ΛCDM
Standard Cosmological Model
or
21st Century Epicycles?

2008 Hadron Collider Physics Summer School
August 2008

Rocky Kolb
University of Chicago

Precision Cosmology

The cosmological standard model ΛCDM

Dark Matter

+

Dark Energy

+

Seed Perturbations

(Inflation)

+

Baryo/Leptogenesis

The Universe seems to demand *NEW* PHYSICS!

Astronomy's is helpful to physics!

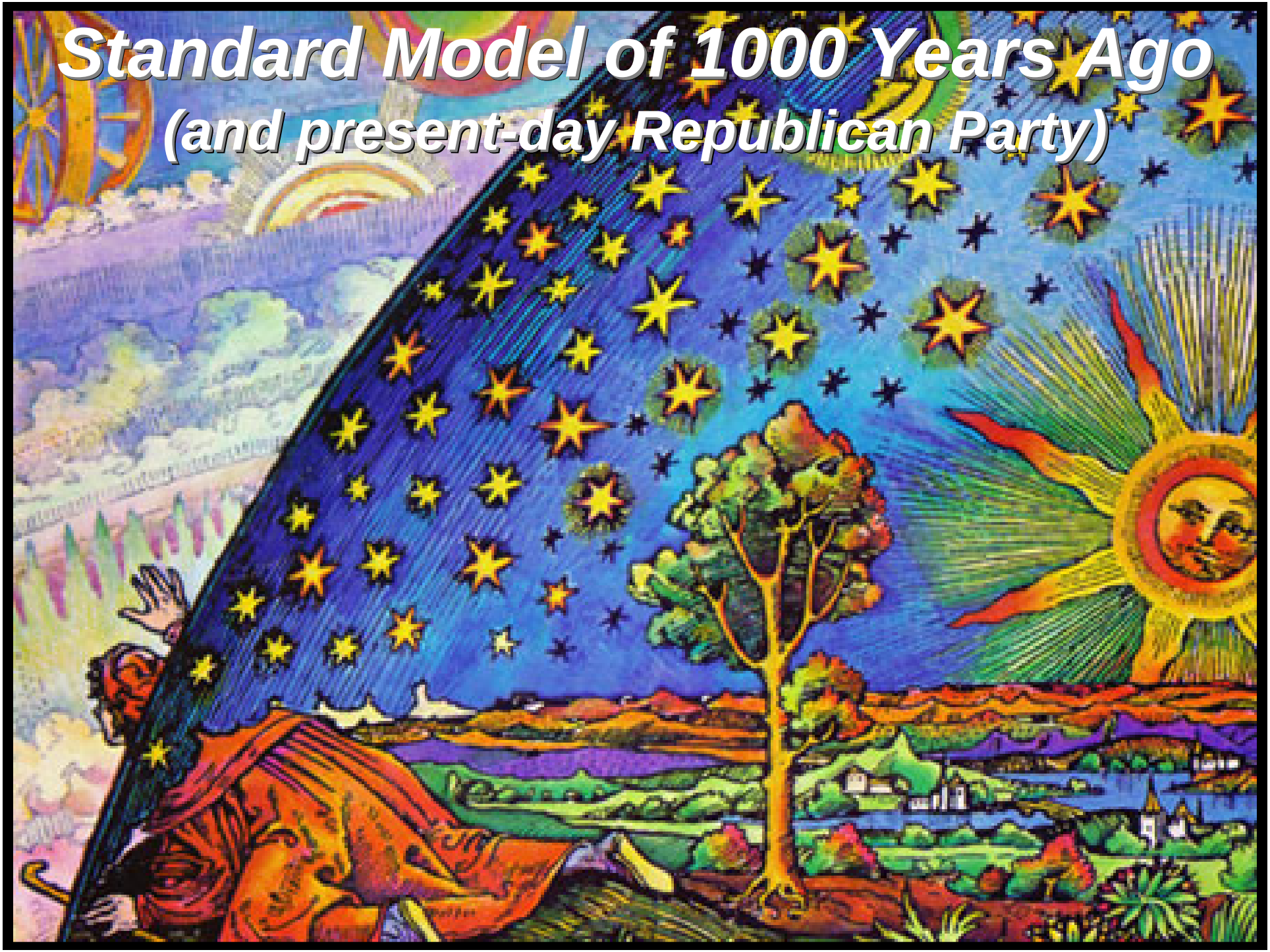
Precision Cosmology

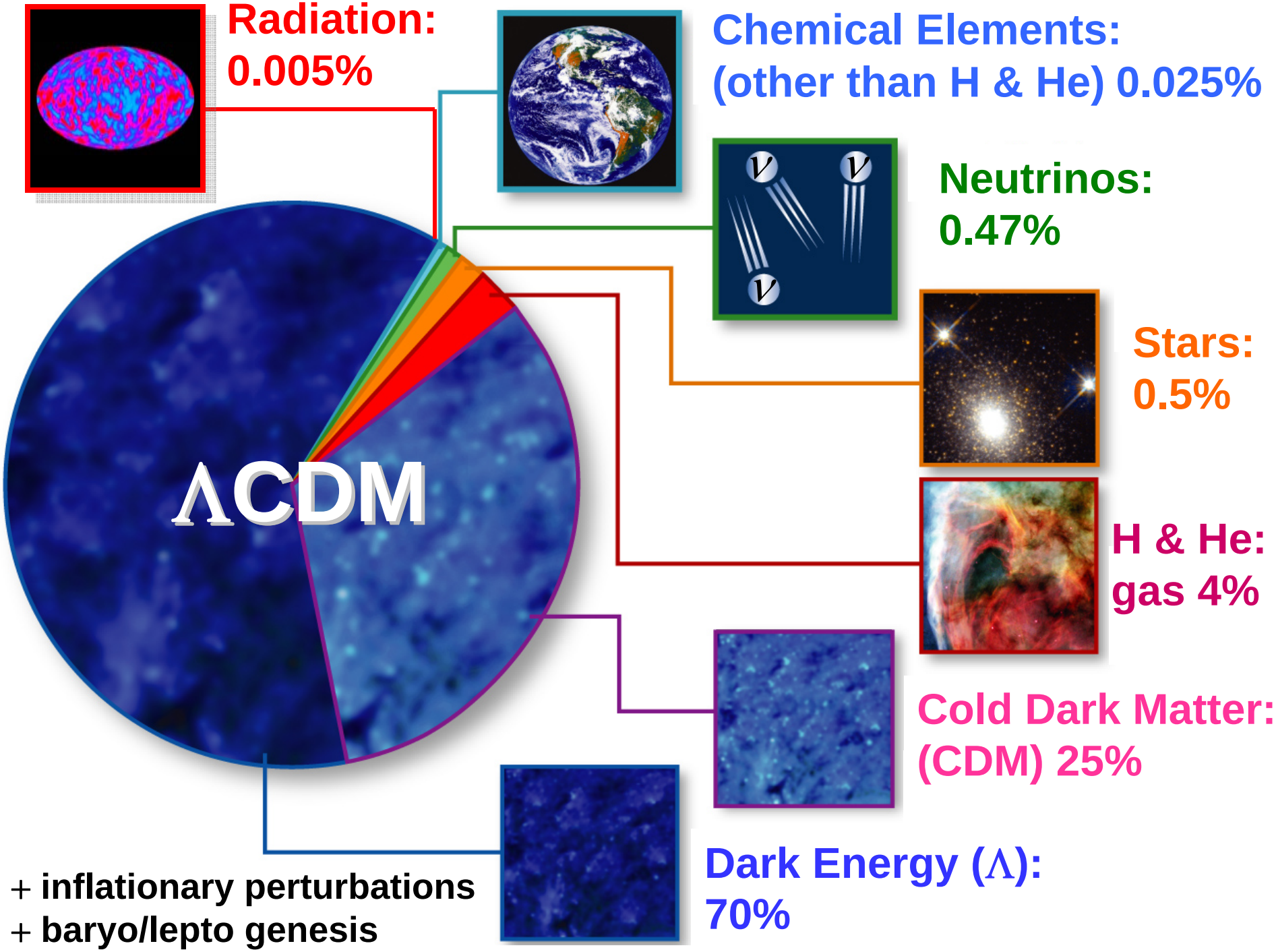
"How helpful to us is astronomy's pedantic accuracy, which I used to secretly ridicule!"

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

Standard Model of 1000 Years Ago

(and present-day Republican Party)




Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
ΛCDM
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
+ inflationary perturbations
+ baryo/lepto genesis

Mission accomplished …

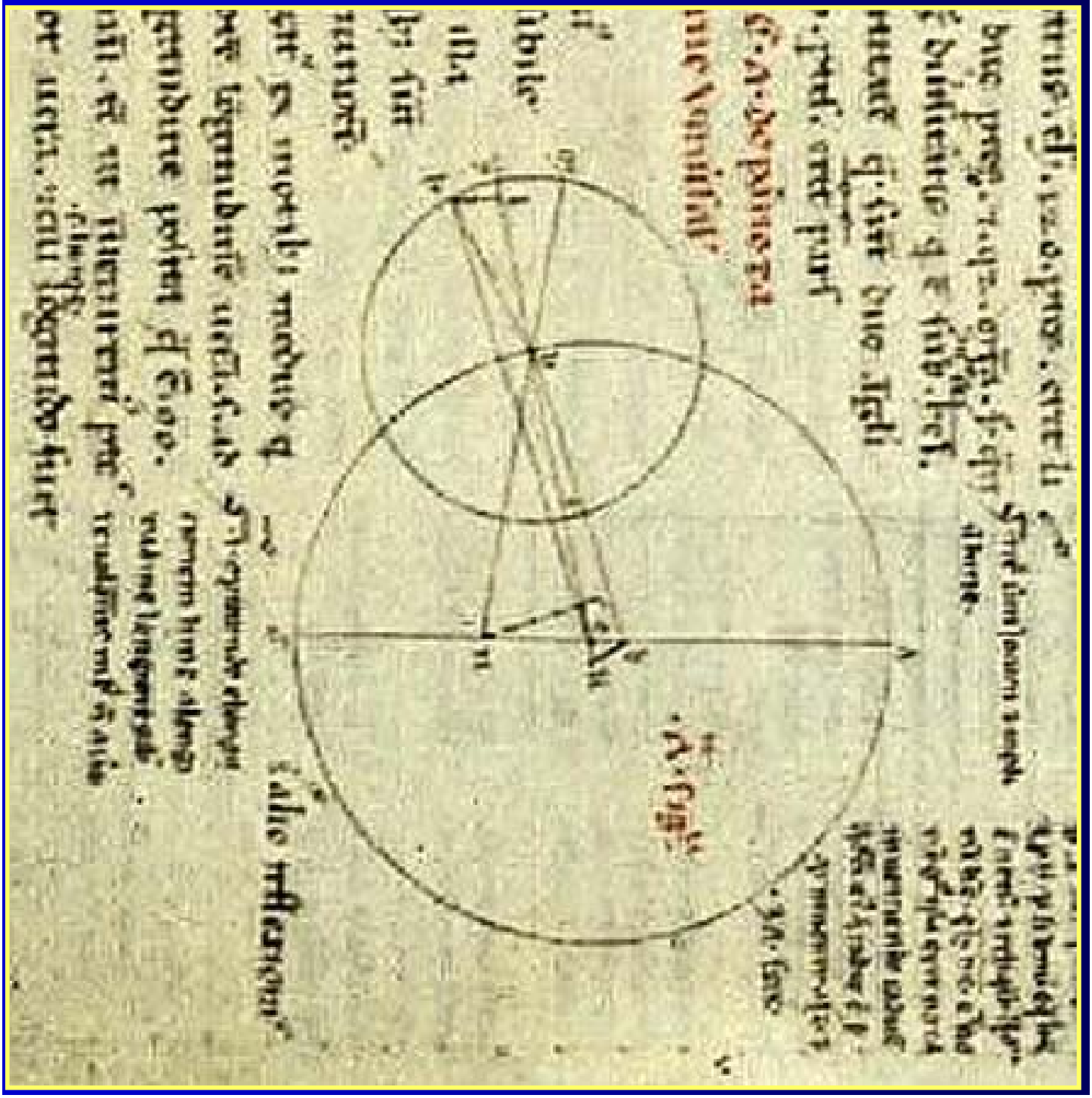
… or premature celebration?

ΛCDM: Reality Or A Substitute?

