The Dark Universe:

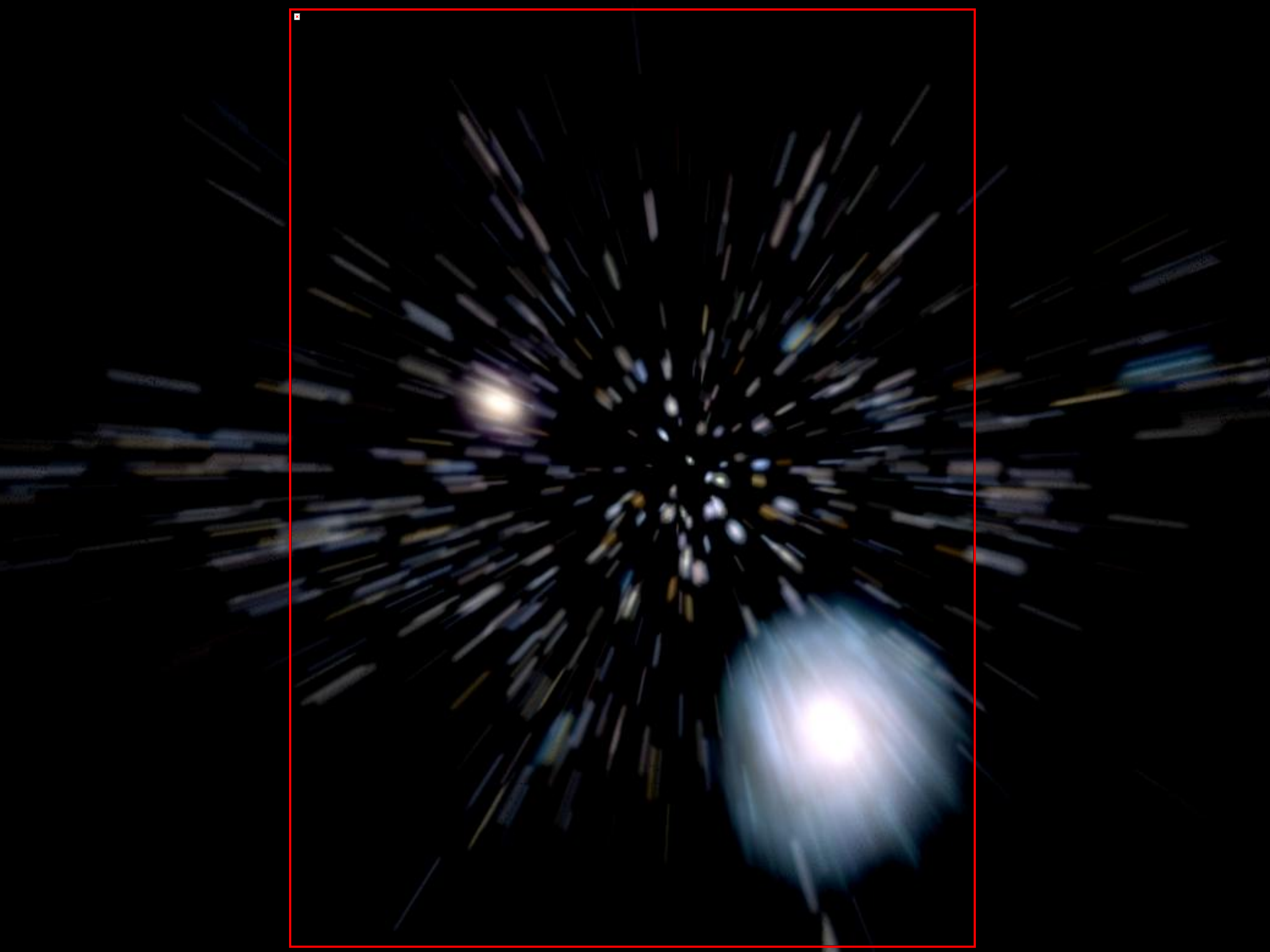
1. Dark Matter
2. Dark Energy

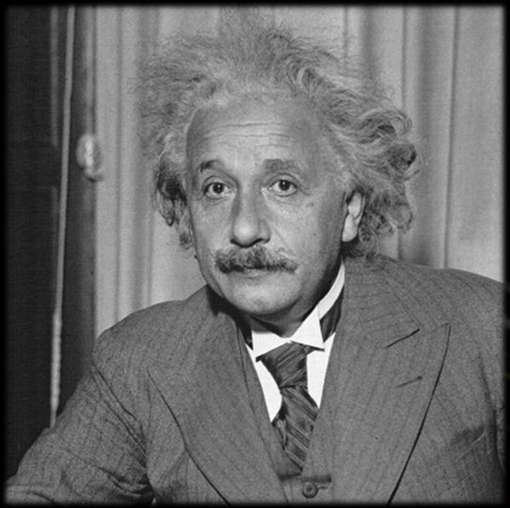
Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago

School
IDPASC Dark Matter School
Évora, Portugal, 14-18 December 2011

Cosmic Acceleration is a central feature of the consensus cosmology

no cosmic acceleration, no consensus cosmology!

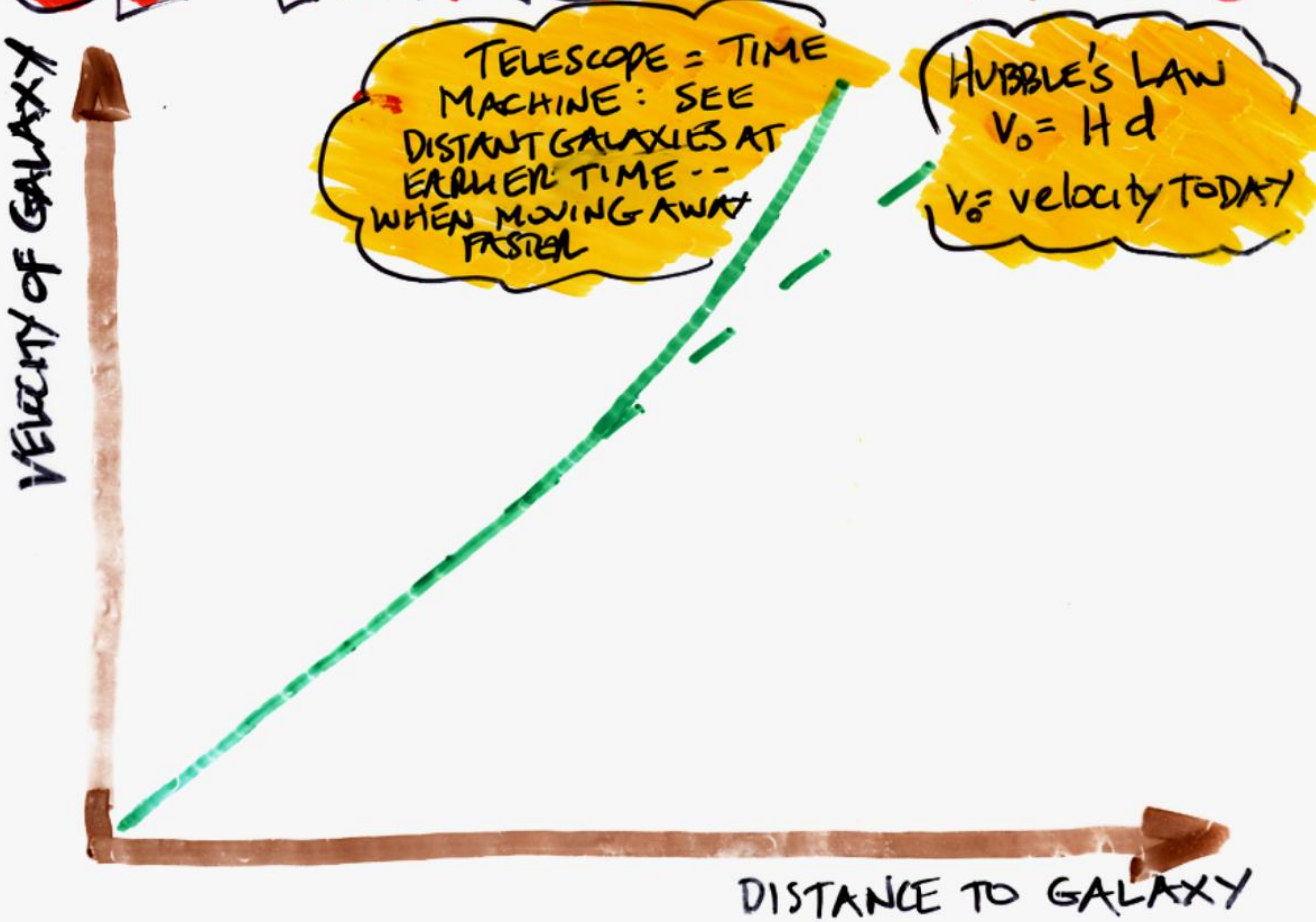




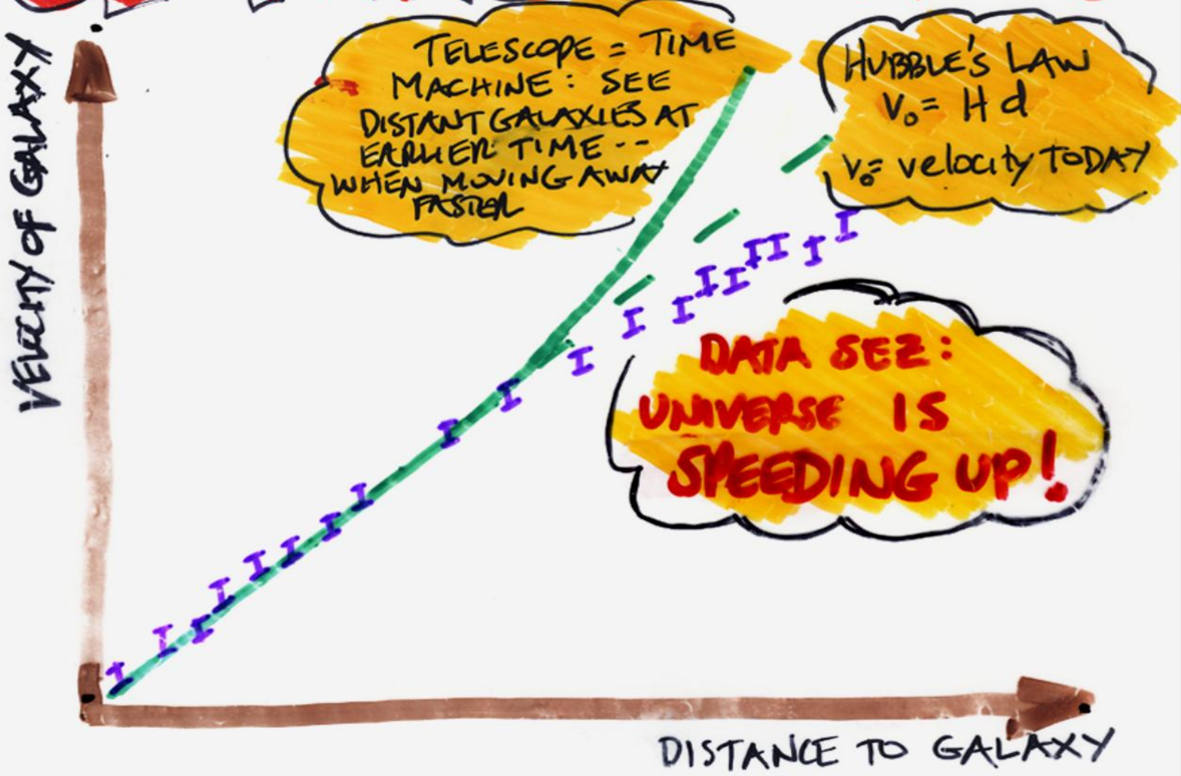
Einstein & Λ

- Introduced Λ to save Mach's principle and create a static Universe solution
- His Λ was ¼ present Λ
- No sense that it was repulsive gravity (Λ on the geometry – LHS – of equations)
- Great man, not the predictor of cosmic acceleration

IS THE UNIVERSE SLOWING DOWN?



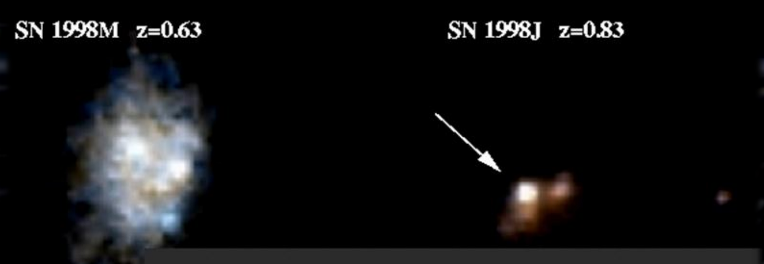
IS THE UNIVERSE SLOWING DOWN?

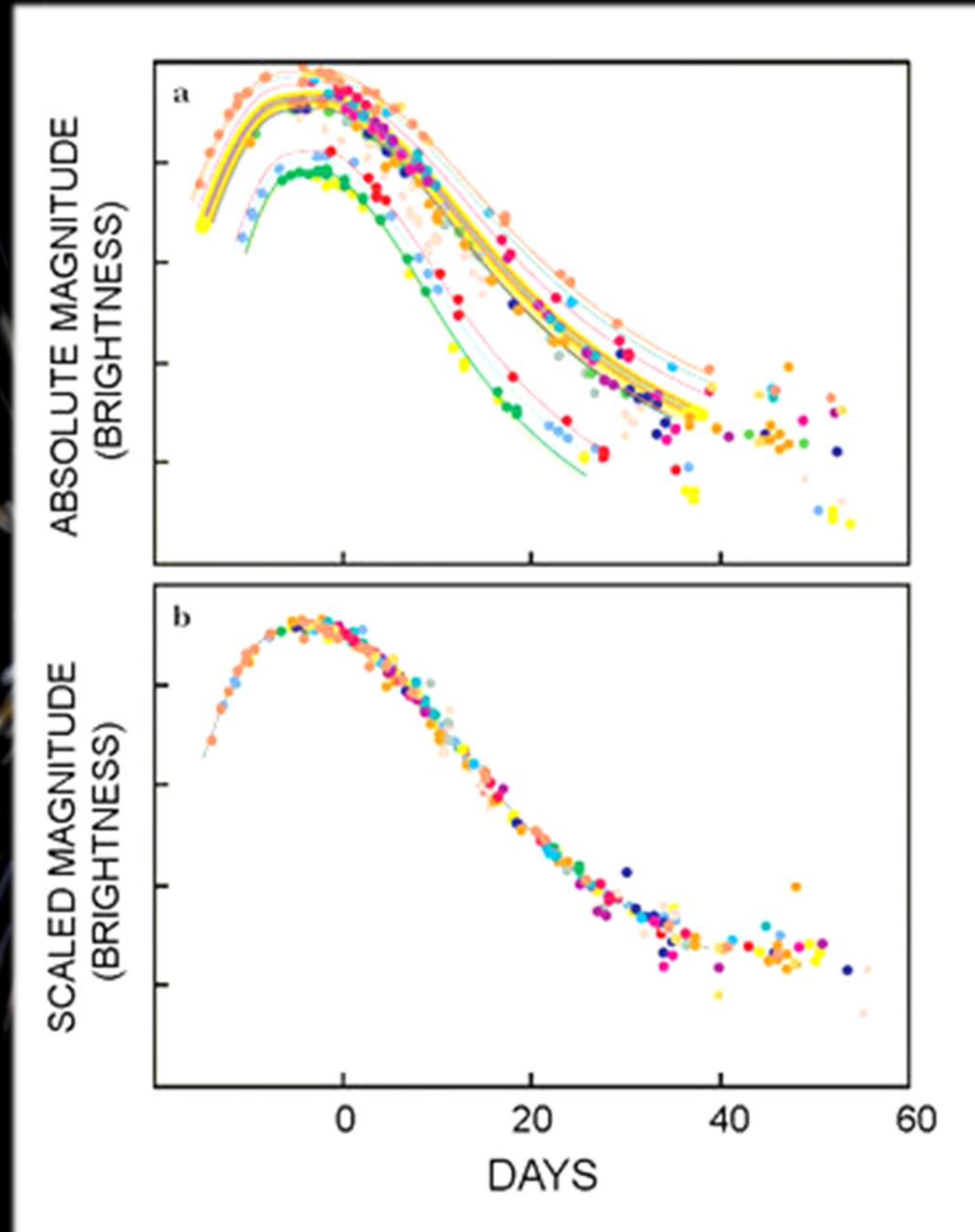


UNIVERSE IS SPEEDING UP!?# WHY?

