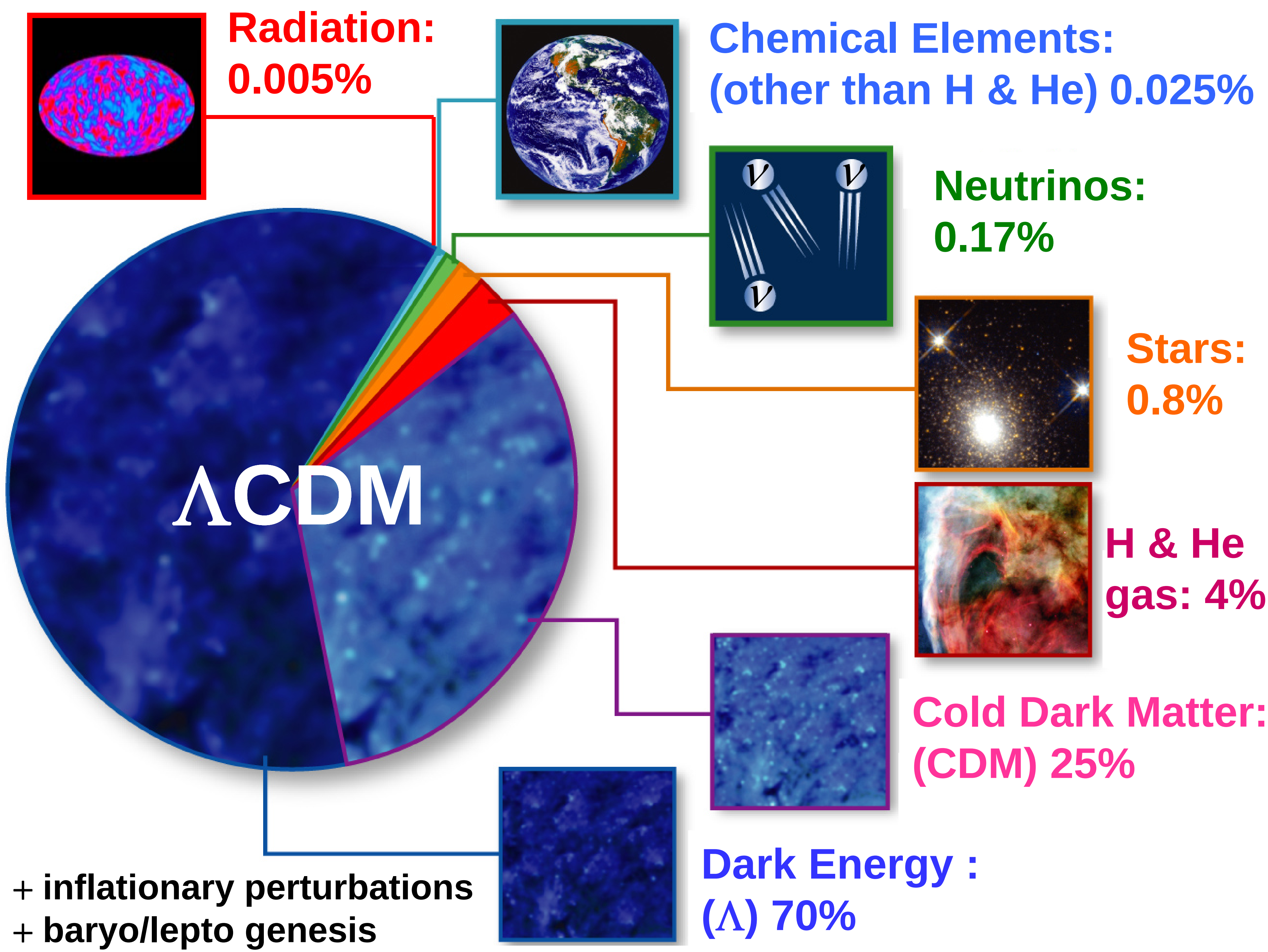
Particle Physics Foundations of Dark Matter, Dark Energy, and Inflation

Rocky I:	Dark Matter	(Wednesday, 11:00)
Rocky II:	Dark Matter II	(Thursday, 11:00)
Rocky III:	Energy	(Friday, 11:00)

Rocky Kolb

University of Chicago


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
+ inflationary perturbations
+ baryo/lepto genesis

Evolution of $H(z)$ Is a Key Quantity

- Robertson–Walker metric
  $k = +1\ (^3S);\ -1\ (^3H);\ 0\ (^3R)$

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

- Photons travel on geodesics:
  $ds^2 = 0$

$$\frac{dr}{\sqrt{1-kr^2}} = \frac{dt}{a(t)} = \frac{da}{\dot{a}(t)\,a(t)}$$

- Define expansion rate $H \equiv \dot{a}/a$
  and redshift $1+z \equiv a_0/a$

$$\int \frac{dr}{\sqrt{1-kr^2}} = \int \frac{da}{Ha^2} = \int \frac{dz}{H(z)}$$

- Photon emitted from $r(z)$ detected
  by observer today

$$r(z) = \begin{matrix}\sin \\ 1 \\ \sinh\end{matrix}\left\{\left(\int_0^z \frac{dz'}{H(z')}\right)\right.$$

Evolution of $H(z)$ Is a Key Quantity

Consider luminosity distance $d_L(z)$: Flux = (Luminosity / $4\pi\, d_L^{\,2}$)

Source at position $r(z)$ with luminosity $\mathcal{L}$. Flux detected is

$$\text{Flux} = \frac{\text{energy}}{\text{area} \times \text{time}} = \frac{\mathcal{L}}{\underbrace{(1+z)^2}\ \underbrace{4\pi\, a_0^{\,2}\, r^2}} = \frac{\mathcal{L}}{4\pi\, d_L^{\,2}}$$

Redshift of energy of photons $1+z$

Stretch of time: $1+z$

area of a two-sphere

observer at center, source at r

$$d_L(z) \propto (1+z)\; r(z)$$

Evolution of $H(z)$ Is a Key Quantity

Robertson–Walker metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Many observables based on $H(z)$ through coordinate distance $r(z)$

$$r(z) = \left.\begin{matrix}\sin\\ 1\\ \sinh\end{matrix}\right\}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

- Luminosity distance

  Flux = (Luminosity / $4\pi d_L^2$)

$$d_L(z) \propto r(z)(1+z)$$

- Angular diameter distance

  $\alpha =$ Physical size / d_A

$$d_A(z) \propto \frac{r(z)}{(1+z)}$$

- Volume (number counts)

  $N / V^{-1}(z)$

$$dV = \frac{r^2(z)}{\sqrt{1-kr^2(z)}}\, dr\, d\Omega$$

- Age of the universe

$$t(z) \propto \int_z^\infty \frac{dz'}{(1+z')H(z')}$$

Expansion History of the Universe $H(z)$

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

$$\left[\text{expansion rate } (z)\right]^2 = \left[\text{Hubble const.}\right]^2 \times \left[\text{curvature } (z) + \text{matter } (z) + \text{radiation } (z)\right]$$

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

$$\Omega_M = \frac{\rho_M}{3H_0^2/8\pi G} \qquad \Omega_R = \frac{\rho_R}{3H_0^2/8\pi G} \qquad \Omega_k = \frac{-3k/8\pi G a_0^2}{3H_0^2/8\pi G}$$

- At $z = 0$, $H = H_0 \;\longrightarrow\; \Omega_k + \Omega_M + \Omega_R = 1$

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

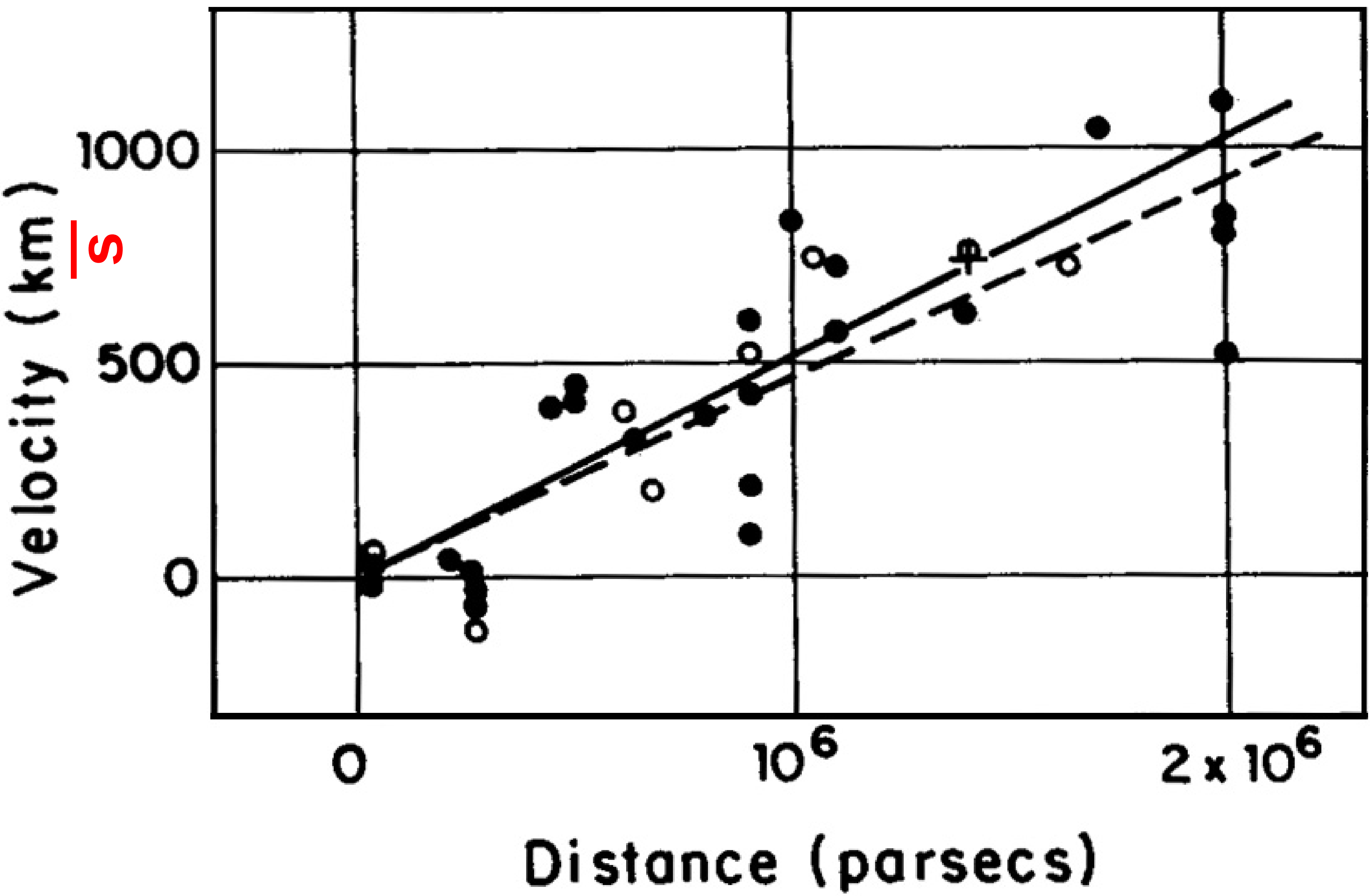
- radiation contribution (Ω_R) small for $z \lesssim 10^3$

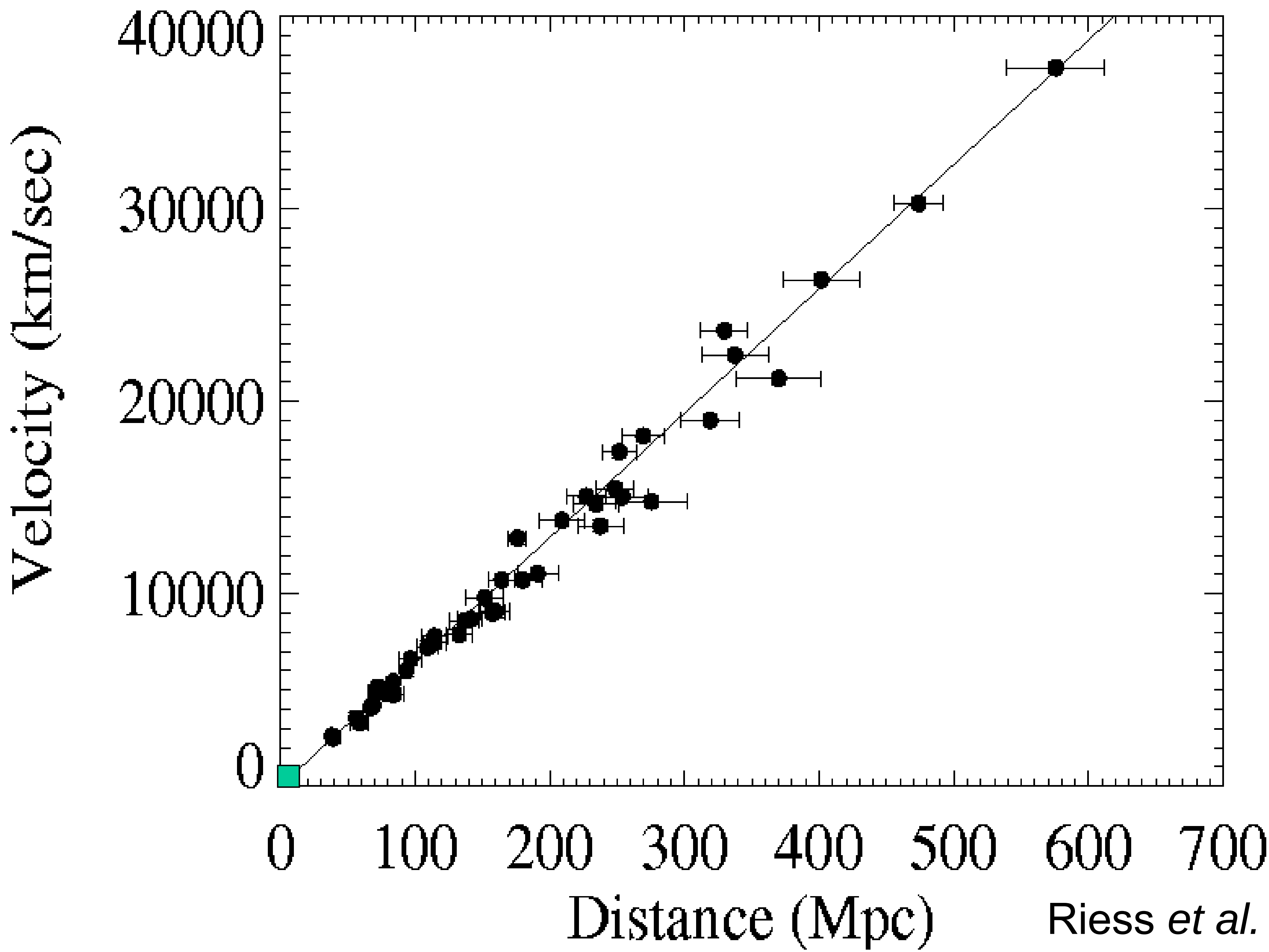
$$H^2(z) = H_0^2 \times \left[(1-\Omega_M)(1+z)^2 + \Omega_M (1+z)^3\right]$$

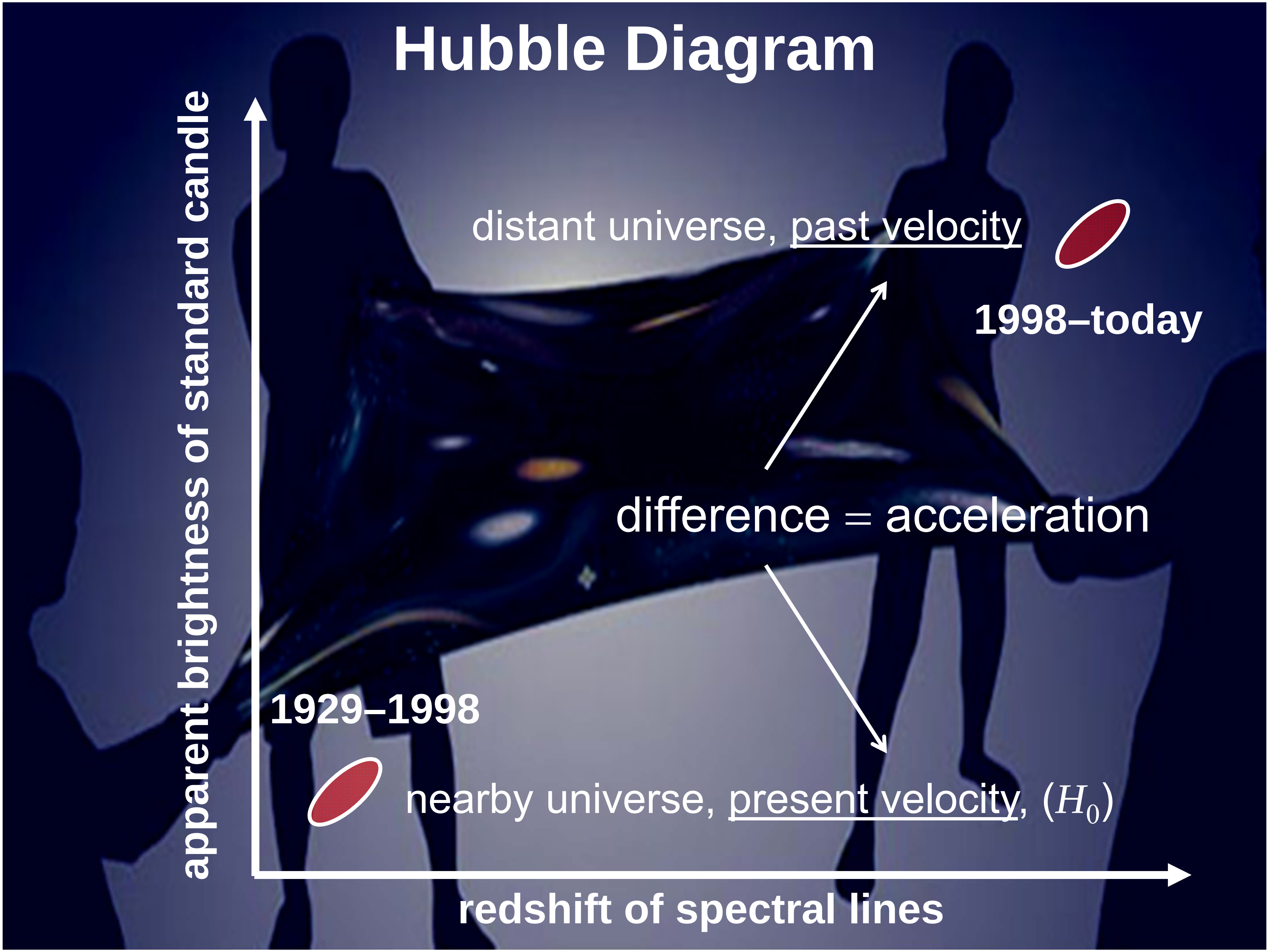
- "All of observational cosmology is a search for two numbers." (H_0 and $q_0 = \Omega_M/2$) — Sandage, *Physics Today,* 1970

