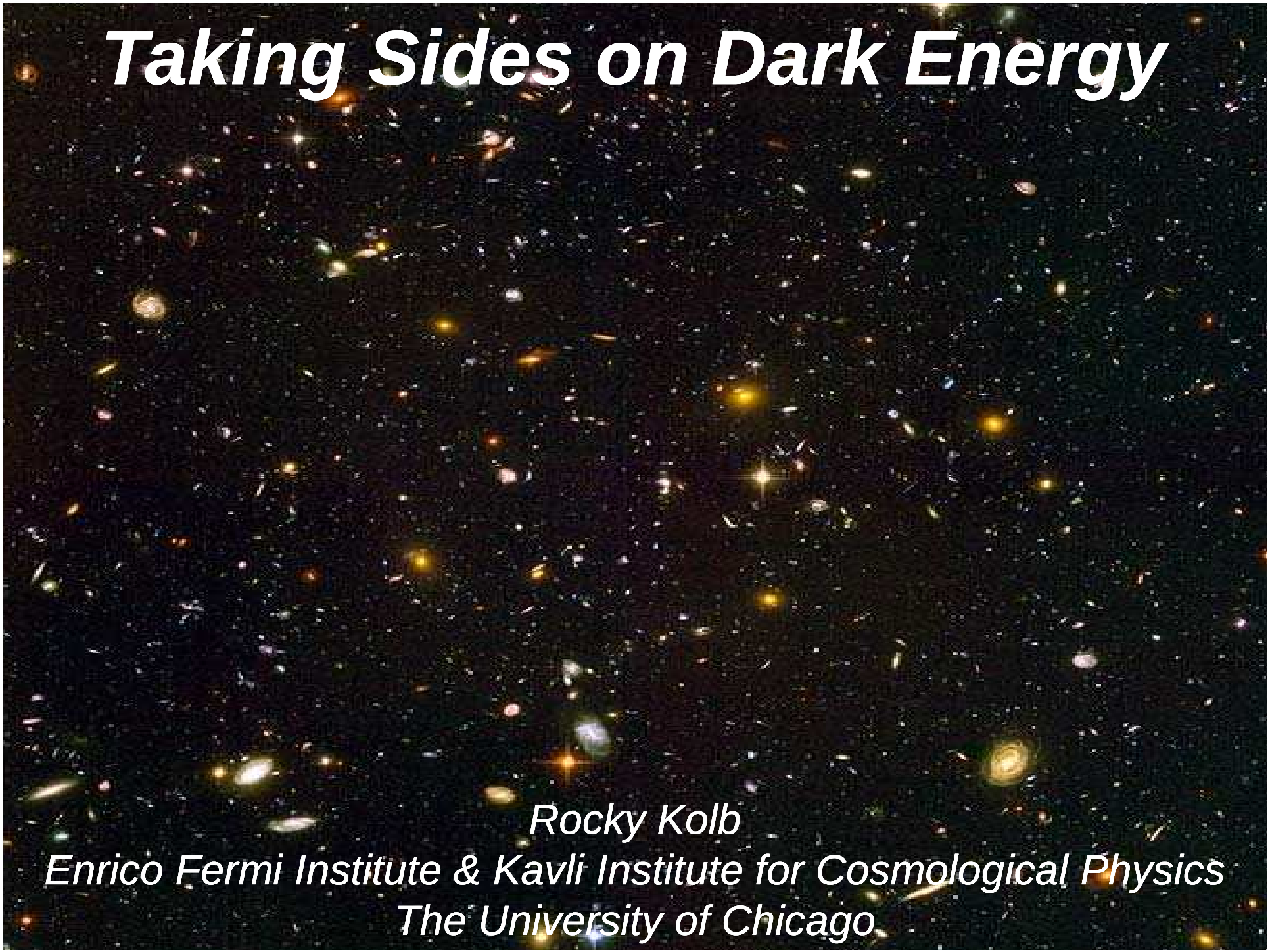
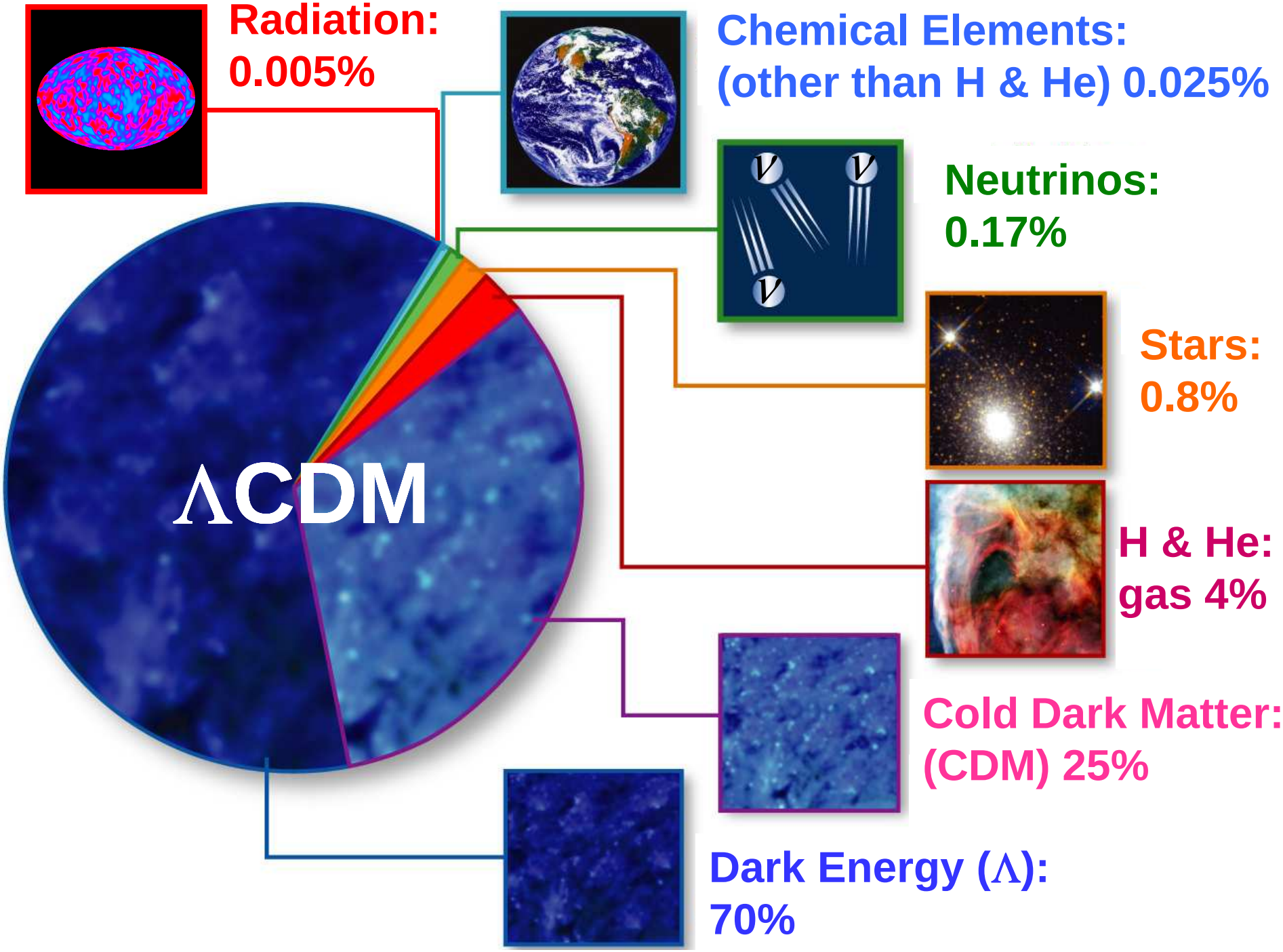


Taking Sides on Dark Energy

Rocky Kolb
Enrico Fermi Institute & Kavli Institute for Cosmological Physics
The University of Chicago

Cosmology 1000 years ago
(and Kansas Today)


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM

Precision Cosmology

Dark Energy
+
Dark Matter
+
Seed Perturbations (Inflation)
+
Baryo/Leptogenesis

The Standard Model of *cosmology* suggests physics beyond the Standard Model of *particle physics!*

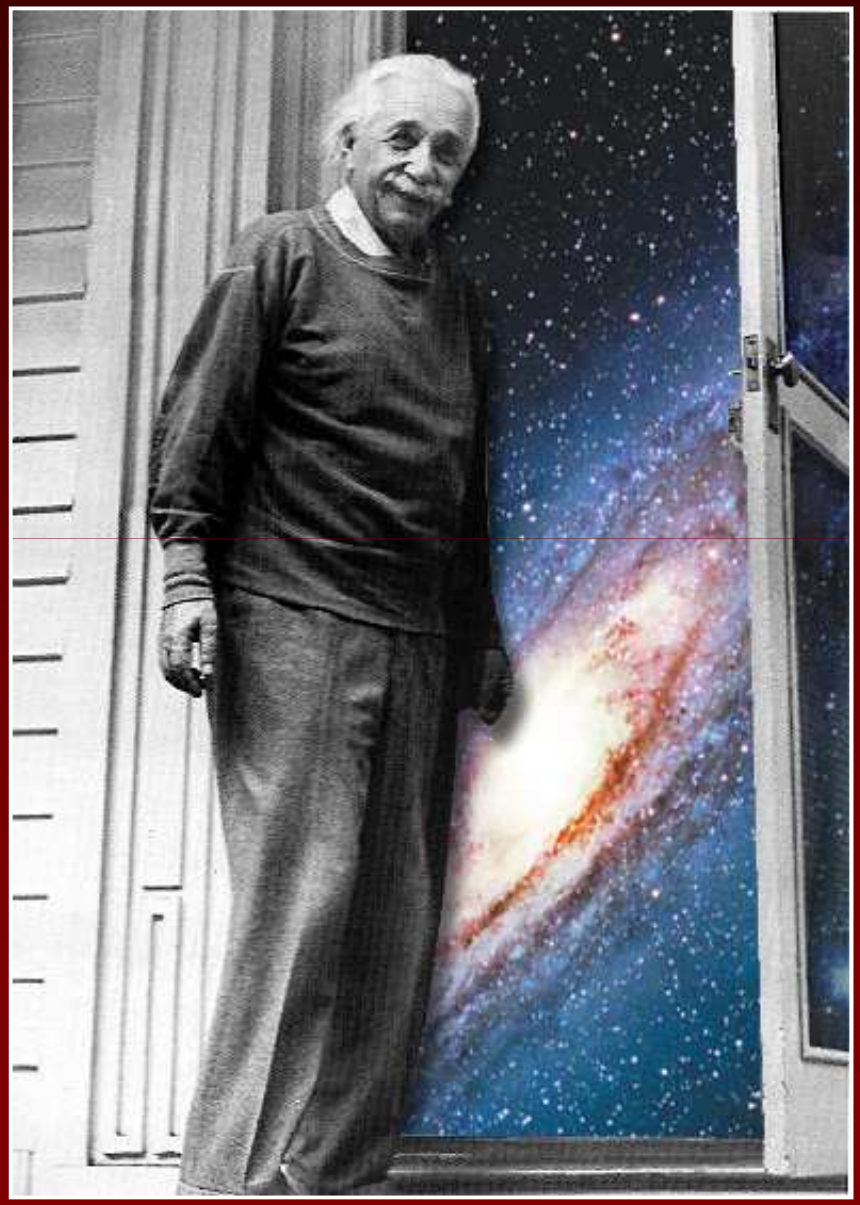
Precision astronomy is helpful to physics!

Precision Cosmology

"How helpful to us is astronomy's pedantic accuracy, which I used to secretly ridicule!"

Einstein's statement to Arnold Sommerfeld on December 9, 1915 (regarding measurements of the advance of the perihelion of Mercury)

Cosmological Constant (Dark Energy)



1917 Einstein proposed cosmological constant, Λ.

1929 Hubble discovered expansion of the Universe.

1934 Einstein called it "my biggest blunder."

1998 Astronomers found evidence for it, and renamed it "Dark Energy."

Cosmological Constant (Dark Energy)

Do not directly *observe*

- acceleration of the universe
- dark energy

We *infer* acceleration/dark energy by comparing

observations

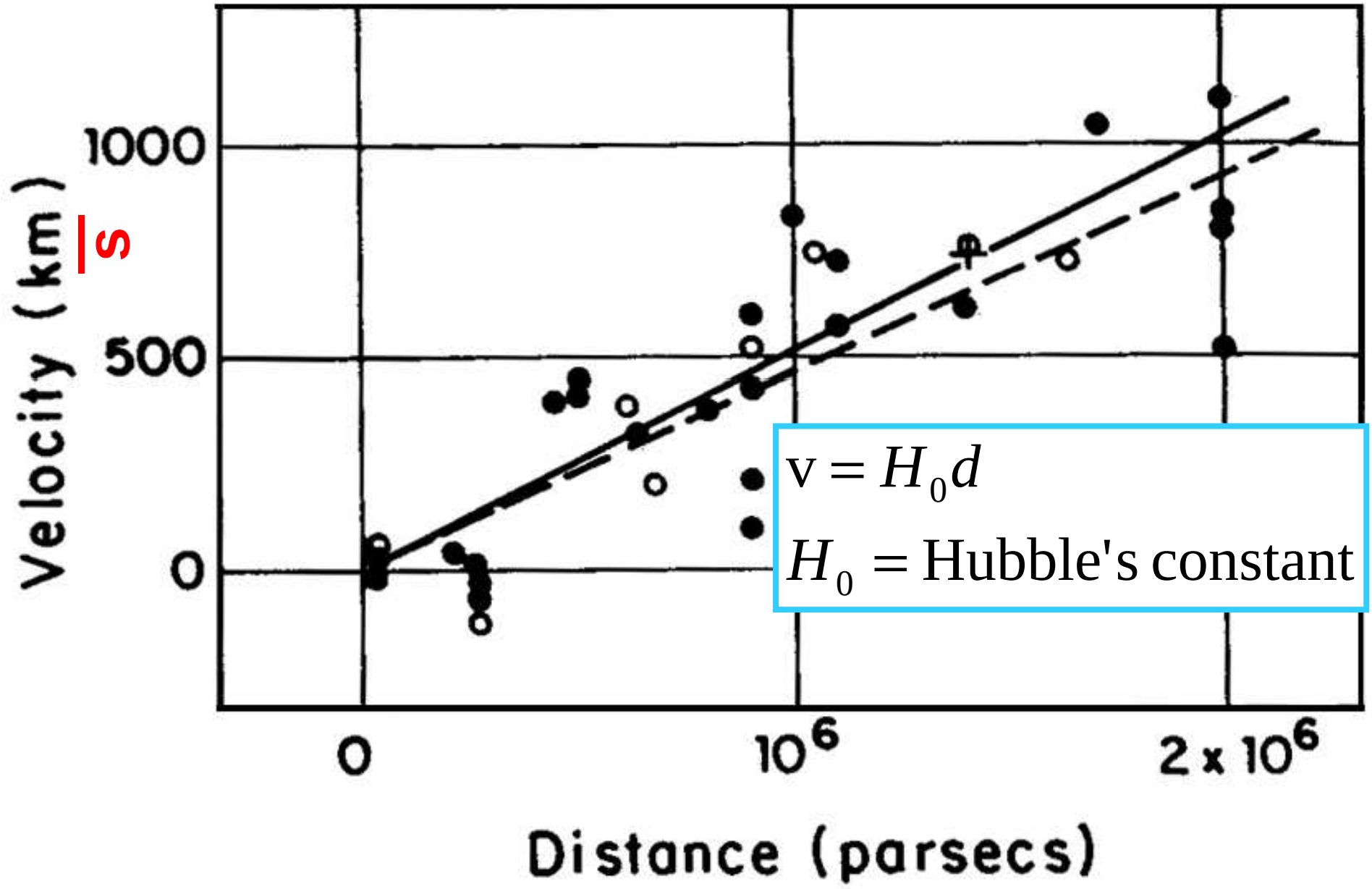
with the predictions of a

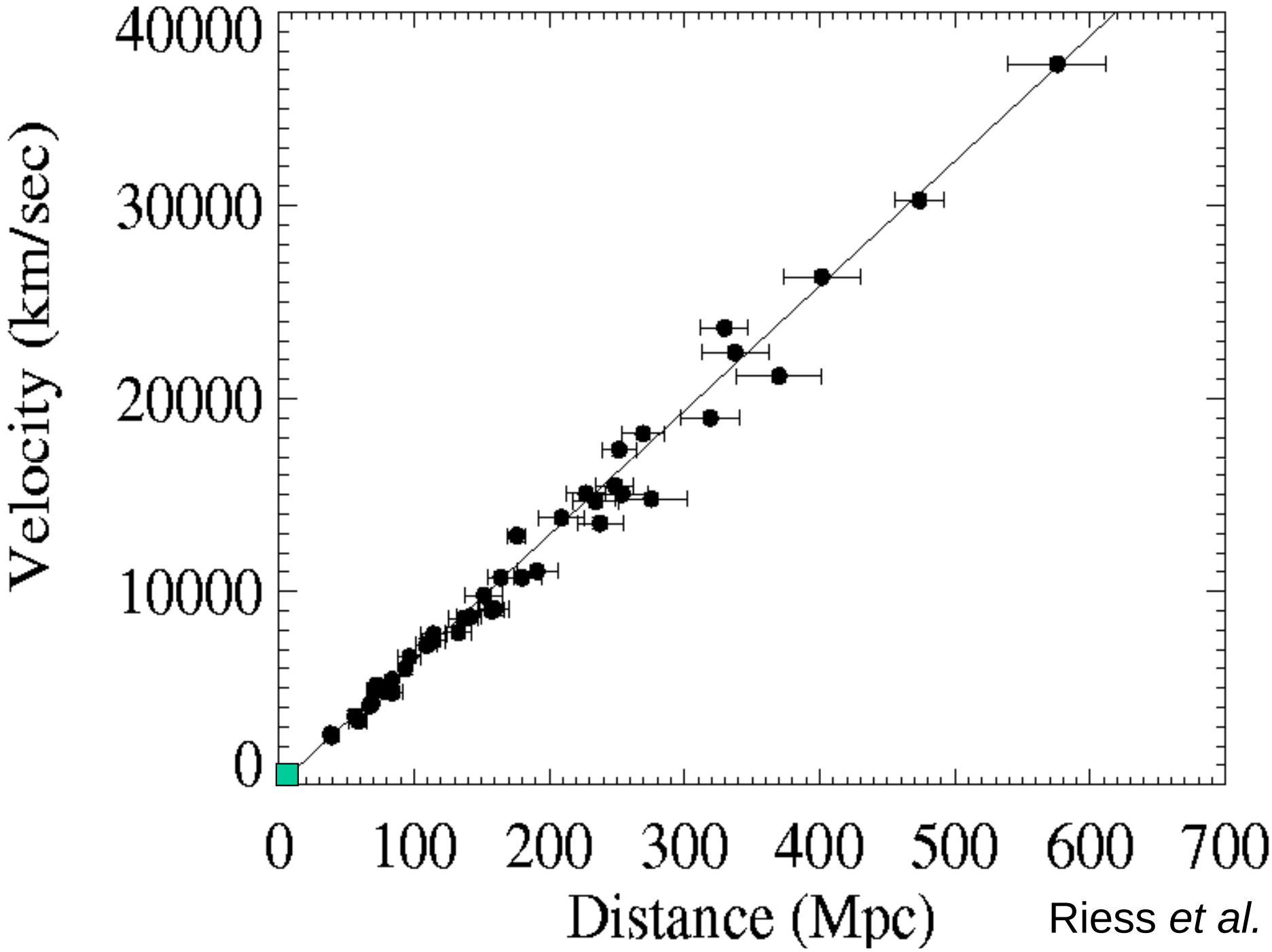
model

All evidence for dark energy/acceleration comes
from measuring the expansion history of the Universe

University of Chicago 1909 National Champions

Hubble's Discovery Paper - 1929




40000
30000
20000
10000
0
Velocity (km/sec)
0
100
200
300
400
500
600
700
Distance (Mpc)
Riess *et al.*

INSTANT

QUAKER OATMEAL®

With Real

Cinnamon & Spice

All Natural Flavors

FACT OR FICTION

SCIENCE

The universe is shrinking and will soon be the size of a golf ball.

