On Theory

thoughts & provocations

16 September 2009
1st Paris-Berkeley
Dark Energy Cosmology Workshop

Michael S. Turner
Kavli Institute for Cosmological Physics

Theory: Triumph & Opportunity

Theory: Triumph & Opportunity

"Prediction of dark energy:" major triumph of theory (since 1984, missing piece needed to make sense of inflation + CDM paradigm)

Theory: Triumph & Opportunity

"Prediction of dark energy:" major triumph of theory (since 1984, missing piece needed to make sense of inflation + CDM paradigm)

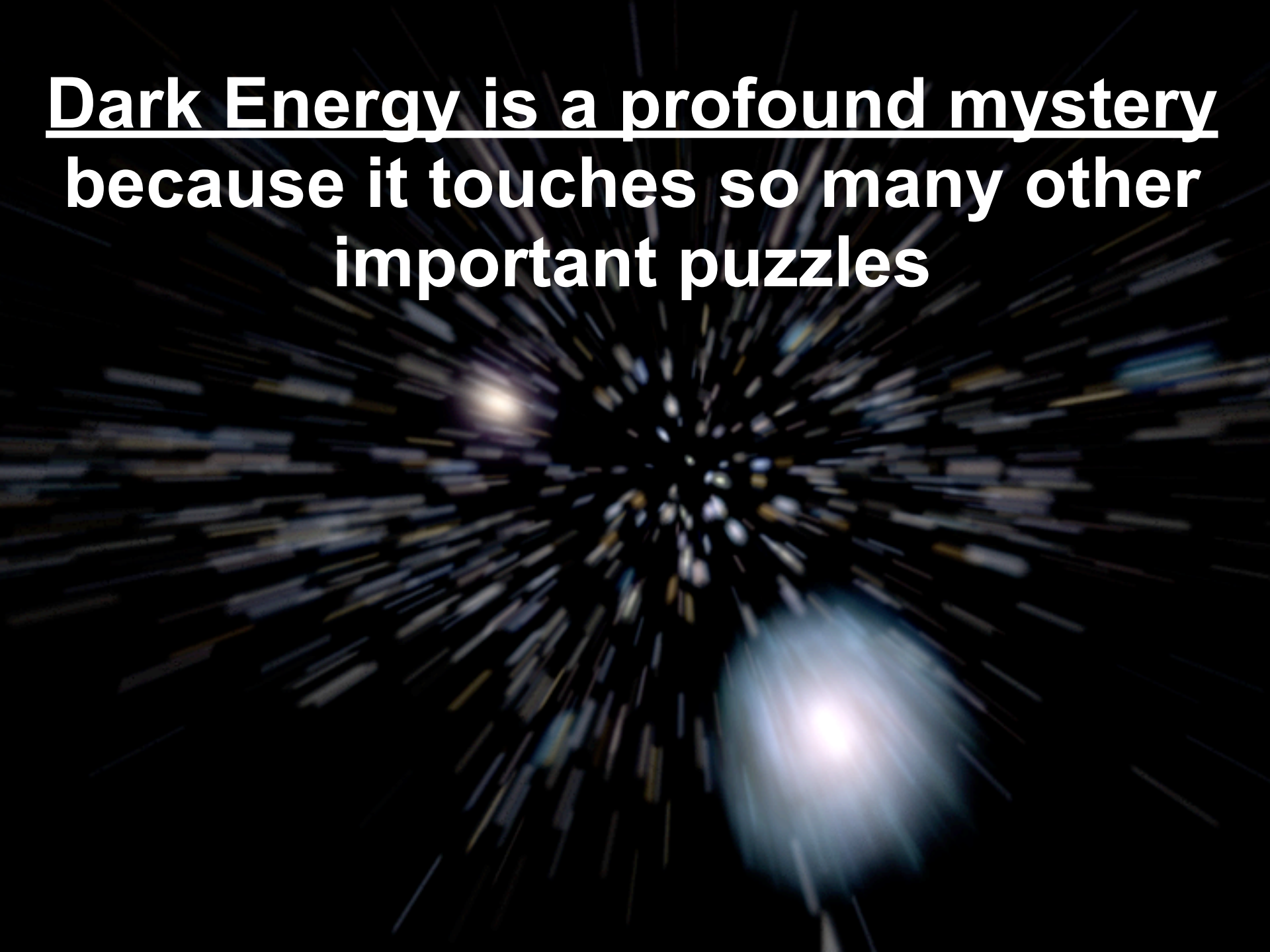
Theory: Triumph & Opportunity

"Prediction of dark energy:" major triumph of theory (since 1984, missing piece needed to make sense of inflation + CDM paradigm)

"Understanding cosmic acceleration/dark energy:" biggest theoretical challenge (since 1998 and SNe evidence for cosmic acceleration)

DARK ENERGY

MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY


Dark Energy is a profound mystery
because it touches so many other
important puzzles

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe
- Related to Dark Matter, Inflation, Neutrino Mass?

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe
- Related to Dark Matter, Inflation, Neutrino Mass?
- Connections to SUSY/Superstrings/Extra dimensions?

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe
- Related to Dark Matter, Inflation, Neutrino Mass?
- Connections to SUSY/Superstrings/Extra dimensions?
- Signal of new gravitational physics?

Dark Energy is a profound mystery because it touches so many other important puzzles

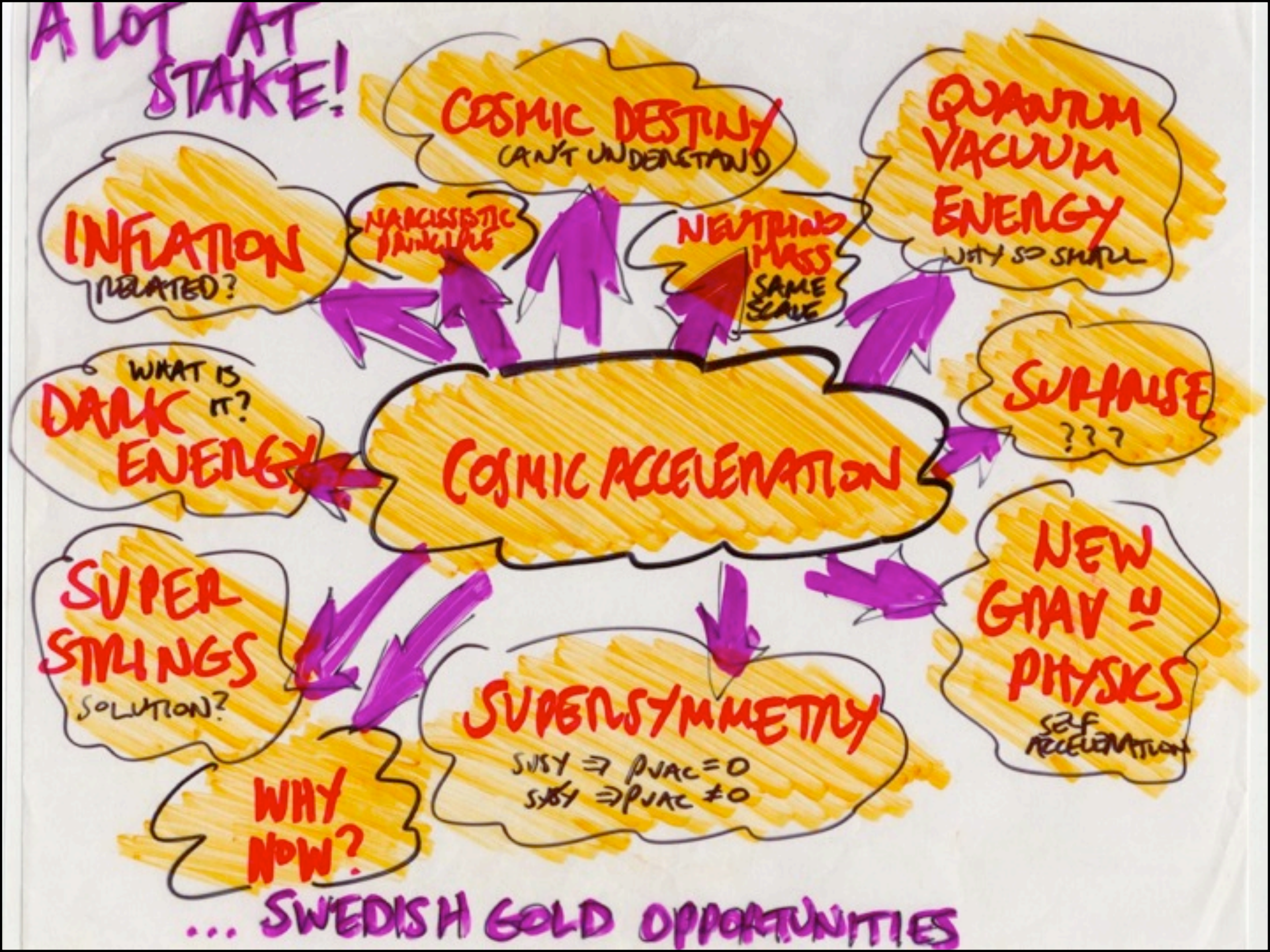
- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe
- Related to Dark Matter, Inflation, Neutrino Mass?
- Connections to SUSY/Superstrings/Extra dimensions?
- Signal of new gravitational physics?
- Hole in the Universe?

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe
- Related to Dark Matter, Inflation, Neutrino Mass?
- Connections to SUSY/Superstrings/Extra dimensions?
- Signal of new gravitational physics?
- Hole in the Universe?
- Crack in the Cosmic Egg?

Dark Energy is a profound mystery because it touches so many other important puzzles

- The bulk of the energy in the Universe
- Vacuum energy/cosmological constant problem
- Destiny of the Universe
- Related to Dark Matter, Inflation, Neutrino Mass?
- Connections to SUSY/Superstrings/Extra dimensions?
- Signal of new gravitational physics?
- Hole in the Universe?
- Crack in the Cosmic Egg?
- Narcissistic Principle?


A LOT AT STAKE!
COSMIC DESTINY
CAN'T UNDERSTAND
QUANTUM VACUUM ENERGY
WHY SO SMALL
INFLATION
RELATED?
NARCISSISTIC PANIC ATTACK
NEUTRINO MASS
SAME SCALE
WHAT IS IT?
DARK ENERGY
COSMIC ACCELERATION
SUBMUSE
???
SUPER STRINGS
SOLUTION?
NEW GRAV !!
PHYSICS
SELF ACCELERATION
SUPERSYMMETRY
SUSY ⇒ ρVAC = 0
SUSY ⇒ ρVAC ≠ 0
WHY NOW?
... SWEDISH GOLD OPPORTUNITIES


CBS
EVENING
NEWS
EXCLUSIVE
cbsnews
.com

Youbetcha Katie, I believe in Dark Energy -- we can see it from Alaska!

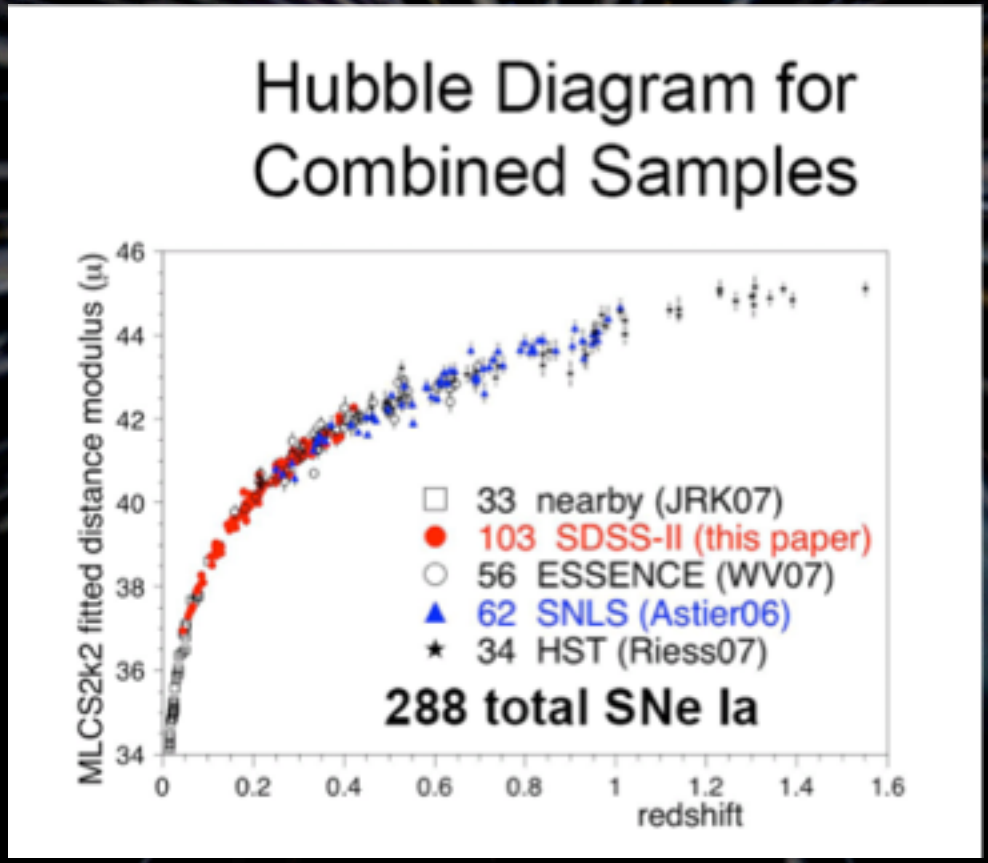
Youbetcha Katie, I believe in Dark Energy -- we can see it from Alaska!

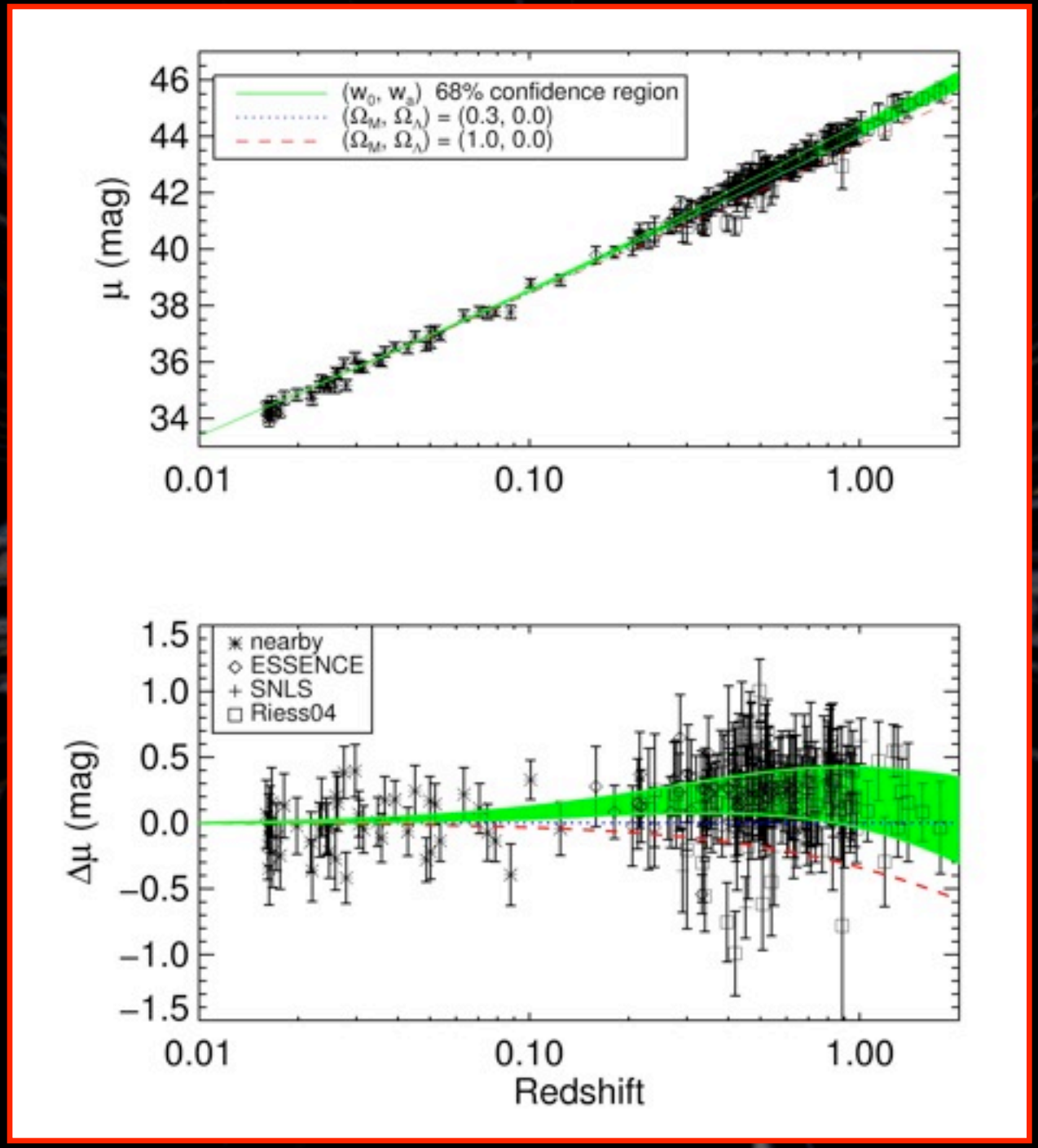
Drill for Dark Energy!