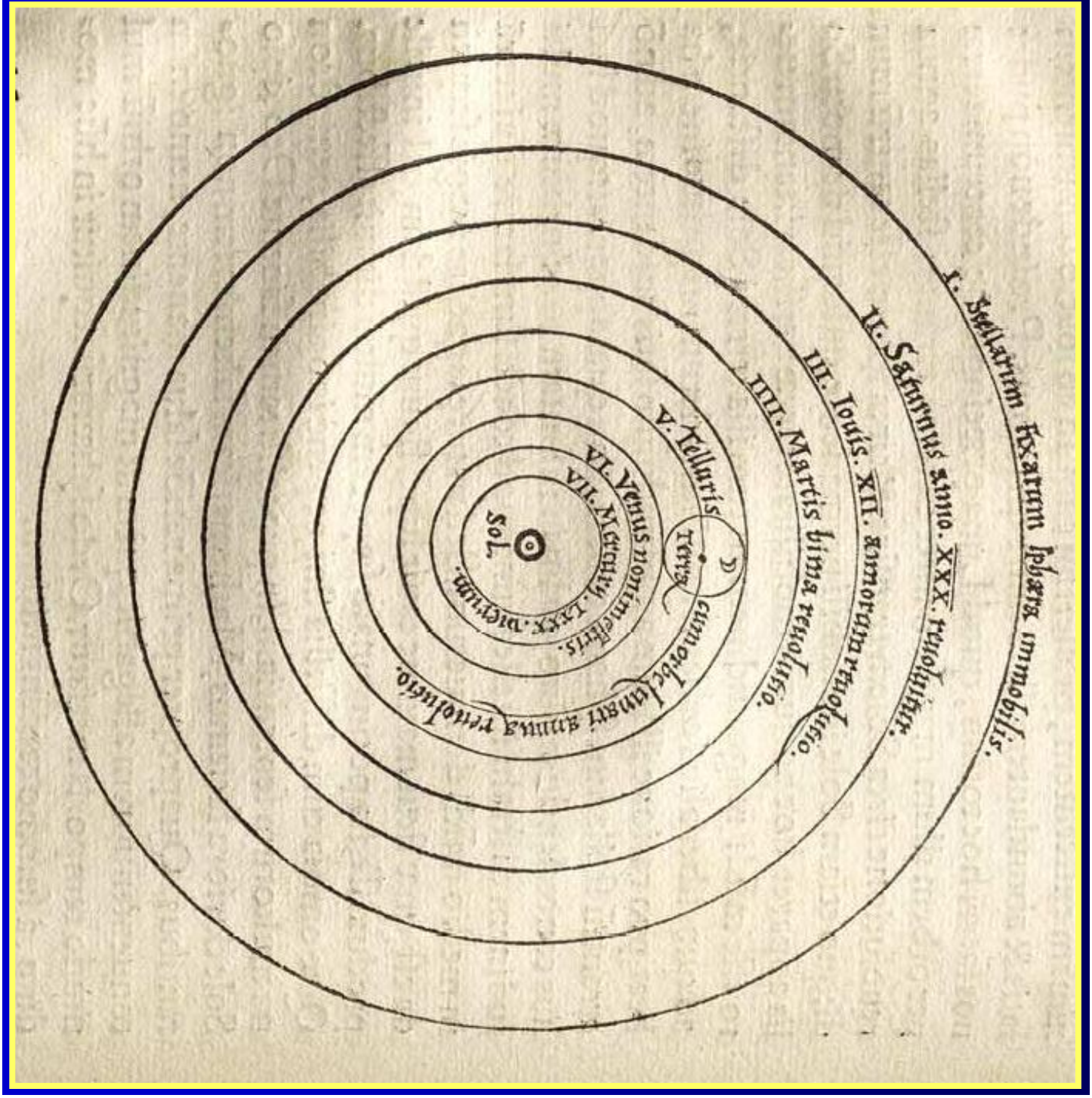
The construction of a model … consists of snatching from the enormous and complex mass of facts called reality a few simple, easily managed key points which, when put together in some cunning way, becomes for certain purposes a substitute for reality itself.

Evsey Domar
Essays on the Theory of Economic Growth

Ptolemaic System From *The Almagest*

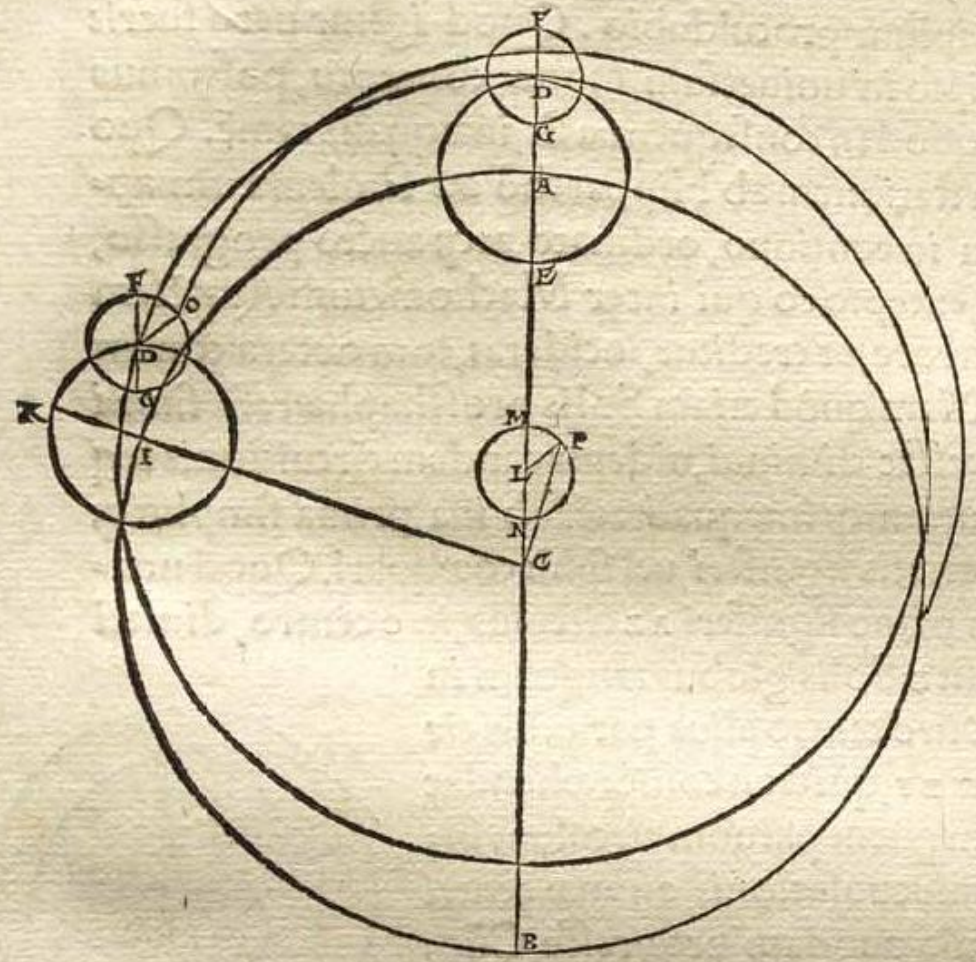


From Book I of *De Revolutionibus*



From Book III of *De Revolutionibus*

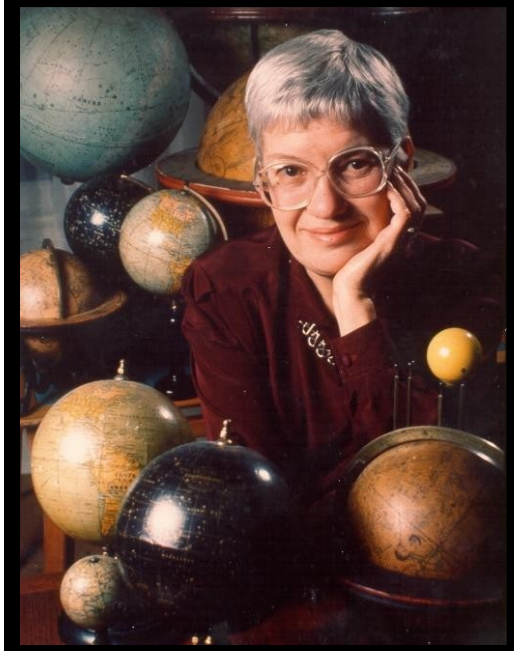
quoq; epicyclum hoc modo. Sit mundo ac Soli homocentrus A B, & A C B diameter, in qua ſumma abſis contingat. Et facto in A centro epicyclus deſcribatur D E, ac rurſus in D centro epicyclium F G, in quo terra uerſetur, omniaq; in eodem plano zodiaci.



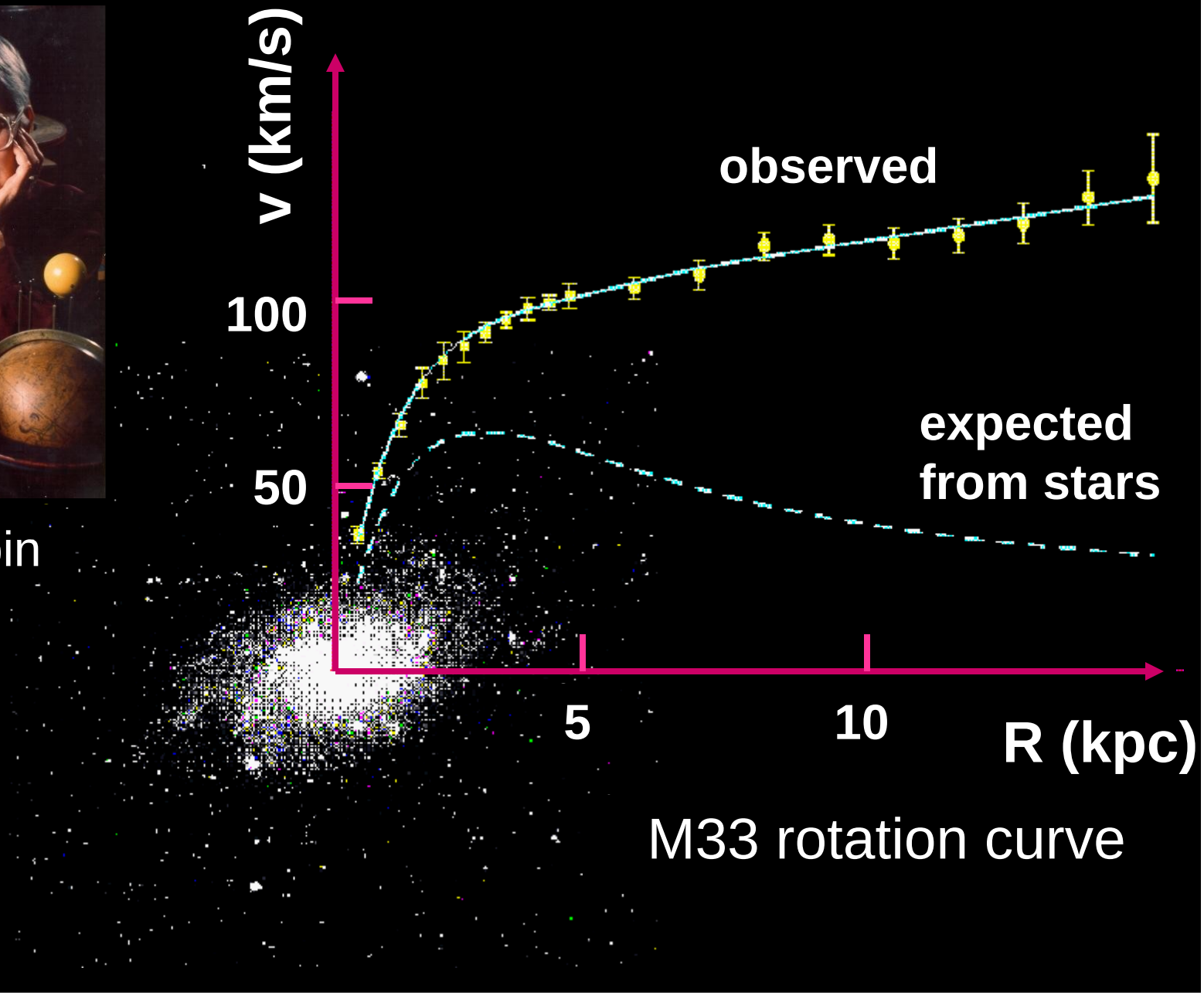
Sitq; epicycli primi motus in ſuccedẽtia, ac annuus ferè, ſecũdi q̃q; hoc eſt D, ſimiliter annuus, ſed in præcedentia, ambo rumq; ad A C lineam pares ſint reuolutiones. Rurſus cẽtrum terræ ex F in præcedentia addat parumper ipſi D. Ex hoc manifeſtũ eſt quôd cum terra fuerit in F, maximum efficiet Solis apogeum, in G minimum: in mediis autem circumferentijs ipſius F G epicyclij faciet ipſum apogeum præcedere uel ſequi, auctum dimi