University of Chicago 1909 National Champions

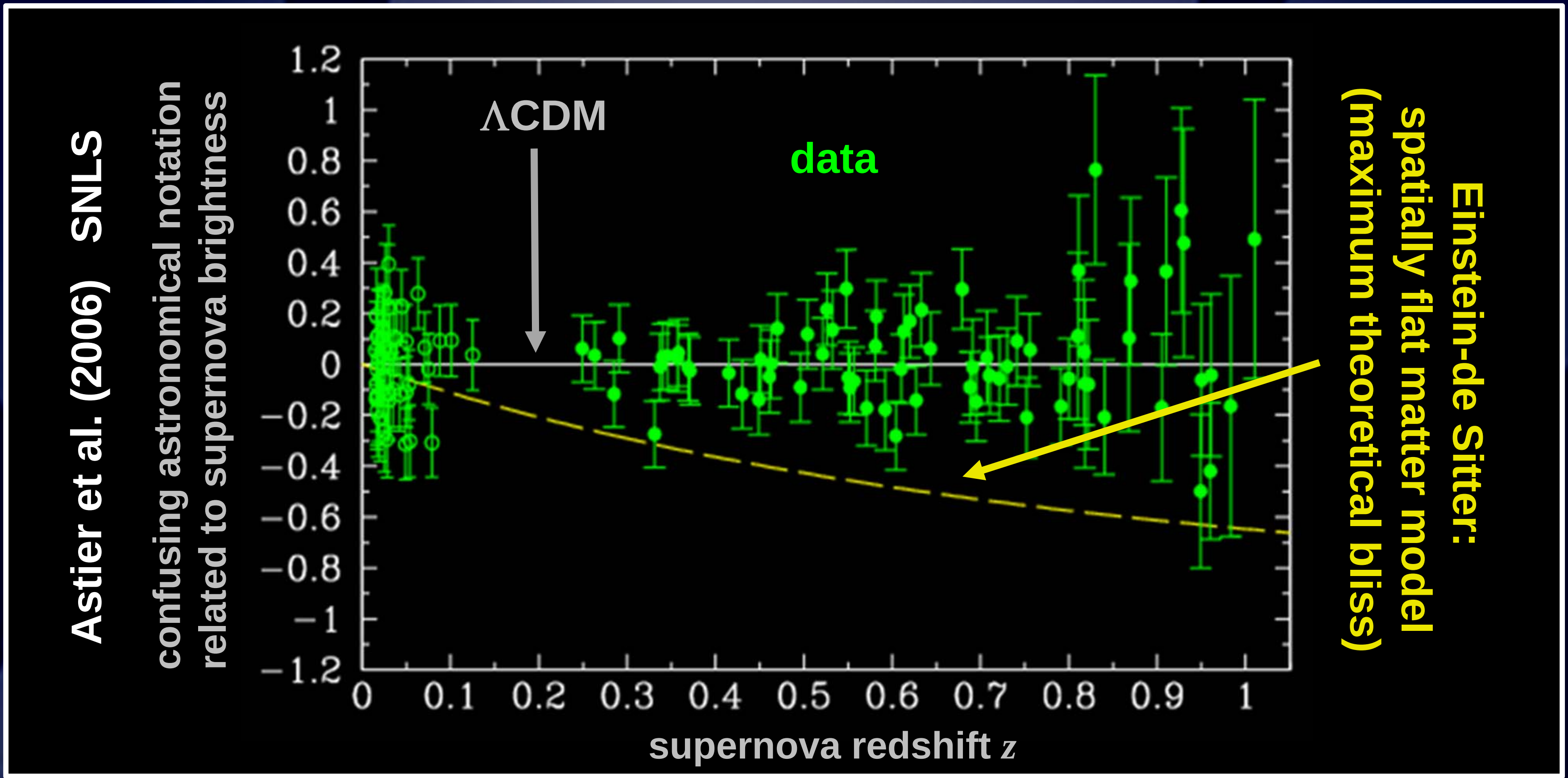
Hubble's Discovery Paper - 1929




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

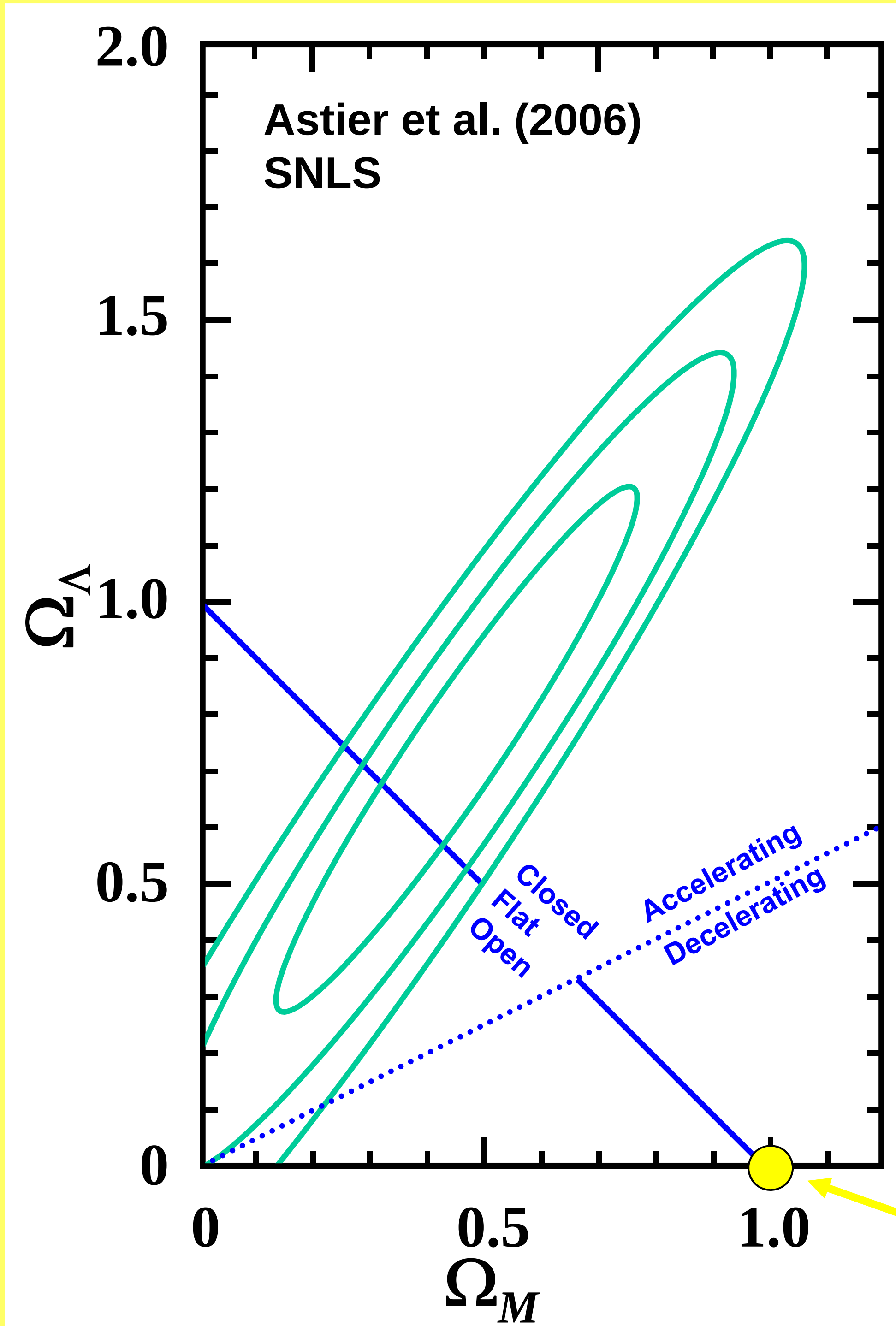

Hubble Diagram
apparent brightness of standard candle
distant universe, past velocity
1998–today
difference = acceleration
1929–1998
nearby universe, present velocity, (H_0)
redshift of spectral lines

Hubble Diagram



Hubble Diagram

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

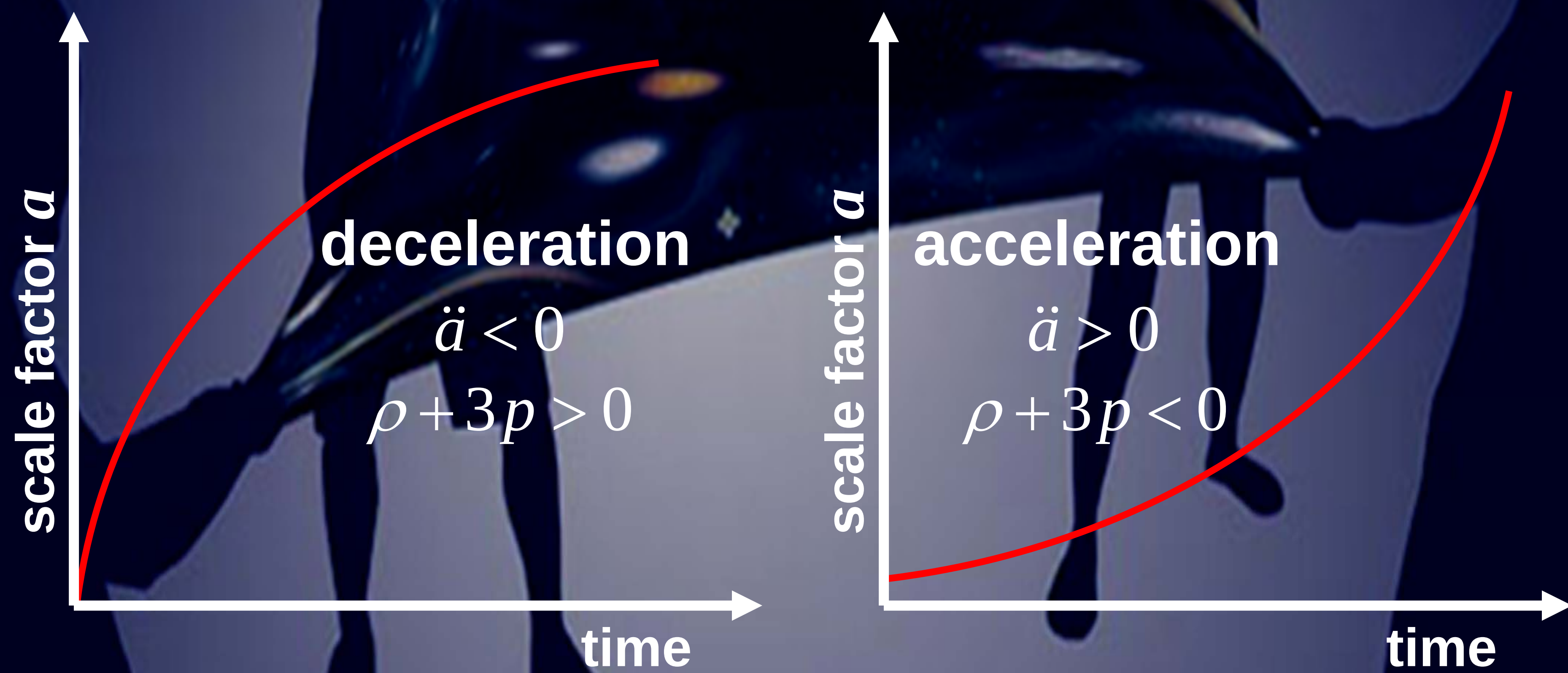


Expansion History of the Universe $H(z)$

distance: $a \propto D$ (cosmic scale factor)

velocity: $\dot{a} \propto H$ (Hubble parameter)

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



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)

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$ Einstein 1915

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda^{CC} g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ Einstein 1917

$\Lambda^{CC} =$ **cosmological constant**

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$ Einstein 1934

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu} + 8\pi G\, T_{\mu\nu}^{\text{vacuum}}$ QFT+

$T_{\mu\nu}^{\text{vacuum}}: \ \rho^{\text{vacuum}} = -p^{\text{vacuum}}$ $\rho^{\text{vacuum}} + 3\, p^{\text{vacuum}} < 0$

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda^{CC} g_{\mu\nu} = 8\pi G\, T_{\mu\nu} + \Lambda^{\text{vacuum}} g_{\mu\nu}$

$\Lambda^{\text{vacuum}} = 8\pi G \rho^{\text{vacuum}}$

CC (à *la* Einstein) & ρ^{vacuum} indistinguishable

Expansion History of the Universe $H(z)$

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 $\Omega_{\text{walls}}\,(1+z)^1$]
- $1 = \Omega_\Lambda + \Omega_k + \Omega_M + \Omega_R$
- radiation contribution (Ω_R) small for $z \lesssim 10^3$
- Ω_k well determined (close to zero) from CMB
- Ω_M reasonably well determined

Expansion History of the Universe $H(z)$

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

dark energy | curvature | matter | radiation

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

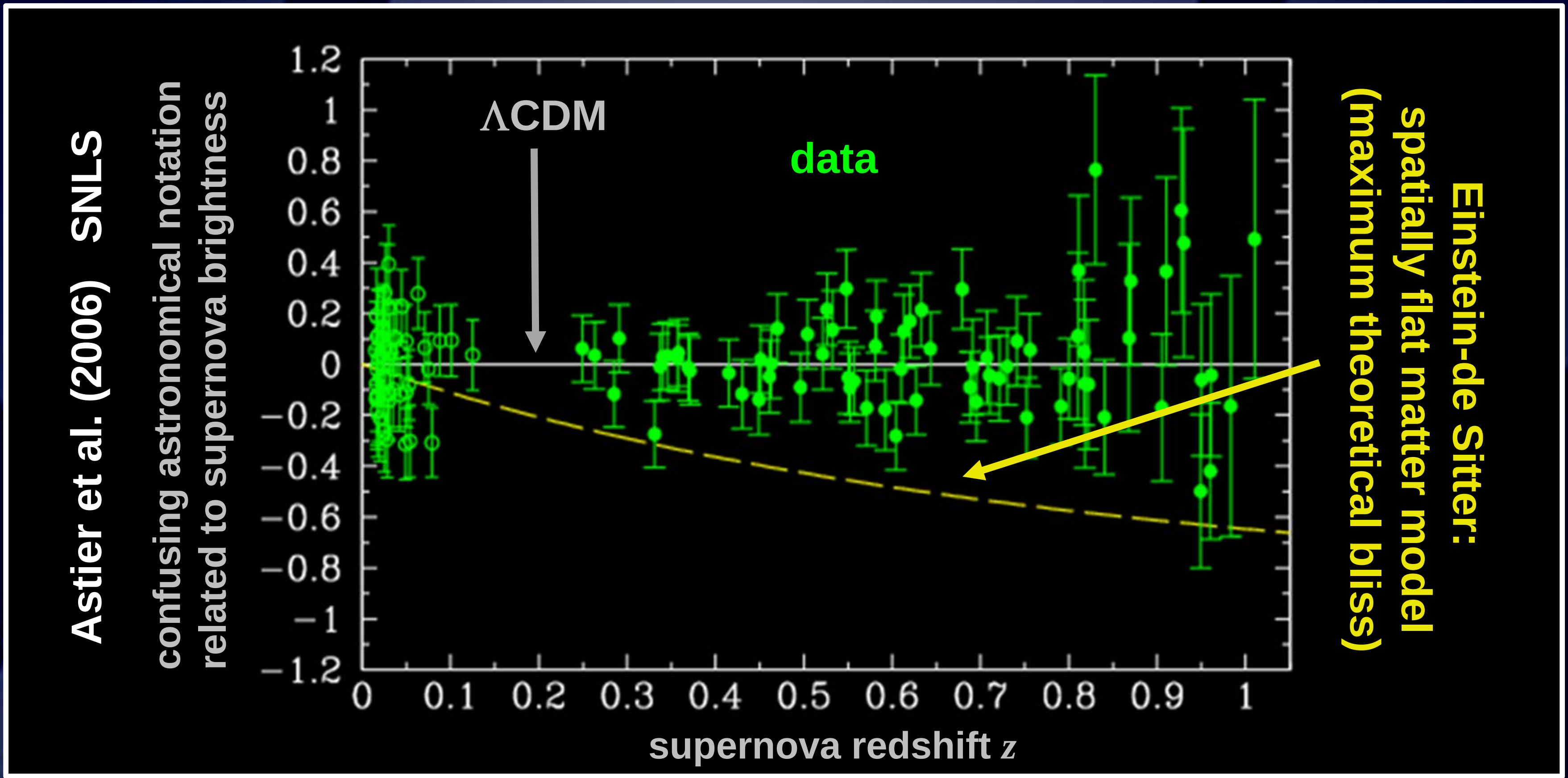
Equation of state parameter: $w = p/\rho$ ($w = -1$ for Λ)

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).

