February 13-15

Science with a Wide-field Infrared Telescope in Space

Dark Energy Theory:

Why lambda isn't enough

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The University of Chicago

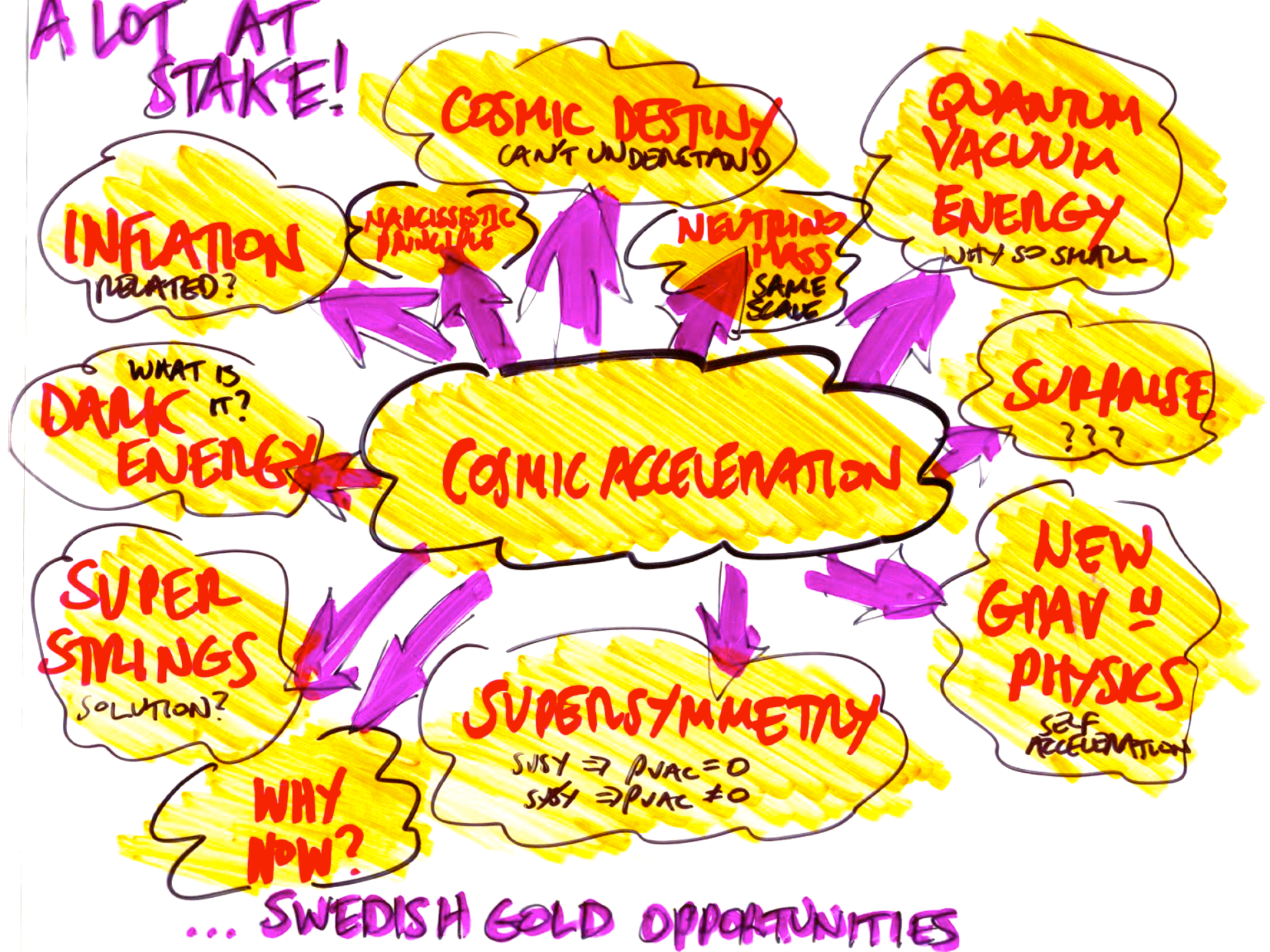
Why is Cosmic Acceleration / Dark Energy Important?

DARK ENERGY

MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

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

Drill for Dark Energy!

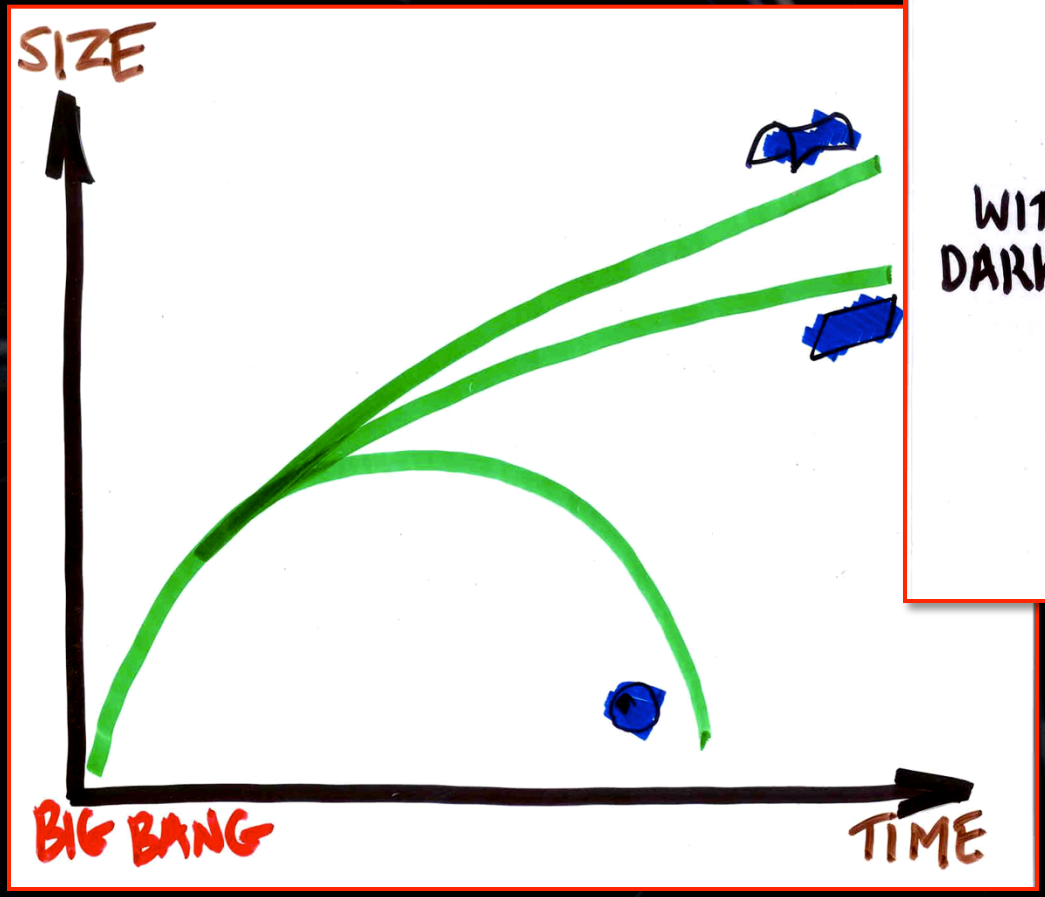

A LOT AT STAKE!
COSMIC DESTINY
CAN'T UNDERSTAND
INFLATION
RELATED?
NARCISSISTIC
FINE-TUNING
NEUTRINO MASS
SAME SCALE
QUANTUM VACUUM ENERGY
WHY SO SMALL
WHAT IS IT?
DARK ENERGY
COSMIC ACCELERATION
SUBMISE
???
SUPER STRINGS
SOLUTION?
SUPERSYMMETRY
SUSY ⇒ ρVAC=0
SUSY ⇒ ρVAC ≠0
NEW GRAV ⇒ PHYSICS
SELF ACCELERATION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