The Dark Universe

The Dark Universe



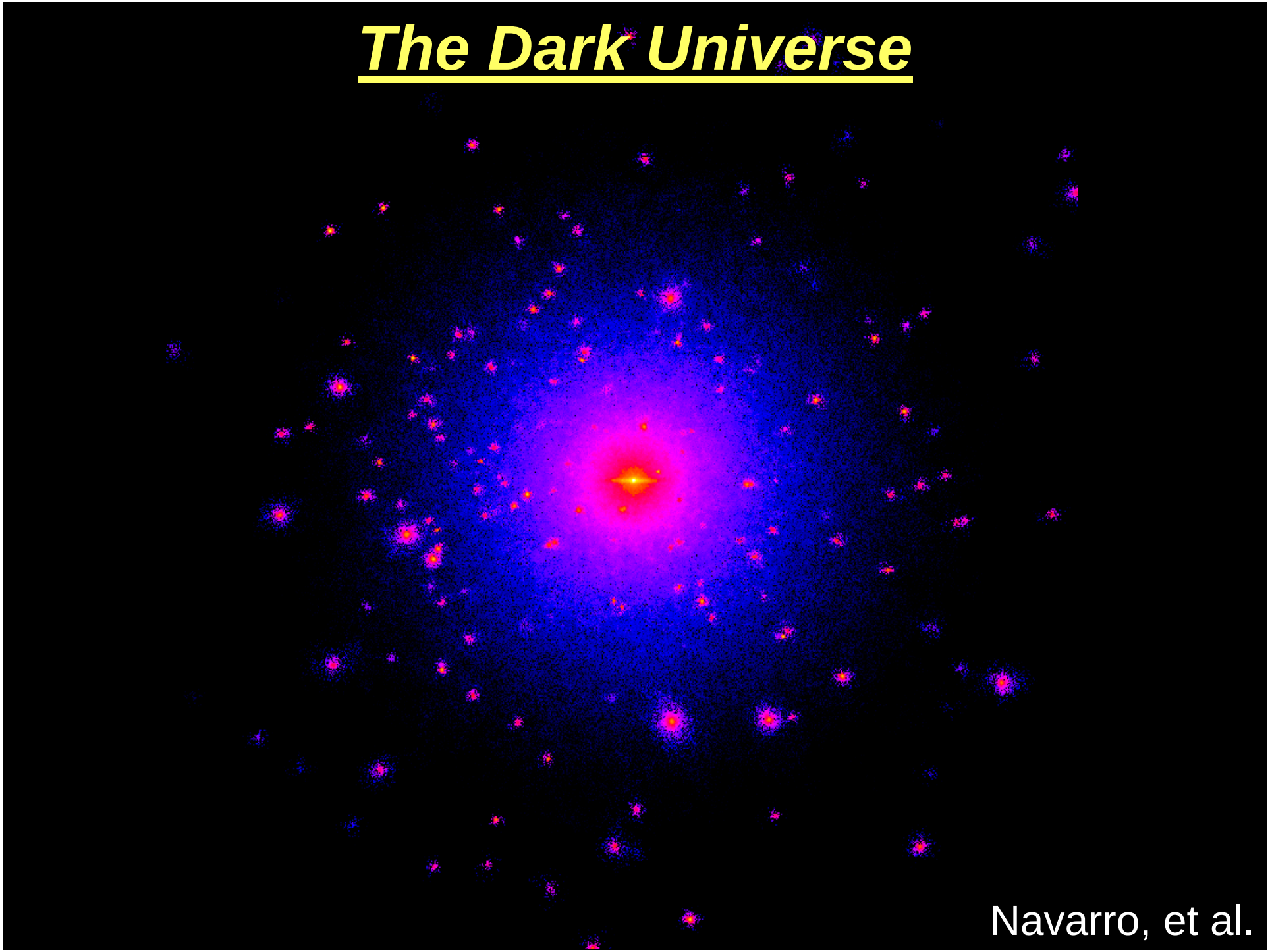
Vera Rubin



M33 rotation curve

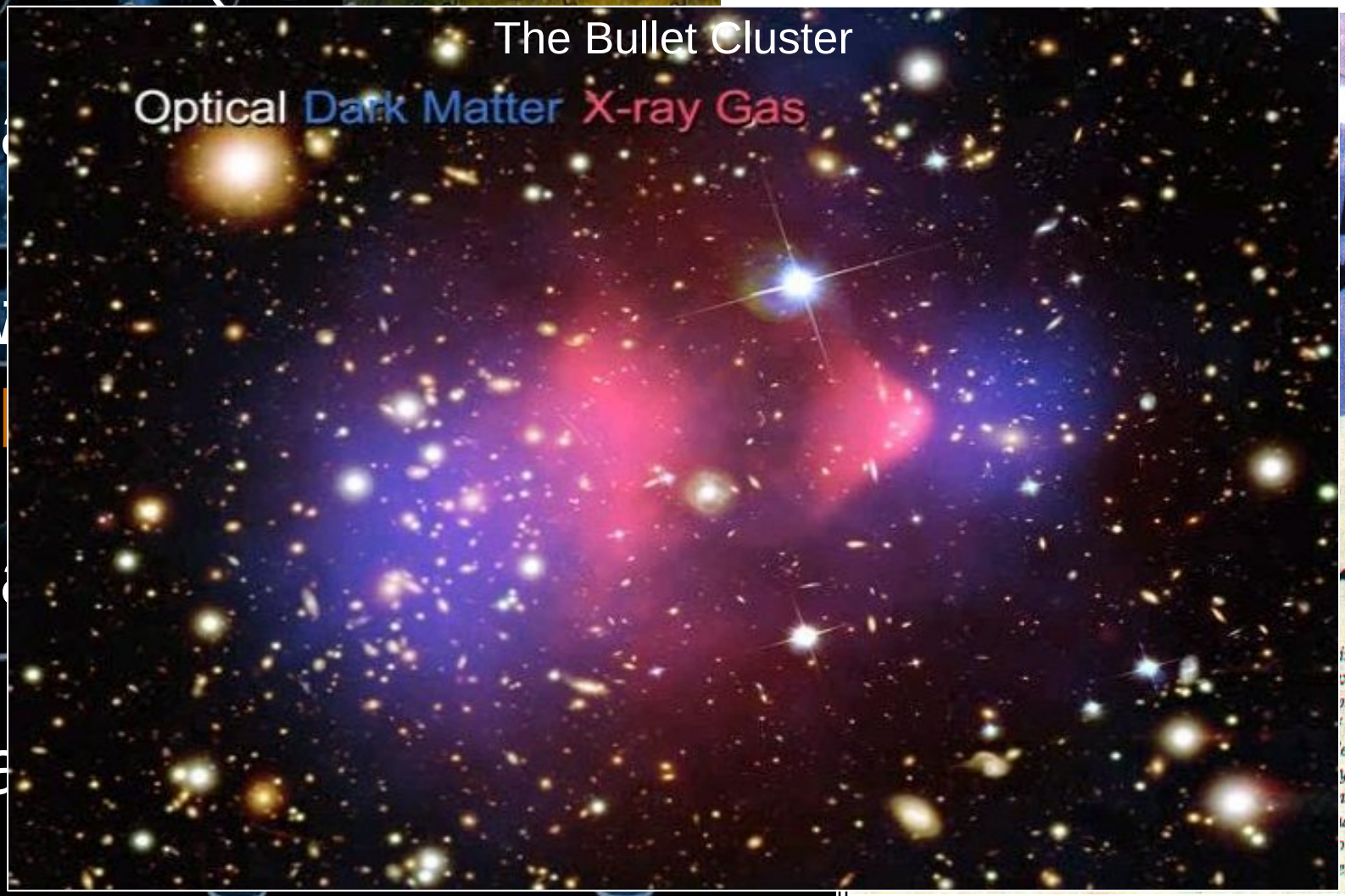
The Dark Universe

The Dark Universe



Dark Matter

- MOND (Modified Newtonian Dynamics)
- Pl
- Di
- Bl
- Pa



The Bullet Cluster

Neutrinos

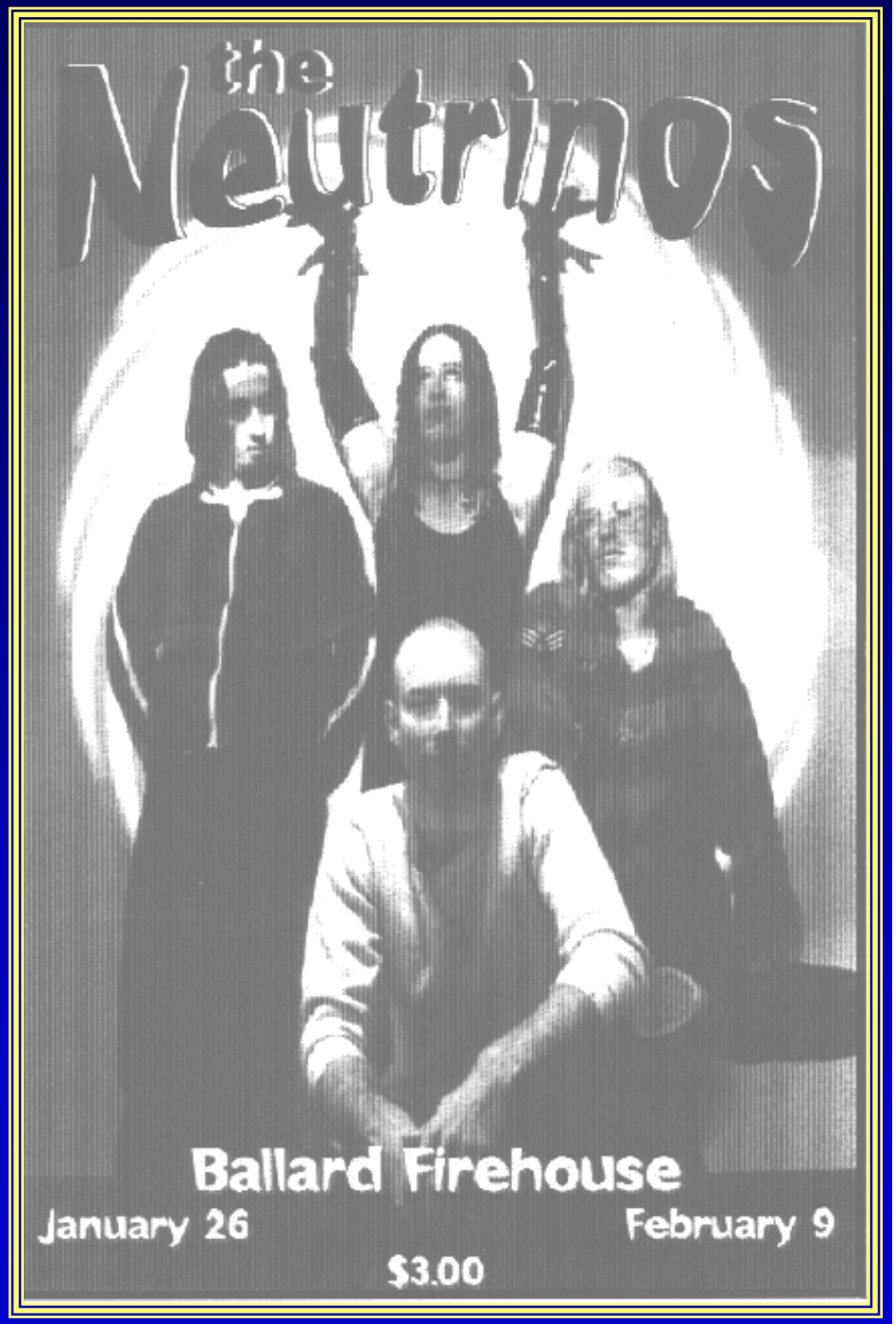
- **Neutrinos exist:**
  three active + sterile?

- **Neutrinos have mass:**
  Atmospheric (10^{-2} eV)
  Solar (10^{-3} eV)

- **Contribute to Ω**
  hot thermal relic:

$$\Omega_{\nu\bar{\nu}} \simeq \frac{m_\nu}{45\ \mathrm{eV}}$$

- **Not most of dark matter**
  too hot!
  too light!



Volume 207, number 1 PHYSICS LETTERS B 9 June 1988

NEUTRINO MASS AND MIXING IMPLIED BY UNDERGROUND DEFICIT OF LOW ENERGY MUON-NEUTRINO EVENTS

John G. LEARNED, Sandip PAKVASA, and Thomas J. WEILER [1]
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA

Received 14 March 1988

Recent observations of a deficit of cosmic ray muon-neutrino interactions in underground detectors suggest that the muon neutrinos may have oscillated to another state. We examine possible neutrino mass and mixing patterns, and their implications for vacuum and matter effects on solar neutrinos, on neutrinos passing through the earth, and on terrastrial neutrino beams. By invoking the see-saw mechanism of neutrino mass generation, we draw inferences on closure of the universe with neutrino masses, on the number of generations, on t-quark and fourth generation masses, and on the Peccei–Quinn symmetry breaking scale. Testable predictions are suggested.

PHYSICS LETTERS B 9 June 1988

e find

(6)

flux is de-
lo estimate
ıcreased by

as much as 50%. (b) Atmospheric electron-neutrinos and muon-neutrinos (not antineutrinos) coming through the earth at $E_\nu \sim 50 - 150$ GeV have matter-enhanced oscillations and the muon-neutrinos down/up flux ratio should be even larger than the nonmatter-enhanced expectation (for energies ~ 1

(d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot

ng angle is

(8)

und (from
are forced

(d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot
dark matter over cold): the tau-neutrino mass may be determined from the time spread of events from a galactic supernova. (e) There are only three generations: the mass of a fourth-generation heavy lepton is bounded from below by the UA1 data [12] and from

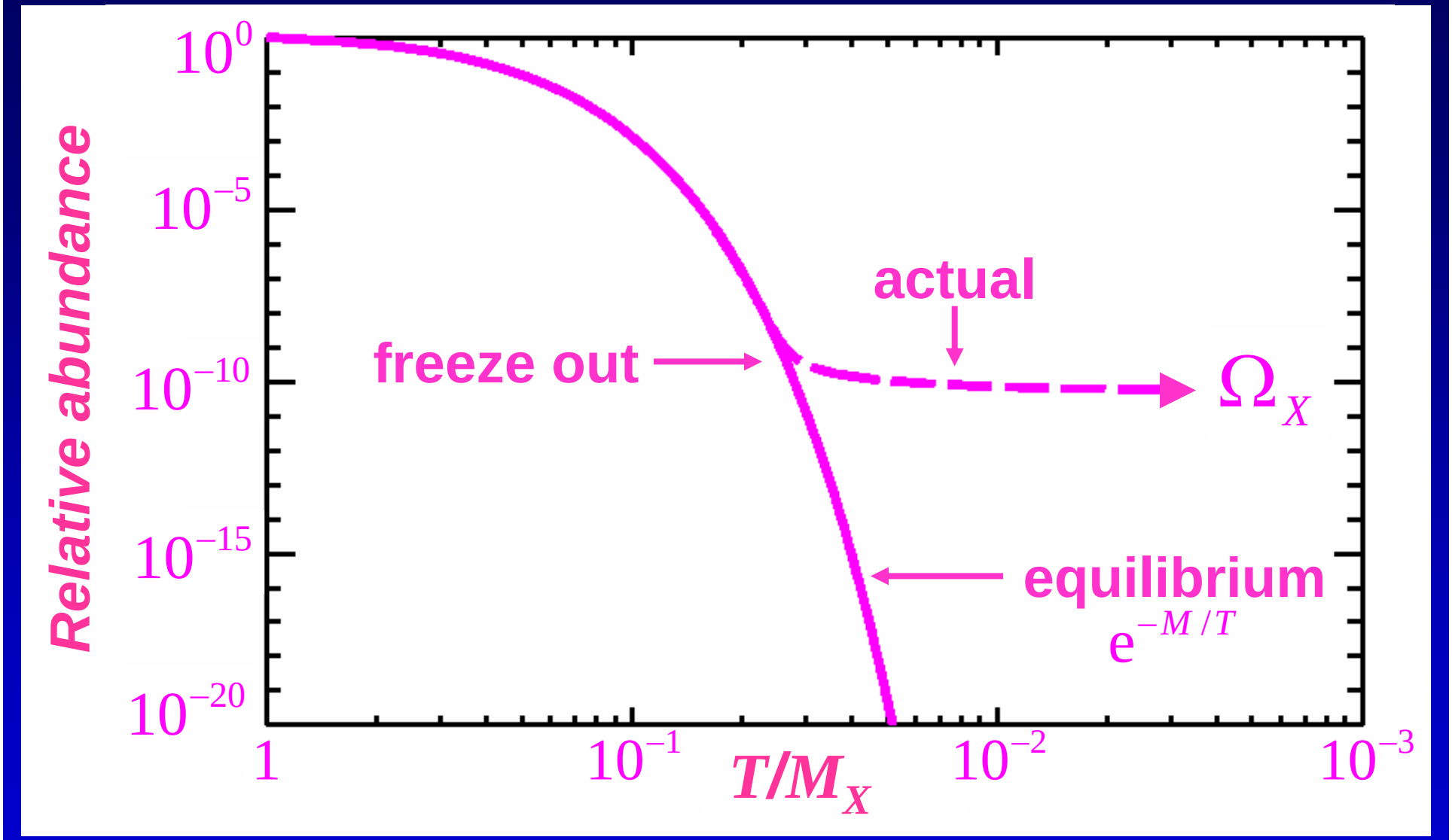
Particle Relic From The Bang

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, axino, …) (cold dark matter)
- LKP (lightest Kaluza-Klein particle)
- axions, axion clusters
- solitons (Q-balls; B-balls; Odd-balls, ….)
- supermassive wimpzillas

