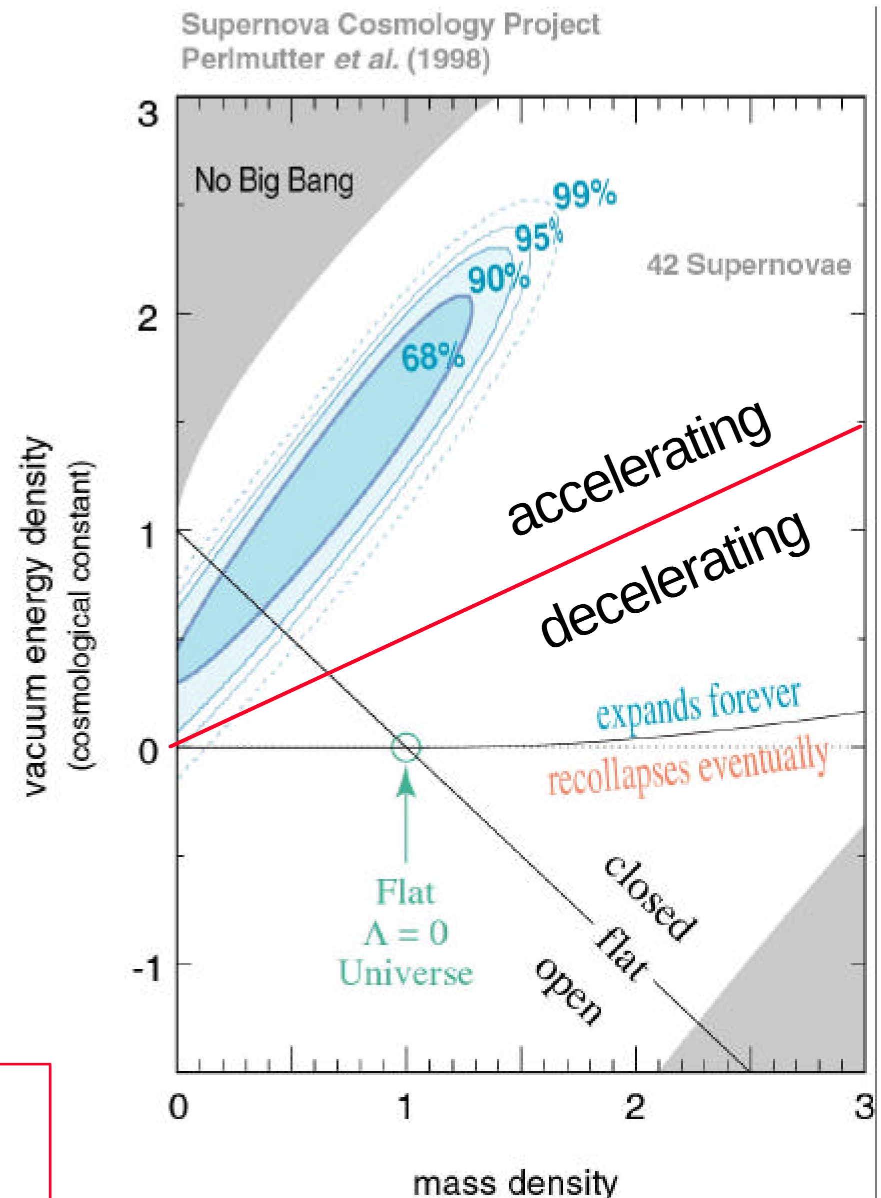


# Supernova Cosmology 2




**In flat universe:** $W_M$**=0.28 [±.085 stat][±.05 syst]**

**Prob. of fit to L=0 universe: 1%**

# Acceleration

**Einstein gravitation says gravitating mass depends on energy-momentum tensor:**

**both energy density r and pressure p,**

**as r+3p**

**Negative pressure can give negative "mass"**

**Newton's 2nd law: Acceleration = Force / mass**

$$\ddot{R} = - G\,(4p/3)\,(r+3p)\,R$$

**Negative pressure can accelerate the expansion**

# Negative pressure

**Relation between r and p (*equation of state*) is crucial:**

$$\boxed{w = p / r}$$

**Acceleration possible for $p < -(1/3)r$ or $w < -1/3$**

**What does negative pressure mean?**

**Consider 1st law of thermodynamics:**

$$dU = -p\, dV$$

| | |
|---|---|
| **But for a spring** | $dU = +k\, x dx$ |
| **or a rubber band** | $dU = +T\, dl$ |

# Dark Energy

**Acceleration of the universe can be caused within general relativity by negative pressure.**

**This can be from a dark energy,**
**arising from the “springiness” of space,**
**i.e. from the quantum vacuum.**
***cf.* Einstein, deSitter, Weyl 1910s-1920s.**

**Is this mysterious dark energy the original cosmological constant, a quantum zeropoint sea?**

# The Hunting of the Dark Energy

He had bought a large map representing the sea
Without the least vestige of land,
And the crew were much pleased when they found it to be
A map they could all understand.

-- Lewis Carroll, *The Hunting of the Snark*

**Two flaws:**

- The sea level should be $10^{120}$ times the height of the land – it really should be a featureless sea!
- The area of sea vs. land should evolve rapidly – why do we see it as 70:30 not all one or the other?

# Cosmological Constant $\Lambda$

The energy scale of the vacuum needed to fit observations of the dark energy density (the sea level) is meV not $M_{pl} \sim 10^{19}$ GeV

