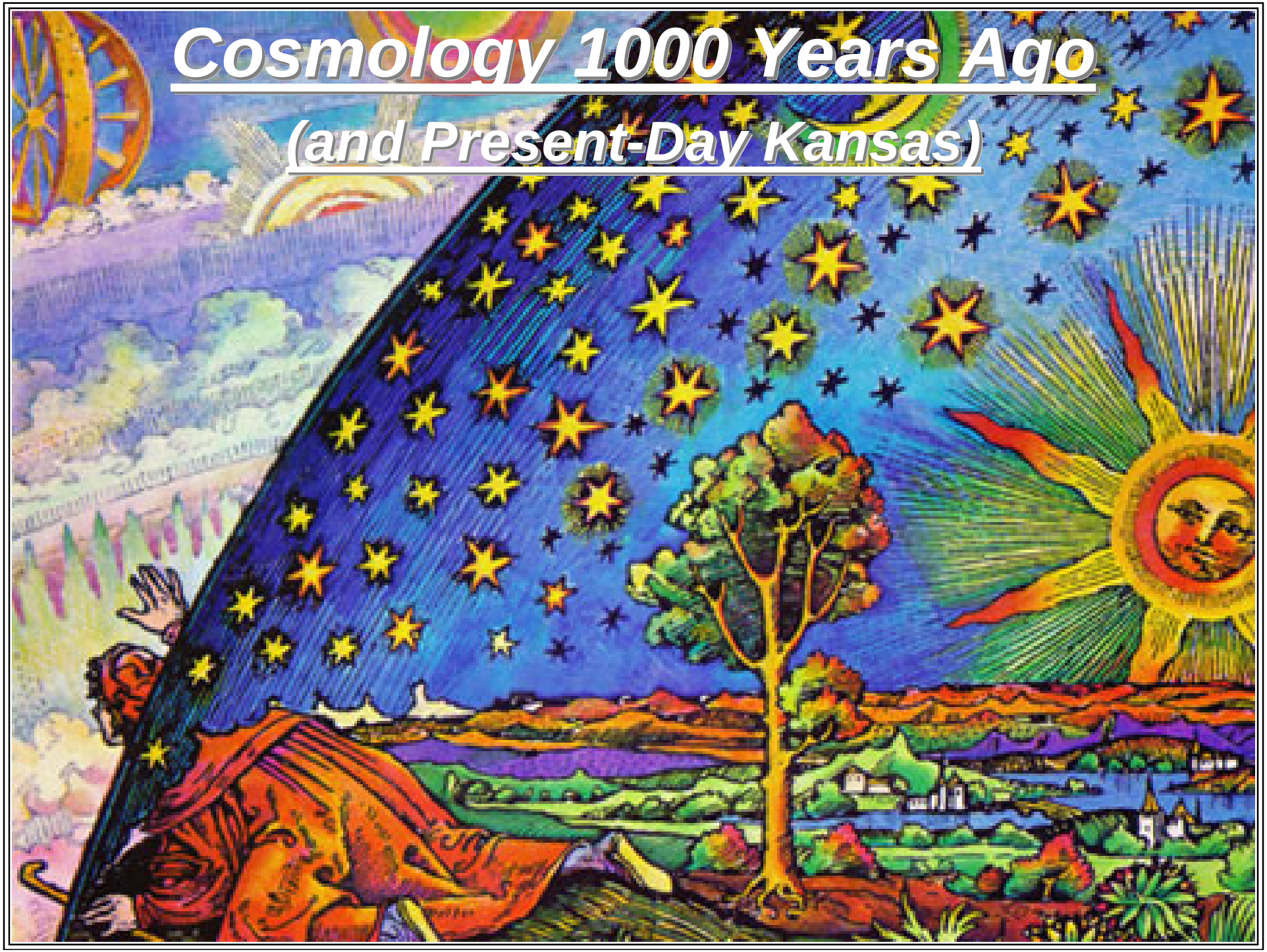
Dark Matter and Dark Energy

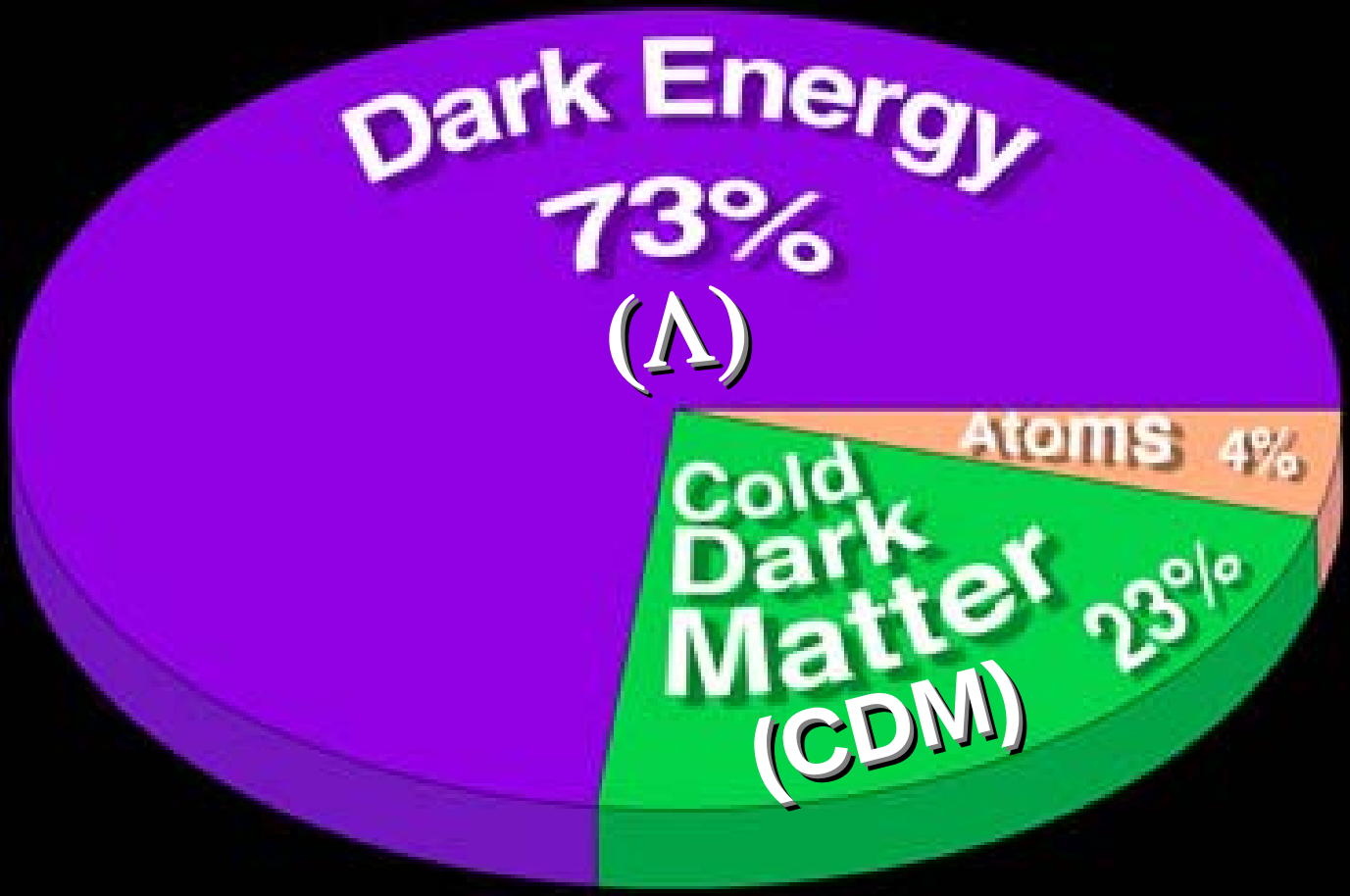
FNAL Summer Students, August 2006
Rocky Kolb, Astronomy & Astrophysics

Cosmology 1000 Years Ago

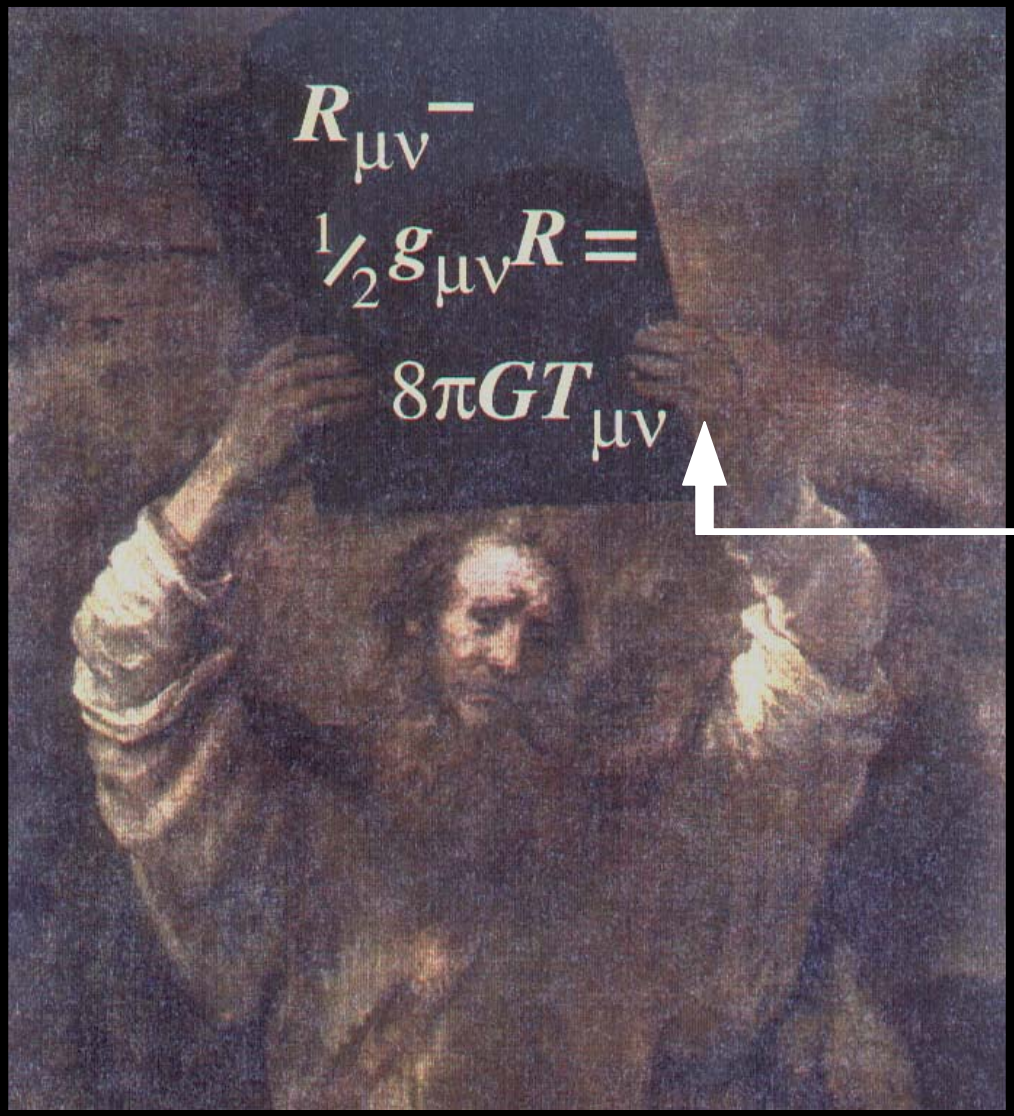
(and Present-Day Kansas)