What We Know 10+ Years On
5 Key Facts

F1: Expansion is accelerating

- Assumption of RW (no GR) + SNe data → accelerated expansion




(w0, wa) 68% confidence region
(ΩM, ΩΛ) = (0.3, 0.0)
(ΩM, ΩΛ) = (1.0, 0.0)
μ (mag)
46
44
42
40
38
36
34
0.01
0.10
1.00
nearby
ESSENCE
SNLS
Riess04
Δμ (mag)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.01
0.10
1.00
Redshift

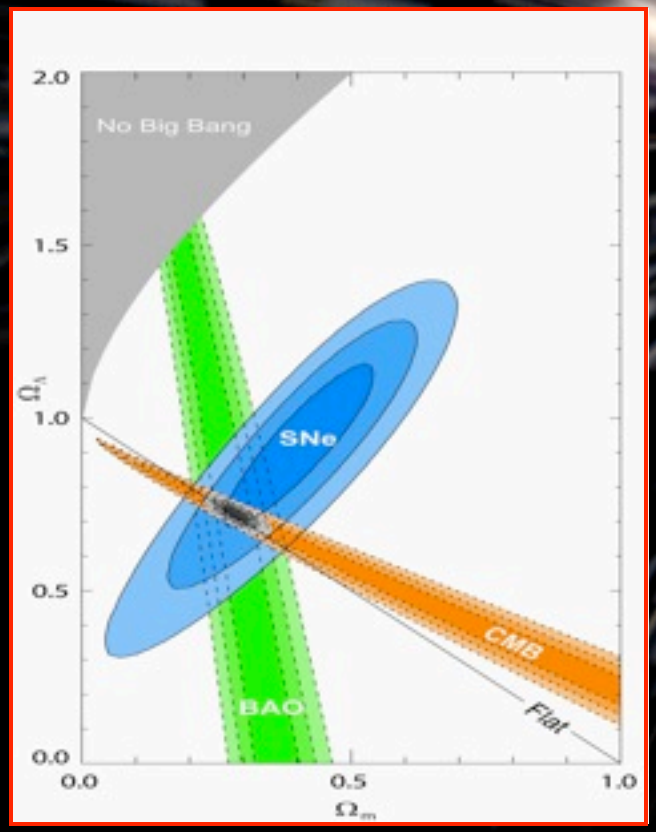
Conclusions from "Friedmannless" Analysis of Riess et al Gold Set

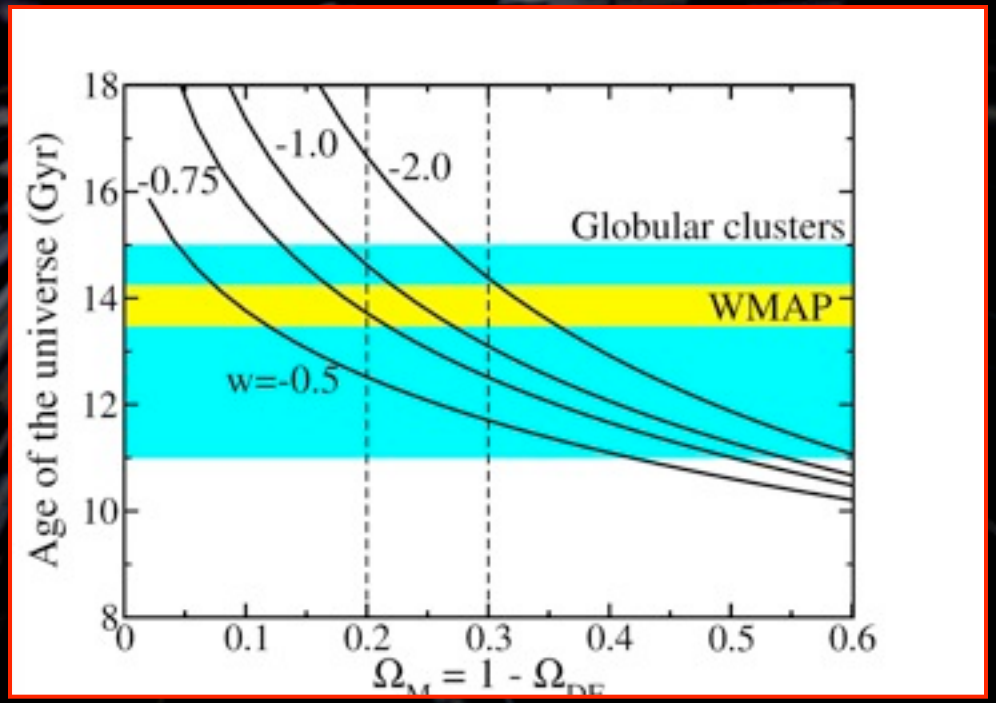
- Very strong evidence (5σ) that Universe once accelerated: q(z) was once negative
- Strong evidence (3σ) that q(z) was larger in the past
- Evidence (2σ) that Universe decelerated in the past
- Universe may not be accelerating today: Model with deceleration since z = 0.3 is acceptable at 10% cl

astro-ph/0512586

F2: Flat, ΛCDM fits all data

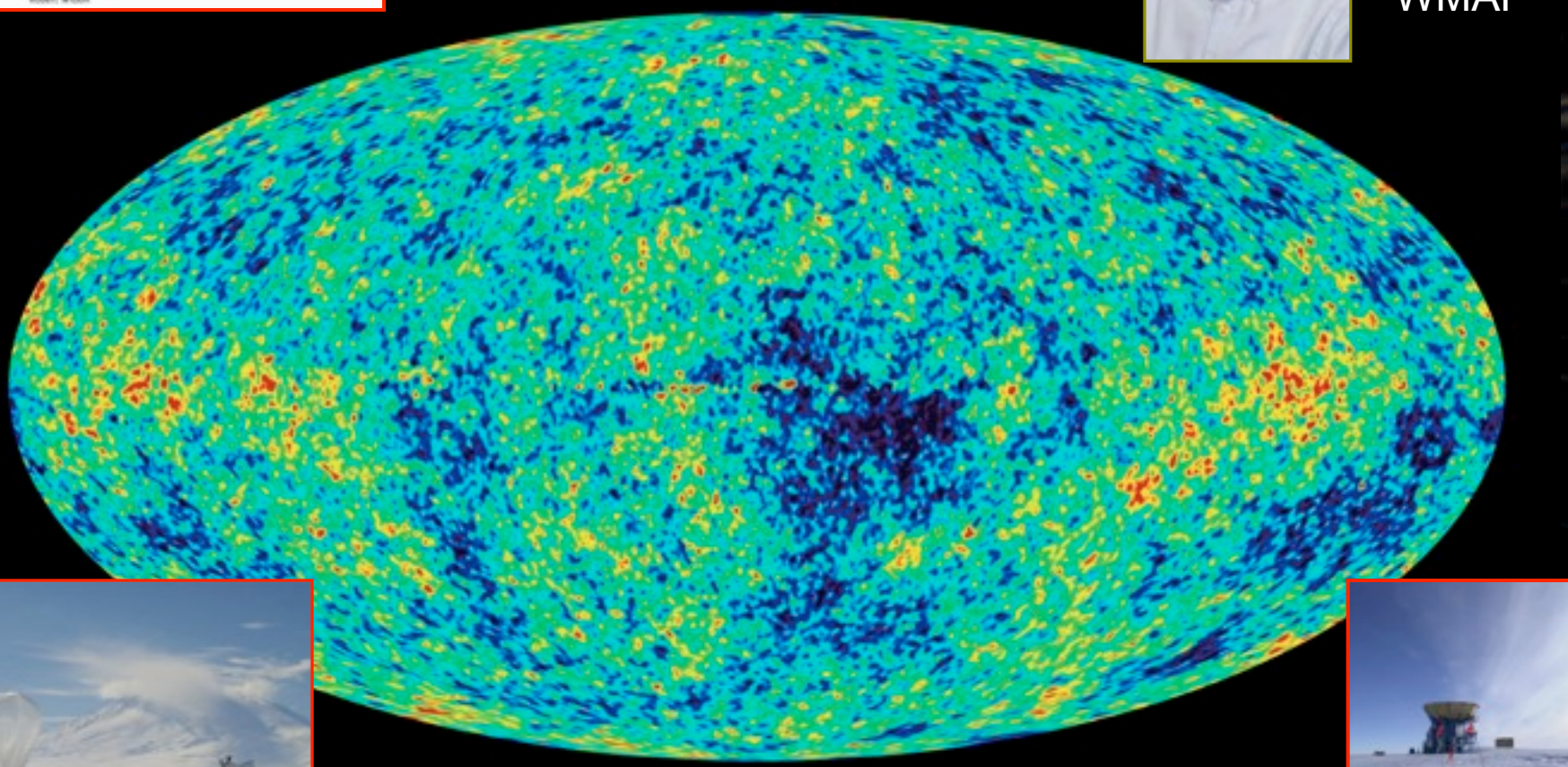
- Consensus cosmology consistent with CMB (WMAP, …), LSS (SDSS), BAO, SNe, x-ray clusters, WL, age of Universe at percent-level precision (!). This is no mean feat