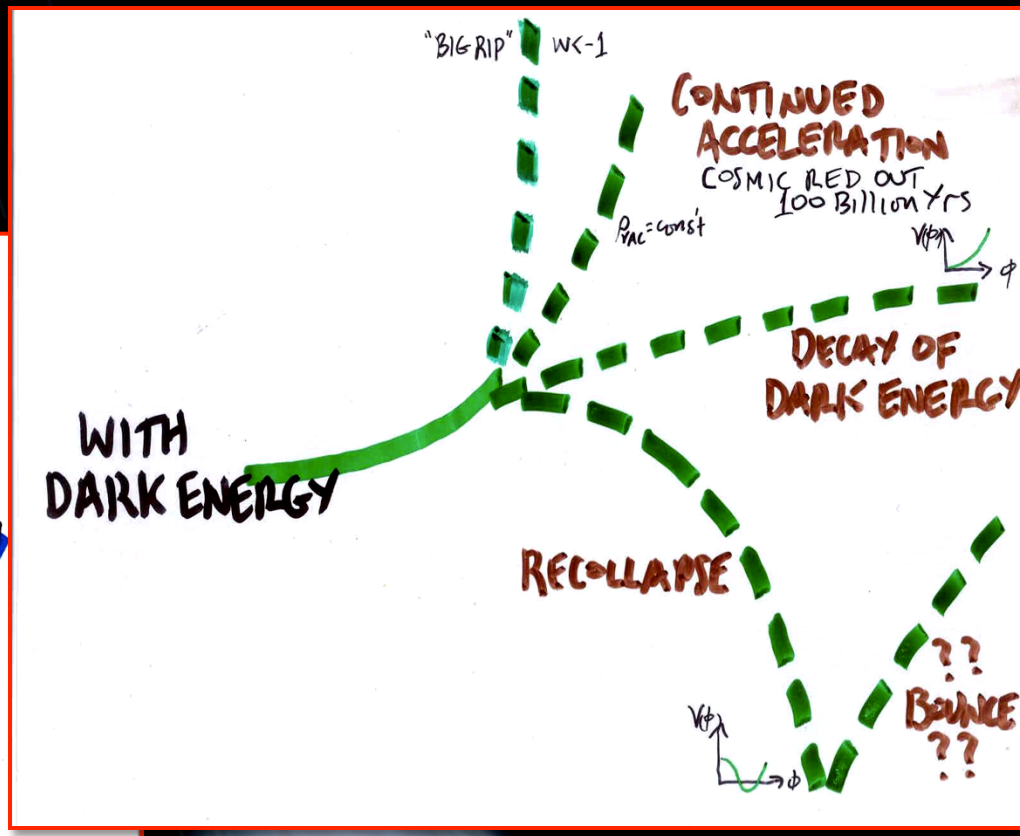
The Consensus Cosmology

Rests upon three mysterious pillars

All implicate new physics!

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





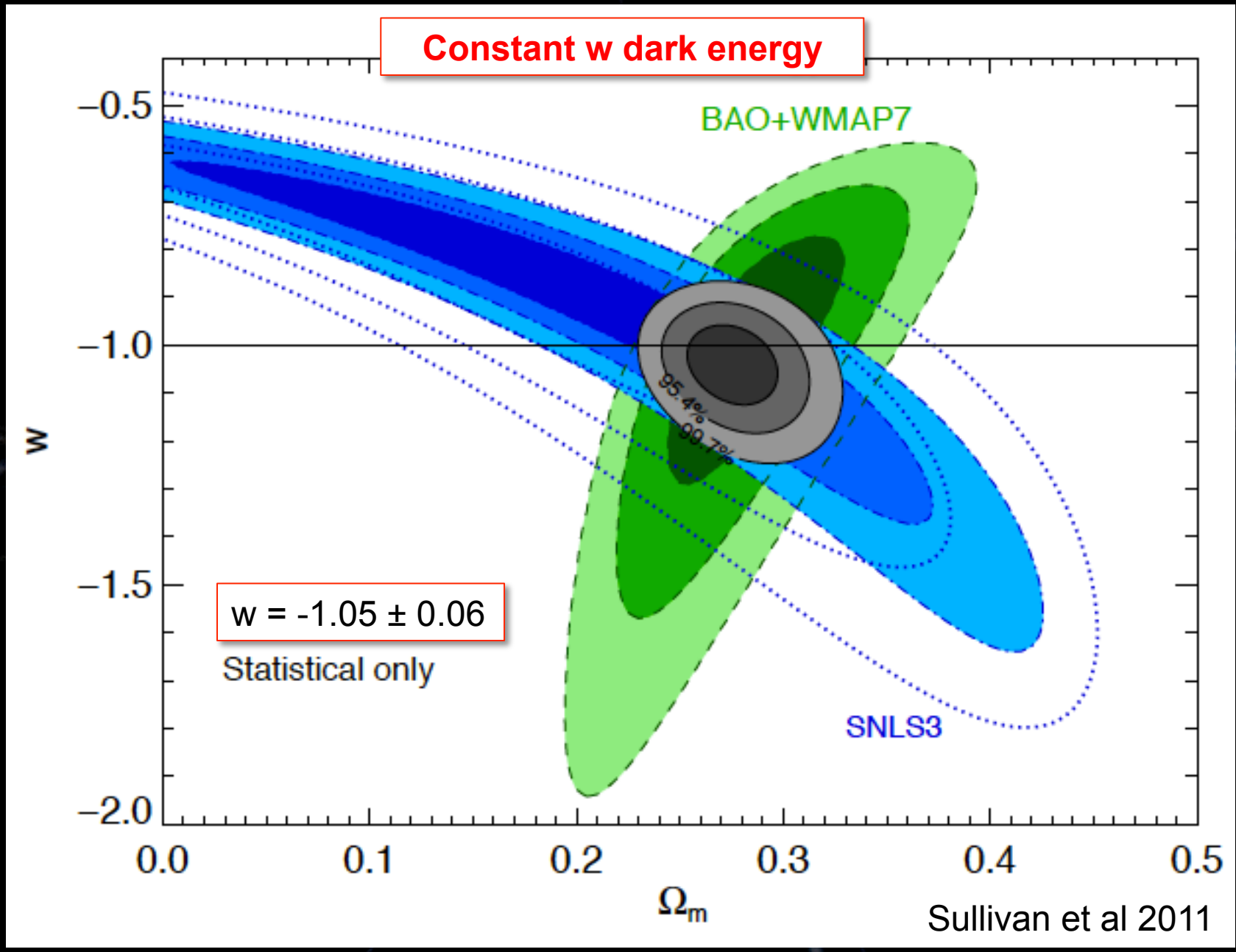
Can't Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