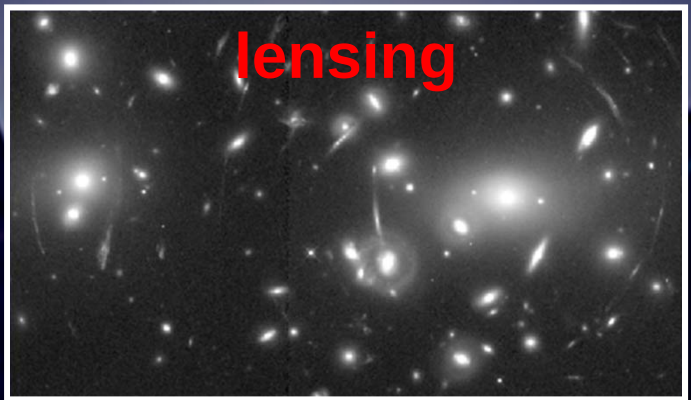
The Cosmological Constant

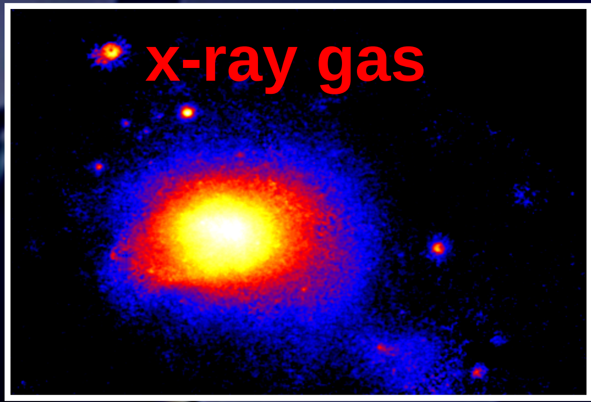


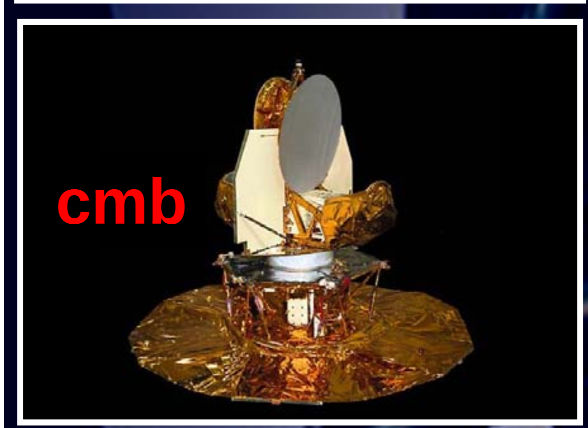
The case for Λ:

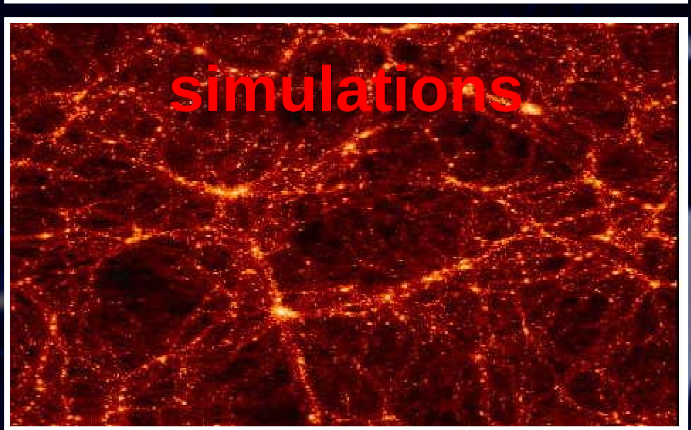
1) Hubble diagram (SNe)
2) Cosmic Subtraction $(1 - 0.3 = 0.7)$
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

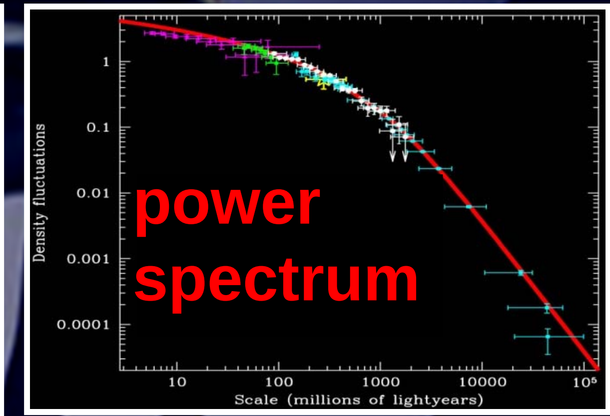
The Cosmological Constant











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

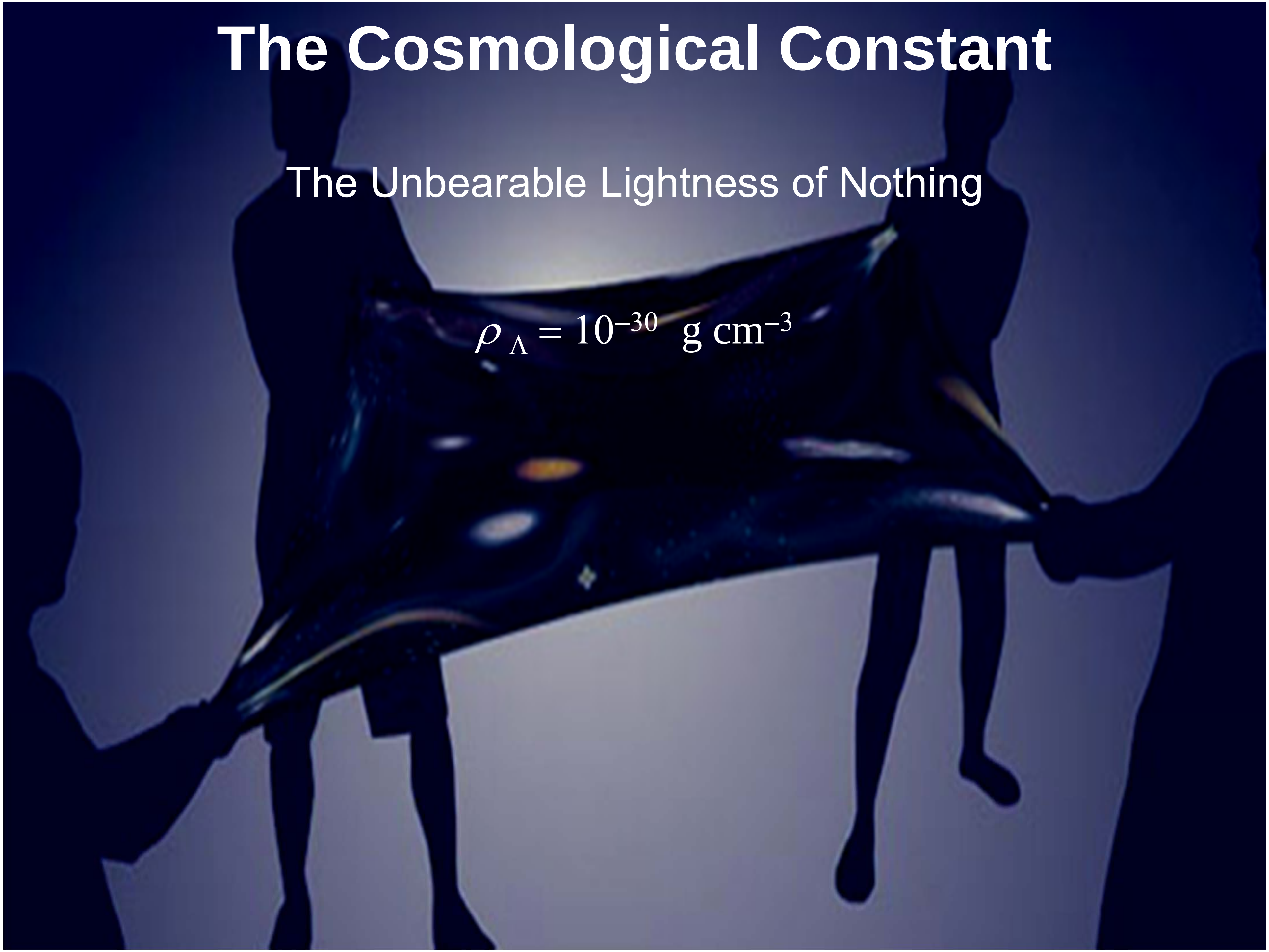
CMB **many methods**

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

The Cosmological Constant

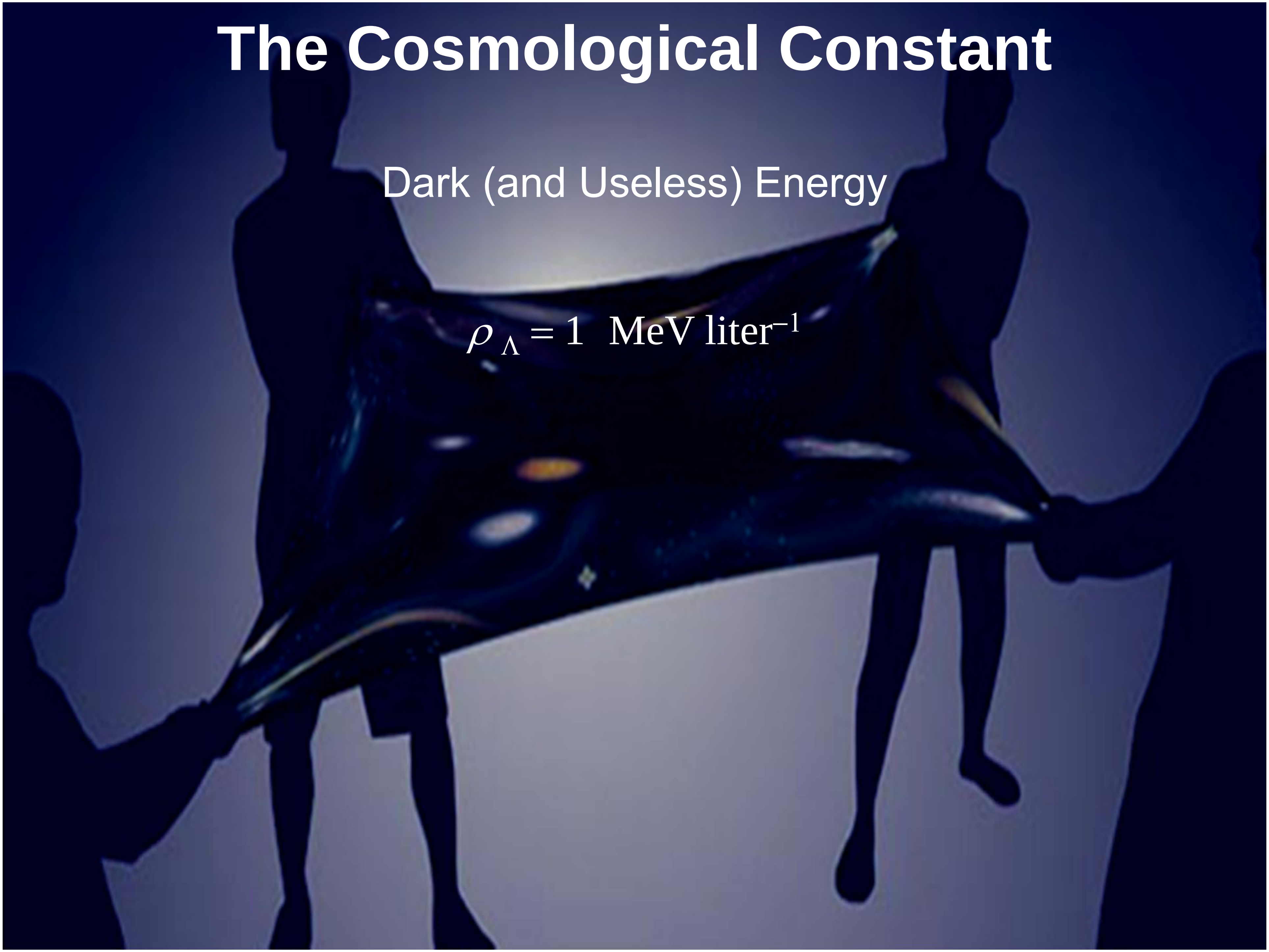
The Unbearable Lightness of Nothing

$$\rho_{\Lambda} = 10^{-30} \ \text{g cm}^{-3}$$



The Cosmological Constant

Dark (and Useless) Energy



$$\rho_{\Lambda} = 1 \text{ MeV liter}^{-1}$$

US006960975B1

(12) **United States Patent**
Volfson

(10) **Patent No.: US 6,960,975 B1**
(45) **Date of Patent: Nov. 1, 2005**

(54) **SPACE VEHICLE PROPELLED BY THE PRESSURE OF INFLATIONARY VACUUM STATE**

(76) Inventor: **Boris Volfson**, 5707 W. Maple Grove Rd., Apt. 3046, Huntington, IN (US) 46750

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 8 days.

(21) Appl. No.: **11/079,670**

(22) Filed: **Mar. 14, 2005**

Related U.S. Application Data

(63) Continuation of application No. 10/633,778, filed on Aug. 4, 2003, now abandoned.

(51) **Int. Cl.**[7] **H01F 6/00**; F03H 5/00
(52) **U.S. Cl.** **335/216**; 60/200.1
(58) **Field of Search** 335/216; 60/200.1

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Primary Examiner—Ramon M. Barrera

(57) **ABSTRACT**

A space vehicle propelled by the pressure of inflationary vacuum state is provided comprising a hollow superconductive shield, an inner shield, a power source, a support structure, upper and lower means for generating an electromagnetic field, and a flux modulation controller.

A cooled hollow superconductive shield is energized by an electromagnetic field resulting in the quantized vortices of lattice ions projecting a gravitomagnetic field that forms a spacetime curvature anomaly outside the space vehicle. The spacetime curvature imbalance, the spacetime curvature being the same as gravity, provides for the space vehicle's propulsion. The space vehicle, surrounded by the spacetime anomaly, may move at a speed approaching the light-speed characteristic for the modified locale.