To try to correct the coincidence problem (neither all land nor all sea today), the effective mass of a varying quantum field must have a Compton wavelength ~ size of universe

$$m \sim H_0 \sim 1/(10^{28}\ \text{cm}) \sim 10^{-33}\ \text{eV}$$

$$[L_{pl} = 10^{-33}\text{cm}] / 10^{28}\ \text{cm} = m / [10^{19}\text{GeV}]$$

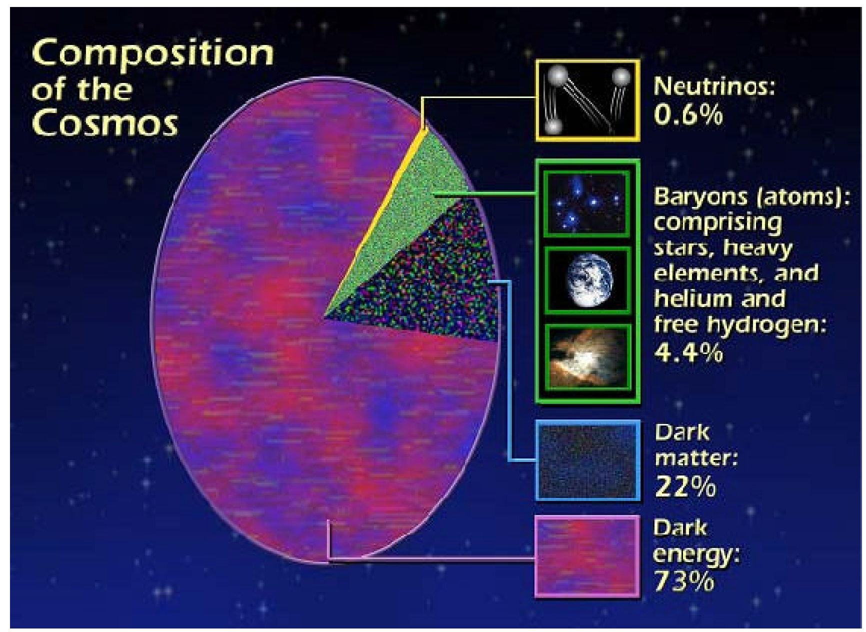
# L Fails

**Other maps are such shapes, with their islands and capes,**
**But we've got our brave [captain] to thank**
**(So the crew would protest) that he's bought us the best –**
**A perfect and absolute blank.**

**-- Lewis Carroll, *The Hunting of the Snark***

**The universe is not simple:**

**So maybe neither is the quantum vacuum (or gravitation?)**



# So… On Beyond L!

**On beyond L! It's high time you were shown**
**That you really don't know all there is to be known.**

**-- à la Dr. Seuss, *On Beyond Zebra***

**How do we find dark energy models inspired by fundamental physics?**

**How do we find the nature of dark energy through observations?**

# Dark Energy – Early Days

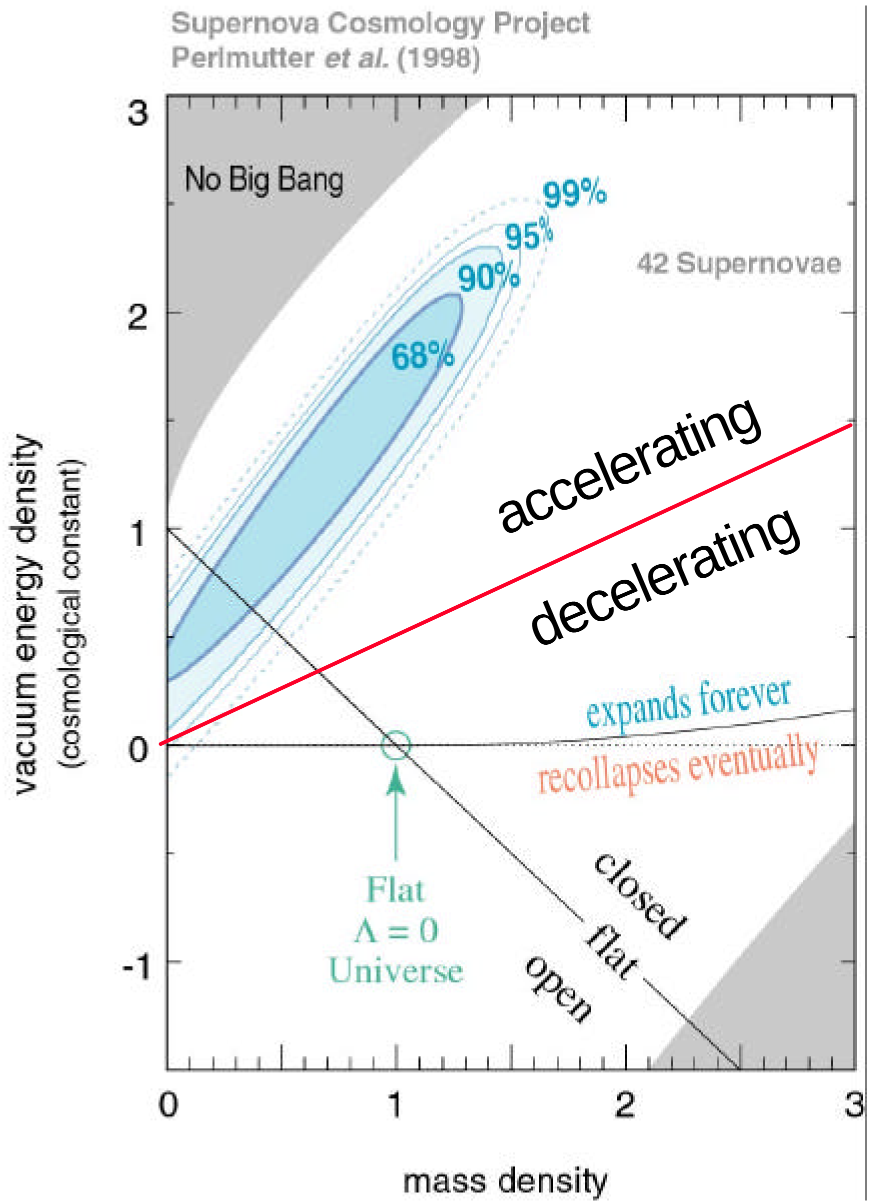
**This is not new!**

- **High energy physics models – Linde 1986**
- **Cosmological probes – Wagoner 1986 (plots by EL)**
- **Cosmological observations – Loh & Spillar 1986**

**But observations were imprecise and inaccurate. Galaxy counts showed $W_M$ » 1 but major difficulties with evolution.**