What do we know?
with increasing assumptions

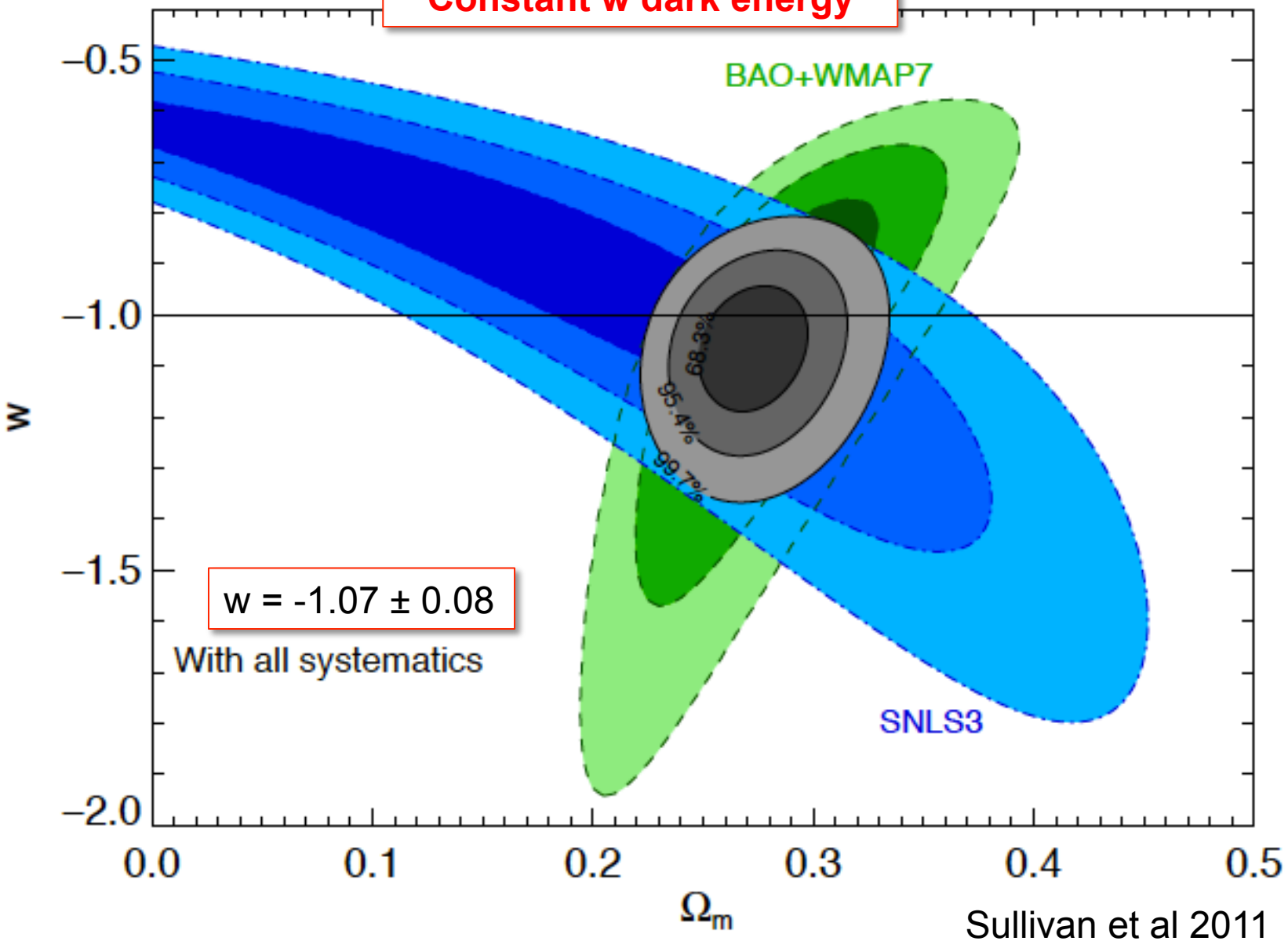
Robertson-Walker metric, no Friedmann equation, $q(z) = -d^2R/dt^2/RH^2$

- Five-sigma evidence for a period with $q(z) < 0$ (acceleration)
- Three-sigma evidence for a period with $q(z) > 0$

C. Shapiro & M.S. Turner, Ap J **649**, 543 (2006)


Constant w dark energy
BAO+WMAP7
SNLS3
95.4%
99.7%
w = -1.05 ± 0.06
Statistical only
w
−0.5
−1.0
−1.5
−2.0
0.0
0.1
0.2
0.3
0.4
0.5
Ω_m
Sullivan et al 2011