See other side for answer.

CONVENTIONAL DIRECTIONS

Empty packet into bowl.
Add **1/2 cup** boiling water; stir.

MICROWAVE DIRECTIONS

Empty packet into microwaveable bowl.
Add **2/3 cup** water or milk.
Microwave at **HIGH** about 1-2 minutes; stir.
Use care when removing cereal from microwave; bowl may be hot.

For **thicker** oatmeal decrease liquid; for **thinner** oatmeal increase liquid.

THE ANSWER

Fiction! Most stars and galaxies are moving away from the earth which means the universe is actually getting bigger.

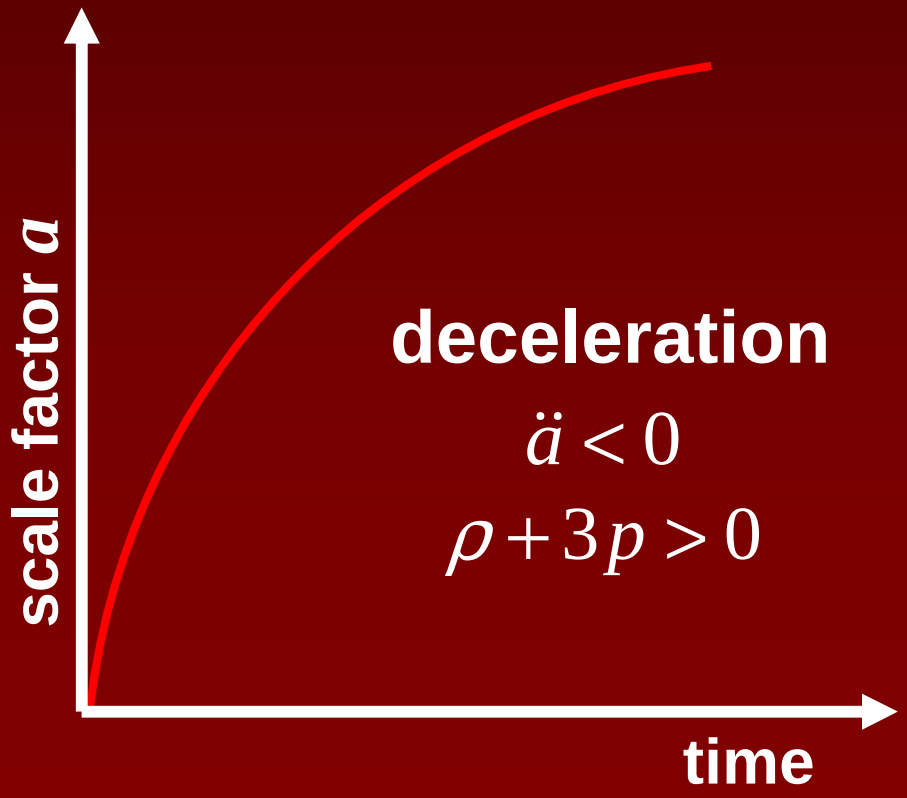
P.O. Box 9003, Chicago, IL 60650-9003

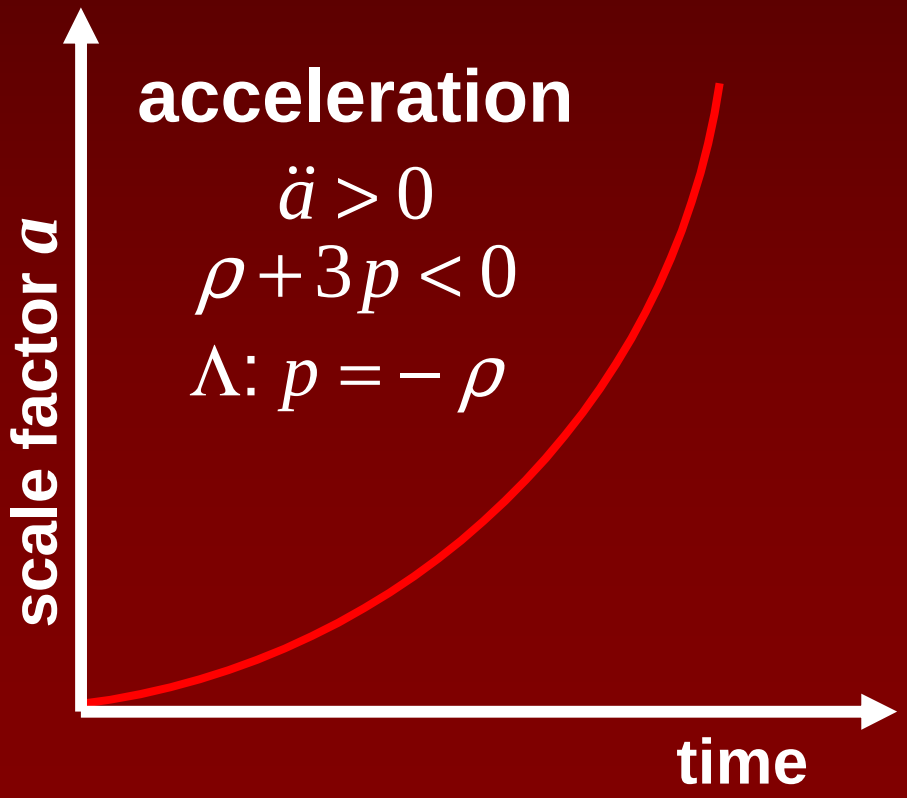
Expansion History of the Universe

distance: $D \quad / \; a$ (cosmic scale factor)

velocity: $\dot{a} \; / \; H$ (Hubble's constant)

acceleration: $\ddot{a} \; / \; -G(\rho + 3p)$





Expansion History of the Universe

Many observables based on $H(z)$

- Luminosity distance Flux = (Luminosity / $4\pi d_L^2$)
- Angular diameter distance α = Physical size / d_A
- Volume (number counts) N / $V^{-1}(z)$
- Age of the universe
- Distances

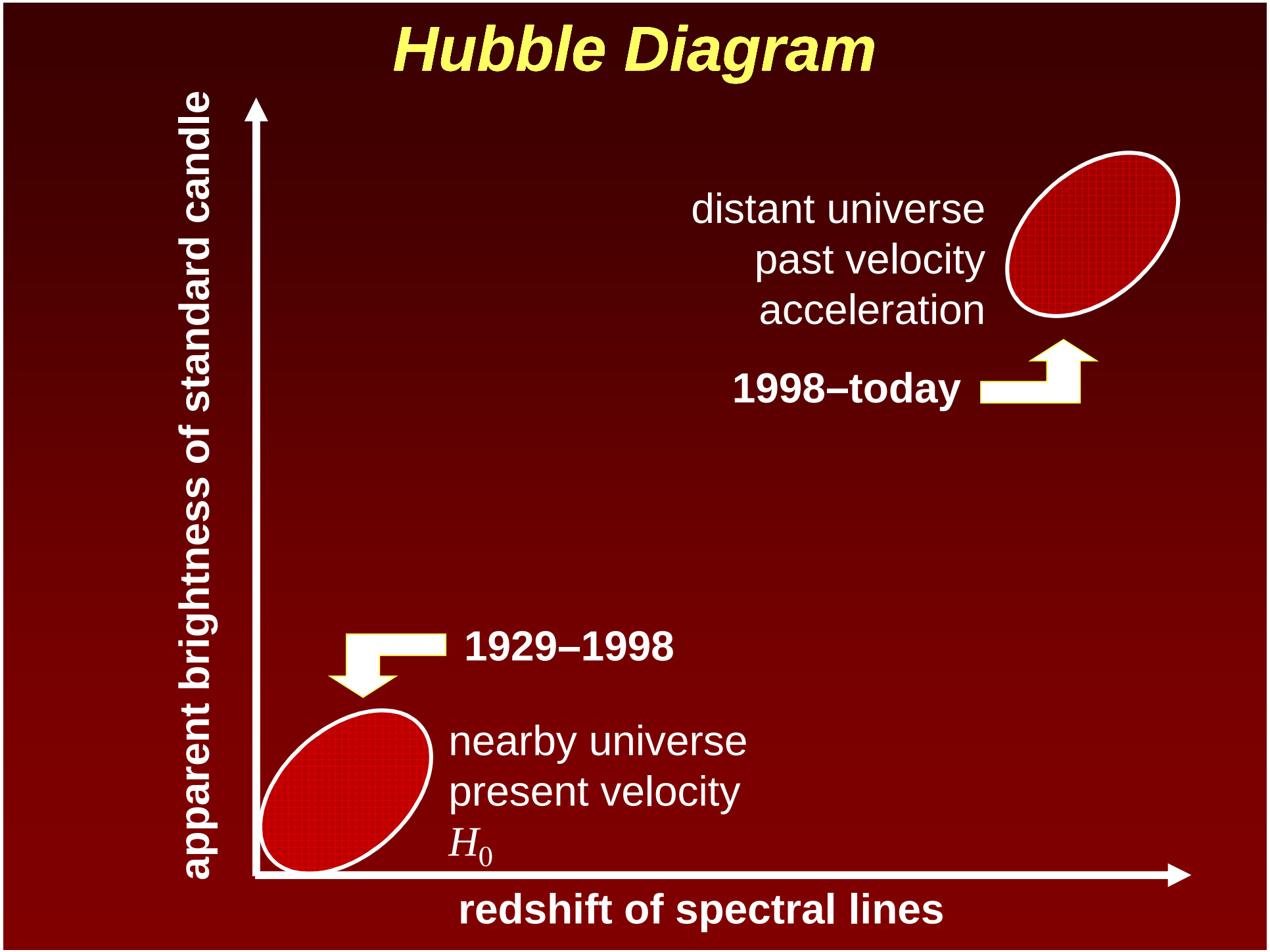
Expansion History of the Universe

Friedmann equation ($G_{00} = 8\pi G T_{00}$)

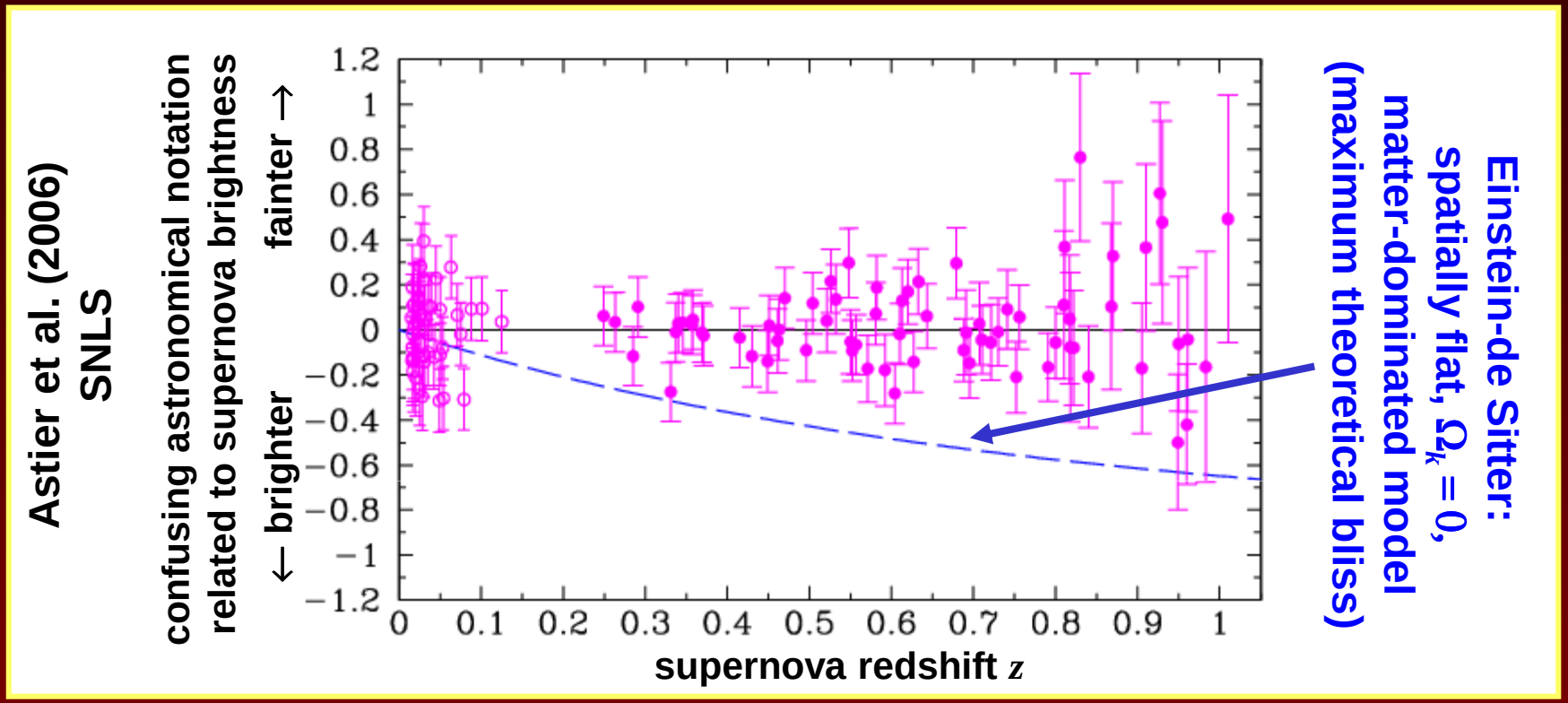
Hubble constant | curvature | matter | radiation

$$H^2(z) = H_0^2 \times \left[\Omega_k (1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4\right]$$

- Ω_R: radiation contribution small for $z \quad 10^4$
- $\Omega_k + \Omega_M + \Omega_R = 1 \Rightarrow \Omega_k \approx 1 - \Omega_M$
- "All of observational cosmology is a search for two numbers." (H_0 and Ω_M) — Sandage, *Physics Today,* 1970
- Ω_k well determined (close to zero) from CMB, post 2000


Hubble Diagram
apparent brightness of standard candle
distant universe
past velocity
acceleration
1998–today
1929–1998
nearby universe
present velocity
H_0
redshift of spectral lines