Mass range	
$10^{-6}\,\mathrm{eV}$ $(10^{-40}\,\mathrm{g})$	axions
$10^{-8}\,\mathrm{M}_{\odot}$ $(10^{25}\,\mathrm{g})$	axion clusters

Interaction strength range
Noninteracting: wimpzillas
Strongly interacting: B balls

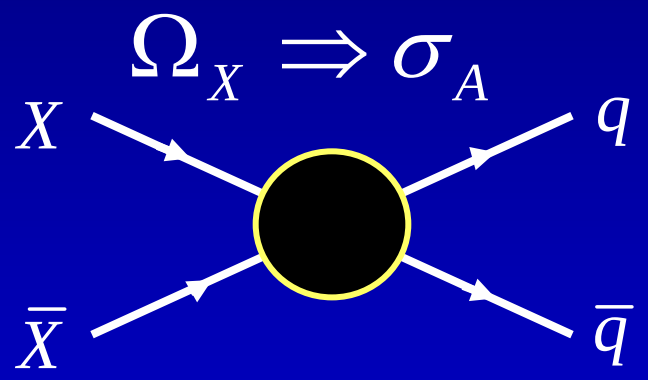
Cold Thermal Relic*



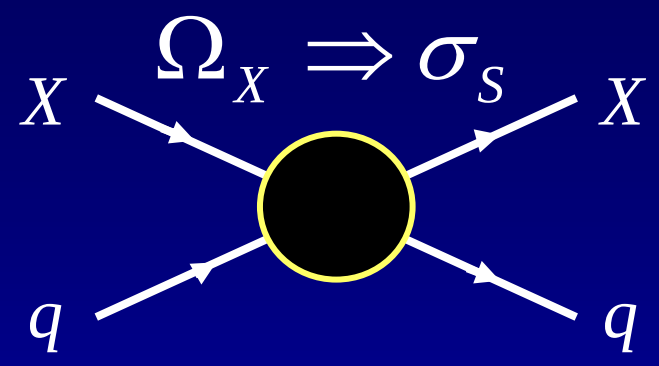
$\Omega_X \propto \sigma_A^{-1}$ *(independent of mass)*

* An object of particular veneration.

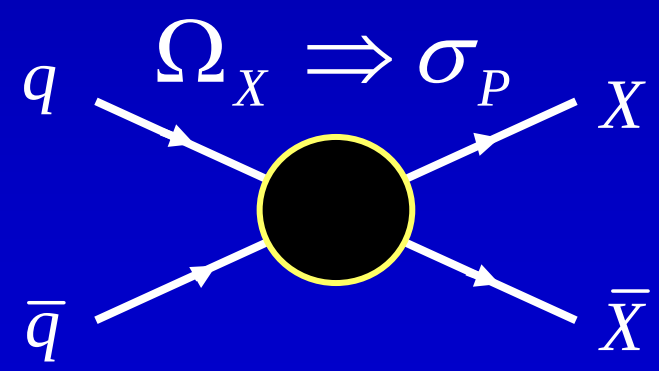
Cold Thermal Relic*



$$X + \bar{X} \rightarrow q + \bar{q}$$



$$X + q \rightarrow X + q$$



$$q + \bar{q} \rightarrow X + \bar{X}$$

* An object of particular veneration.

Cold Thermal Relic*

- **Direct detection (σ_S)**

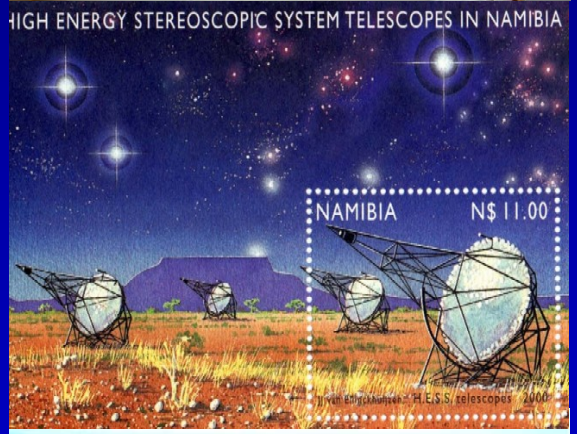
  More than a dozen experiments

- **Indirect detection (σ_A)**

  Annihilation in sun, Earth, galaxy. . .

  neutrinos, positrons,

  antiprotons, γ rays, . . .



- **Accelerator production (σ_P)**

  Tevatron, LHC

*** An object of particular veneration.**

Cold Thermal Relic*

Favorite cold thermal relic: the neutralino (SUSY)

- Direct detectors, indirect detectors, & colliders race for discovery
- Suppose by 2010 have credible signals from all three???

How will we know we all seeing the same phenomenon?

- Lots of opinions (papers)
  - Will learn enough from LHC (Arnowitt & Dutta)
  - Need ILC (Baltz, Battaglia, Peskin, Wizansky)
  - Depends where in SUSY space (Chung, Everett, Kong, Matchev)
  - …
- *Let's hope for this problem!!!!*

*** An object of particular veneration.**

Cold Thermal Relic*

Favorite cold thermal relic: the neutralino (SUSY)

"a simple, elegant, compelling explanation for a complex physical phenomenon"

"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."

- Tommy Gold

*** An object of particular veneration.**

Evidence For Dark Energy

Measuring the expansion history of the Universe

Expansion Rate Is A Key Quantity

Friedmann equation ($G_{00} = 8\pi G T_{00}$) : Expansion rate $H(z)$

Hubble's constant, radiation, matter, curvature, dark energy

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

CMB, LSS, CMB, $H(z)$

Equation of state parameter: $w = p/\rho$

$$w = \begin{cases} 1/3 & \text{radiation} \\ 0 & \text{matter} \\ -1/3 & \text{curvature} \\ -1 & \Lambda \end{cases}$$

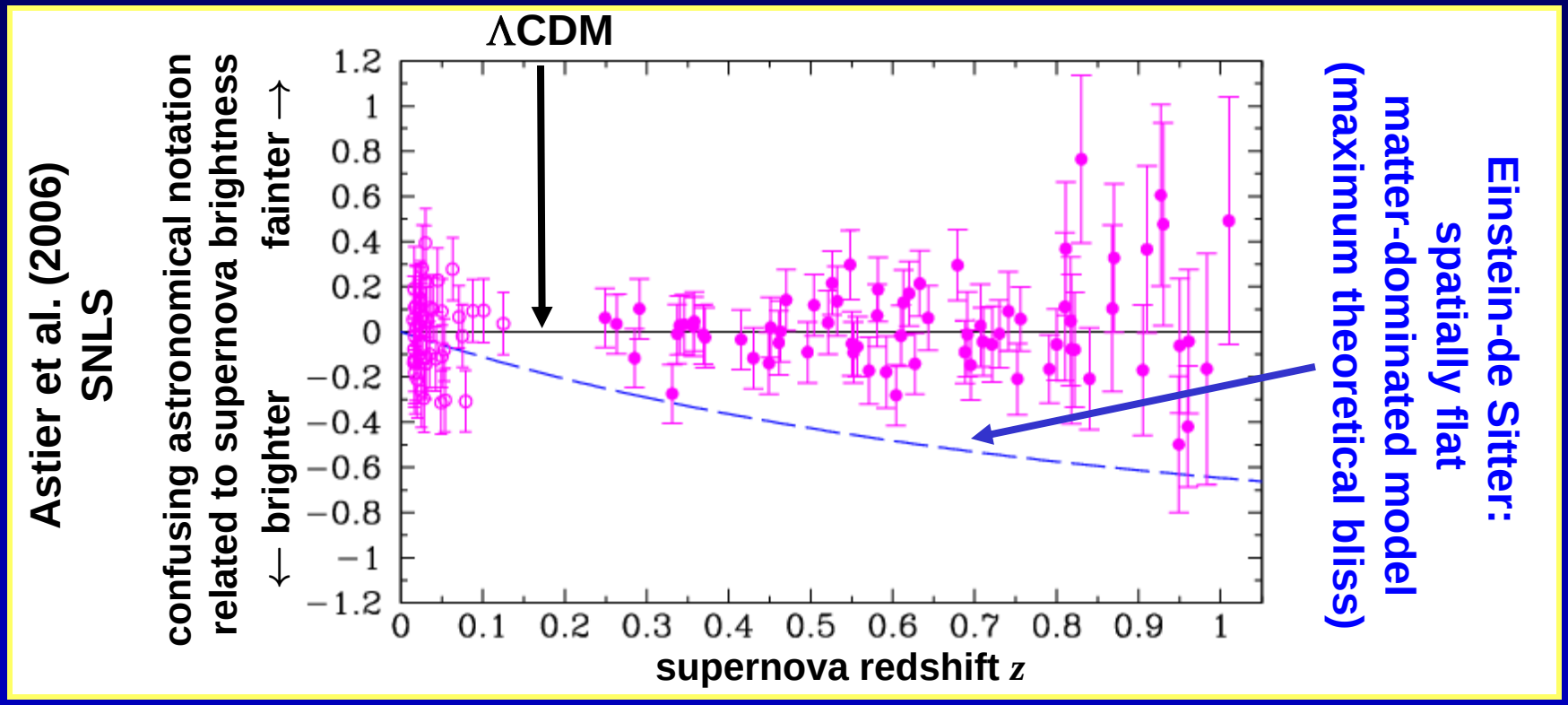
Expansion Rate Is A Key Quantity

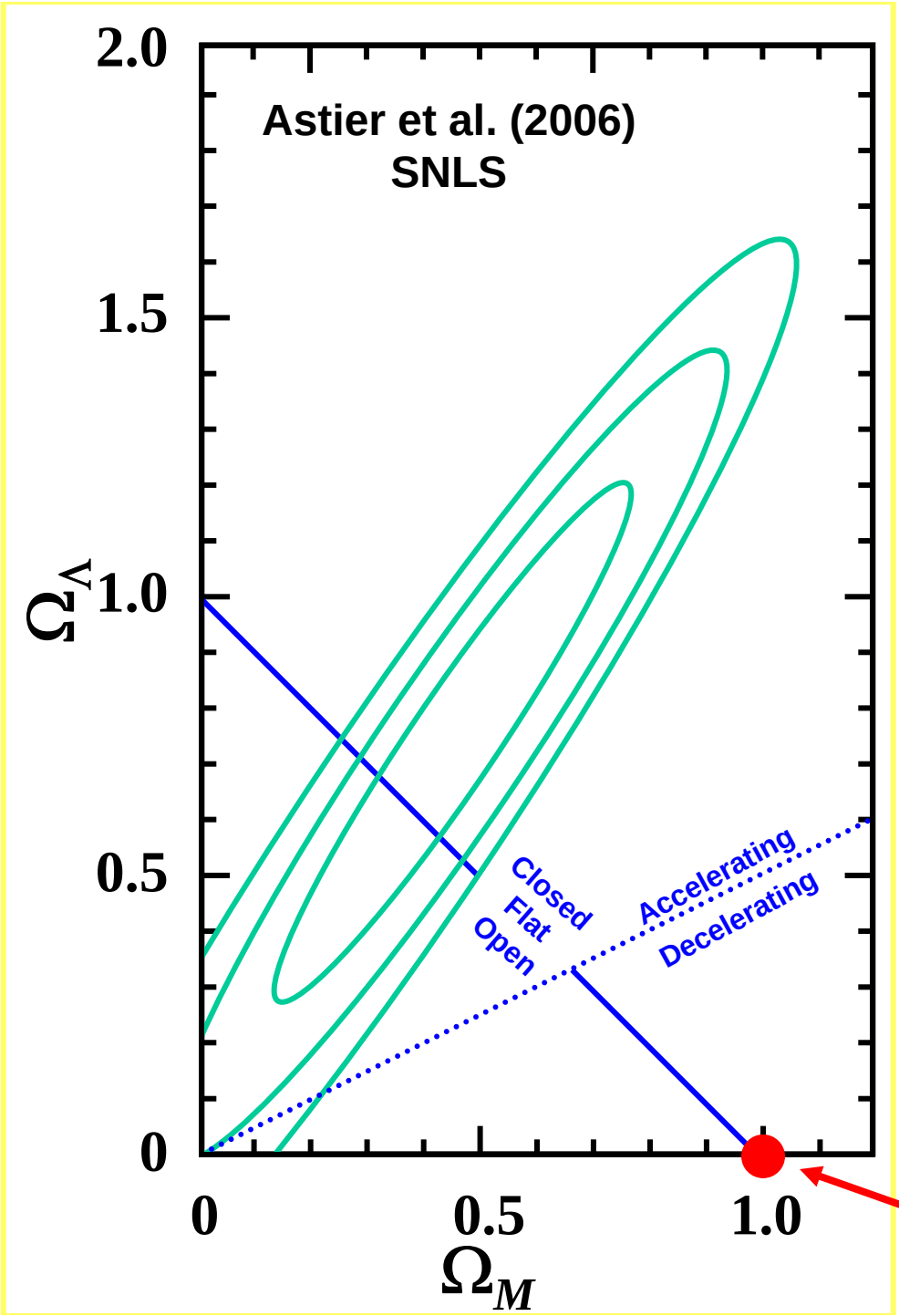
Many observables based on $H(z)$

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

University of Chicago 1909 National Champions

Evidence For Dark Energy





Evidence For Dark Energy

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

   Assumes $w = -1$ (i.e., Λ)

   Assumes priors on H_0, etc.