ΛCDM



Modern Genesis



$+\Lambda g_{\mu\nu}$
cosmological term (dark energy)

(10 nonlinear partial differential equations)

University of Chicago 1909 National Champions

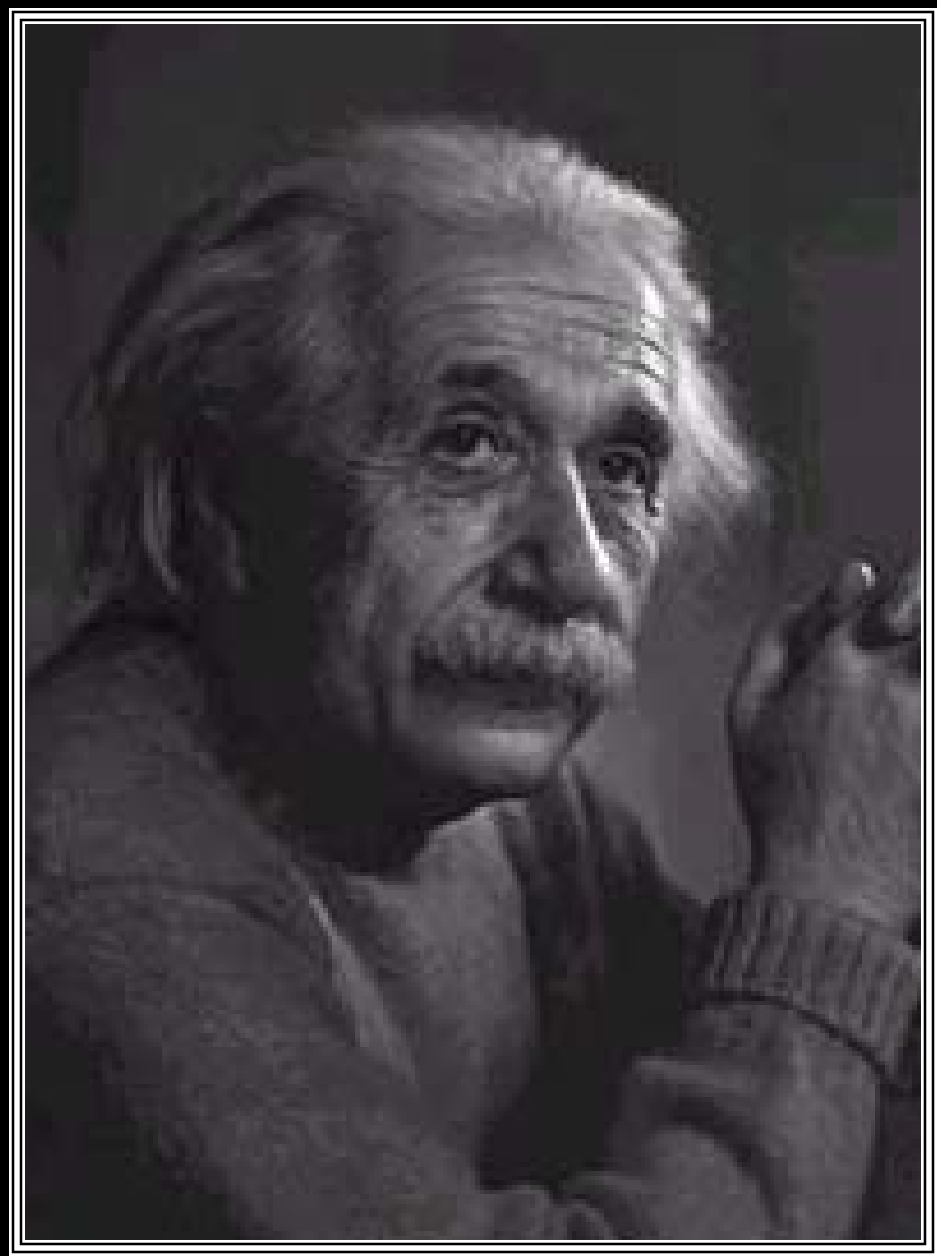
Dark Energy (Λ)

<u>1917</u> Einstein proposed cosmological constant.

<u>1929</u> Hubble discovered expansion of the Universe.

<u>1934</u> Einstein called it "my biggest blunder."

<u>1998</u> Astronomers found evidence for it.



What We "Know"

1) The matter density is dominated by cold dark matter …

2) The overall mass/energy density is dominated by a cosmological term (dark energy)

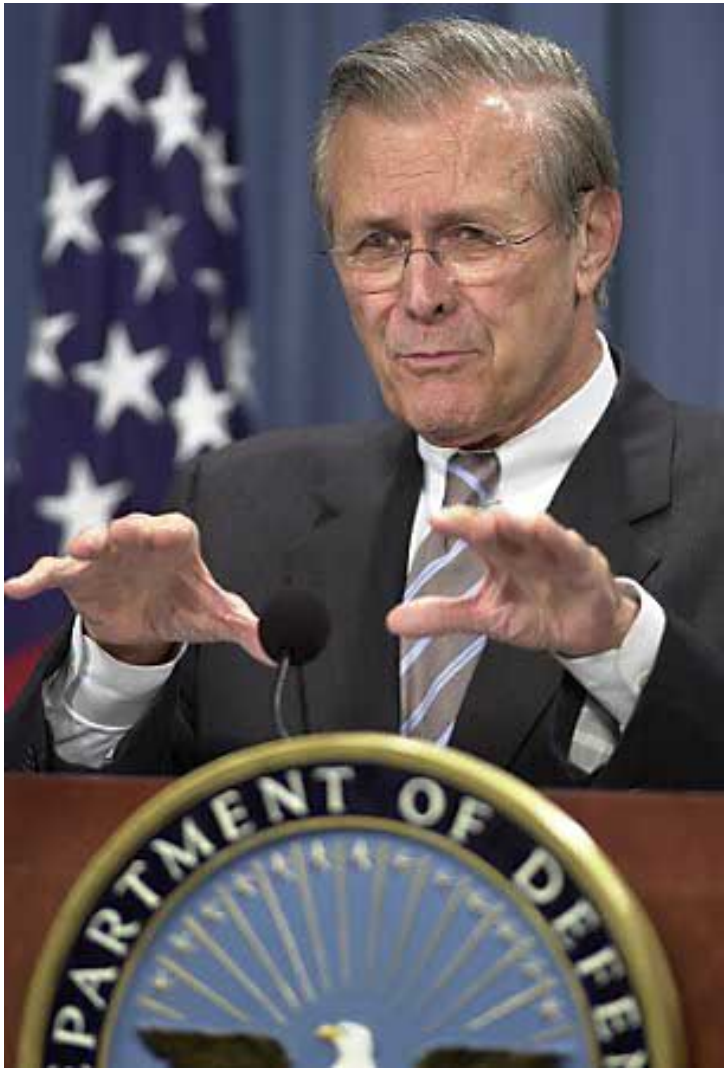
Mission accomplished …

… or premature jubilation?

On Knowing

As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say, we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know.

Donald Rumsfeld
Feb. 12, 2002
Department of Defense
news briefing



He left out the most important one!

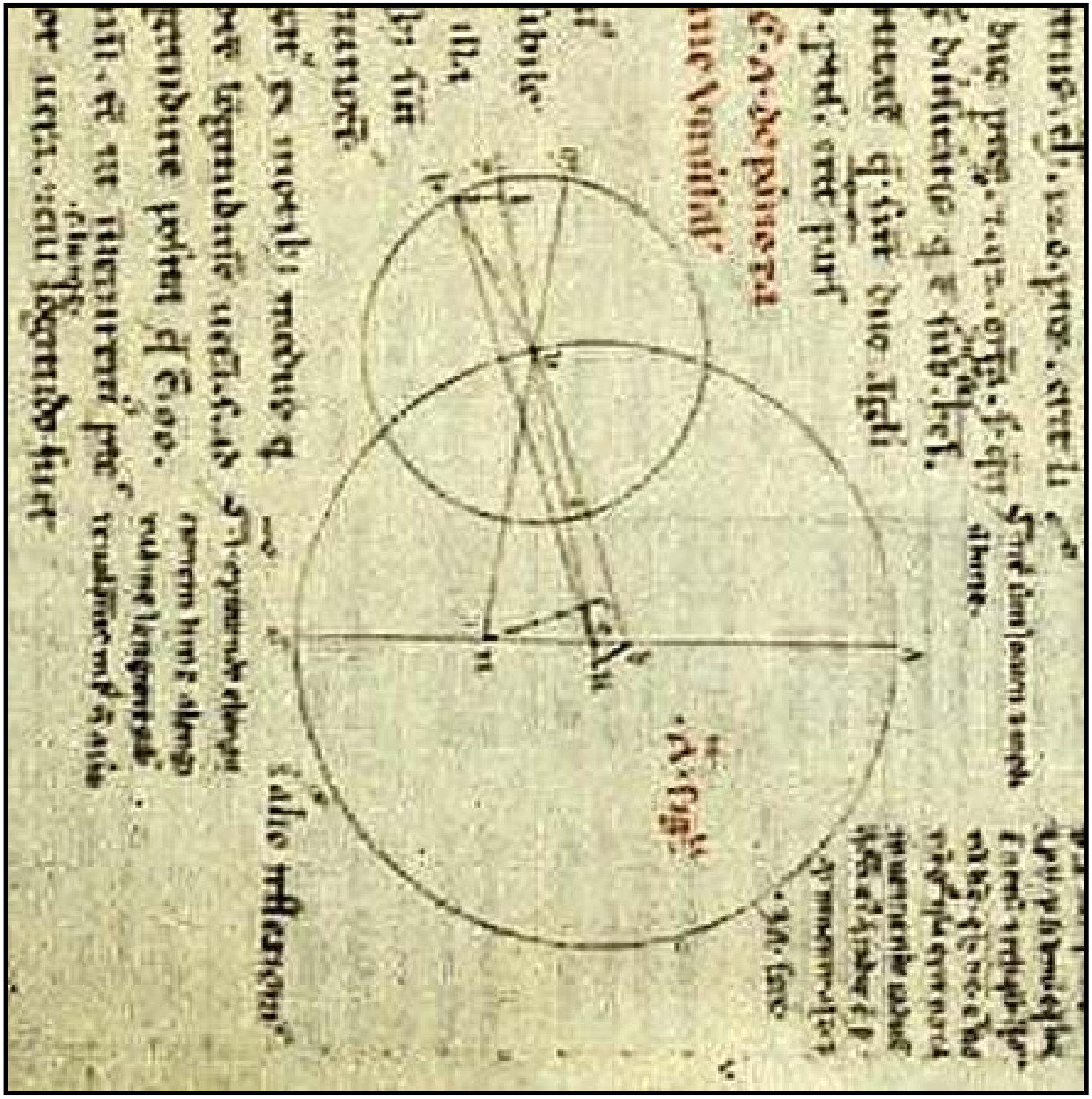
The Unknown “Knowns”?