Hubble Diagram



Expansion History of the Universe

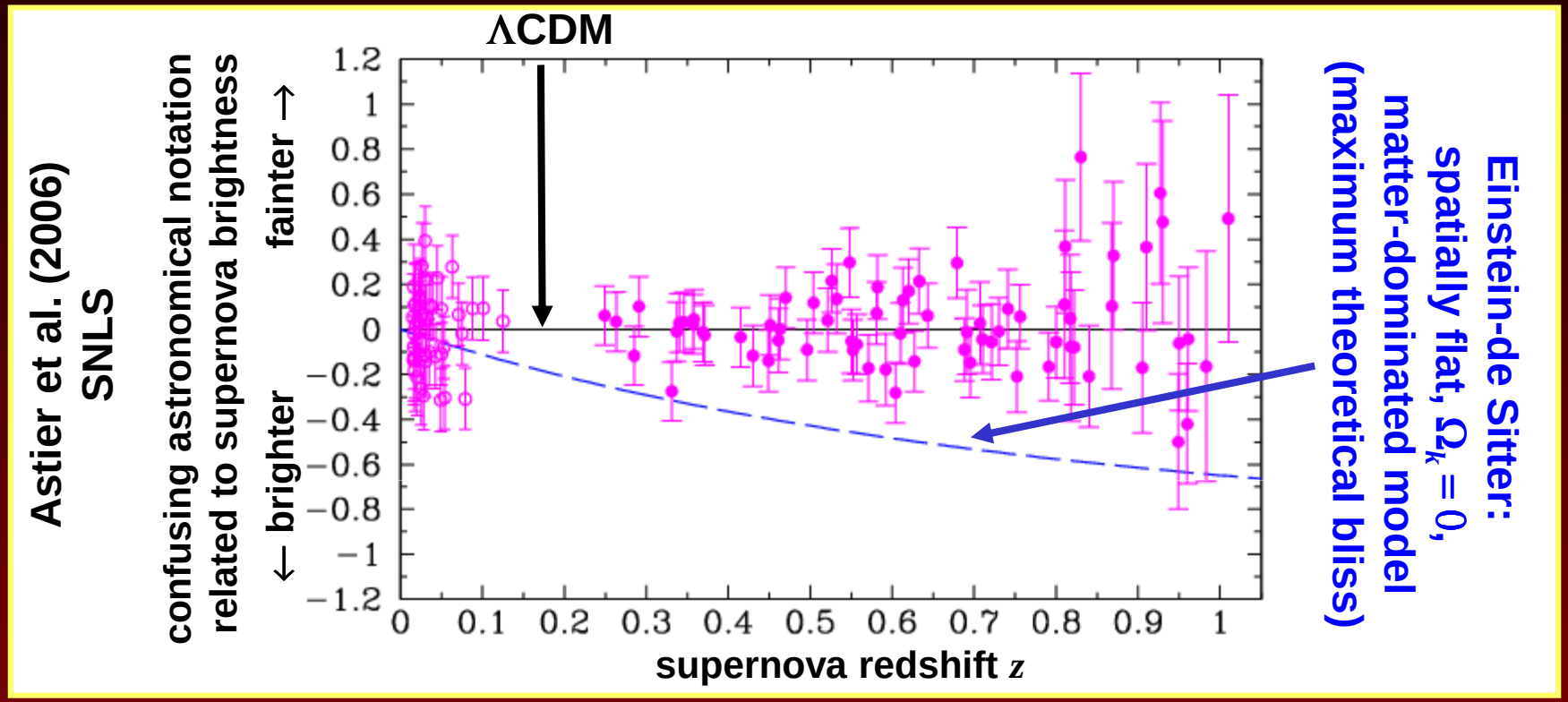
Friedmann equation ($G_{00} = 8\pi G T_{00}$)

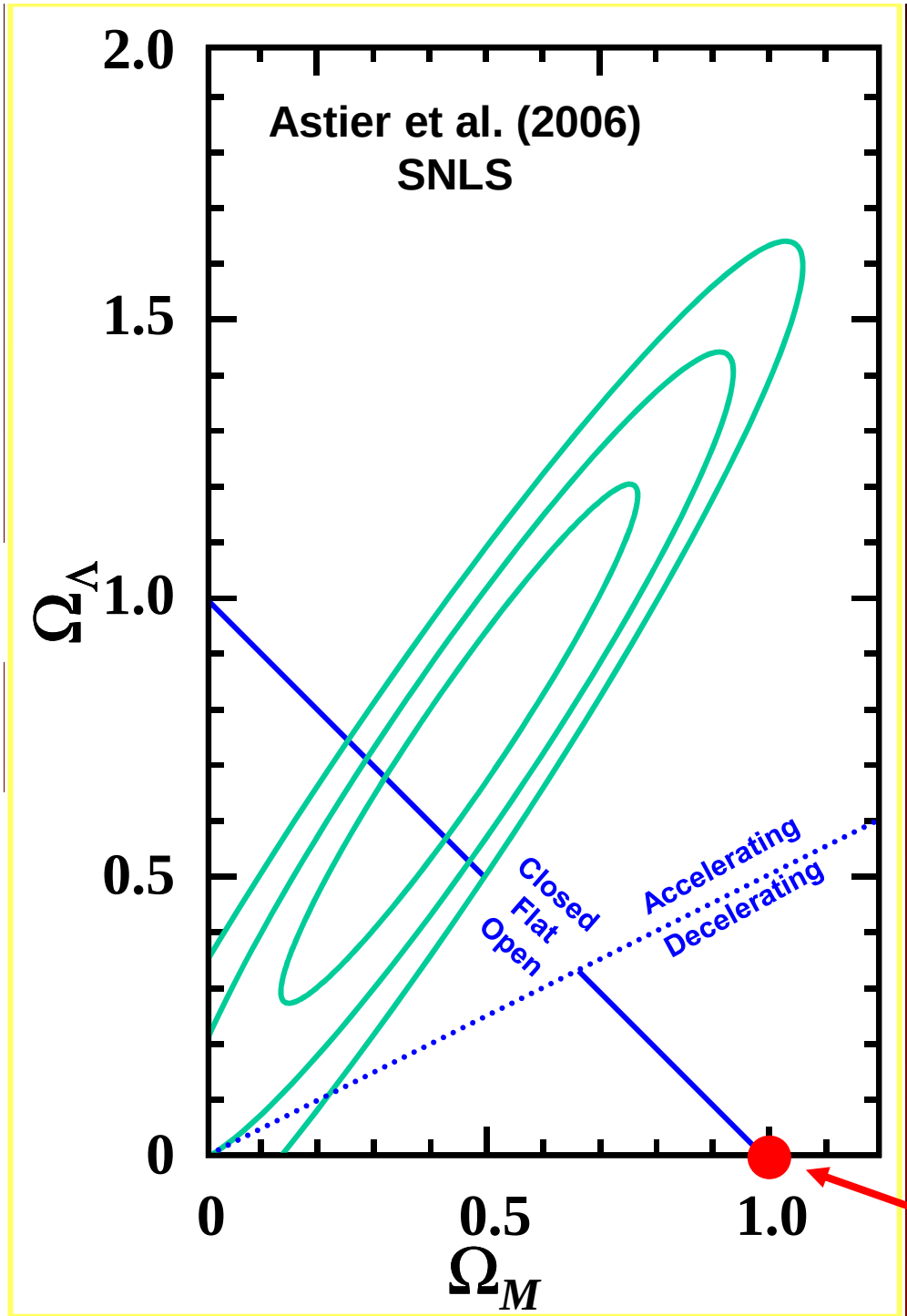
Hubble constant | cosmological constant | curvature | matter | radiation

$$H^2(z) = H_0^2 \times \left[\Omega_\Lambda (1+z)^0 + \Omega_k (1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 \right]$$

- [Could add $\Omega_{\text{walls}} (1+z)^1$]
- Ω_R: radiation contribution small for $z \quad 10^4$
- $1 = \Omega_\Lambda + \Omega_k + \Omega_M + \Omega_R$
- Ω_k well determined (close to zero) from CMB
- Ω_M reasonably well determined

Hubble Diagram





Evidence For Dark Energy

1. Find standard candle (SNe Ia)
2. Observe magnitude & redshift
3. Assume a cosmological model
4. Compare observations & model

← { Assumes $w = -1$ (i.e., Λ)
  { Assumes priors on H_0, etc.

5. Fit needs cosmoillogical constant

$$\rho_V \sim 10^{-30} \text{ g cm}^{-3}$$

Einstein–de Sitter model

Expansion History of the Universe

Friedmann equation ($G_{00} = 8\pi G T_{00}$)

dark energy | curvature | matter | radiation

$$H^2(z) = H_0^2 \times \left[\Omega_w (1+z)^{3(1+w)} + \Omega_k (1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 \right]$$

Equation of state parameter: $w = p / \rho$ ($w = -1$ for Λ)

if $w = w(z)$: $(1+z)^{3(1+w)} \rightarrow \exp\left(-3 \int_0^z \frac{dz'}{z'} \left[1 + w(z') \right] \right)$

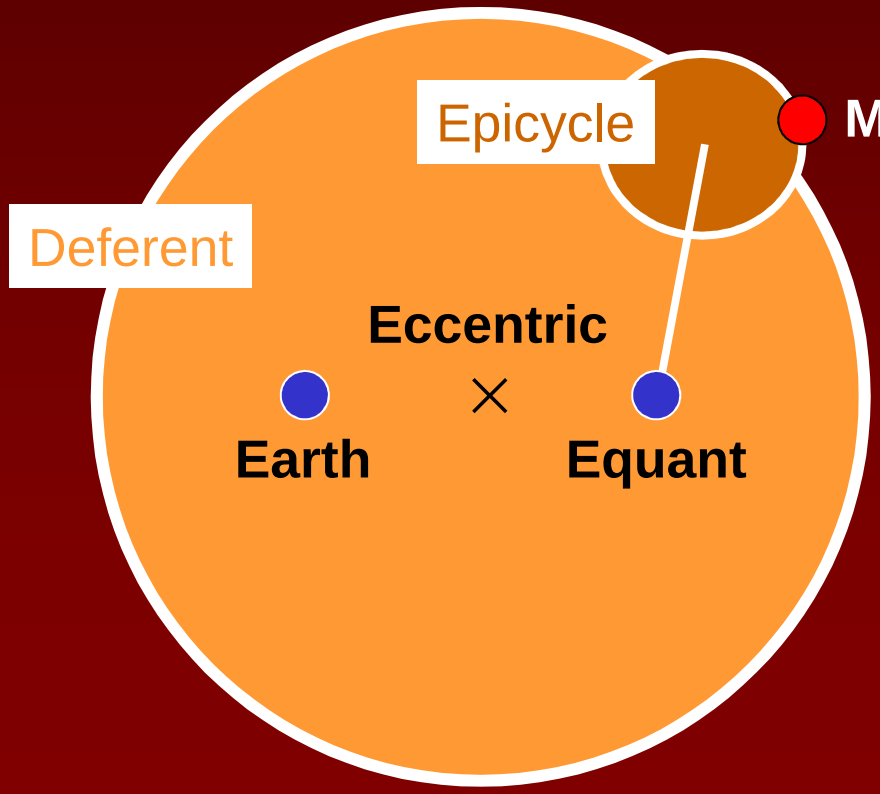
parameterize: $w(z) = w_0 + w_a \, z / (1+z)$

Cosmology is a search for two numbers (w_0 and w_a).

ΛCDM: *The Standard Model*

The construction of a model … consists of snatching from the enormous and complex mass of facts called reality a few simple, easily managed key points which, when put together in some cunning way, becomes for certain purposes a substitute for reality itself.

Evsey Domar
20th-century economist



This cosmological model agreed with observations for 1300 years!

The Cosmological Constant

10^{-30} g cm^{-3}

So small, and yet not zero!

The Unbearable Lightness of Nothing

The Cosmoillogical Constant

Dark (and Useless) Energy

1 MeV liter^{-1}

The Cosmoillogical Constant

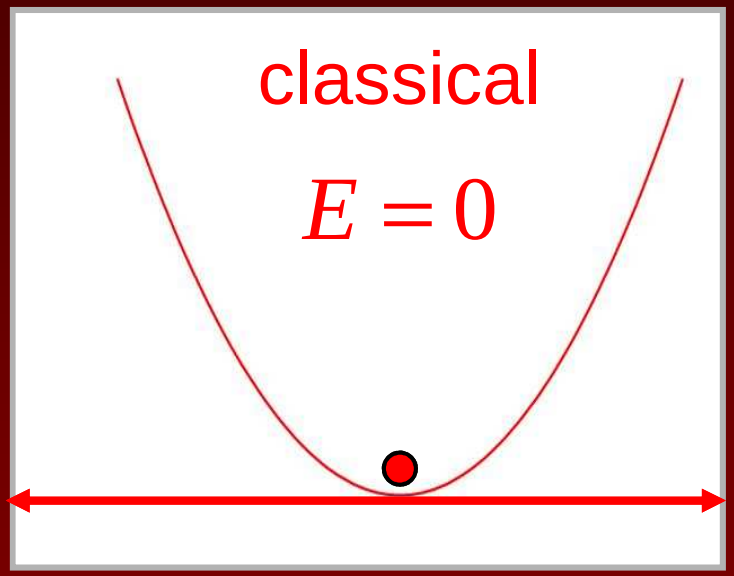
Illogical magnitude (what's it related to?):

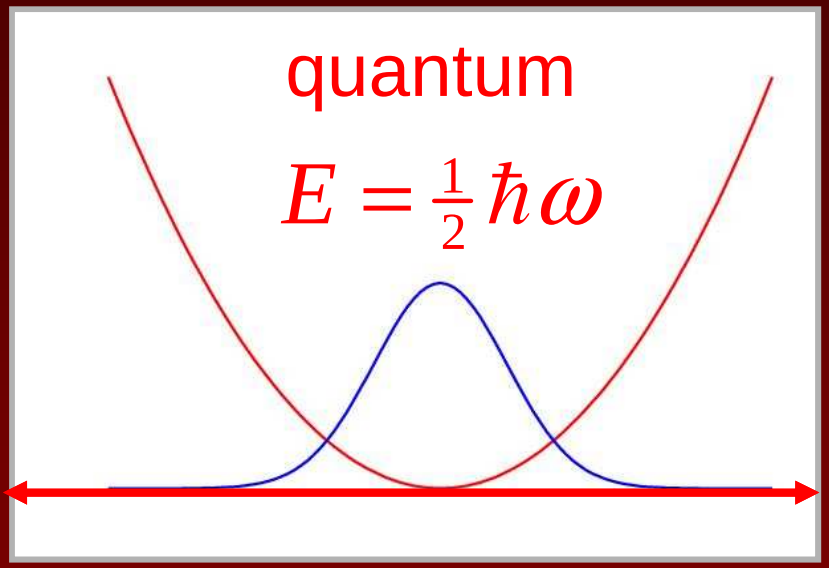
$$\rho_\Lambda \sim 10^{-30}\,\mathrm{g\ cm^{-3}} \sim \left(10^{-4}\ \mathrm{eV}\right)^4 \sim \left(10^{-3}\ \mathrm{cm}\right)^{-4}$$

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

The Cosmoillogical Constant

All fields: harmonic oscillators with zero-point energy

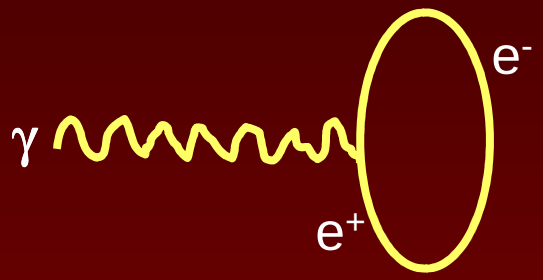




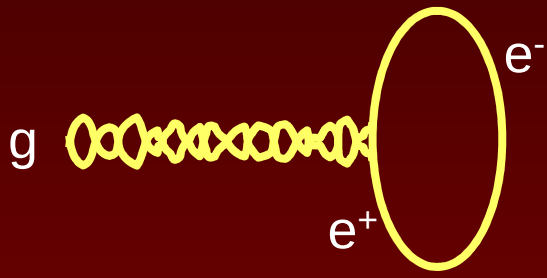
The Cosmoillogical Constant

All fields: harmonic oscillators with zero-point energy

Photons: Lamb shift



Gravitons: Vacuum energy



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

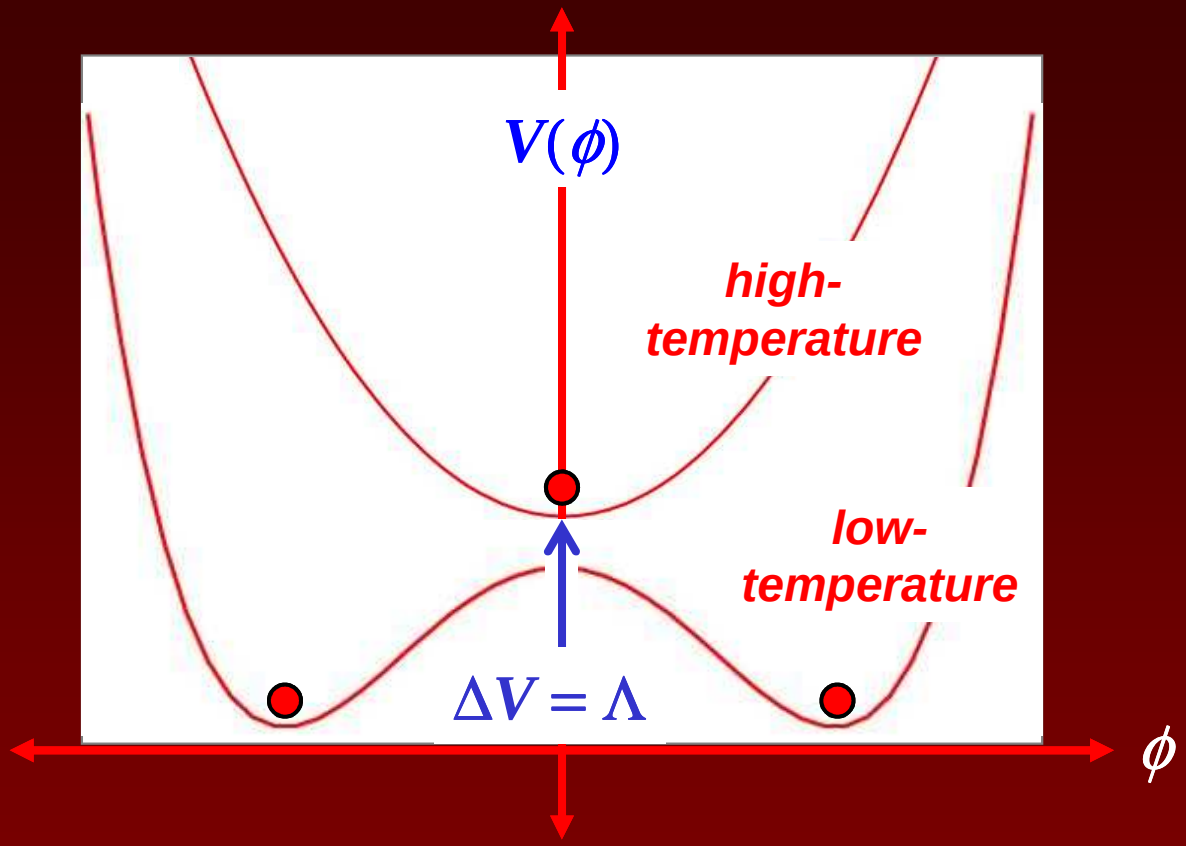
$$\Lambda_C = \infty: \quad \rho_\Lambda = \infty^4 \quad = \text{bad prediction}$$

$$\Lambda_C = M_{Pl}: \quad \rho_\Lambda = M_{Pl}^4 \quad = 10^{+90}\ \text{g cm}^{-3}$$

$$\Lambda_C = M_{SUSY}: \quad \rho_\Lambda = M_{SUSY}^4 \quad = 10^{+30}\ \text{g cm}^{-3}$$

$$\Lambda_C = 10^{-4}\ \text{eV}: \quad \rho_\Lambda = \text{Observed} \quad = 10^{-30}\ \text{g cm}^{-3}$$