***12 years passed…***

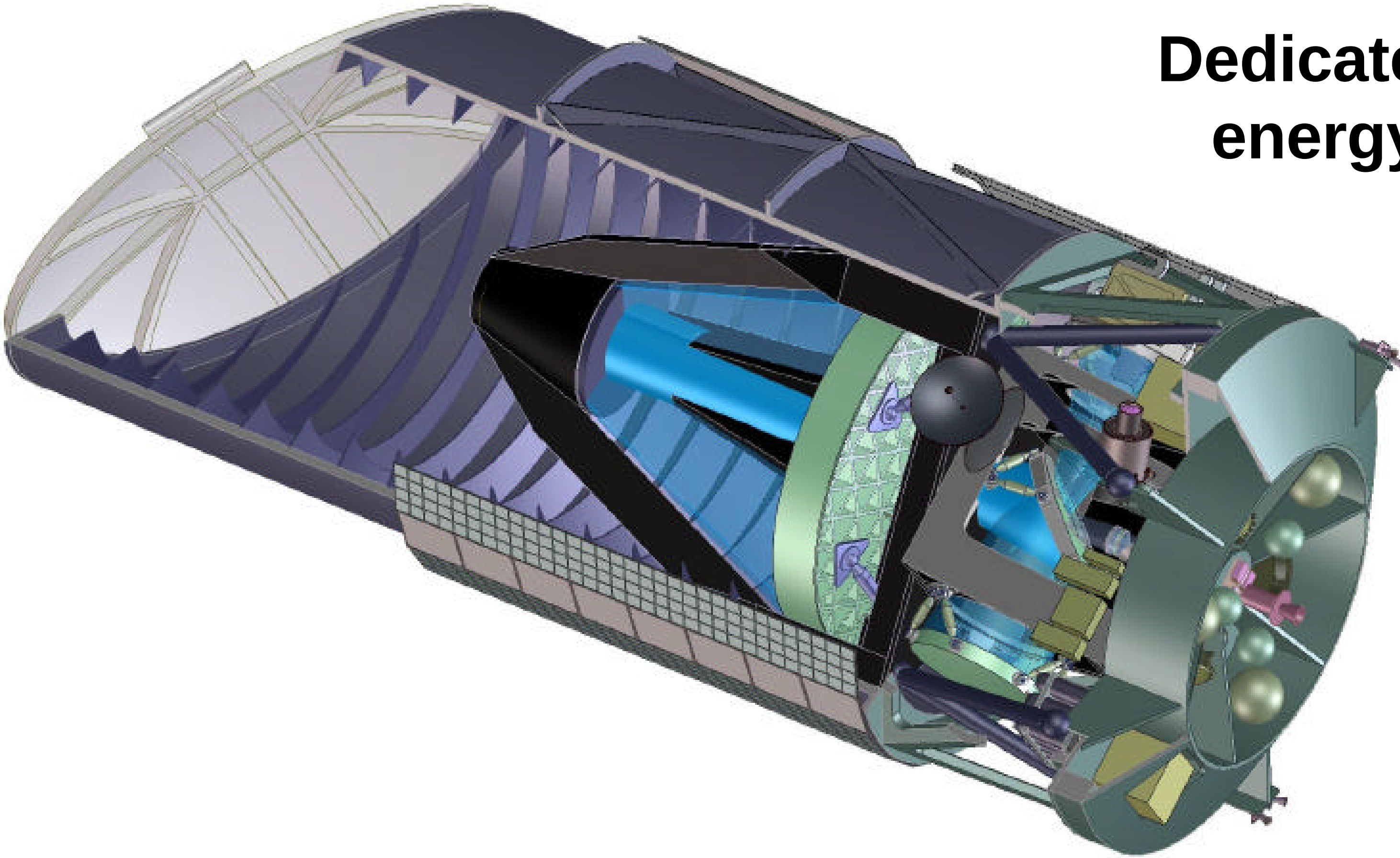
# Dark Energy – The Discovery




**Λ > 0 at 99% confidence**

# Dark Energy – The Next Generation

## Supernova/Acceleration Probe: SNAP



**Dedicated dark energy probe**

**Discovery +12 years**

# Fundamental Physics

**Astrophysics ® Cosmology ® Field Theory**

**r(z) ® Equation of state w(z) ® V(f)**

**SN**
**CMB**
**LSS**

**V ( f( a(t) ) )**

**The subtle slowing and growth of scales with time – a(t) – map out the cosmic history like the tree rings map out the Earth's climate history.**

**Map the expansion history of the universe**

# Dark Energy at z > 1

**Time variation w´ is a critical clue to fundamental physics.**

- **Deep surveys of galaxies and SN to *z>1***
- **Large scale structure formation**
- **CMB constraints from $z_{lss}=1100$**