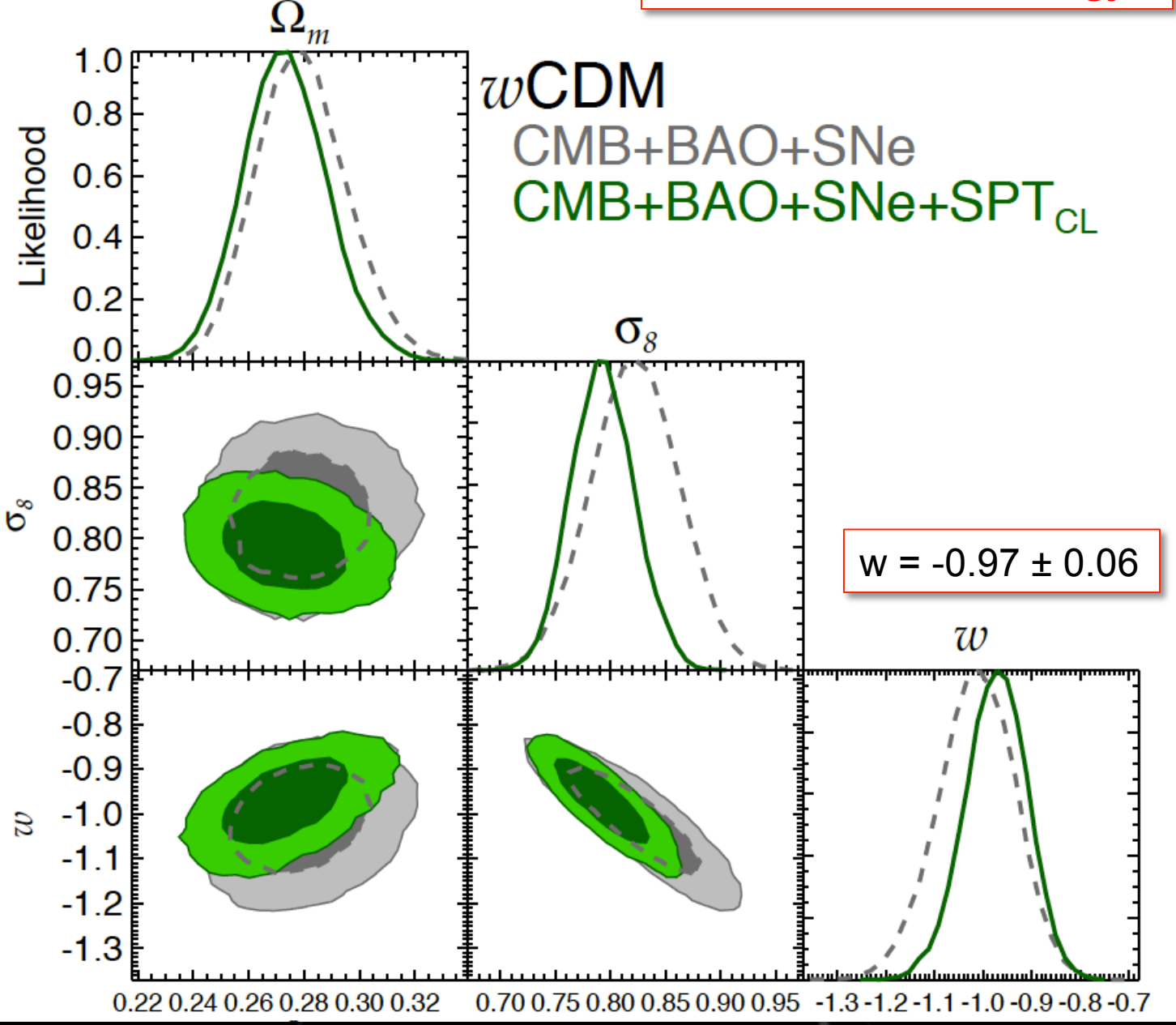
Constant w dark energy



Sullivan et al 2011

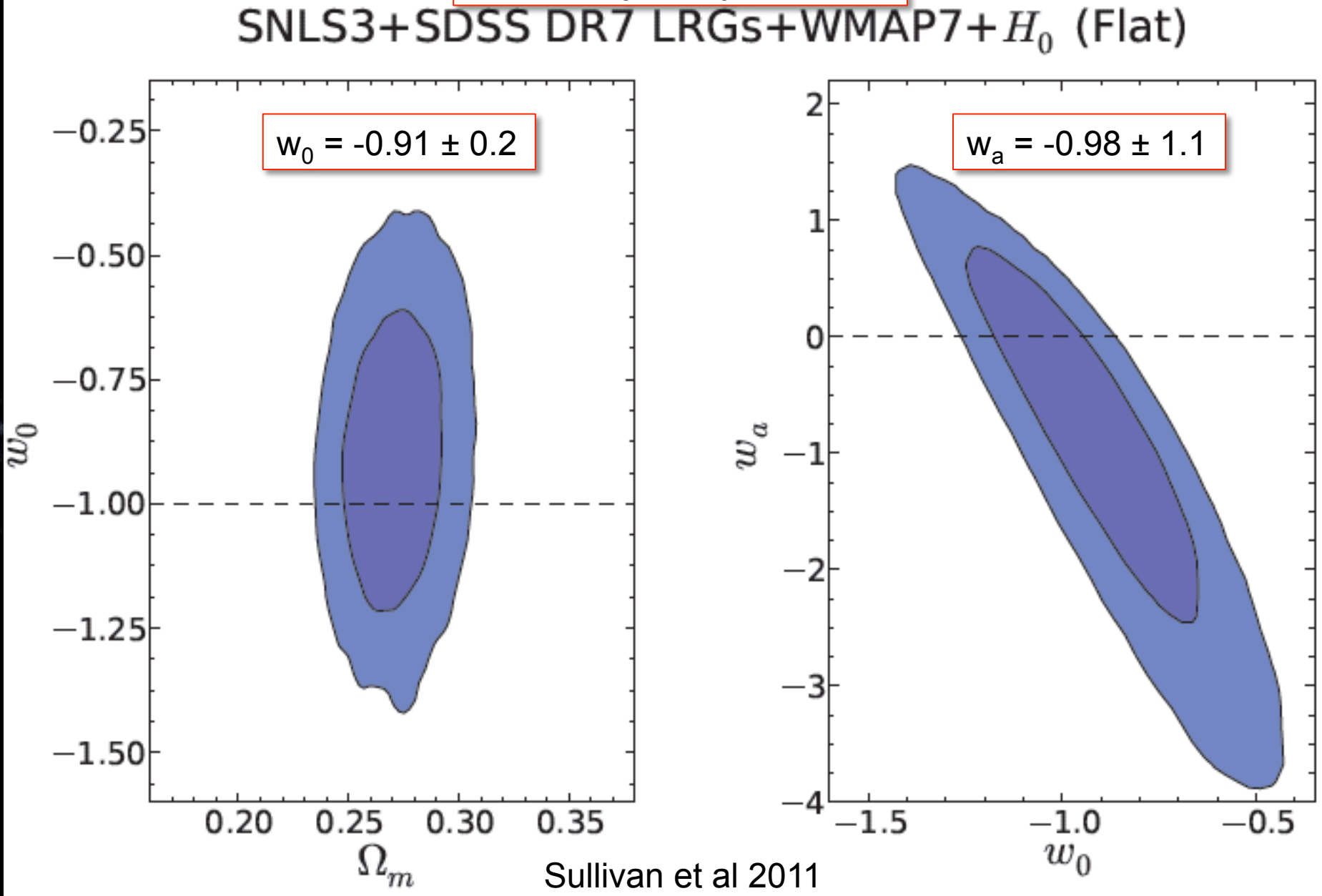
Benson et al 2011 (SPT)