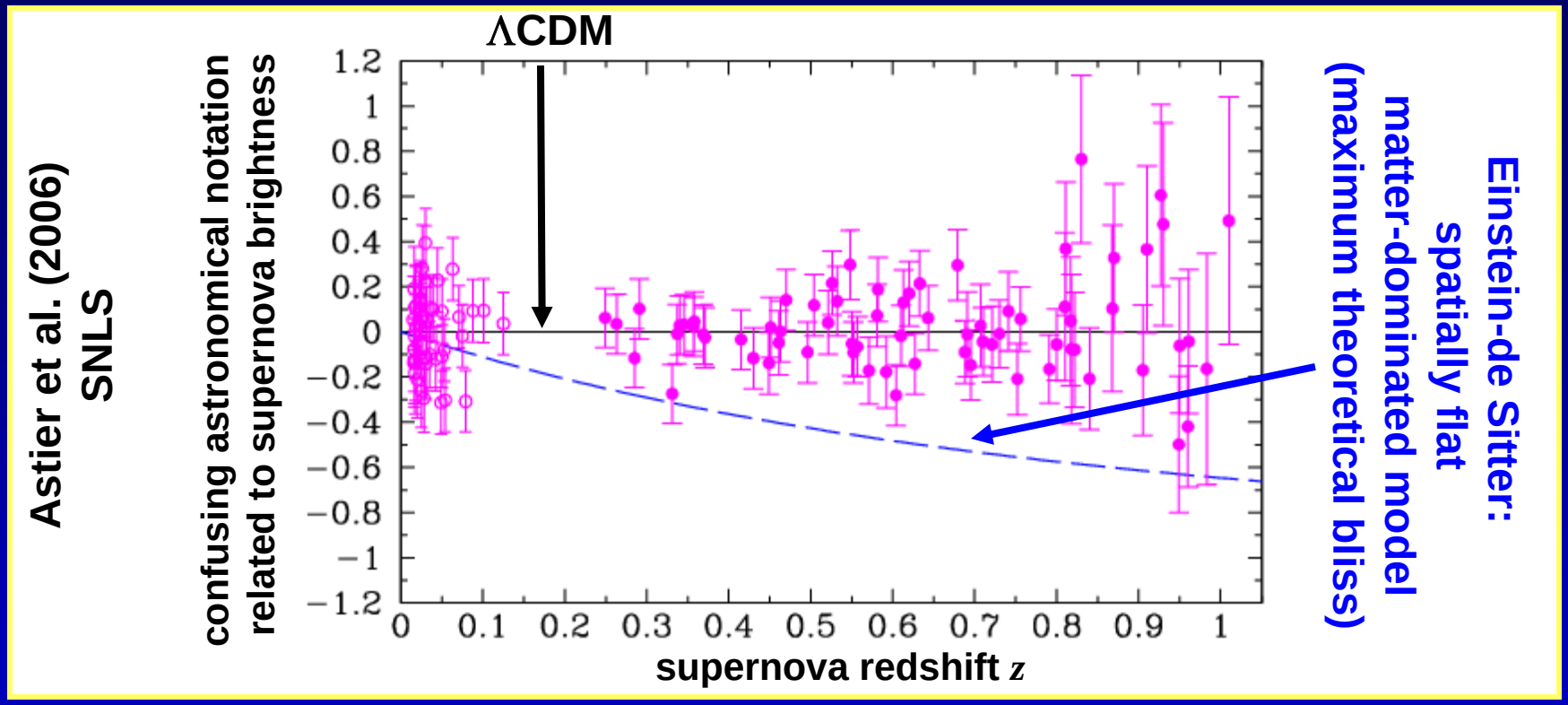
6. Fit needs cosmoillogical constant

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

	ρ_V	$\Lambda = 8\pi G\rho_V$
length scale	10^{-3} cm	10^{+29} cm
mass scale	10^{-4} eV	10^{-33} eV

Einstein–de Sitter model

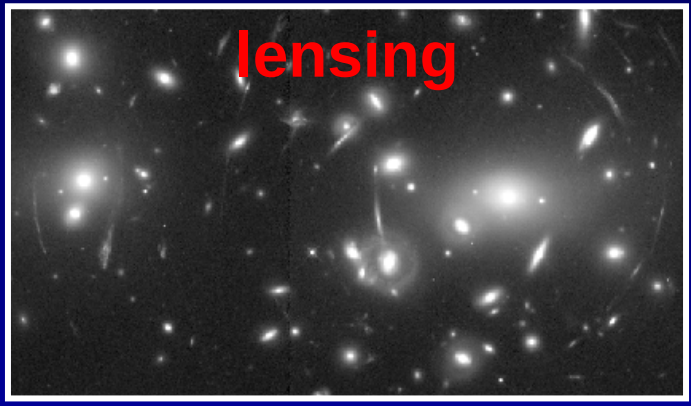
Evidence For Dark Energy

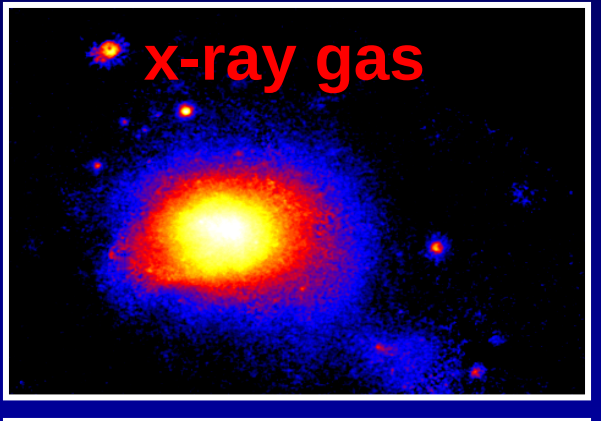


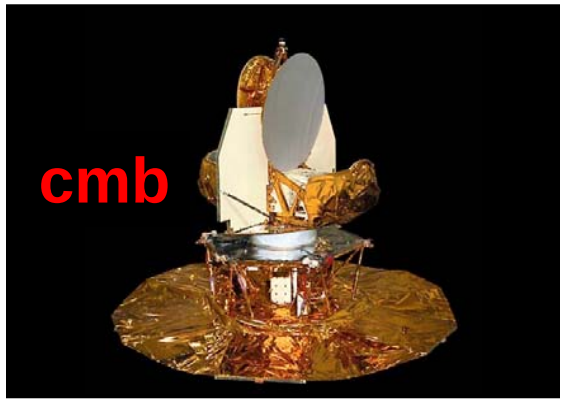
The case for Λ:

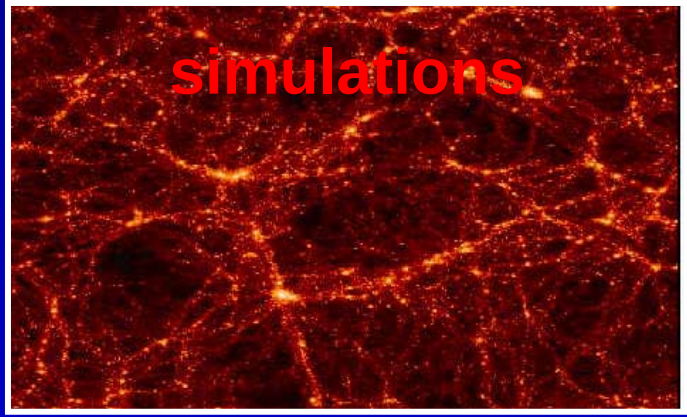
1) Hubble diagram (SNe)
2) Cosmic Subtraction
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

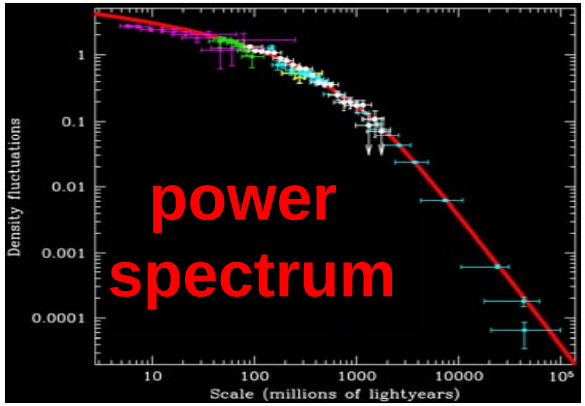
Cosmic Subtraction











$\Omega_{TOTAL} = 1$

CMB

$\Omega_M \sim 0.3$

many methods

$\Omega_B \sim 0.04$

CMB/BBN

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

Cosmoillogical Constant

$$\rho_V \simeq 10^{-30}\ \mathrm{g\ cm^{-3}}\ !!!!!$$

(The Unbearable Lightness of Nothing)

	ρ_V	$\Lambda = 8\pi G \rho_V$
length scale	10^{-3} cm	10^{+29} cm
mass scale	10^{-4} eV	10^{-33} eV

Cosmoillogical Constant

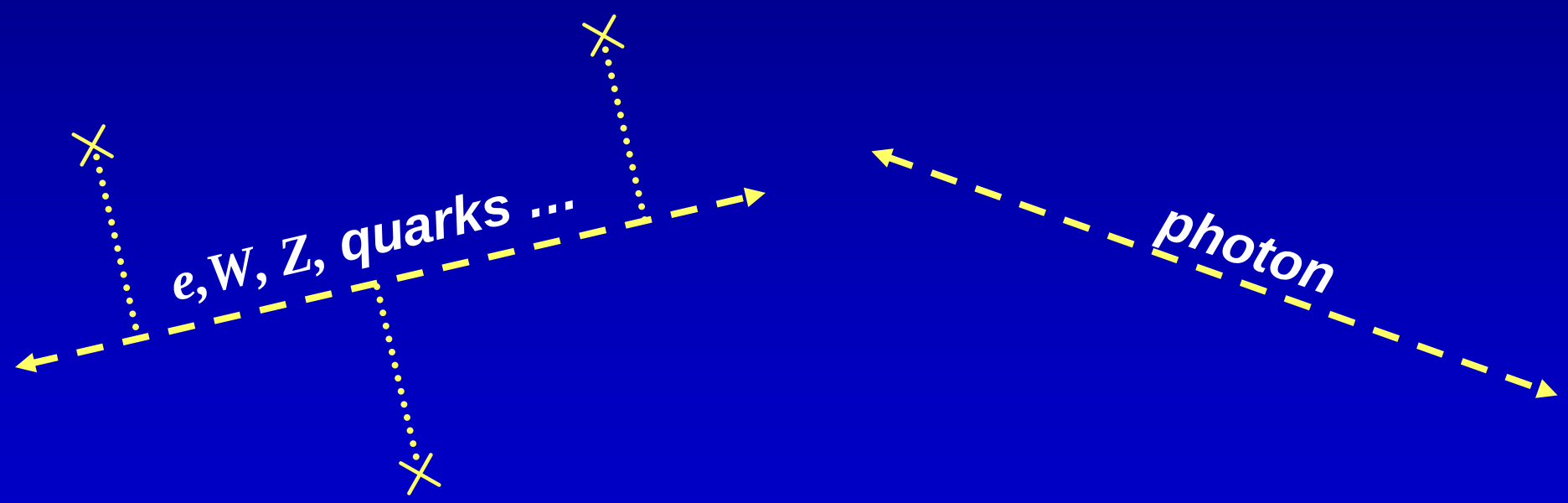
All fields: harmonic oscillators with zero-point energy

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

$\Lambda_C = \infty:$	$\rho_\Lambda = \infty^4$	$=$ relax, it's field theory
$\Lambda_C = M_{Pl} = 10^{19}\,\mathrm{GeV}:$	$\rho_\Lambda = M_{Pl}^4$	$= \left(10^{28}\ \mathrm{eV}\right)^4 = 10^{112}\ \mathrm{eV}^4$
$\Lambda_C = M_{SUSY} = 10^3\,\mathrm{GeV}:$	$\rho_\Lambda = M_{SUSY}^4$	$= \left(10^{12}\ \mathrm{eV}\right)^4 = 10^{48}\ \mathrm{eV}^4$
$\Lambda_C = 10^{-13}\,\mathrm{GeV}:$	$\rho_\Lambda = \rho_{\mathrm{Observed}}$	$= \left(10^{-4}\ \mathrm{eV}\right)^4 = 10^{-16}\ \mathrm{eV}^4$

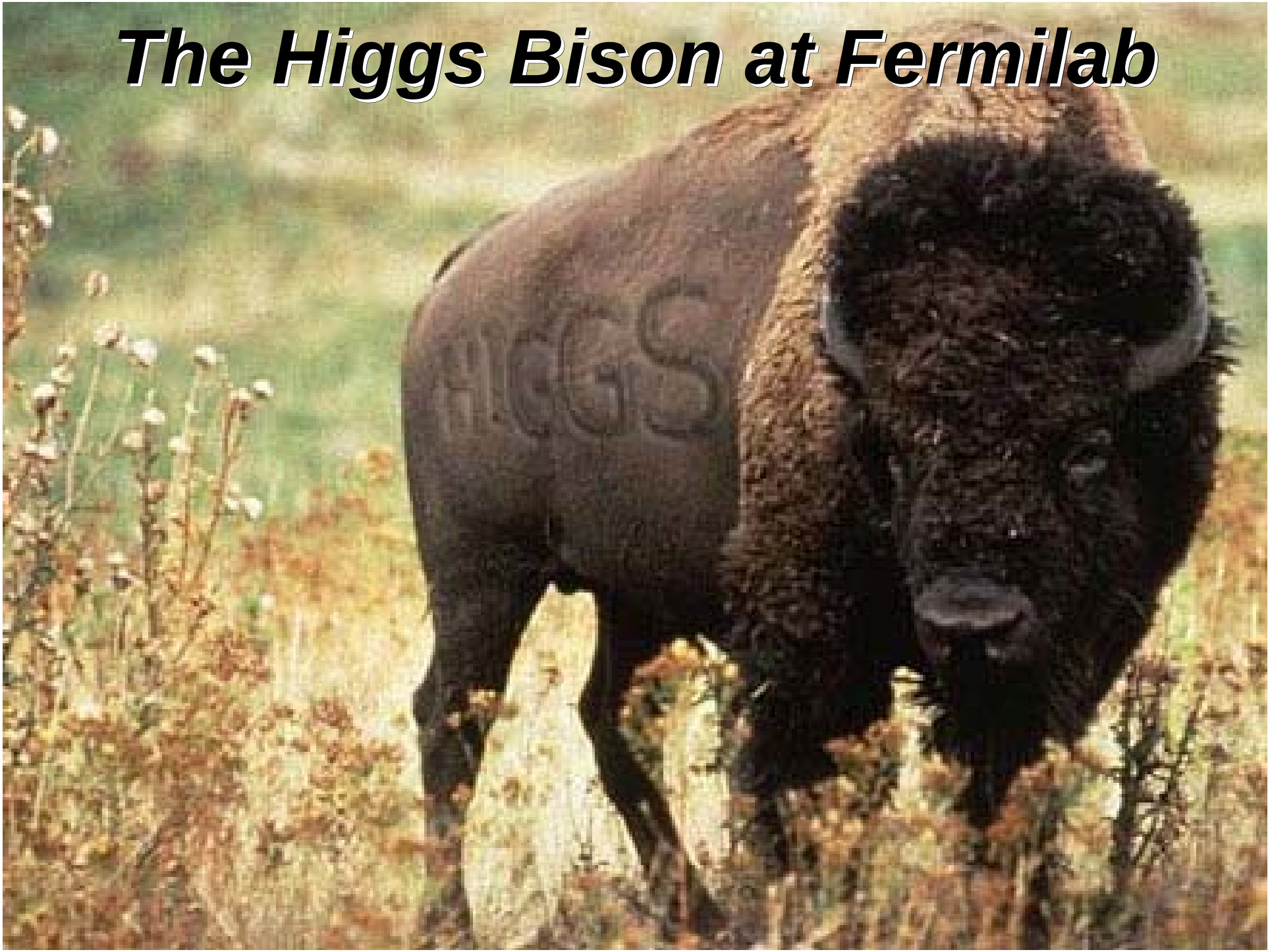
Cosmoillogical Constant

- The quantum vacuum has a Higgs potential
- Higgs potential gives mass to quanta like quarks and electrons