Two Technological Enablers:

1. Large (100 Mpixel) CCD Cameras
2. SNe Ia: Bright, Standardizable Candles (1.4 solar mass bomb)





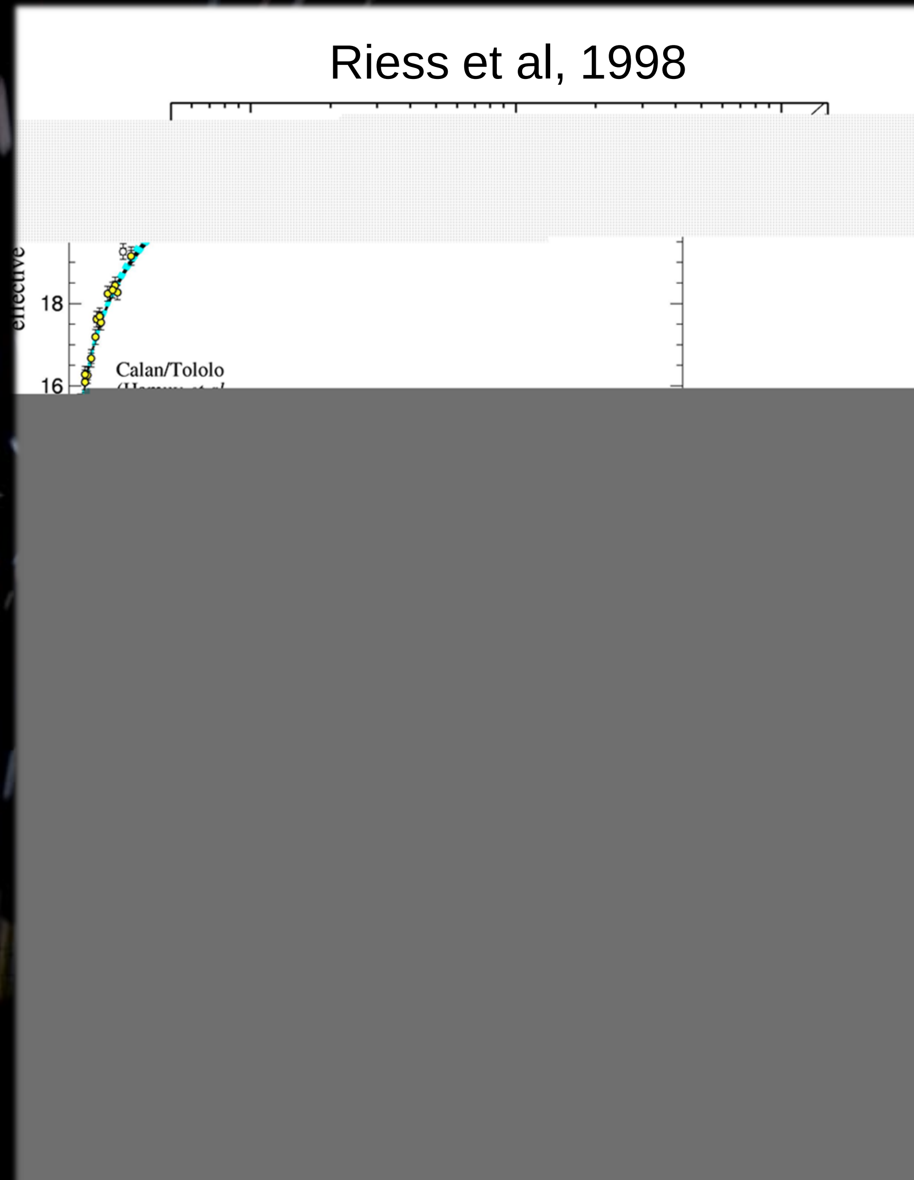
Discovery! – 1998

Hi z Supernova Team

Mark Philips

Supernova Cosmology Project

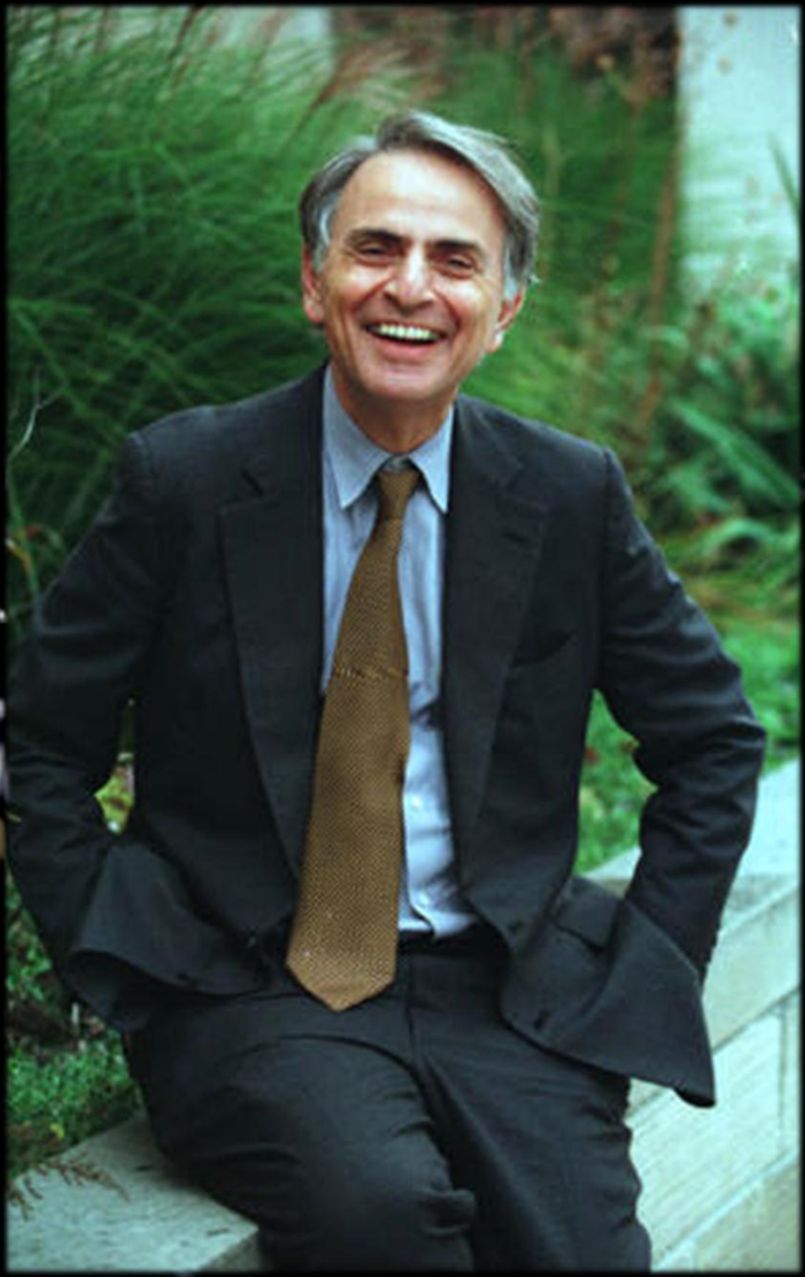
The Discovery Data

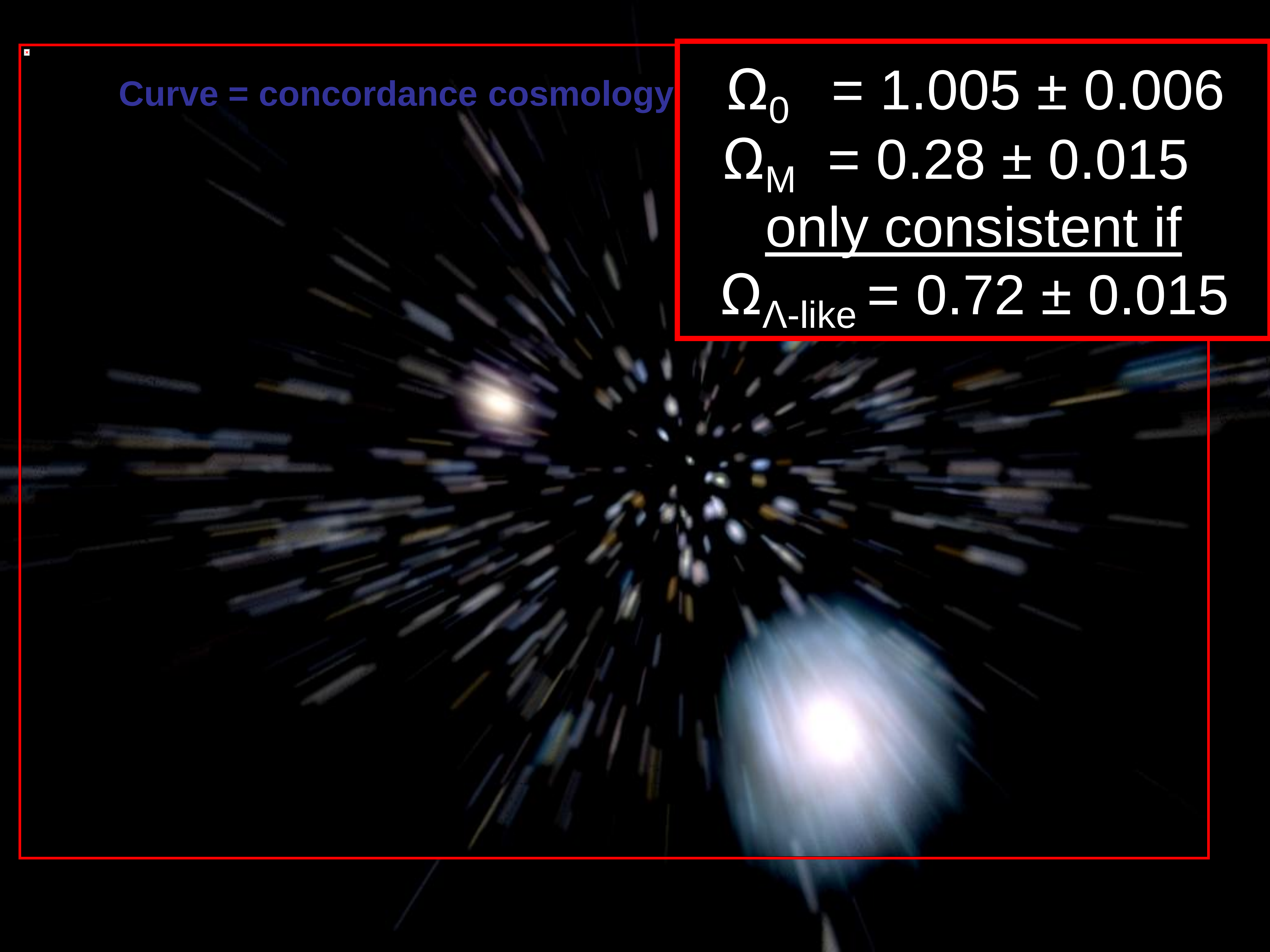


Carl Sagan:

Extraordinary Claims Require Extraordinary Evidence

Now Certified by Stockholm!





Curve = concordance cosmology

$\Omega_0 = 1.005 \pm 0.006$

$\Omega_M = 0.28 \pm 0.015$

only consistent if

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

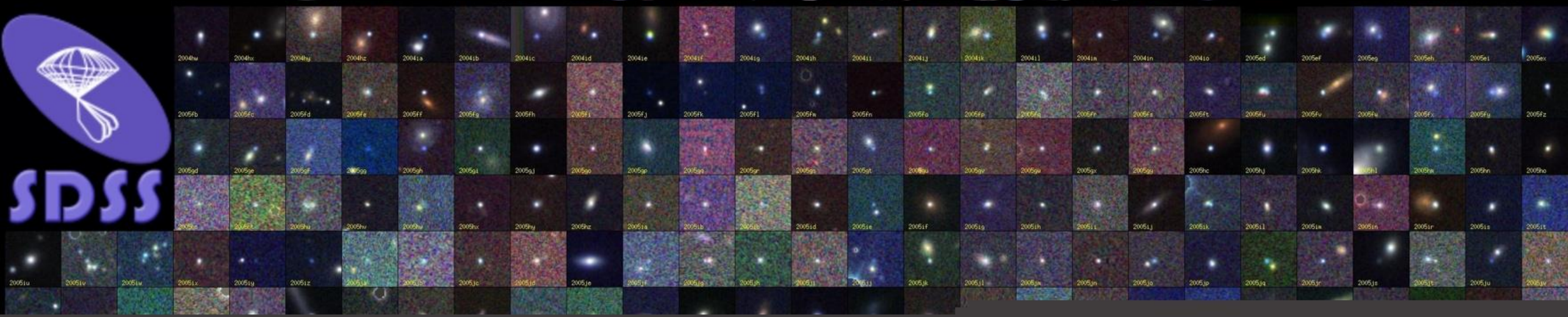
1000 SNe from:

the original teams +

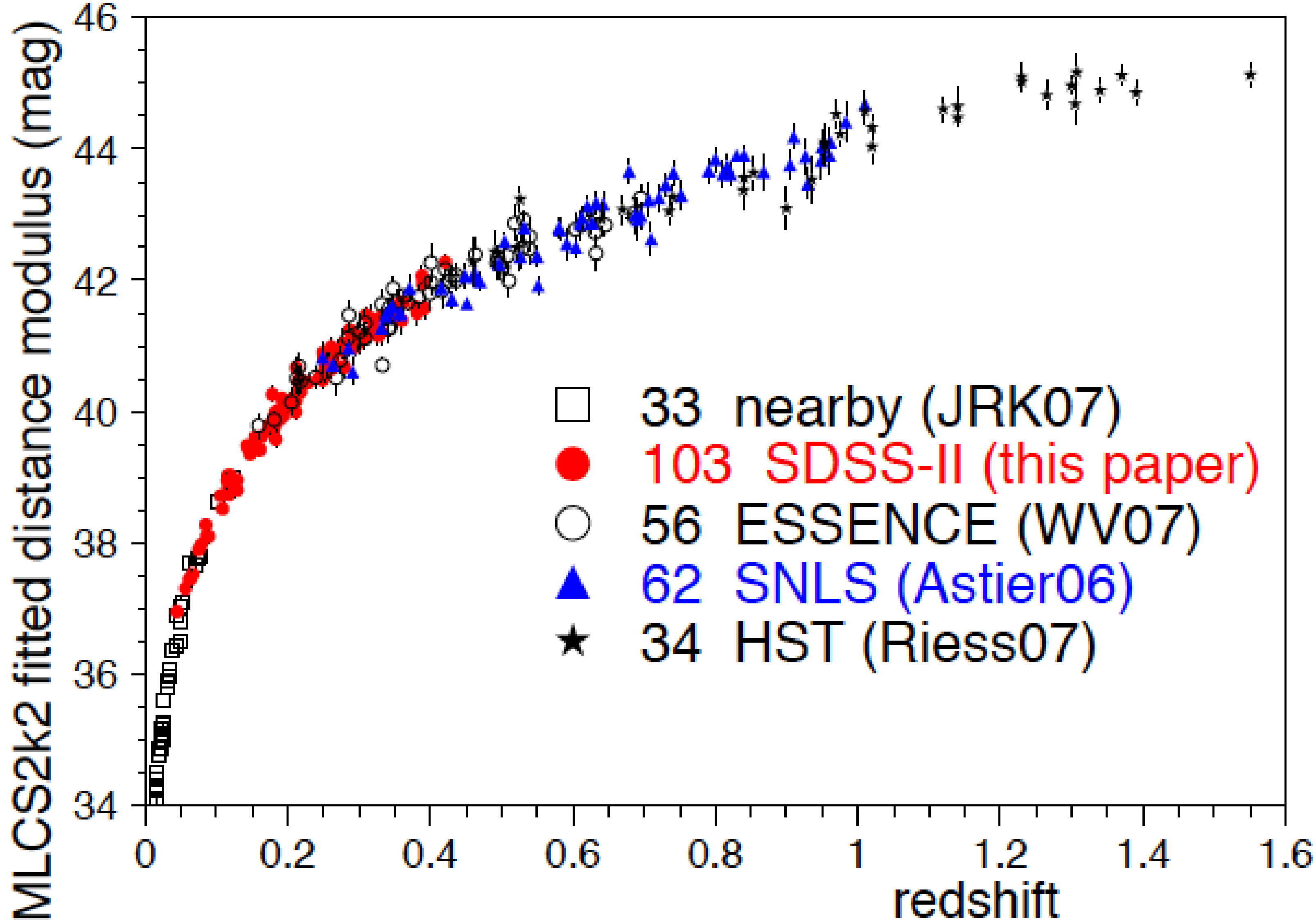
SNLS, ESSENCE, SDSS, CfA, CSP, …

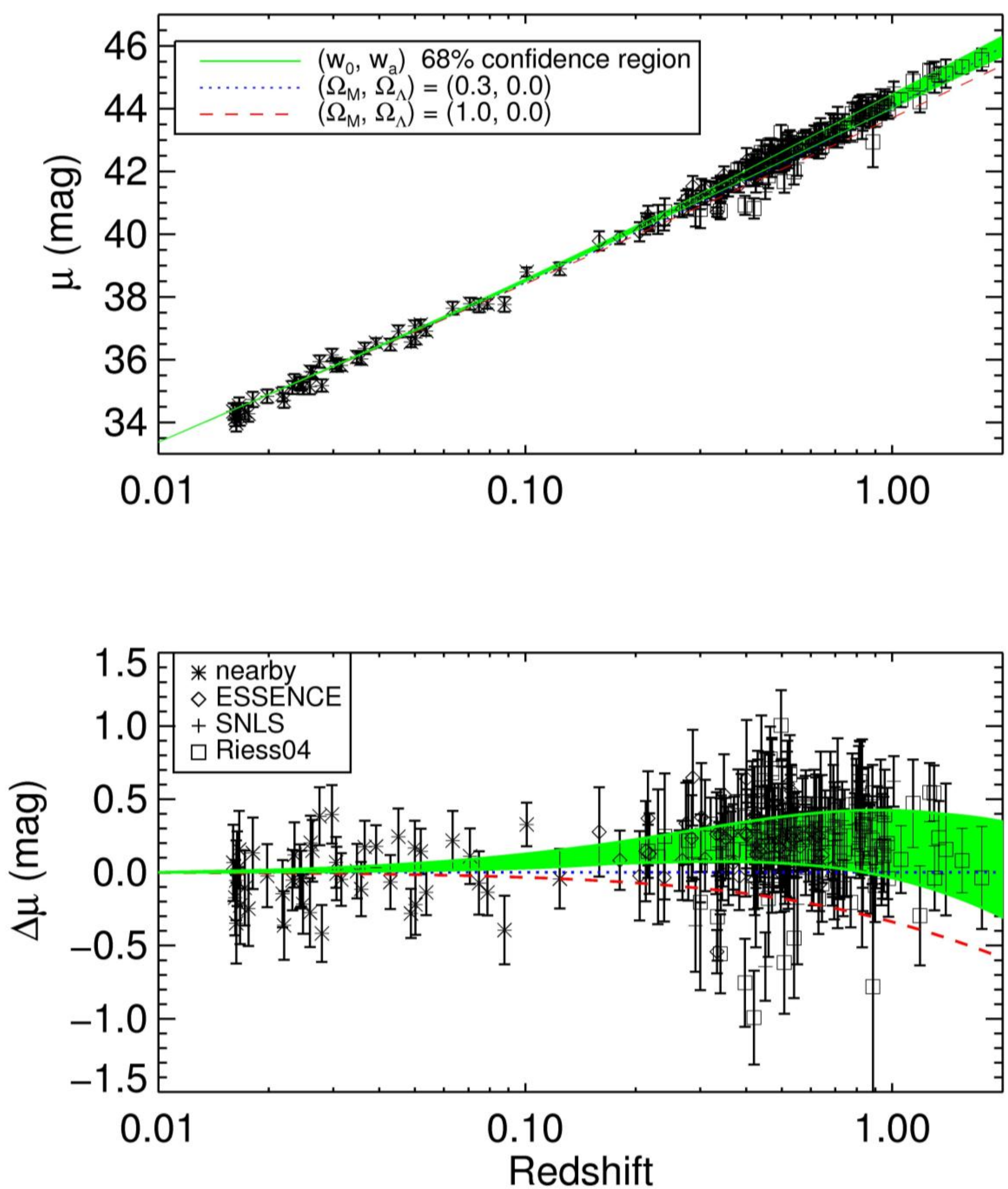
More data stronger signal

SDSS-II Supernova Survey



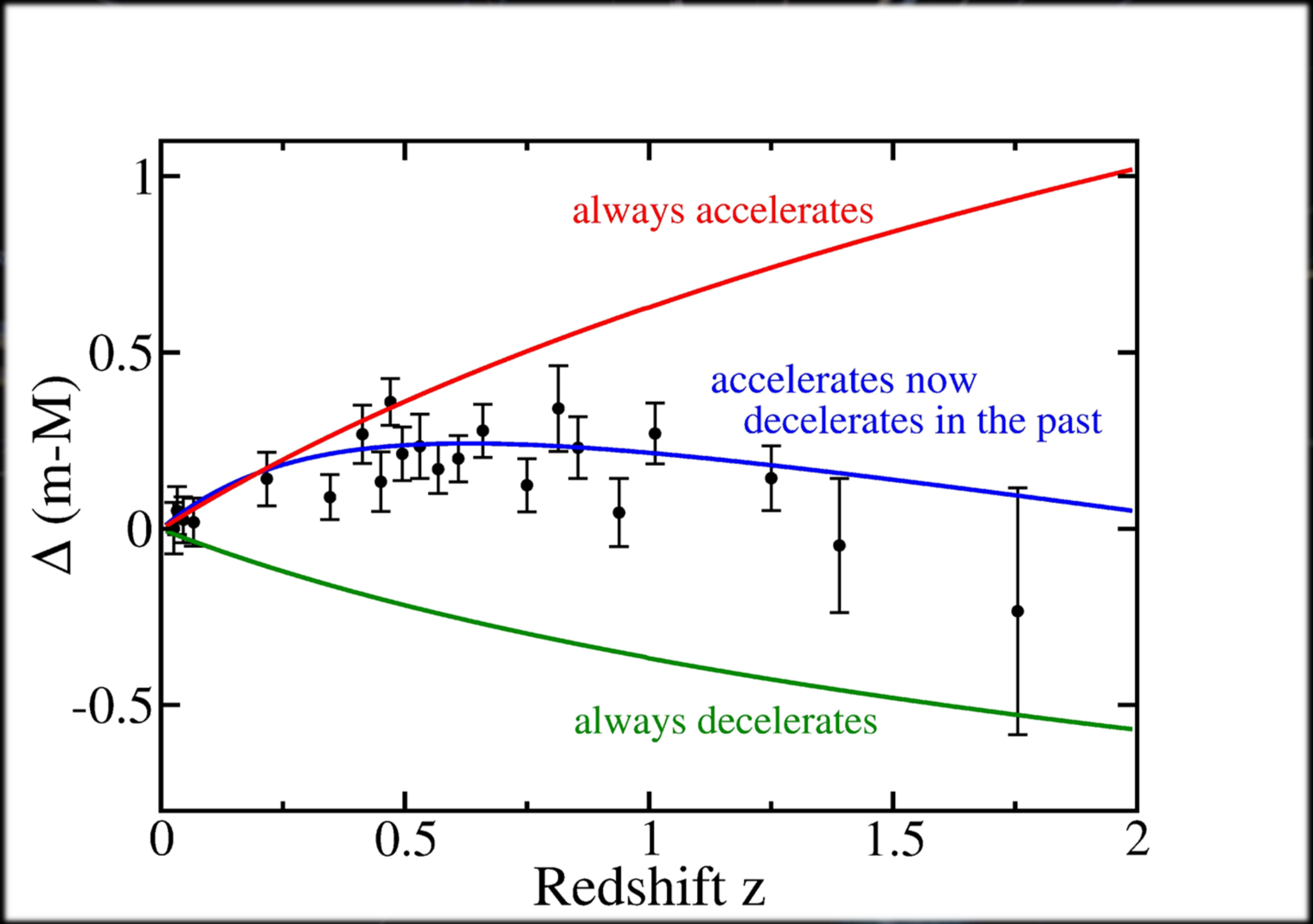
~500 Well studied SNe Ia, suitable for framing


MLCS2k2 fitted distance modulus (mag)
46
44
42
40
38
36
34
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
redshift
33 nearby (JRK07)
103 SDSS-II (this paper)
56 ESSENCE (WV07)
62 SNLS (Astier06)
34 HST (Riess07)



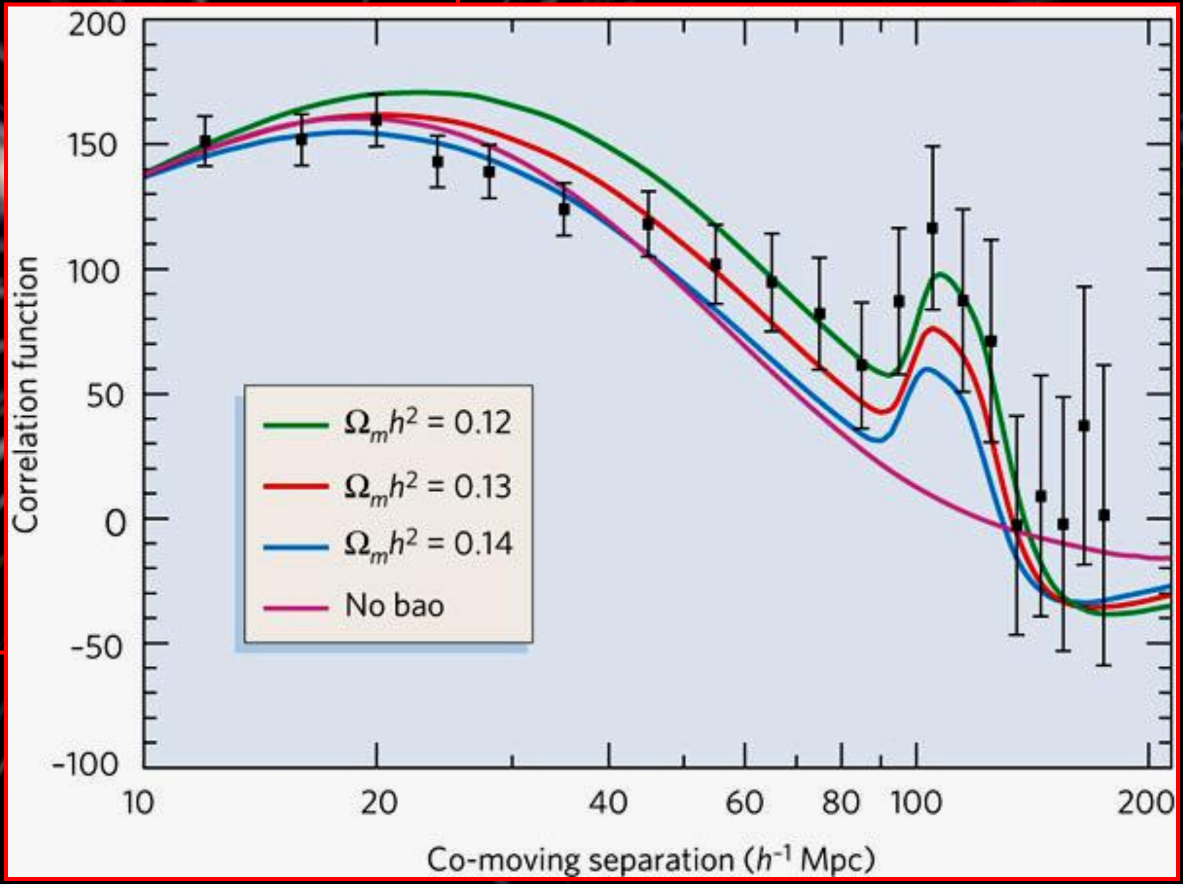
(w0, wa) 68% confidence region
(ΩM, ΩΛ) = (0.3, 0.0)
(ΩM, ΩΛ) = (1.0, 0.0)
μ (mag)
46
44
42
40
38
36
34
0.01
0.10
1.00
nearby
ESSENCE
SNLS
Riess04
Δμ (mag)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.01
0.10
1.00
Redshift

Evidence for past acceleration: Important reality check

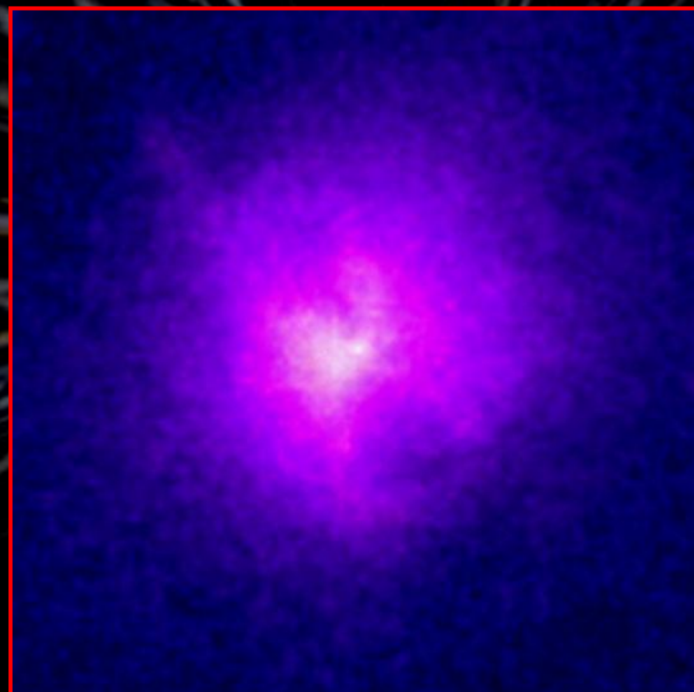


HST ACS Sample of high-z SNe: A. Riess et al, Ap.J **607**, 665 (2004)