Constant w dark energy

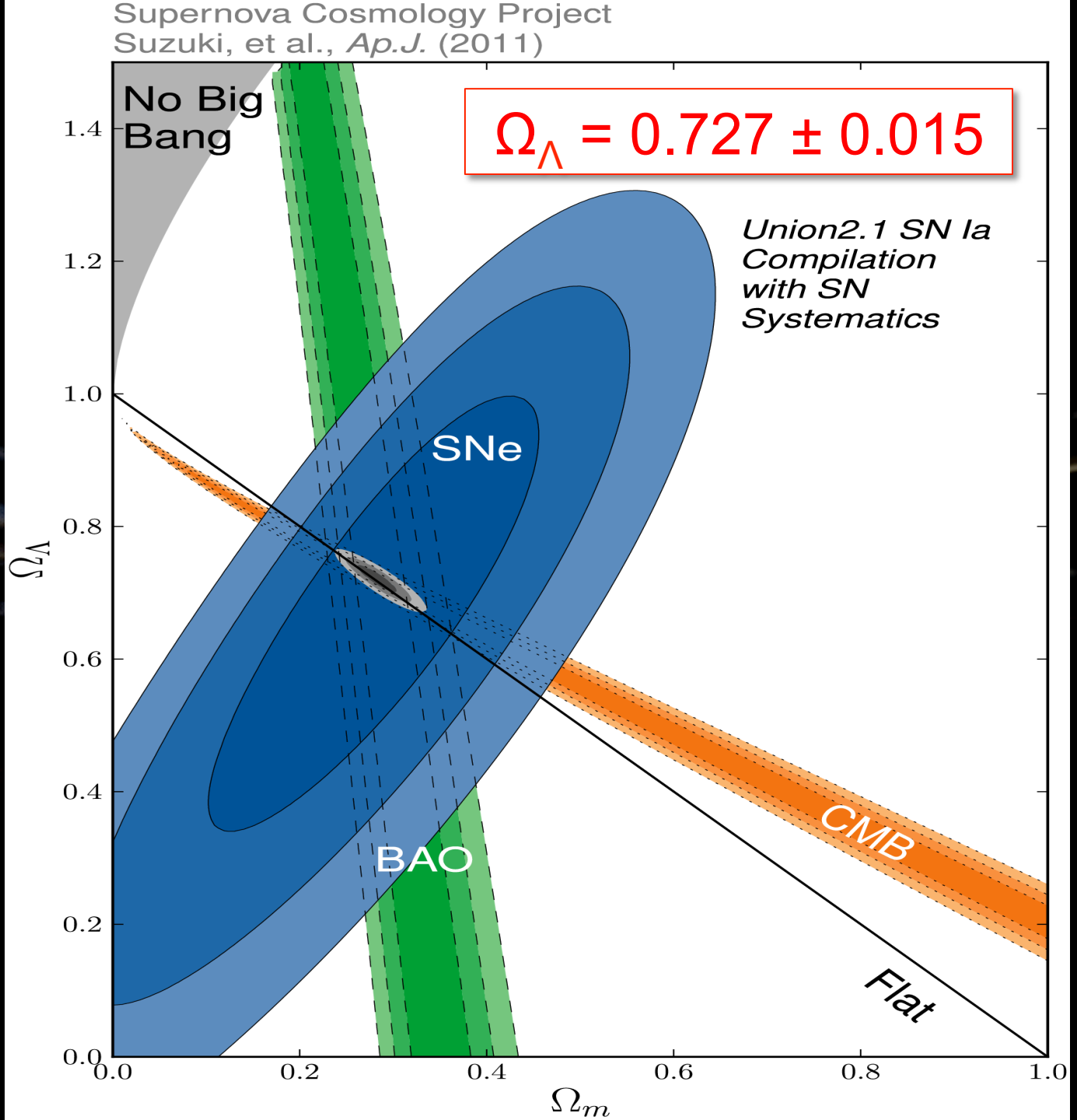


w = -0.97 ± 0.06

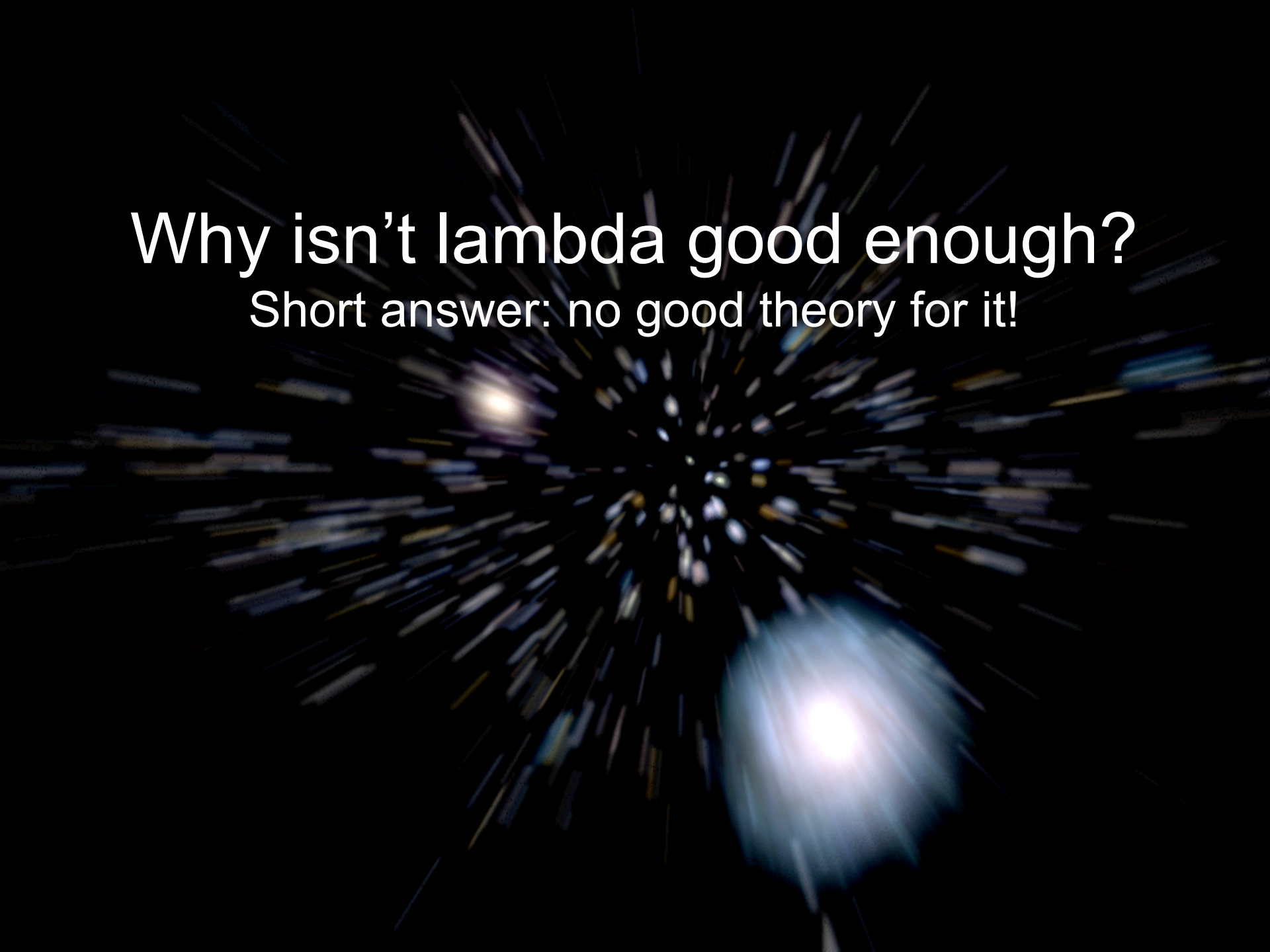
$w = w_0 + w_a(1 - a)$

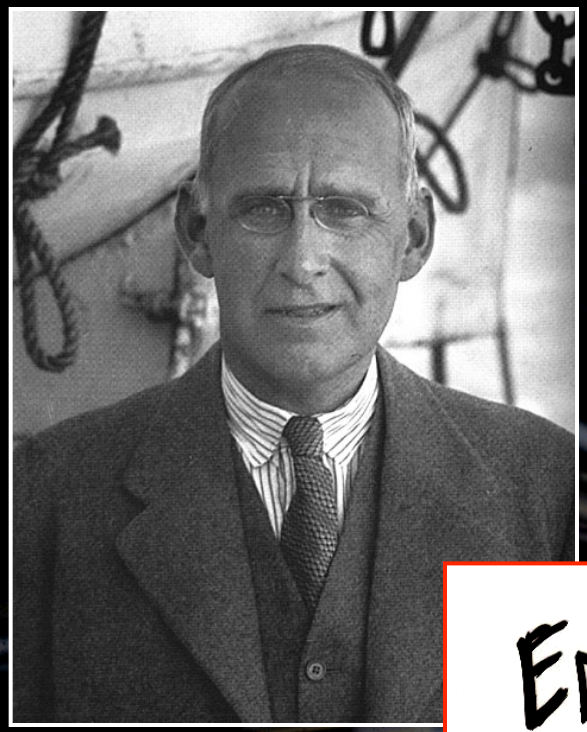


Sullivan et al 2011


Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)
No Big Bang
$\Omega_\Lambda = 0.727 \pm 0.015$
Union2.1 SN Ia Compilation with SN Systematics
SNe
BAO
CMB
Flat
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

So, it's Lambda??!##


Why isn’t lambda good enough?
Short answer: no good theory for it!