CMB Provides An Independent Line of Evidence

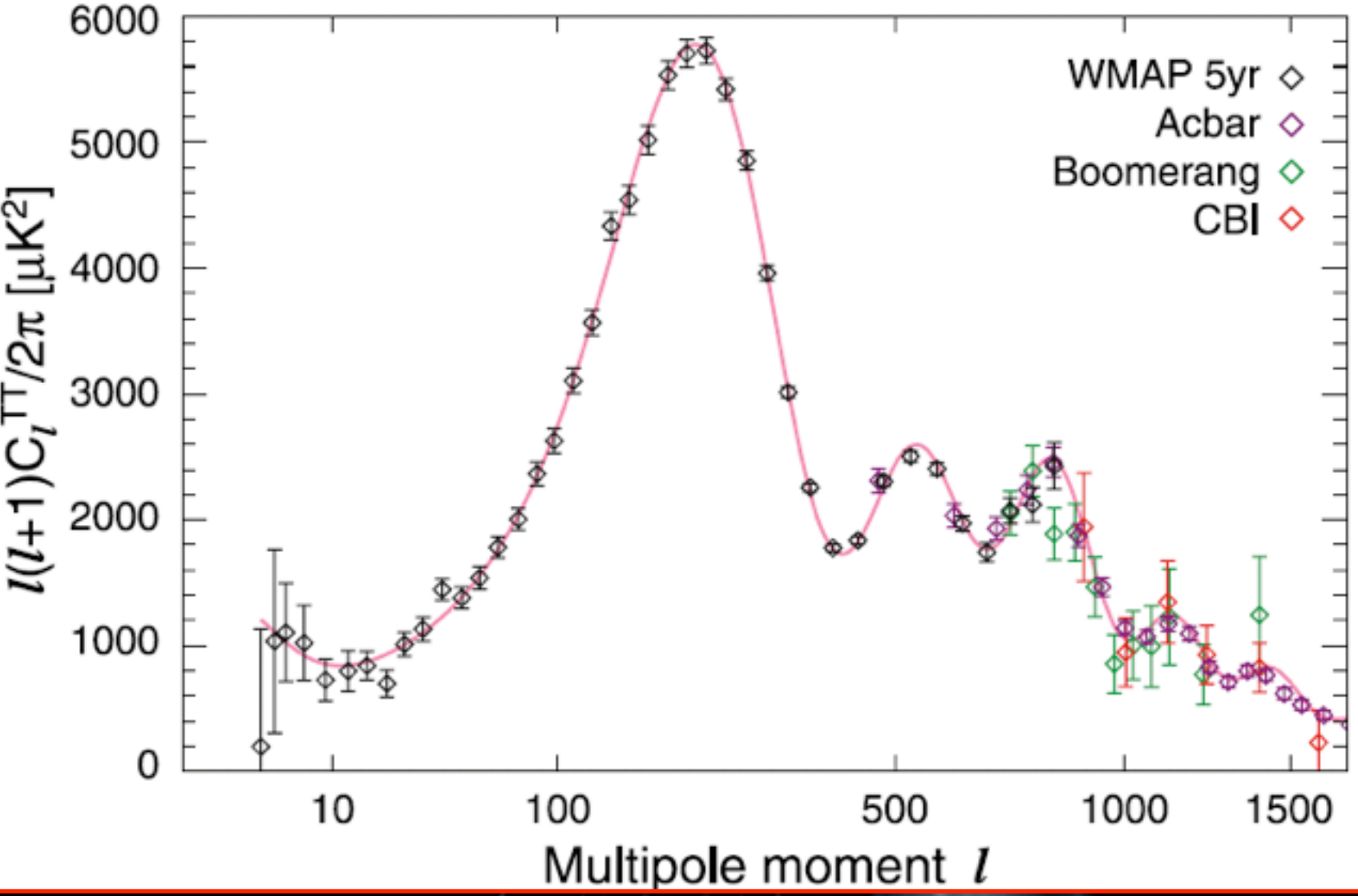
WMAP



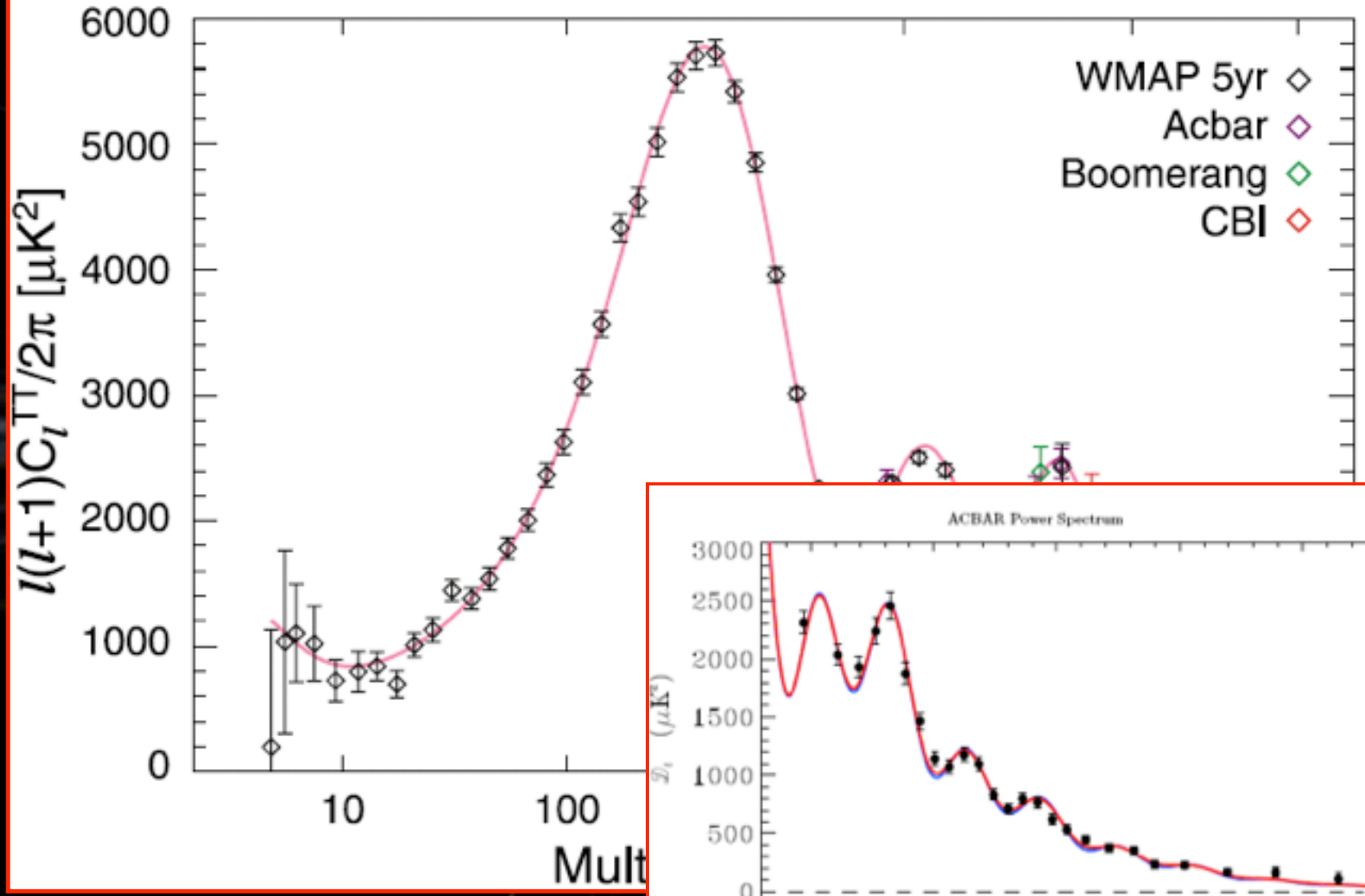
BOOMERanG

DASI

Curve = concordance cosmology



Curve = concordance cosmology



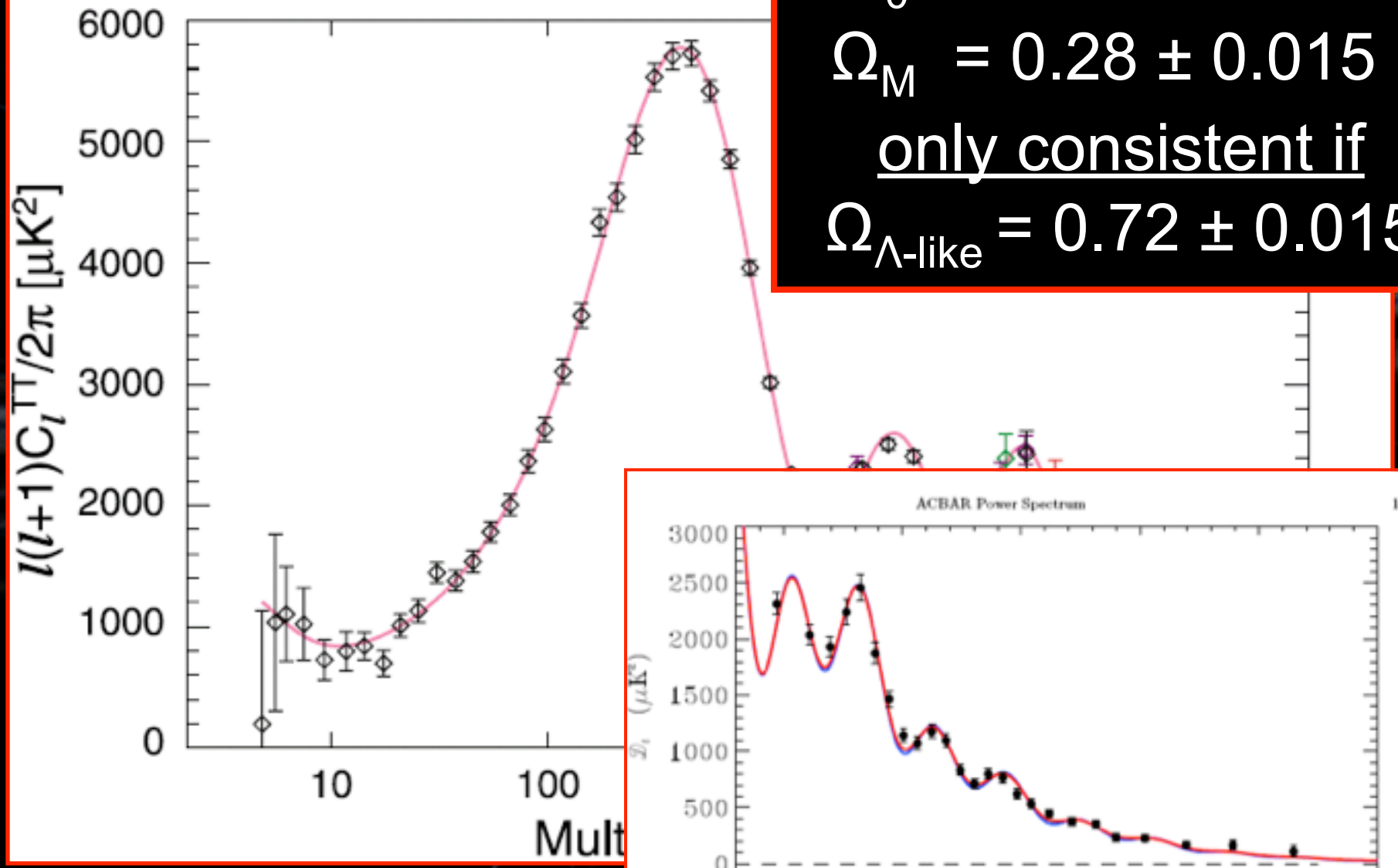
Curve = concordance cosmology

$\Omega_0 = 1.005 \pm 0.006$

$\Omega_M = 0.28 \pm 0.015$

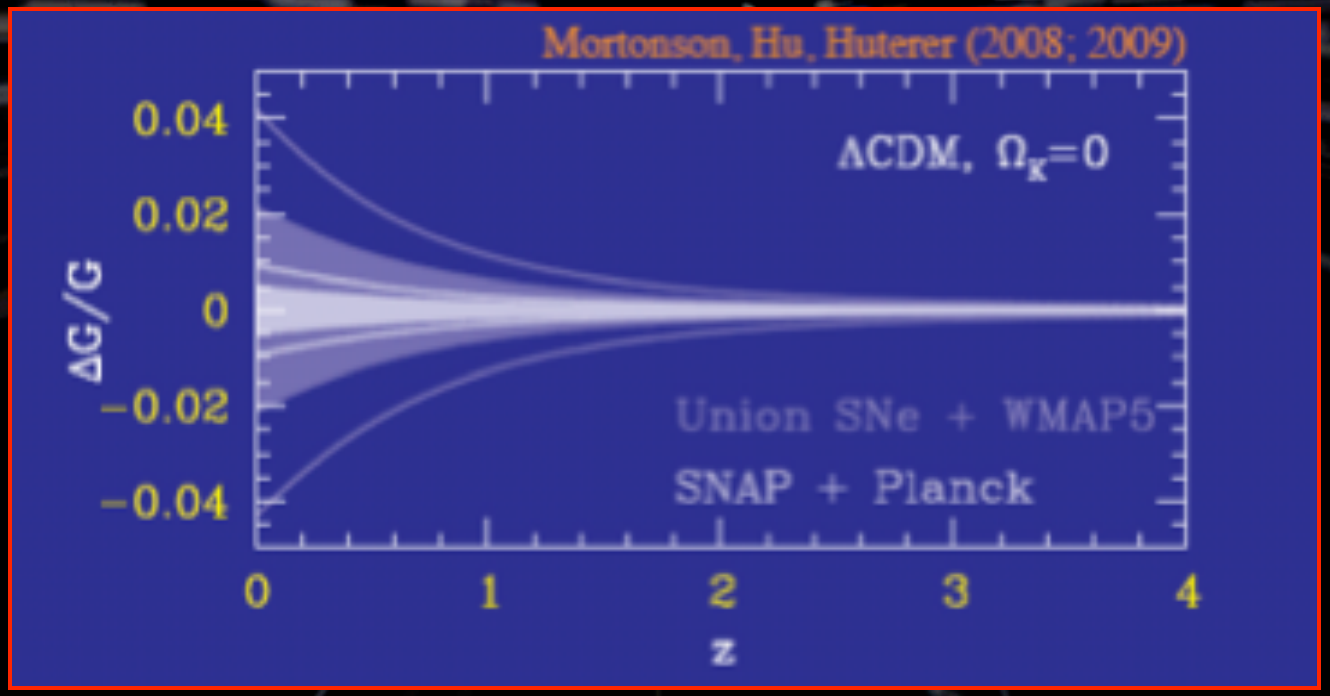
<u>only consistent if</u>

$\Omega_{\Lambda\text{-like}} = 0.72 \pm 0.015$



F3: Flat, ΛCDM and GR fits LSS and abundance of clusters

- Very little room for deviation from “standard growth of structure” (few percent)



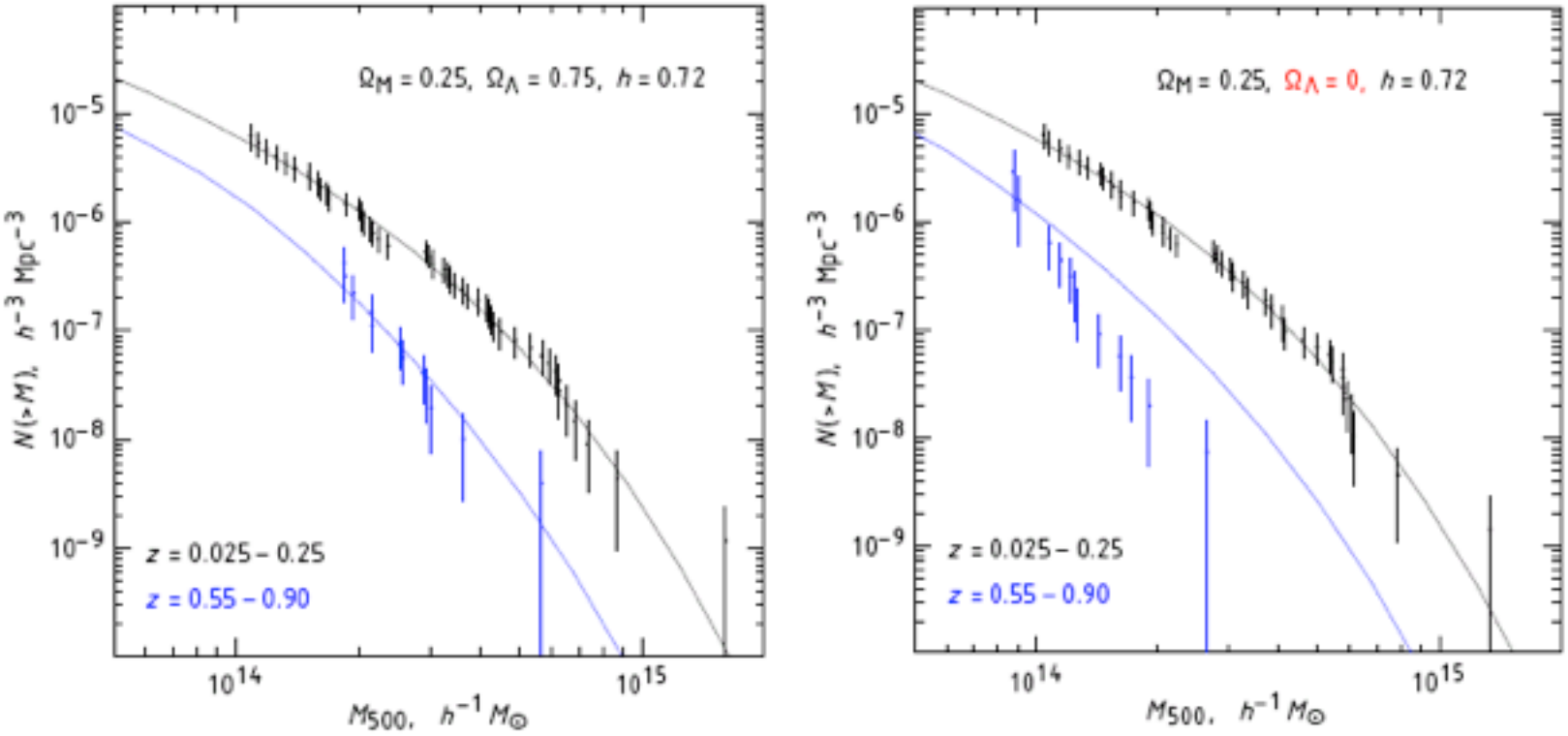
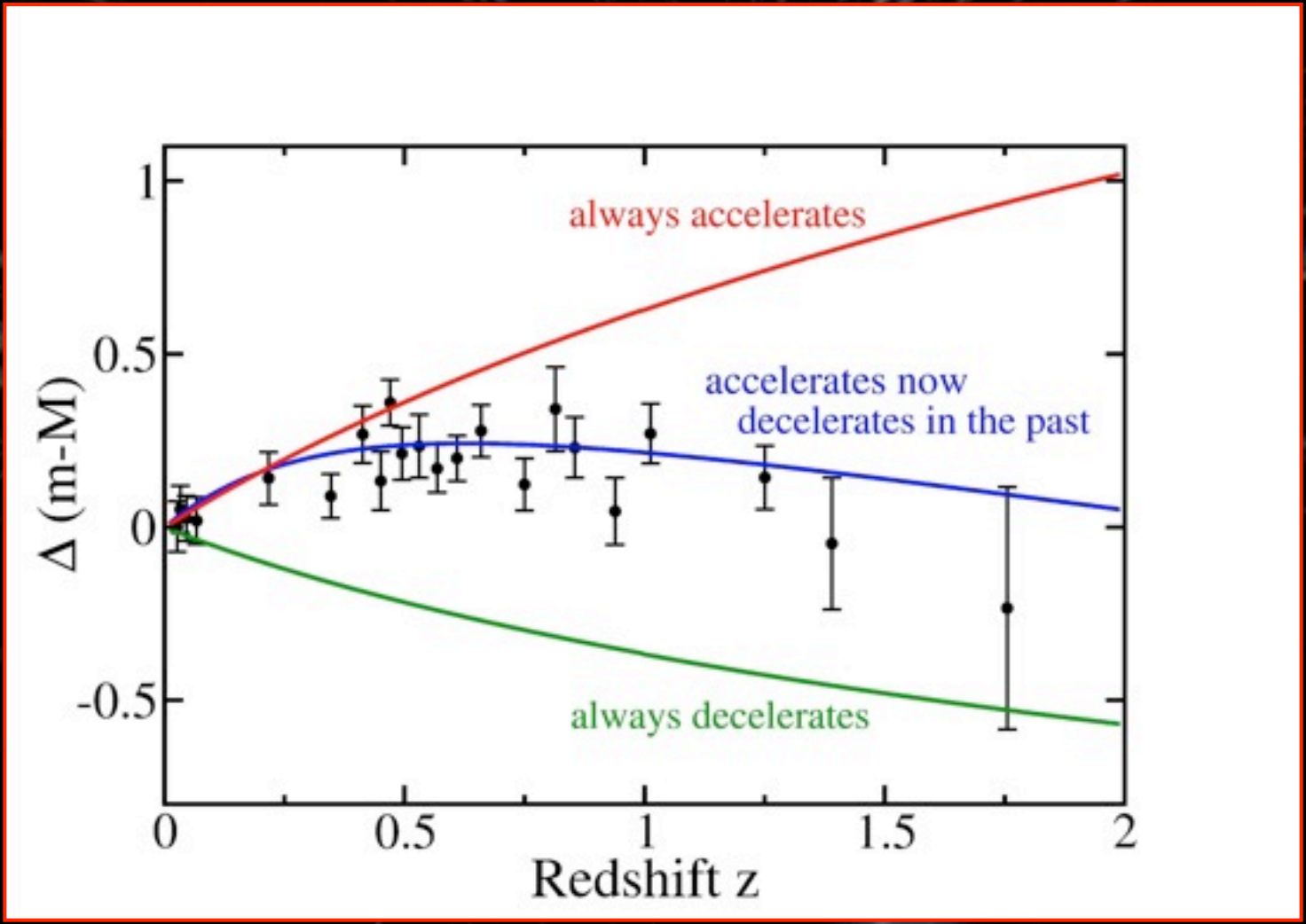


FIG. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at $z = 0$ adjusted) computed for a cosmology which is close to our best-fit model. The low-z mass function is reproduced from Fig. 1, which for the high-z cluster we show only the most distant subsample ($z > 0.55$) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with $\Omega_\Lambda = 0$. Both the model and the data at high redshifts are changed relative to the $\Omega_\Lambda = 0.75$ case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to $\Delta_{crit} = 500$ are different. When the overall model normalization is adjusted to the low-z mass function, the predicted number density of $z > 0.55$ clusters is in strong disagreement with the data, and therefore this combination of Ω_M and Ω_Λ can be rejected.

F4: Success of CMB, BBN leave essentially little room for early acceleration

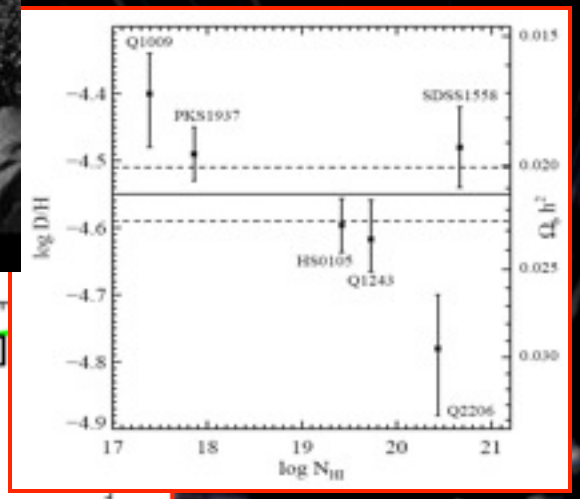
- Highest z SNe show deceleration
- CMB anisotropy and polarization (see Smoot)
- Agreement of BBN and CMB on baryon density

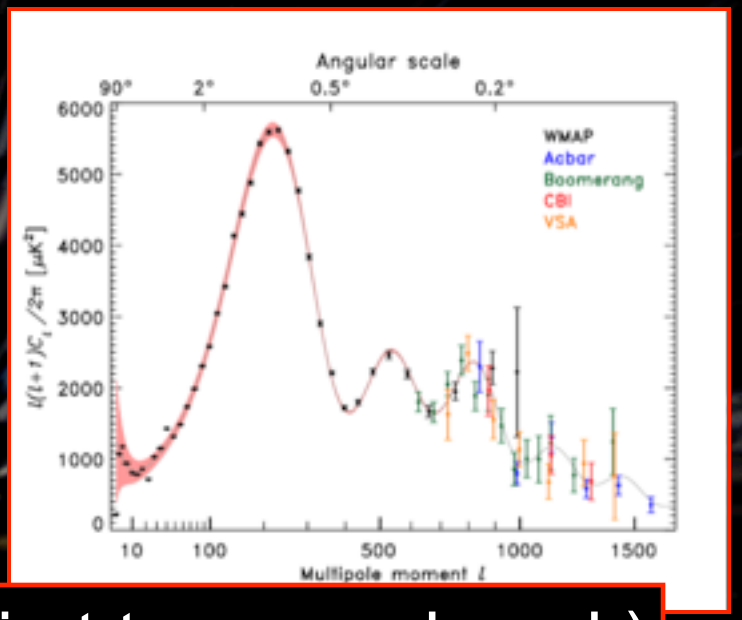
Evidence for past acceleration: Important reality check

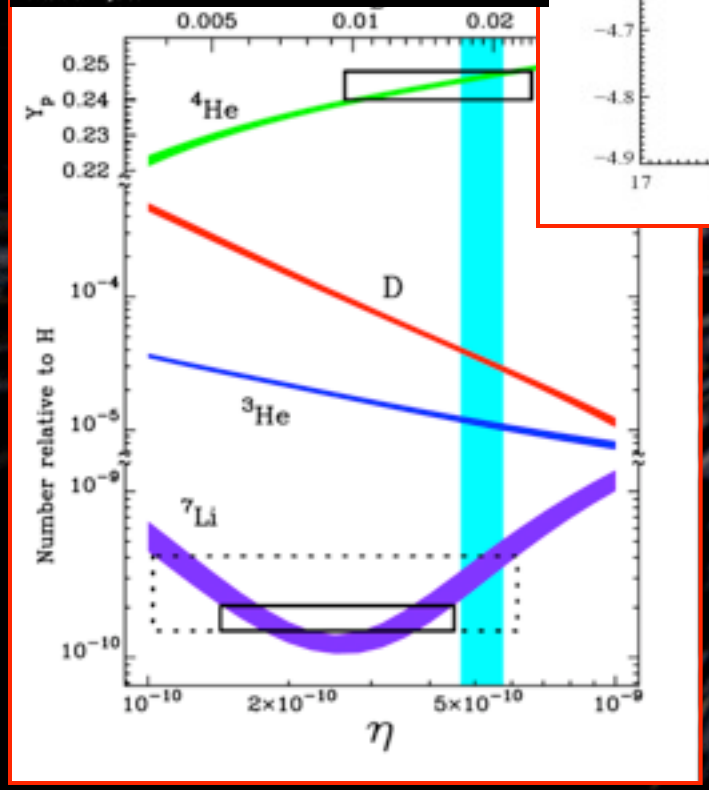


HST ACS Sample of high-z SNe: A. Riess et al, Ap.J **607**, 665 (2004)

Precision Cosmology Indeed!







CMB (first to second peak)

$\Omega_b h^2 = 0.0225 \pm 0.0006$

vs.