"It ain't so much the things we don't know that get us in trouble. It's the things we know that ain't so."

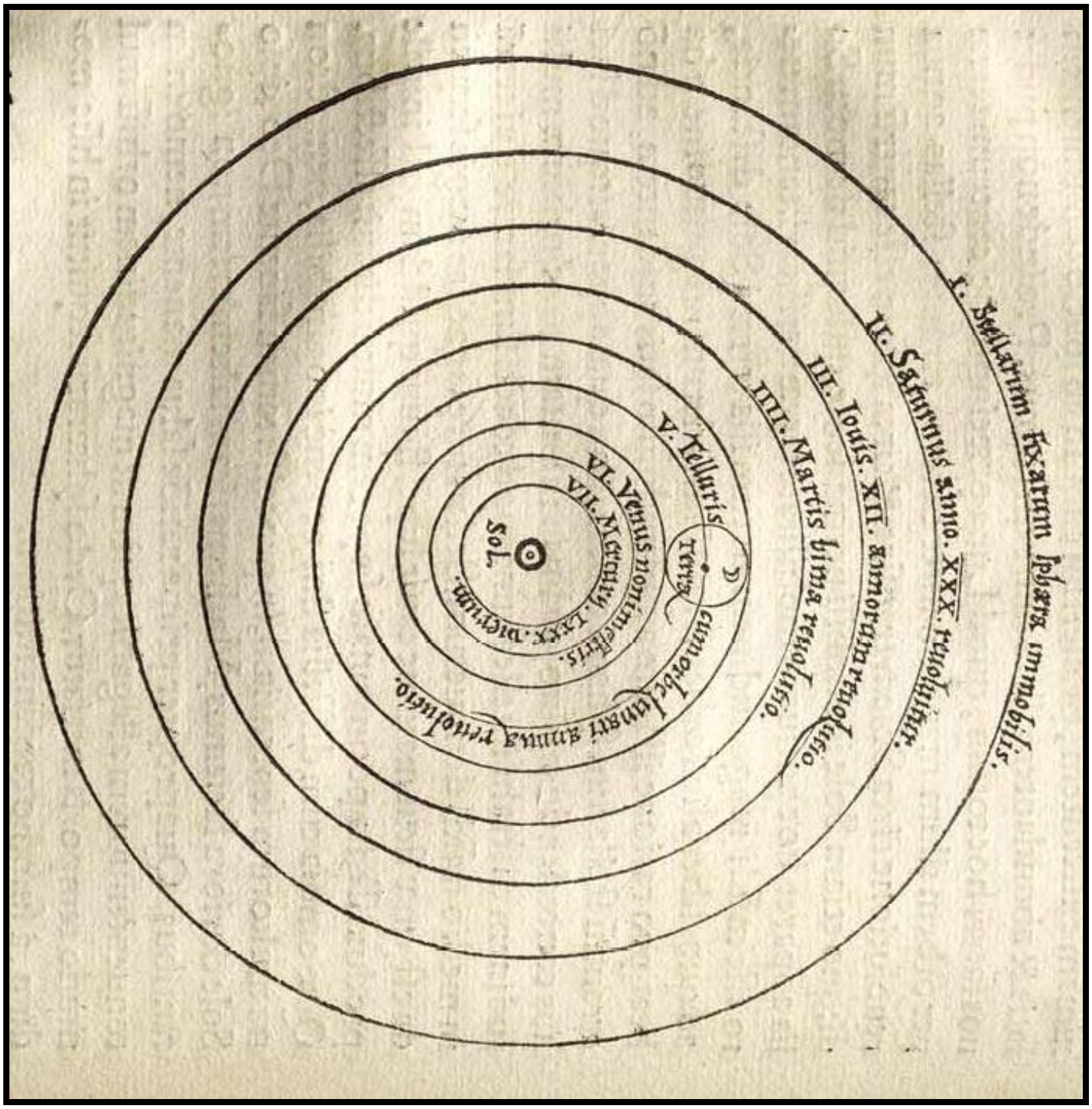
Artemus Ward
American writer
1834-1867

Not everything “known” is true!

Ptolemaic System From *The Almagest*

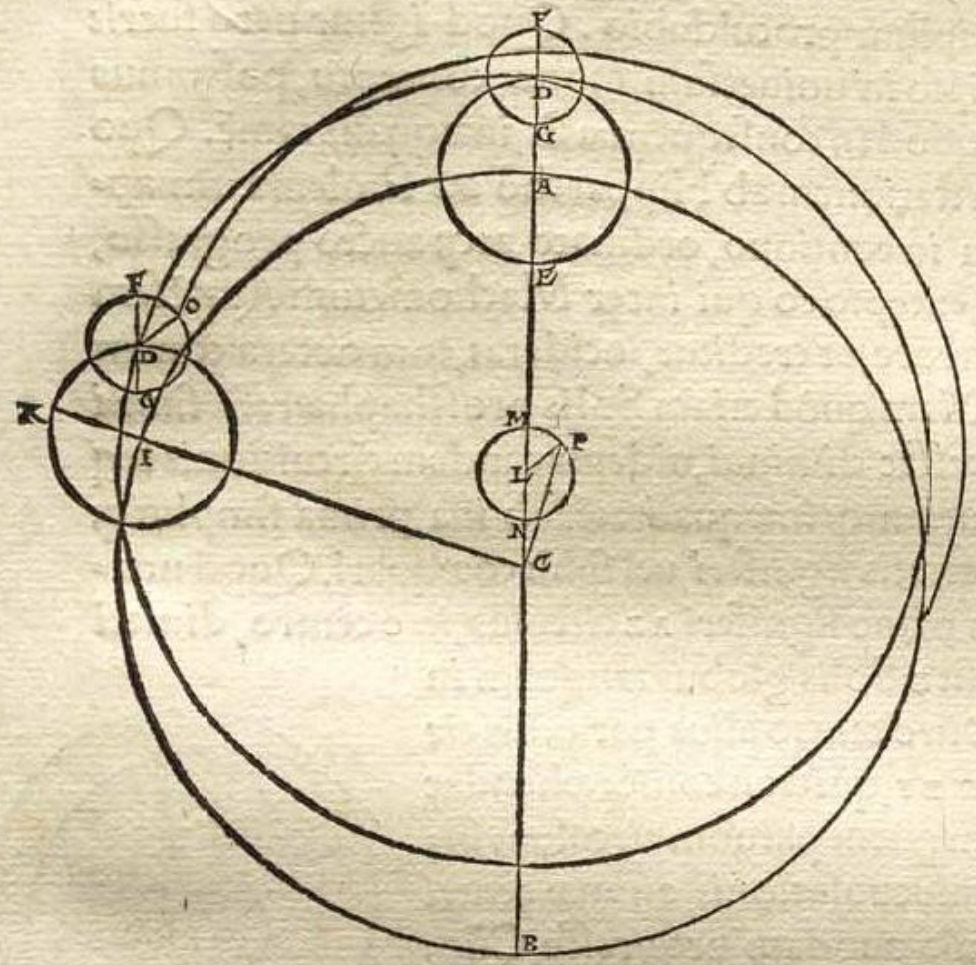


From Book I of
De Revolutionibus



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 mediijs autem circumferentijs ipſius F G epicycliij faciet ipſum apogeum præcedere uel ſequi, auctum dimi

What Copernicus "Knew"

"First of all, we must note that the universe is spherical."

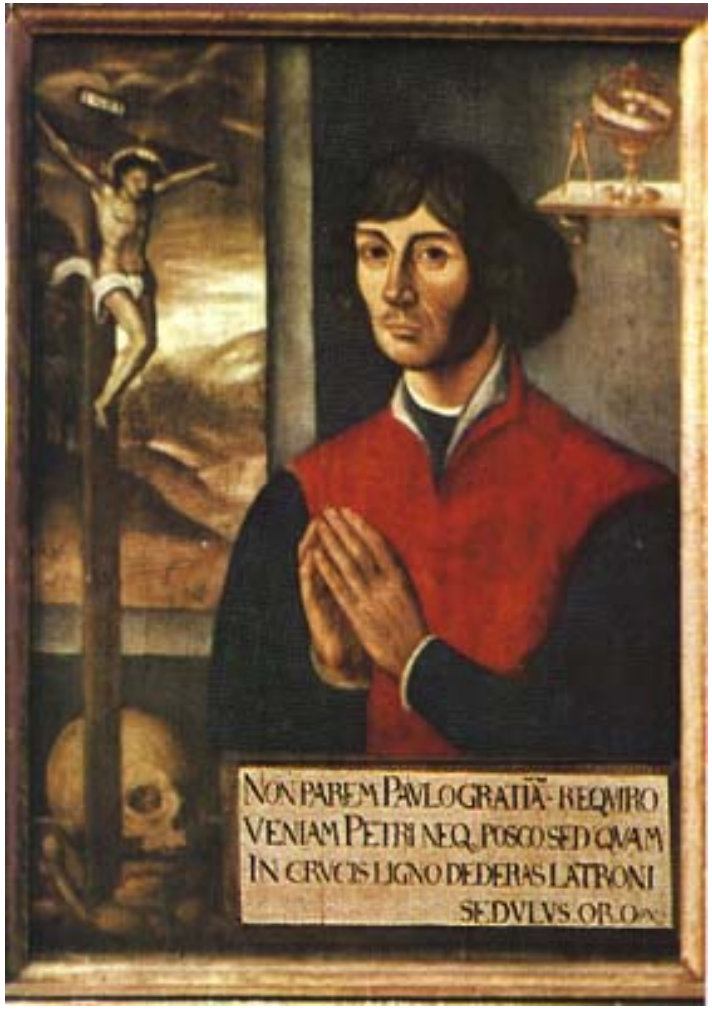
Elliptical orbits!

Motions are centered on the sun

Sun at a focus!

Uniform velocities

Equal areas in equal times!



What Kepler "Knew"

Gravity is an inverse-square force

Kepler thought it was repulsive!

…

…

…

Epicycle I – Dark matter

What is dark matter?

"In questions like this, truth is only to be had by laying together many variations of error."