Baryon Acoustic Oscillations (BAO): Zel’dovich’s Standard Ruler



New stand alone evidence for cosmic acceleration from clusters observed by Chandra



A.Vikhlinin et al, ApJ 692, 1060 (2009) [arXiv:0812.2720]
36 Clusters w/<z>~0.55 and 49 w/<z>~0.05

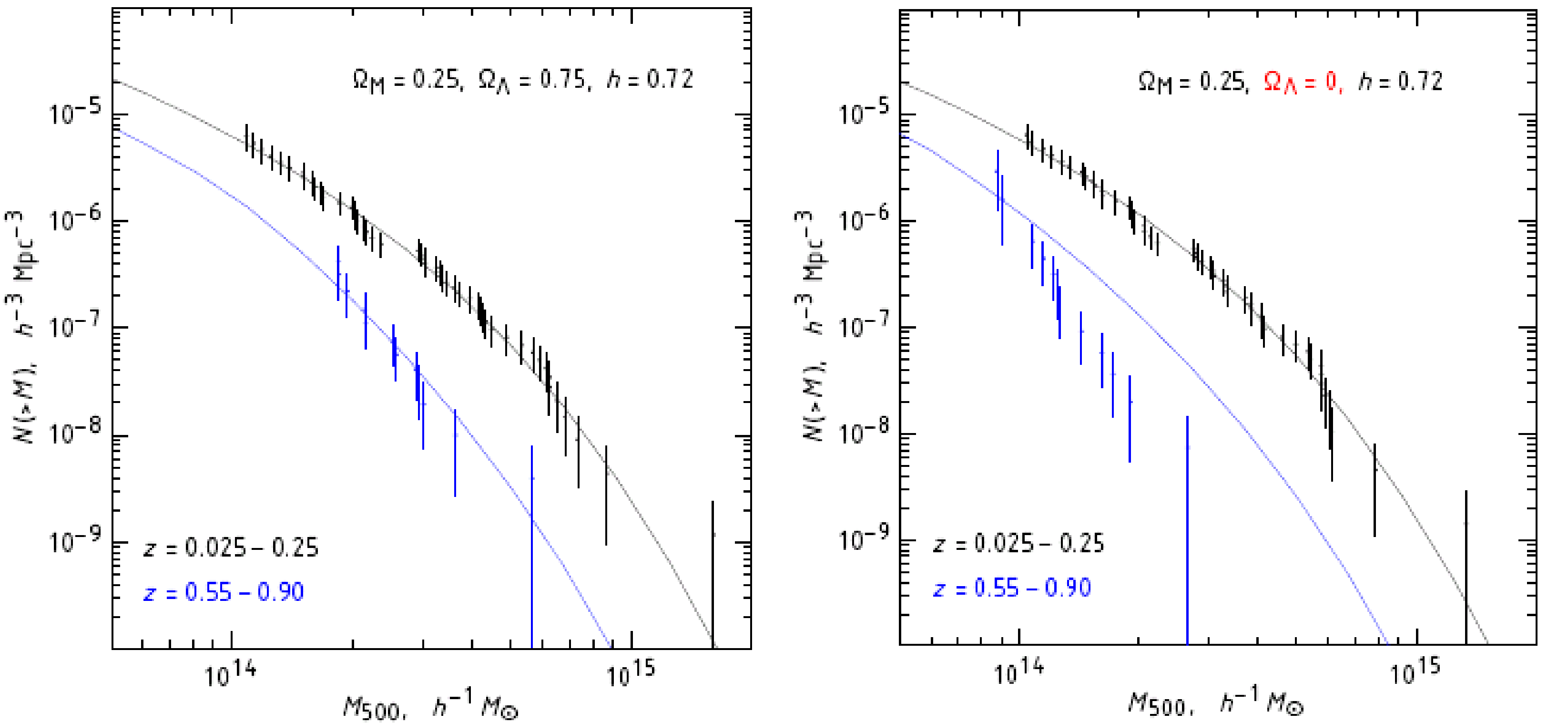
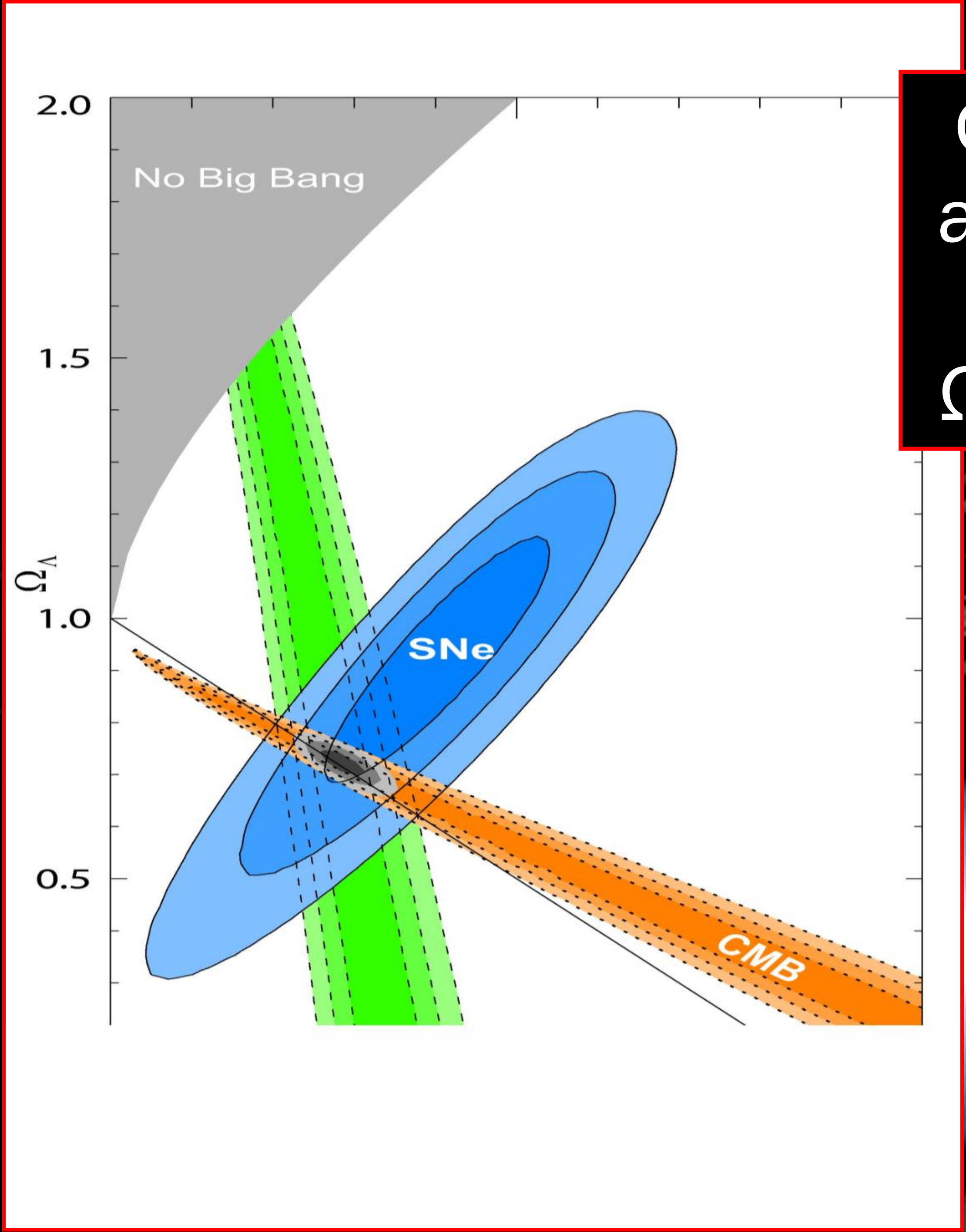


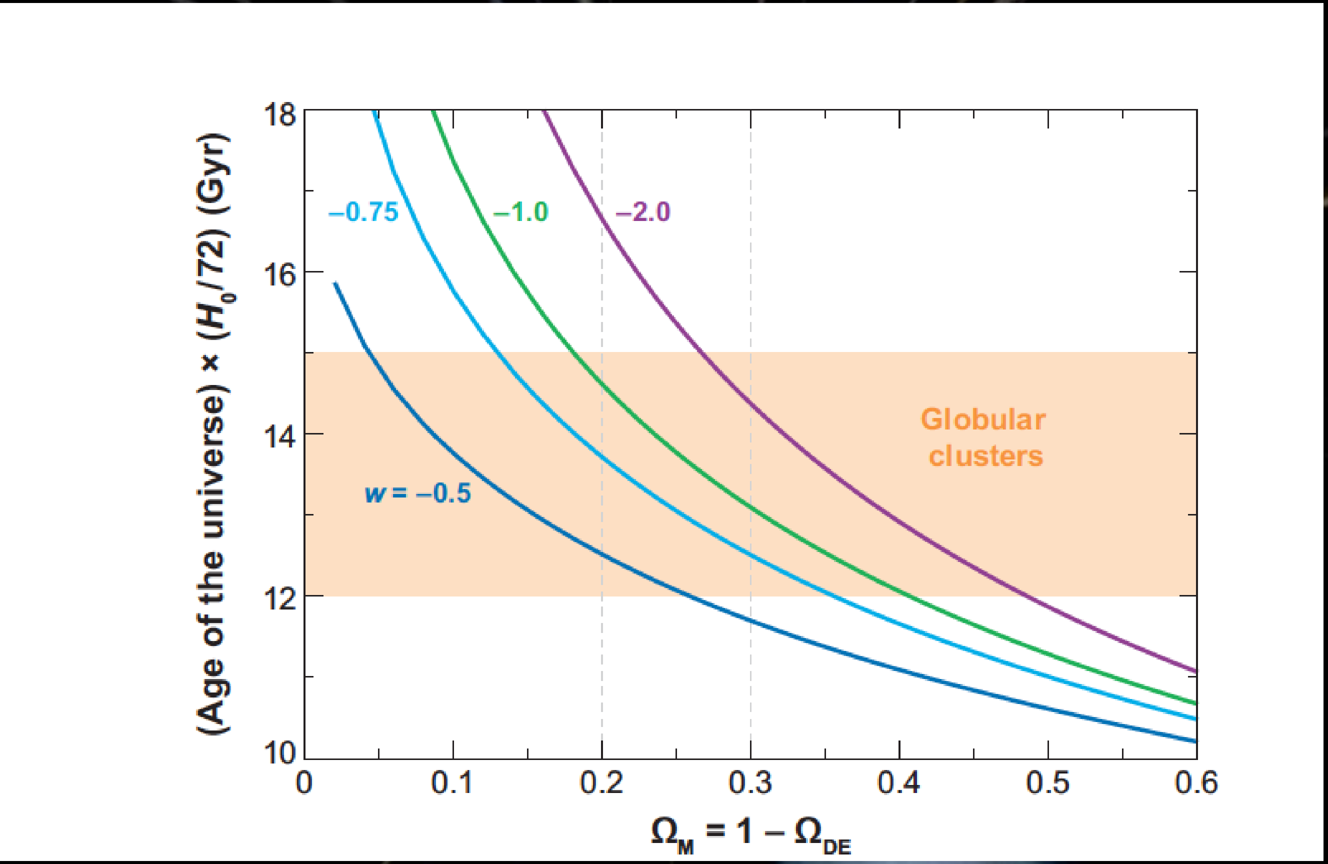
FIG. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at $z = 0$ adjusted) computed for a cosmology which is close to our best-fit model. The low-z mass 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.

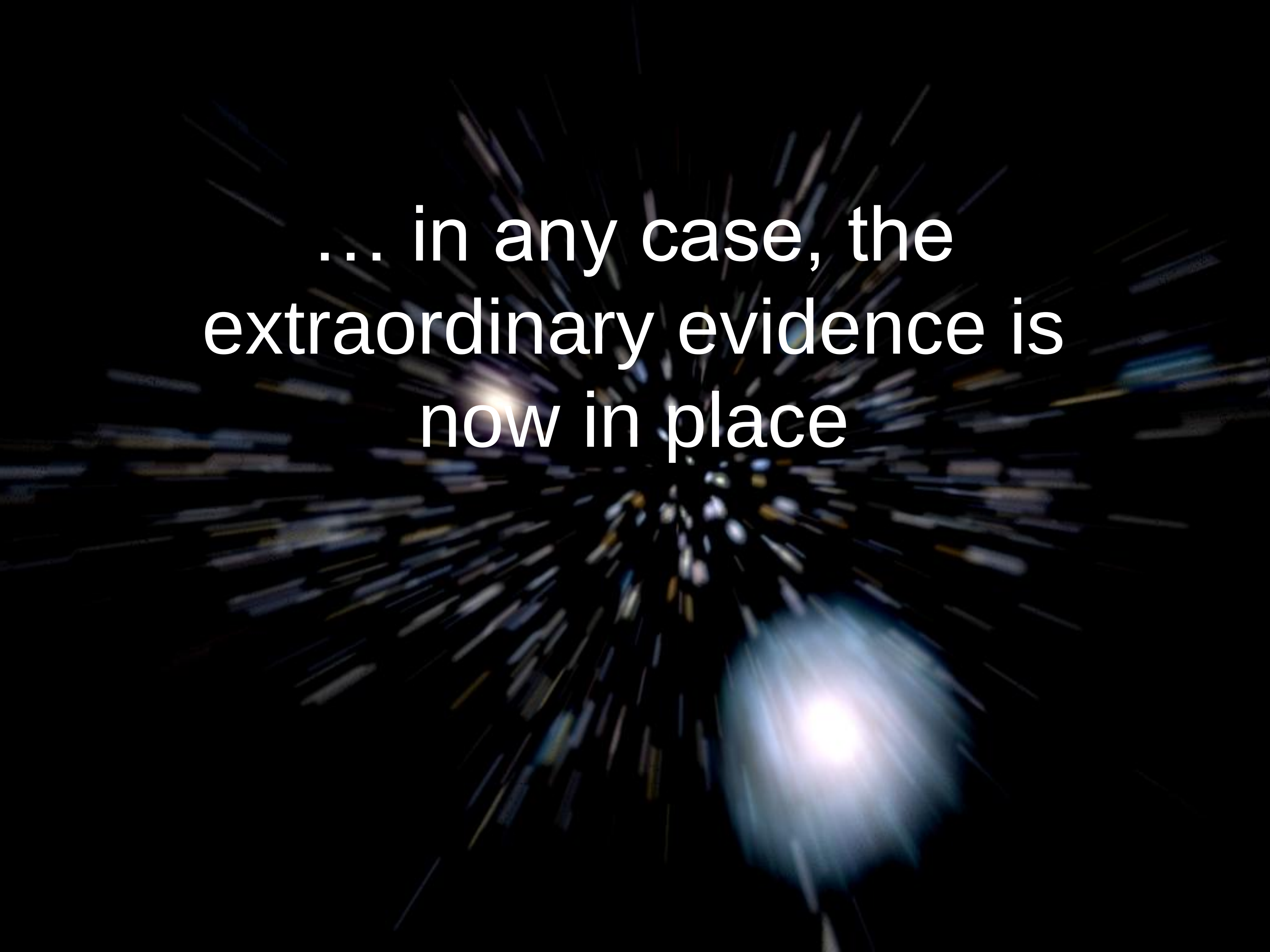


Consistent with all observations:

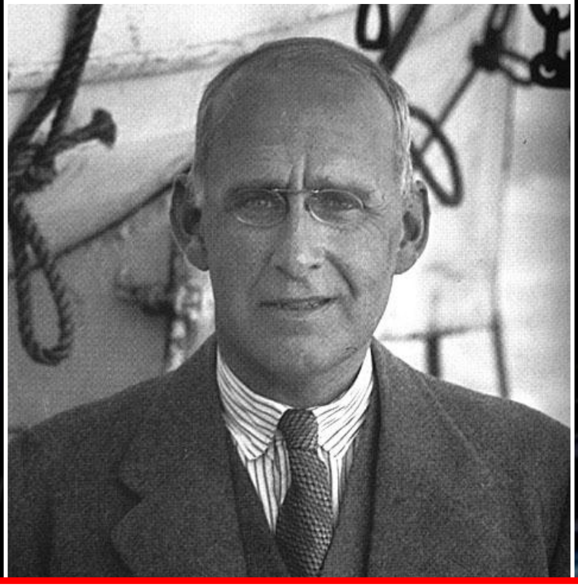
$\Omega_\Lambda = 0.71 \pm 0.02$

Consistent Age




… in any case, the
extraordinary evidence is
now in place

Eddington Criterion



EDDINGTON:

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

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3}$$

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

GR ALLOWS FOR REPULSIVE GRAVITY:

SOURCE OF GRAVITY IN GR:

$\rho + 3p$

(SPHERICAL SYMMETRY)

FEATURE NOT A BUG!