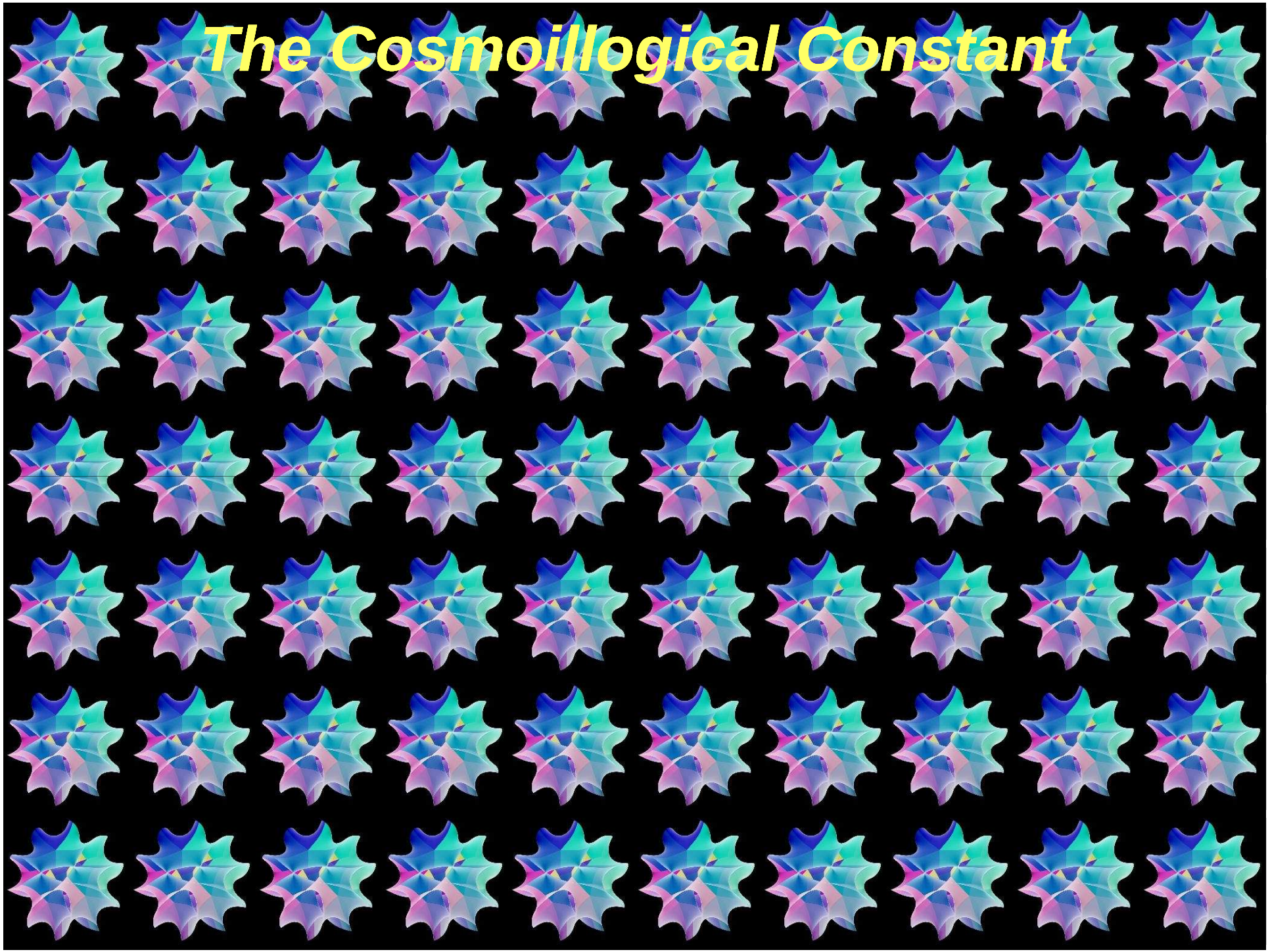
The Cosmoillogical Constant



GUT: 10^{74} g cm^{-3} **SUSY:** 10^{30} g cm^{-3}

EWK: 10^{24} g cm^{-3} **CHIRAL:** 10^{13} g cm^{-3}

OBSERVED: 10^{-30} g cm^{-3}


The Cosmoillogical Constant

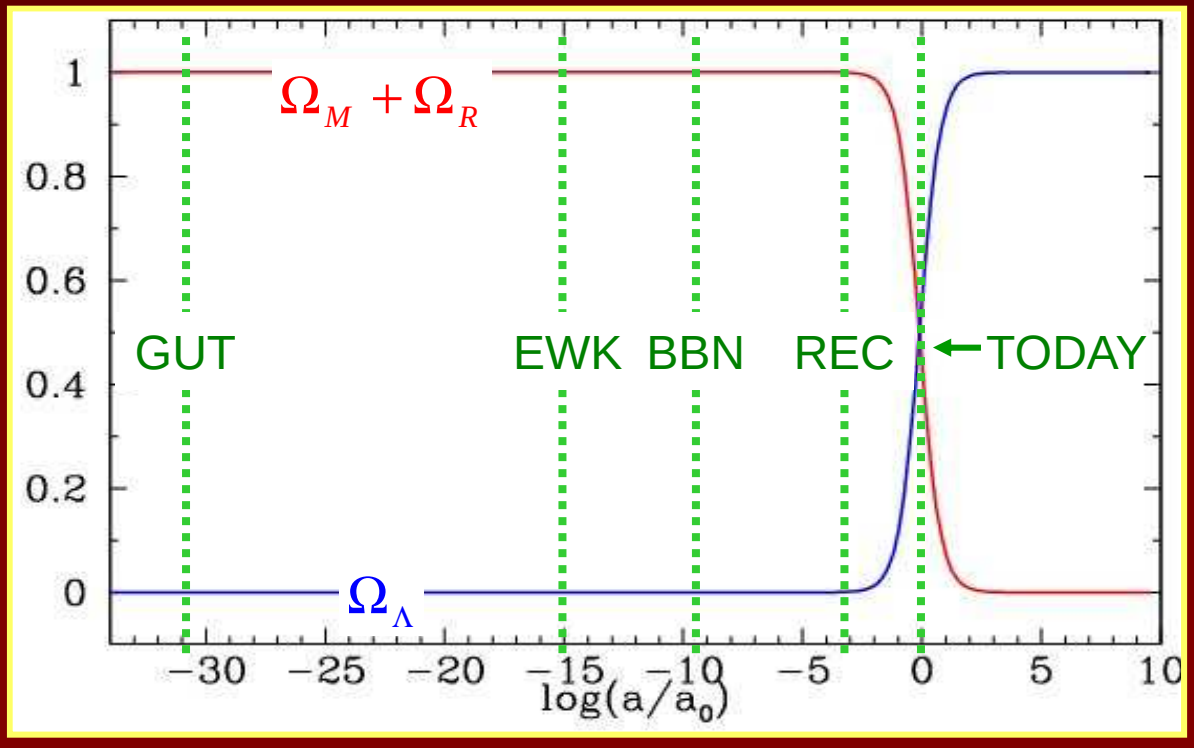
The Cosmoillogical Constant

Illogical magnitude (what's it related to?):

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

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

Illogical timing (cosmic coincidence?):



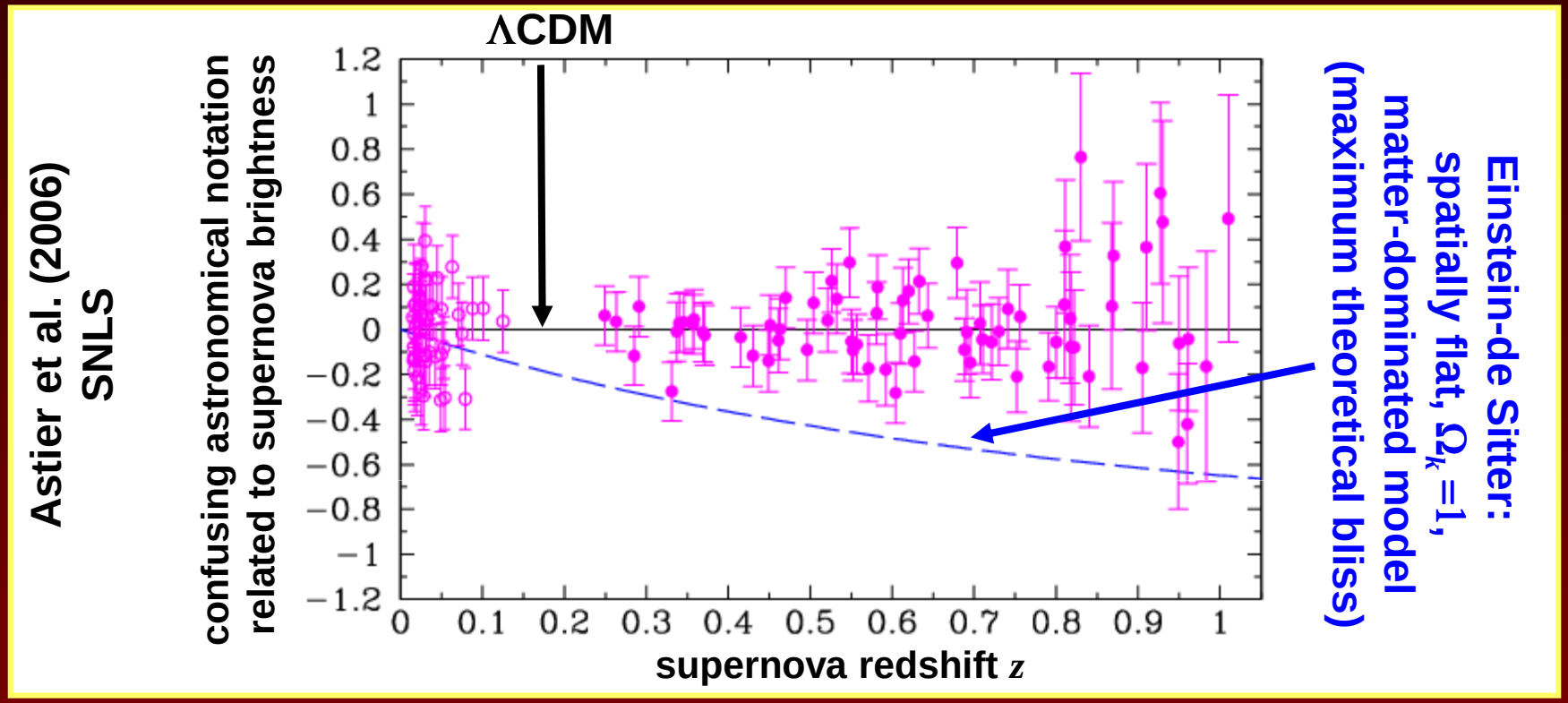
The Cosmoillogical Constant

Global warming, but universal cooling:

The Universe is cold and dark….and getting colder and darker!

(Dark Energy is now $700{,}000$ ppm and will only increase!)

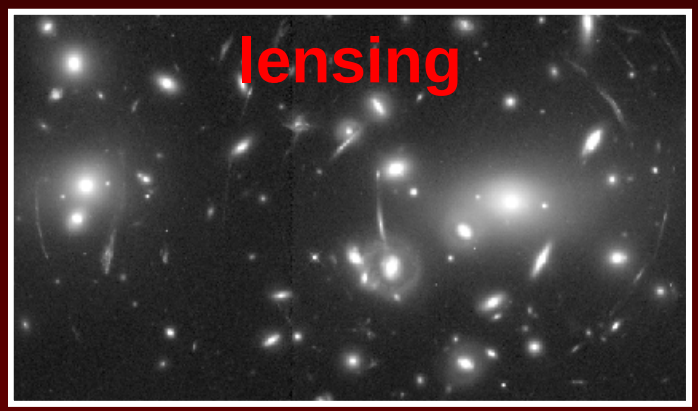
The Cosmoillogical Constant

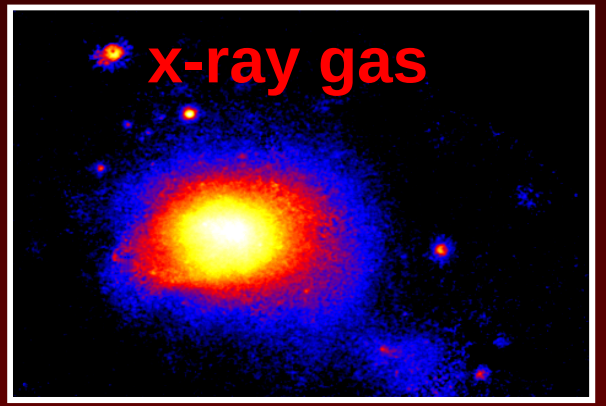


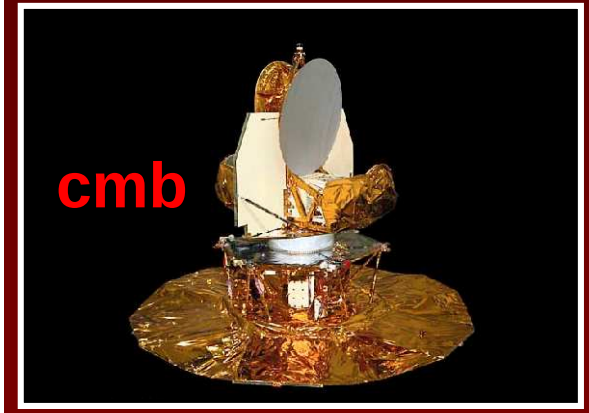
The case for Λ:

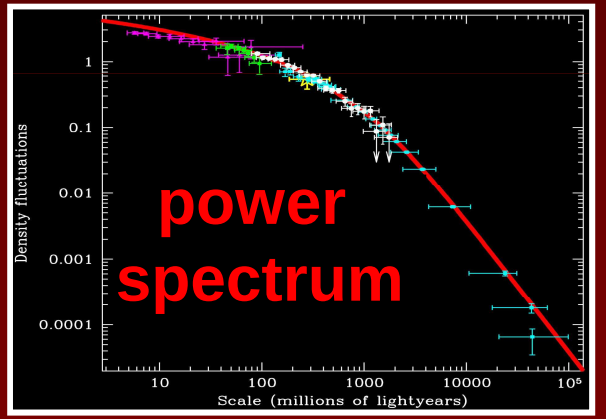
1) Hubble diagram (SNe)
2) Cosmic Subtraction
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

The Cosmoillogical Constant









$\Omega_{TOTAL} = 1$ $\Omega_M \sim 0.3$

CMB **many methods**

$$1.0 - 0.3 = 0.7 \neq 0$$

How We "Know" Dark Energy Exists

- Assume model cosmology:
  - Friedmann-Lemaître-Robertson-Walker (FLRW) model
    Friedmann equation: $H^2 = 8\pi G\rho / 3 - k/a^2$
  - Energy (and pressure) content: $\rho = \rho_M + \rho_R + \rho_\Lambda + \ldots$
  - Input or integrate over cosmological parameters: H_0, Ω_B, *etc*.

- Calculate observables $d_L(z)$, $d_A(z)$, $H(z)$, …

- Compare to observations

- Model cosmology fits with ρ_Λ, but not without ρ_Λ

- All evidence for dark energy is *indirect* : observed $H(z)$ is *not* described by $H(z)$ calculated from the Einstein-de Sitter model [spatially flat (from CMB) ; matter dominated ($\rho = \rho_M$)]

Taking Sides!