**Robust parametrization:** $w(a)=w_0+w_a\,(1-a)$

**Community recognition: CMB*fast*, CMB*easy***

**Alterations to Friedmann framework ® *w(z)***

**Friedmann equation:**

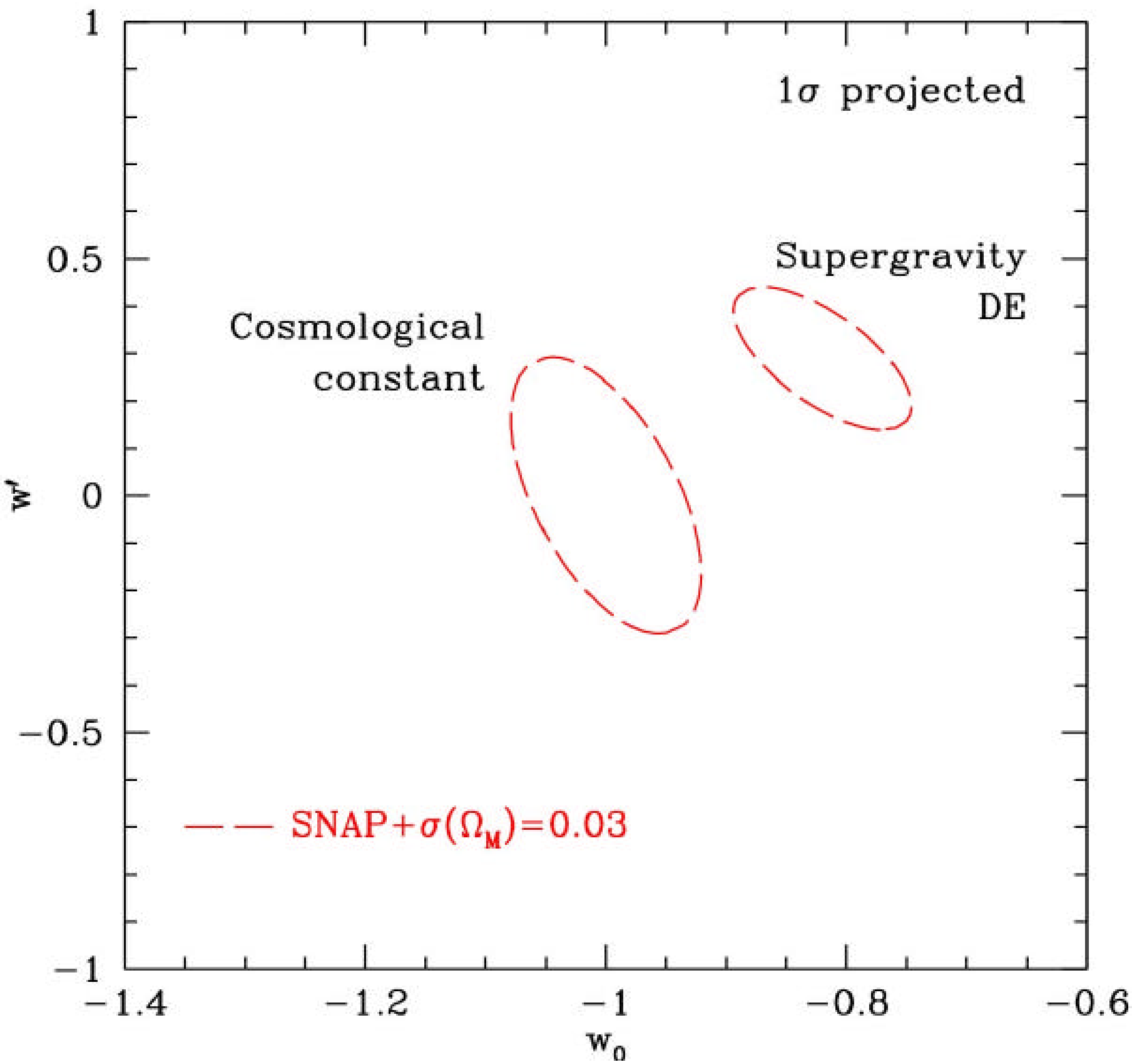
$$H^2 = (8p/3)\ r_m + dH^2(z)$$

**Effective equation of state:**

$$w(z) = -1 + (1/3)\ d\ \ln(dH^2)/\ d\ \ln(1+z)$$

# Supernovae Probe Dark Energy

## SNAP tightly constrains dark energy models.

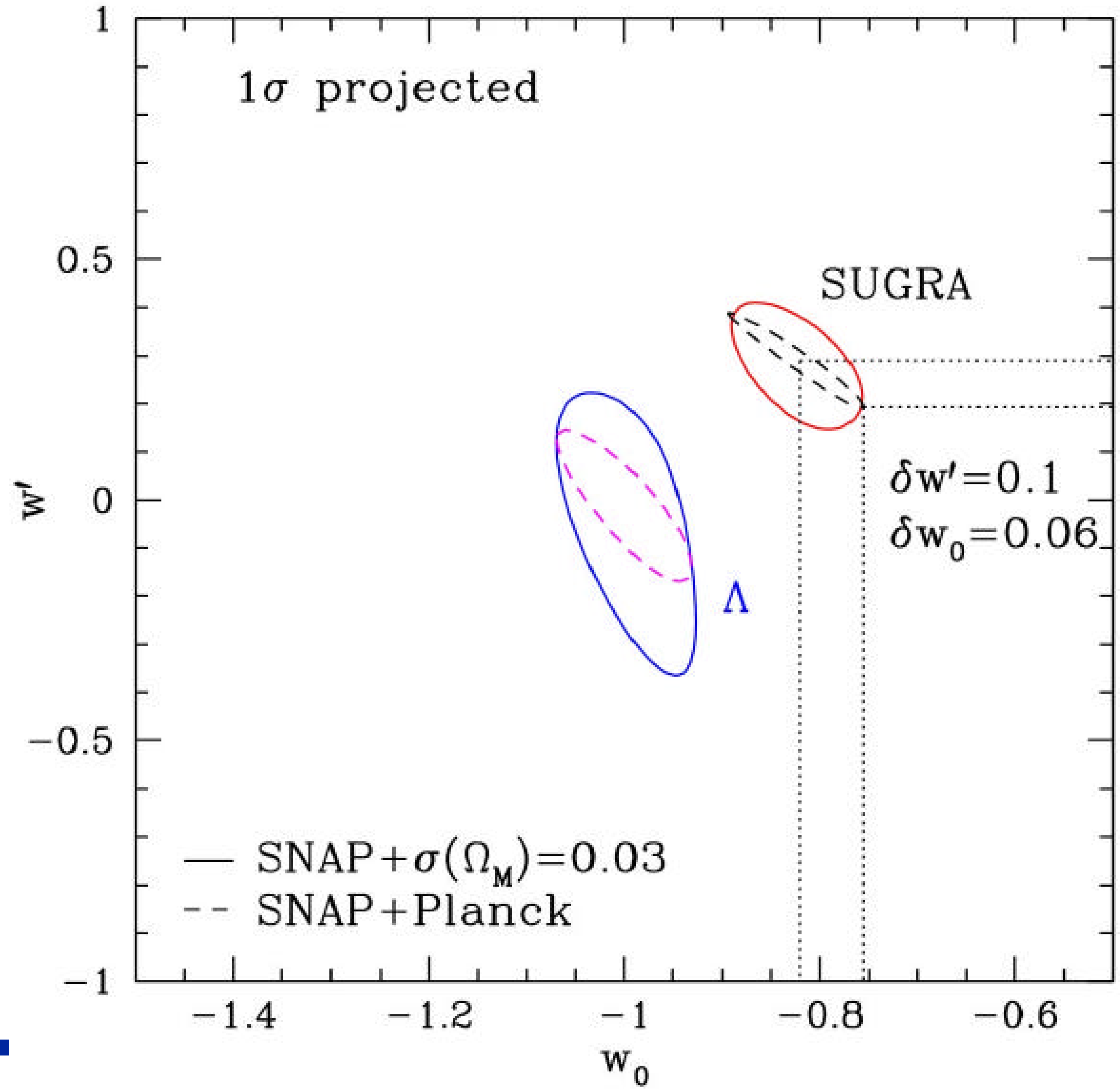



BORATORY

# Complementarity

## SNAP tightly constrains dark energy models…

**And plays well with others.**



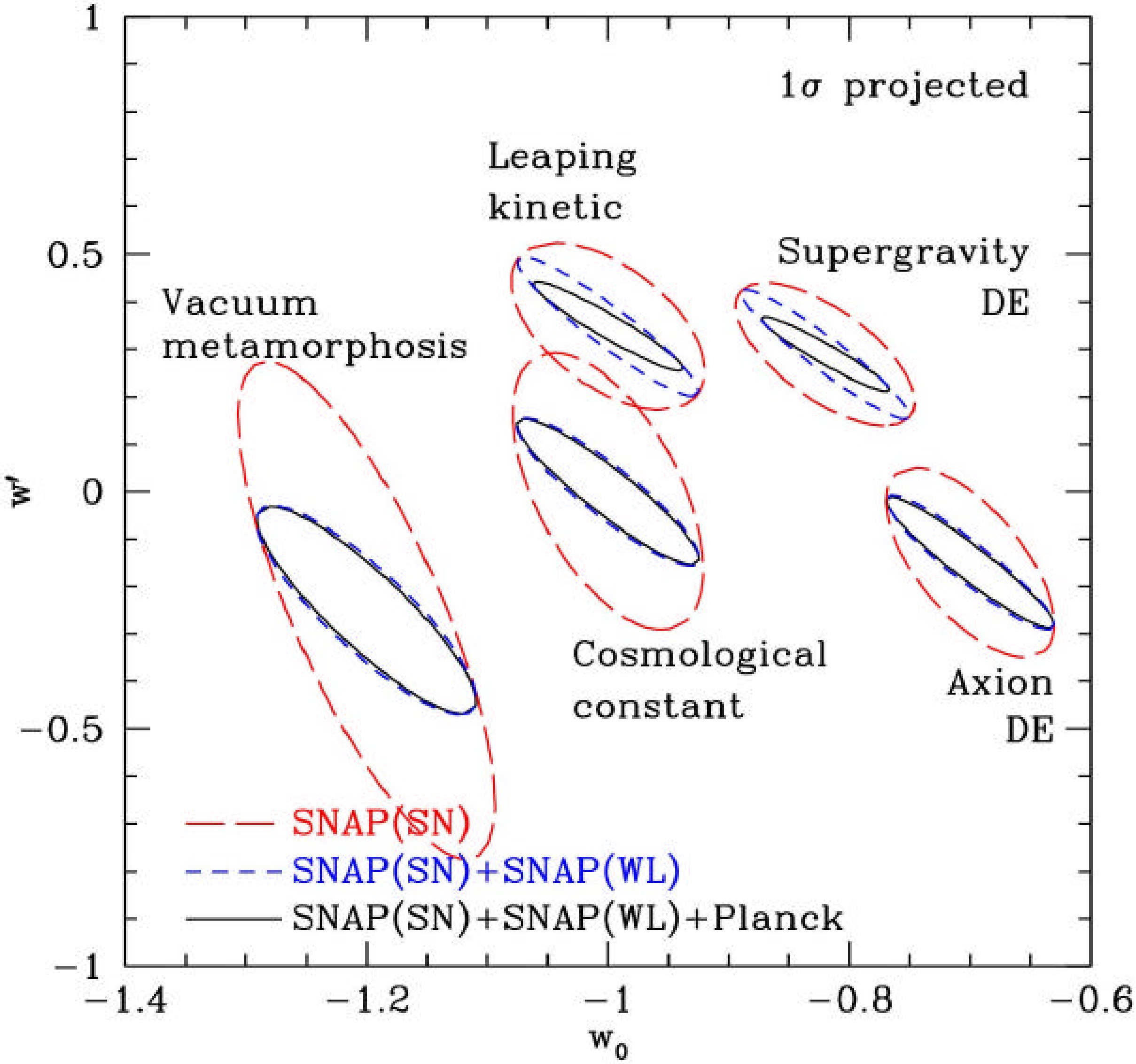

**SNAP+Planck have excellent complementarity, equal to a prior $\sigma(\Omega_M)\leq 0.01$.**

Frieman, Huterer, Linder, & Turner 2002

**SNAP+Planck can detect time variation w´ at 99% cl (e.g. SUGRA).**

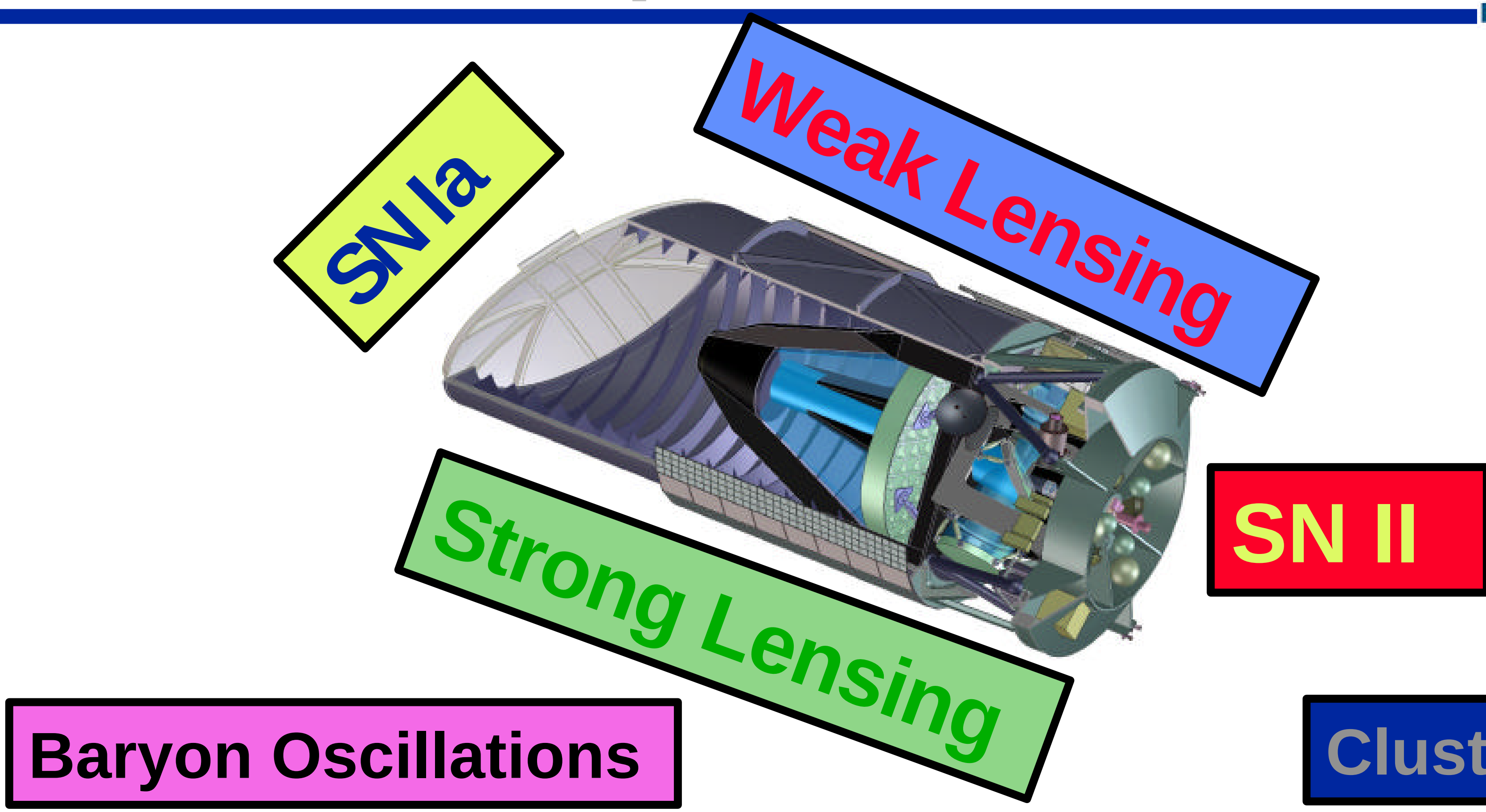
# Fundamental Physics 2

**SNAP tightly constrains dark energy models…**
**And plays well with others. Lots of others.**




- **Probing the nature of dark energy**
- **Structure of the vacuum**
- ***w´(z)* ® *V´ / V(f)***
- **High energy physics**
- **Synergy and complementary methods**

# SNAP Complements SNAP




## Wide, Deep and Colorful

- 9000 times the area of Hubble Deep Field