-- Virginia Woolf
A Room of Ones Own

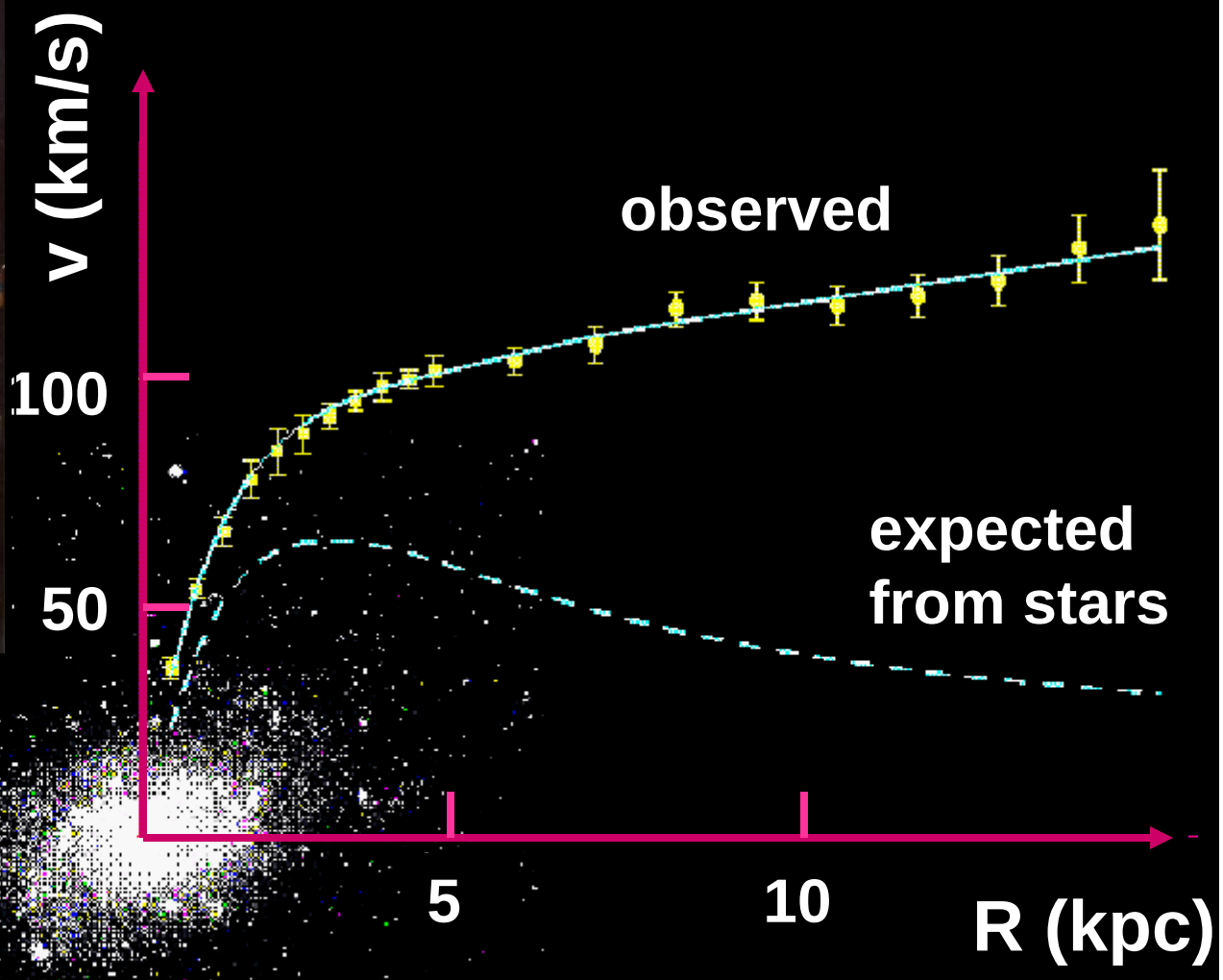
The Visible Universe

Spitzer Space Telescope

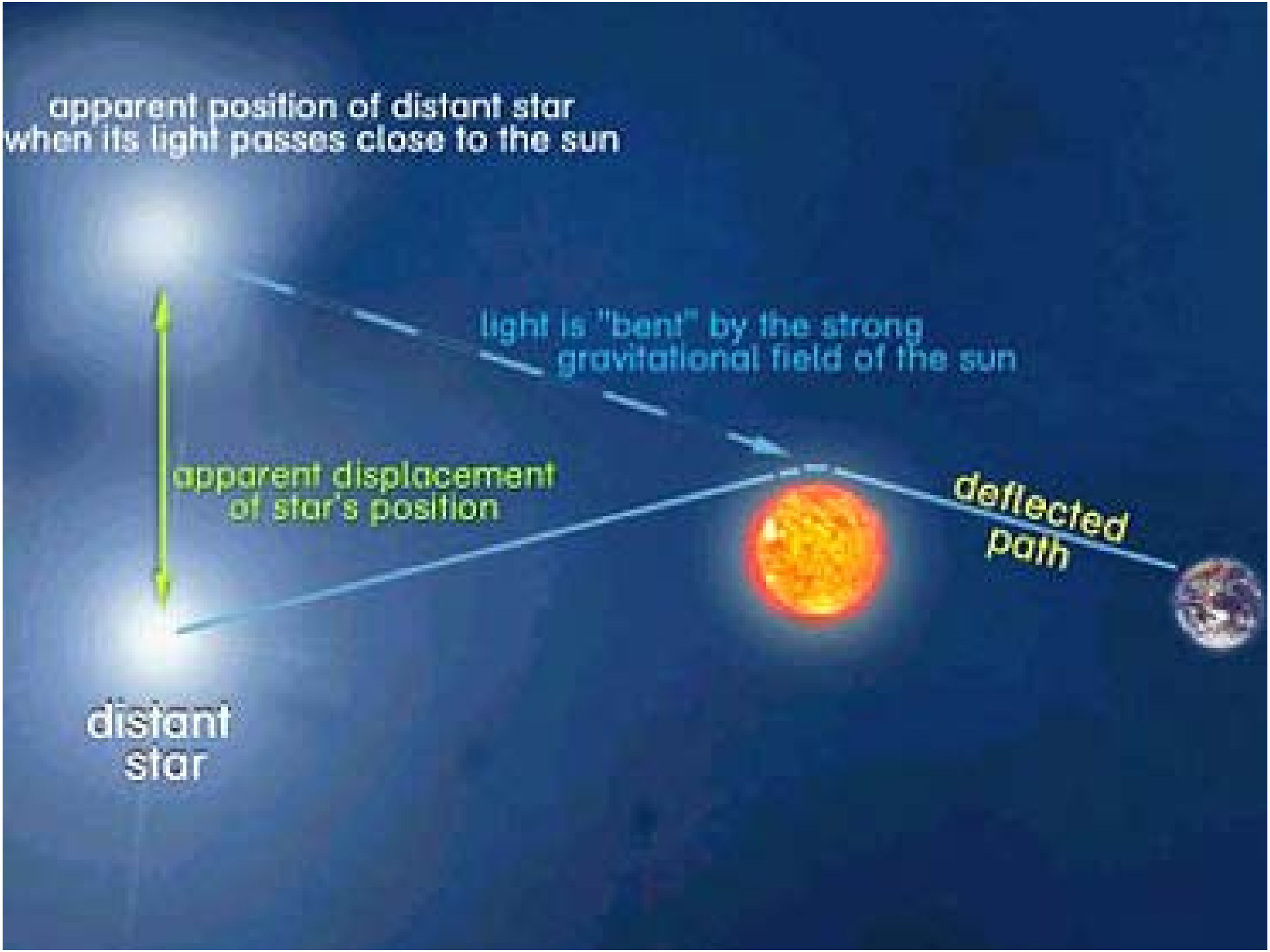
M81

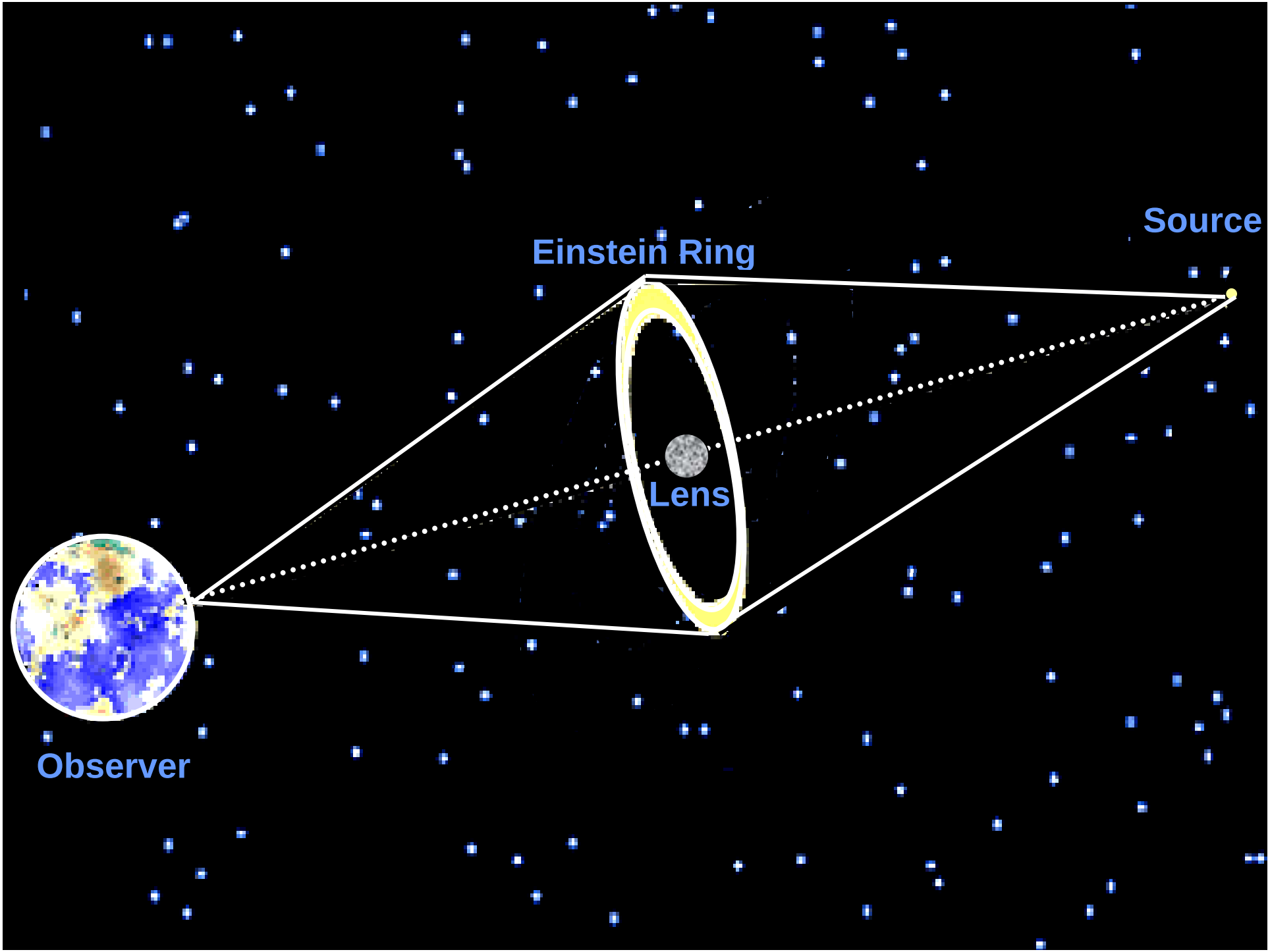
The Invisible Universe

Vera Rubin

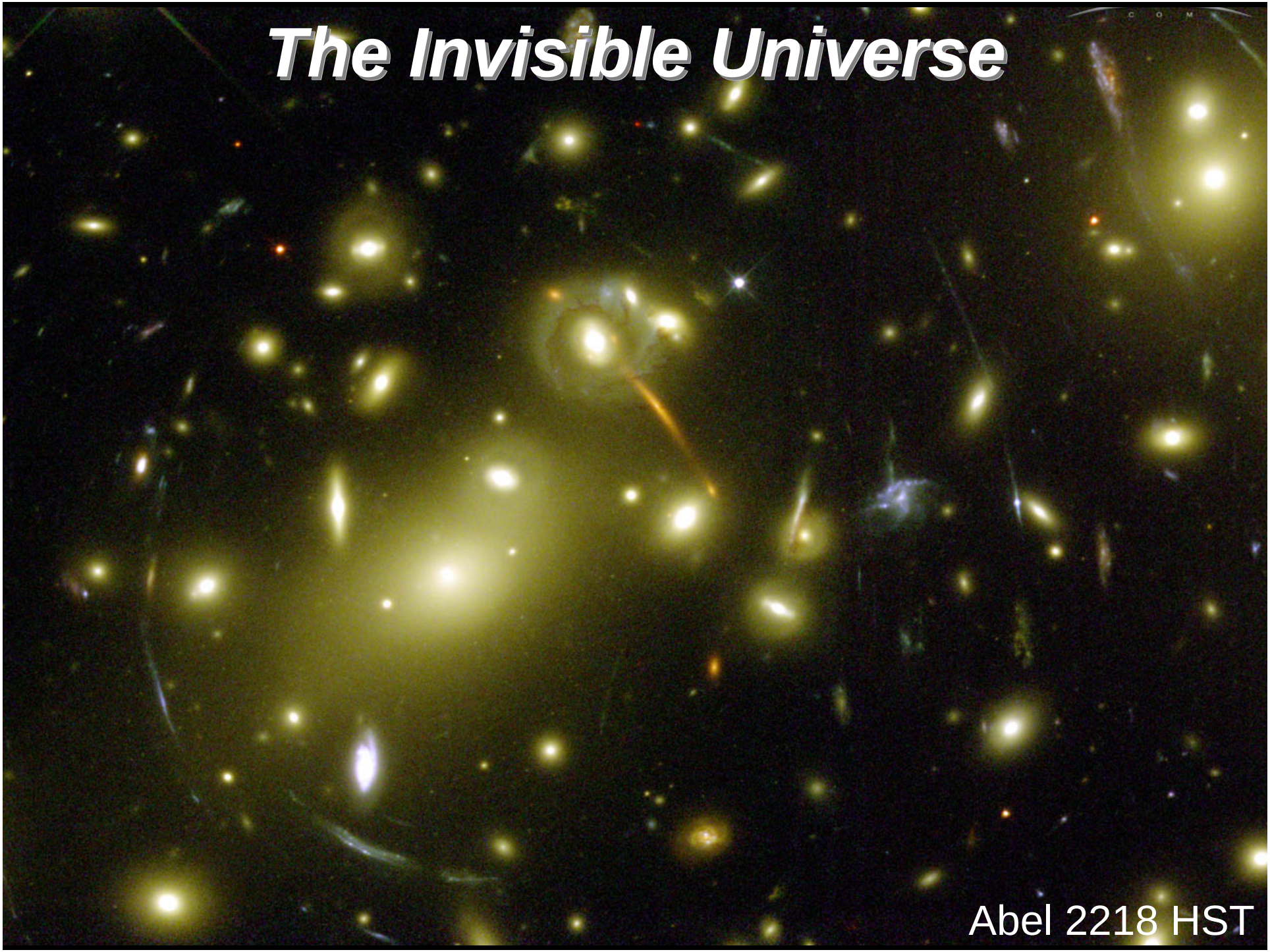


M33 rotation curve

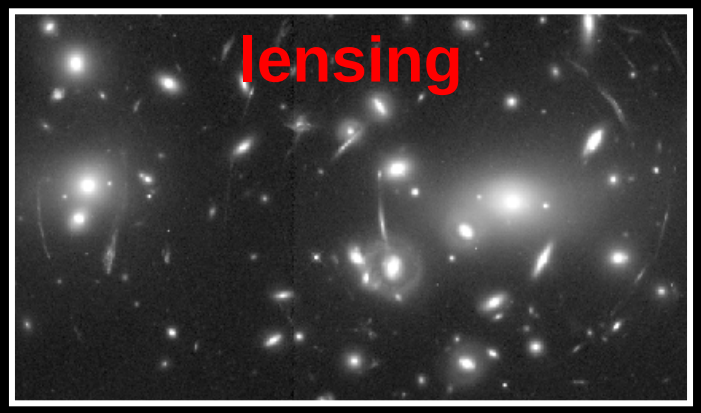

apparent position of distant star
when its light passes close to the sun
light is "bent" by the strong
gravitational field of the sun
apparent displacement
of star's position
deflected
path
distant
star