- Can't hide from the data – ΛCDM too good to ignore
  - SNe
  - Subtraction: $1.0 - 0.3 = 0.7$
  - Baryon acoustic oscillations
  - Galaxy clusters
  - Weak lensing
  - …

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

$G_{00}(\text{FLRW}) \neq 8\pi G T_{00}(\text{matter})$

- Modify <u>right-hand side</u> of Einstein equations (ΔT_{00})
  1. Constant ("just" a cosmoillogical constant)
  2. Not constant (dynamics described by a scalar field)
- Modify <u>left-hand side</u> of Einstein equations (ΔG_{00})
  3. Beyond Einstein (non-GR)
  4. (Just) Einstein (back reaction of inhomogeneities)

Tools to Modify the Right-Hand Side

1964 Austin-Healey Sprite

1974 Fiat 128

Tools to Modify the Right-Hand Side

scalar fields (quintessence)

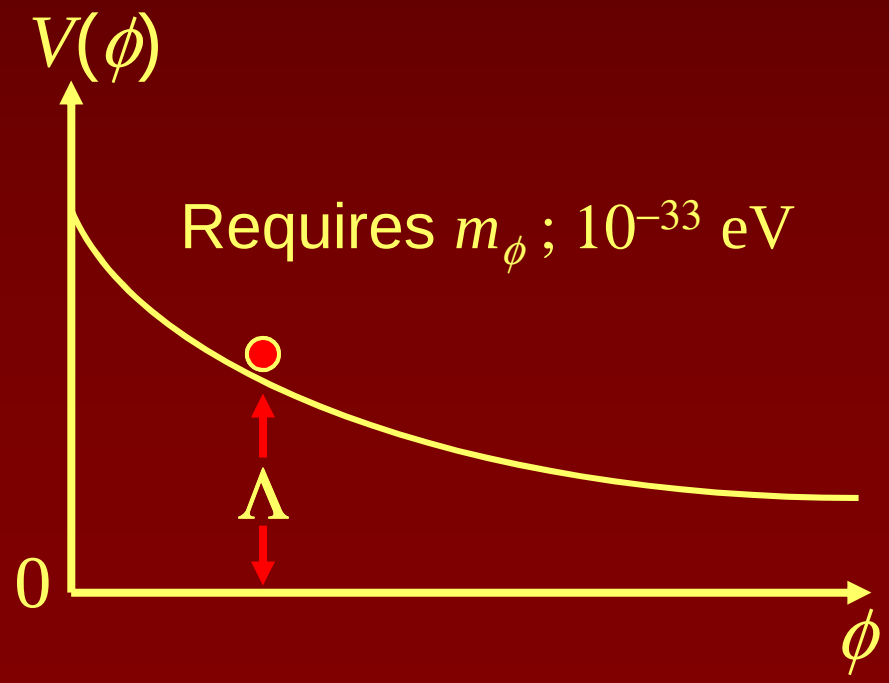
anthropic principle (the landscape)

Anthropic/Landscape/DUCTtape

- Many sources of vacuum energy
- String theory has many ($>10^{500}$?) vacua
- Some of them correspond to cancellations that yield a small Λ
- Although exponentially uncommon, they are preferred because …
- More common values of Λ results in an inhospitable universe

Quintessence/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!*



Tools to Modify the Left-Hand Side

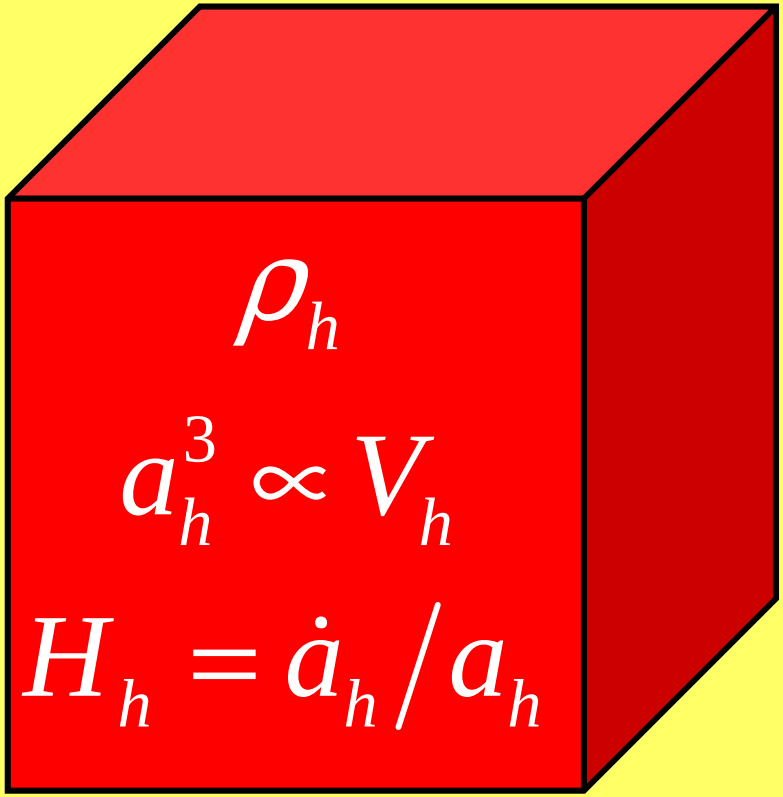
- Braneworld modifies Friedmann equation — Binetruy, Deffayet, Langlois
- Gravitational force law modified at large distance — Deffayet, Dvali & Gabadadze
  Five-dimensional at cosmic distances
- Tired gravitons — Gregory, Rubakov & Sibiryakov; Dvali, Gabadadze & Porrati
  Gravitons metastable - leak into bulk
- Gravity repulsive at distance $R \approx \mathrm{Gpc}$ — Csaki, Erlich, Hollowood & Terning
- $n = 1$ KK graviton mode very light, $m \approx (\mathrm{Gpc})^{-1}$ — Kogan, Mouslopoulos, Papazoglou, Ross & Santiago
- Einstein & Hilbert got it wrong $f(R)$ — Carroll, Duvvuri, Turner, Trodden

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

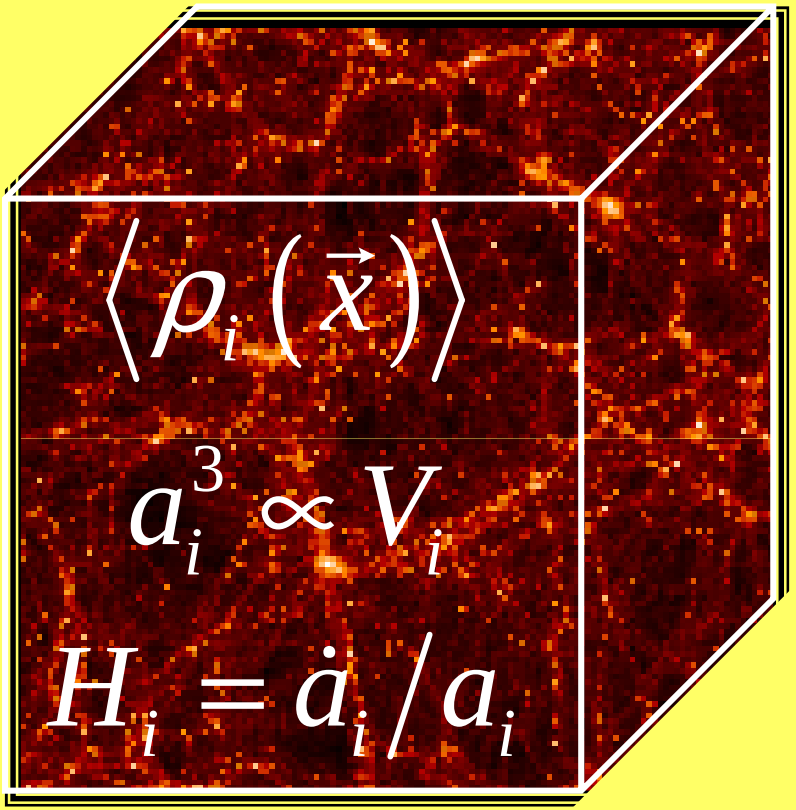
- "Backreaction" of inhomogeneities — Räsänen; Kolb, Matarrese, Notari & Riotto; Notari; Kolb, Matarrese & Riotto

Backreaction of Inhomogeneities

Homogeneous model



Inhomogeneous model



$$\rho_h = \langle \rho_i(\vec{x}) \rangle \Rightarrow H_h = H_i \ ?$$

We think not!

(Buchert & Ellis)

Backreaction of Inhomogeneities

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

  Ellis, Barausse, Buchert

- Difference is a new term that enters an effective Friedmann equation — the new term need not satisfy energy conditions!
- We deduce dark energy because we are comparing to the wrong model universe.

  Räsänen; Kolb, Matarrese, Notari & Riotto; Schwarz

Backreaction of Inhomogeneities

- Most conservative approach — nothing new
  - no new fields (like $10^{-33}\,\mathrm{eV}$ mass scalars)
  - no extra long-range forces
  - no modification of general relativity
  - no modification of gravity at large distances
  - no Lorentz violation
  - no extra dimensions, bulks, branes, *etc*.
  - no anthropic/landscape/faith-based reasoning
- Magnitude?: calculable from observables related to $\delta\rho/\rho$
- Why now?: acceleration triggered by era of non-linear structure
- Possible attractor for effective Ω_Λ

Backreaction of Inhomogeneities

ΛCDM is the correct phenomenological model, but …

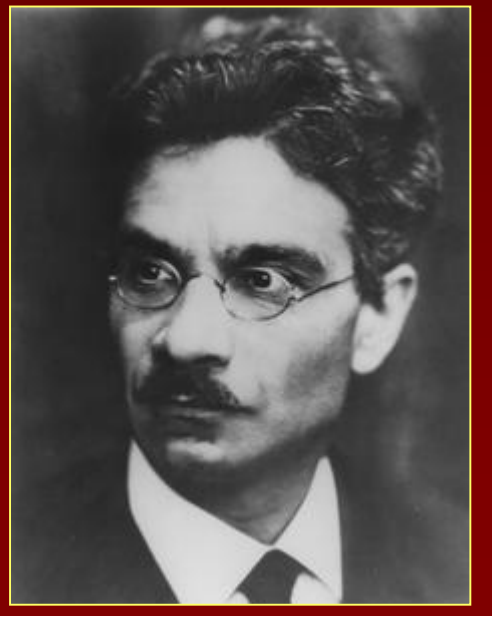
… there is no dark energy, gravity is not modified,
and the universe is not accelerating (in the usual sense).

Backreaction Causes Allergic Reaction

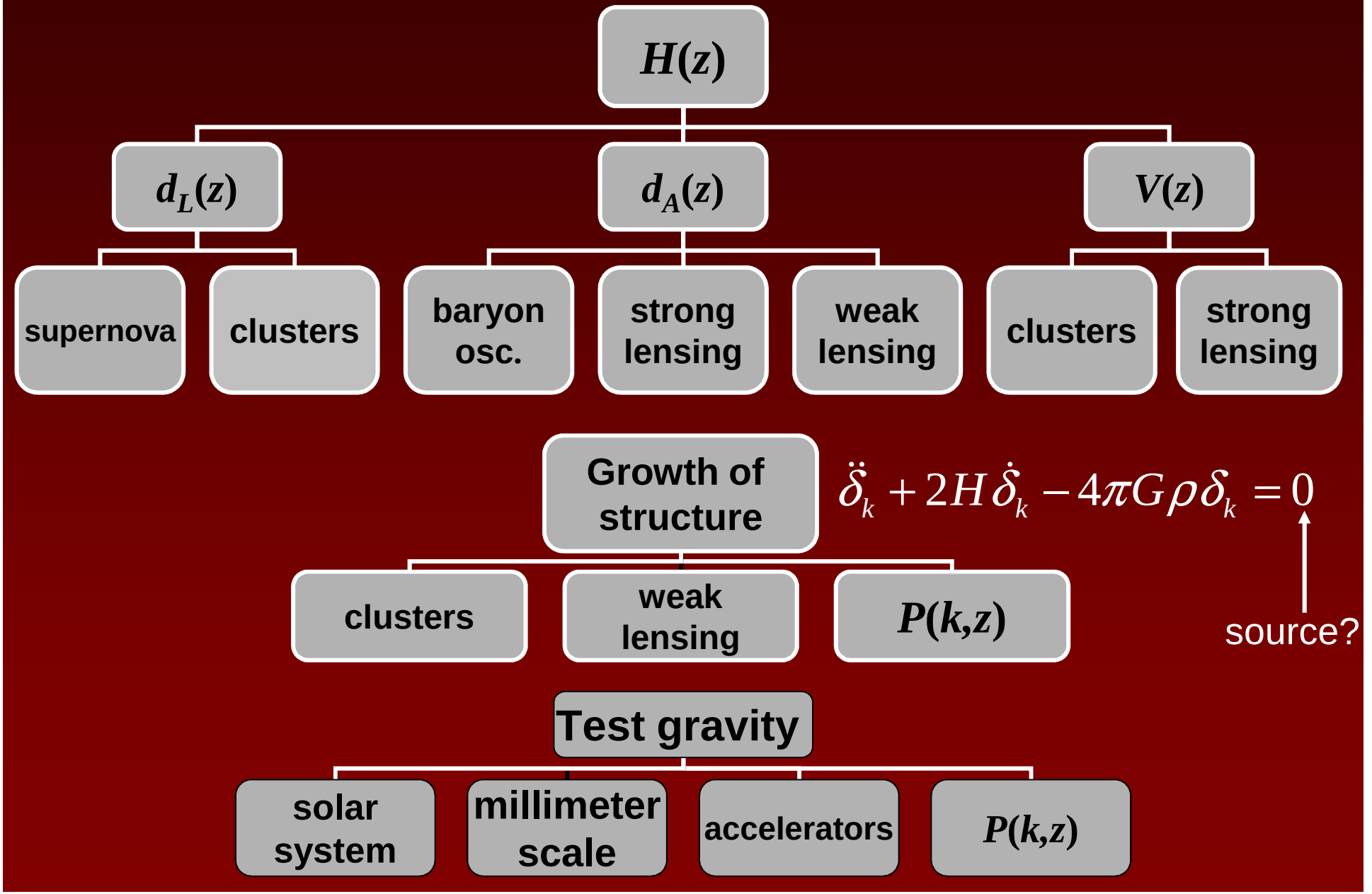
Dark Energy

"Nothing more can be done by the theorists. In this matter it is only you, the astronomers, who can perform a simply invaluable service to theoretical physics."

Einstein in August 1913 to Berlin astronomer Erwin Freundlich encouraging him to mount an expedition to measure the deflection of light by the sun.



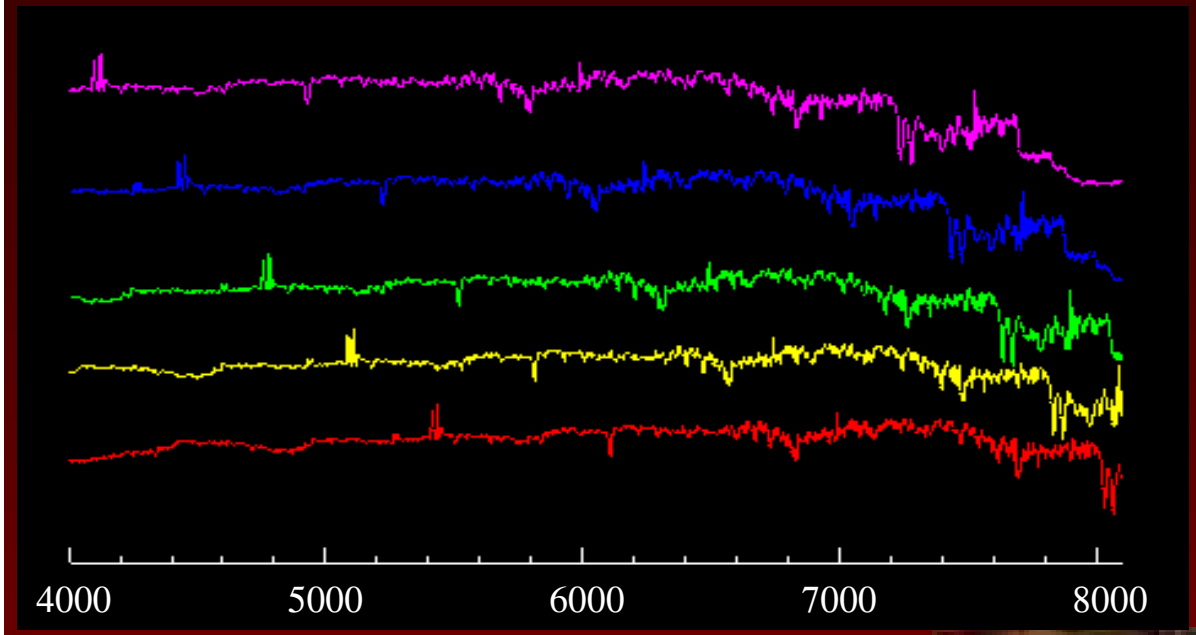
Observational Program



Supernova Type Ia

- Measure redshift and intensity as function of time (light curve)
- Systematics (dust, evolution, intrinsic luminosity dispersion, etc.)
- A lot of information per supernova
- Well developed and practiced
- Present procedure:
  - Discover SNe by wide-area survey (the “easy” part)
  - Follow up with spectroscopy (the “hard” part)
    (requires a lot of time on 8m-class telescopes)
  - Photometric redshifts?