13 Claims, 6 Drawing Sheets

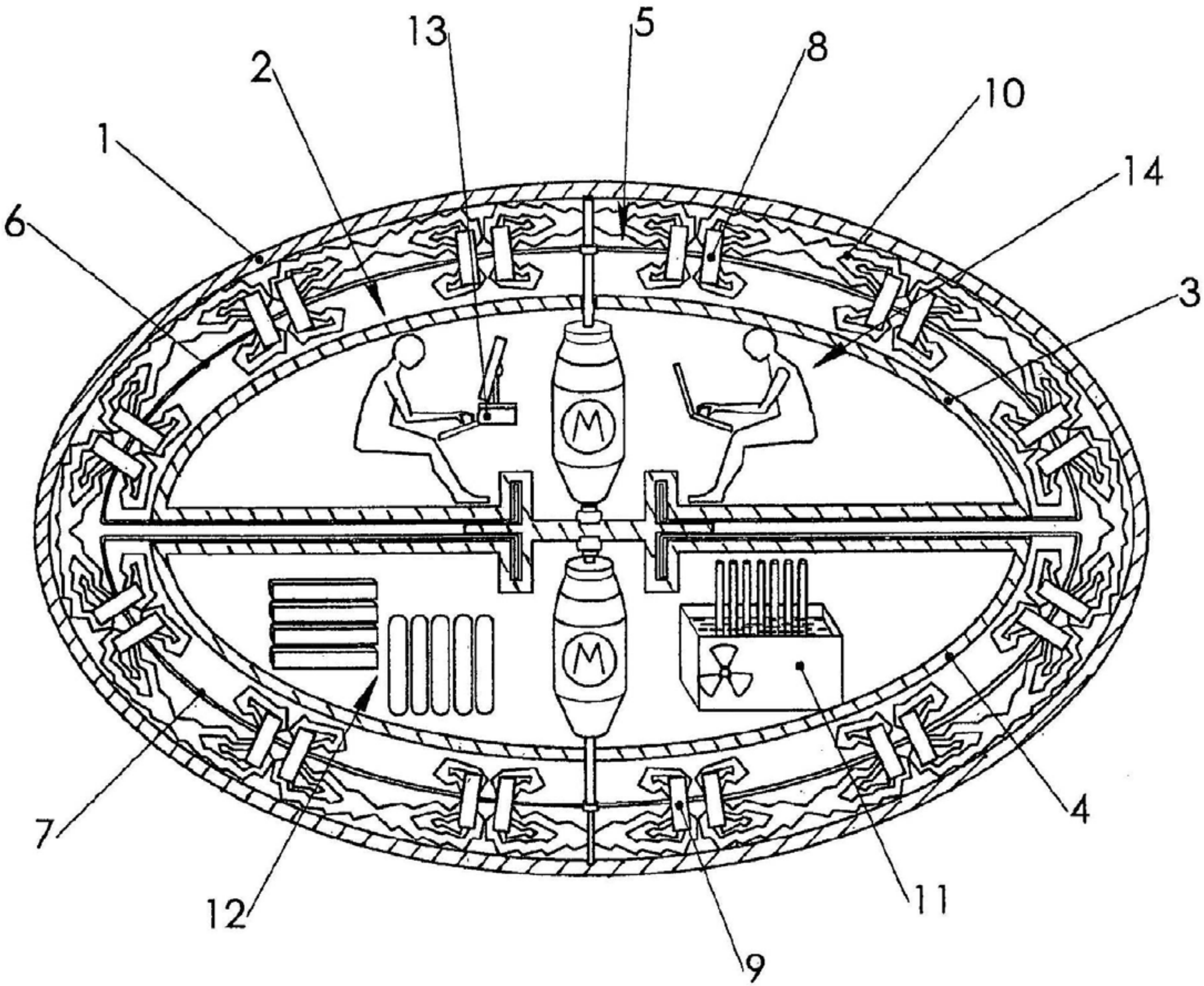


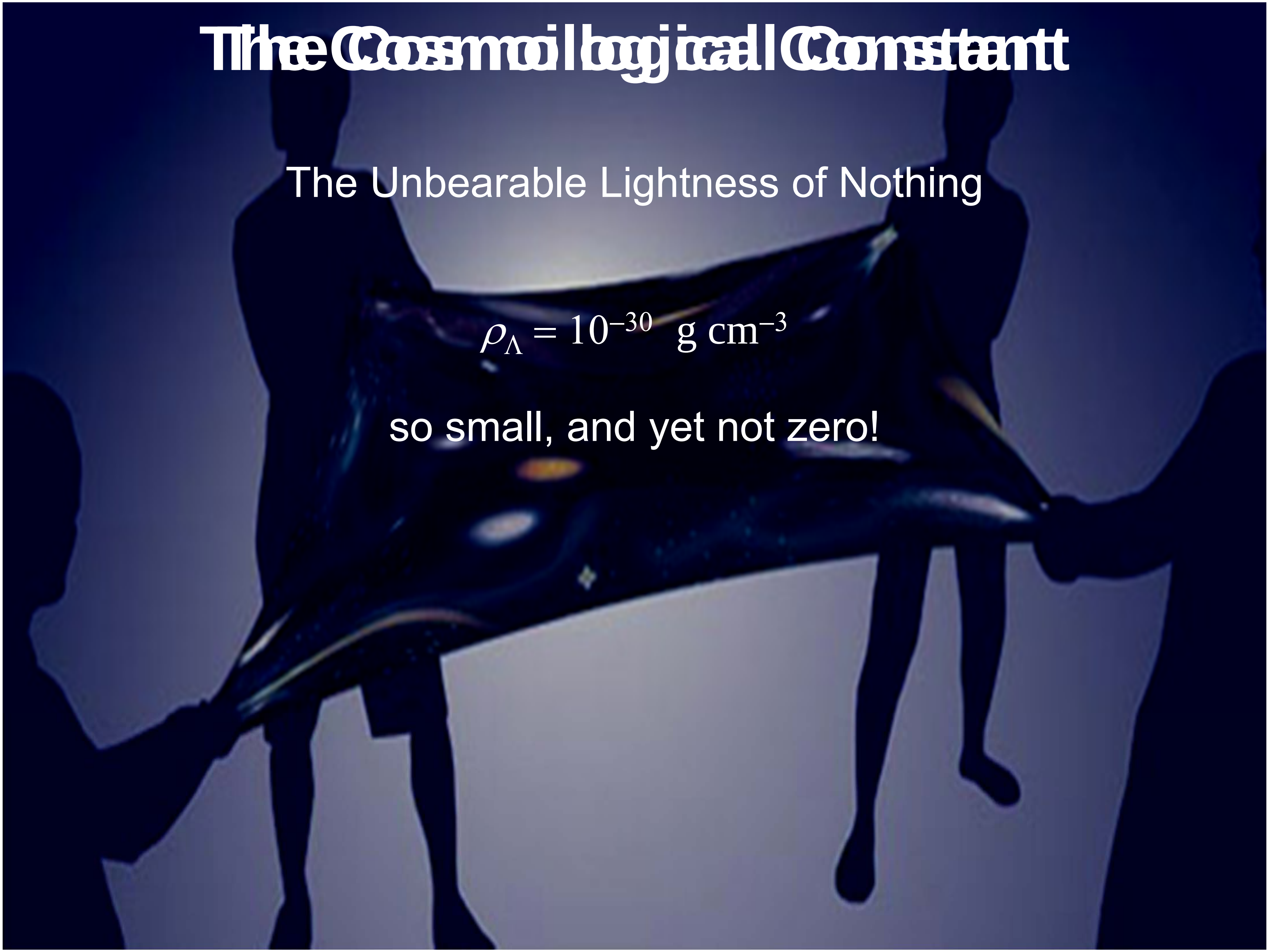
FIG. 1

The Cosmological Constant

The Unbearable Lightness of Nothing

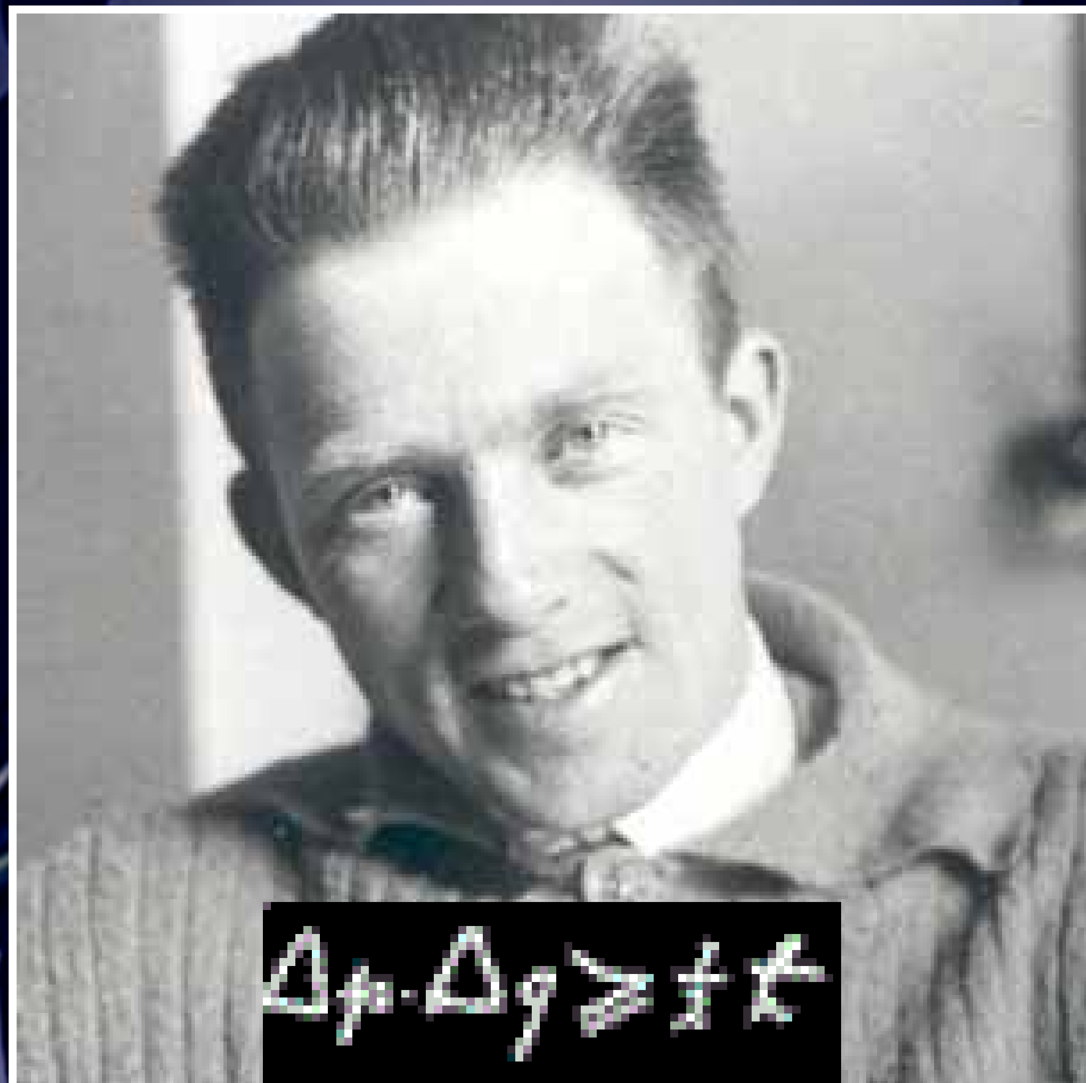
$$\rho_\Lambda = 10^{-30} \ \text{g cm}^{-3}$$

so small, and yet not zero!




The Cosmoillogical Constant
10^{-30} grams per cc
0.000000000000000000000000000001
grams per cubic centimeter
The Unbearable Lightness of Nothing
Seven Secrets Of Nothingness
1) Nothing is uncertain
2) Nothing is something
3) Nothing has energy
4) Nothing changes
5) Nothing is hidden
6) Nothing is mysterious
7) Nothing matters

1) Nothing Is Uncertain



Werner Heisenberg 1901—1976

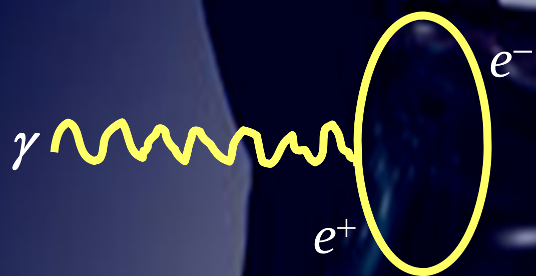
2) Nothing Is Something

There is Something in the Quantum Vacuum

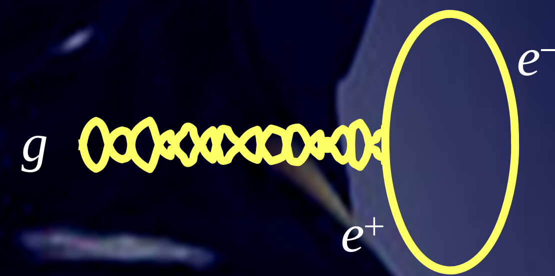
3) Nothing Has Energy

All fields: harmonic oscillators with zero-point energy

Photons: Lamb shift



Gravitons: Vacuum energy



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

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

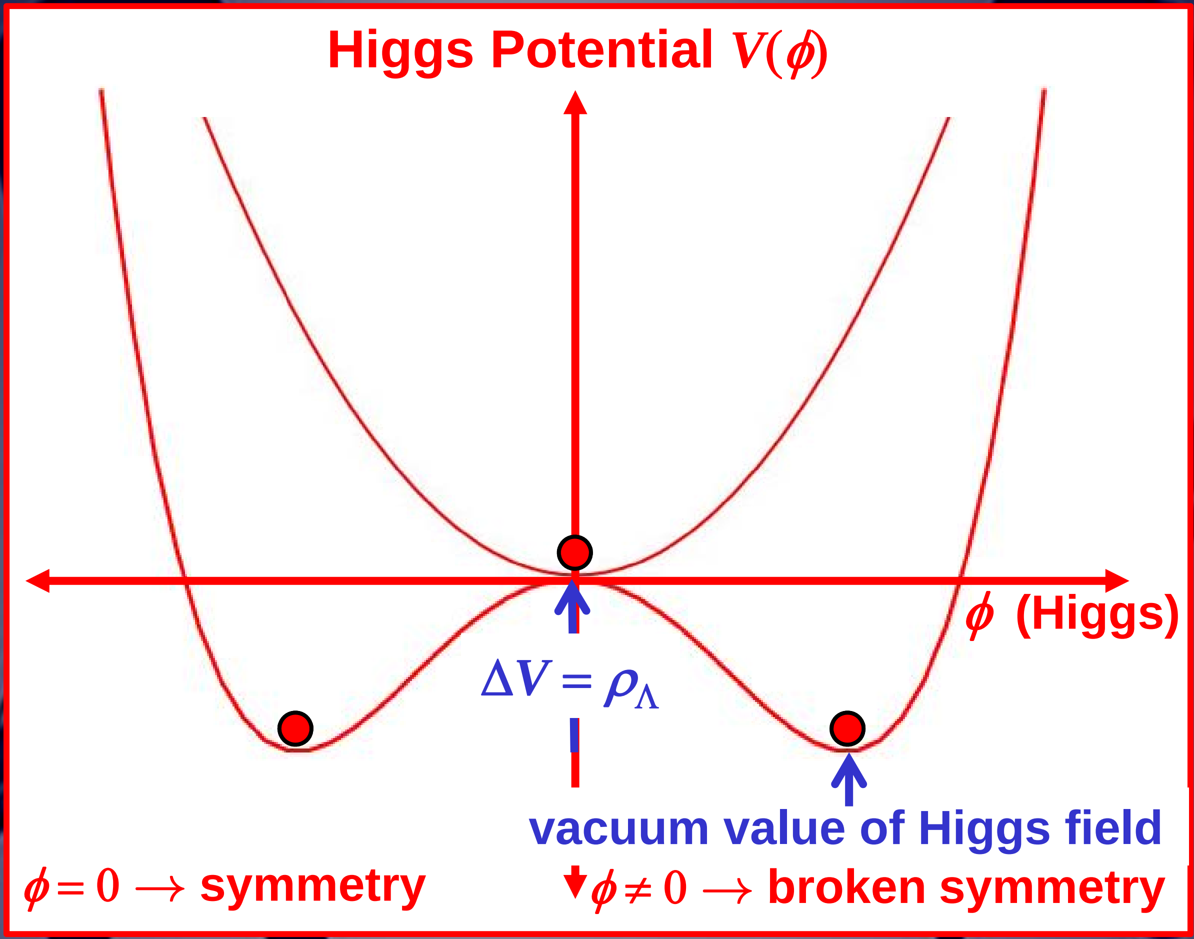
$$\Lambda_C = M_{Pl} : \quad \rho_\Lambda = M_{Pl}^4 \quad = 10^{+90}\ \text{g cm}^{-3}$$

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

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

3) Nothing Has Energy

- "Nature weaves her tapestry from the longest threads." — Richard Feynman
- Nature seems to like symmetry, then hide it



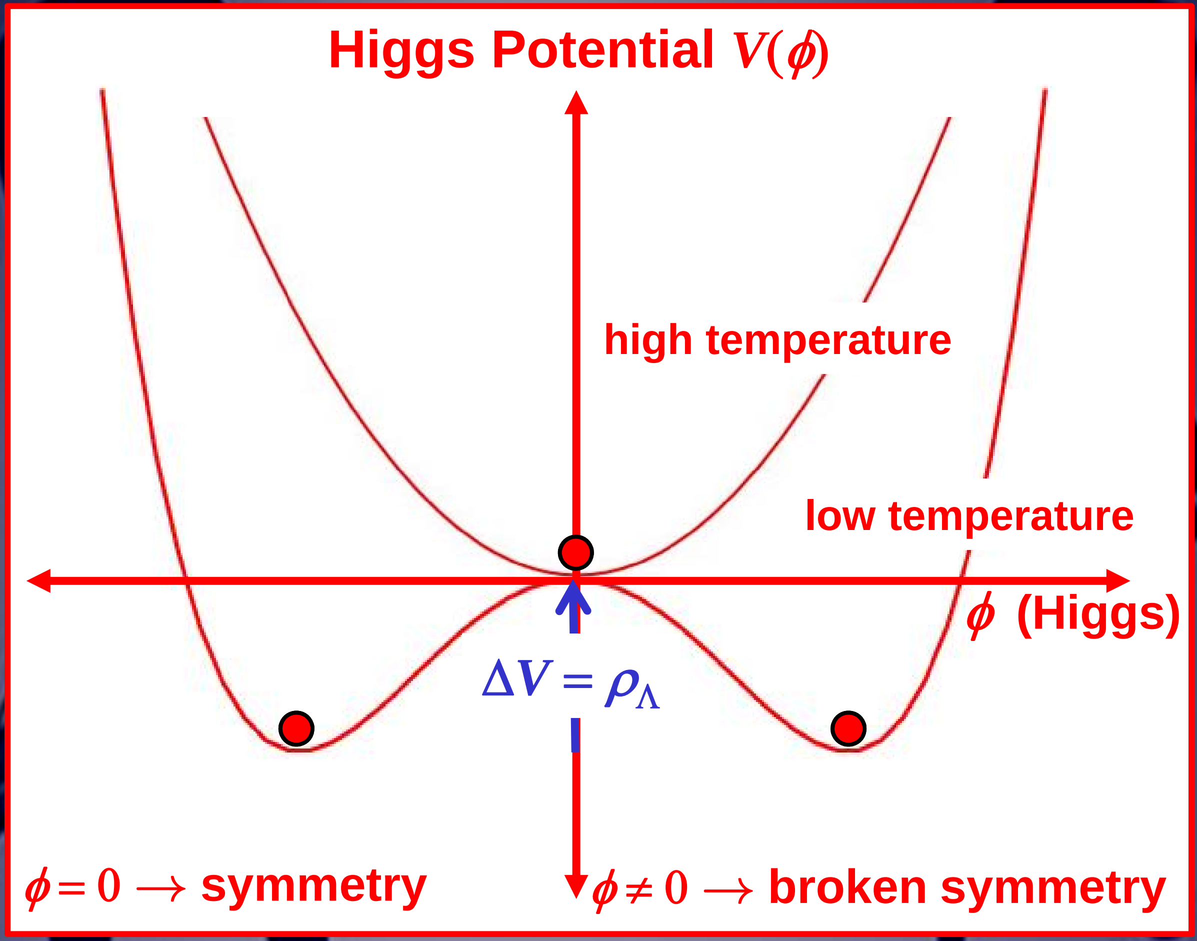
GUT: 10^{74} g cm^{-3} **SUSY:** 10^{30} g cm^{-3}