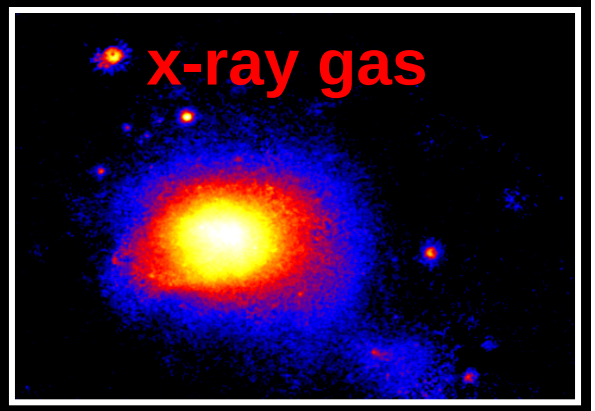

Source
Einstein Ring
Lens
Observer

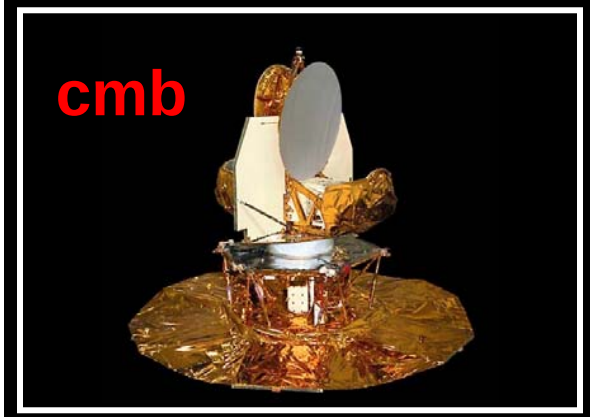
The Invisible Universe

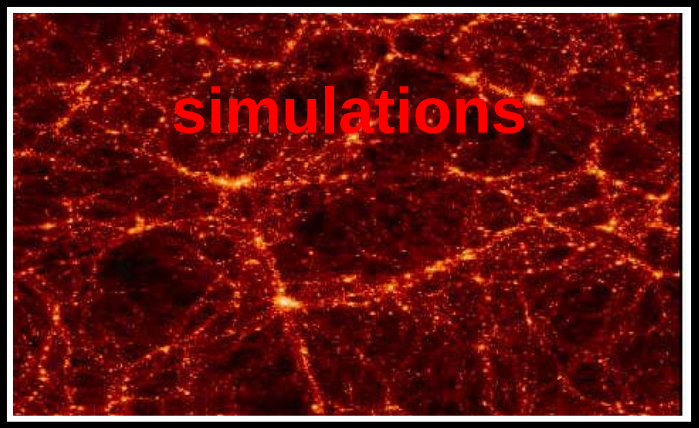


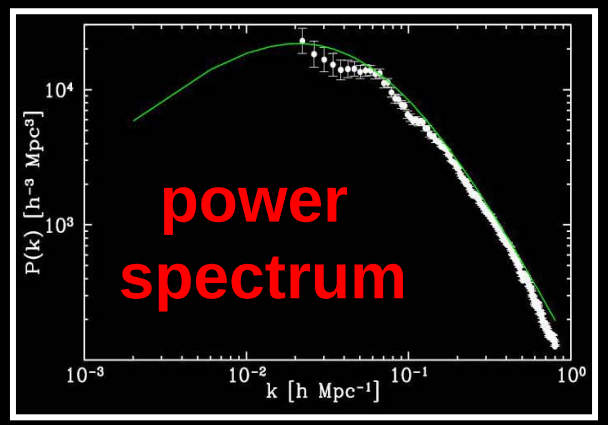
Matter $\Omega_M \sim 0.27$





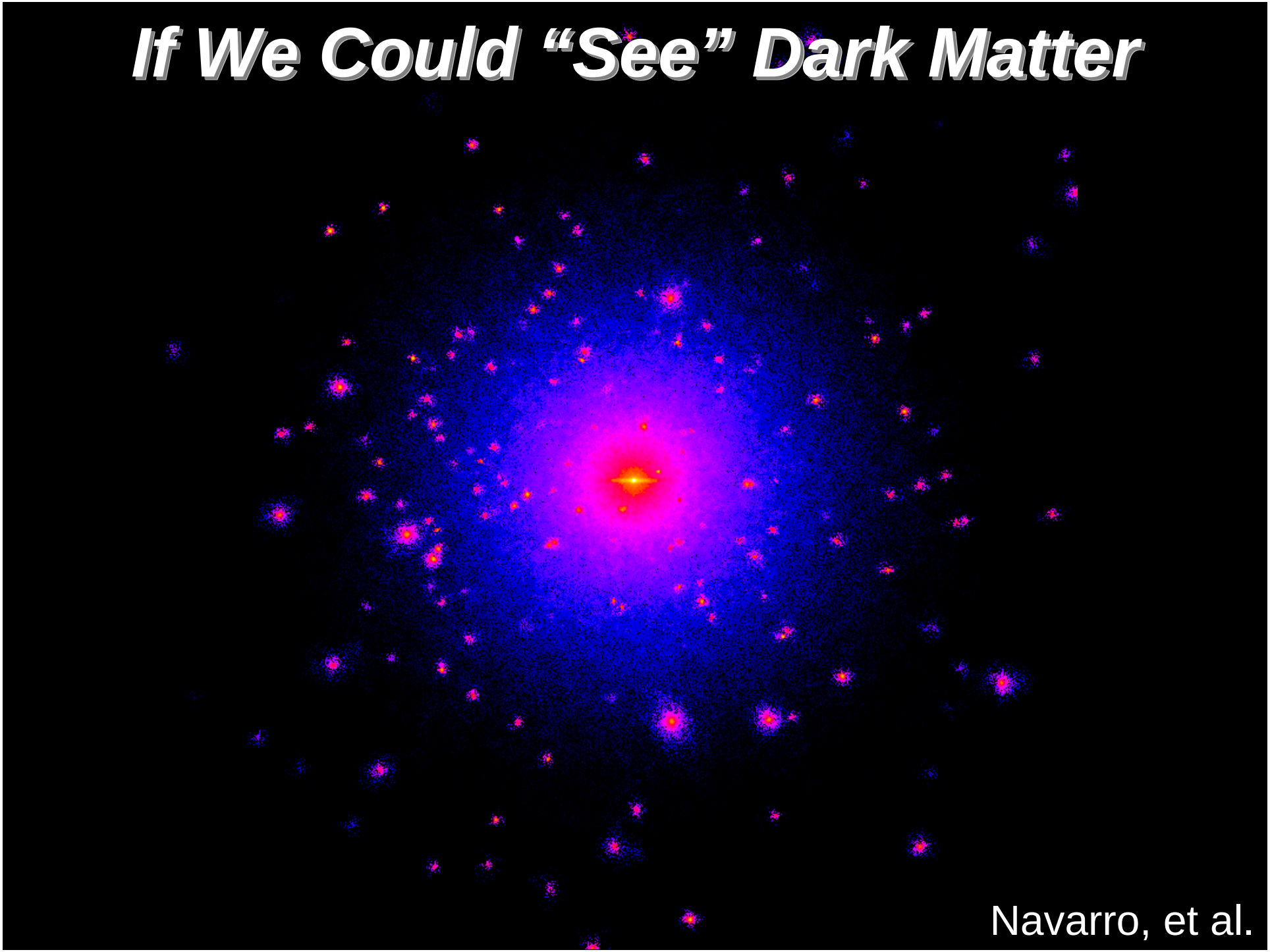




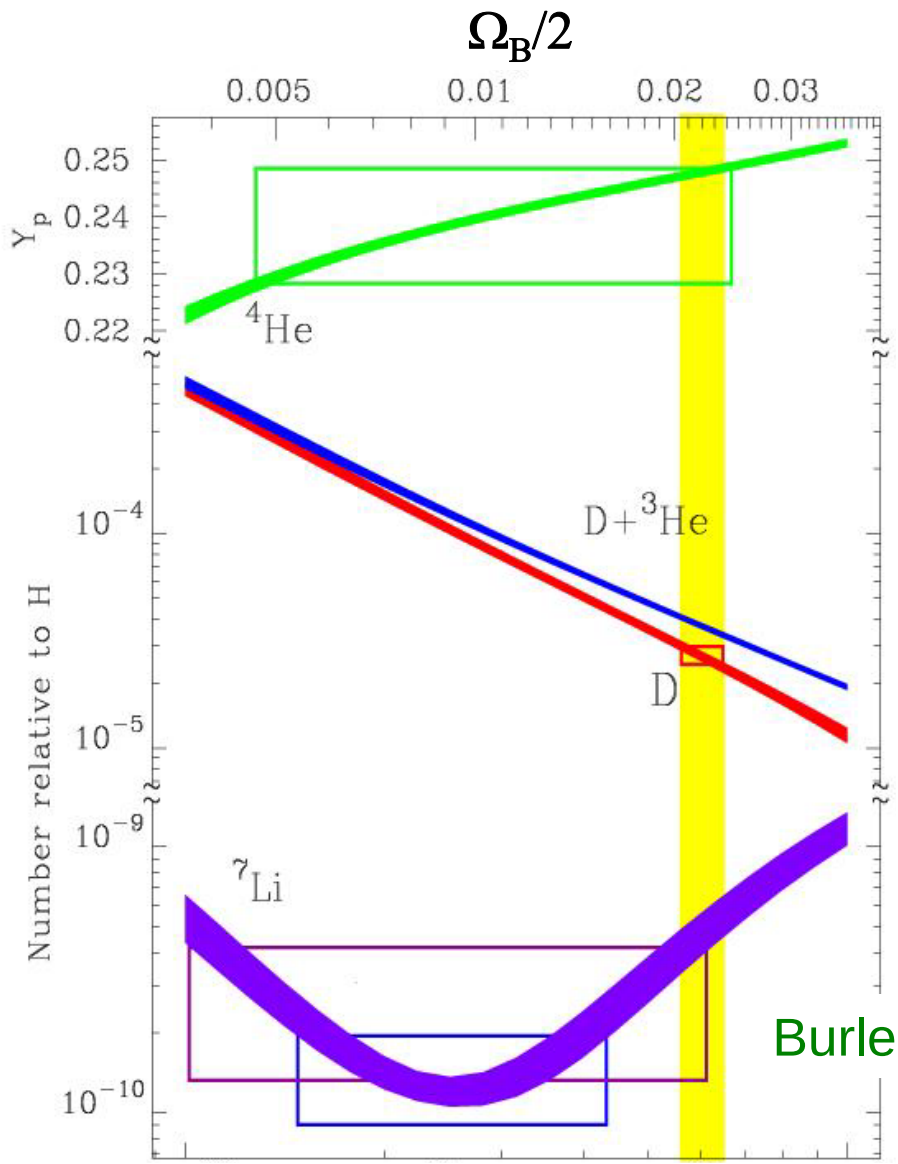