→ BLACK HOLES WHEN $p \gtrsim \rho/3$

→ REPULSIVE GRAVITY WHEN $p < -\rho/3$

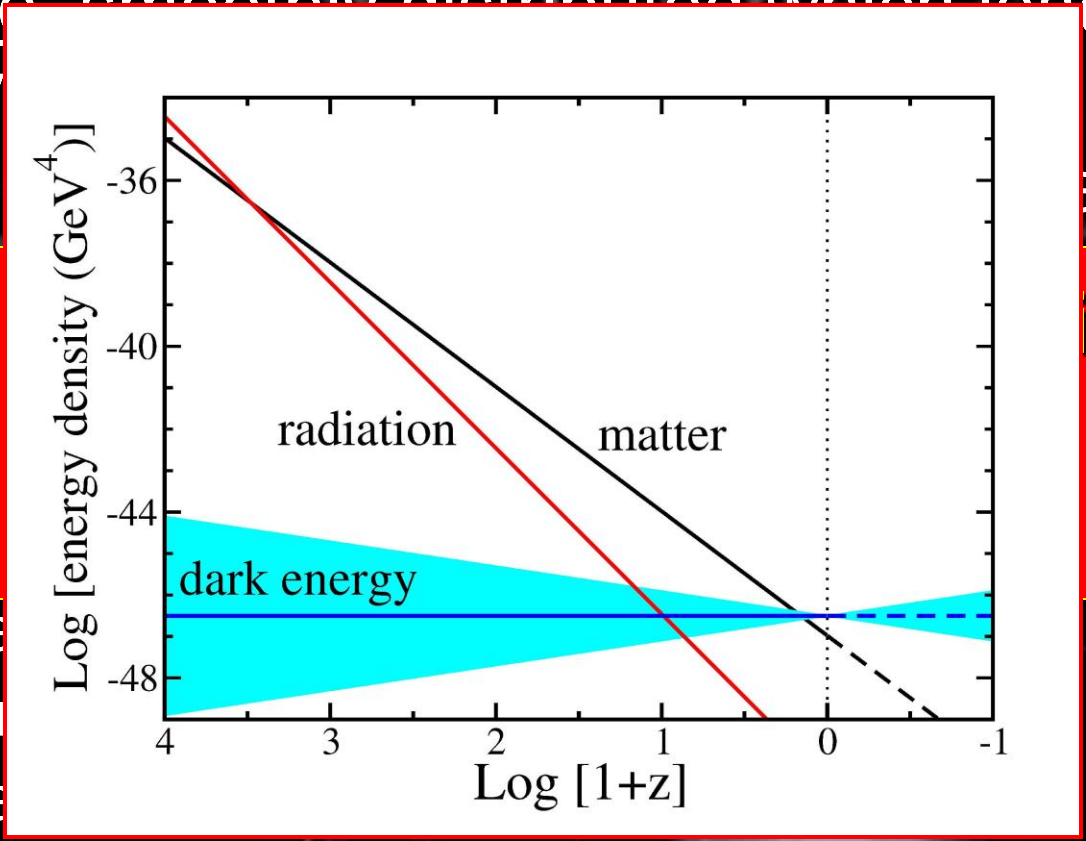
Test of (ρ + 3p) Term in 2nd Friedmann Eqn

- (ρ + 3p) powers accelerated expansion
- BBN = test of the (ρ + 3p) term
- Neglect 3p (i.e., Newtonian limit)
  - Friedmann Equation becomes: $H^2 = 4\pi G\rho/3$ instead of $H^2 = 8\pi G\rho/3$
  - BBN predictions no longer agree with observations

Describing Dark Energy

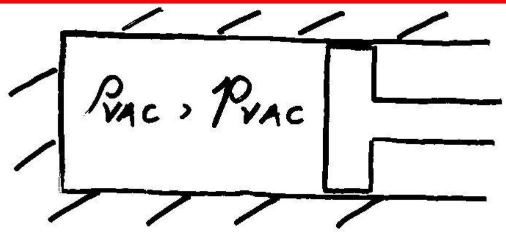
- Defining feature of dark energy: <u>large negative pressure</u>, smoothly distributed which leads to repulsiv
- Describ er w

w ity



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

The Gravity of Nothing Is Repulsive



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

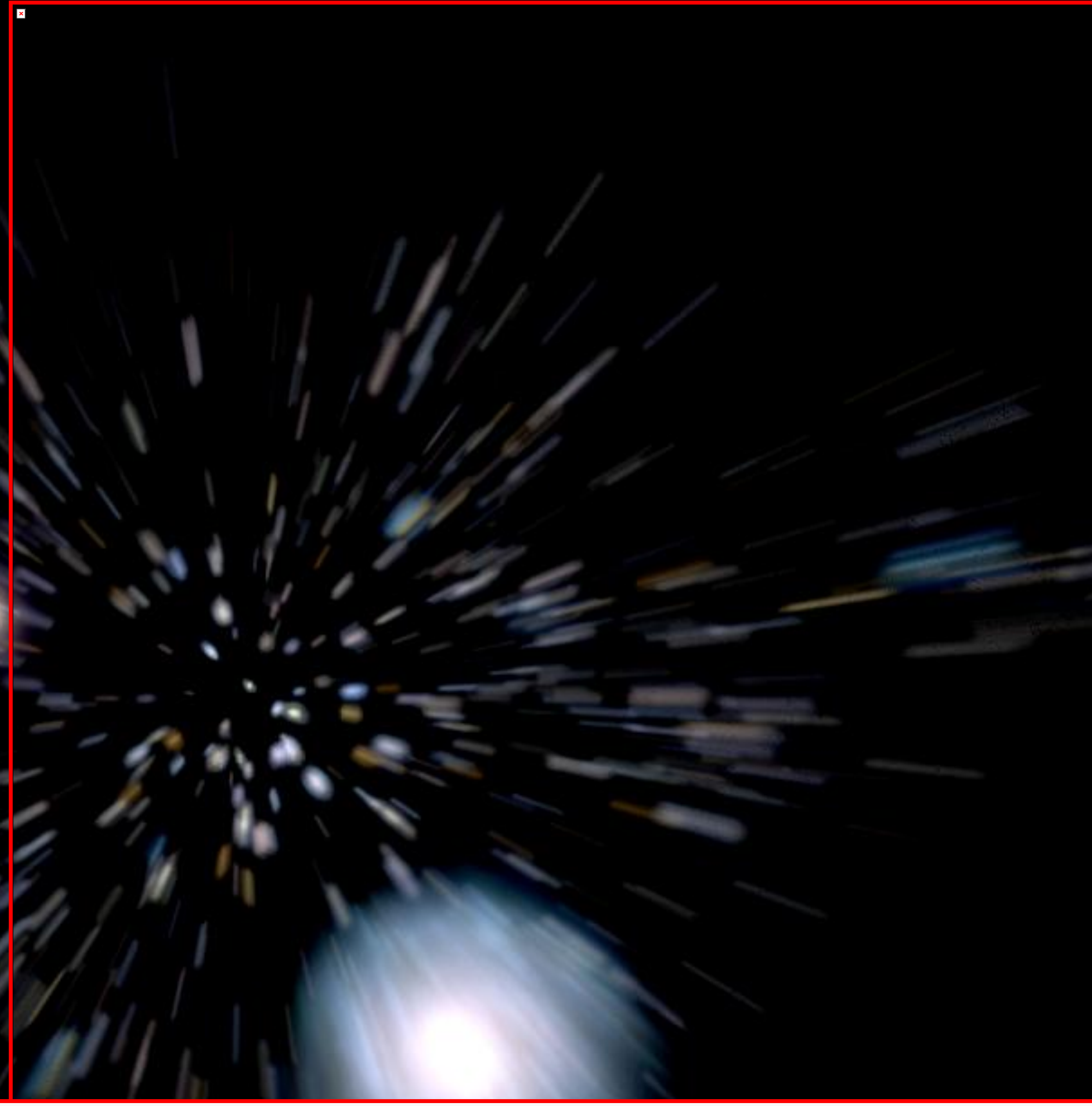
$$\rho_{VAC}\,dV = -p_{VAC}\,dV \Rightarrow \underline{p_{VAC} = -\rho_{VAC}}$$

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

(same as Λ)

finite ans wer that is off by
orde f magnitude

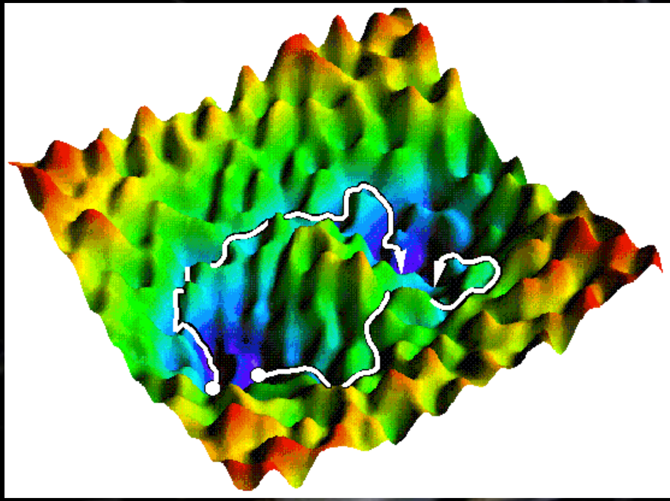
$\rho_{vac} \approx 3 \times 10^{-11}\ \mathrm{eV}^4$

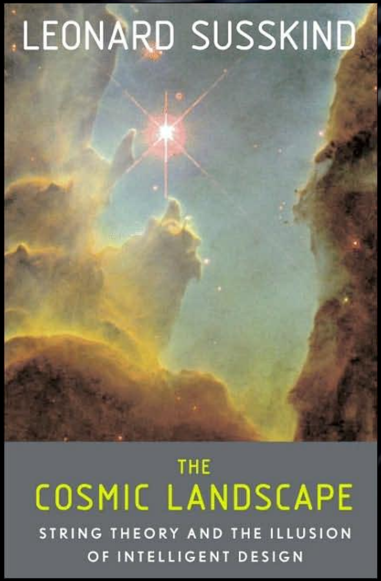


$$\rho_{\mathrm{zero\,pt}} = \frac{1}{2}\int_0^{\infty} \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} = \frac{1}{16\pi^2}k_{\max}^4$$

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

Vacuum Energy Problem Solved by Supersymmetry or ?





Now we have two puzzles:

Why does nothing weighs so little?

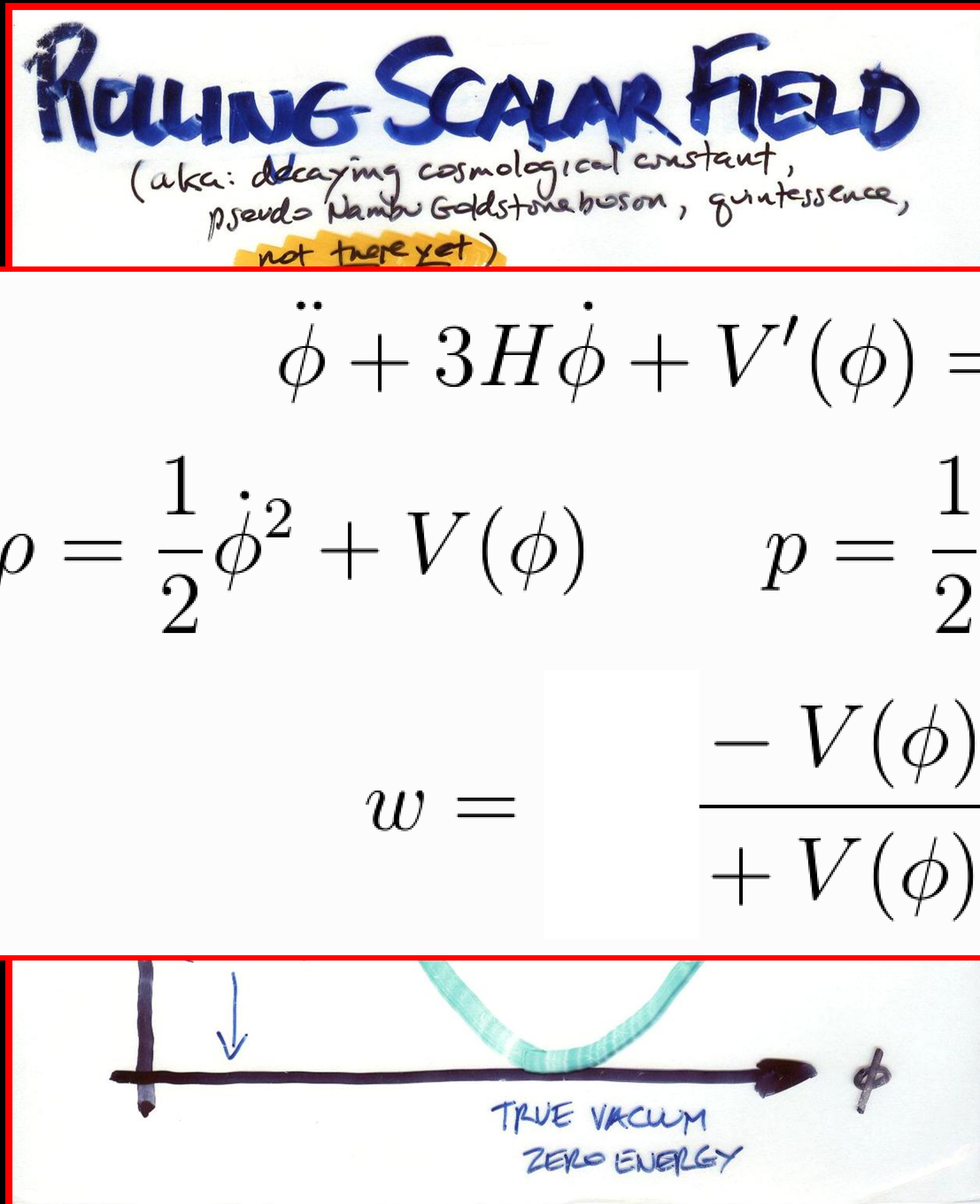
&

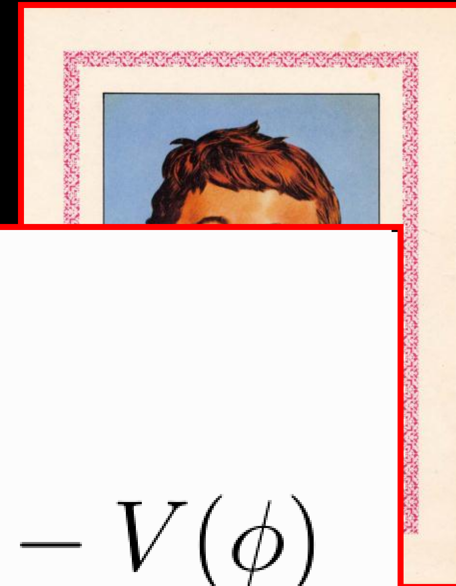
What is dark energy?