EDDINGTON:

"NO EXPERIMENTAL RESULT SHOULD BE ACCEPTED UNTIL CONFIRMED BY THEORY"

$$G + \Lambda = 8\pi T$$

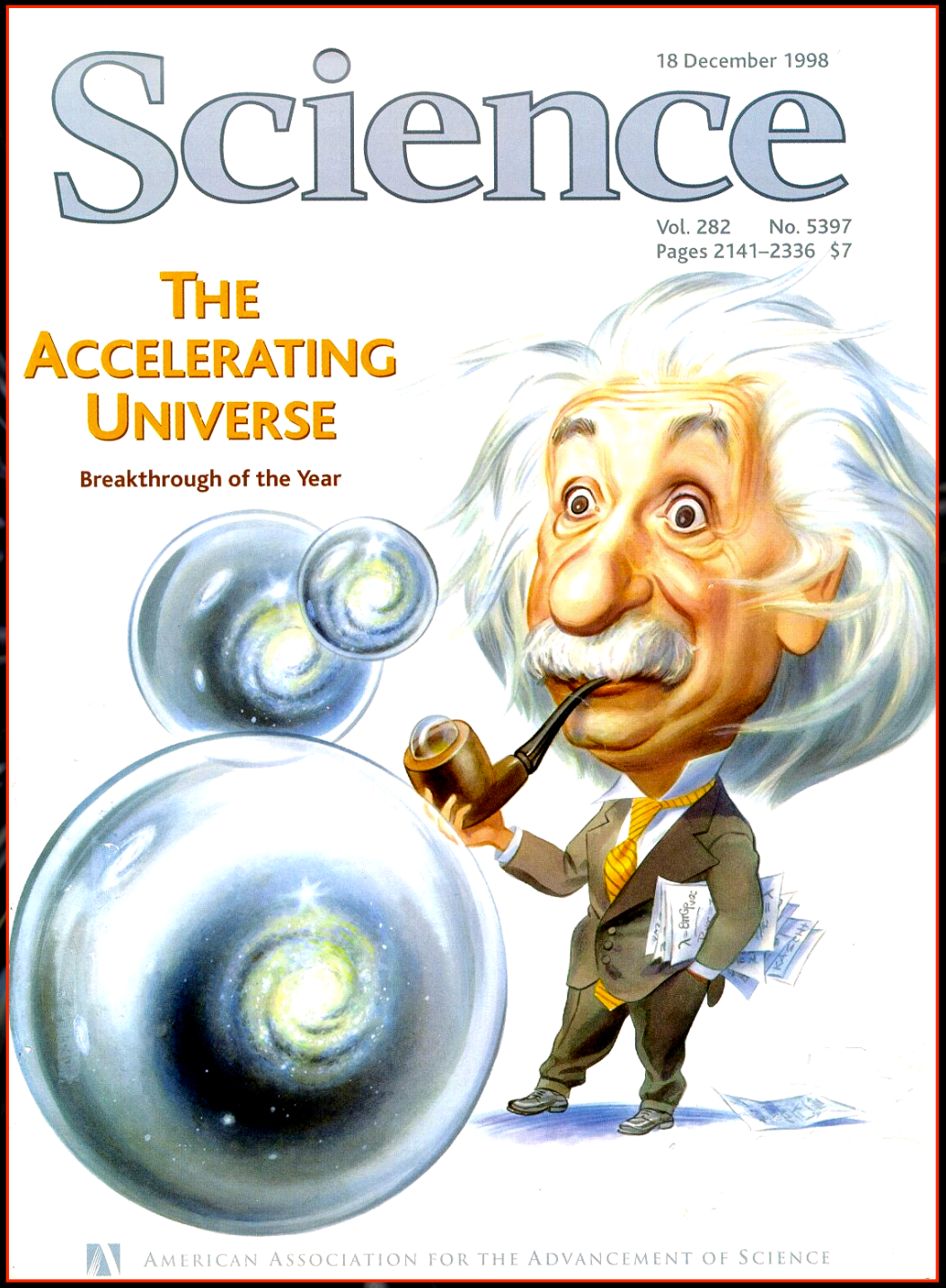
Geometry Matter

Einstein added optional Λ

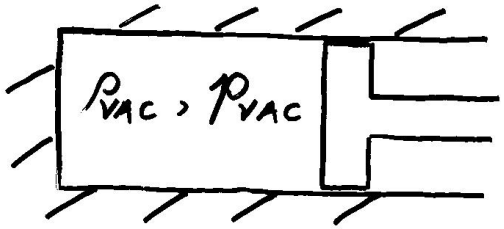
$\Lambda \leftrightarrow T_{vacuum}$

QM vacuum energy problem known since 1930s (Pauli),

T_{vac} not optional!



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

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

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...