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

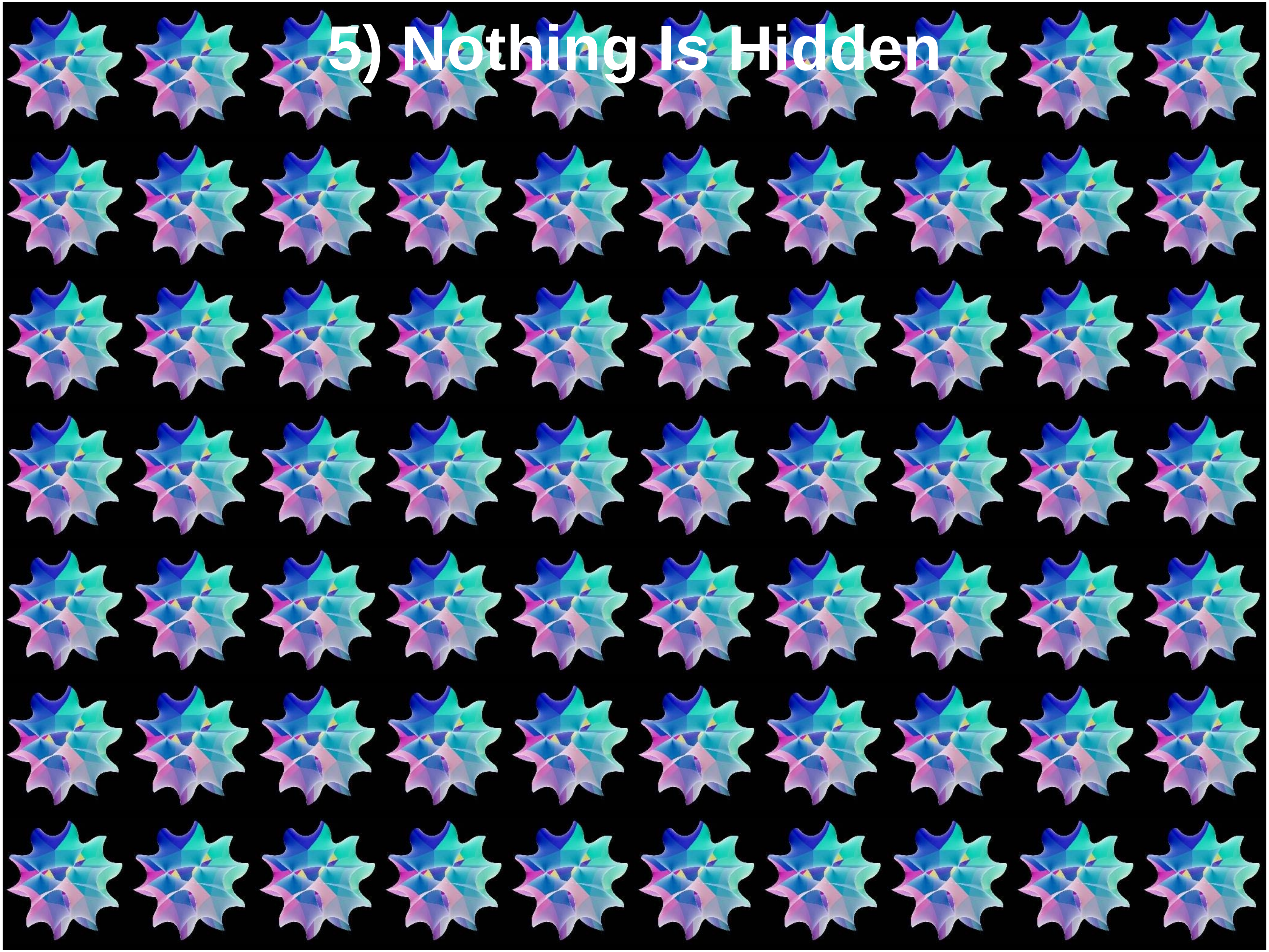
OBSERVED: 10^{-30} g cm^{-3}

4) Nothing Changes

- The Higgs potential changes with temperature

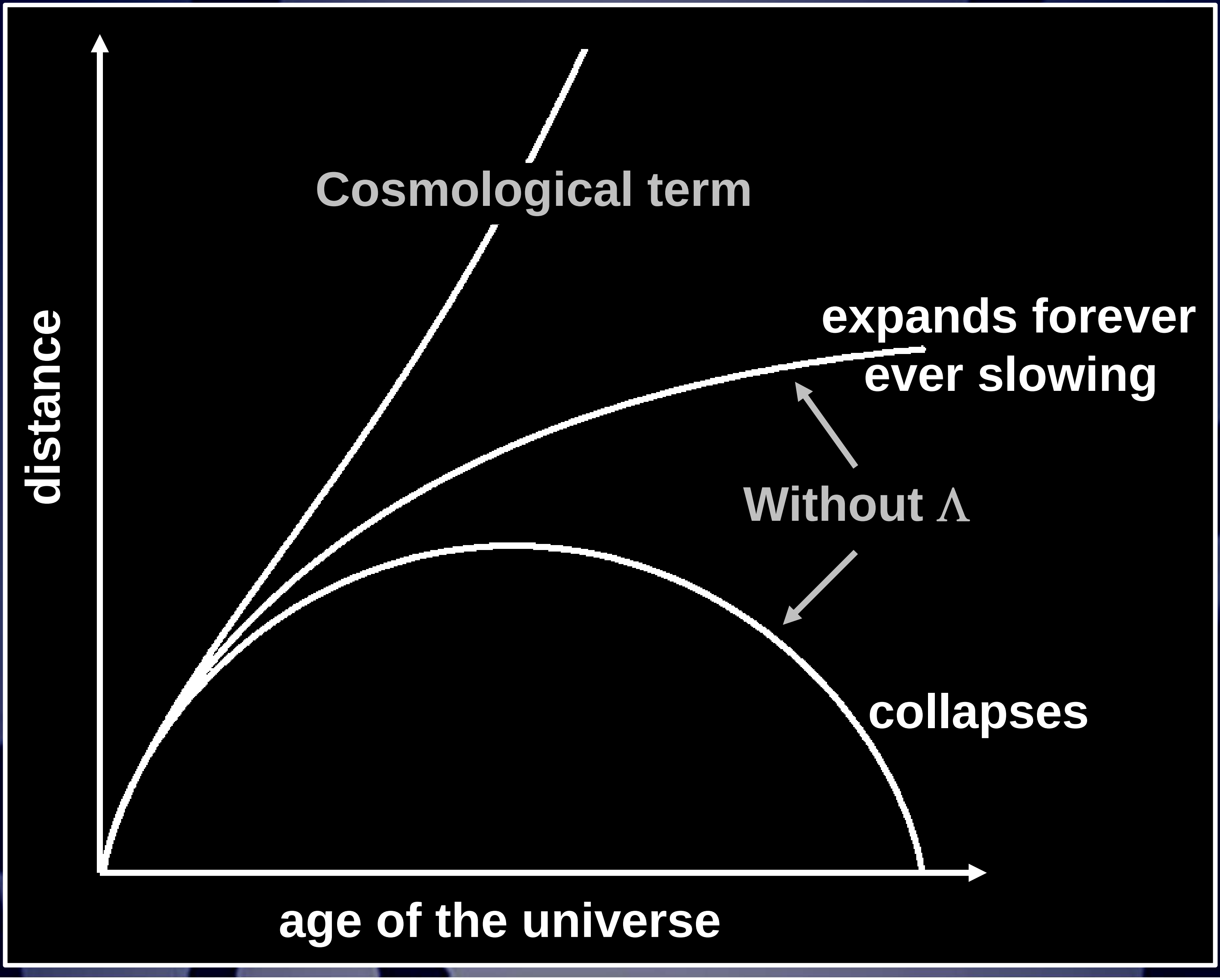


5) Nothing Is Hidden

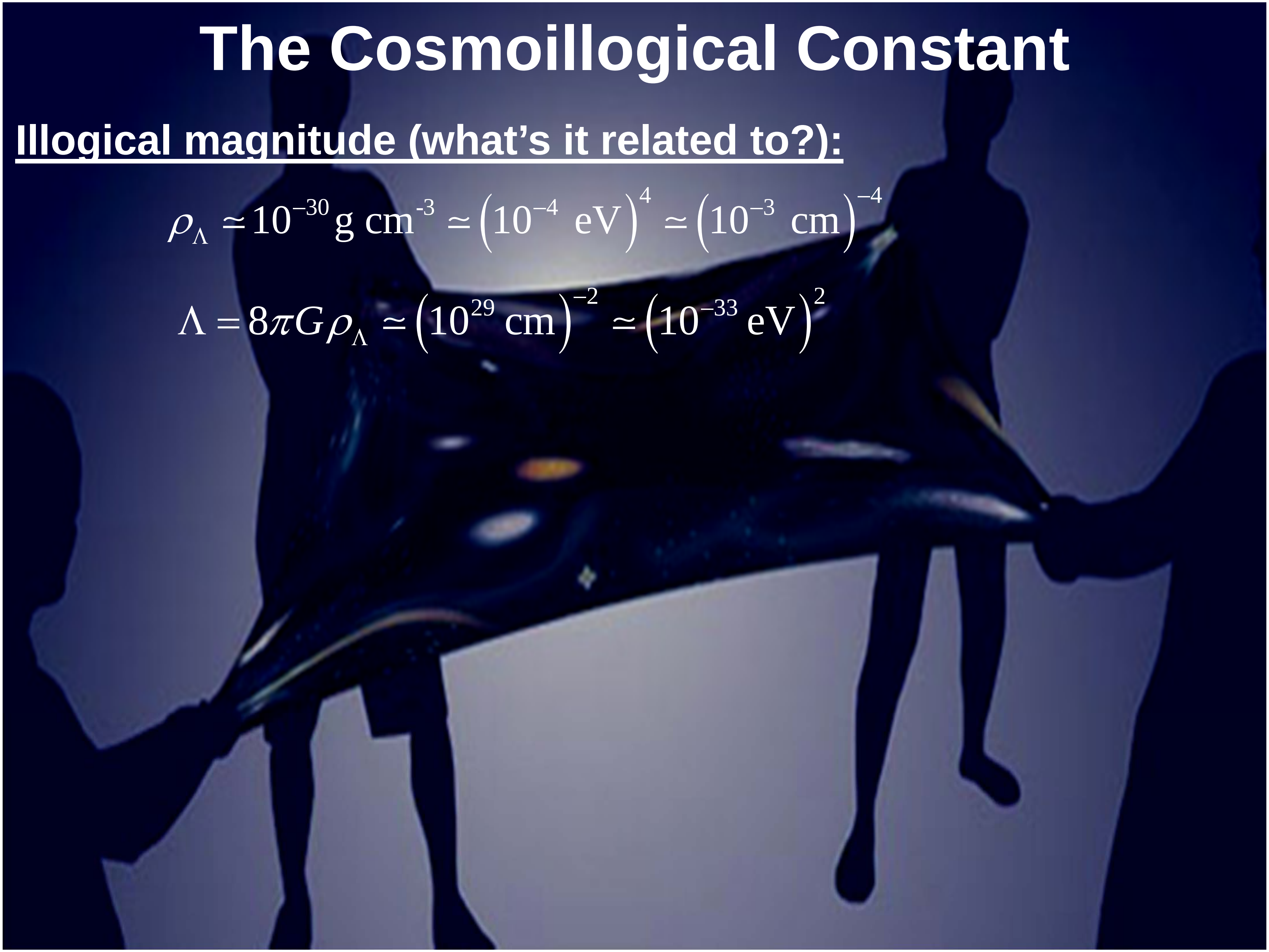



6) Nothing Is Mysterious
Illogical magnitude (what's it related to?):
Observed Dark Energy Density: 10^{-30} g cm^{-3}
Uncertainty Energy
∞^4 g cm^{-3}
10^{30} g cm^{-3}
10^{90} g cm^{-3}
Symmetry Breaking
GUT: 10^{74} g cm^{-3}
SUSY: 10^{30} g cm^{-3}
EWK: 10^{24} g cm^{-3}
CHIRAL: 10^{13} g cm^{-3}
Extra Dimensions
10^{90} g cm^{-3}

7) Nothing Matters



The Cosmoillogical Constant



<u>Illogical magnitude (what's it related to?):</u>

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

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

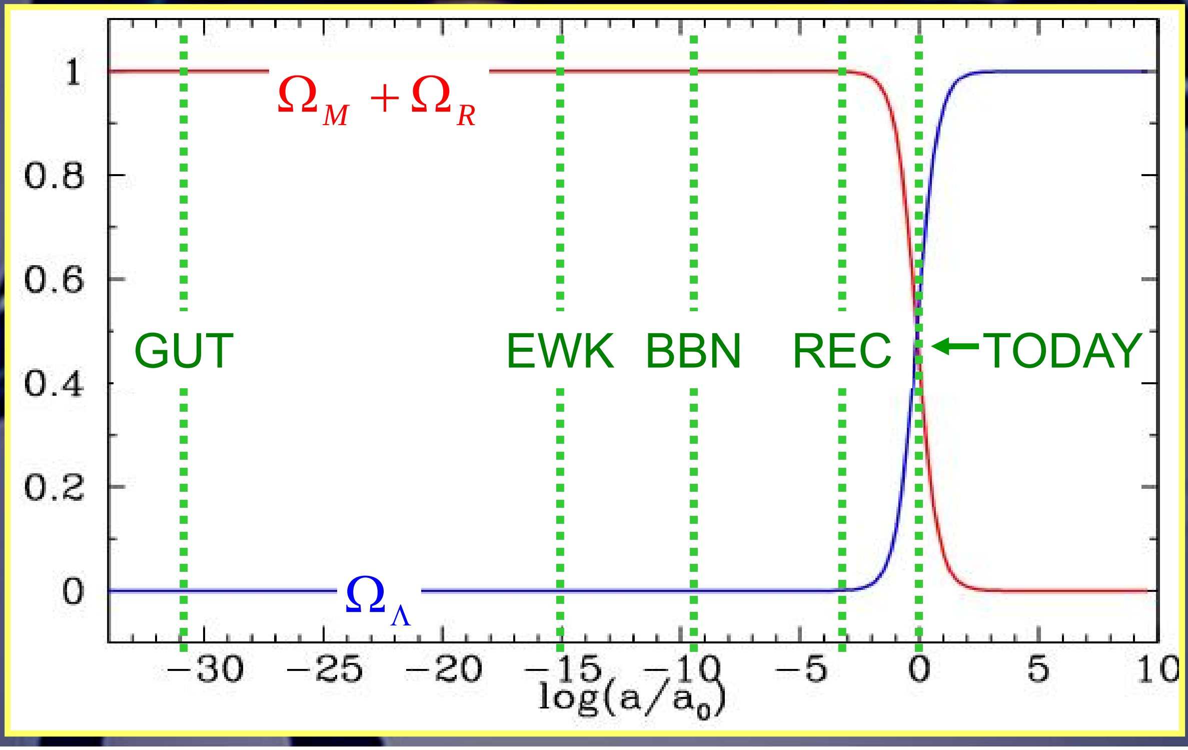
Cosmoillogical Constant

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

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

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

Illogical timing (cosmic coincidence?):



Cosmoillogical Constant

Do not directly *observe*

- acceleration of the universe
- cosmoillogical constant
- dark energy

We *<u>infer</u>* acceleration/dark energy by comparing
<u>observations</u>
with the predictions of a
<u>model</u>

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

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

anthropic principle (the landscape)

scalar fields (quintessence)

Anthropic/Landscape/DUCTtape

- Many sources of vacuum energy.
- String theory has many ($>10^{500}$?) vacua … the landscape.
- The multiverse could populate many (all?) vacua.
- Very, very rarely vacua have cancellations that yield a small Λ.
- While exponentially uncommon, they are preferred because …
  … more common values of Λ results in an inhospitable universe.

Anthropic principle requires $\Lambda \leq \Lambda_{OBS}$.
Explains a $(10^{120} - 1)\sigma$ result.

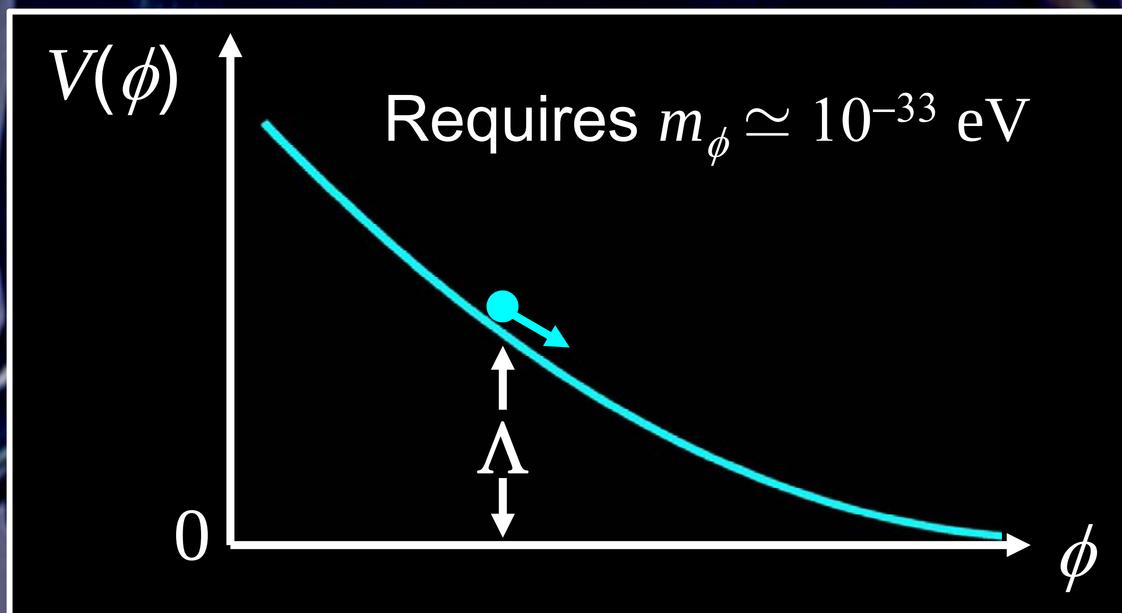
A change in the 47^{th} decimal place in the up-quark mass makes a 100% change in Λ.

Anthropic/Landscape/DUCTtape

- The anthropic “principle” can explain the cosmoillogical constant.
- Perhaps there is no better idea than the anthropic principle …
  … (people without ideas can still have principles).
- But principles must not be applied selectively.
- What does this mean for particle physics?
  - Does it explain the weak scale/Planck scale hierarchy?
  - Who needs low-energy SUSY?
  - Give up searching for many answers (masses, etc.).
  - No dreams of a final theory.
- Is particle physics an environmental science?

Quintessence/WD–40

- Many possible contributions.
- Why then is total so small?
- Perhaps some dynamics sets global vacuum energy to zero …
  … but we're not there yet!



- Can nature admit ultralight scalar fields?
- Long-range forces?

Tools to Modify the Left-Hand Side

- Braneworld modifies Friedmann equation

  Friedmann equation not from $G_{00} = 8\pi G\, T_{00}$ — Binetruy, Deffayet, Langois

- Gravitational force law modified at large distance

  Five-dimensional at cosmic distances — Deffayet, Dvali, Gabadadze

- Tired gravitons

  Gravitons unstable-leak into bulk — Gregory, Rubakov & Sibiryakov

- Gravity changes at distance $R \approx \mathrm{Gpc}$

  Becomes repulsive — 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

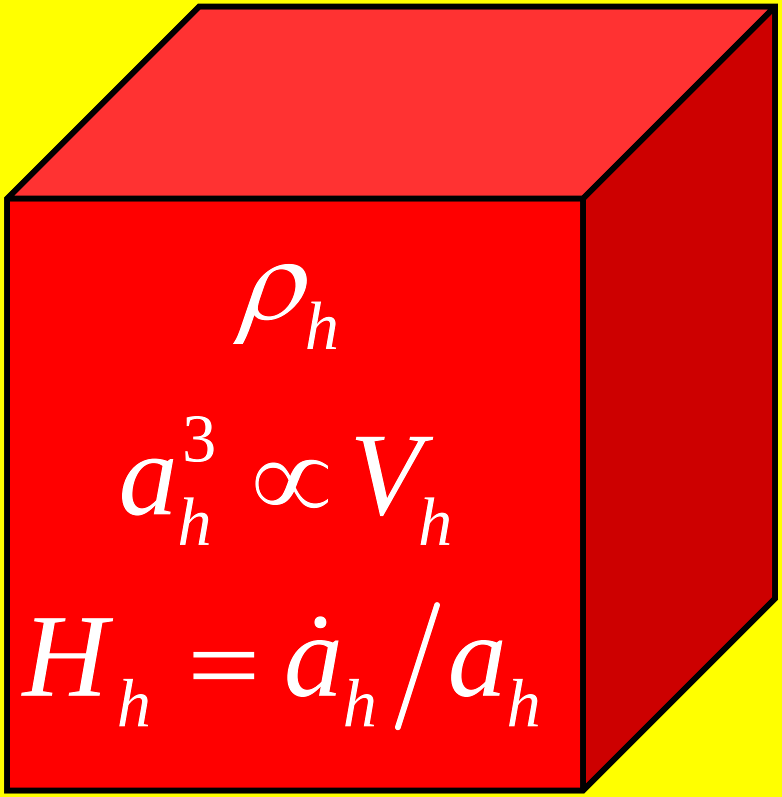
  $f(R)$ $S = (16\pi G)^{-1} \int d^4x \sqrt{-g}\left(R - \mu^4/R\right)$ — Carroll, Duvvuri, Turner & Trodden

- "Backreaction" of inhomogeneities

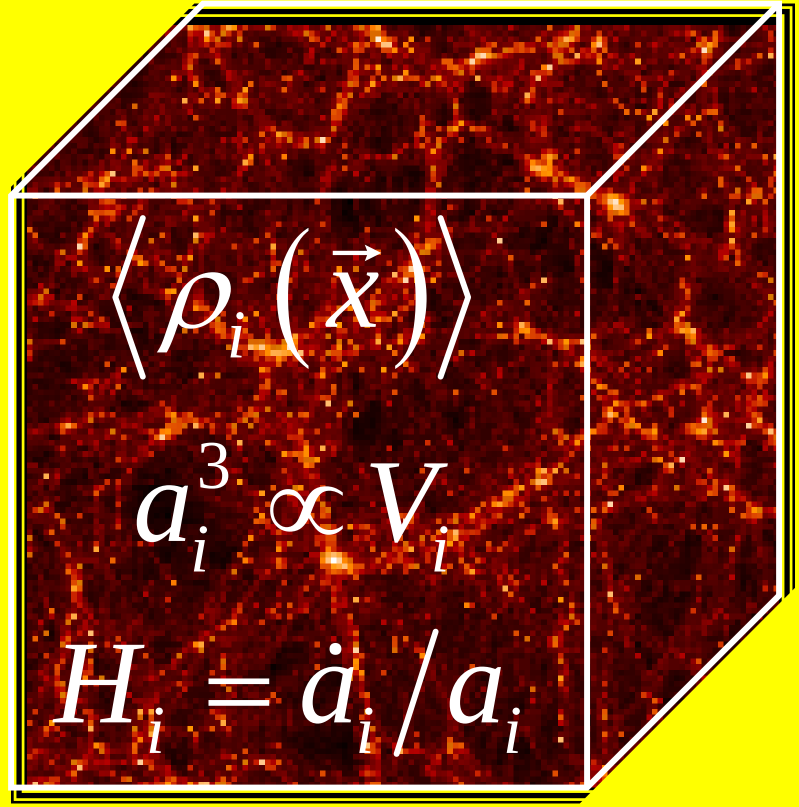
  No dark energy — Räsänen, Kolb, Matarrese, Notari, Riotto, Buchert; Ellis; Celerier