BBN (Deuterium)

$\Omega_b h^2 = 0.021 \pm 0.001$

~5% agreement

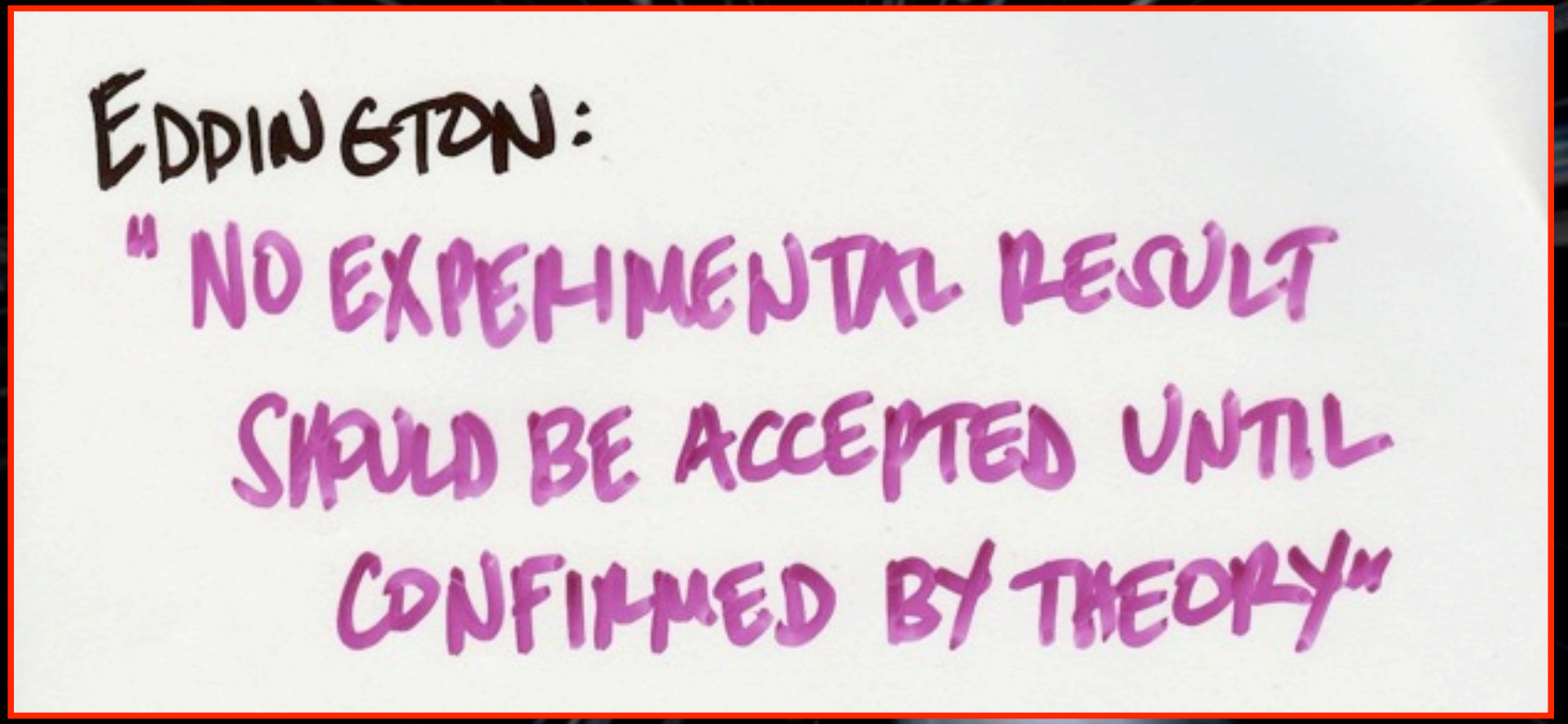
$\Omega_b = 0.044 \pm 0.002$

$h = H_0/100$ km/s/Mpc ~ 0.7

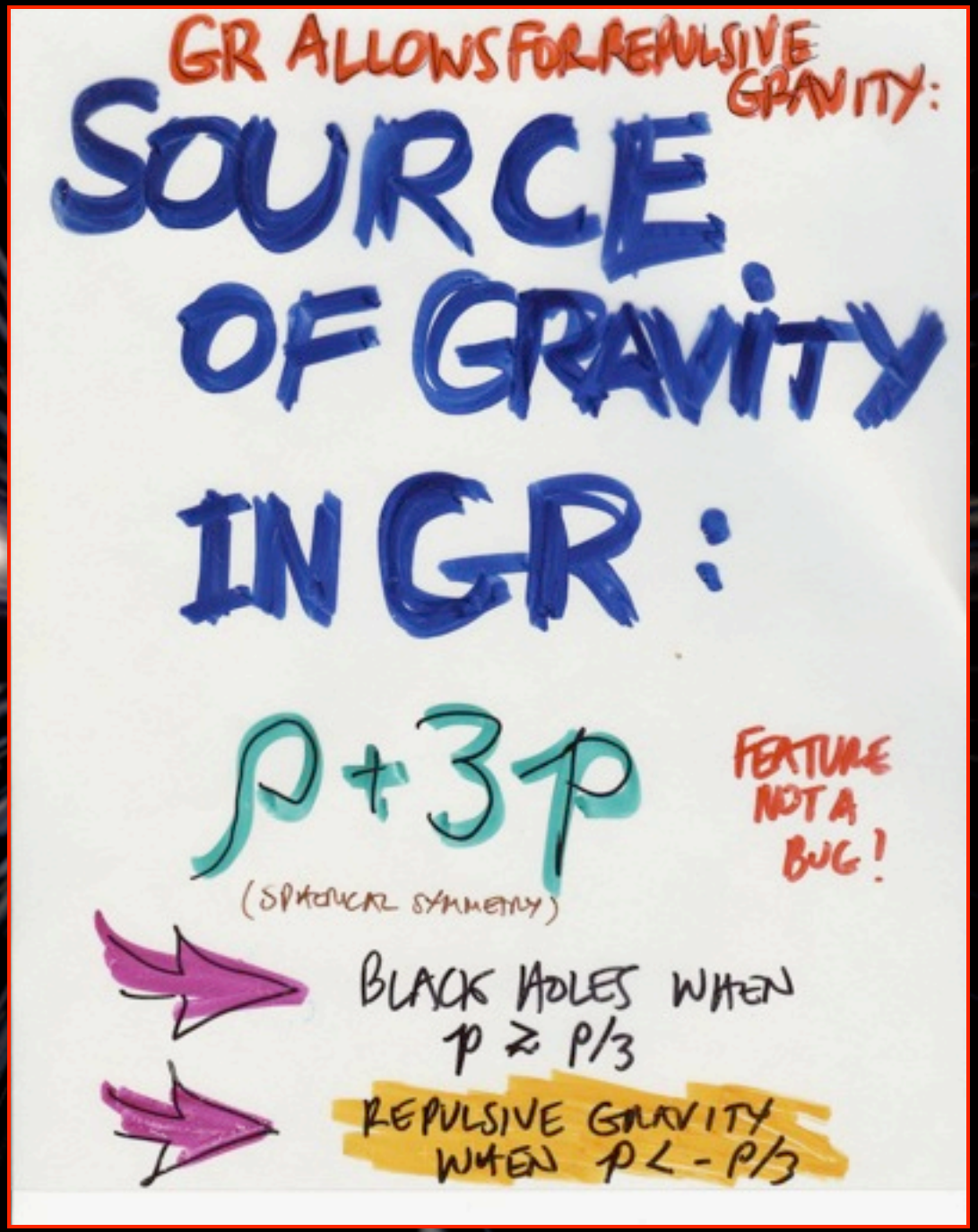

What we understand

“Eddington Criterion”:

“Eddington Criterion”:



Very elastic stuff ($p < -\rho/3$) with repulsive gravity aka "dark energy" can explain acceleration



Dark Energy

Defining features:

- Large negative pressure, $p \sim -\rho$, so that $(\rho + 3p) < 0$
- $w = p/\rho$ (equation-of-state parameter) ~ -1
- Smoothly distributed (much less clustered than matter
- Not particulate (dark matter has $p \sim 0$)

Simplest example:

- Energy of the quantum vacuum: $w = -1$

The Gravity of Nothing Is Repulsive

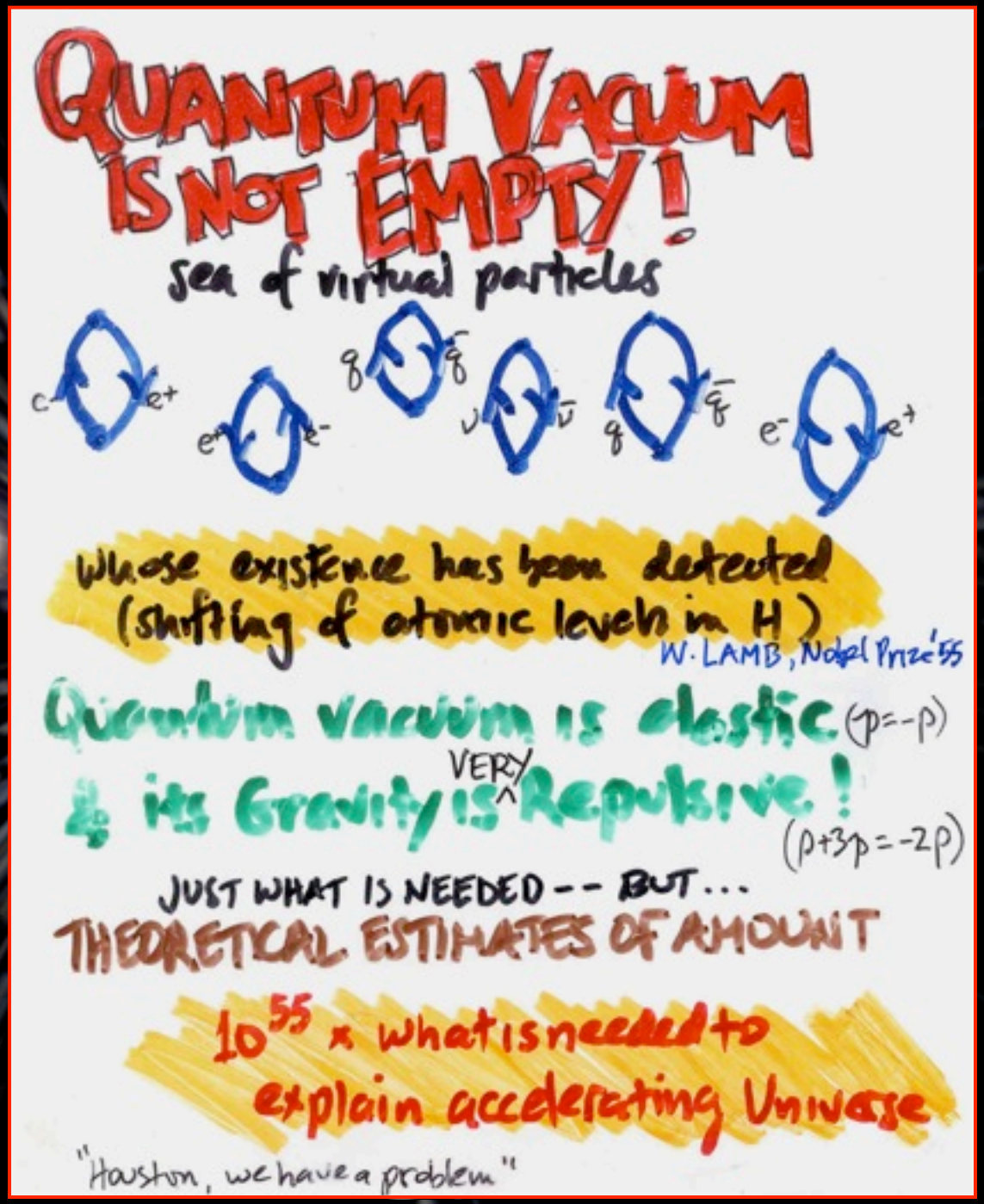
… But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing

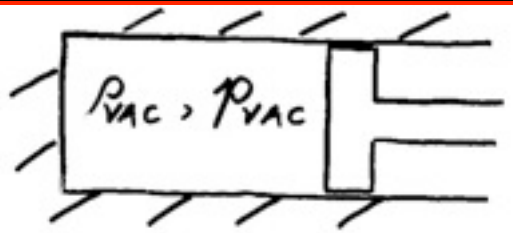
to be more precise, the answer is nonsensical (infinite) – not as bad as a finite answer that is off by orders of magnitude

$\rho_{vac} \approx 3 \times 10^{-11}\ eV^4$

$E_{DE} \approx 0.03\ eV$



The Gravity of Nothing Is Repulsive



$$dE = -p\,dV \quad \text{(First Law)}$$

$$\rho_{VAC}\,dV = -\rho_{VAC}\,dV \Rightarrow \underline{\rho_{VAC} = -\rho_{VAC}}$$

$$T^{\mu\nu}_{VAC} = \rho_{VAC}\, g^{\mu\nu}$$

(same as Λ)

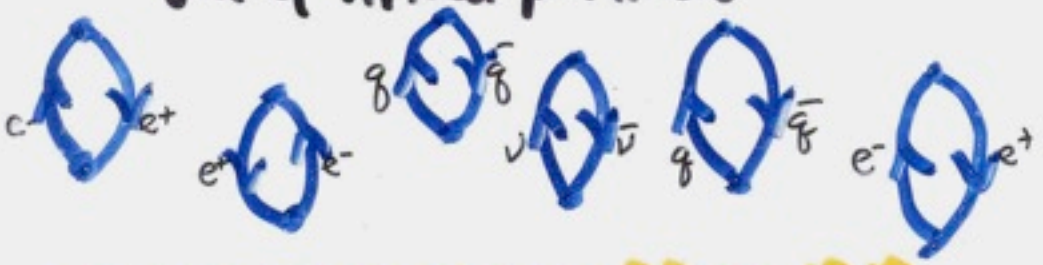
finite answer that is off by orders of magnitude

$\rho_{vac} \approx 3 \times 10^{-11}\ eV^4$

$E_{DE} \approx 0.03\ eV$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected (shifting of atomic levels in H)

W. LAMB, Nobel Prize '55

Quantum vacuum is elastic ($p = -\rho$)

& its Gravity is VERY Repulsive! ($\rho + 3p = -2\rho$)

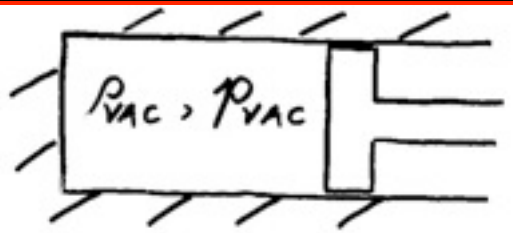
JUST WHAT IS NEEDED -- BUT...

THEORETICAL ESTIMATES OF AMOUNT

10^{55} x what is needed to explain accelerating Universe

"Houston, we have a problem"

The Gravity of Nothing Is Repulsive



$dE = -p\,dV$ (First Law)

$\rho_{VAC}\,dV = -p_{VAC}\,dV \Rightarrow \underline{p_{VAC} = -\rho_{VAC}}$

$T^{\mu\nu}_{VAC} = \rho_{VAC}\, g^{\mu\nu}$

(same as Λ)

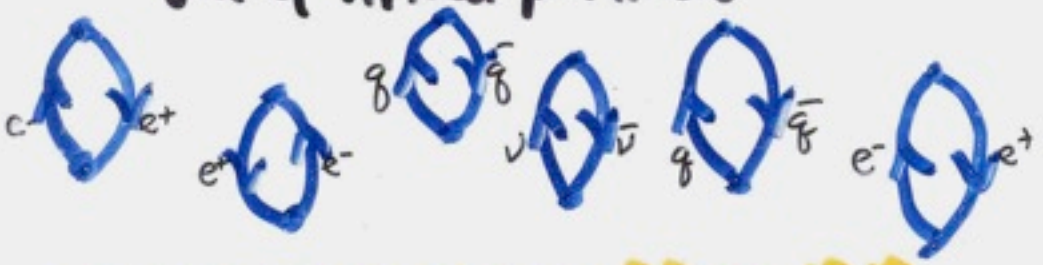
finite answer that is off by order of magnitude

$\rho_{vac} \approx 3 \times 10^{-11}\ eV^4$

$E_{DE} \approx 0.03\ eV$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected (shifting of atomic levels in H)

W. LAMB, Nobel Prize '55

Quantum vacuum is elastic ($p = -\rho$)

& its Gravity is VERY Repulsive! ($\rho + 3p = -2\rho$)

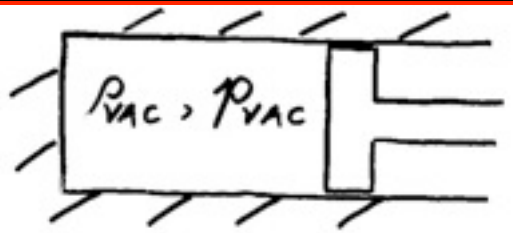
JUST WHAT IS NEEDED -- BUT...