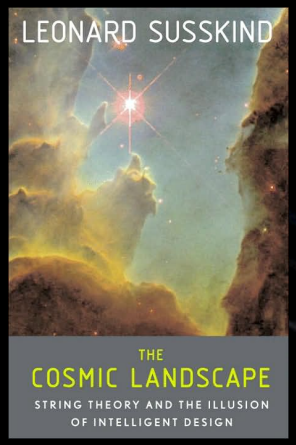
THEORETICAL ESTIMATES OF AMOUNT

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

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

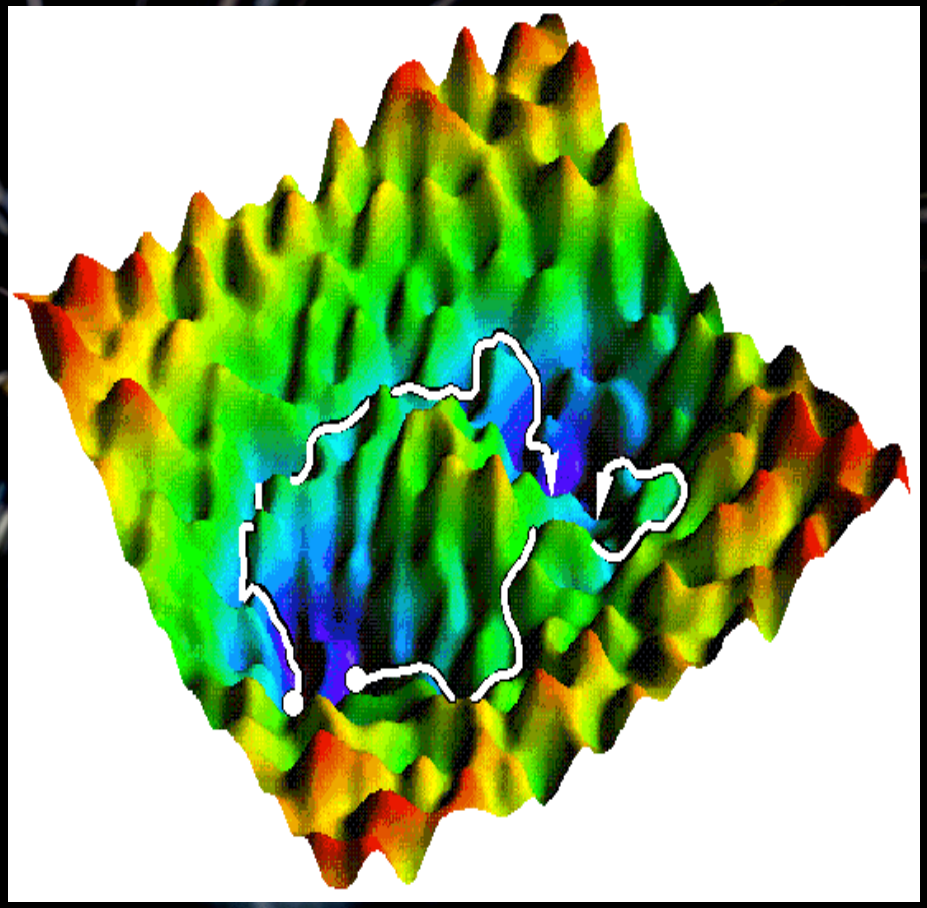
Vacuum Energy and Supersymmetry

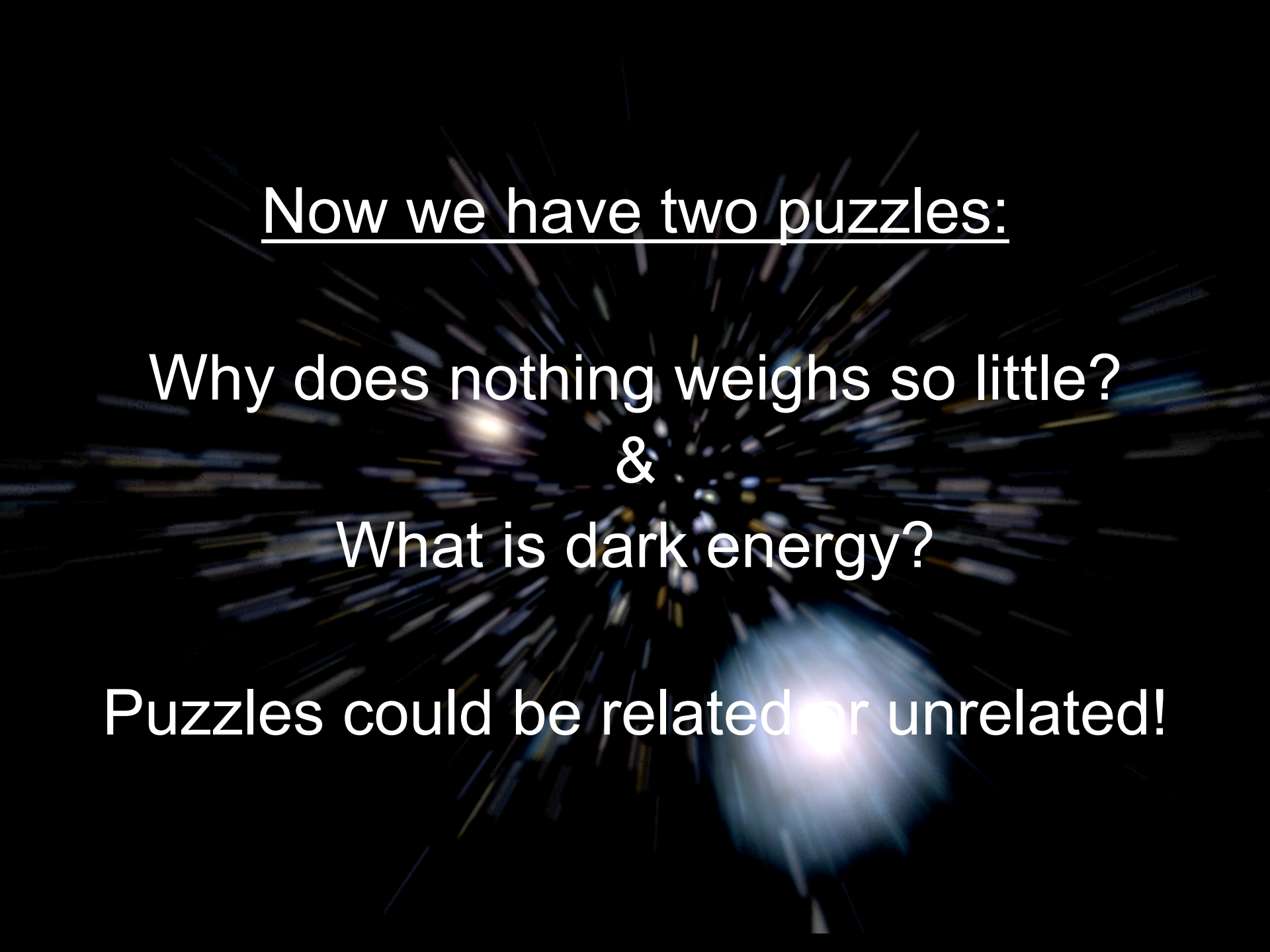
- SUSY → quantum vacuum energy = 0
- Our world is not supersymmetric
- Broken SUSY → $\rho_{vac} \sim O(M_{SUSY}^4)$
- NB: don't known if SUSY is broken or how?
- C. Burgess (PI): mm-size extra dimensions?



The Cosmic Landscape of Superstring Theory

- M-theory → 10^{500} vacua
- $\rho_{vac} \sim O(m_{Pl}^4) \pm O(m_{Pl}^4)$
- Universe has a multiverse structure & we were lucky (narcissistic principle)
- Testable??
- Extravagant solution!




Now we have two puzzles:
Why does nothing weighs so little?
&
What is dark energy?
Puzzles could be related or unrelated!

SOLVING THE COSMIC ACCELERATION RIDDLE WILL REQUIRE A CRAZY, NEW IDEA!

NB: NOT EVERY CRAZY IDEA IS A SOLUTION TO A PROFOUND PROBLEM!

The theory menu

- Vacuum energy (see above)
- Rolling scalar field (quintessence)
- Very elastic topological defects
- Modified gravity
- Dark energy/dark matter models
- Hole in the Universe
- ??

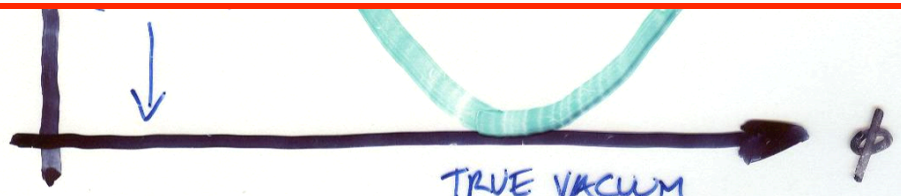
ROLLING SCALAR FIELD

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

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

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

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



NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98

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

INGGELA.: $p = -N/3\ \rho$

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

DUVVURI, CARROLL, TRODDEN, MST

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

“Old Gravitational Physics” hitherto undiscovered aspects of GR

Hole in the Center of the Universe
Bondi-Tolman (spherically symmetric sol^n)
→ Large decrease in H_0 at $z \sim 1$

- Primordial in[illegible] explains why the [illegible]erse is accelerating [illegible]day, [illegible] W. Kolb, S. Mata[illegible]se, A. Notari, A. Riotto (a[illegible]o-ph/0[illegible]117)
- On cosmi[illegible]cceleratio[illegible]thout dark ene[illegible], E.W. Kolb, S. Matarre[illegible] A. Riotto (a[illegible]ph/050653[illegible]
- Commen[illegible]n Backreactio[illegible]d Cosmi[illegible]cceleration, E. Kolb, S. [illegible]tarrese, A. Riotto [illegible]tro-p[illegible]511073)
- Cosmologica[illegible]ckground solutio[illegible]osmological backreactions, [illegible]olb, V. Marra, S[illegible]arrese, (arXiv: 0901.4566)