Backreaction of Inhomogeneities

Homogeneous model



Inhomogeneous model

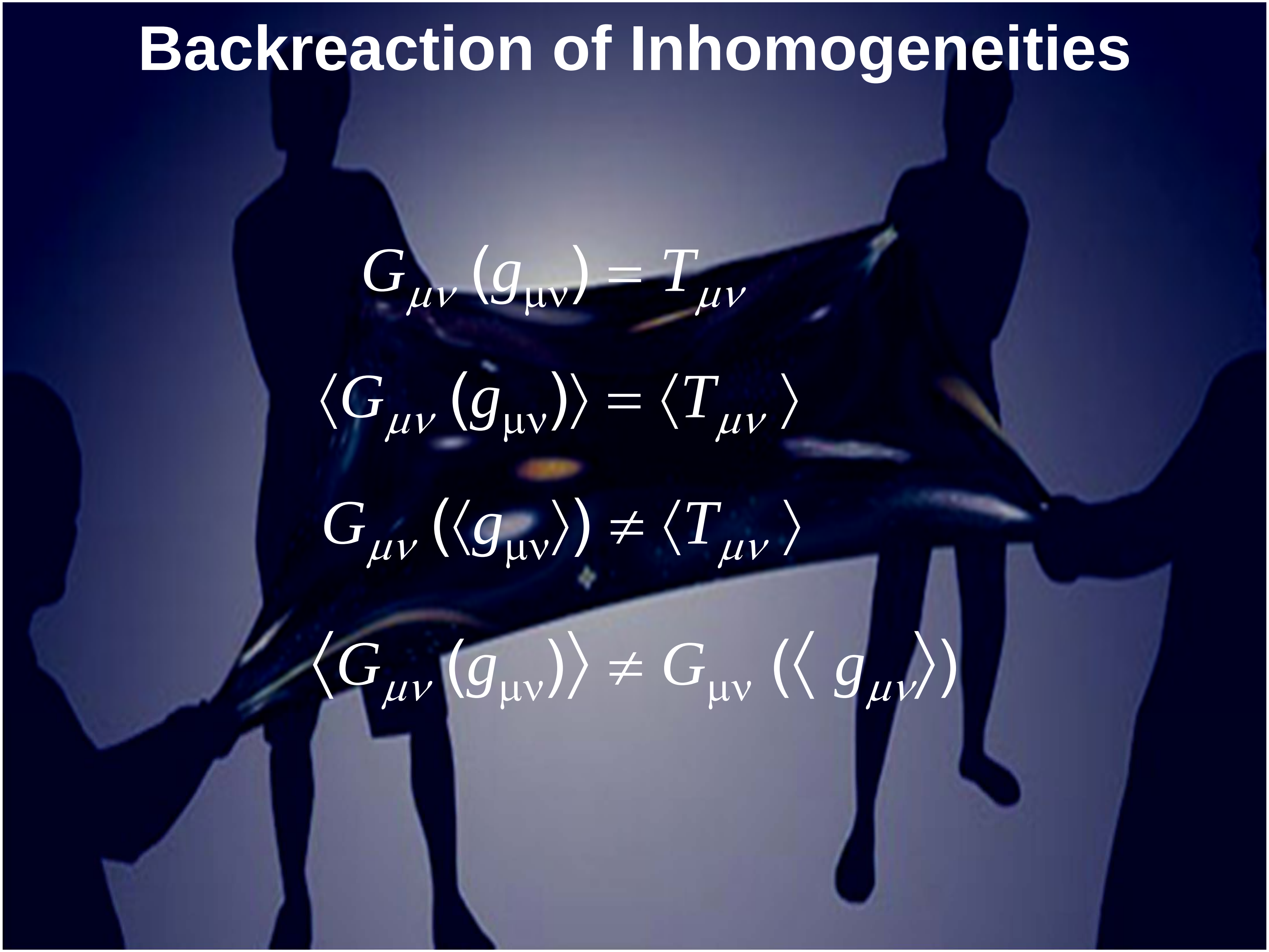


$$\rho_h = \langle \rho_i(\vec{x}) \rangle \Rightarrow H_h = H_i \; ?$$

We think not!

(Buchert & Ellis)

Backreaction of Inhomogeneities



$$G_{\mu\nu}\left(g_{\mu\nu}\right) = T_{\mu\nu}$$

$$\left\langle G_{\mu\nu}\left(g_{\mu\nu}\right)\right\rangle = \left\langle T_{\mu\nu}\right\rangle$$

$$G_{\mu\nu}\left(\left\langle g_{\mu\nu}\right\rangle\right) \neq \left\langle T_{\mu\nu}\right\rangle$$

$$\left\langle G_{\mu\nu}\left(g_{\mu\nu}\right)\right\rangle \neq G_{\mu\nu}\left(\left\langle g_{\mu\nu}\right\rangle\right)$$

Backreaction of Inhomogeneities

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

Ellis, Barausse, Buchert

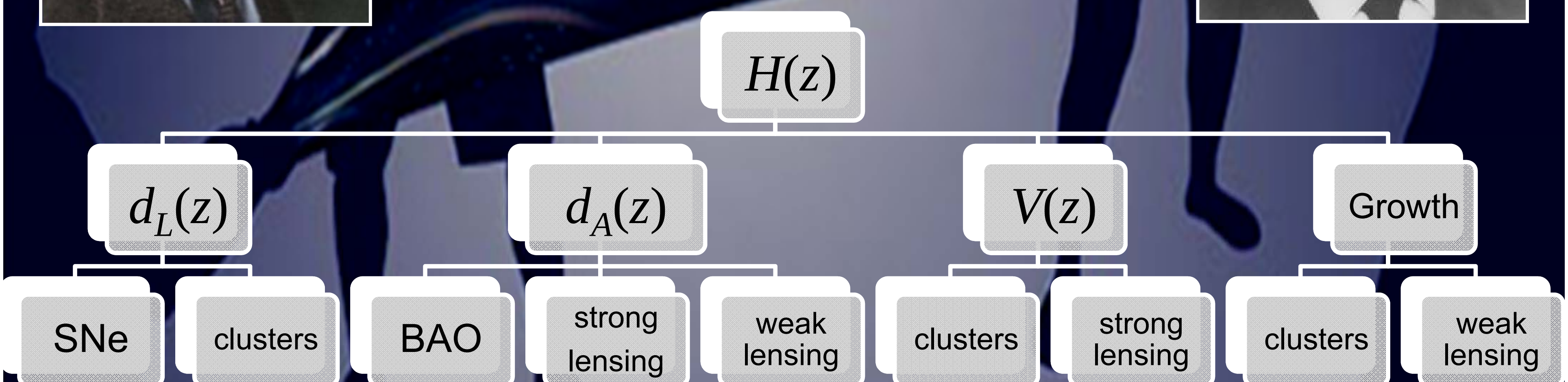
- Difference is a new term that enters an effective Friedmann equation — the new term need not satisfy energy conditions!
- We deduce dark energy because we are comparing to the wrong model universe.

Célérier; Räsänen; Kolb, Matarrese, Notari & Riotto; Schwarz, …

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."

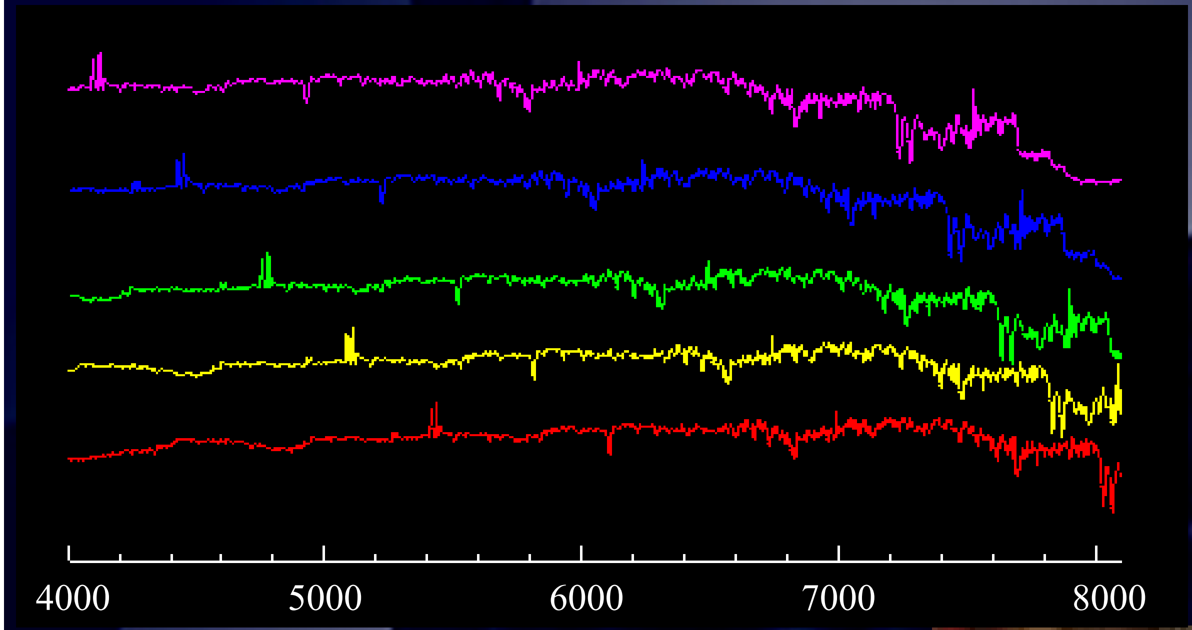
Einstein in August 1913 to astronomer Erwin Freundlich encouraging him to measure the deflection of light by the sun.



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

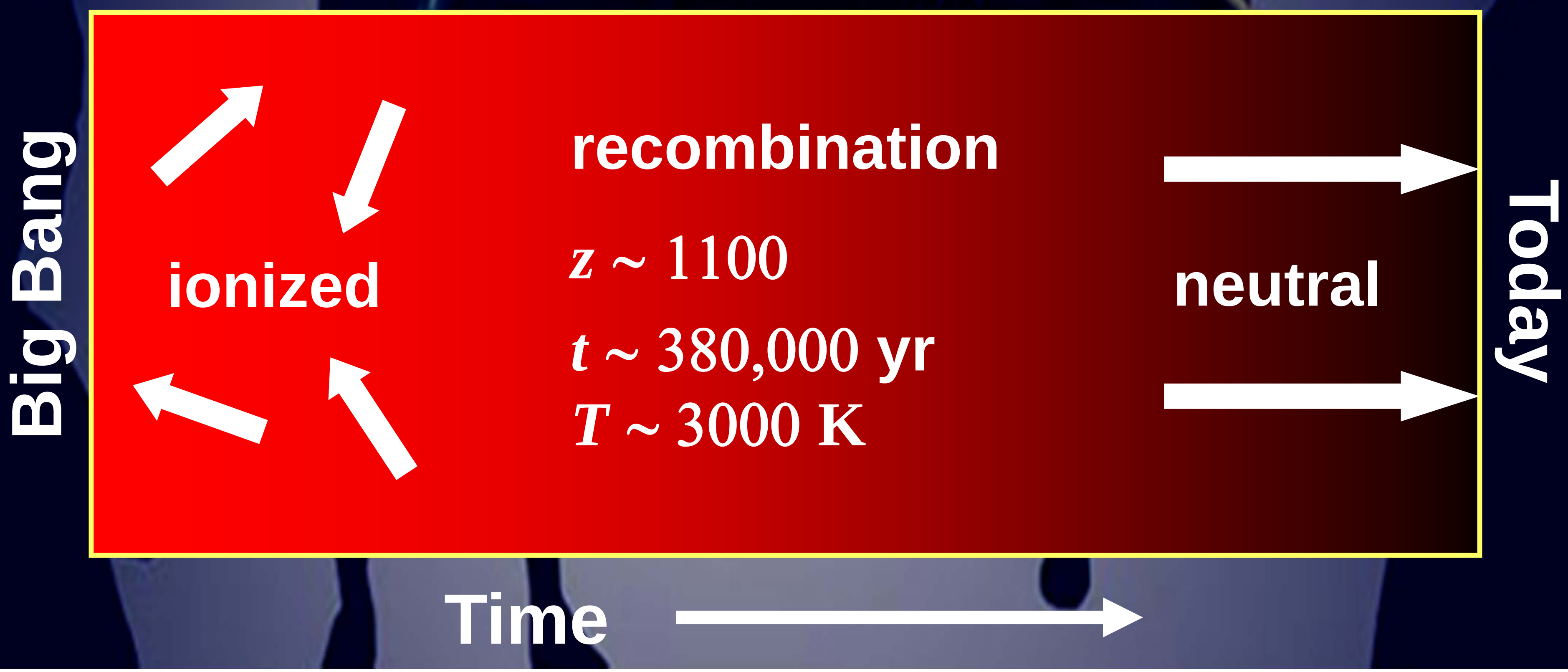
Baryon Acoustic Oscillations

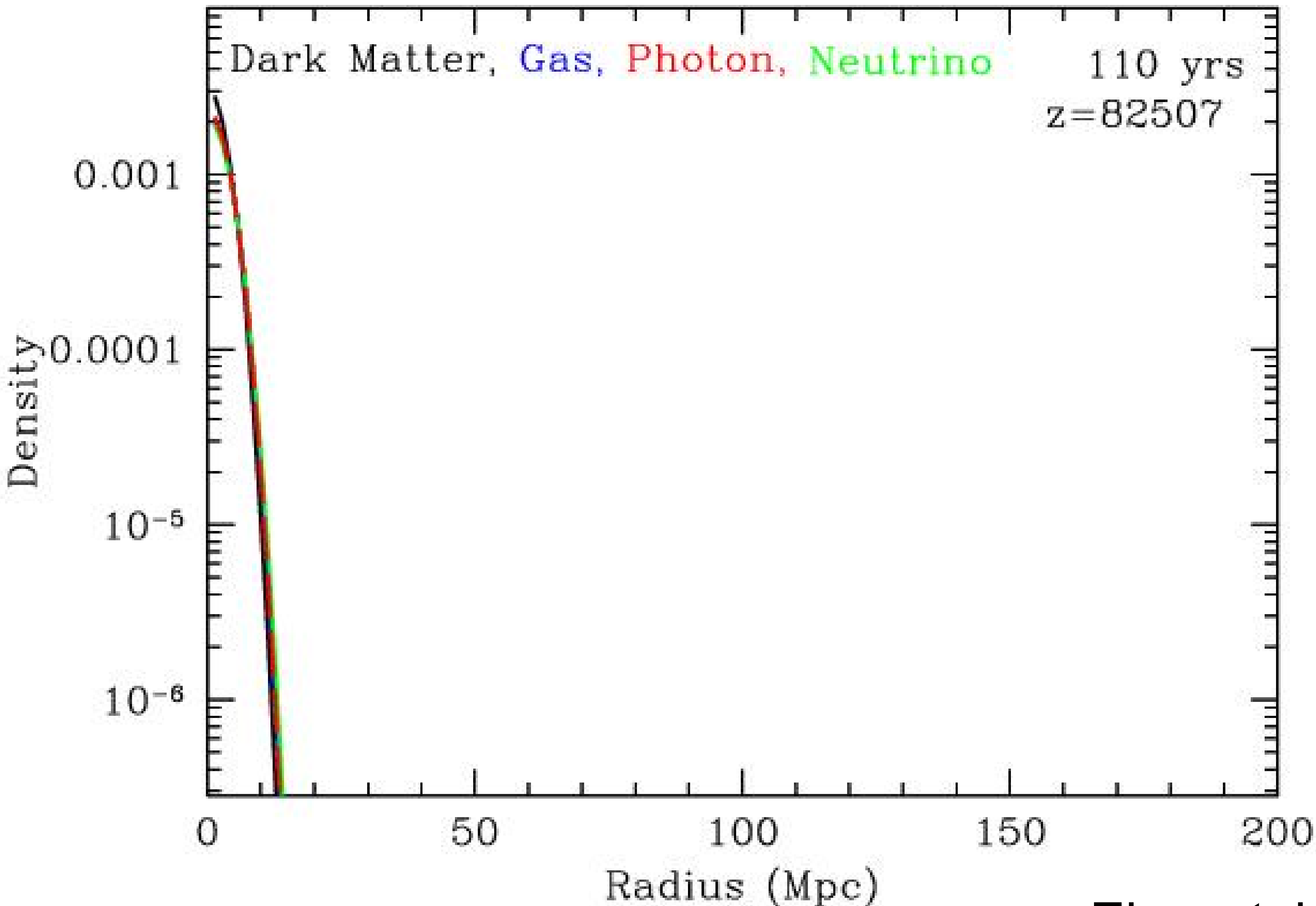
<u>Pre-recombination</u>

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

<u>Post-recombination</u>

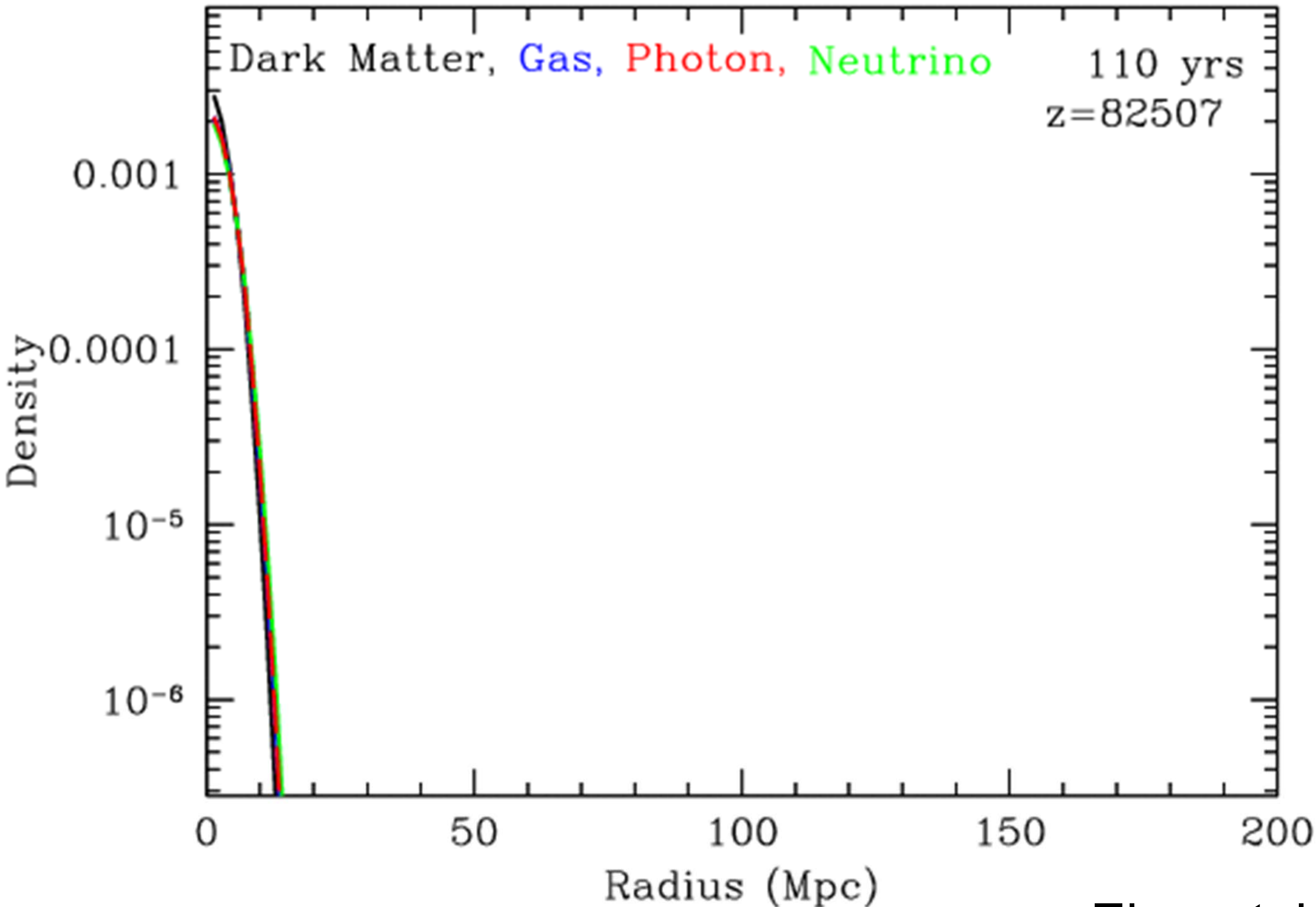
- universe neutral
- photons travel freely (decoupled from baryons)
- perturbations grow (structure formation)