Photometric Redshifts



Traditional redshift from spectroscopy

Photometric redshift from multicolor photometry

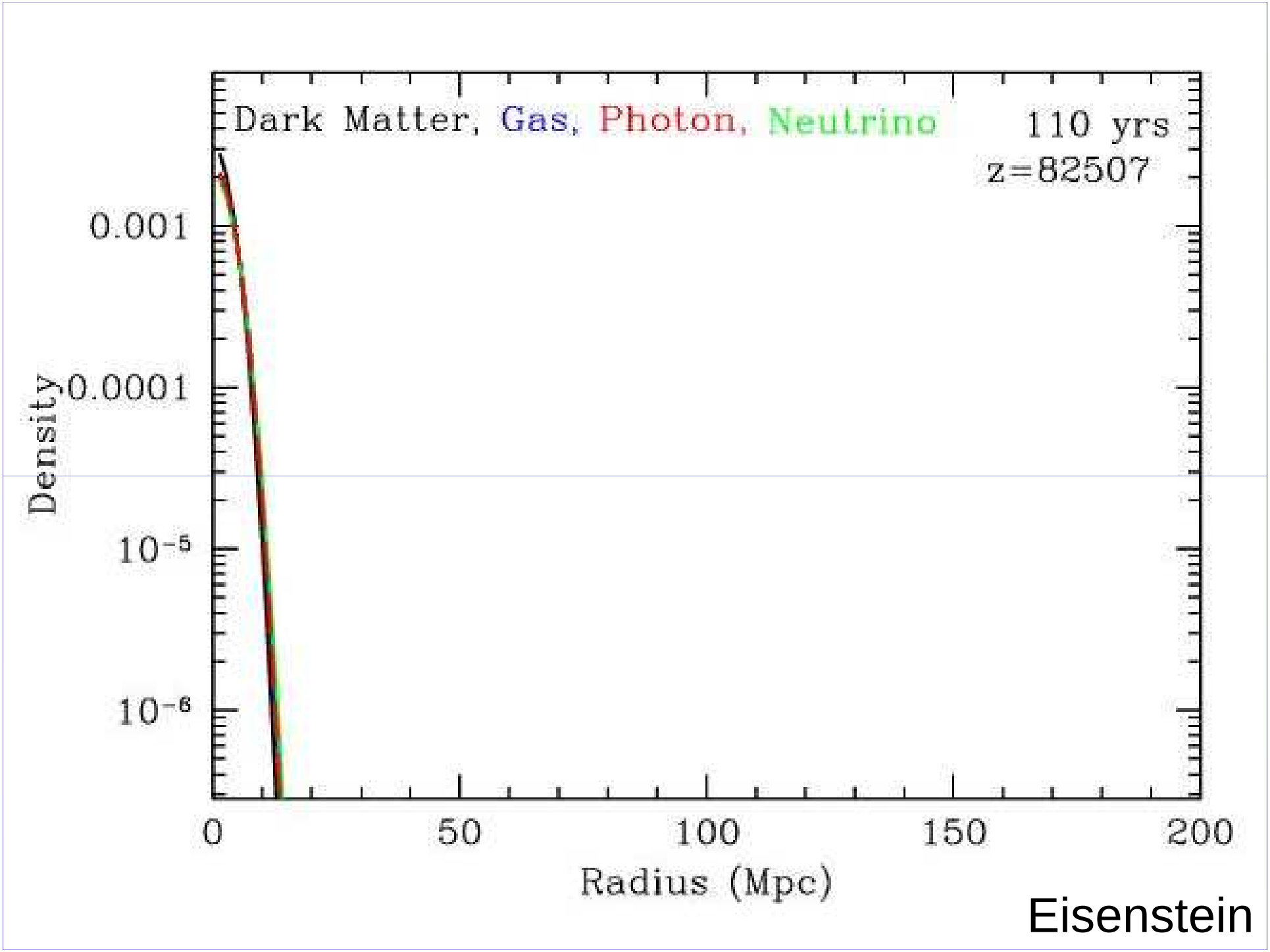
Baryon Acoustic Oscillations

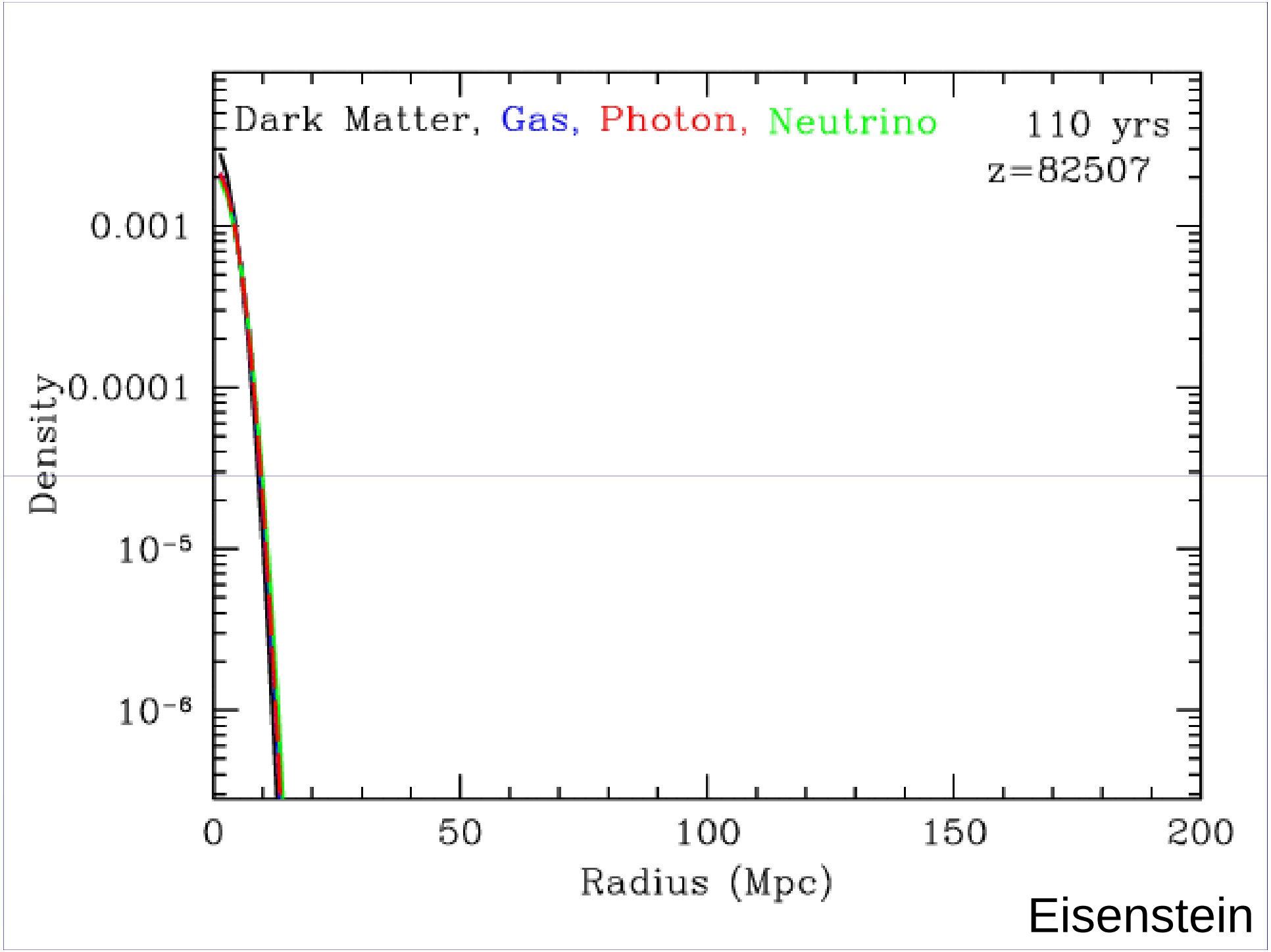
Pre-recombination

- universe ionized
- photons provide enormous pressure and restoring force
- perturbations oscillate (acoustic waves)

Post-recombination

- universe neutral
- photons travel freely (decoupled from baryons)
- perturbations grow (structure formation)


Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
0.001
0.0001
10^{-5}
10^{-6}
Density
0
50
100
150
200
Radius (Mpc)
Eisenstein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110 yrs
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0.001
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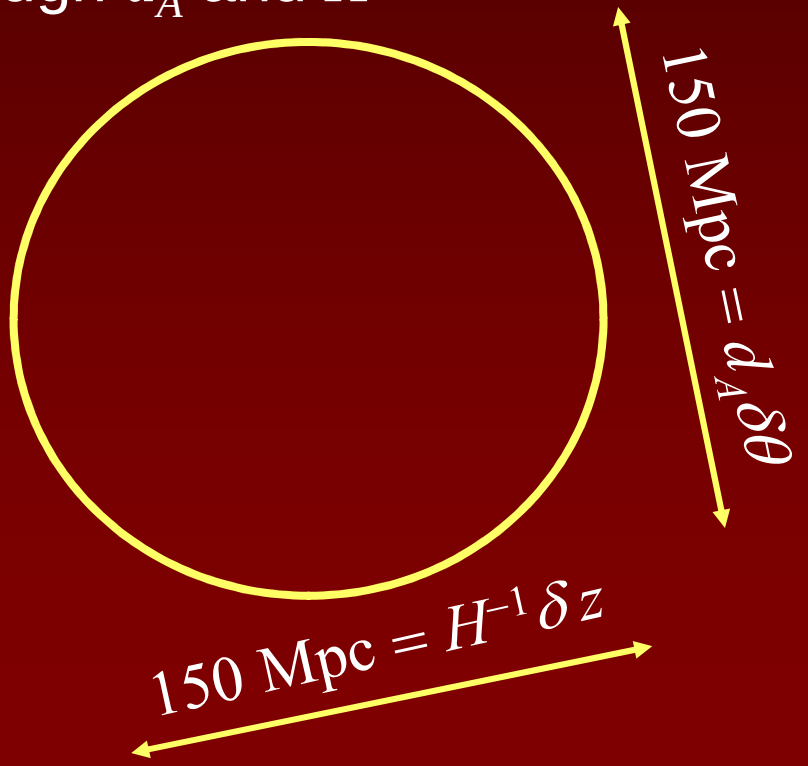
10^{-5}
10^{-6}
Density
0
50
100
150
200
Radius (Mpc)
Eisenstein

Baryon Acoustic Oscillations

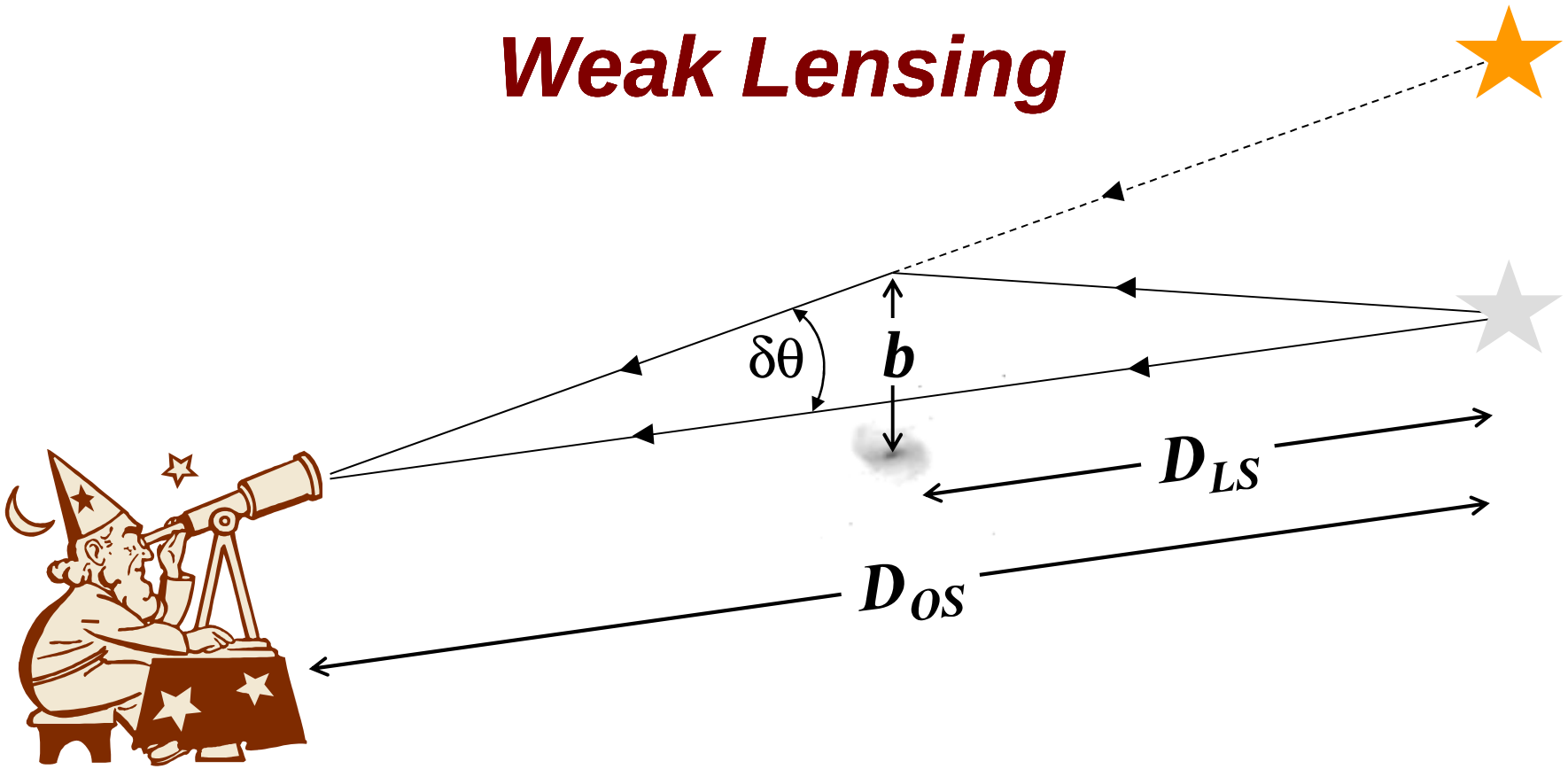
- Acoustic oscillation scale depends on $\Omega_M h^2$ and $\Omega_B h^2$ (set by CMB acoustic oscillations)
- It is a small effect ($\Omega_B h^2$ ¿ $\Omega_M h^2$)
- Dark energy enters through d_A and H



Baryon Acoustic Oscillations

- Virtues
  - Pure geometry.
  - Systematic effects should be small.
- Problems:
  - Amplitude small, require large scales, huge volumes
  - Photometric redshifts?
  - Nonlinear effects at small z, cleaner at large $z \sim 2$–3, but … dark energy is not expected to be important at large z

Weak Lensing



observe deflection angle

$$\delta\theta = \frac{4GM}{b}\frac{D_{LS}}{D_{OS}}$$

dark energy affects geometric distance factors

dark energy affects growth rate of M

Weak Lensing

The signal from any single galaxy is *very* small,
but there are a *lot* of galaxies! Require photo-z's?

Space vs. Ground:

- Space: no atmosphere PSF
- Space: Near IR for photo-z's
- Ground: larger aperture
- Ground: less expensive

- DES (2012)
  - 1000's of sq. degs. deep multicolor data
- LSST (2015)
  - full hemisphere, very deep 6 colors
- JDEM/Euclid (???)

Galaxy Clusters

Cluster redshift surveys measure

- cluster mass, redshift, and spatial clustering

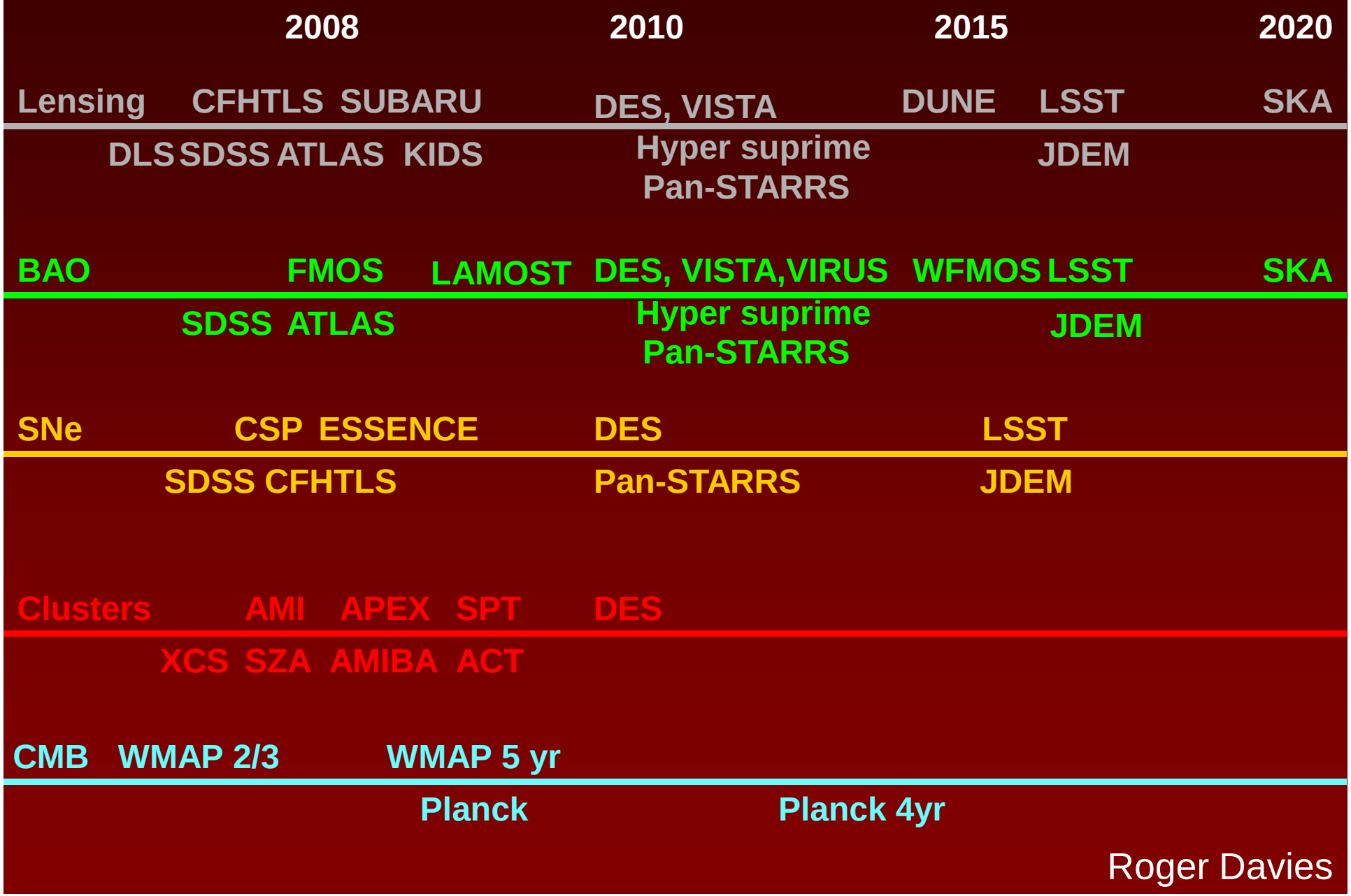
Sensitivity to dark energy

- volume-redshift relation
- angular-diameter distance–redshift relation
- growth rate of structure
- amplitude of clustering

Problems:

- cluster selection must be well understood
- proxy for mass?
- need photo-z's

What's Ahead



Roger Davies

Taking Sides

The expansion history of the universe is not described by the Einstein-de Sitter model:

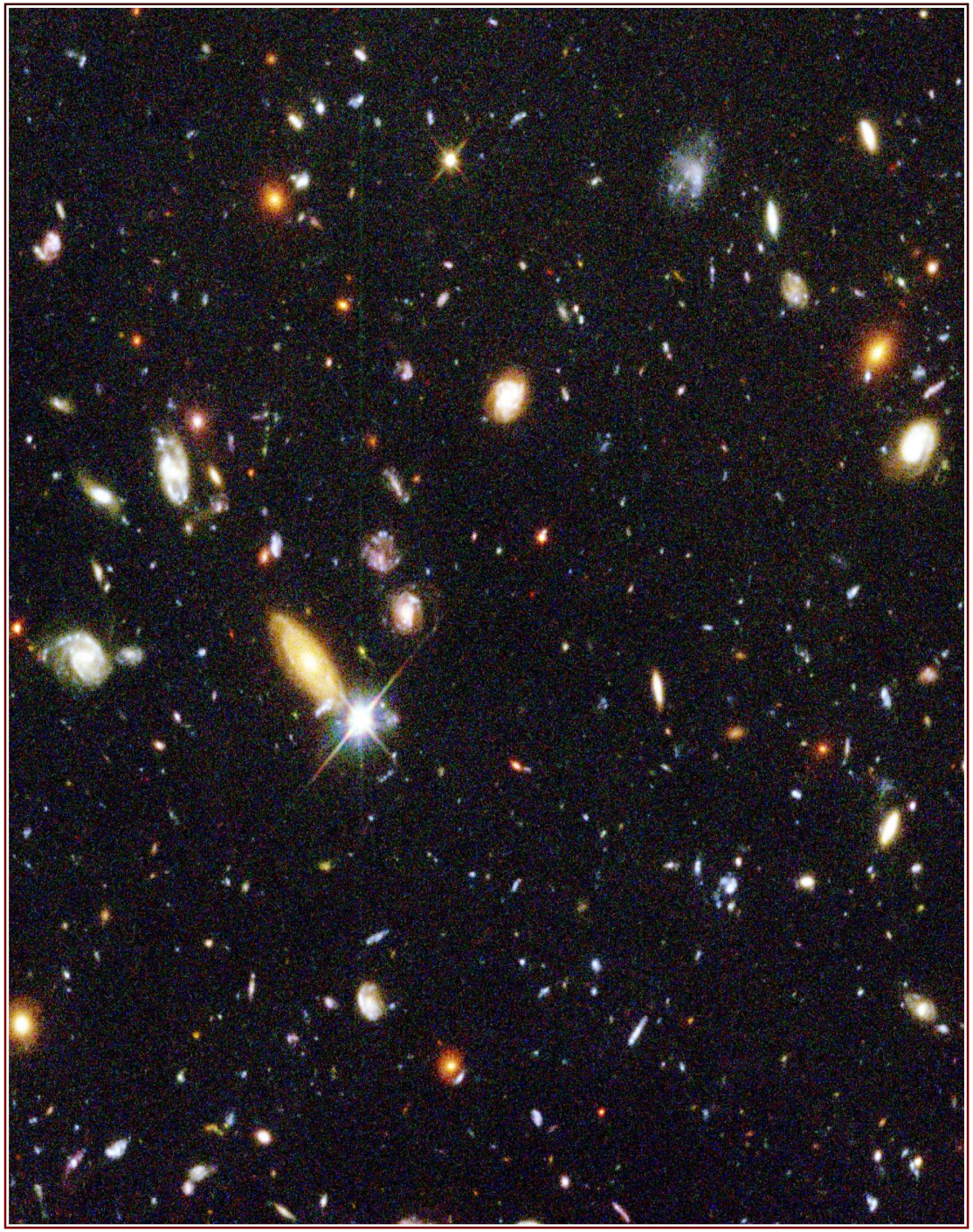
1. Well established: Supernova Ia
2. Circumstantial: subtraction, age, structure formation, …
3. Emergent techniques: baryon acoustic oscillations, clusters, weak lensing

Explanations:

1. Right-Hand Side: Dark energy
   - Constant vacuum energy, *i.e.,* a cosmoillogical constant
   - Time varying vacuum energy, *i.e.,* quintessence
2. Left-Hand Side
   - Modification of GR
   - Standard cosmological model (FLRW) not applicable

Phenomenology:

1. Measure evolution of expansion rate: is $w = -1$?
2. Order of magnitude improvement feasible

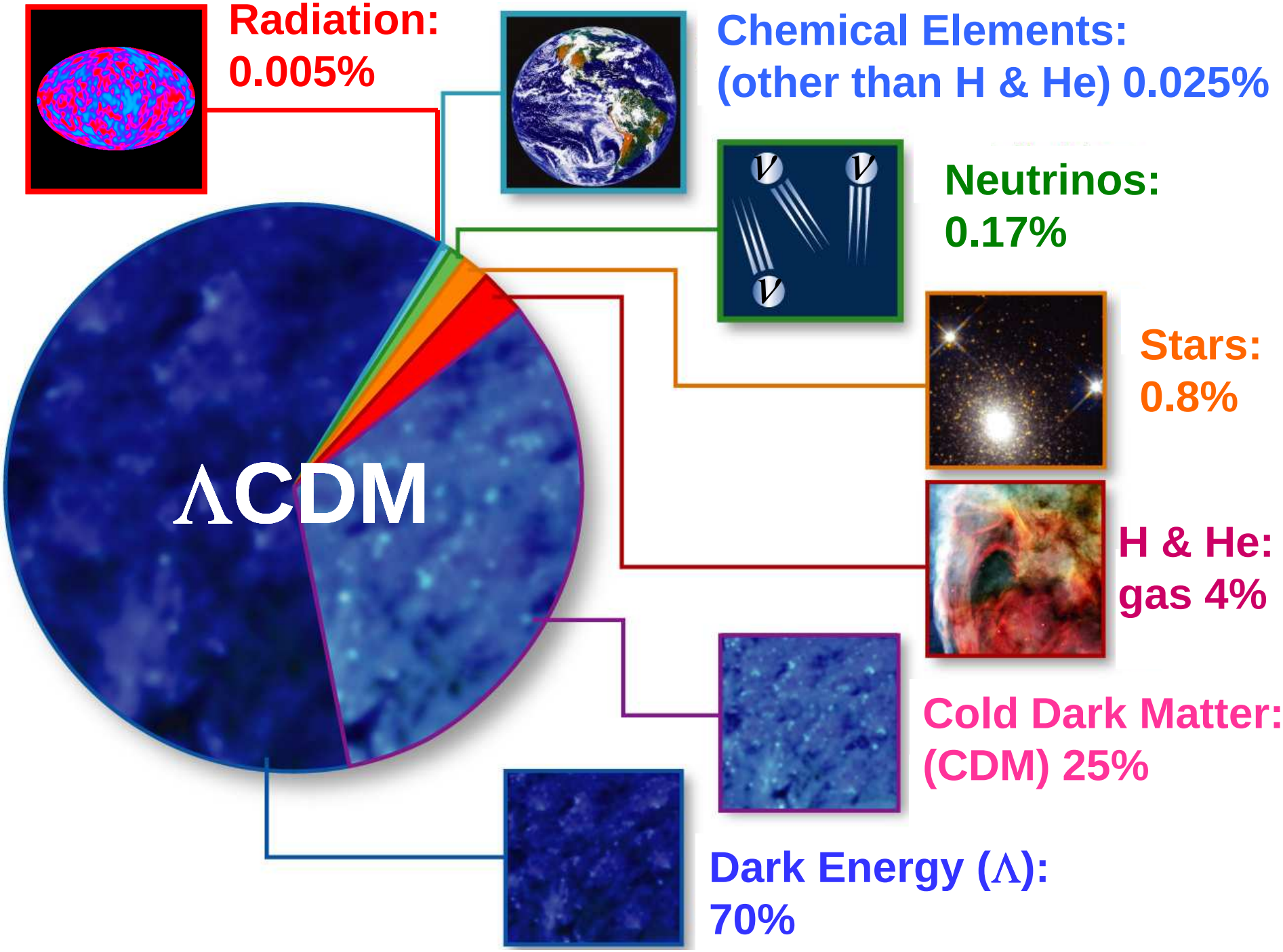


“To me every hour of the light and dark is a miracle. Every cubic inch of space is a miracle.”

– Walt Whitman

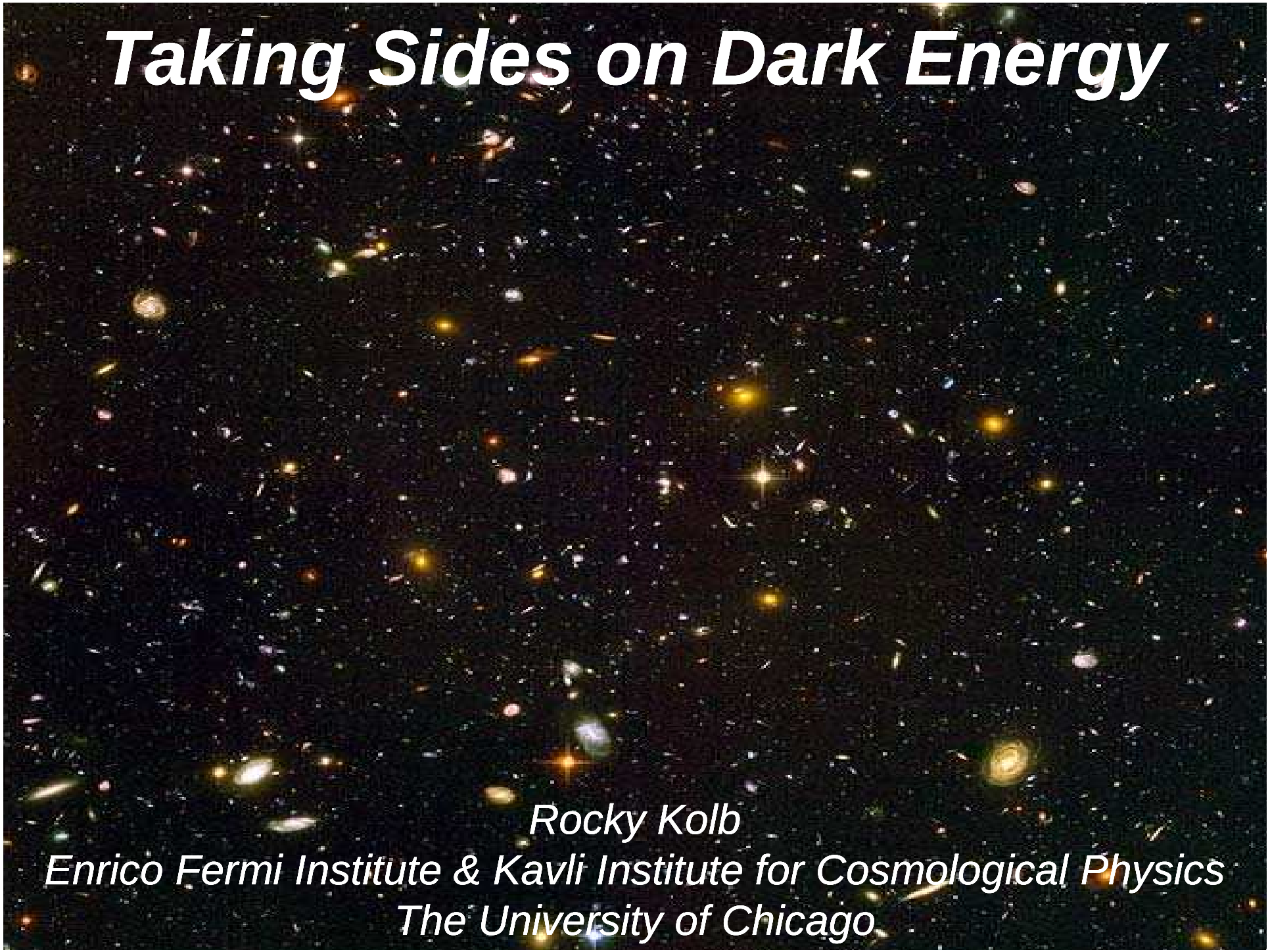
Every cubic inch of space is a miracle!

- **cosmic radiation**
- **virtual particles**
- **Higgs potential**
- **extra dimensions**
- **dark matter**
- **dark energy**


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM

I must reject fluids and ethers of all kinds, magnetical, electrical, and universal, to whatever quintessential thinness they may be treble-distilled and (as it were) super-substantiated.

Samuel Taylor Coleridge
Theory of Life (1816)

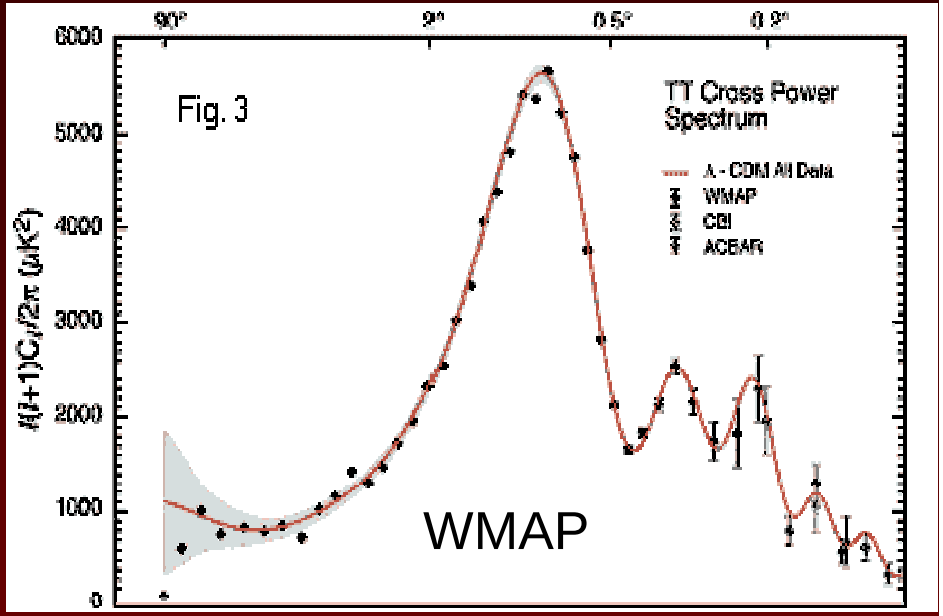


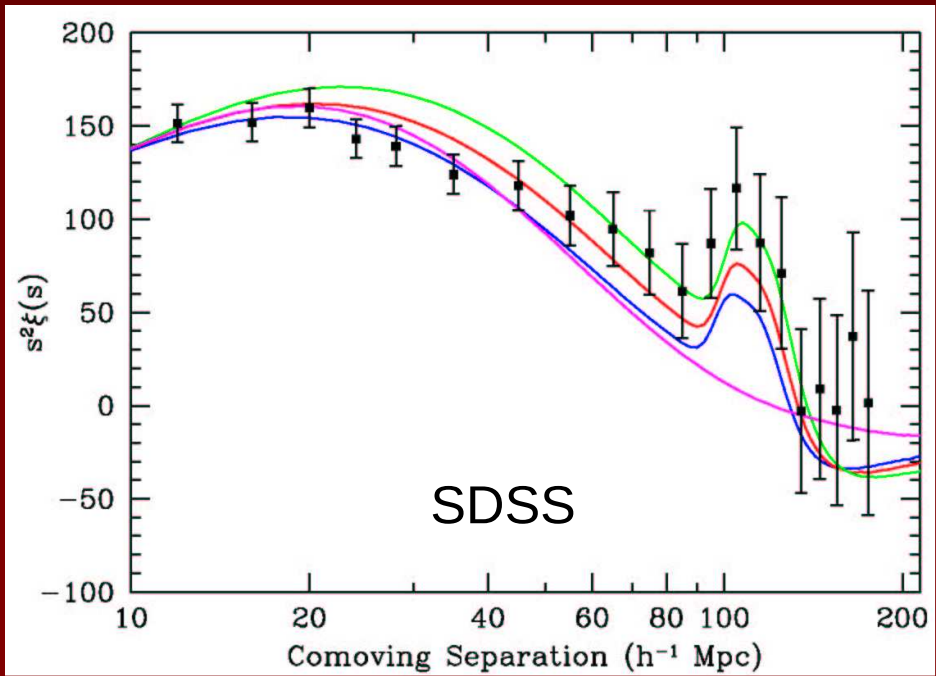
Taking Sides on Dark Energy

Rocky Kolb
Enrico Fermi Institute & Kavli Institute for Cosmological Physics
The University of Chicago

Baryon Acoustic Oscillations

- Each overdense region is an overpressure that launches a spherical sound wave
- Wave travels outward at $c/\sqrt{3}$
- Photons decouple, travel to us and observable as CMB acoustic peaks
- Sound speed plummets, wave stalls
- Total distance traveled 150 Mpc imprinted on power spectrum





DETF Experimental Strategy:*

- Determine as well as possible whether the accelerating expansion is consistent with being due to a cosmological constant. (Is $w = -1$?)
- If the acceleration is not due to a cosmological constant, probe the underlying dynamics by measuring as well as possible the time evolution of the dark energy. (Determine $w(z)$.)
- Search for a possible failure of general relativity through comparison of the effect of dark energy on cosmic expansion with the effect of dark energy on the growth of cosmological structures like galaxies or galaxy clusters. (Hard to quantify.)