$$\Omega_i \equiv \rho_i/\rho_C \qquad \rho_C \equiv 3H_0^2/8\pi G$$

If We Could "See" Dark Matter



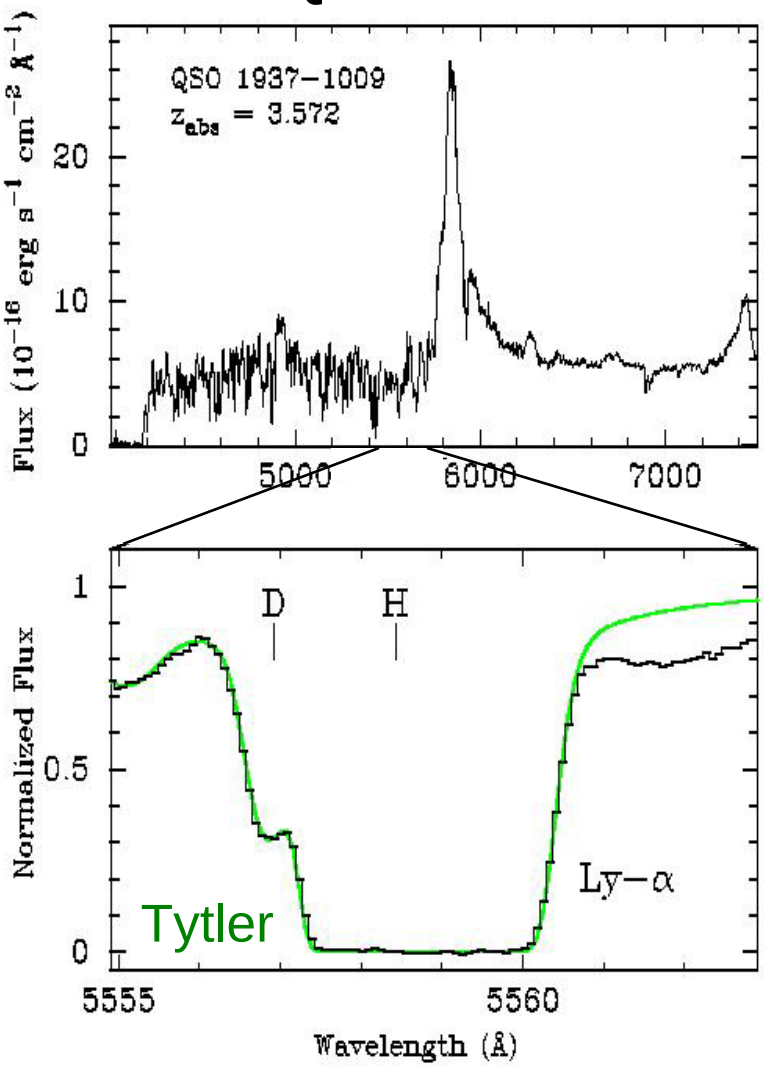
Baryons $\Omega_B \sim 0.04$



Burles et al.

Ly–α

QSO 1937-1009



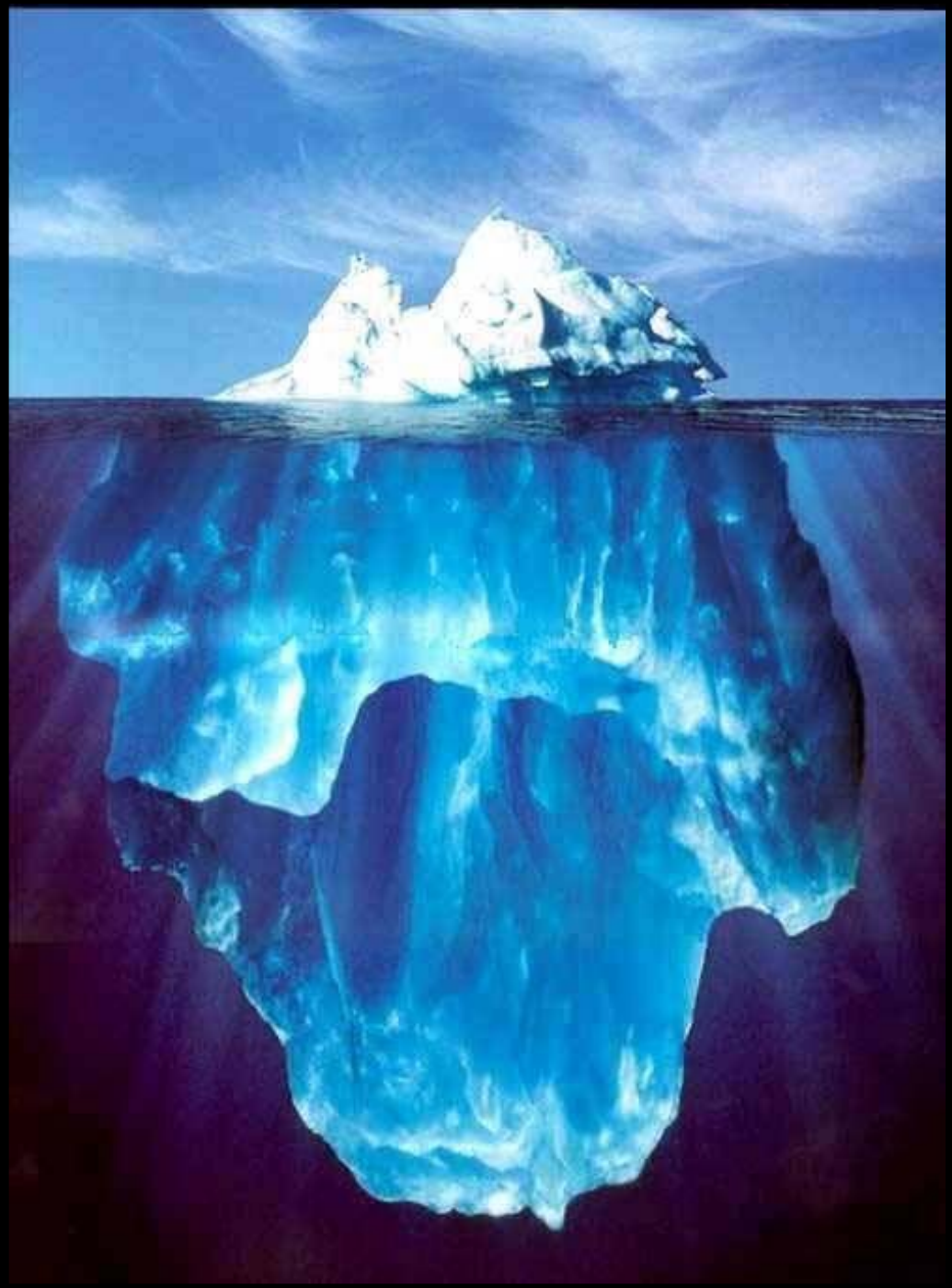
Tytler

Dark Matter

What you don’t see, matters.