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



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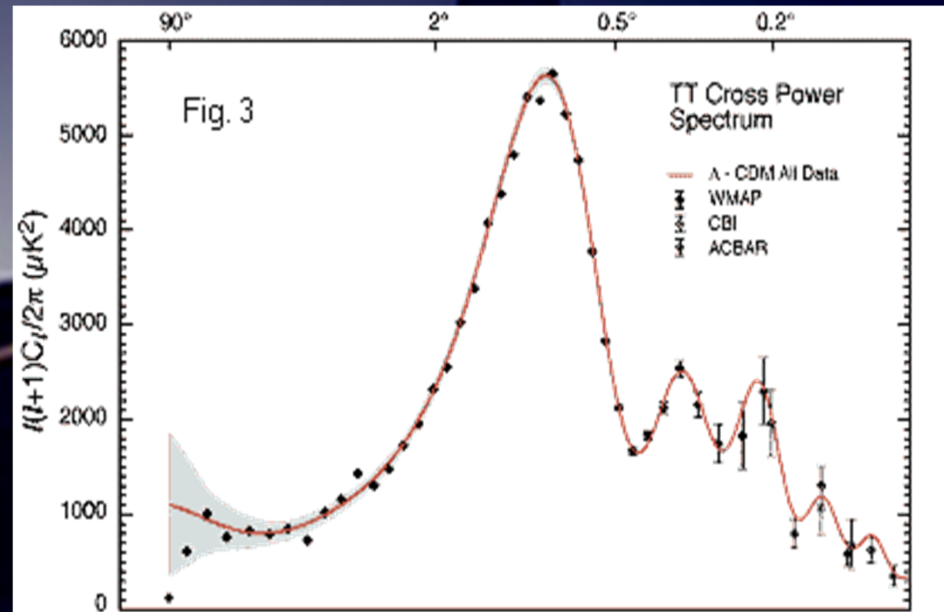
Density
10^{-5}
10^{-6}
0
50
100
150
200
Radius (Mpc)

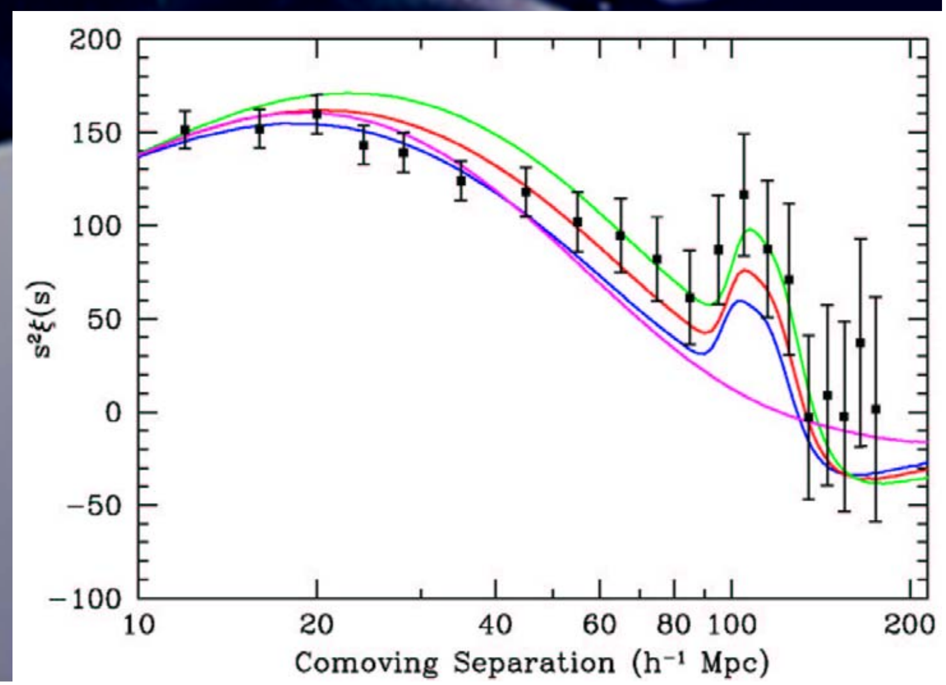
Eisenstein

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

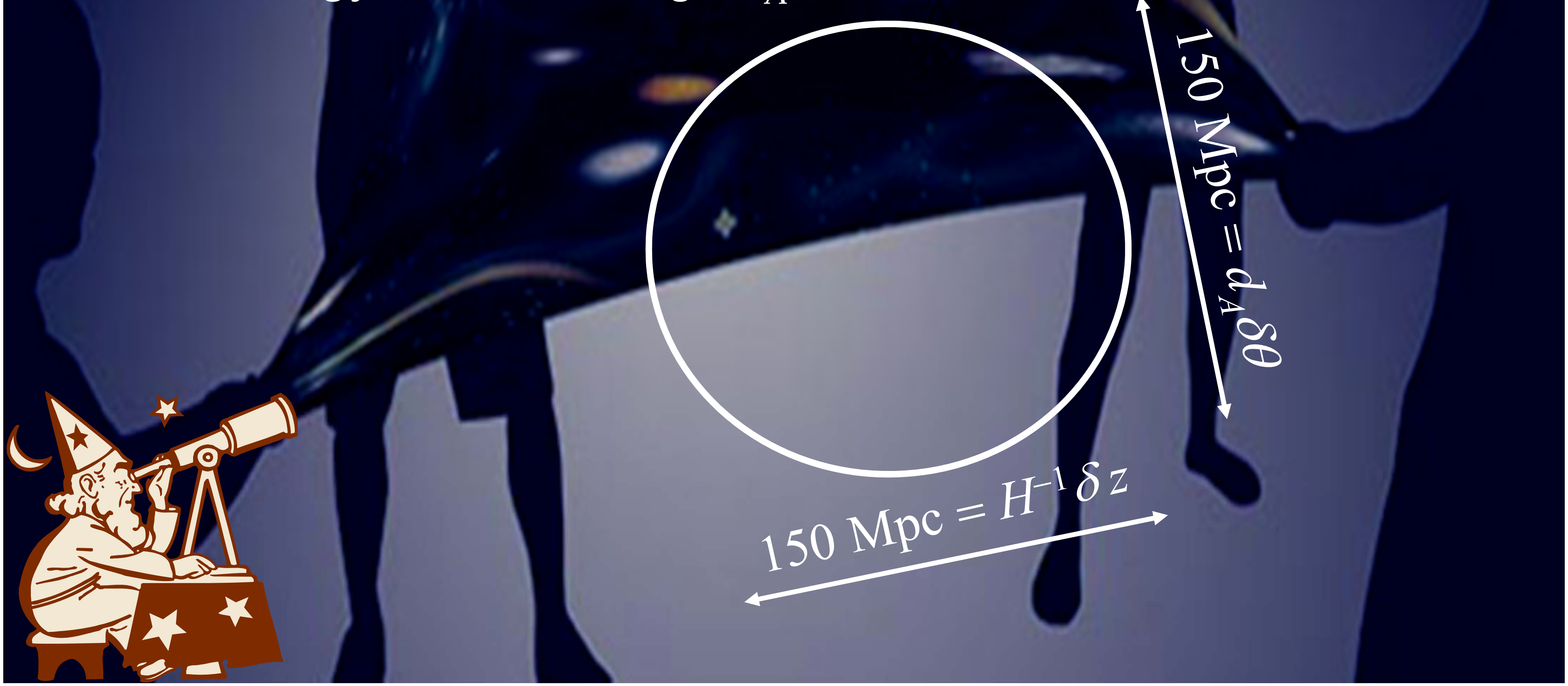


- Sound speed plummets, wave stalls
- Total distance traveled 150 Mpc imprinted on power spectrum



Baryon Acoustic Oscillations

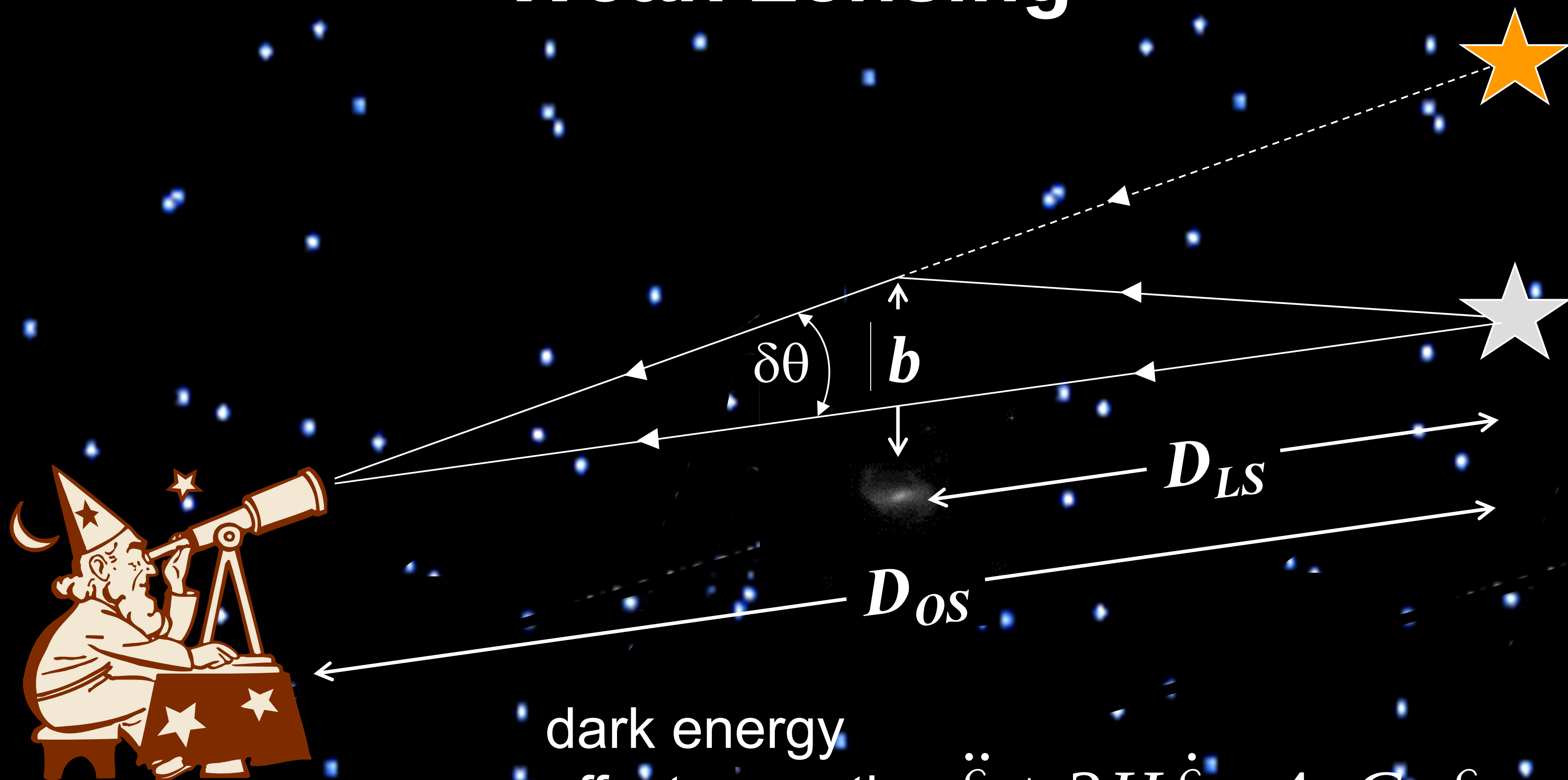
- Acoustic oscillation scale depends on $\Omega_M h^2$ and $\Omega_B h^2$ (set by CMB acoustic oscillations)
- It is a small effect ($\Omega_B h^2 \lll \Omega_M h^2$)
- Dark energy enters through d_A and H



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



dark energy affects growth rate of M

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho\delta = 0$$

observe deflection angle

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

dark energy affects geometric distance factors

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 (2021)
  - full hemisphere, very deep 6 colors
- JDEM/Euclid (???)

Galaxy Clusters

<u>Cluster redshift surveys measure</u>

- cluster mass, redshift, and spatial clustering

<u>Sensitivity to dark energy</u>

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

<u>Problems:</u>

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

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.)

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* Dark Energy Task Force

DETF Cosmological Model

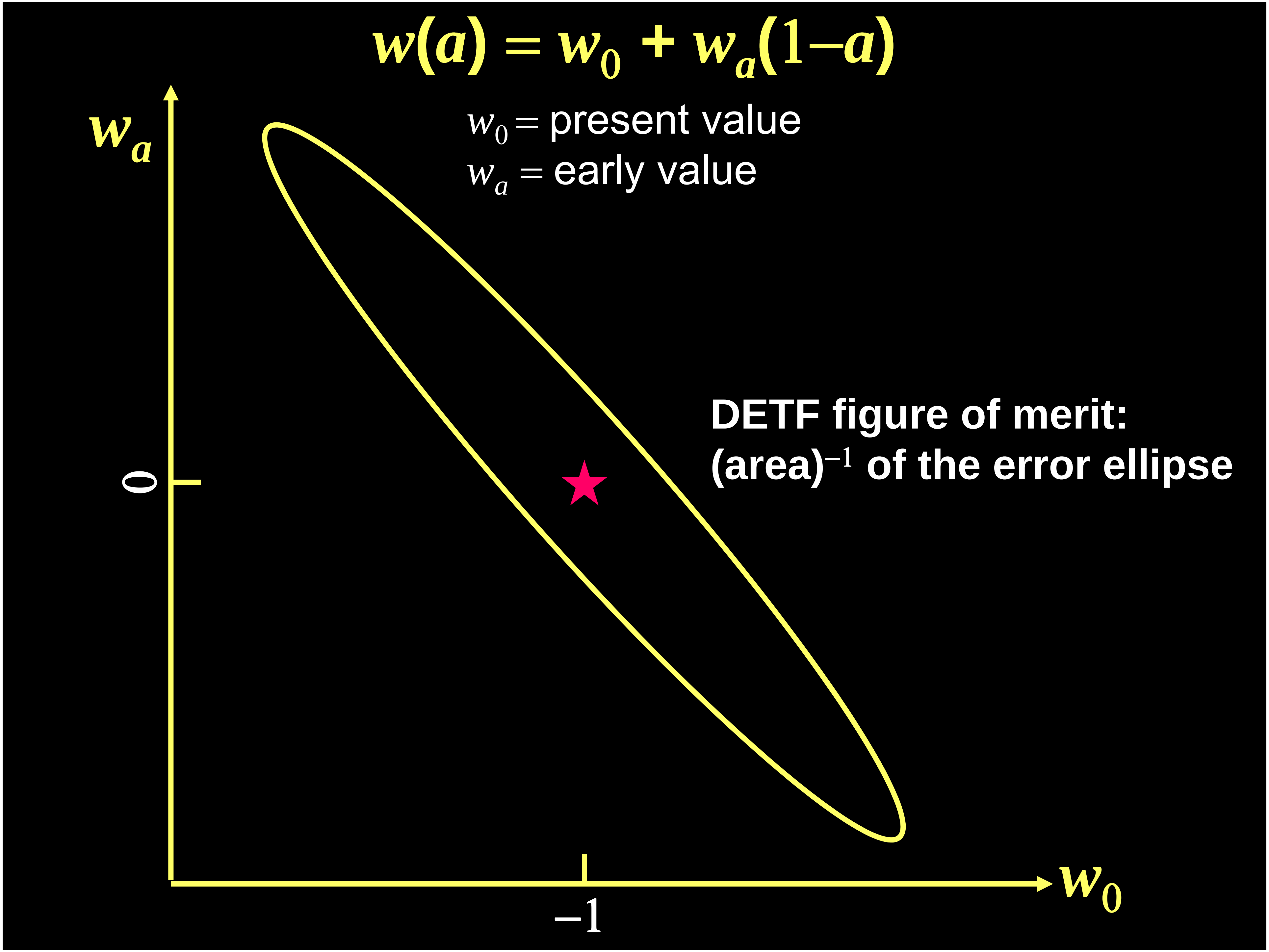
Parameterize dark-energy equation of state parameter w as:

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

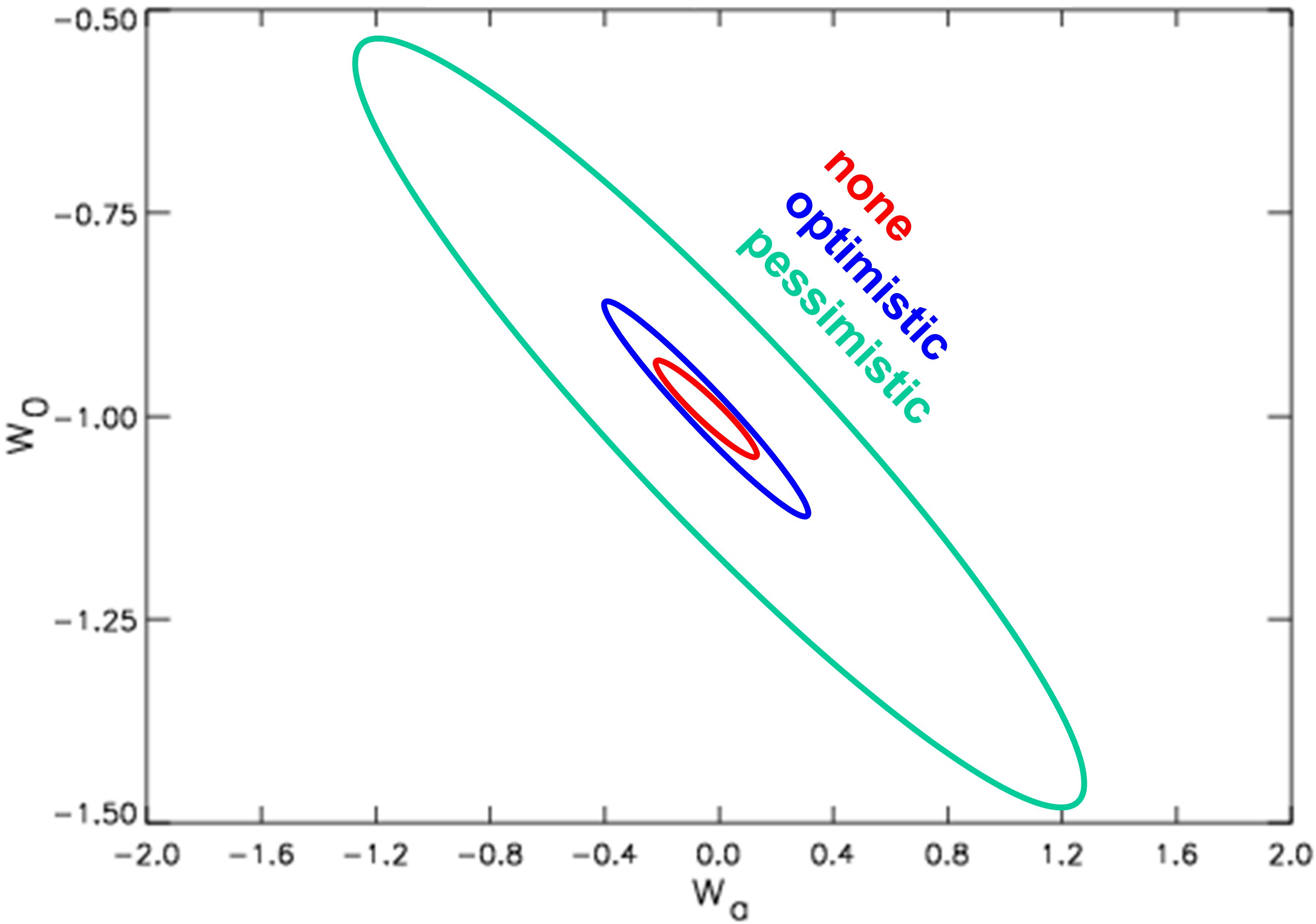
- Today ($a = 1$) $\quad w(1) = w_0$
- In the far past ($a \to 0$) $\quad w(0) = w_0 + w_a$

Standard eight-dimensional cosmological model:

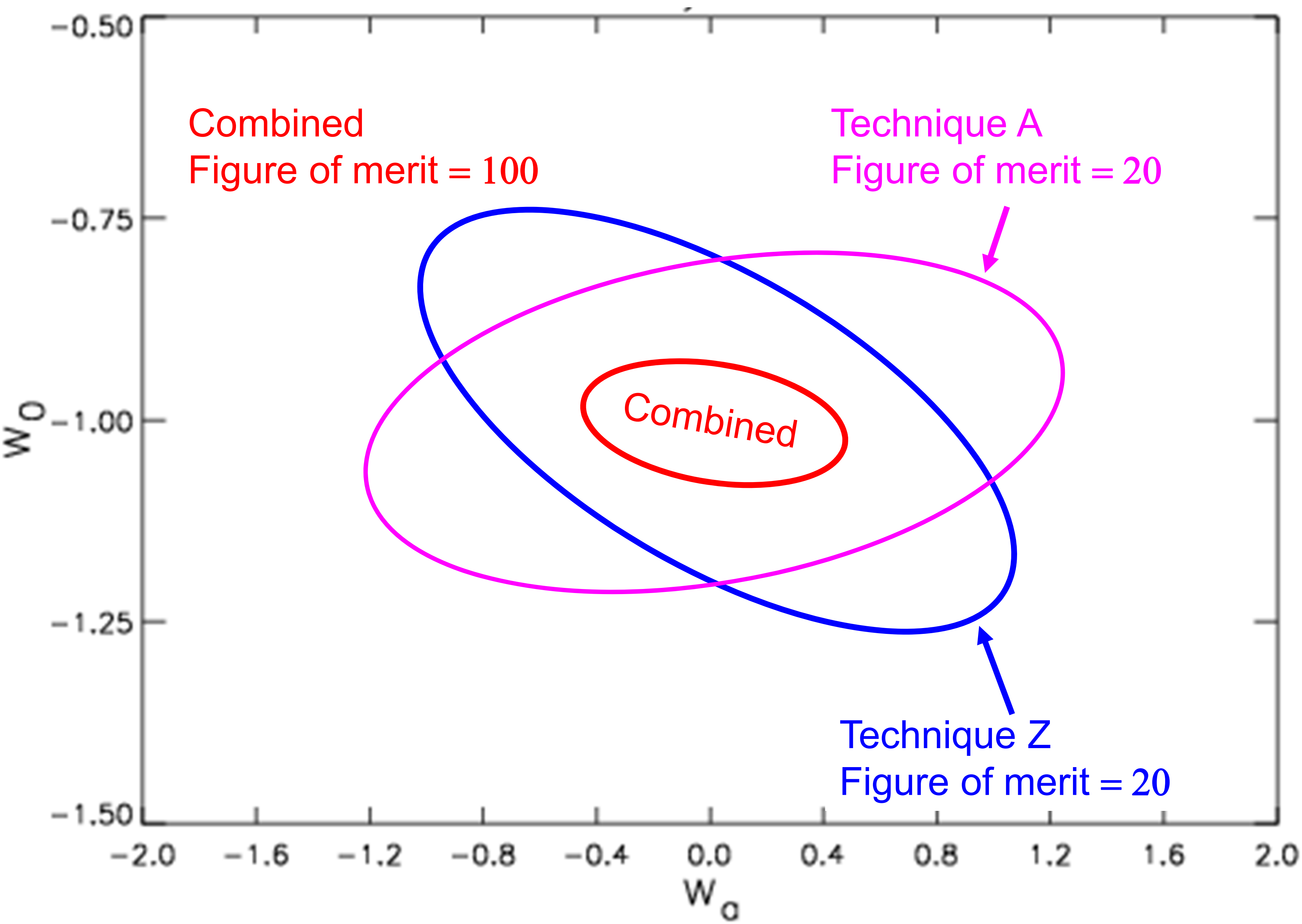
w_0 : the present value of the dark-energy *eos* parameter
w_a : the rate of change of the dark-energy *eos* parameter
Ω_{DE} : the present dark-energy density
Ω_M : the present matter density
Ω_B : the present baryon density
H_0 : the Hubble constant
δ_ζ : amplitude of *rms* primordial curvature fluctuations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

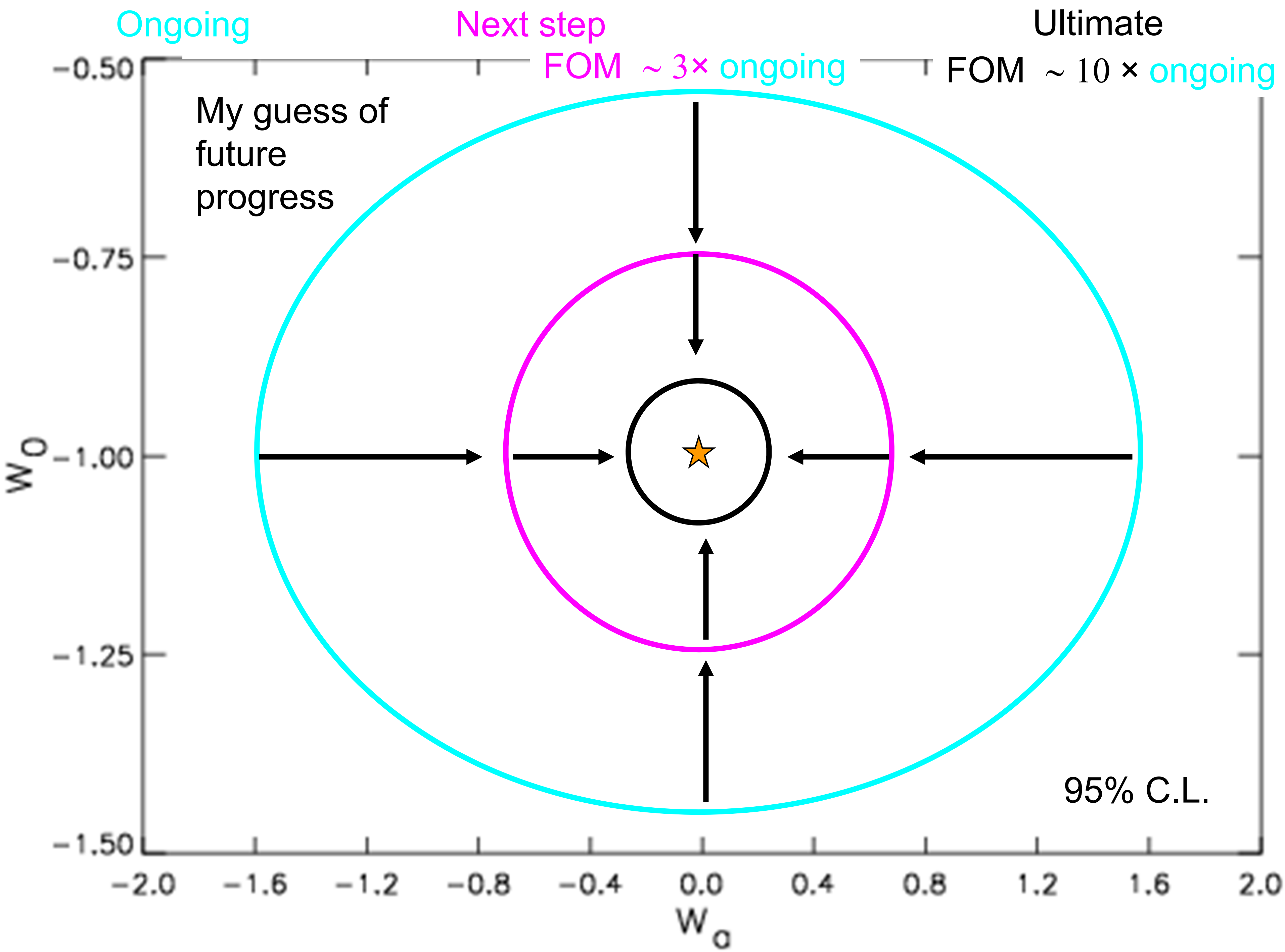

$w(a) = w_0 + w_a(1-a)$
w_0 = present value
w_a = early value
DETF figure of merit:
$(\text{area})^{-1}$ of the error ellipse
w_a
0
-1
w_0

Systematics Are The Key



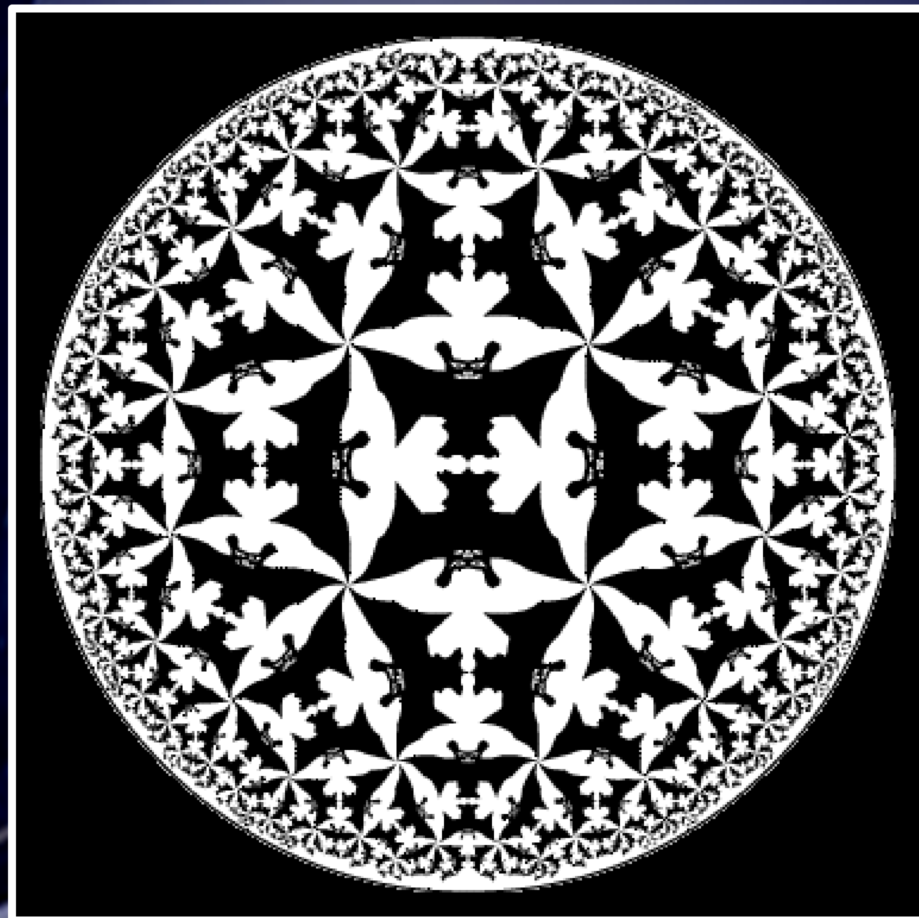
The Power of Two (or 3, or 4)





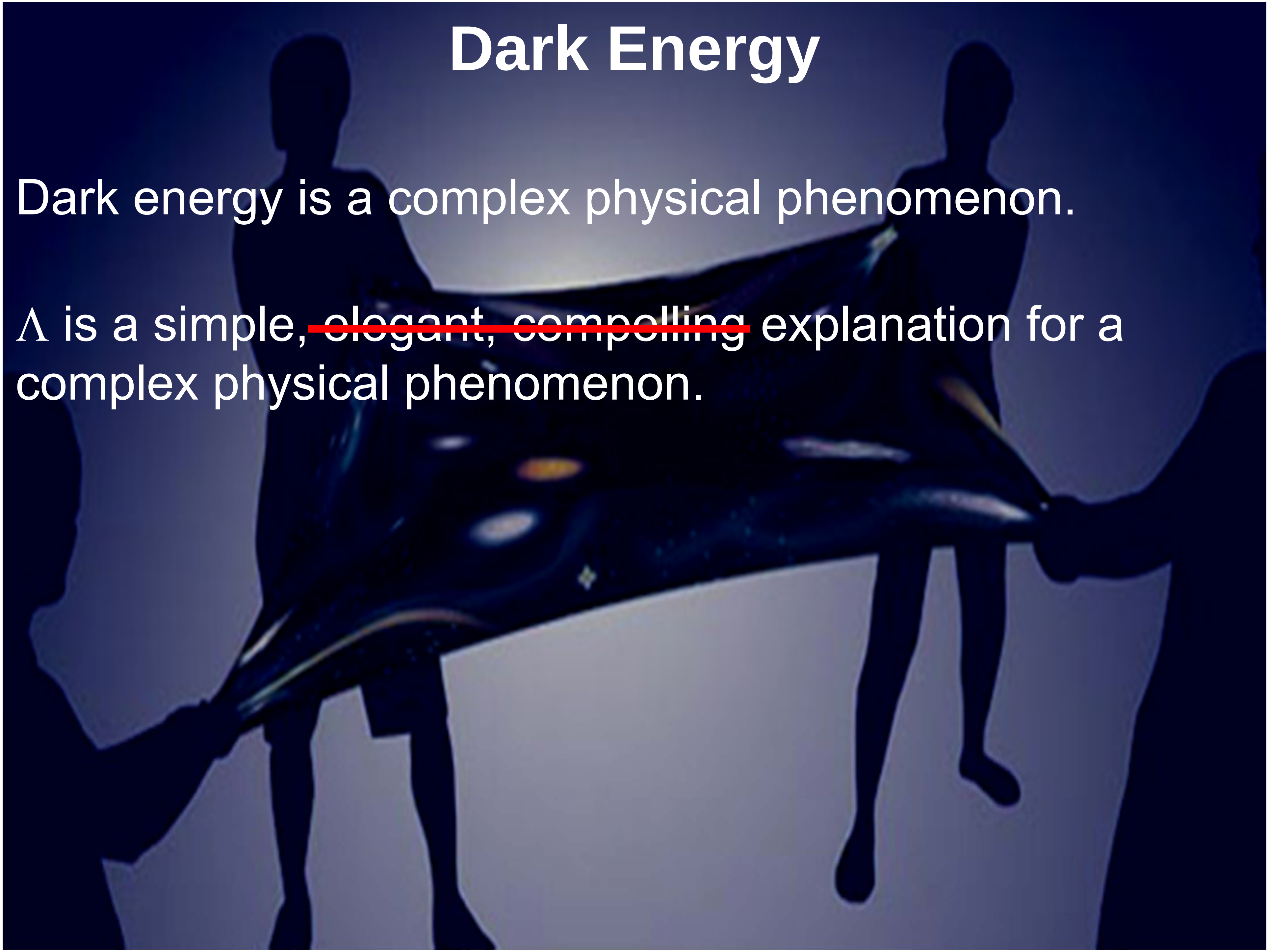
Ongoing
Next step
FOM ~ 3× ongoing
Ultimate
FOM ~ 10 × ongoing
My guess of future progress
95% C.L.
−0.50
−0.75
−1.00
−1.25
−1.50
−2.0
−1.6
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
1.6
2.0
w_0
w_a

Asymptotic de Sitter Space?



- Our cosmic horizon is limited — finite visible Universe
- Finite-dimensional Hilbert space
- Have to do astronomy now!

Dark Energy



Dark energy is a complex physical phenomenon.

Λ is a simple, ~~elegant, compelling~~ explanation for a complex physical phenomenon.

Particle Physics Foundations of Dark Matter, Dark Energy, and Inflation

Rocky I:	Dark Matter	(Wednesday, 11:00)
Rocky II:	Dark Matter II	(Thursday, 11:00)
Rocky III:	Energy	(Friday, 11:00)

Rocky Kolb

University of Chicago