- 15 sq.deg. to AB mag R=30 ; 120 epochs
- 300 sq.deg. to AB mag R=28

# On Beyond L

## Dark energy is…

- Dark
- Smooth on cluster scales
- Accelerating

Maybe not completely!
Clumpy in horizon?
Maybe not forever!

## It's not quite so simple!

**You'll be sort of surprised what there is to be found**
**Once you go beyond L and start poking around.**

**-- à la Dr. Seuss, *On Beyond Zebra***

# The Zoo Beyond Zebra

**Motivation:**

**Because it's there?!**

**More natural than cosm-illogical constant?** Kolb

**Particle physics has zebrons, zebrillas, zebrinos…**

**Inflation has its hybrids, supernaturals, etc.**

**Quintessence has its mutations in attempt to make physics more natural.**

**Simplicity vs. naturalness – epicycles**

# Heart of Darkness

**Is dark energy dark – only interacts gravitationally?**

**Self interaction:**

**Scalar fields have radiative corrections leading to instability to self clumping: Qballs**

Þ **pseudoscalar quintessence**

**Axion quintessence, PNGB**

**THE HORROR! THE HORROR!**

**Coupling to matter:**

**Leads to 5th force: limited by lab tests**

**Unify dark energy with dark matter?**

Þ **Chaplygin gas**