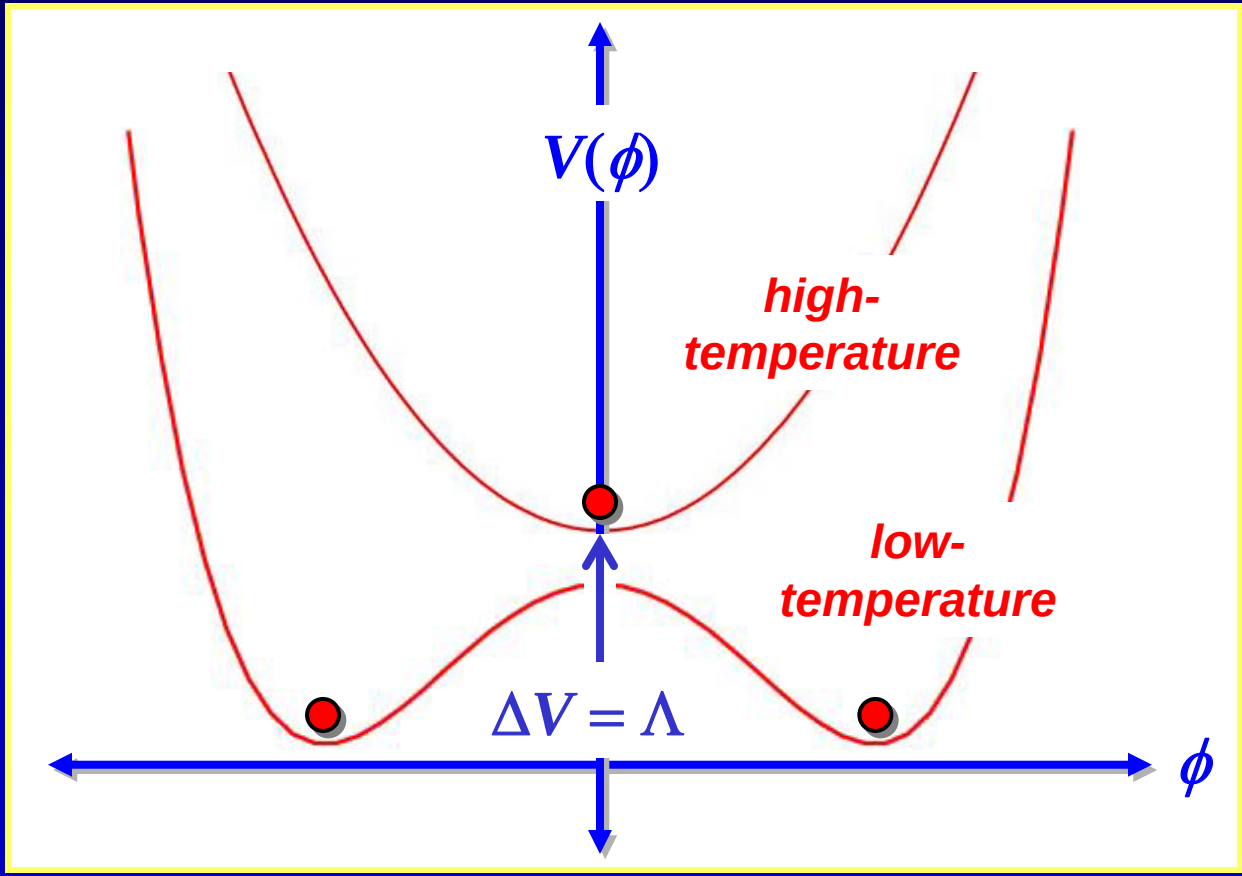


Higgs potential: 246×10^9 eV

The Higgs Bison at Fermilab



Cosmoillogical Constant

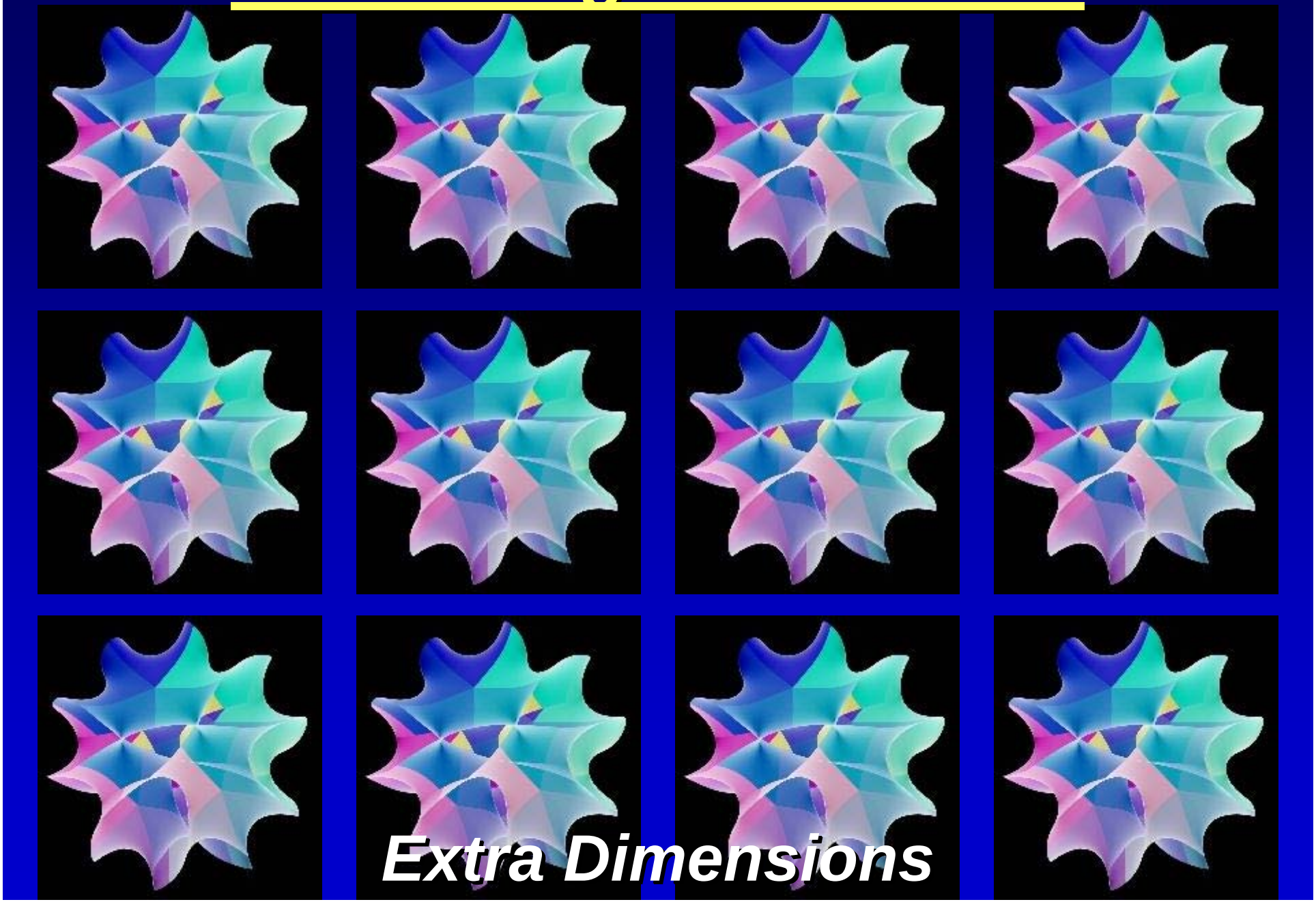


GUT: 10^{100} eV^4 SUSY: 10^{48} eV^4

EWK: 10^{45} eV^4 CHIRAL: 10^{32} eV^4

OBSERVED: 10^{-16} eV^4

Cosmoillogical Constant



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

- Modify <u>right-hand side</u> of Einstein equations (ΔT_{00})
  1. Constant ("just" a cosmoillogical constant Λ)
  2. Not constant (dynamics driven by scalar field)
- Modify <u>left-hand side</u> of Einstein equations (ΔG_{00})
  3. Beyond Einstein (non-GR: $f(R)$, extra dimensions, *etc*.)
  4. (Just) Einstein (back reaction of inhomogeneities)

Tools for the Right-Hand Side

1964 Austin-Healey Sprite

1974 Fiat 128

Tools For The Right-Hand Side

scalar fields
(quintessence)

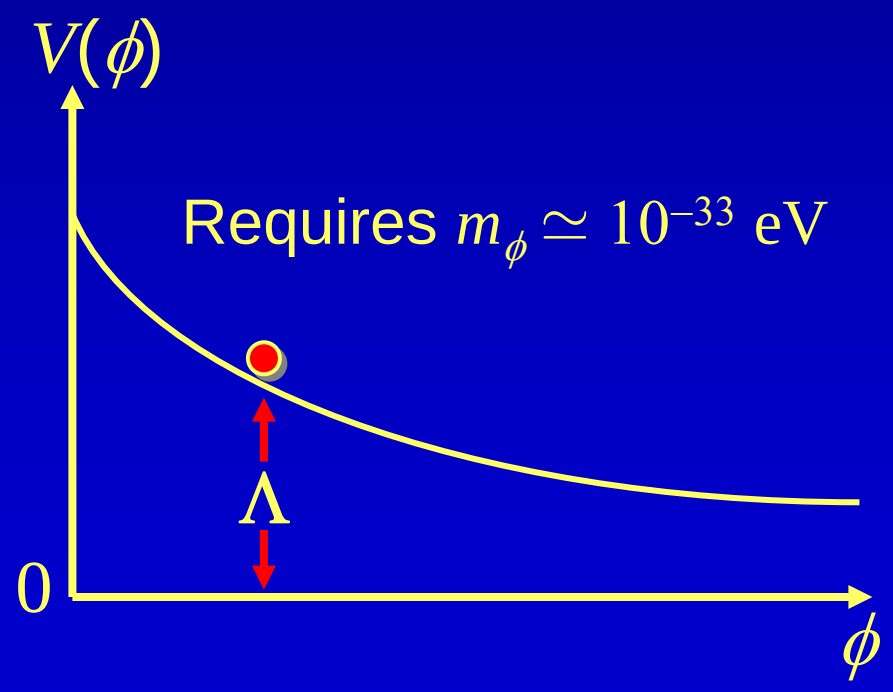
anthropic principle
(the landscape)

Anthropic/Landscape/DUCTape

- 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!*



Modifying 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

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

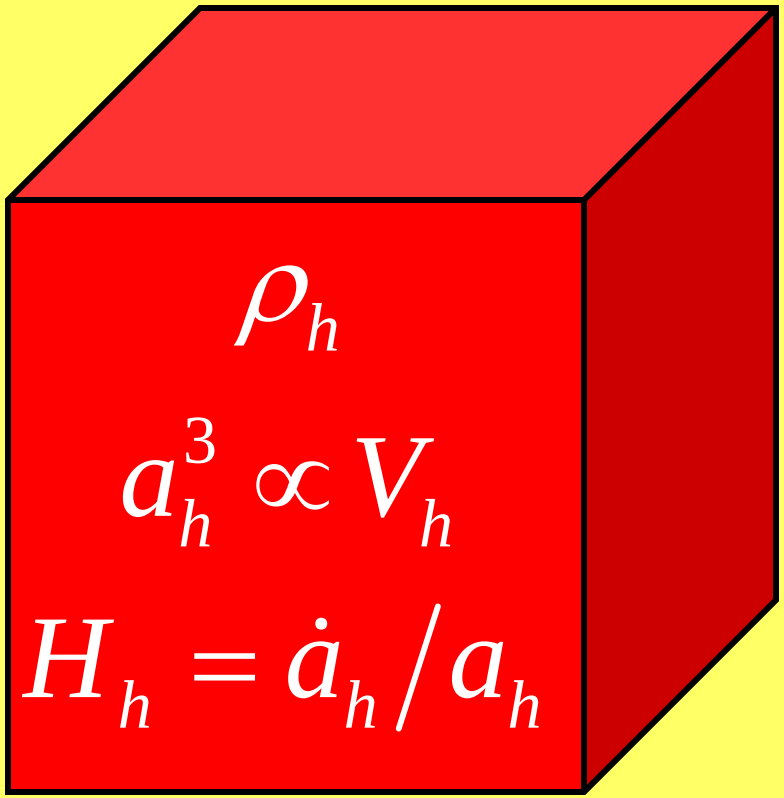
- Backreaction of inhomogeneities — Räsänen; Kolb, Matarrese, Notari & Riotto; Notari; Kolb, Matarrese & Riotto