the Birthers

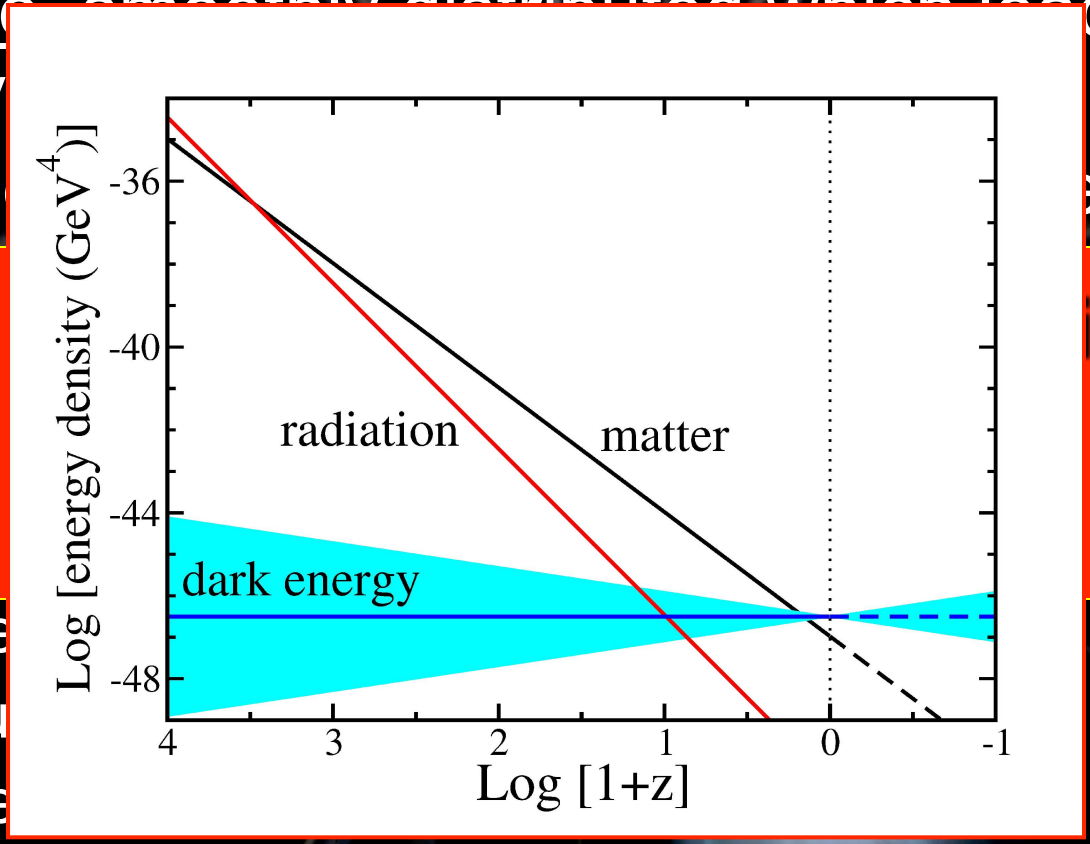
Dedicated to the rebirth of our Constitutional Republic

URBAN DICTIONARY

Birther: *A conspiracy theorist who believes that Barack Obama is ineligible for the Presidency of the United States, based on any number of claims related to his place of birth, birth certificate, favorite birthday, or whether or not he has heard the song Africa by Toto. Birthers also believe cosmic acceleration is part of the very same conspiracy.*

Generic description

- Defining feature of dark energy: large negative pressure, smoothly distributed which leads to repulsiv
- Describ



1. Not ne
2. Vacuu
3. Quinte
4. Ghostly quintessence < -1 (ρ_{DE} increases with time)
5. $w = w_0 + w_a(1 - a)$

Moving forward: looking for clues

“Breaking lambda”

WFIRST

- $w \neq -1$ (Q, MG, TD)
- $w_a \neq 0$ (Q, MG)
- “Early dark energy” (Q, MG)
- Growth of structure (MG)
- Gravitational lensing (MG)

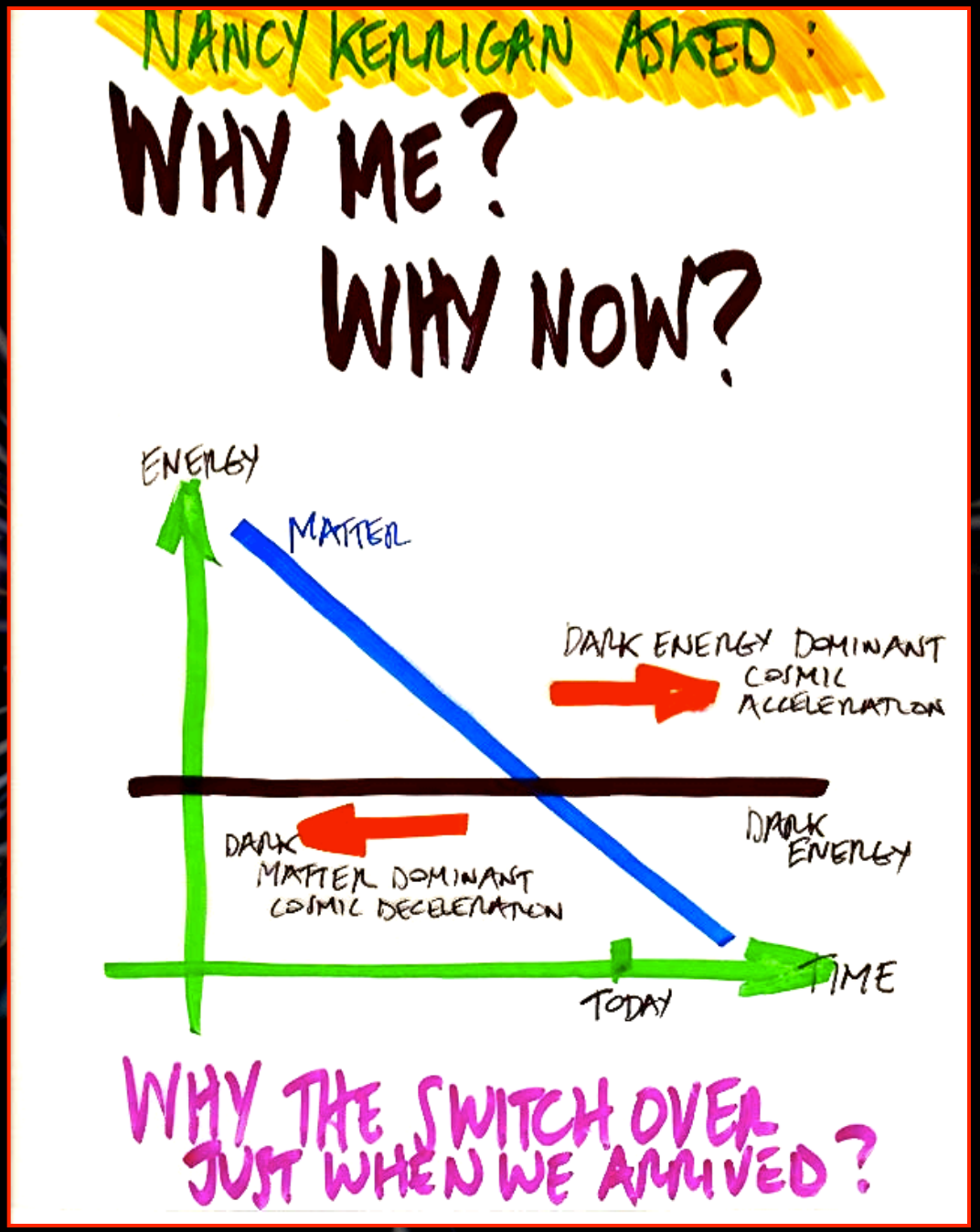
Elsewhere

- Solar system anomaly (MG)
- New long-range force (MG, Q)
- Clustering dark energy (Q)
- Dark matter/dark energy coupling (Q, MG)
- SZ kinetic (Hole in U)

Q = quintessence, MG = modified gravity, TD = topological defect

Important clue or coincidence?

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



Dark energy/cosmic acceleration is a big deal

Pillar of the consensus cosmology

Controls destiny of the Universe

Involves an age-old problem

New physics (dark energy)

New gravity?

Could be ours to solve, or

a problem for the 22nd century discovered by accident in the 20th century