**Distorts matter power spectrum: ruled out unless within $10^{-5}$ of L**

# Heart of Darkness 2

**Coupling to gravitation:**

**Scalar-tensor theories**

Þ **Extended quintessence**

**Can clump on subhorizon scales**

**Can "turn on" from nonlinear structure formation?!**

**Higher dimension gravity**

Þ **Scalaron quintessence**

**Can be written in terms of scalar-tensor and $w_{eff}$**

**Same game as early universe inflation – just want to occur at late times, low curvature, potential, etc.**

# Heart of Darkness 3

**For flat, Robertson-Walker metric**

$$R = 6\ (\text{ä}/a + \text{å}^2/a^2) = 6H^2\ (1 - q)$$

**So acceleration related to Ricci scalar**

$$w_{tot} = -(1/3)\ (R/3H^2 - 1)$$

**(also follows from R = -8pGT).**

**So acceleration for $R > 3H^2$. But can't get $w_{eff}$ by dR like before with dH, since changes field equations.**

$$S = \text{ò}\ d^4x\ \text{Ö}\text{-}g\ [\ R + L_M\ ]$$

**Can get acceleration by**

1. **Change RHS $T^{mn}$, e.g. dark energy**
2. **Add terms in R, e.g. modify gravity**
3. **Couplings or imperfect fluid $L_M$**

# Phantoms, Strings, and Branes

*w* < -1:

Phantom energy – why not allow it?

Requires non-canonical kinetic energy, e.g. negative or nonlinear function.