Acceleration From Inhomogeneities

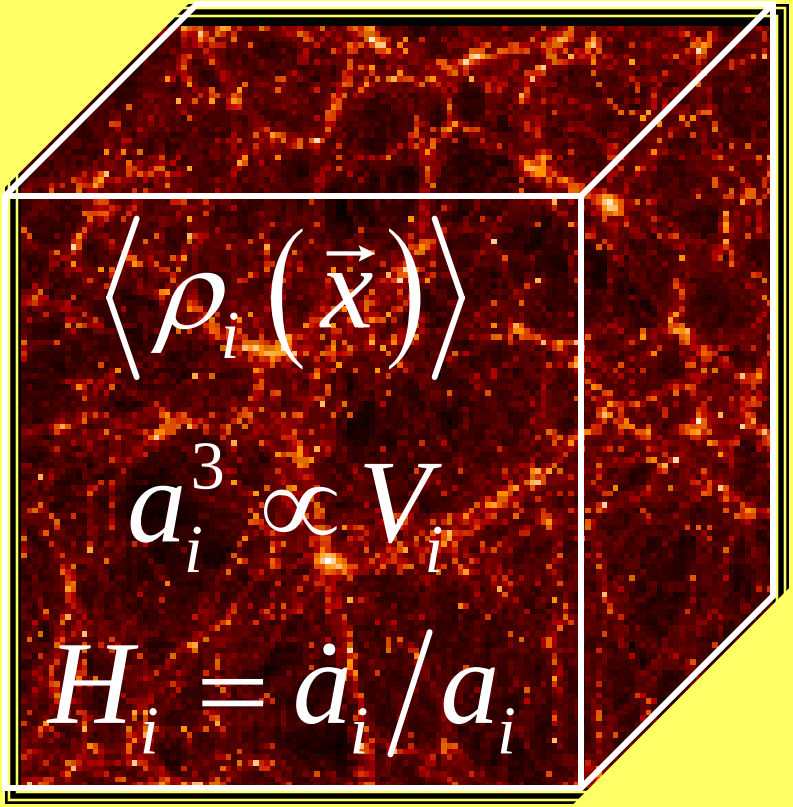
- Most conservative approach — nothing new
  - no new fields (like $10^{-33}\,\mathrm{eV}$ mass scalars)
  - no extra long-range forces
  - no modification of general relativity
  - no modification of gravity at large distances
  - no Lorentz violation
  - no extra dimensions, bulks, branes, etc.
  - 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

Homogeneous model



Inhomogeneous model



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

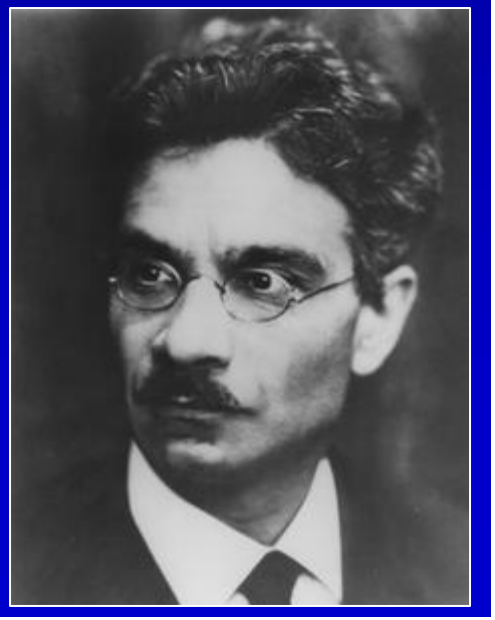
We think not!

(Buchert & Ellis)

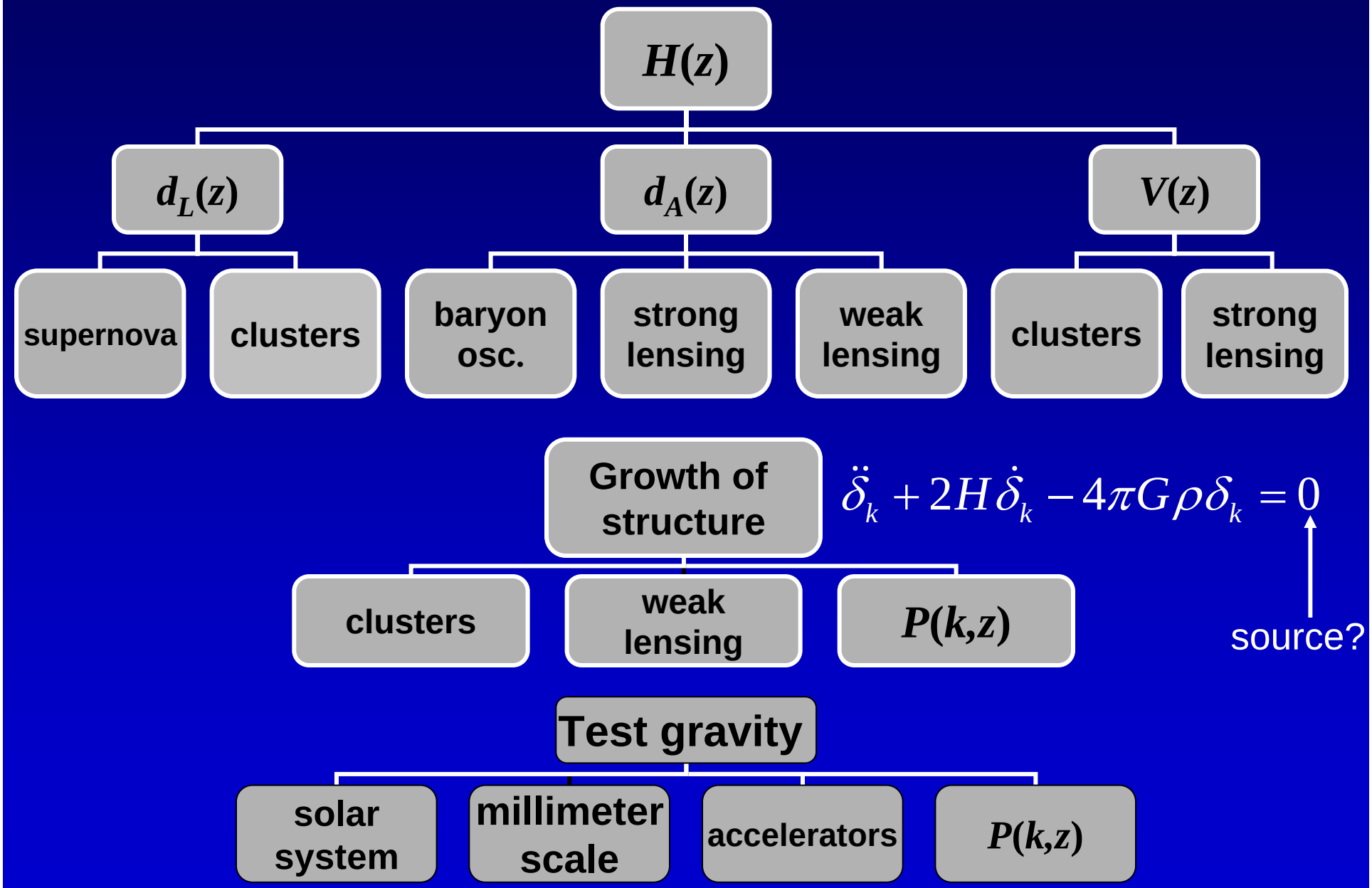
Dark Energy

"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



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

source?