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!





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

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

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

NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98

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

IN GENERAL: $p = -N/3\ \rho$

NO DARK ENERGY

NEW ASPECT OF GRAVITY

→ "EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION !

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

$\approx 10^{-100} \times$ 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

$$H^2 = \frac{8\pi G \rho_M}{3} + H/r_c$$

$r_c \sim H_0^{-1} \sim 10^{28}\,\mathrm{cm}$

SMALL CORRECTION TO GR

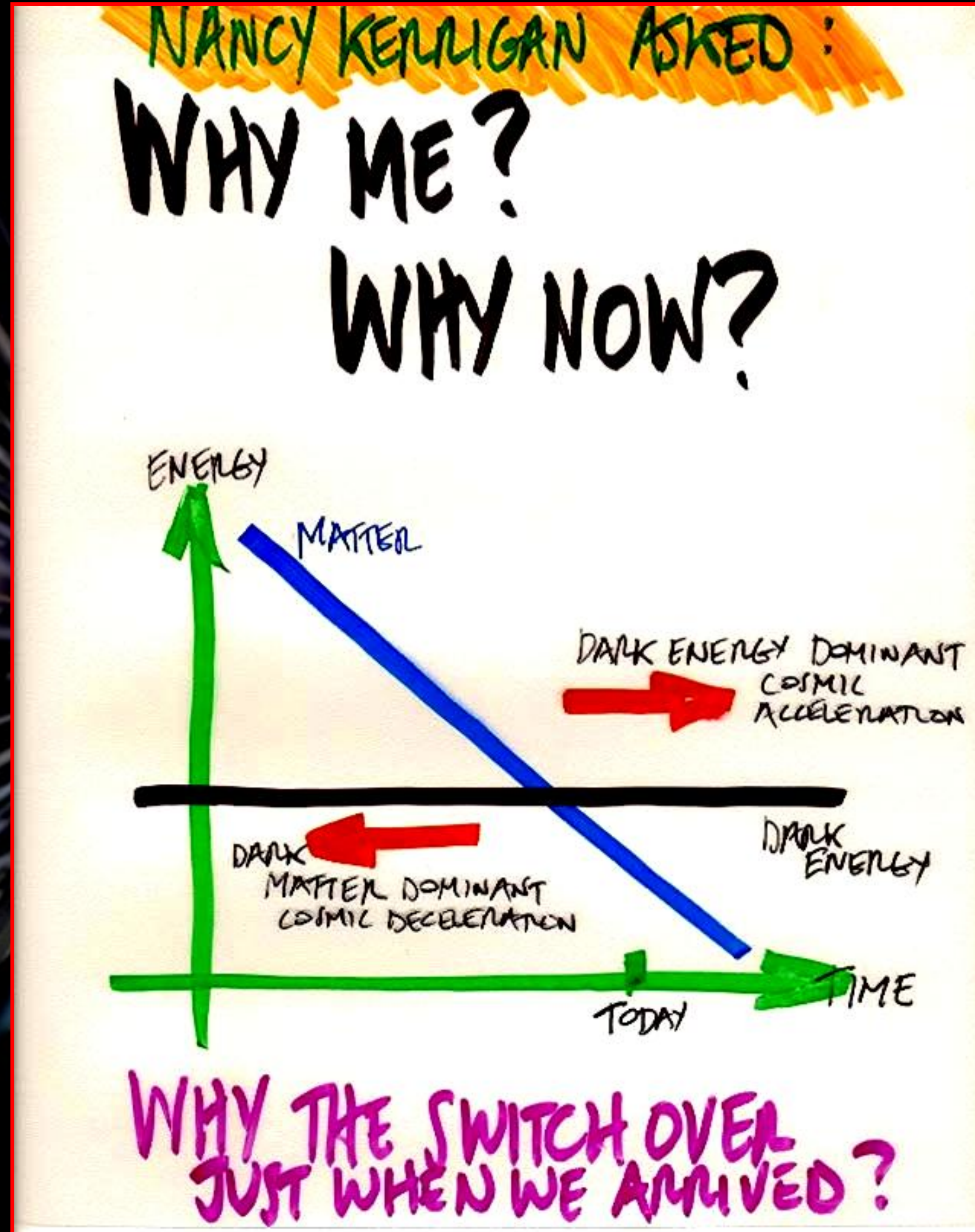
DUVVURI, CARROLL, TRODDEN, MST

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

$\mu \sim H_0$

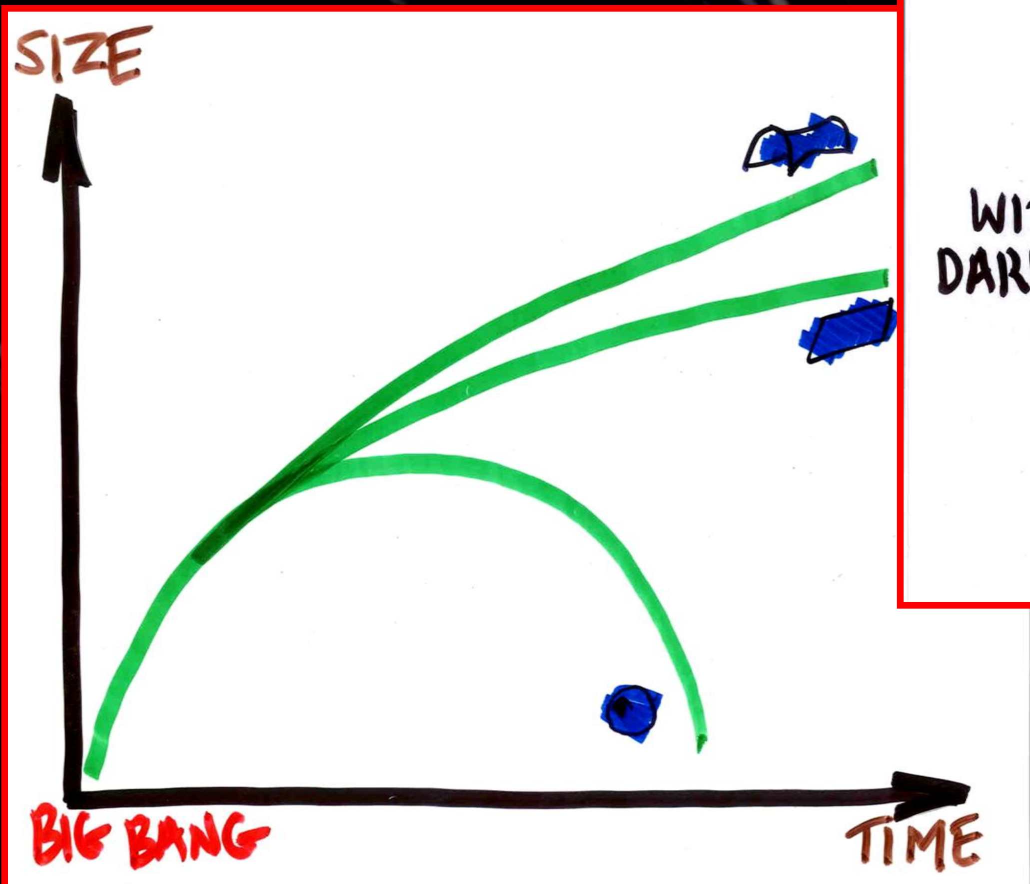
Important clue or coincidence?

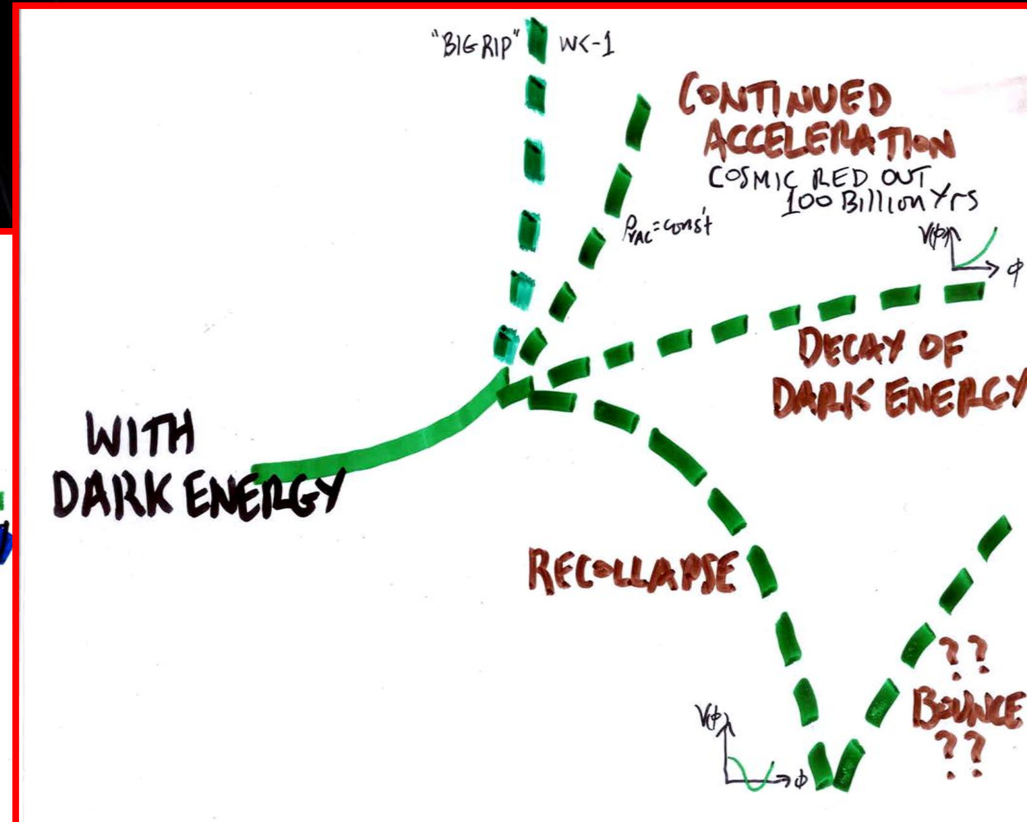
At the very least, we can now say that cosmology is the battle between two dark titans



From Here to Eternity

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

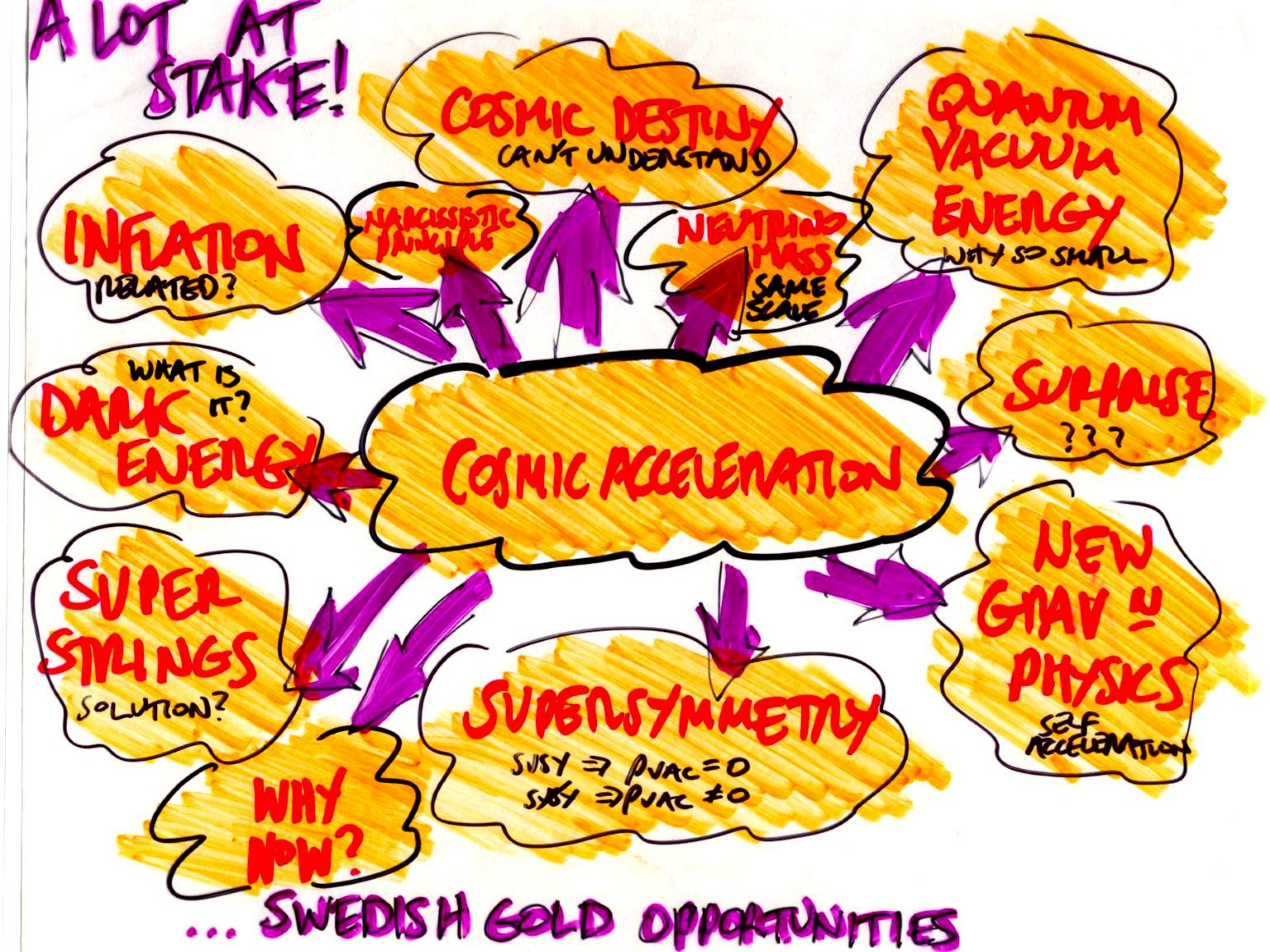




Can[illegible]t Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

DARK ENERGY

MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY


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

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

Drill for Dark Energy!

Two Big Dark Questions

Does Dark Energy change with time (i.e., is dark energy vacuum energy)?

No, at the 10 to 20% level

Does Cosmic Acceleration require going beyond General Relativity?