THEORETICAL ESTIMATES OF AMOUNT

10^{55} x what is needed to explain accelerating Universe

"Houston, we have a problem"

The Gravity of Nothing Is Repulsive



$dE = -p\,dV$ (First Law)

$\rho_{VAC}\,dV = -\rho_{VAC}\,dV \Rightarrow \rho_{VAC} = -\rho_{VAC}$

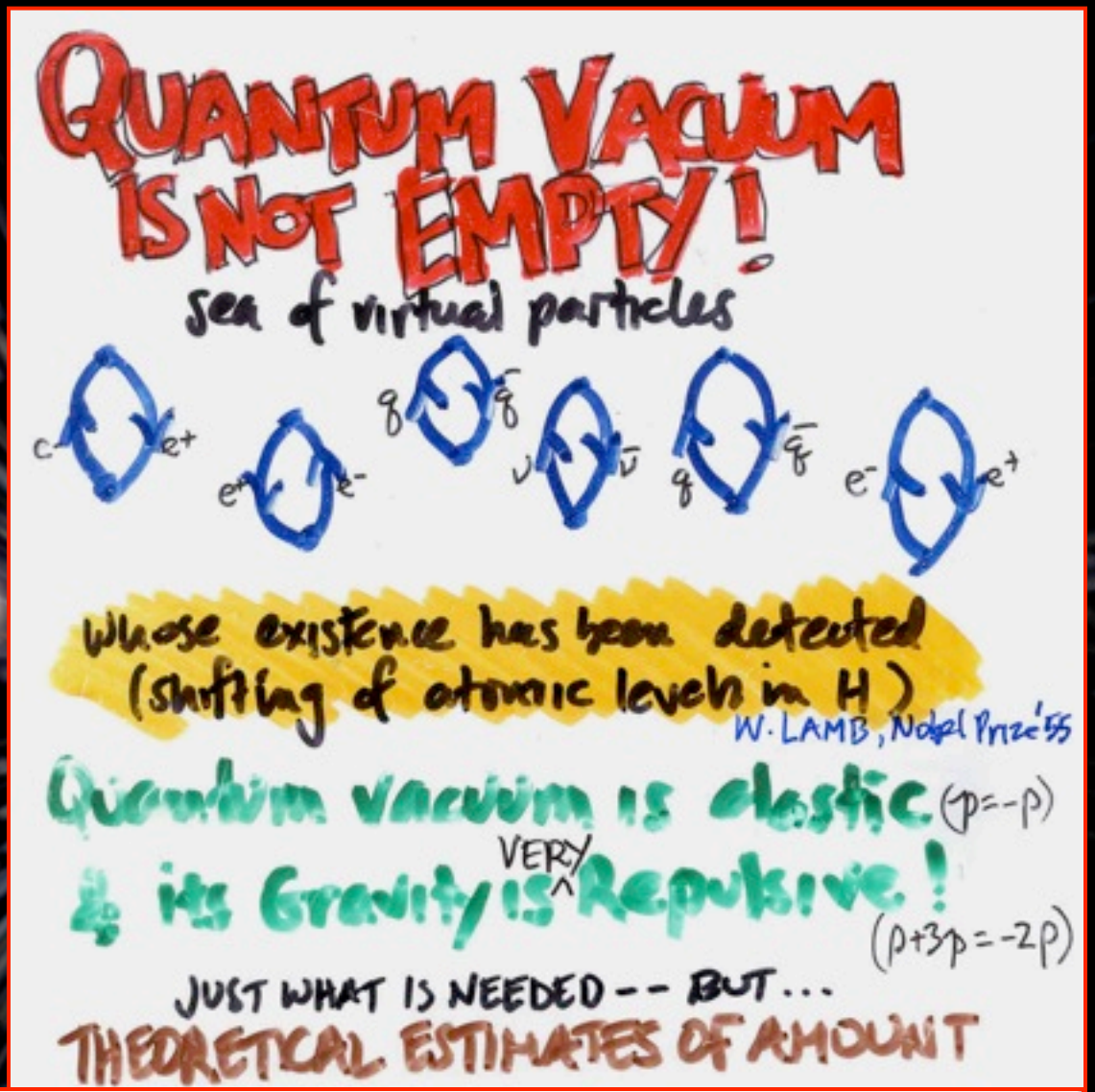
$T^{\mu\nu}_{VAC} = \rho_{VAC}\, g^{\mu\nu}$

(same as Λ)

finite answer that is off by
order of magnitude

$\rho_{vac} \approx 3 \times 10^{-11}$ eV^4

$E_{DE} \approx 0.03$ eV

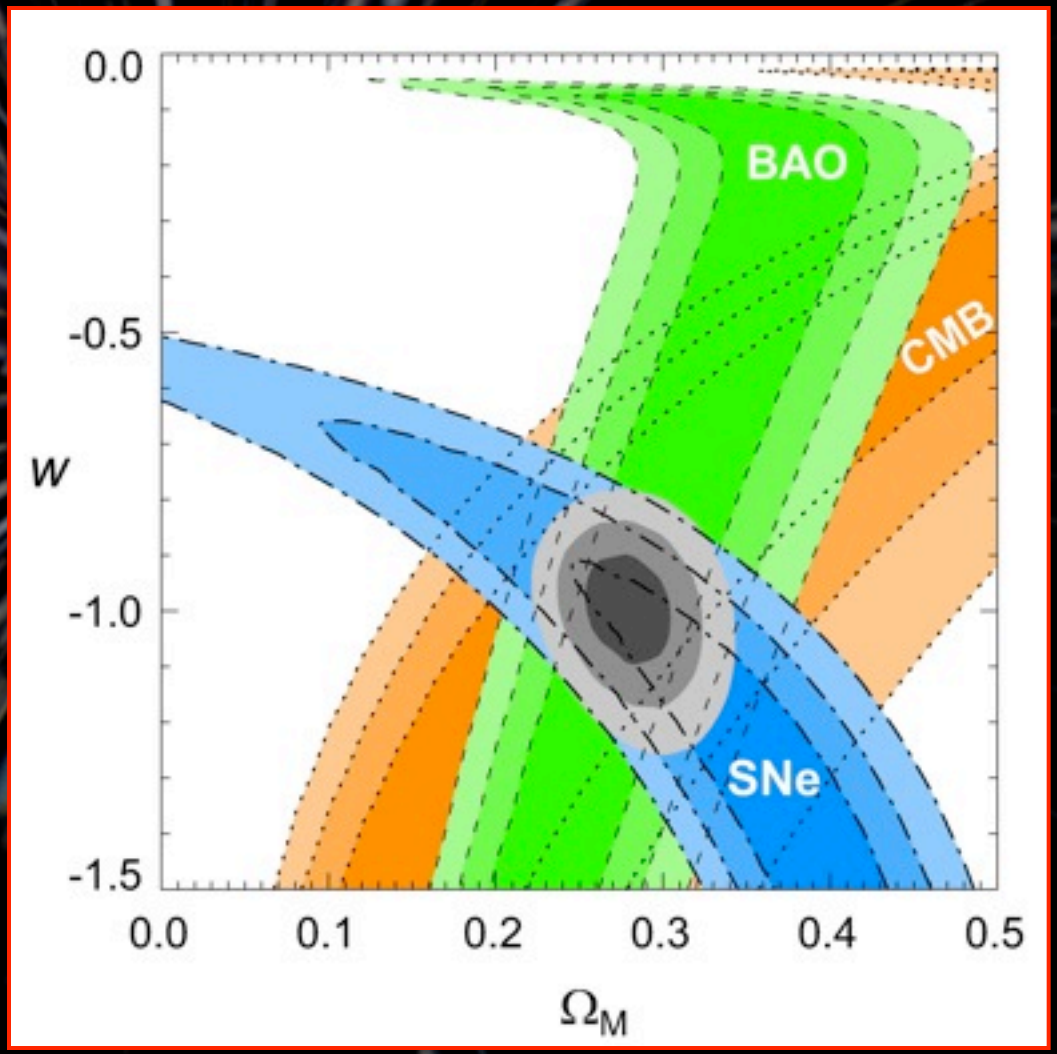


$$\rho_{\text{zero pt}} = \frac{1}{2}\int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} = \frac{1}{16\pi^2}k_{\max}^4$$

$$\rho_{\text{zero pt}} < \rho_{\text{crit}} \Rightarrow k_{\max} < 0.03\,\text{eV}$$

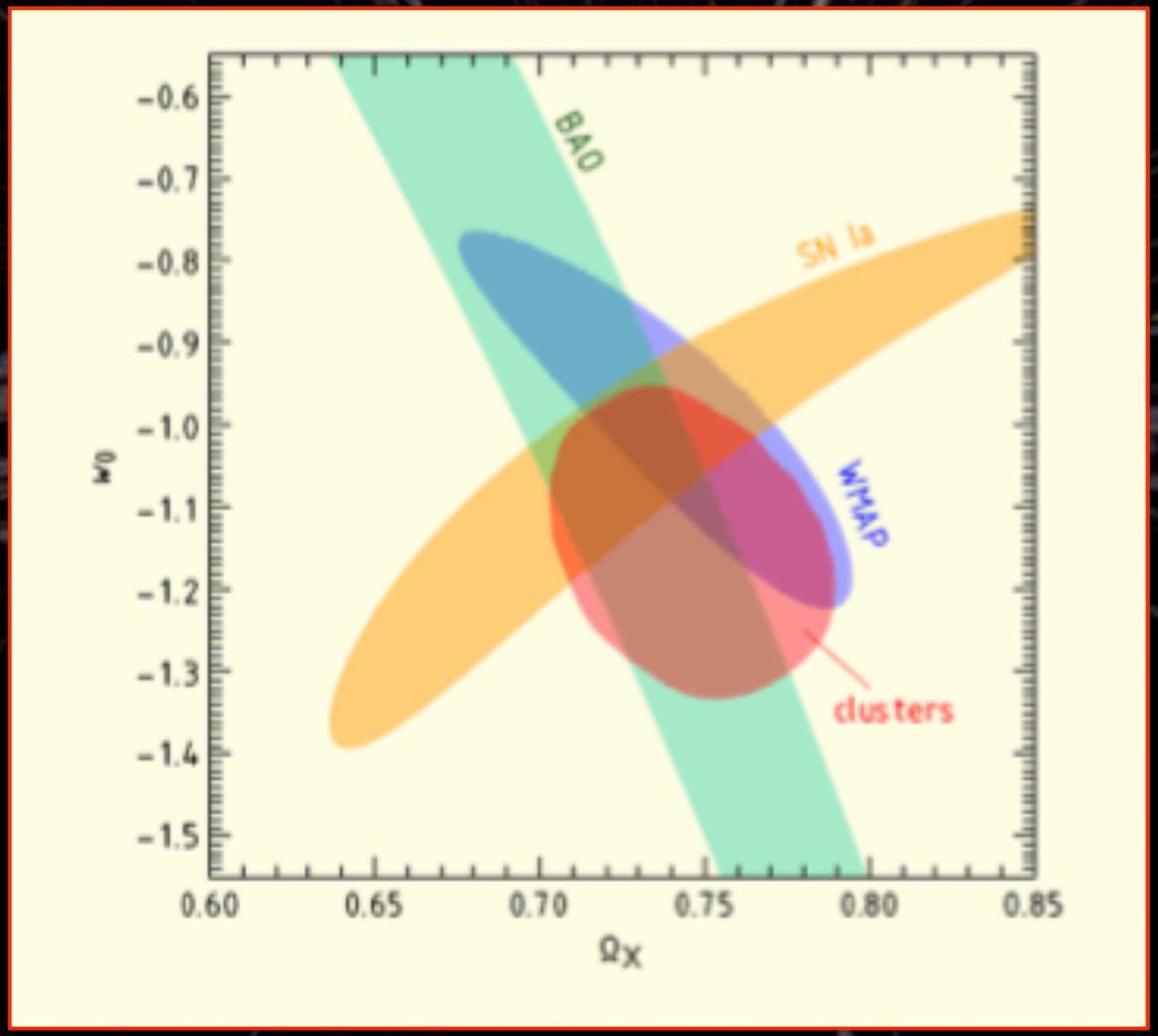
F5: w = -1 ± “0.2” (SNe et al)

- See Kessler talk

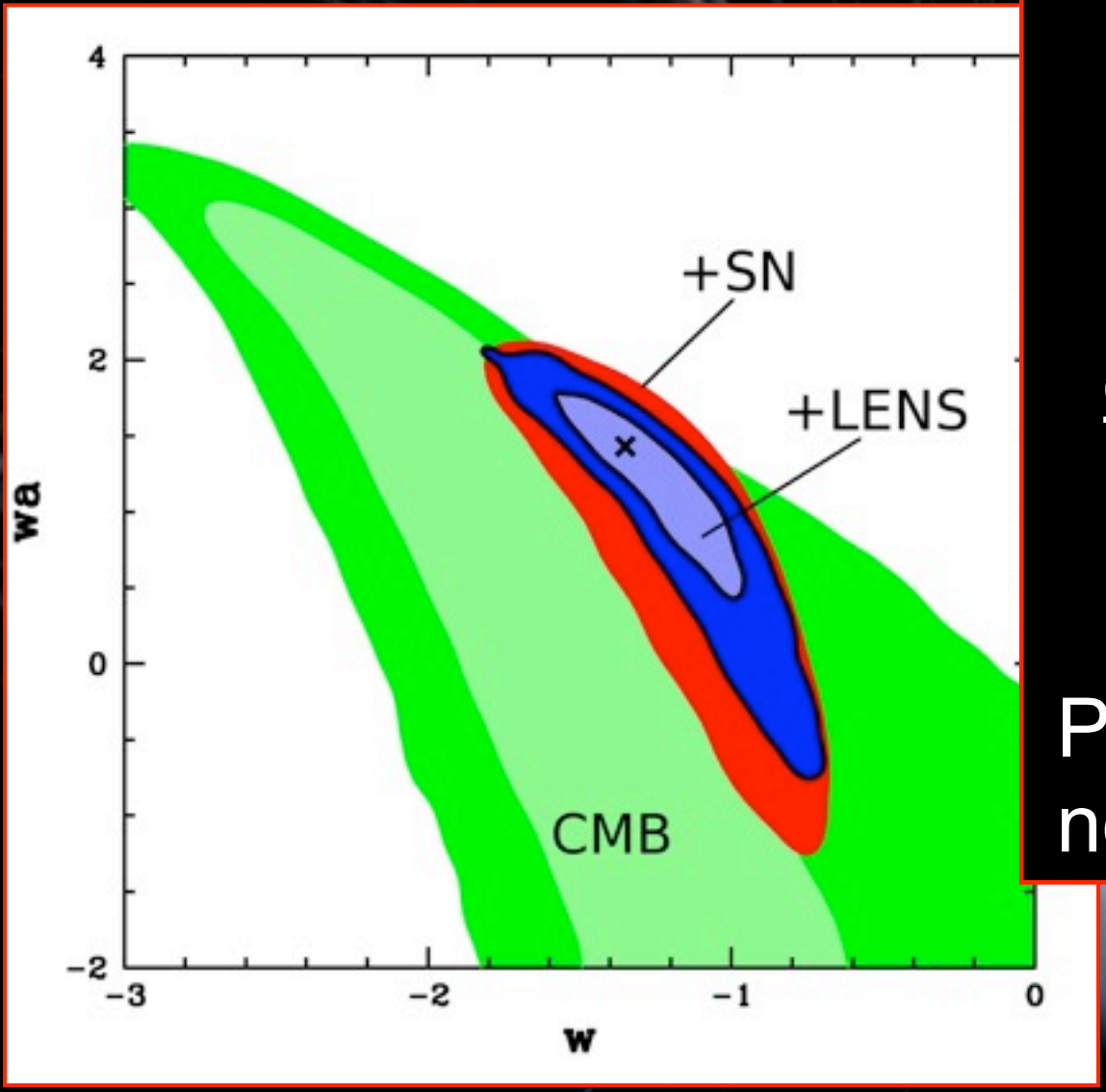


New Results 400d Survey

Alexey Vikhlinin et al, CCCP



variation of w not constrained at all



Allow w to vary:

$w = w_0 + w_a(1-a)$

$\Omega_{DE} = 0.76 \pm 0.02$

$w_0 = -1 \pm 0.2$

$w_a \sim 0 \pm 1$

Possible variation is not well constrained

Summary of “The Facts”

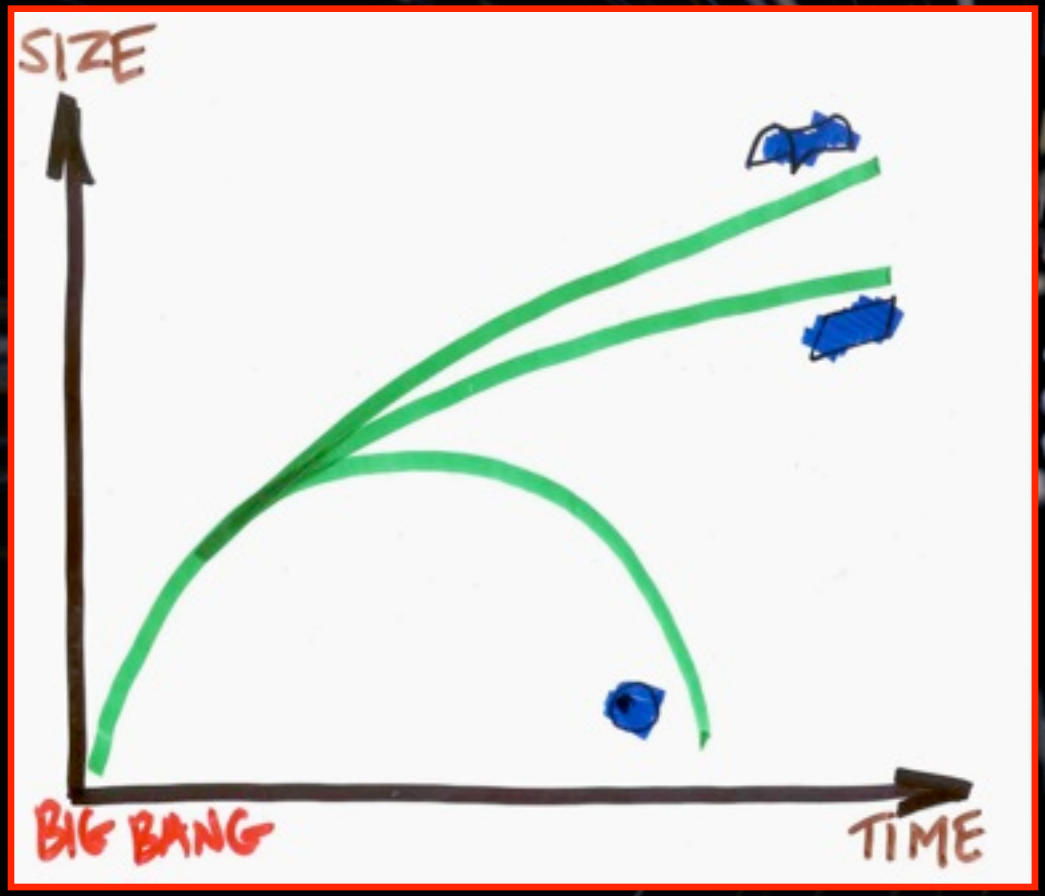
- F1: Expansion is accelerating
- F2: Flat, ΛCDM fits all data
- F3: Little room for deviation from standard structure growth
- F4: Little room for early acceleration
- F5: w = -1 ± “0.2” (SNe)