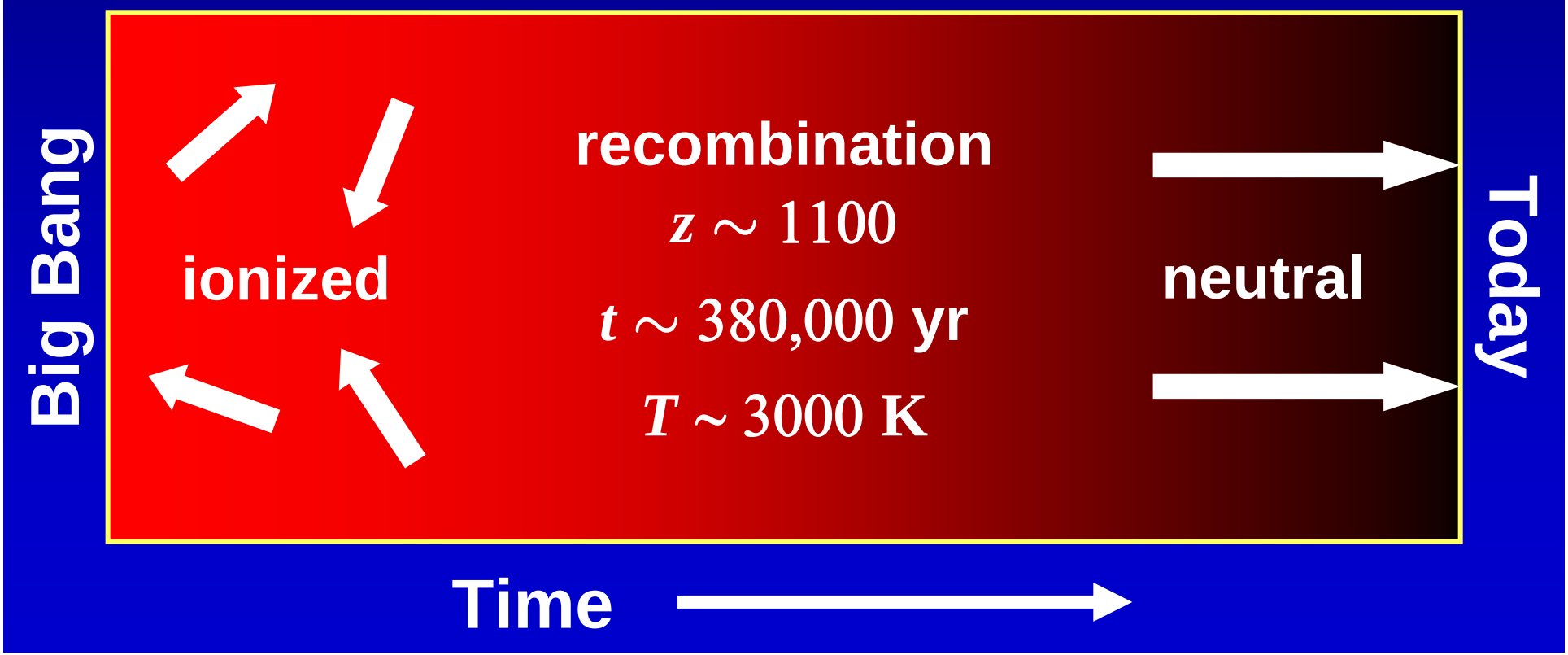
Baryon Acoustic Oscillations

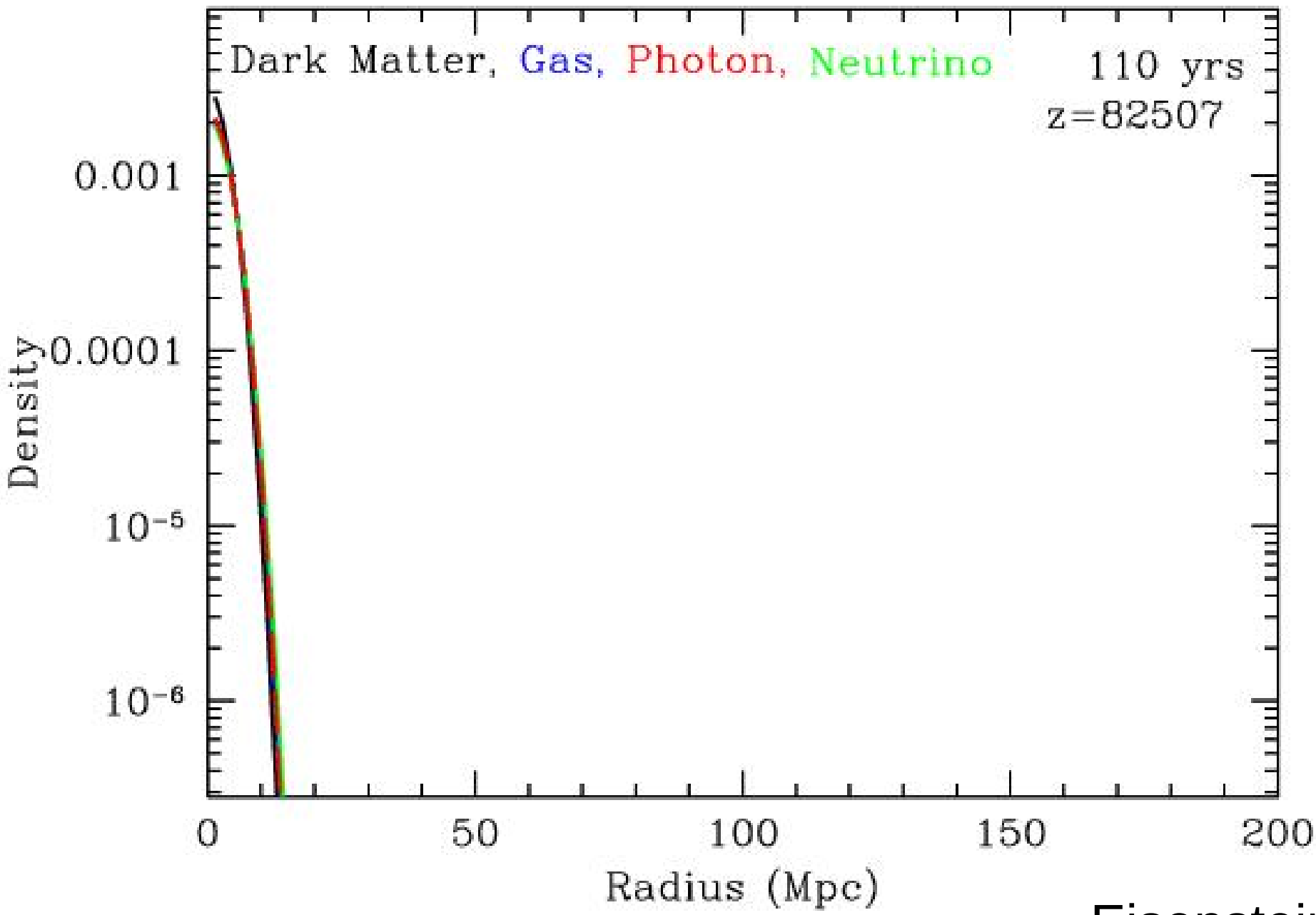
Pre-recombination

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

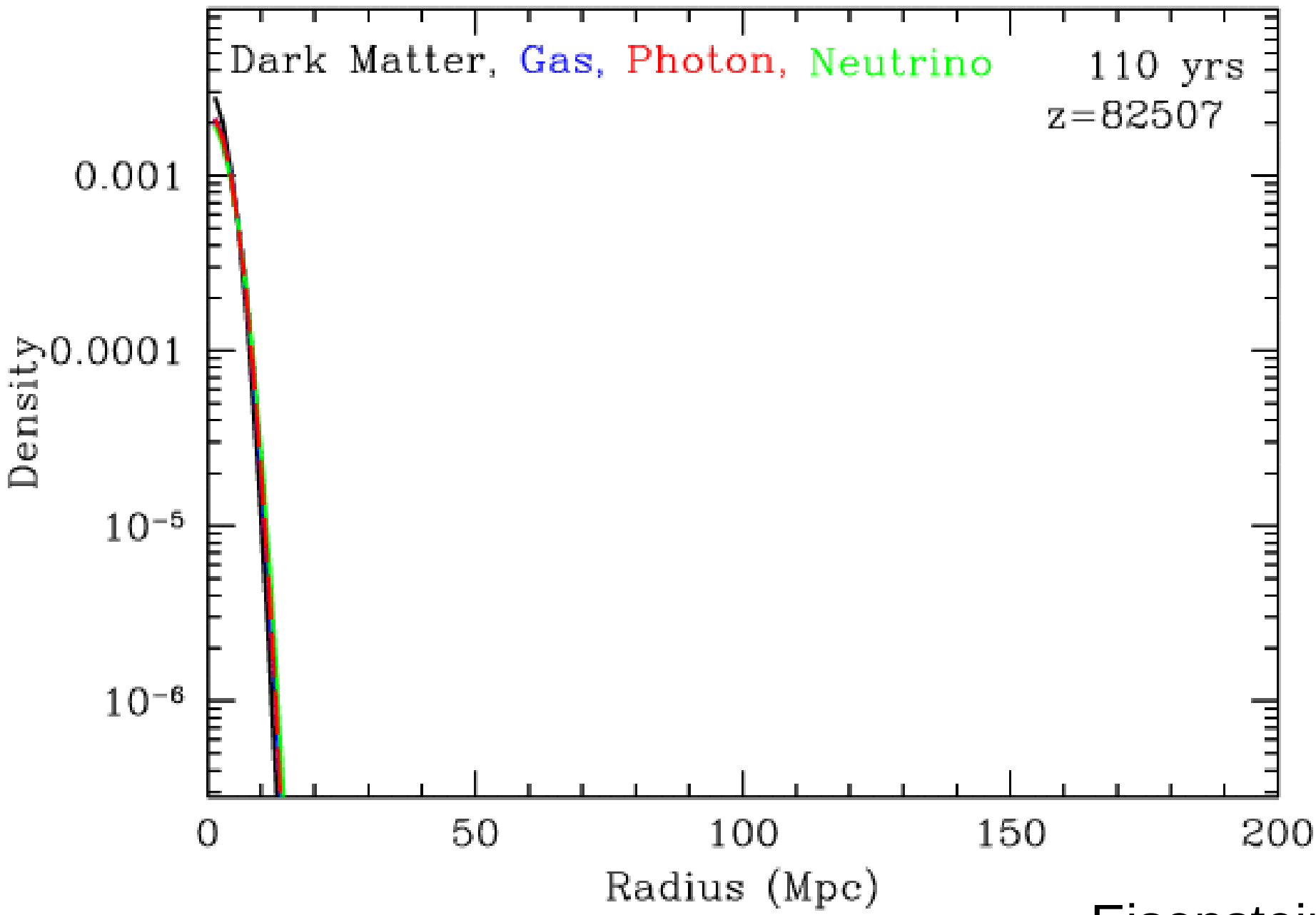
Post-recombination

- 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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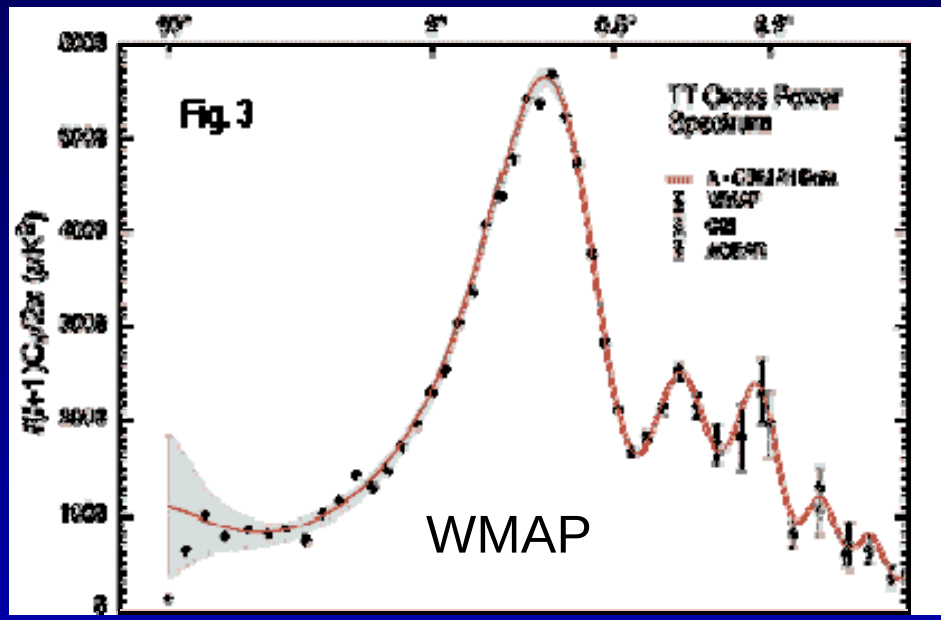
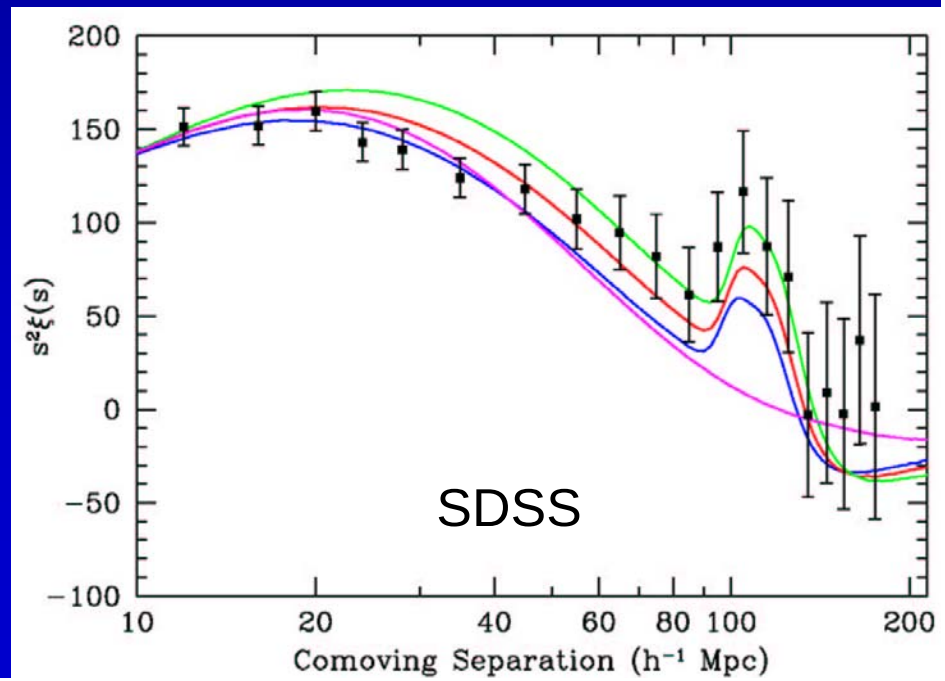
Density
0
50
100
150
200
Radius (Mpc)

Eisenstein

Baryon Acoustic Oscillations

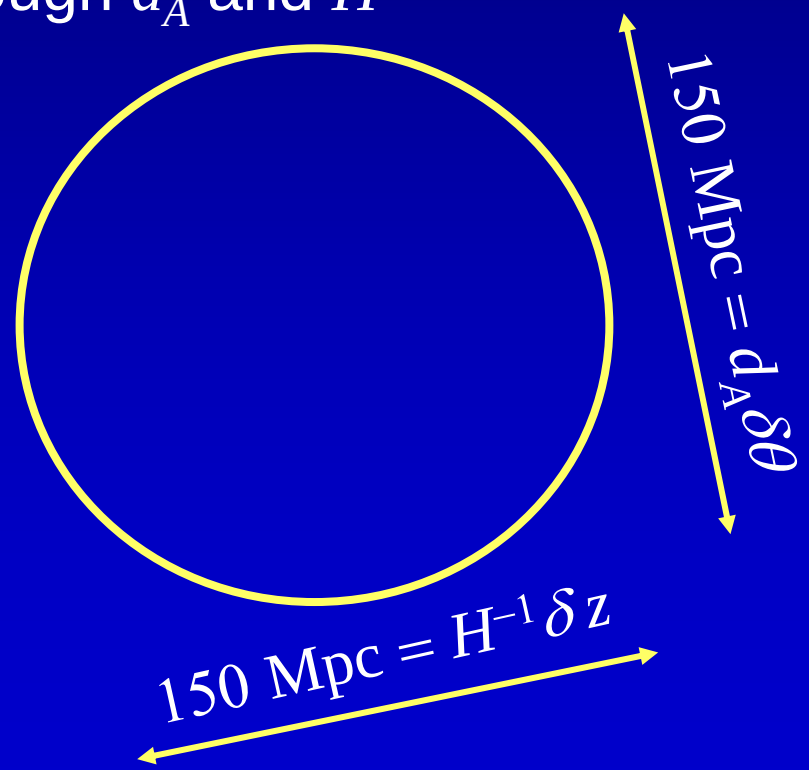
- Each overdense region is an overpressure that launches a spherical sound wave
- Wave travels outward at $c/\sqrt{3}$
- Photons decouple, travel to us and observable as CMB acoustic peaks
- Sound speed plummets, wave stalls
- Total distance traveled 150 Mpc imprinted on power spectrum





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 ($\Omega_B h^2 \ll \Omega_M h^2$)
- 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

Conclusions: Two Sides To Every Story

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

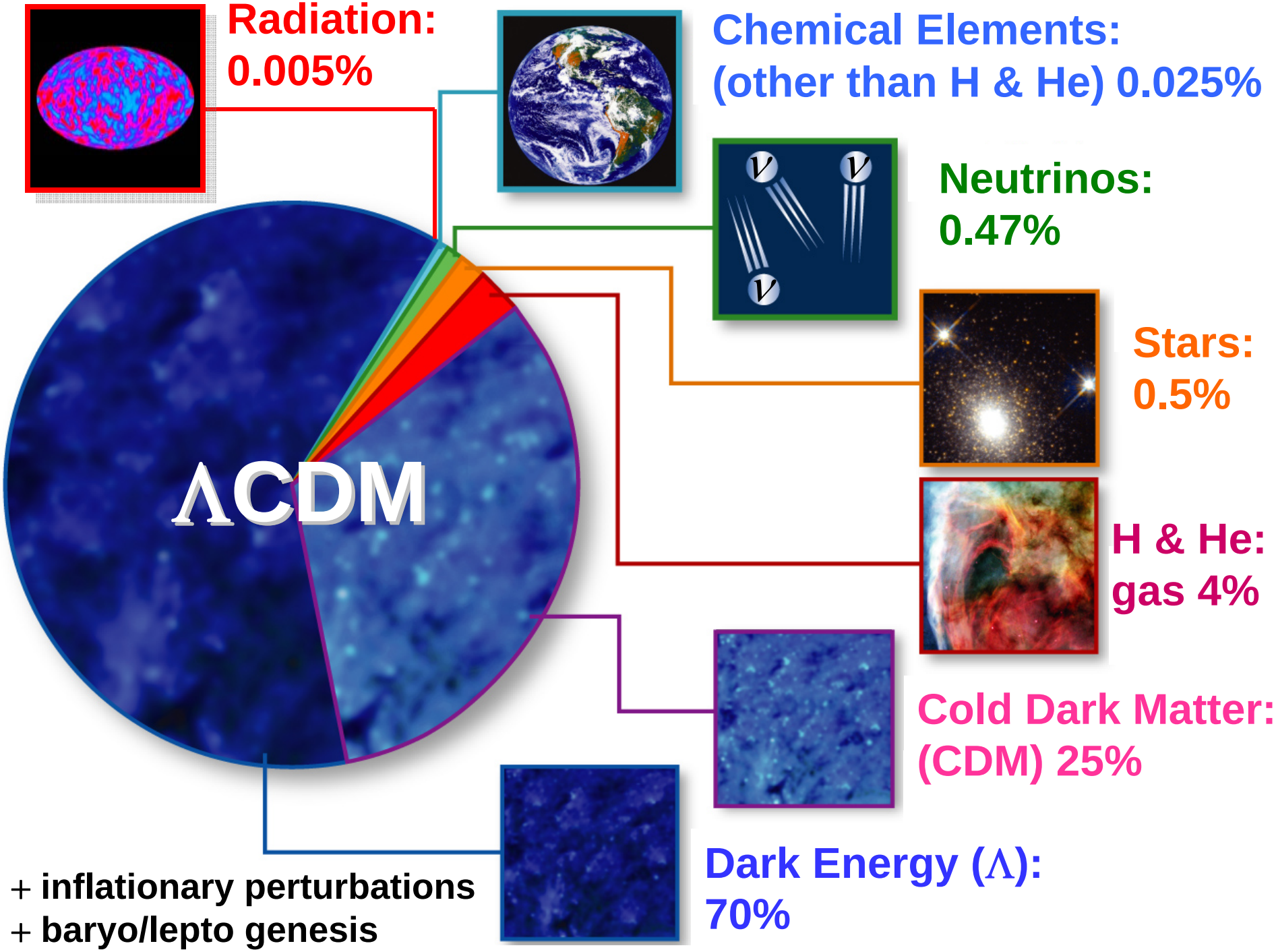
1. Well established: Supernova Ia
2. Circumstantial: subtraction, age, structure formation, …
3. Emergent techniques: baryon acoustic oscillations, clusters, weak lensing

Explanations:

1. Right-Hand Side: Dark energy
   - "constant" vacuum energy, *i.e.,* Λ
   - 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


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

ΛCDM
Standard Cosmological Model
or
21st Century Epicycles?

2008 Hadron Collider Physics Summer School
August 2008

Rocky Kolb
University of Chicago