Not well tested

Where We Are Today

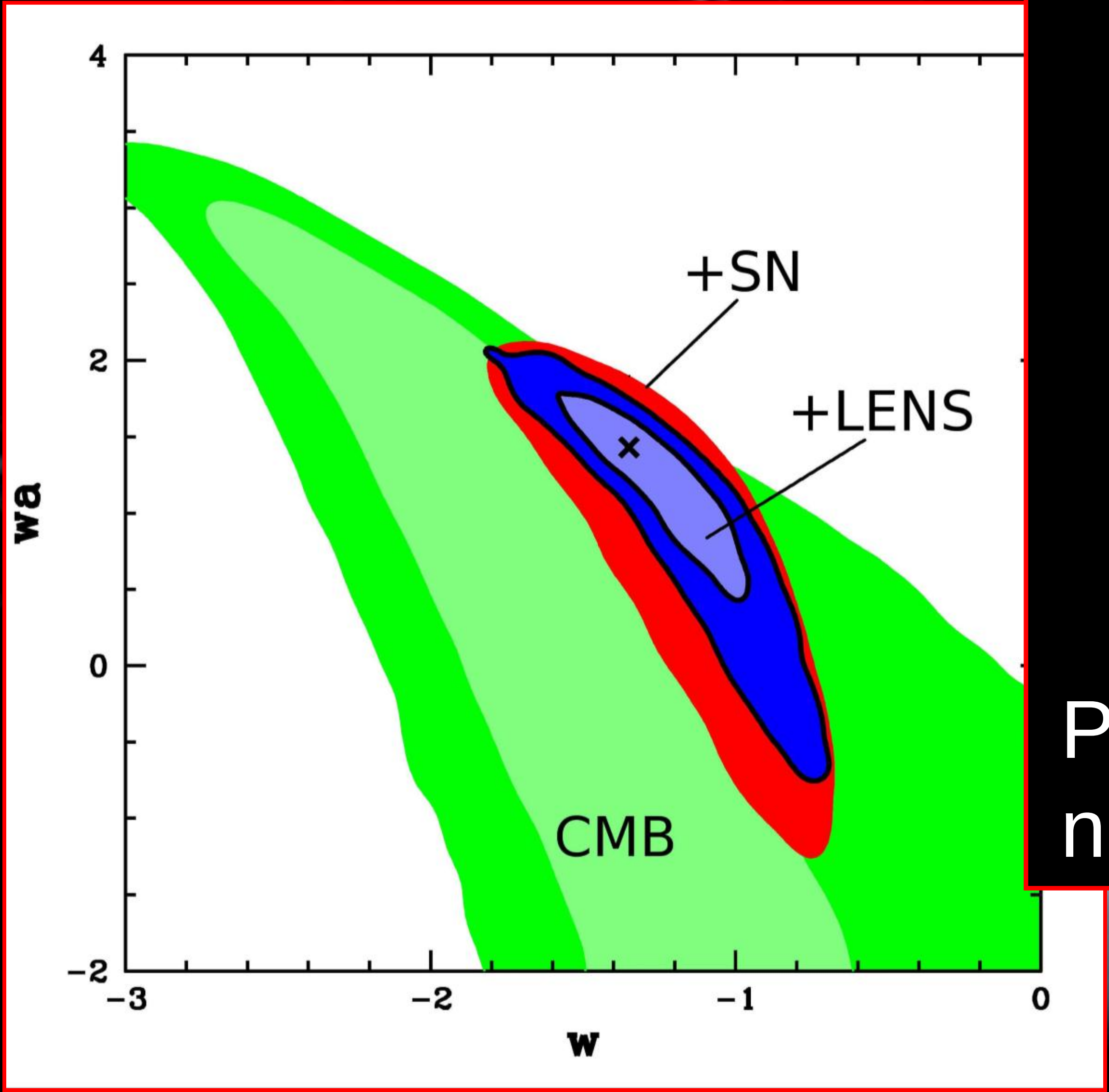
Dark Energy:

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

$w = -0.94 \pm 0.1$

($\pm$ 0.1 sys)

No Reason to Believe w is Constant



Allow w to vary:

$w = w_0 + w_a(1\text{-}a)$

a = scale factor

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

$w_0 = -1 \pm 0.2$

$w_a \sim 0 \pm 1$

Possible variation is not well constrained

Probing Cosmic Acceleration and Dark Energy

- Primary effect is on the expansion rate

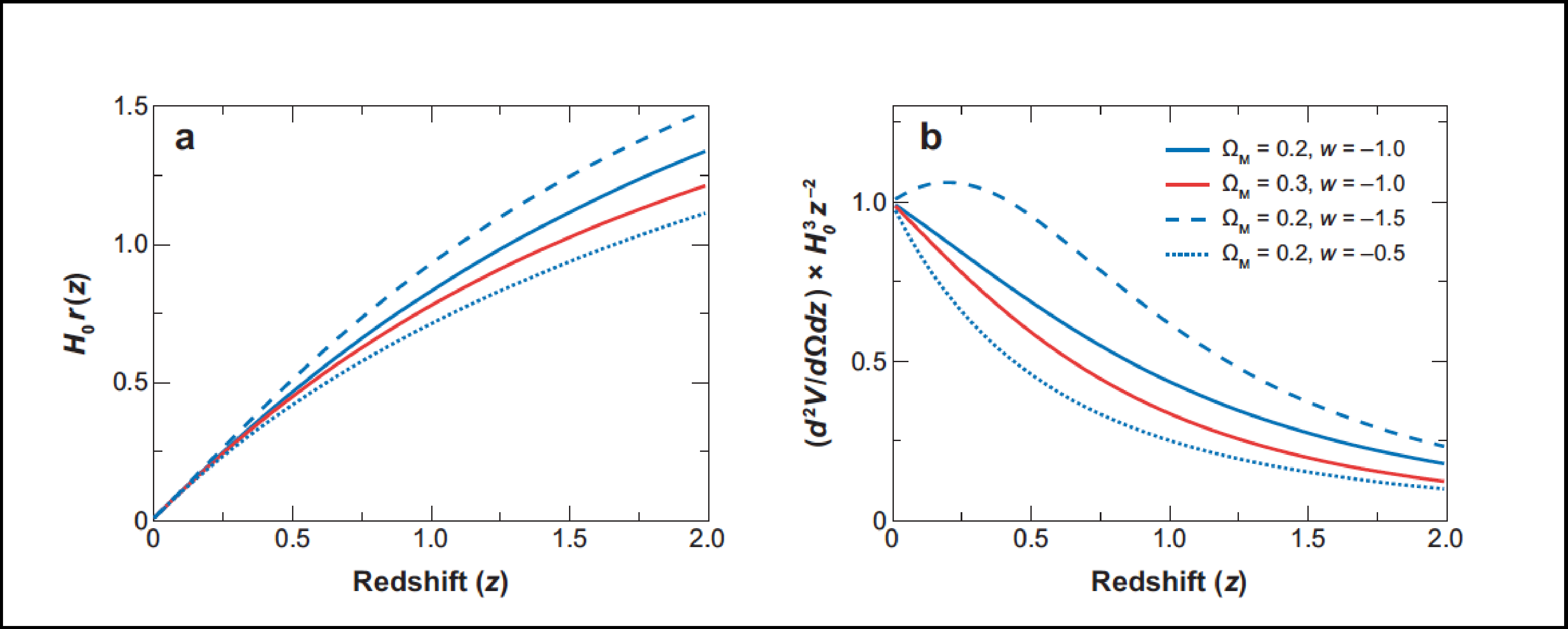
$$\begin{aligned} H^2(z) &= \frac{8\pi G}{3}\left[\rho_M + \rho_{\mathrm{DE}}\right] \\ &= H_0^2\left[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}\right] \end{aligned}$$

- Expansion rate controls distances, structure growth

$$d_L = (1+z)\int_0^z dz/H(z) \qquad \ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_M\delta_k = 0$$

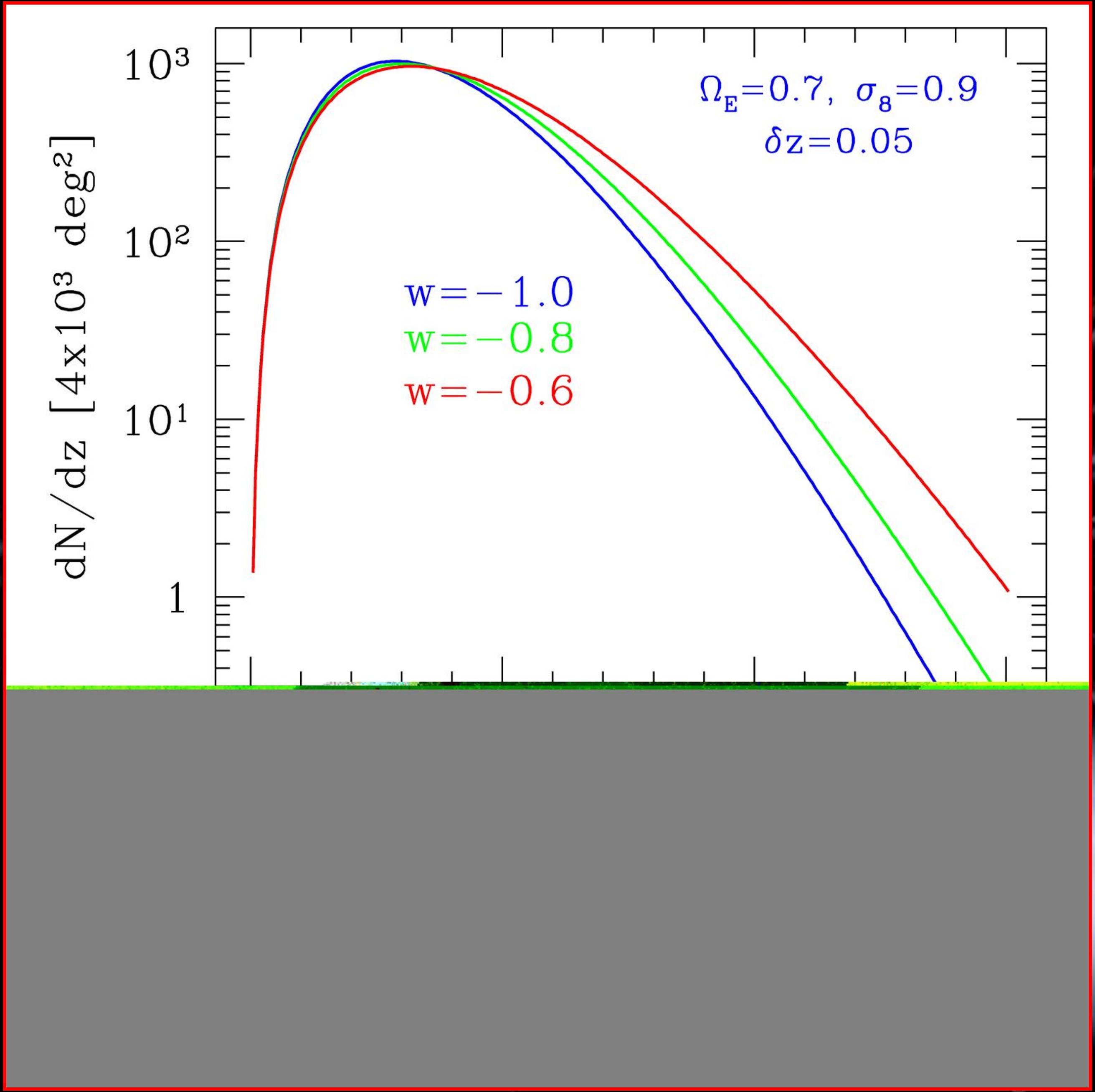
- Two Qualitatively Different Probes
  - Geometric: distances
  - Dynamic: growth of structure
  - NB: if not GR, changes in growth, lensing