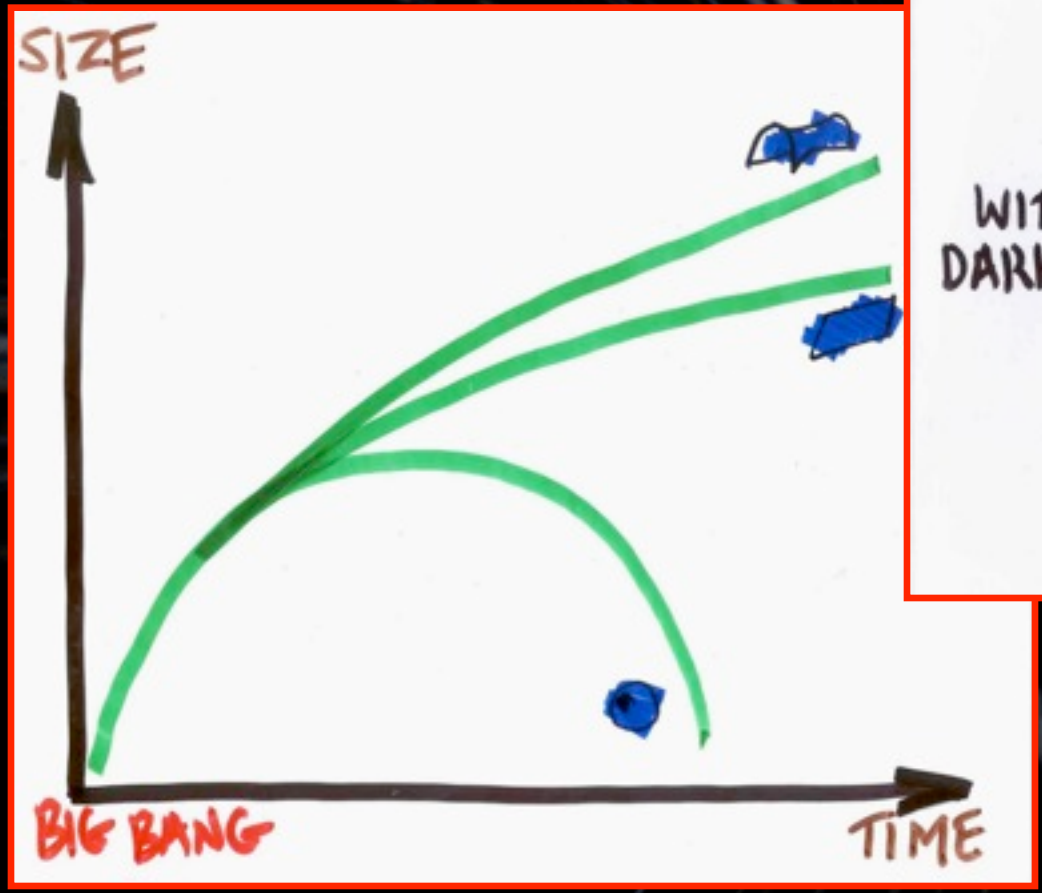

The Big Questions

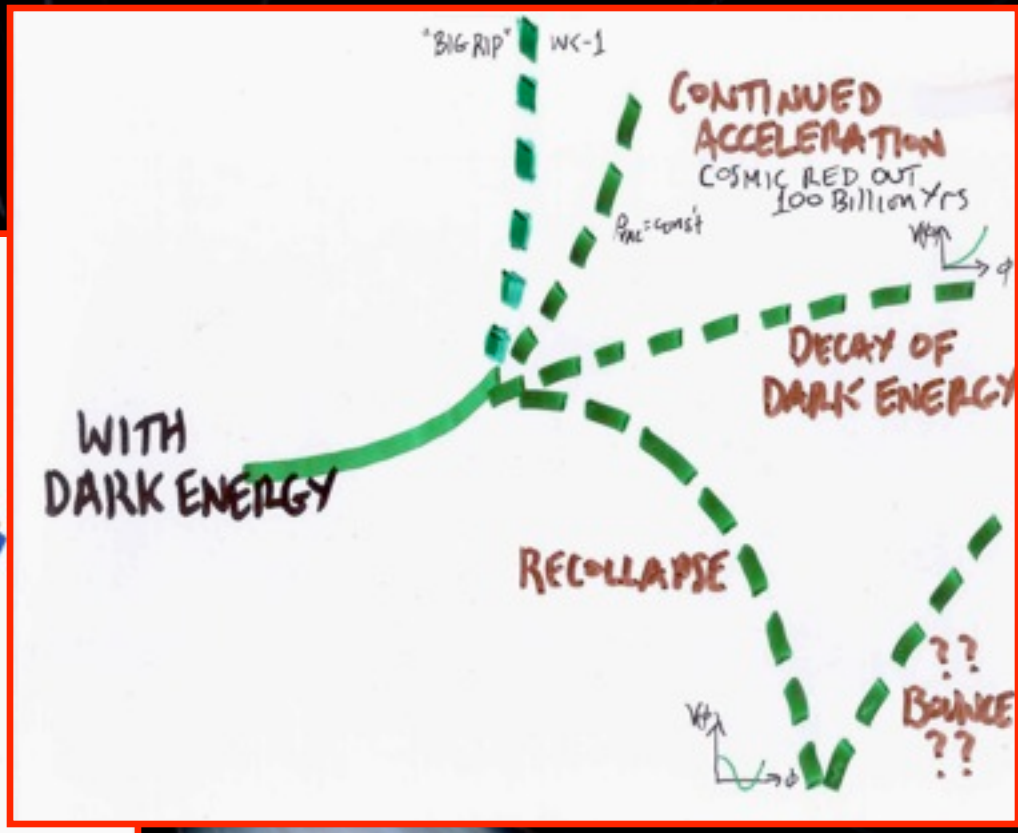
For Astrophysical Cosmologists

1. Is the background cosmological model ΛCDM to ±1%? (the current ±10% has led to tremendous progress in understanding astrophysical evolution)
2. Destiny of the Universe

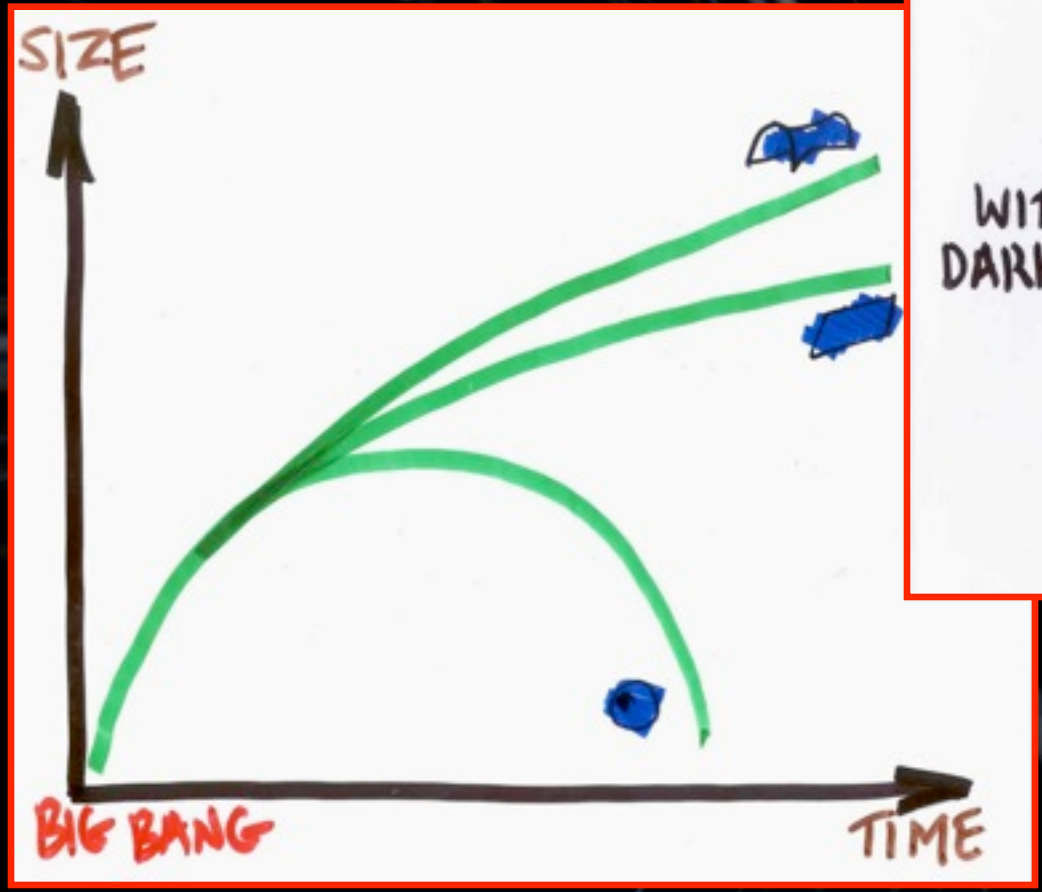

From Here to Eternity

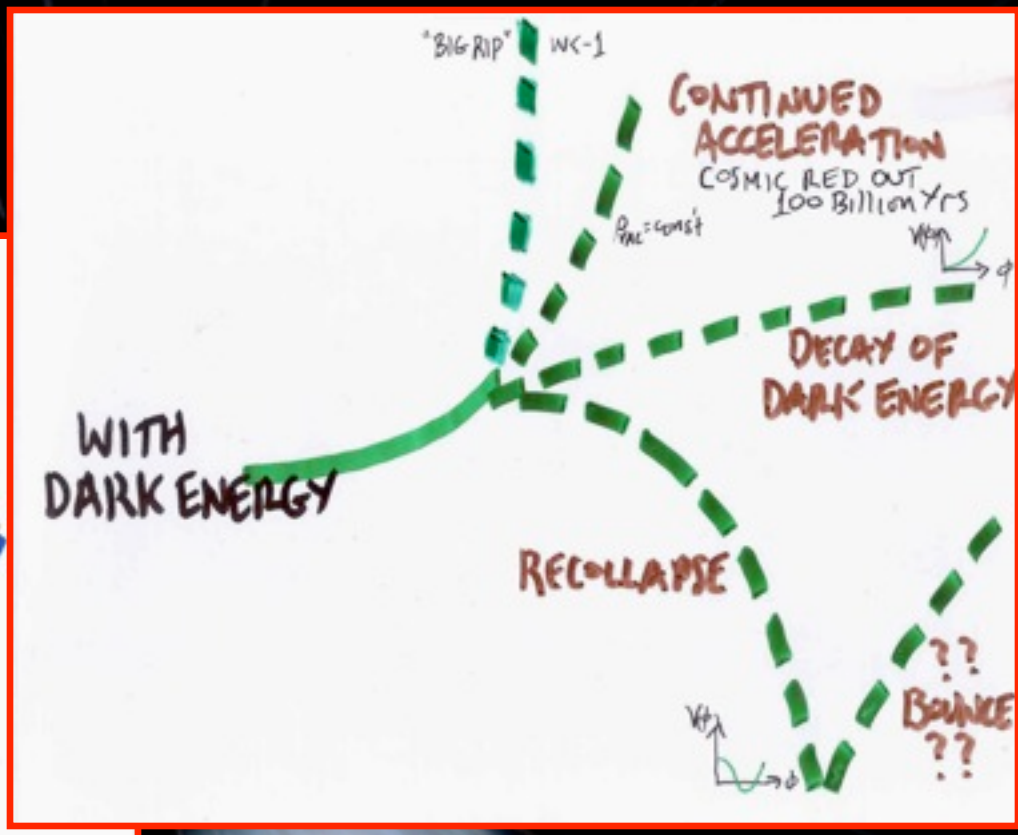

SIZE
BIG BANG
TIME


SIZE
BIG BANG
TIME

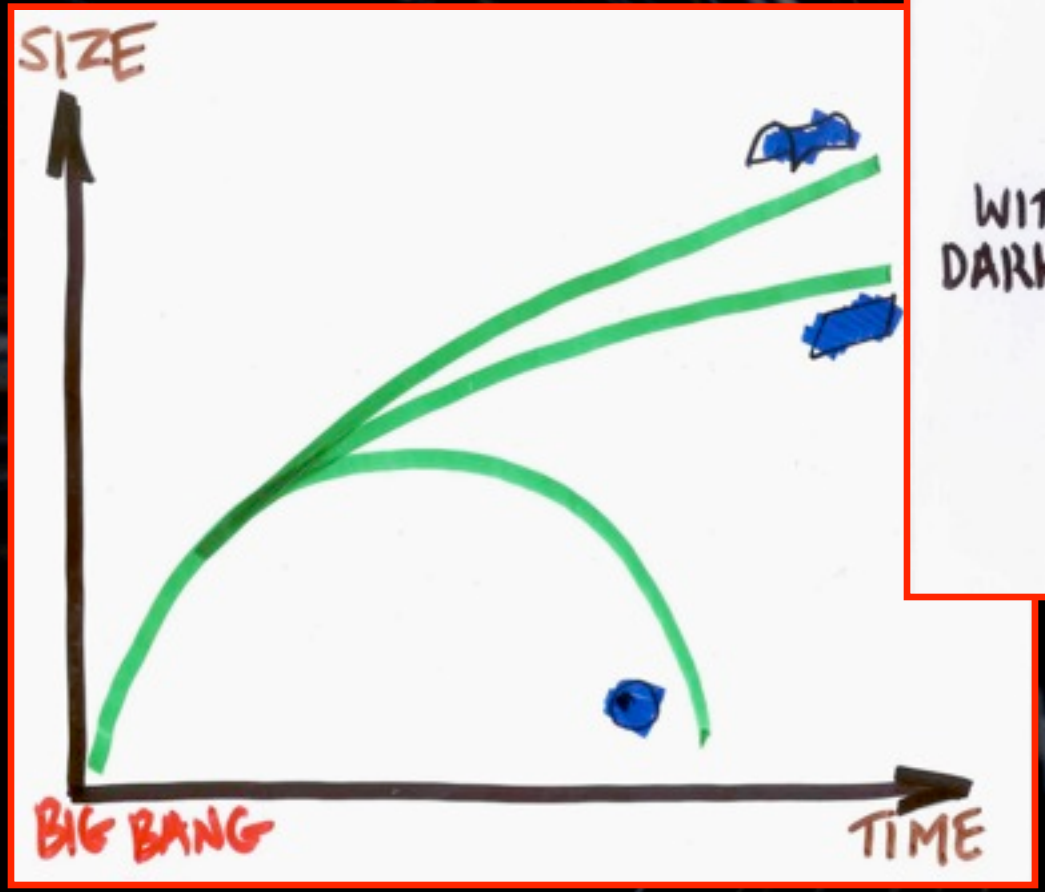

"BIG RIP"
w<-1
CONTINUED ACCELERATION
COSMIC RED OUT
100 Billion Yrs
ρvac = const
V(φ)
φ
DECAY OF DARK ENERGY
WITH DARK ENERGY
RECOLLAPSE
??
BOUNCE
??
V(φ)
φ

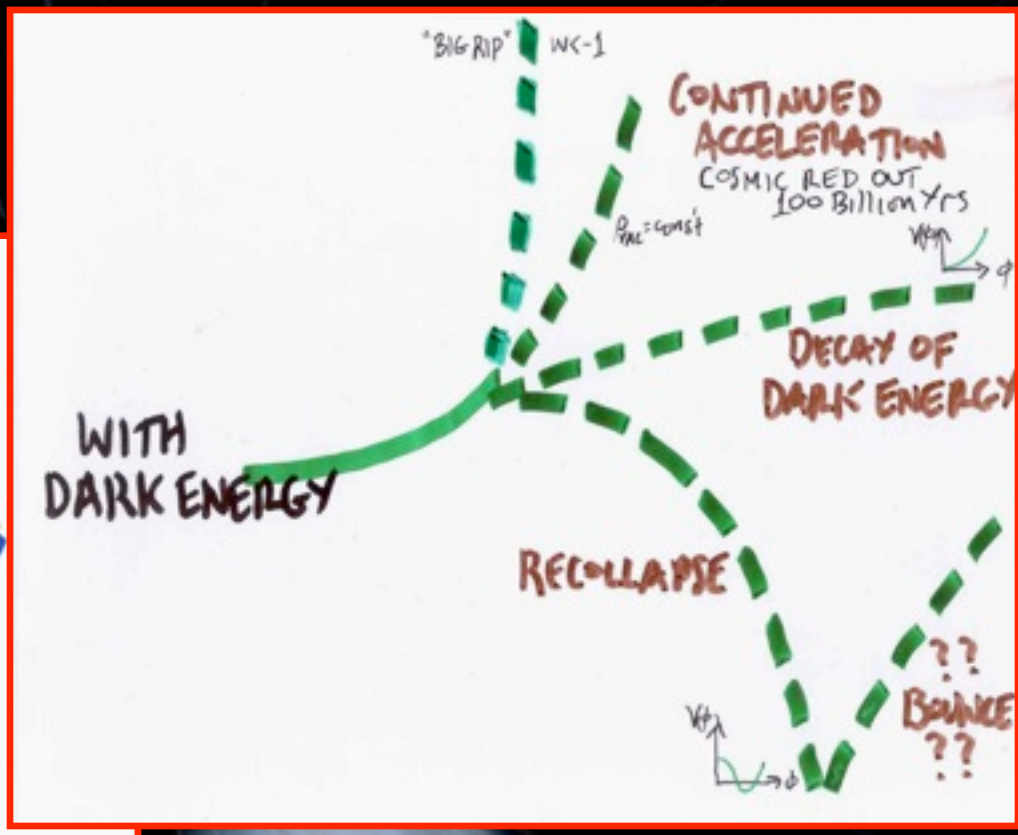
In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!





In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!





Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

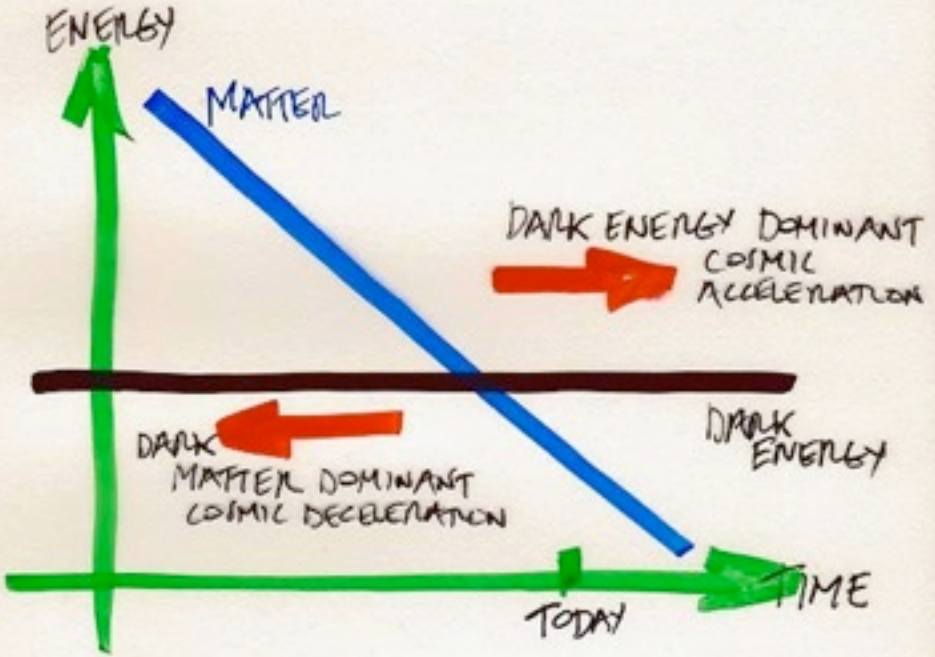
For Fundamental Cosmologists

1. How much does nothing weigh? (the vacuum energy problem that traces back to Pauli, Zel'dovich and Weinberg)
2. What is causing the expansion of the Universe to accelerate?
3. The mix?: ratios of baryons, cold dark matter, hot dark matter, photons, dark energy (not photons/neutrinos)

NANCY KERRIGAN ASKED:

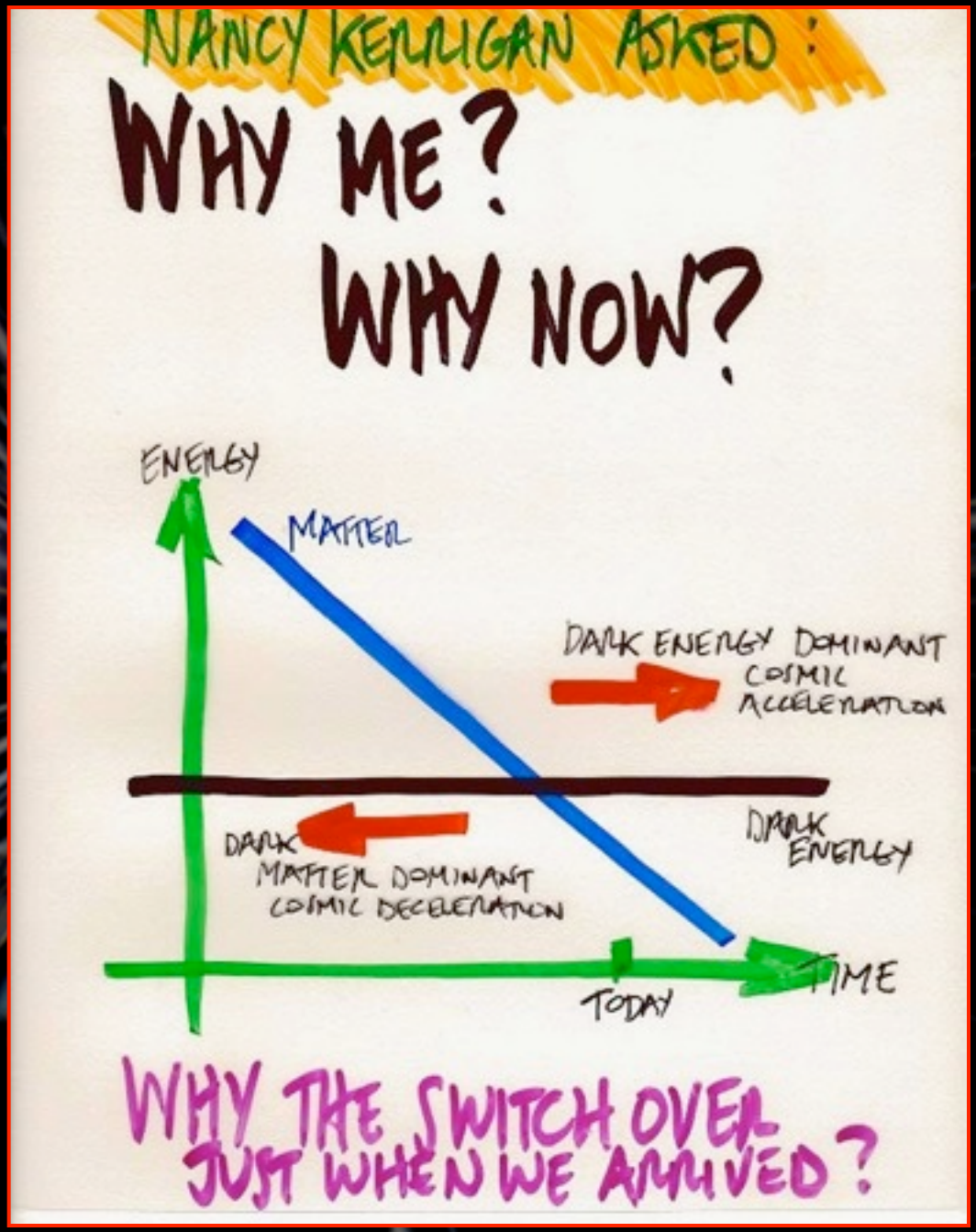
WHY ME?

WHY NOW?

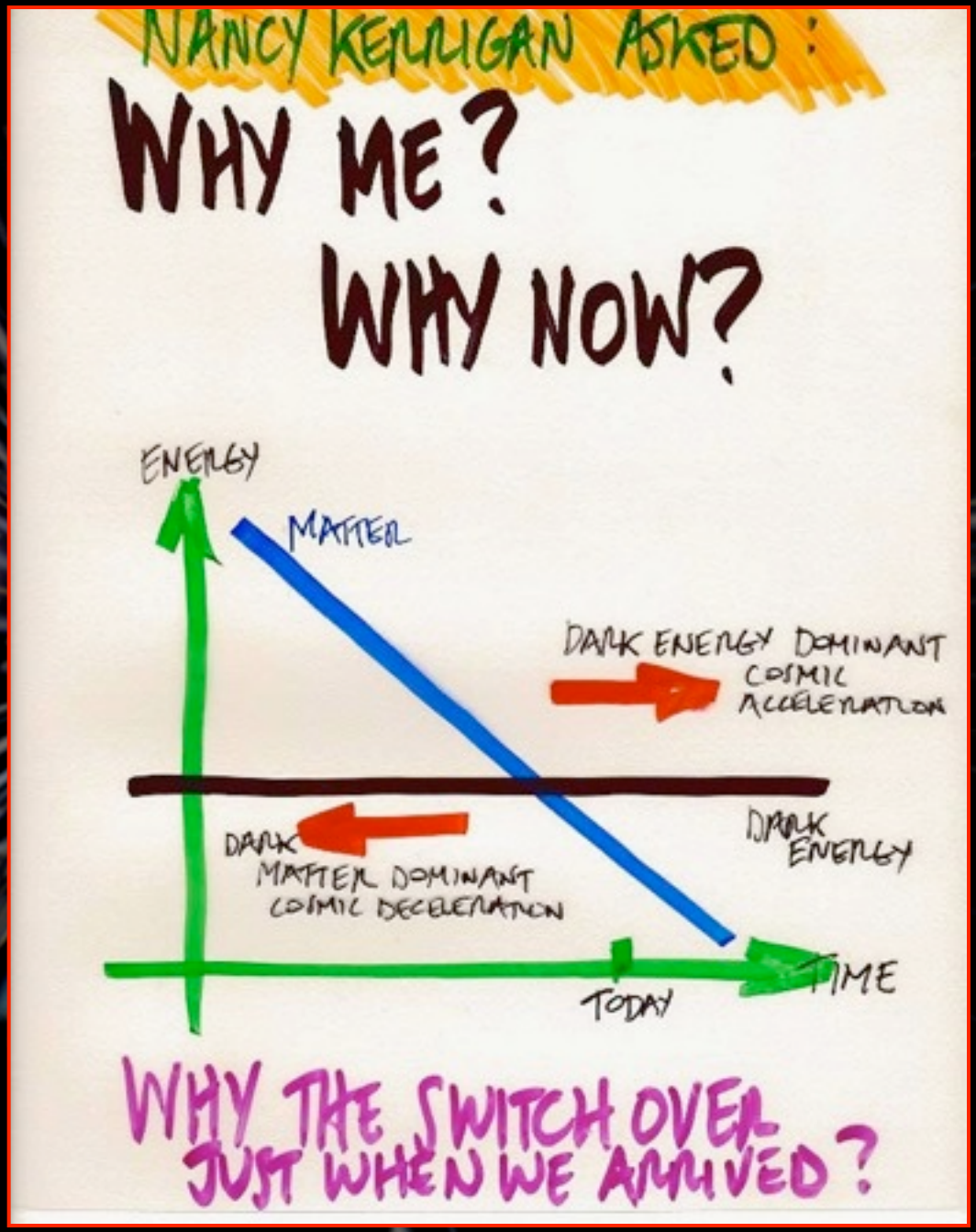


WHY THE SWITCH OVER JUST WHEN WE ARRIVED?

Important clue or coincidence?



At the very least, we can now say that cosmology is the battle between two dark titans



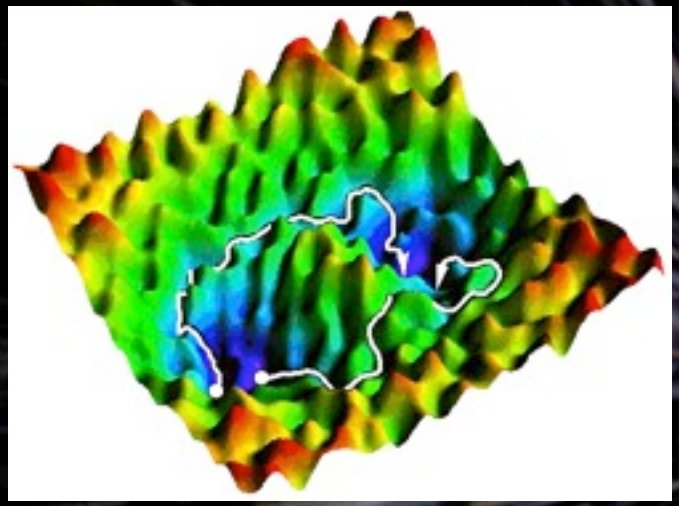
Dark Theory: Three Classes of Solutions

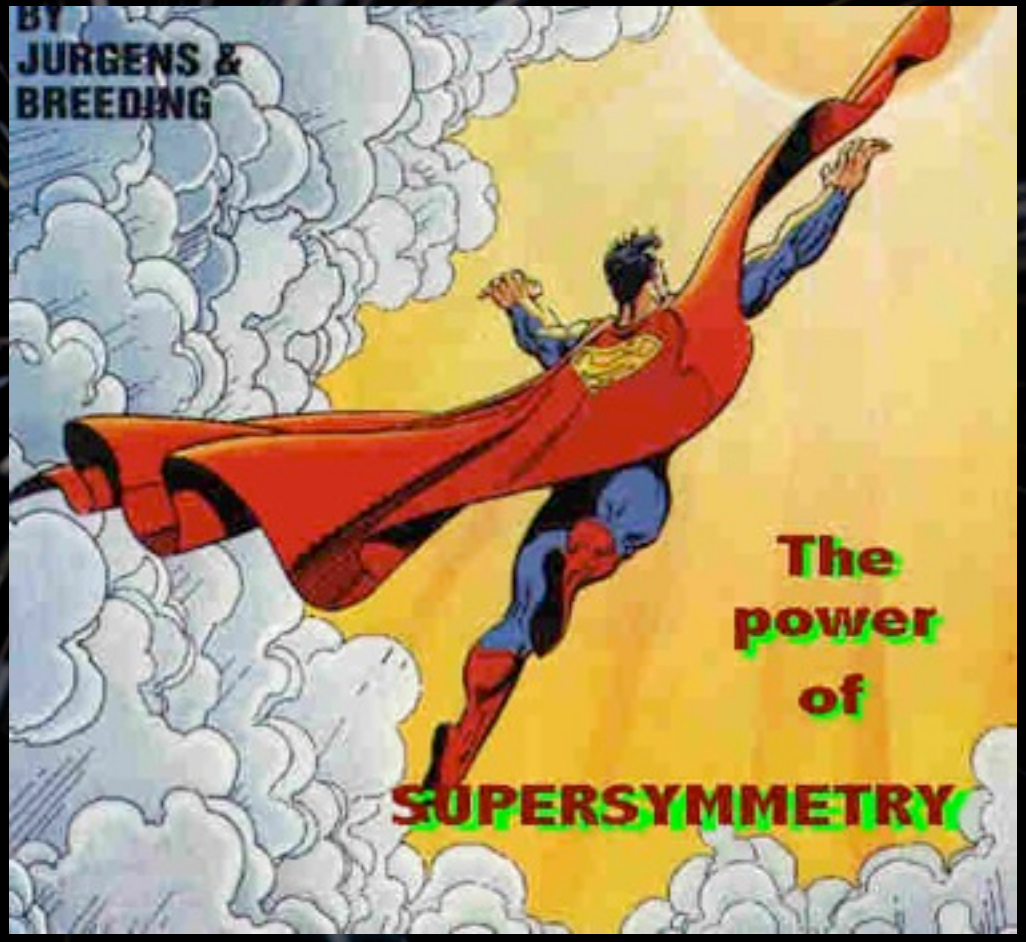
1. Assume GR, RW; focus on dark energy; e.g., vacuum energy, quintessence, topological defects or ??

2. Assume RW, but not GR; focus on modified gravity, e.g., DGP or f(R) theories

3. Assume GR, but not RW; e.g., LTB models (hole in the Universe)

Vacuum Energy Problem Solved by Supersymmetry or ?



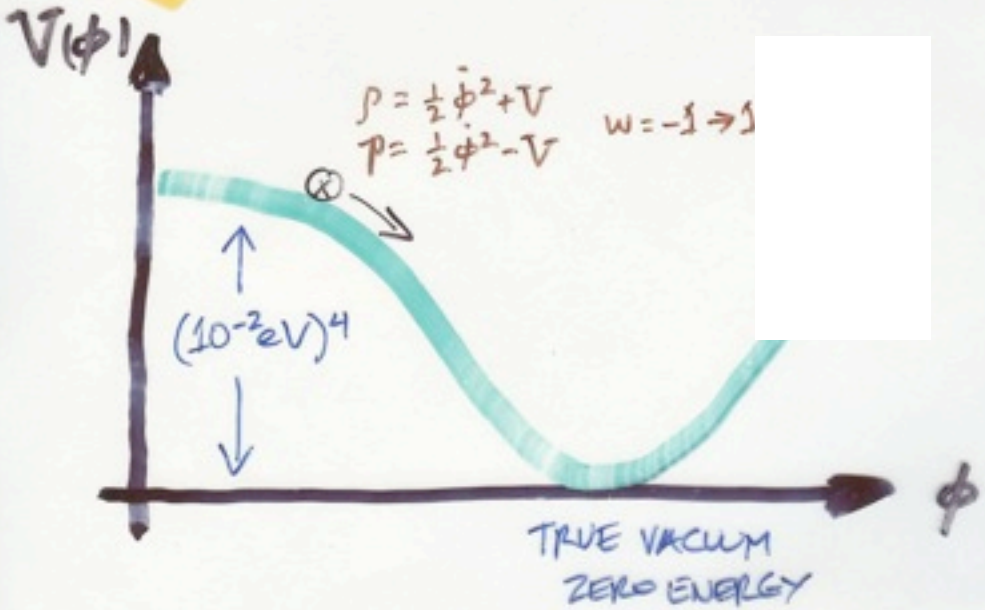


ROLLING SCALAR FIELD

(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

Bronstein 1933 (executed by Stalin 1935)
Hill Schramm Fry 1986
Freese et al 1987
Ratra-Peebles 1988
Frieman et al 1995
Caldwell et al 1998
& others

A. GREENSPAN 1998: "... Brief Episodes of Inflation Are Unavoidable."

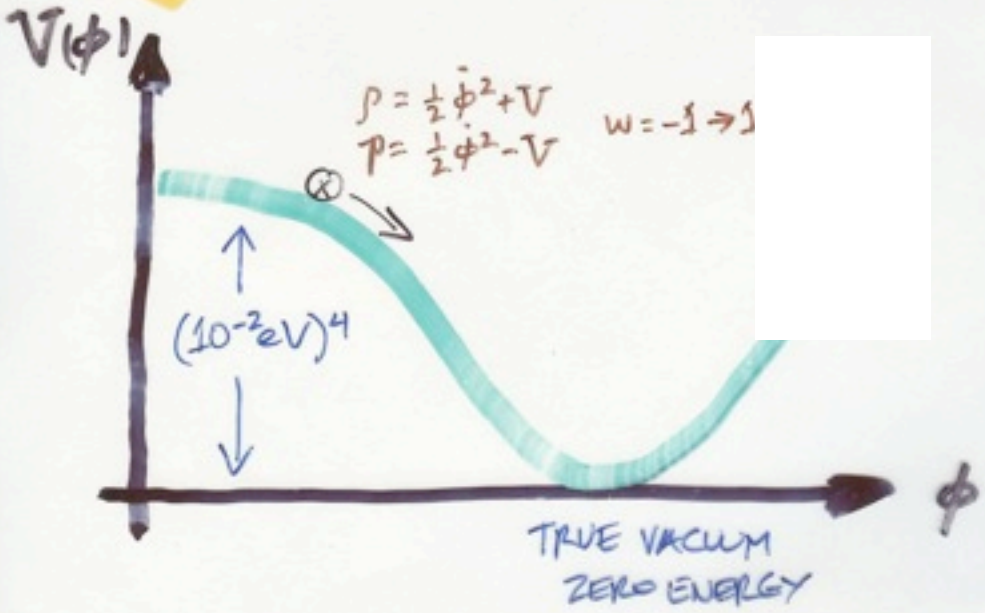


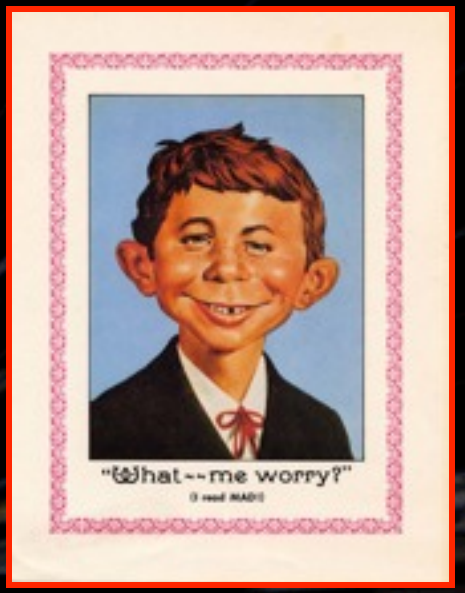
ROLLING SCALAR FIELD

(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

Bronstein 1933 (executed by Stalin 1935)
Hill Schramm Fry 1986
Freese et al 1987
Ratra-Peebles 1988
Frieman et al 1995
Caldwell et al 1998
& others