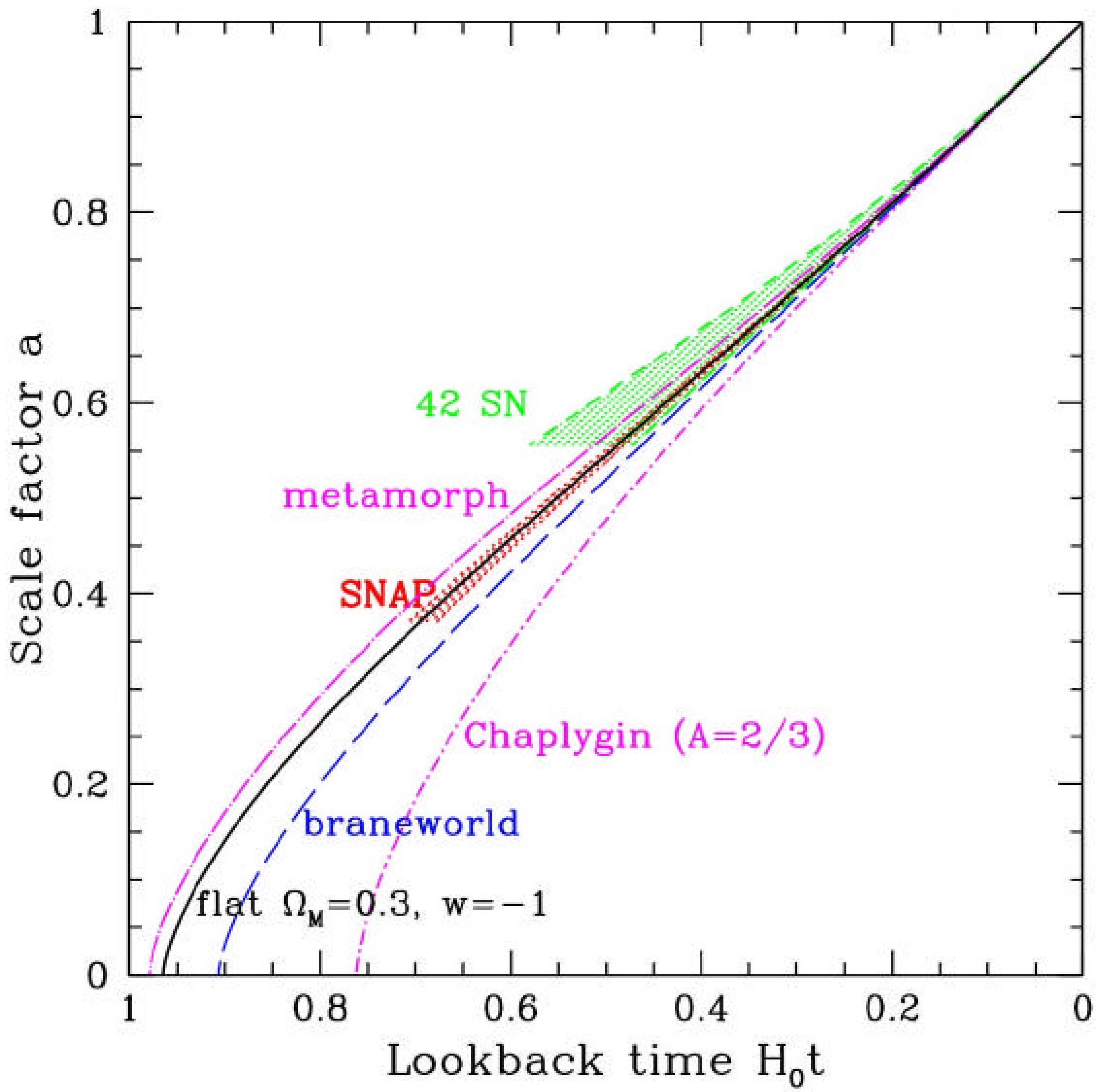
k-essence, strings, branes

Ties to quantum gravity

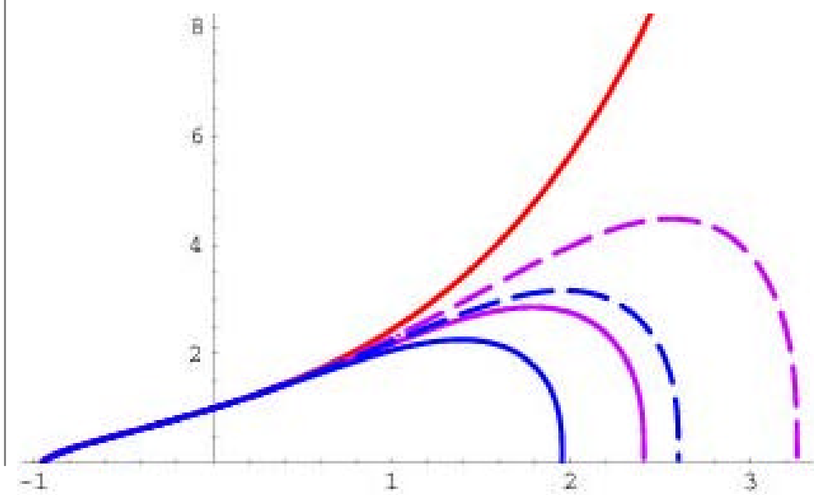
e.g. vacuum metamorphosis

Fate of universe is not deSitter but superacceleration (if *w* stays < -1)

# History and Fate




**Mapping the history of the expansion tells us the fate of the universe – if very precisely mapped.**



# Collapsing Universe

Work in collaboration with Renata Kallosh, Jan Kratochvil, Andrei Linde, Marina Shmakova

**To map out use of observations to probe fate of the universe, start with simplest model:**

**1 parameter linear potential**

$$V(\phi) = V_0 + \alpha \, M_{Pl}^3 \, \phi$$

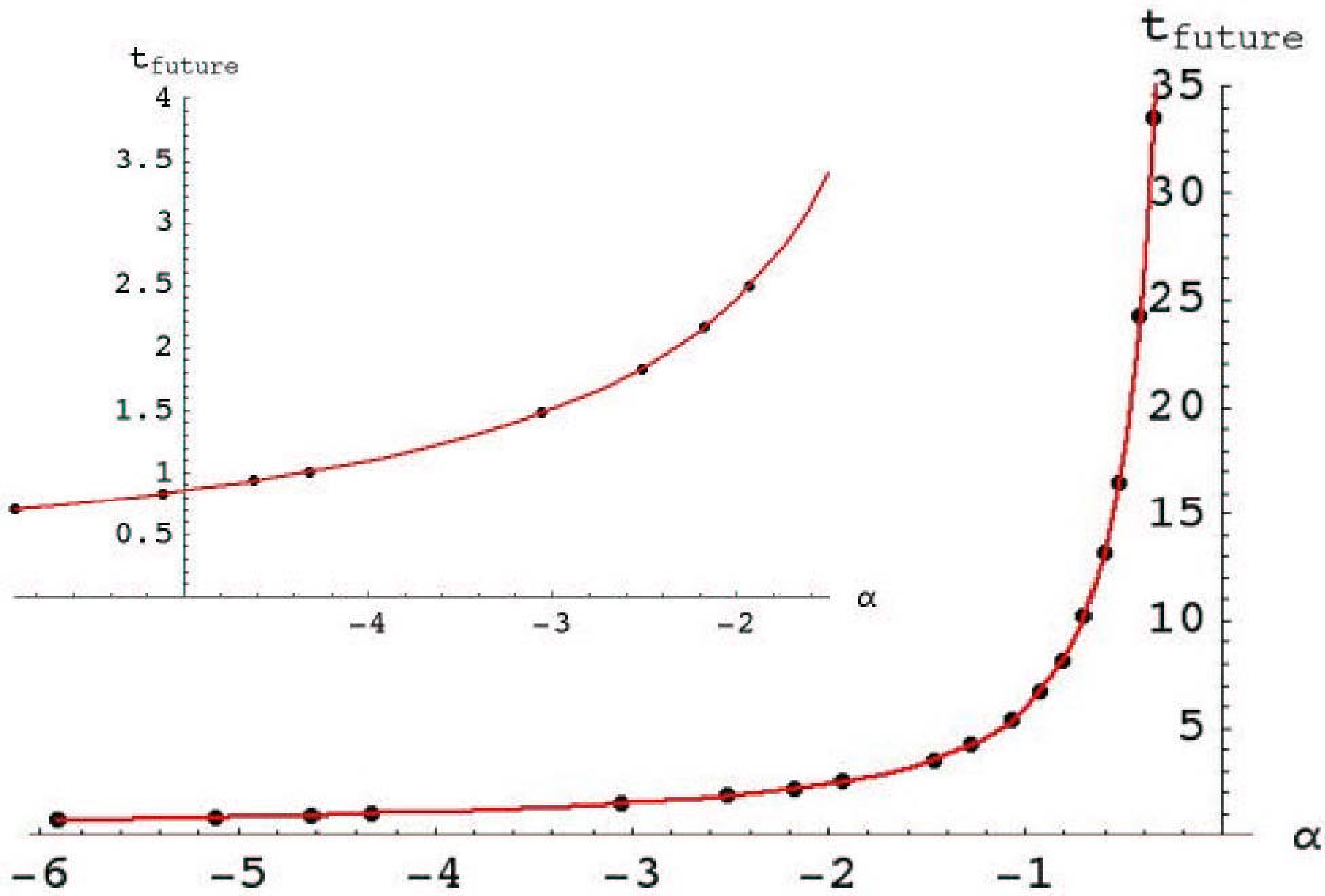
**Eventually $V(\phi) < 0$ and universe collapses.**