* Dark Energy Task Force

DETF Cosmological Model

Parameterize dark-energy equation of state parameter w as:

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

- Today ($a = 1$) $w(1) = w_0$
- In the far past ($a \to 0$) $w(0) = w_0 + w_a$

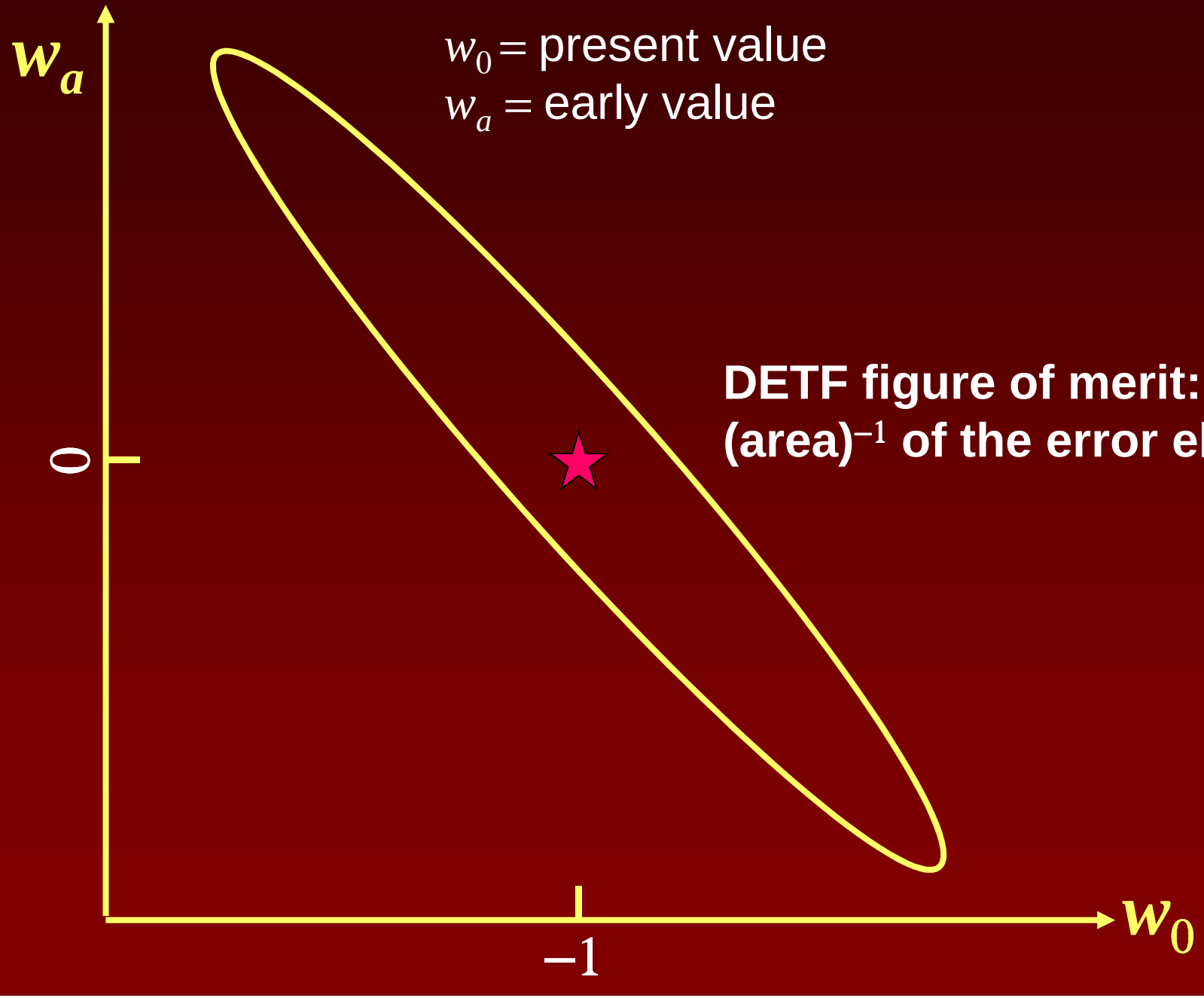
Standard eight-dimensional cosmological model:

w_0 : the present value of the dark-energy *eos* parameter
w_a : the rate of change of the dark-energy *eos* parameter
Ω_{DE} : the present dark-energy density
Ω_M : the present matter density
Ω_B : the present baryon density
H_0 : the Hubble constant
δ_ζ : amplitude of *rms* primordial curvature fluctuations
n_S : the spectral index of primordial perturbations.

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

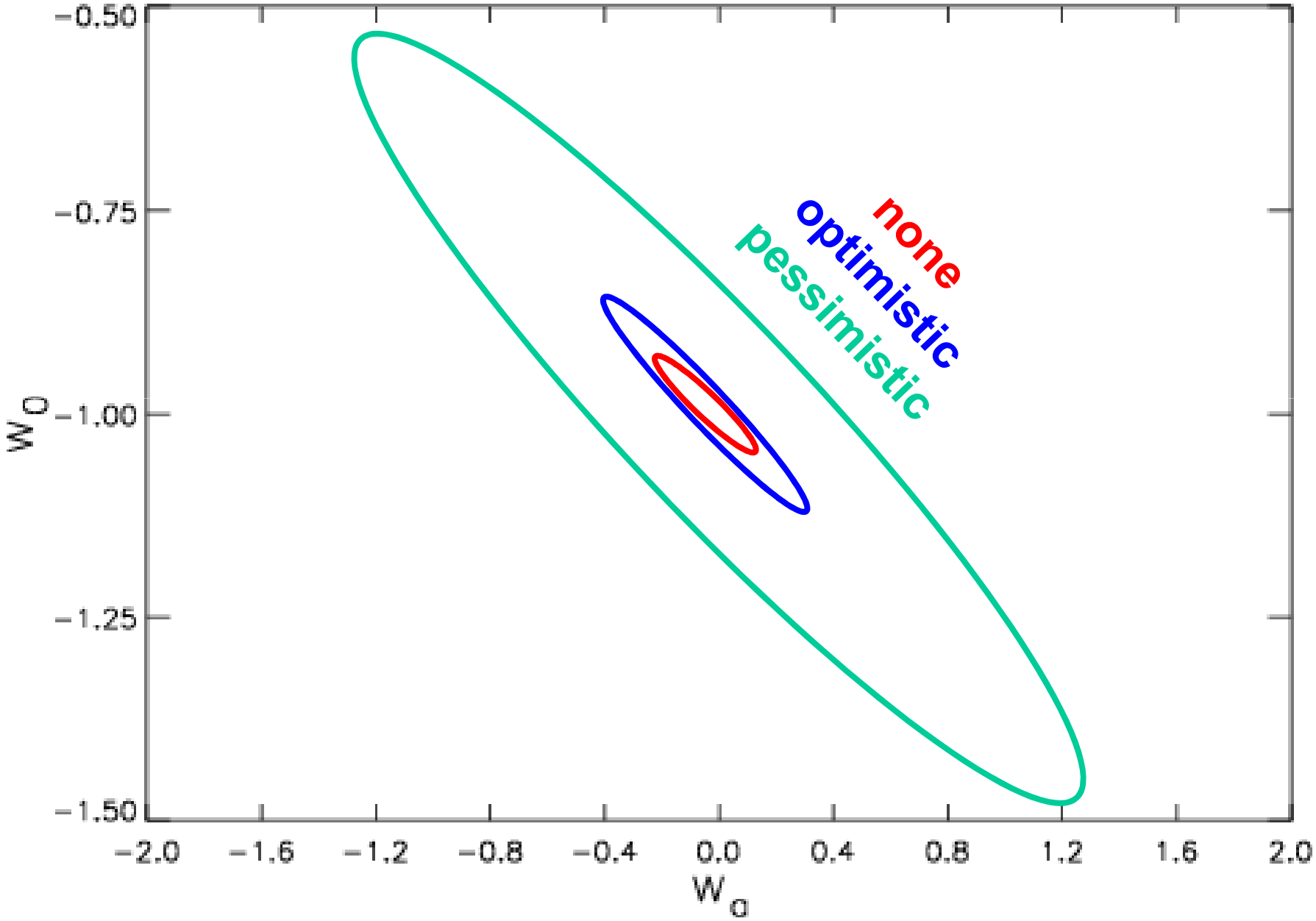
w_0 = present value

w_a = early value

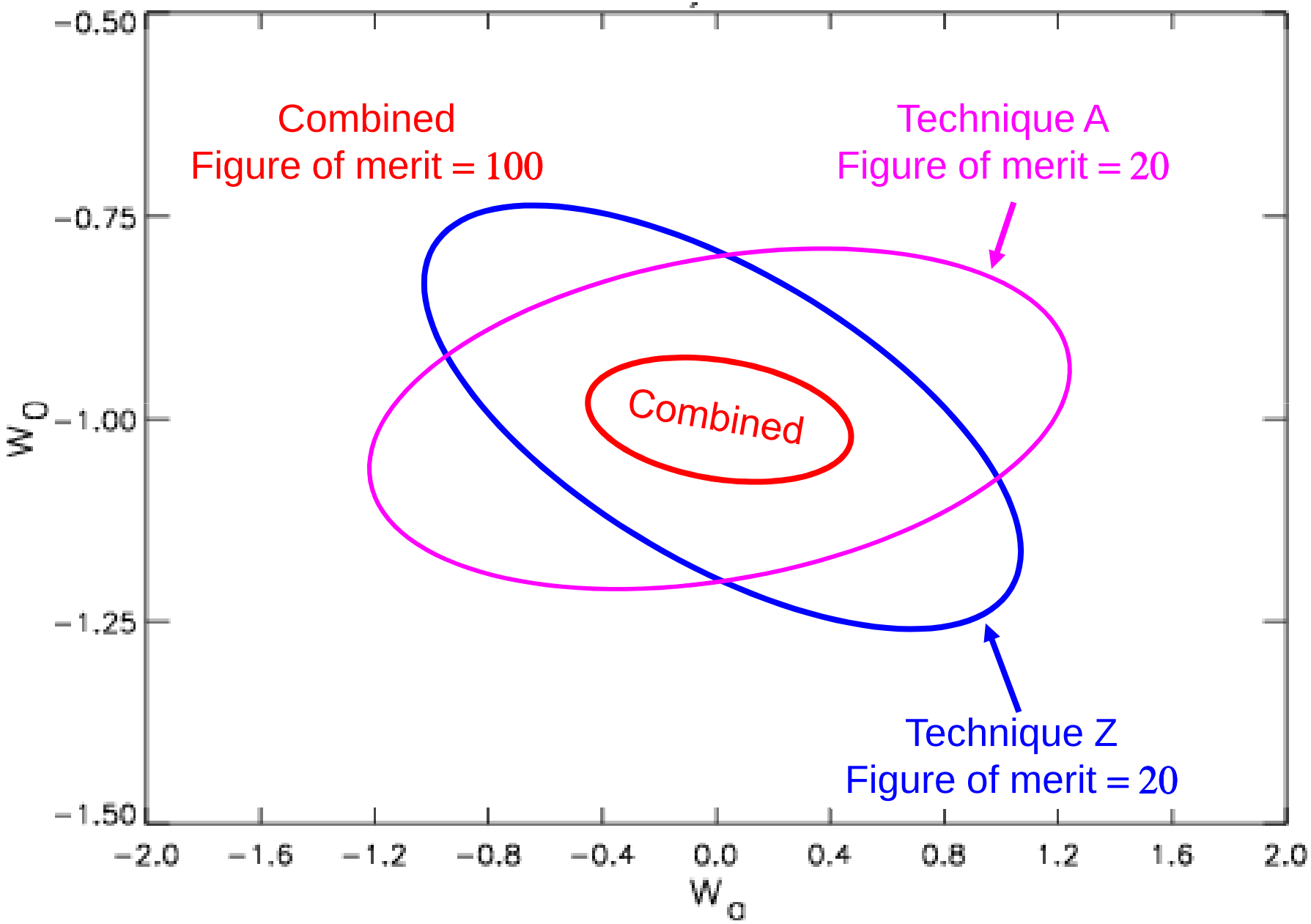


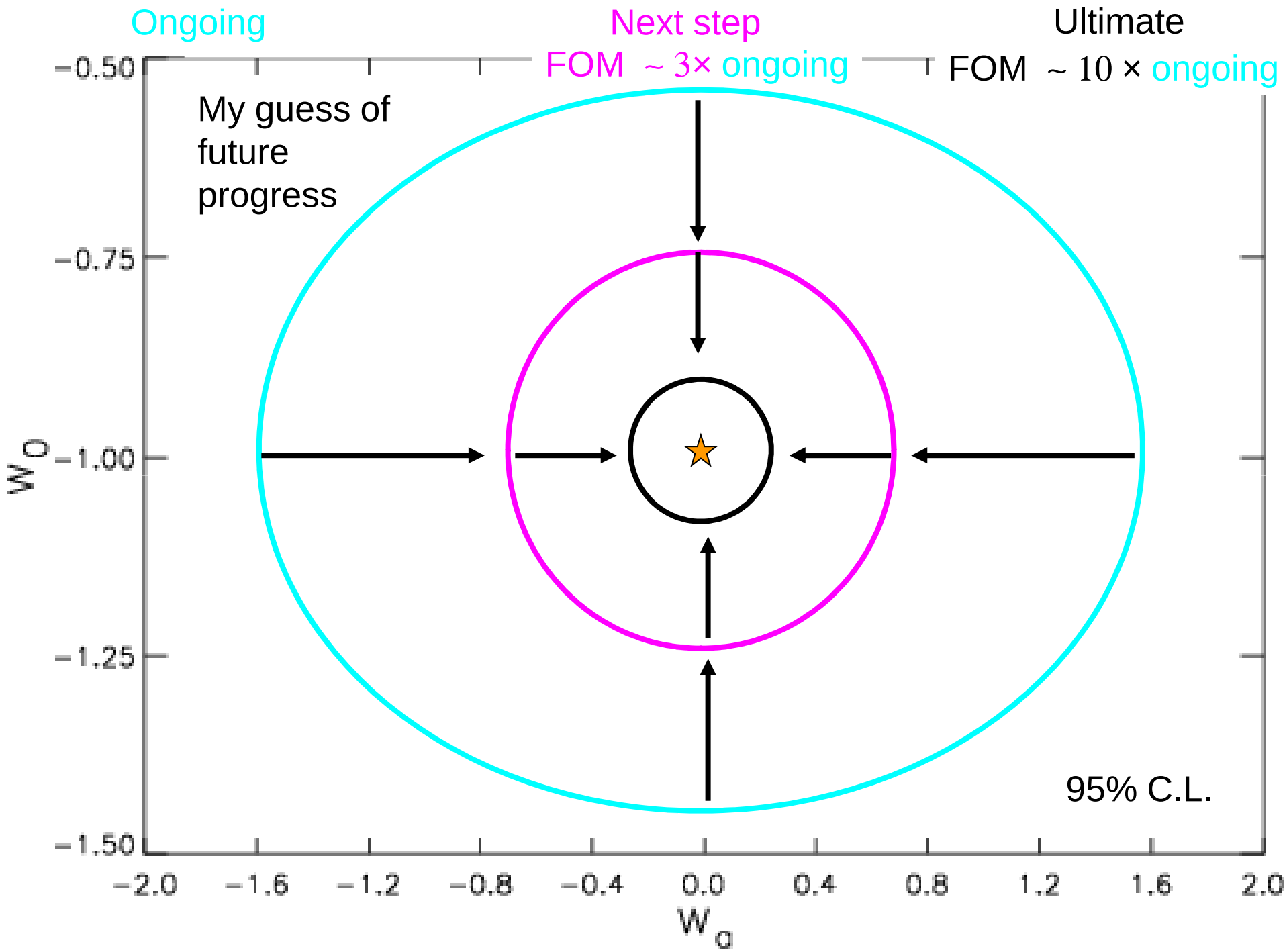
DETF figure of merit: (area)$^{-1}$ of the error ellipse

Systematics Are The Key



The Power of Two (or 3, or 4)




Ongoing
Next step
FOM ~ 3× ongoing
Ultimate
FOM ~ 10 × ongoing
My guess of future progress
95% C.L.
−0.50
−0.75
−1.00
−1.25
−1.50
w0
−2.0
−1.6
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
1.6
2.0
wa

Acceleration From Inhomogeneities

- Most conservative approach — nothing new
  - no new fields (like $10^{-33}\,\mathrm{eV}$ mass scalars)
  - no extra long-range forces
  - no modification of general relativity
  - no modification of gravity at large distances
  - no Lorentz violation
  - no extra dimensions, bulks, branes, etc.
  - no anthropic/landscape/faith-based reasoning
- Magnitude?: calculable from observables related to $\delta\rho/\rho$
- Why now?: acceleration triggered by era of non-linear structure

Acceleration From Inhomogeneities

- View scale factor as zero-momentum mode of gravitational field
- In homogeneous/isotropic model it is the only degree of freedom
- Inhomogeneities: non-zero modes of gravitational field
- Non-zero modes interact with and modify zero-momentum mode

Cosmology $\leftrightarrow$ scalar field theory analogue

	cosmology	scalar-field theory
zero-mode	a	hϕi (vev of a scalar field)
non-zero modes	inhomogeneities	thermal/finite-density bkgd.
physical effect	modify $a(t)$ *e.g.*, acceleration	modify h$\phi(t)$i *e.g.*, phase transitions

Acceleration From Inhomogeneities

Standard approach	Our approach
• Model an inhomogeneous Universe as a homogeneous Universe model with $\rho = \mathrm{h}\rho\mathrm{i}$	• Expansion rate of inhomogeneous Universe $\neq$ expansion rate of homogeneous Universe with $\rho = \mathrm{h}\rho\mathrm{i}$
• $a(t) \propto V^{1/3}$ is the zeromode of a homogeneous model with $\rho = \mathrm{h}\rho\mathrm{i}$	• Inhomogeneities modify zeromode [effective scale factor is $a_D \equiv V_D{}^{1/3}$]
• Inhomogeneities only have a local effect on observables	• Effective scale factor has a (global) effect on observables
• Cannot account for observed acceleration	• Potentially can account for acceleration without dark energy or modified GR