A. GREENSPAN 1998: "... Brief Episodes of Inflation Are Unavoidable."

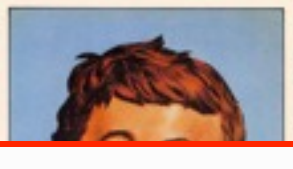




Theorists: When in doubt, just add a scalar field

ROLLING SCALAR FIELD

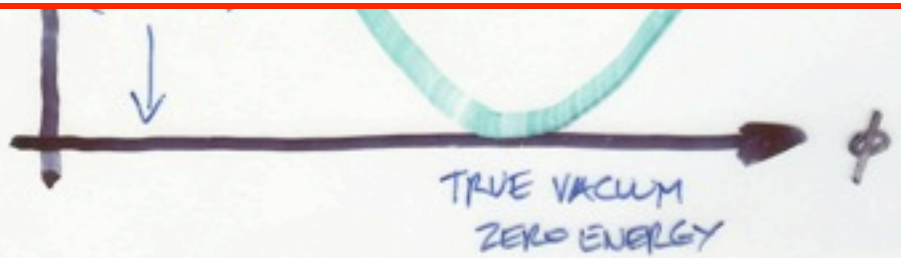
(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)



$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$



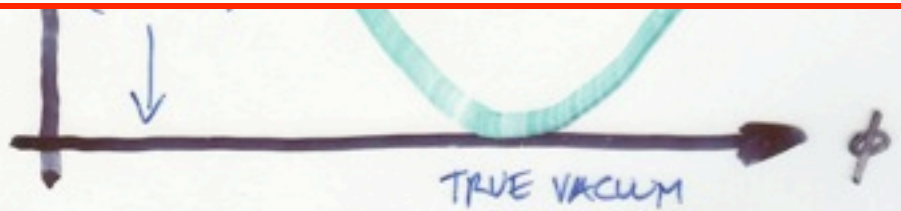
ROLLING SCALAR FIELD

(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

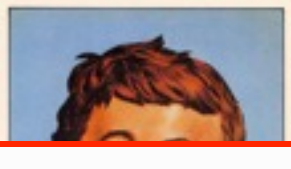
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w = \frac{-V(\phi)}{+V(\phi)} \approx -1$$



ROLLING SCALAR FIELD

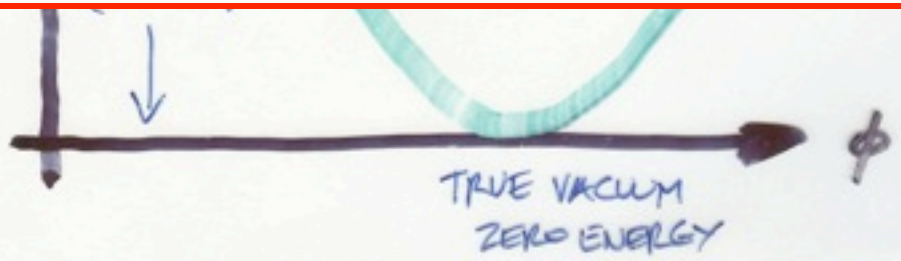
(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)



$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w = \frac{-V(\phi)}{+V(\phi)} \approx -1$$



Many, many variations on this theme (not unlike inflation)

NETWORK OF (FILAMENTED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98

VERY ELASTIC: $p = -\rho/3$

INCOHERENT: $p = -N/3\ \rho$

NO DARK ENERGY

NEW ASPECT OF GRAVITY

→ "EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION !

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm^3

$\approx 10^{-100}$ × DENSITY AFTER INFLATION

NEW GRAVITATIONAL PHYSICS

BECAUSE GR DOES NOT MARRY QM & GRAVITY EXPECT A THEORY BEYOND EINSTEIN'S

BUT ... ALSO EXPECT NEW GRAV PHYSICS TO APPEAR AT SHORT DISTANCES

SURPRISE?

INFLUENCE OF EXTRA DIMENSIONS

DEFFAYET, DVALI & GABADADZE

$$H^2 = \frac{8\pi G}{3}\rho_M + \left(H/r_c\right) \qquad r_c \sim H_0^{-1} \sim 10^{28}\,cm$$

SMALL CORRECTION TO GR

DVVUM, CARROLL, TRODDEN, MST

$$S = \frac{1}{16\pi G}\int d^4x\, F_g\left(R - \left(\mu^4/R\right)\right) \qquad \mu \sim H_0$$

Summary of Dark Theory

– Quantum Vacuum Energy (static)
  + it exists(!), same as Λ, w = -1 (F1 – F5)
  - 55 orders-of-magnitude discrepancy (or more!)
– "Quintessence" (dynamical scalar field)
  + temporary, related to cosmic inflation?, great variety of models, dark energy clumps, w varies, w < -1 possible (F1-F4)
  - doesn't solve vacuum energy, coupling to the world (F5)
– No Dark Energy, Modified Gravity!
  + Einstein didn't get last word, superstring inspired, no dark energy, inconsistencies when analyzed as GR (F1, F2, F4)
  - Cosmology good, gravity bad (F3, F5)
- Hole in the Universe (GR, but no RW)
  + no dark energy (F1)
  - Reconciling the rest of cosmology, we're at the center of the Universe (F2, F5)

F1: Expansion is accelerating
F2: Flat, ΛCDM fits all data
F3: Little room for non standard structure formation
F4: Little room for early acceleration
F5: w = -1 ± "0.2" (SNe)

Theory has provided strong guidance & interpretation

Theory has provided strong guidance & interpretation

- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times

Theory has provided strong guidance & interpretation

- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times
- Simple physics model: quantum vacuum energy (current null hypothesis)

Theory has provided strong guidance & interpretation

- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times
- Simple physics model: quantum vacuum energy (current null hypothesis)
- Dynamical models: rolling scalar field

Theory has provided strong guidance & interpretation

- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times
- Simple physics model: quantum vacuum energy (current null hypothesis)
- Dynamical models: rolling scalar field
- Physical parameter that describes and discriminates between models: $w = p/\rho < -1/3$

Theory has provided strong guidance & interpretation

- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times
- Simple physics model: quantum vacuum energy (current null hypothesis)
- Dynamical models: rolling scalar field
- Physical parameter that describes and discriminates between models: $w = p/\rho < -1/3$
- Look out for new gravitational physics

Theory has provided strong guidance & interpretation

- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times
- Simple physics model: quantum vacuum energy (current null hypothesis)
- Dynamical models: rolling scalar field
- Physical parameter that describes and discriminates between models: $w = p/\rho < -1/3$
- Look out for new gravitational physics
- Framework for treating GR alternatives

Theory has provided strong guidance & interpretation

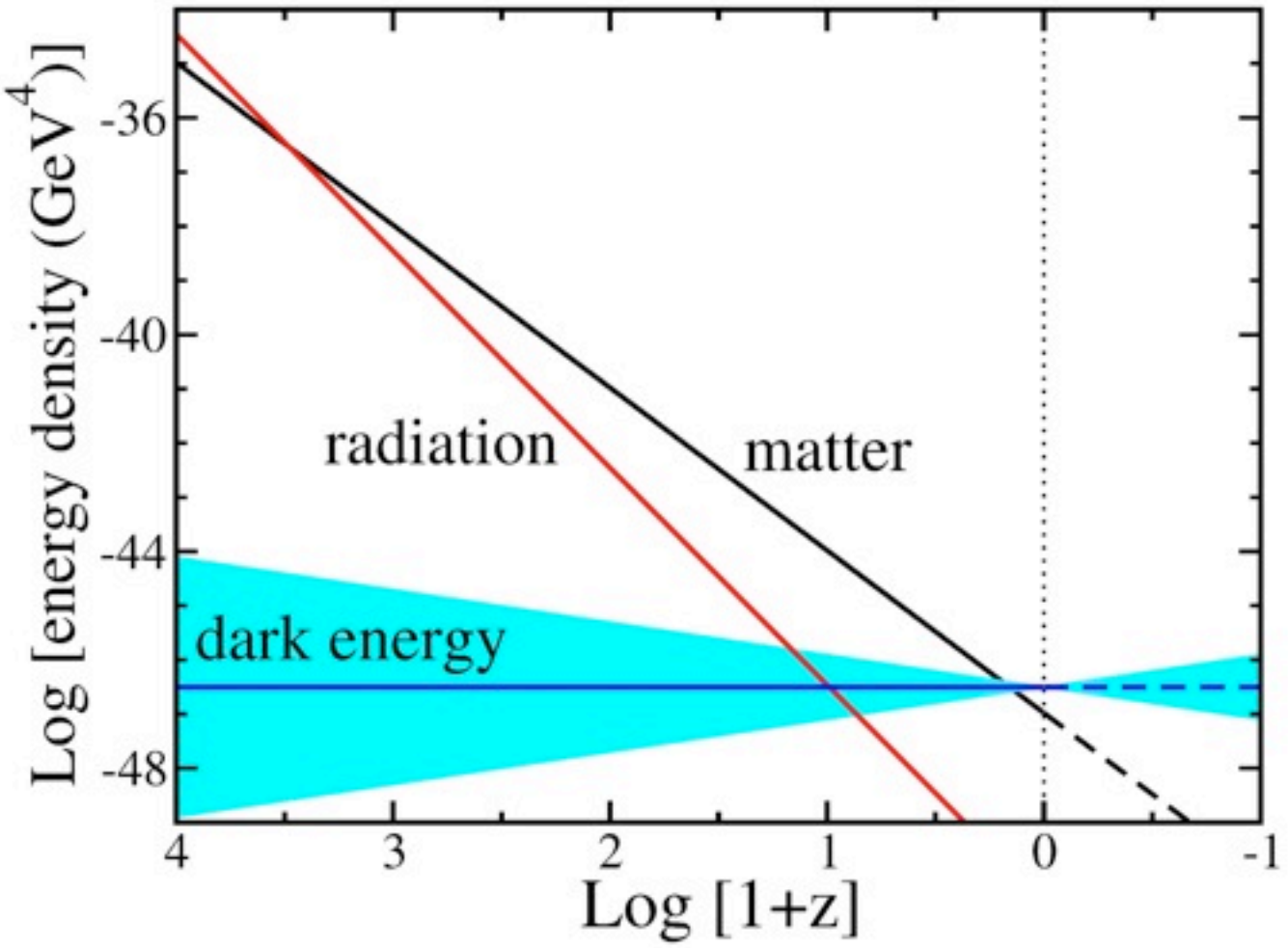
- Smooth, very elastic, non-particulate (medium) dark energy w/in GR, important at late times
- Simple physics model: quantum vacuum energy (current null hypothesis)
- Dynamical models: rolling scalar field
- Physical parameter that describes and discriminates between models: $w = p/\rho < -1/3$
- Look out for new gravitational physics
- Framework for treating GR alternatives
- Other effects: Long range forces, …

Goals for Stage IV

- Test null hypothesis: GR + dark energy = quantum vacuum energy
  - Falsify by $w \neq -1$, variation of w, "percent level measurements"; or clustering of dark energy
- Test consistency of GR by multiple independent measurements and dynamic measurements
- [Rule out LTB e.g. direct measure of acceleration or make untenable by other cosmological measurements]

NB:

- control of systematic error is crucial
- focus on $z < 2$ most profitable (every reason to believe dark energy less important, challenges of hi-z)
- synergy – complementarity between ground and space is essential


Log [energy density (GeV^4)]
-36
-40
-44
-48
radiation
matter
dark energy
4
3
2
1
0
-1
Log [1+z]

Some Comments on Techniques

- **SNe:** proven, direct, geometric, warts but no cancer, not the most powerful
- **Clusters:** detection, dynamic/geometric, huge numbers/ multiwavelength coming, mass proxy, gaussian assumption (flipside: very sensitive)
- **BAO:** some results, largely (all?) geometric, no obvious systematics (biasing?), coarse-grained, powerful
- **WL:** yet to be proven, could be limited by image quality or power spectrum, potentially most powerful (but not most sensitive probe, cf, Mellier)

NB: CMB and other data (e.g., H_0) provide important priors

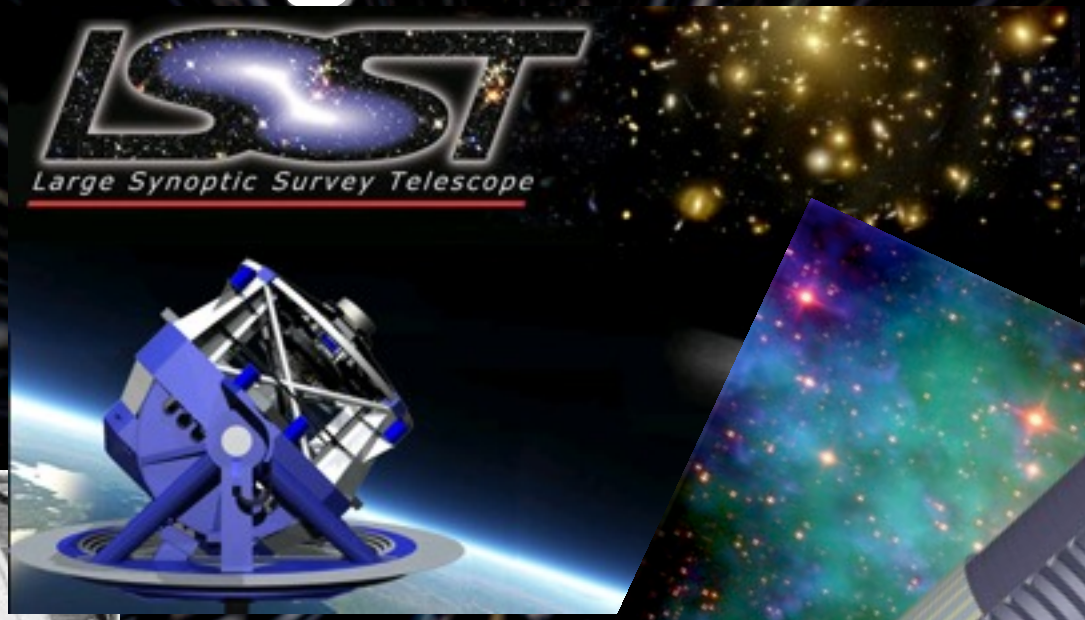
How Much is Enough?!#

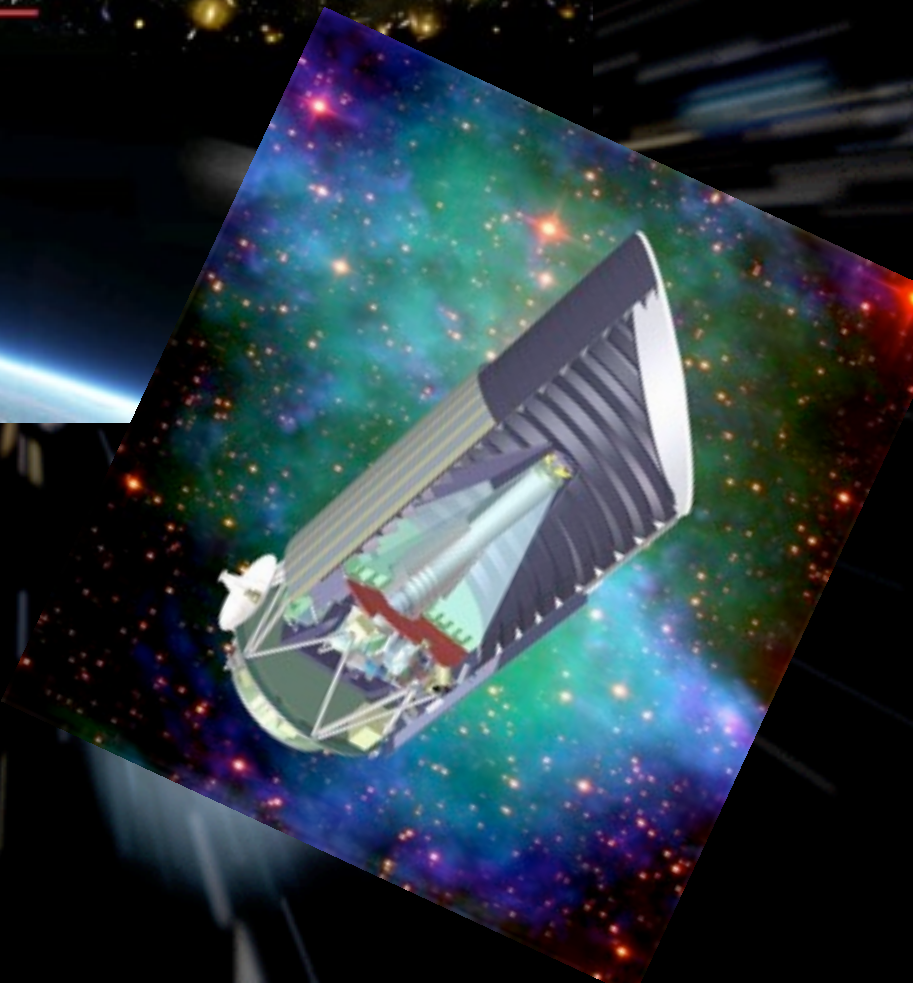
No prediction or clear goal to guide thinking

Stage IV: spend to the break in the cost curve (diminishing returns) "one really good go" on a really big problem

…but then what? Stage V?

Four “Stage IV” Futures





1. w = -1 & theory breakthrough

Percent level measurements of w and w_a and LSS consistent with ΛCDM

+

Theoretical understanding of small vacuum energy

=

Problem Solved for Cosmologists and Particle Physicists

2. “w = -1” & theory breakthrough

Percent level measurements of w and w_a and LSS consistent with ΛCDM

+

New compelling theoretical prediction for time variation of w and/or w_a – just beyond the reach of Stage IV

=

Problem Solved for Cosmologists, Particle Physicists think about Stage V

3. “$w \neq -1$” or $w_a \neq 0$

Detection of signature that DE is not vacuum energy

→

Potential implications for both particle physics and cosmology

=

With or without theoretical breakthrough both Cosmologists, Particle Physicists think about what to measure in Stage V

4. w = -1 & no theory breakthrough

Percent level measurements of w and w_a and LSS consistent with ΛCDM

+

No theoretical understanding of small vacuum energy

=

Problem solved for cosmologists, but not for particle physicists

“Time out”: take a break and think hard about what to do next

Last but not least, don't forget Stage IV theory

- Better parametric/nonparametric probes of dark energy
- Better modified gravity theories and ways to test them
- New/testable ideas about the mix
- Ideas for testing clustering of dark energy
- Laboratory predictions of dark energy models
- Vacuum energy problem