**Inspired by supergravity models, fairly generic fit for any collapsing model.**

**How long until cosmic doomsday?**

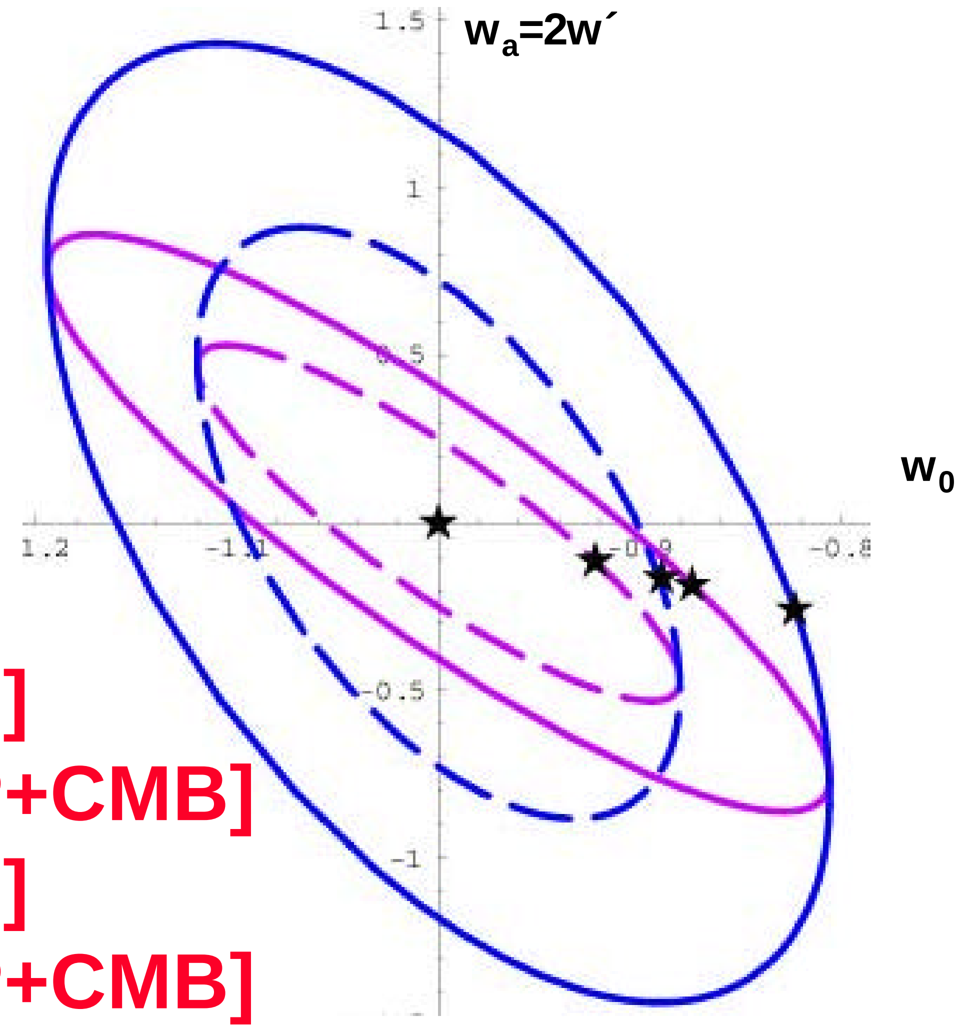
# Linear Potential

**These dark energy models look like $\Lambda$ in the past, but develop a strong *w*´.**



# Cosmic Doomsday

**By measuring $w_0$, $w´$, SNAP will be able to limit the time until doomsday.**




**$t_{doom}$= ¥ (L)**

**$t_{doom}$ > 28 Gyr [95% SNAP]**

**$t_{doom}$ > 35 Gyr [95% SNAP+CMB]**

**$t_{doom}$ > 35 Gyr [68% SNAP]**

**$t_{doom}$ > 47 Gyr [68% SNAP+CMB]**

# On Beyond…

**$w'$ is the 1st step for fundamental physics beyond L.**

**Then $w(z)$.**
**Eventually spatial variations $C_l^Q$ ?**

**In our hunt for the dark energy, the data decides how to go on beyond L.**

**SNAP[SN] + SNAP[WL] + CMB (+…) tells us if**

**In the places I go there are things that I see**
**That I never could spell if I stopped with the Z**

**-- Dr. Seuss, *On Beyond Zebra***