Distance/volume

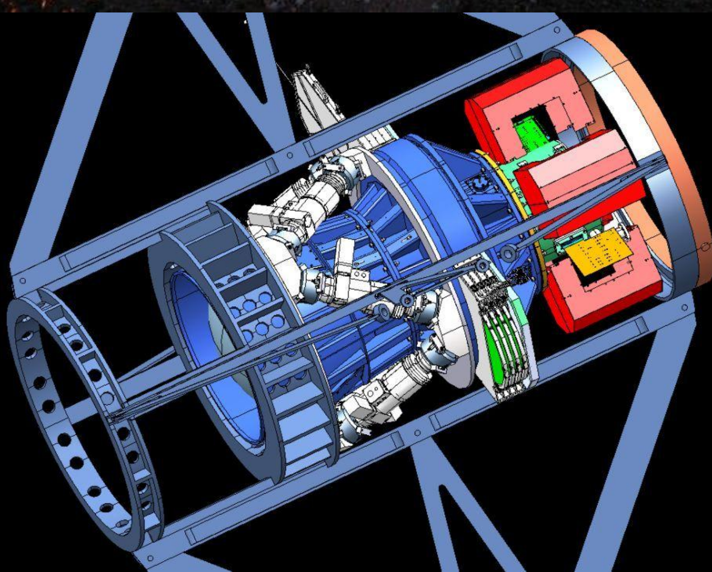


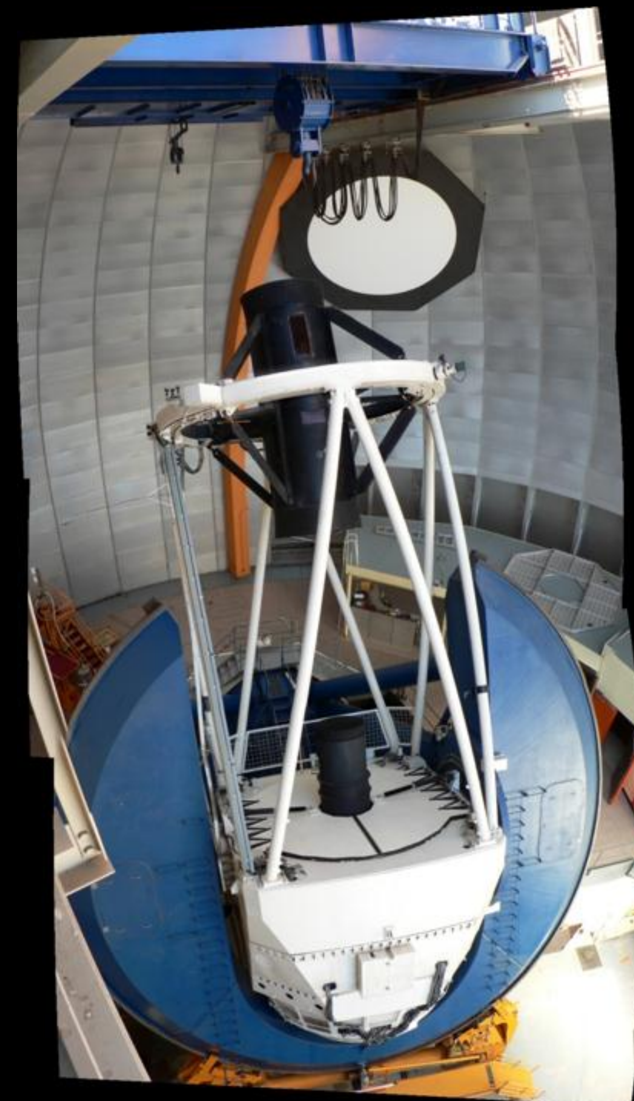
NB: $d(z) = (1+z)r(z)$

NB: $d^2V/dzd\Omega = r^2/H(z)$

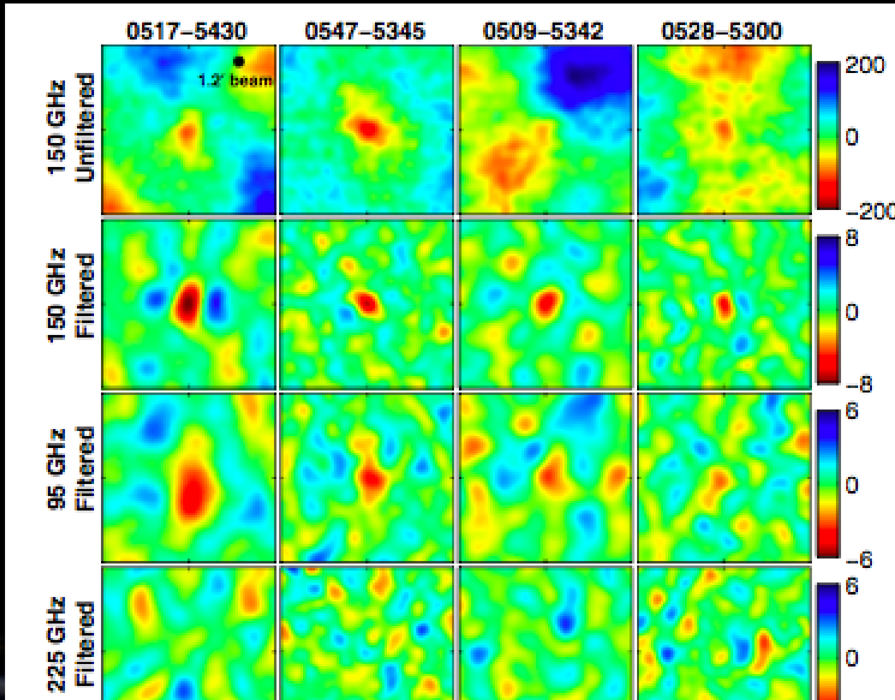


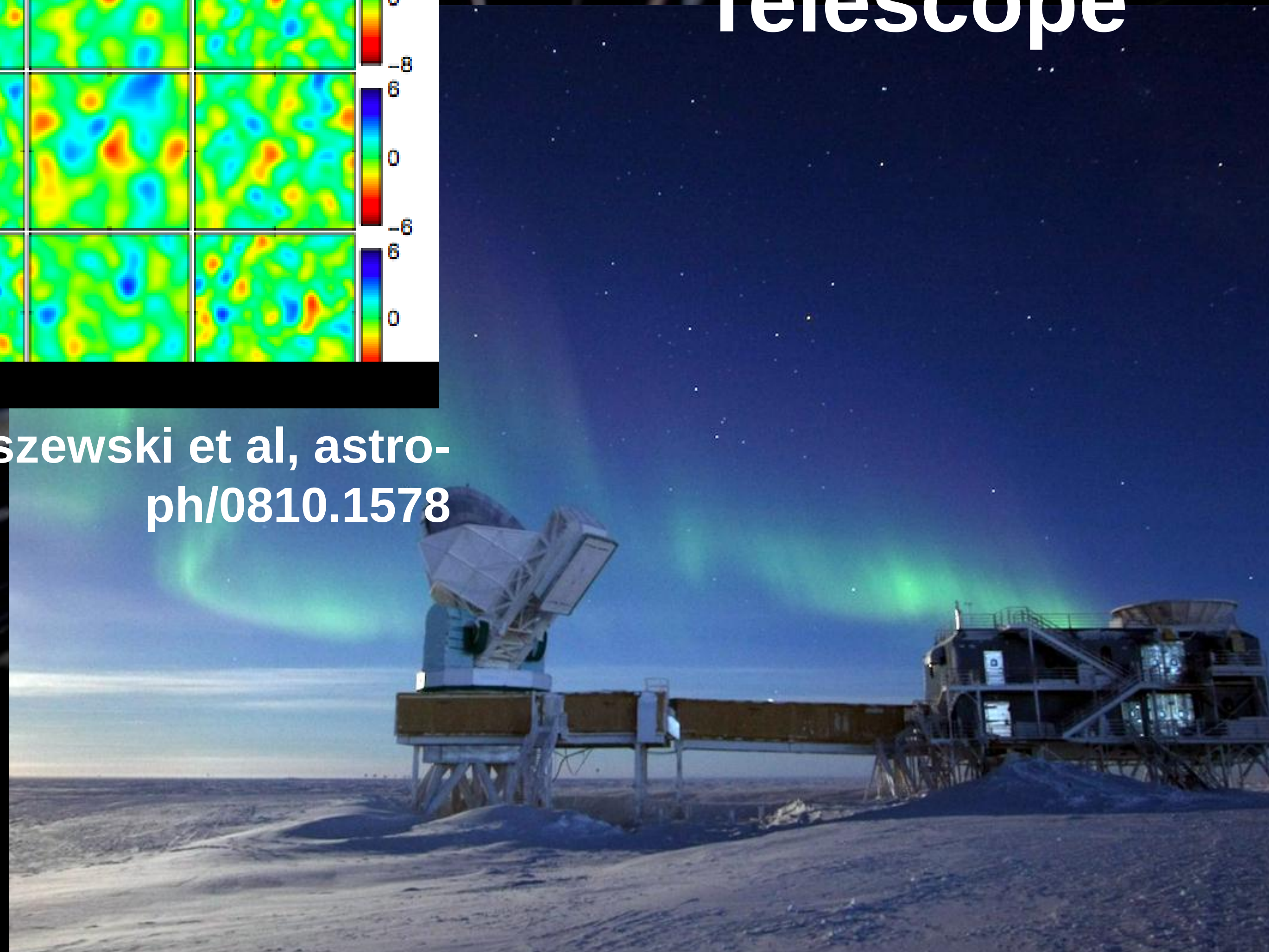
Clusters:
Cosmic Frogs:
very sensitive
to cosmic
environment





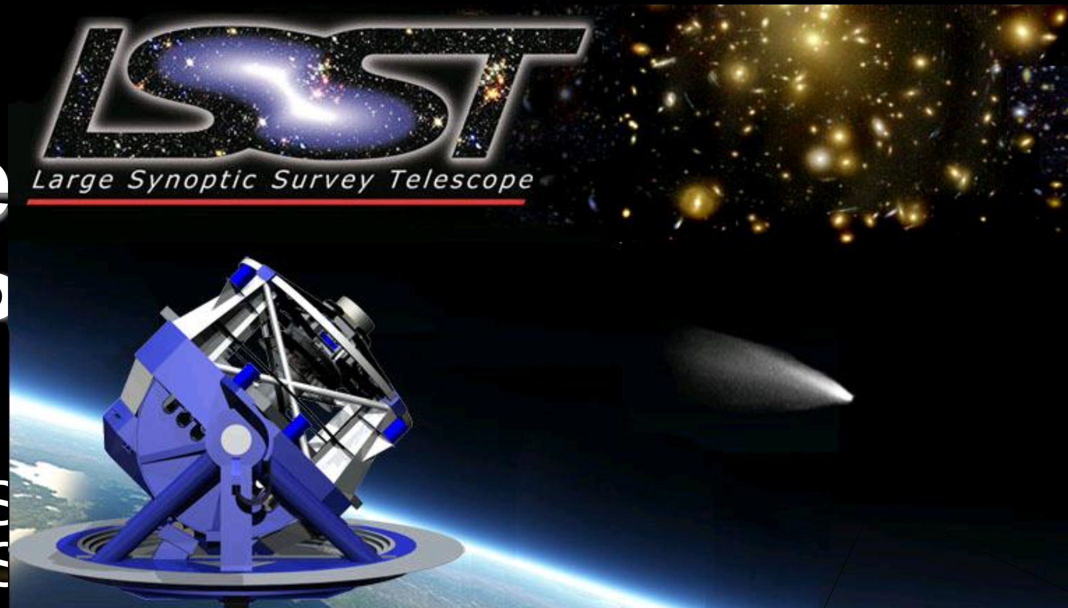
First Results from the South Pole Telescope



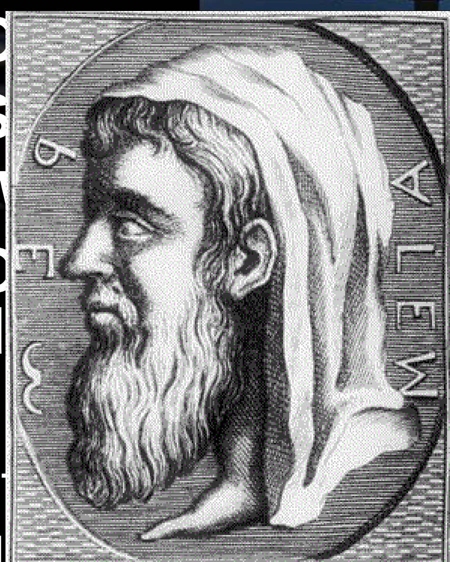


Staniszewski et al, astro-ph/0810.1578

Impre nergy P n



- **BAO:** S TDEX, WFMOS
- C DES, ACT, Chandra → eROSITA
- S STARRS → LSST, EUCLID & JDEM
- W TARRS → LSST, EUCLID & JDEM
- C AP/ACT/SPT/Planck – cosmological d ke many other observations valuable



On t 10% in w_a, s nificant tests of u . and deeper understanding of dark energy

Mapping out w(z)

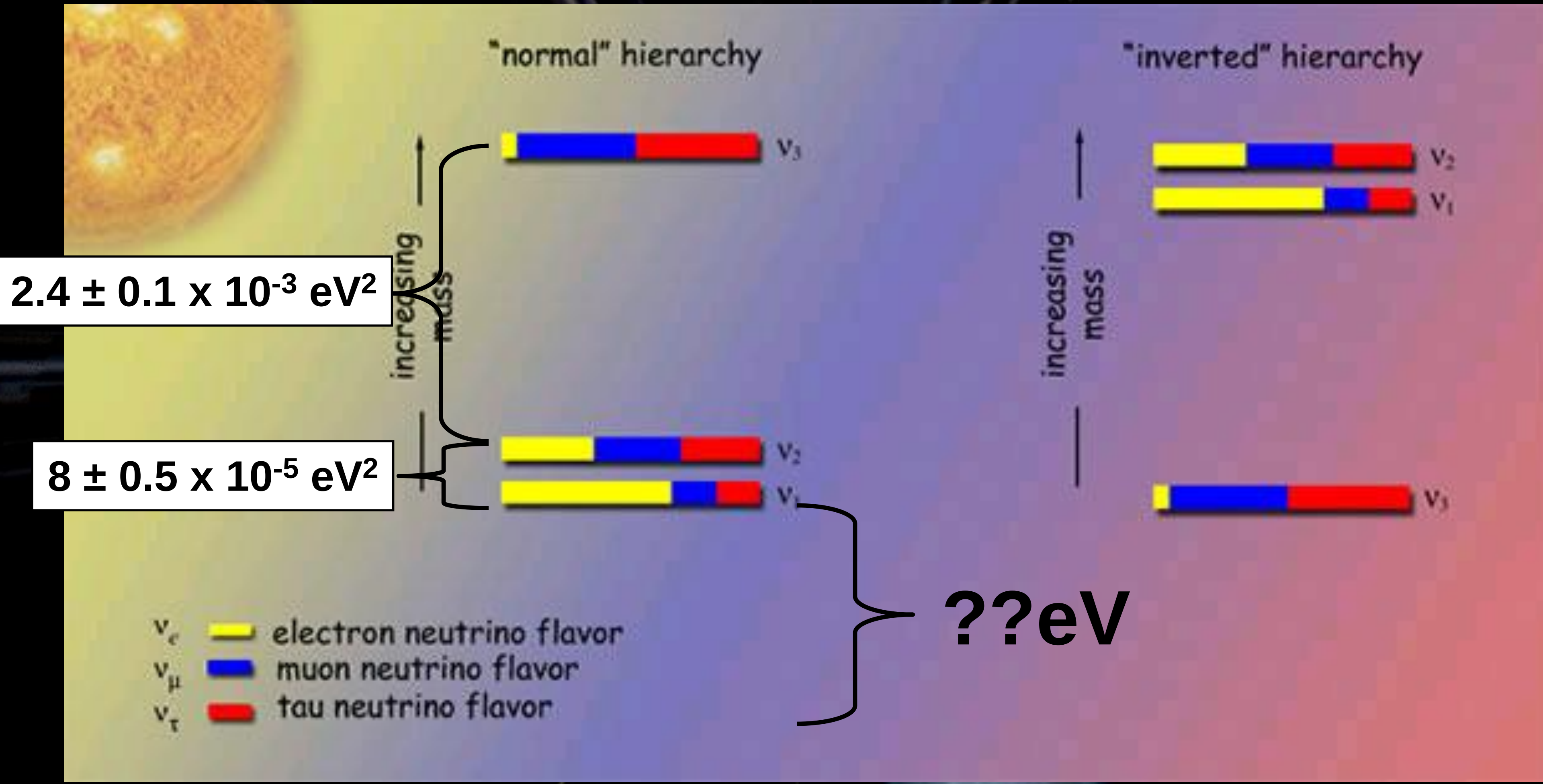
Determining w, $w_a = dw/dR$

Lecture 2 “take homes”

- Cosmic acceleration well established
- Simplest explanation: repulsive gravity of quantum vacuum energy within General Relativity
- Two big questions: 1. Is the simplest hypothesis correct? 2. Does GR self consistently describe cosmic acceleration?
- Kinematic (SNeIa, BAO) and dynamic tests (growth of structure, WL, clusters)
- Dark Energy/Cosmic Acceleration may take many decades to solve (cf, WIMP decade)


eROSITA 2011

Neutrinos have mass!



The Complicated Universe

- Matter: 28.5%
  - Baryons: 4.5%
  - Neutrinos: 0.1%
  - CDM: 24%
- Radiation: 0.01%
  - Photons: 0.005%
  - Neutrinos (for T >> m): 0.68 x photons
  - NB: ratio determined by simple physics:

$$\rho_\nu/\rho_\gamma = (21/8)[4/11]^{1/3}$$

- Dark Energy: 71.5%

3 Epochs
3 dimensionless ratios

- $1 + z_{DE} = [\Omega_{DE}/\Omega_M]^{1/3} \approx 1.37$
- $1 + z_M = \Omega_M/\Omega_R \approx 3300$
- NB: $1 + z_{DEC} \approx 1100 \sim [13.6\ \mathrm{eV}/3\ \mathrm{K}]/\ln(1/\eta)$

- $\Omega_{CDM}/\Omega_B \approx 7$
- $\Omega_B/\Omega_\nu \sim 40$
- $(1 + z_M)/(1 + z_{DEC}) \sim 3$

Some Numerology

Turner/Carr, MLPA 2, 1 (1987)

- $\Omega_{CDM}/\Omega_B \approx 7$
  - Neutralino: $m_W{}^2 \sim 10^{-6}\, \varepsilon\, m_{PL}\, \Lambda_{QCD} << m_{Pl}{}^2$
  - Axion: $f_a/m_{PL} \sim 10\, \varepsilon$
- $\Omega_B/\Omega_\nu \sim 40$
  - Neutrinos: $m_\nu \sim 10^{-4}\, \varepsilon\, \Lambda_{QCD}$
  - See-saw: $m_{GUT} \sim 10^4\, m_W{}^2/[\Lambda_{QCD}\, \varepsilon] >> m_W$
- $z_{EQ} \sim z_{DEC}$: $\eta \ln(\eta^{-1}) \sim 13.6\ \mathrm{eV}/m_N \sim \alpha^2\, (m_e/m_N)$

The Complex Universe Challenge

Understand the mix!