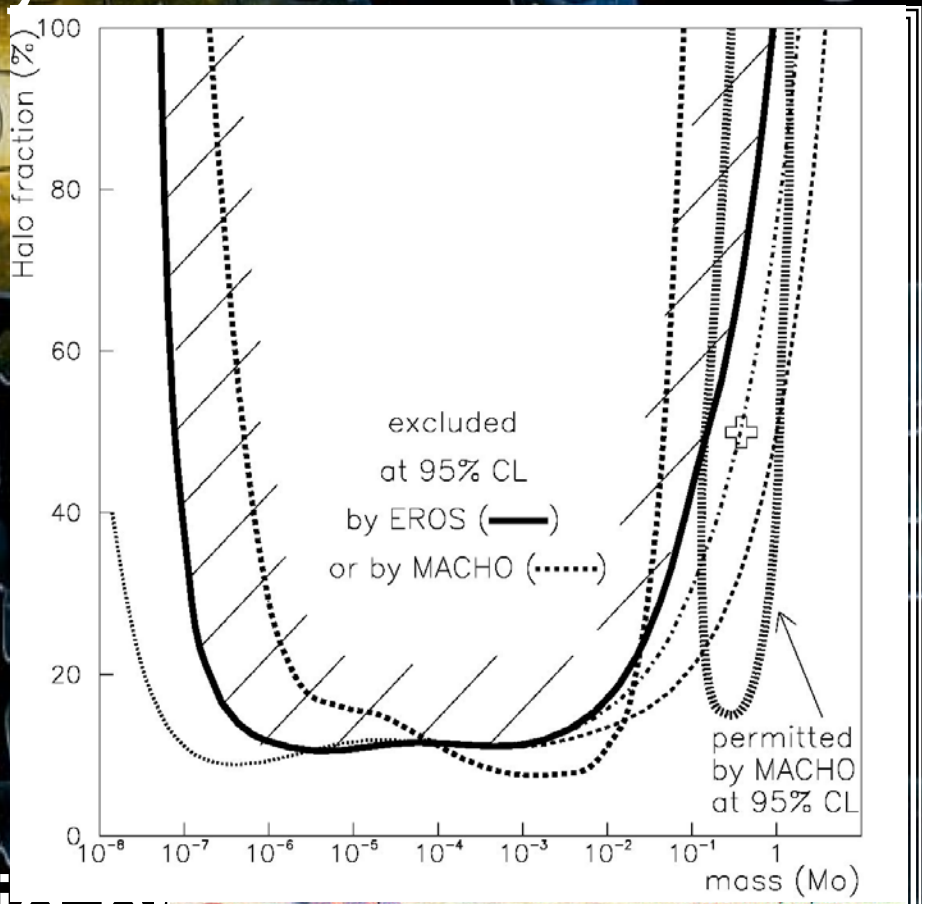
We don’t see most of the matter.

It doesn’t seem to be “normal” matter.



Dark matter?

- Modified Newtonian dynamics
- Planets
- Dwarf stars
  brown red white
- Black holes
- Fossil relic from the big b



Mathey-Tissot®
have lead you to the edge.
Each moment must be
precise and confident. At
this point there is one
direction; forward.

Neutrinos

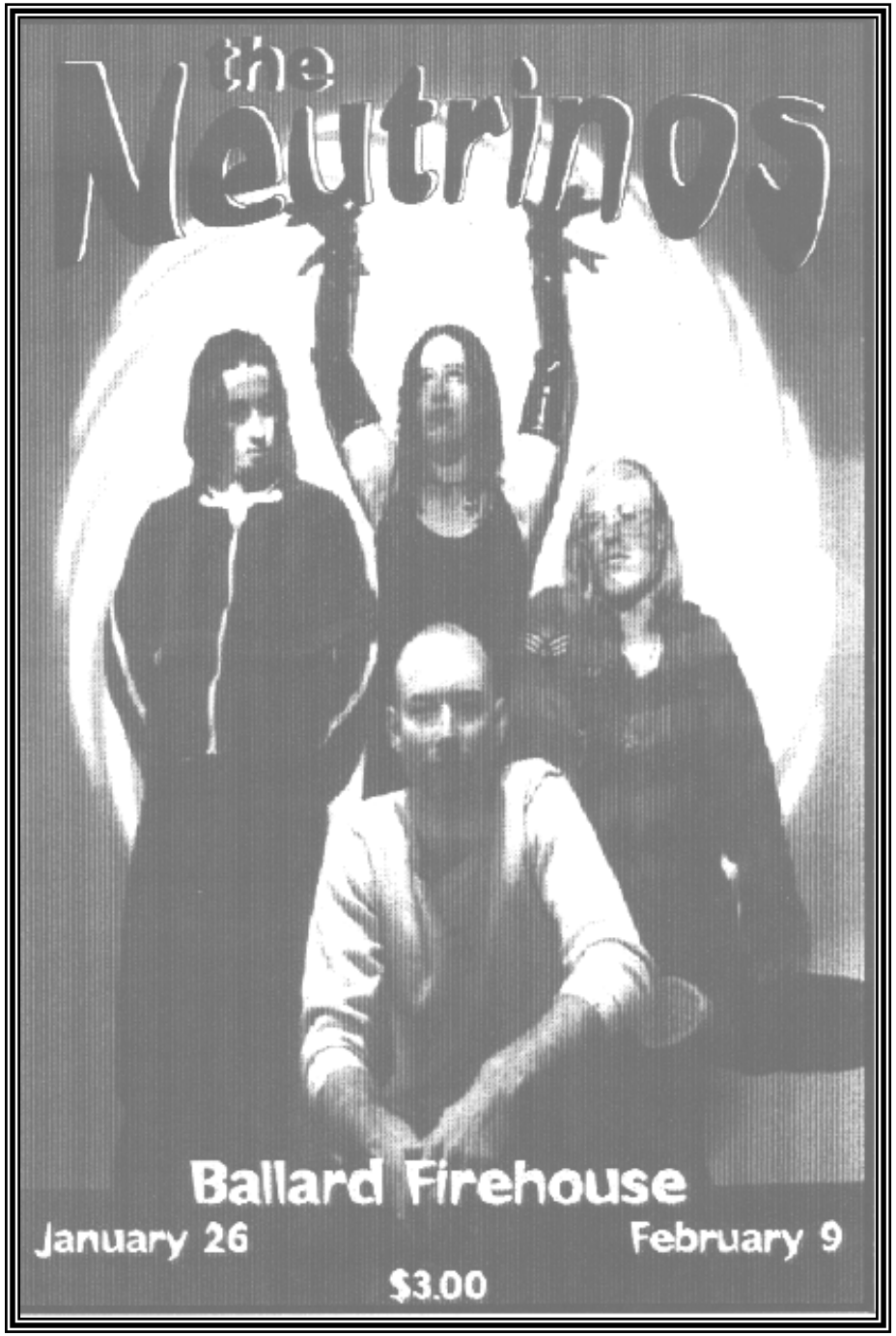
- **Neutrinos exist:**
  three active + sterile?

- **Neutrinos have mass:**
  - **Atmospheric (10^{-2} eV)**
  - **Solar (10^{-3} eV)**
  - **LSND (1 eV)**

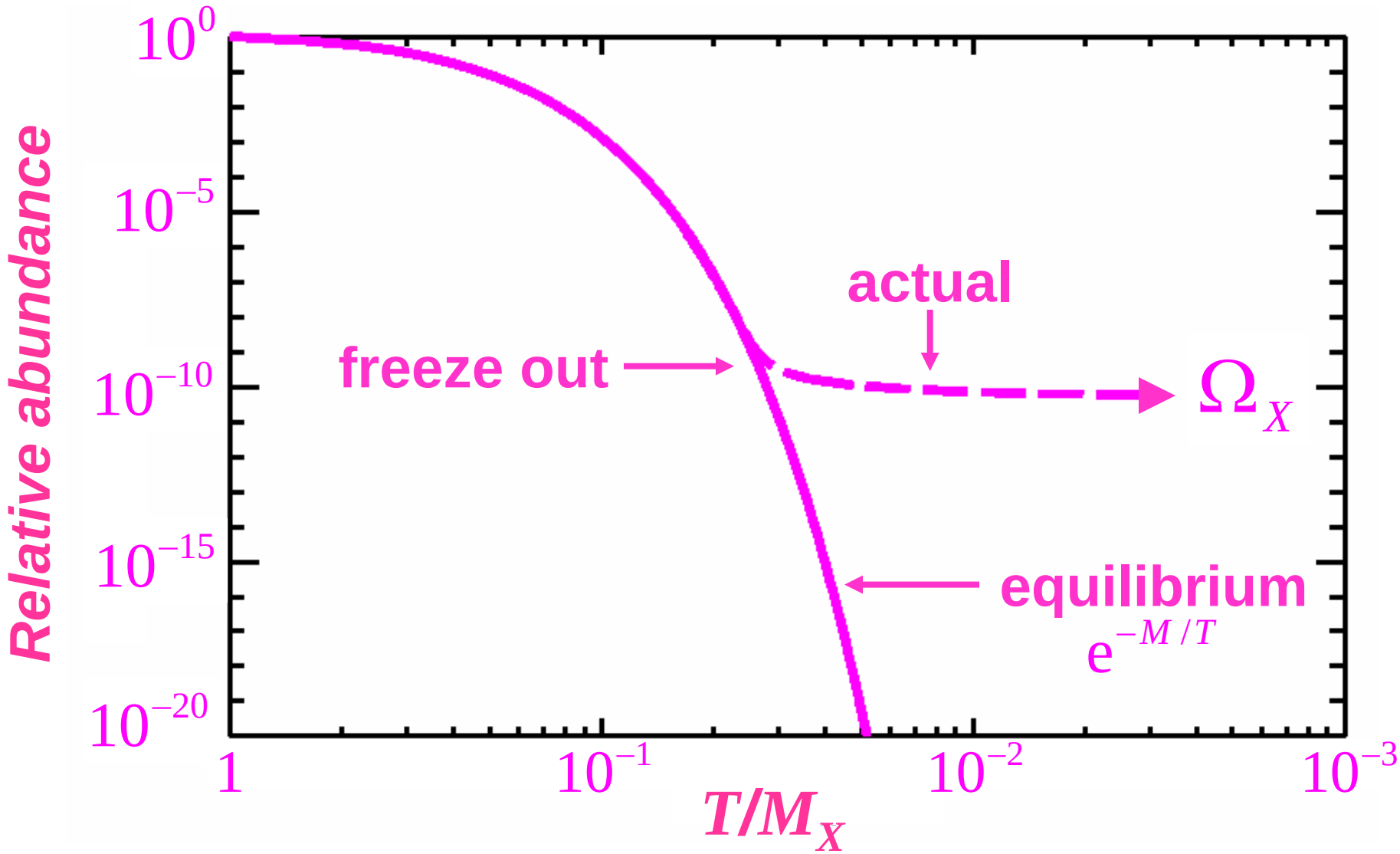
- **Contribute to Ω**
  hot thermal relic:

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

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



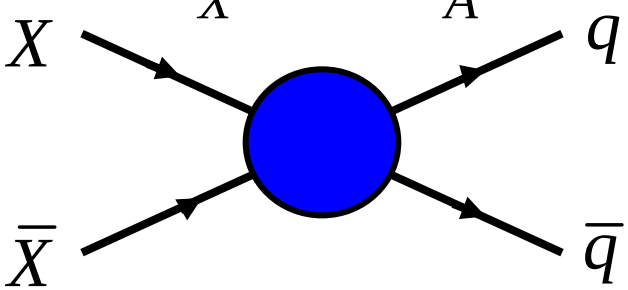
Cold Thermal Relics



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

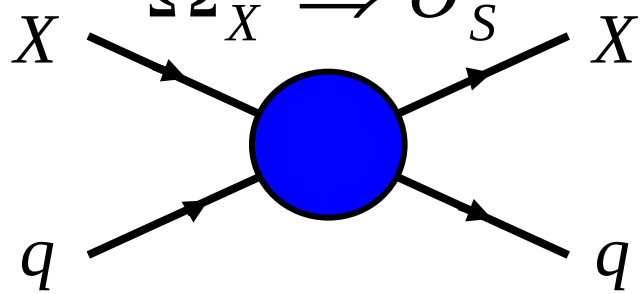
Cold thermal relics $\Omega_X \propto \sigma_A^{-1}$

$$\Omega_X \Rightarrow \sigma_A$$



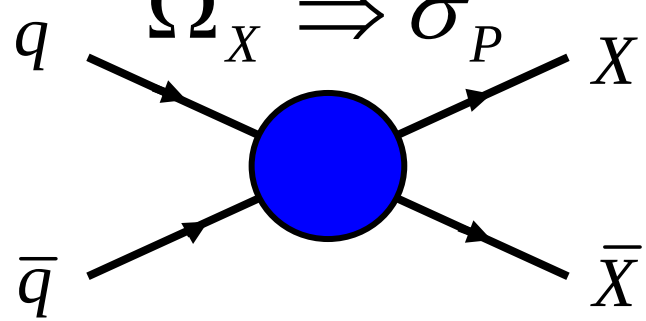
$$X + \bar{X} \rightarrow q + \bar{q}$$

$$\Omega_X \Rightarrow \sigma_S$$



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

$$\Omega_X \Rightarrow \sigma_P$$



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

Seeking SUSY

Hierarchy problem:

- fundamental scale is Planck mass*
- observe particles with mass much less than Planck mass
  - gauge bosons protected by gauge symmetry
  - fermions protected by chiral symmetry
  - scalars (e.g., Higgs) defenseless!
- introduce supersymmetry to protect scalars

Supersymmetric Standard Model:

105 parameters

Constrained Minimal Supersymmetric Standard Model:

3 parameters

Lightest supersymmetric particle (LSP) stable:

neutralino?

---

* Assumed here to be $G_N^{-1/2}$

Cold Thermal Relics (neutralino)

- **Direct detection (σ_S)**

  More than a dozen experiments

- **Indirect detection (σ_A)**

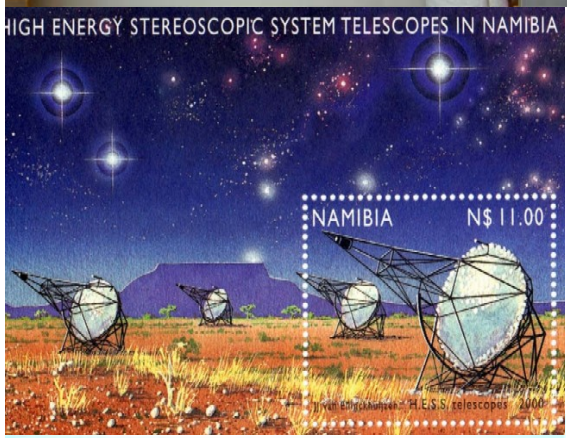
  Annihilation in sun, Earth, galaxy. . .

  neutrinos, positrons,

  antiprotons, γ rays, . . .

- **Accelerator production (σ_P)**

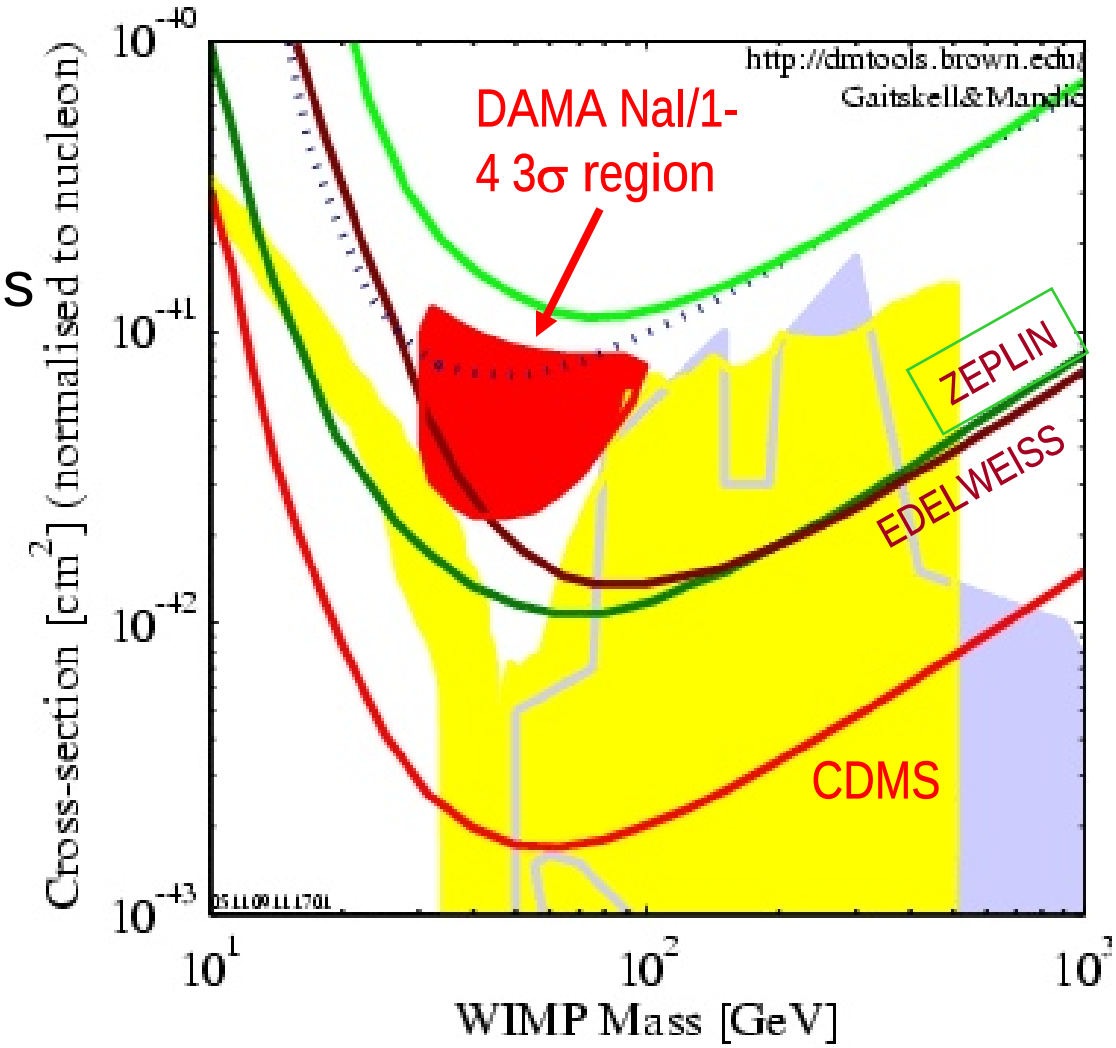
  Tevatron, LHC, ILC



Cold Thermal Relics

Cryogenic Dark Matter Search

- SUSY shaded areas
- Probing significant regions of MSSM model space
- Light-mass region largely ruled out
- Another factor of 100 may be needed



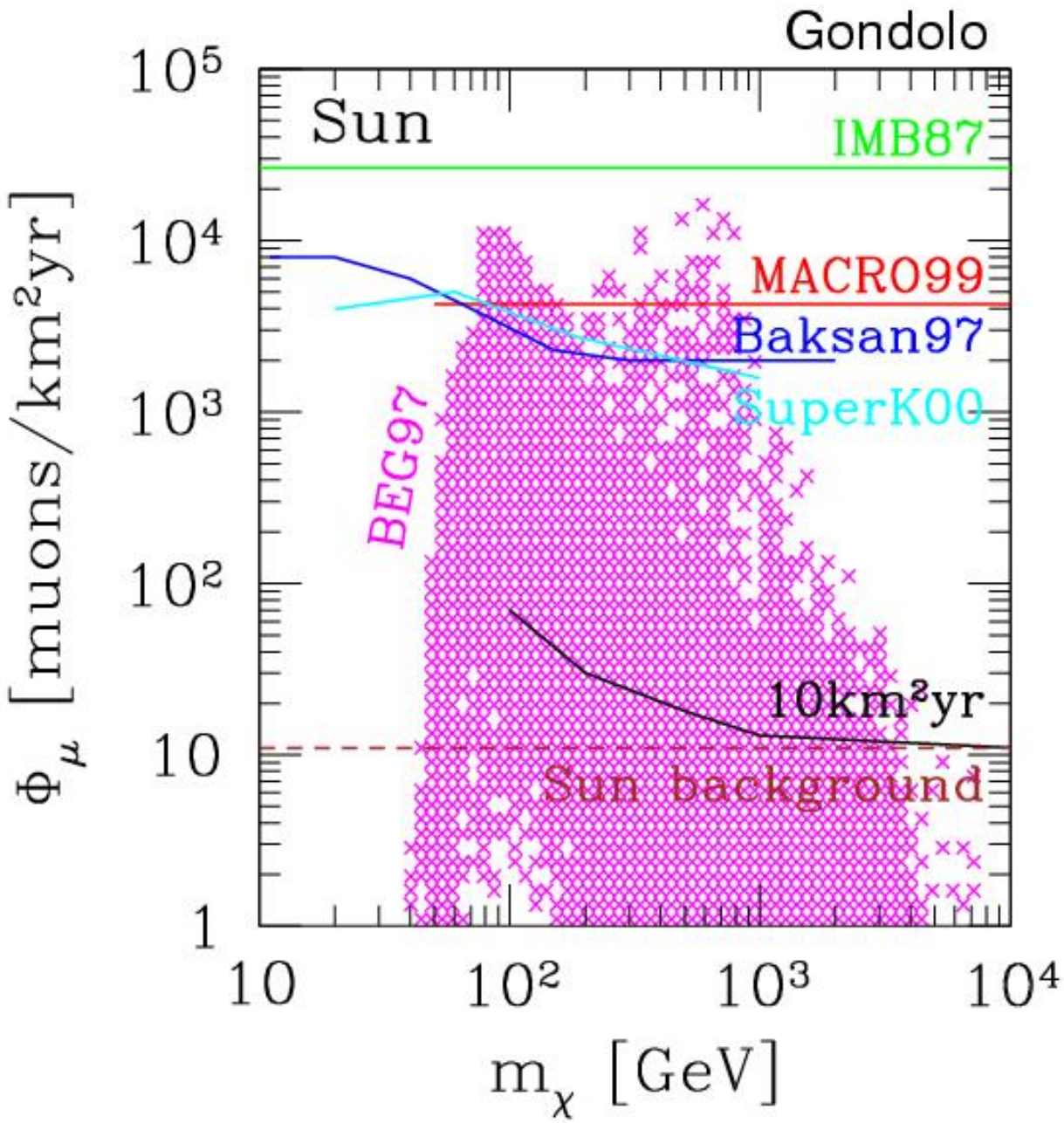
Indirect detection

- Neutrinos from the sun or Earth
- Anomalous cosmic rays and γ rays from galactic halo(s)
- Neutrinos, γ rays , radio waves from our galactic center
- Role of halo substructure [rate $\propto$ (density)^2]

  Galactic center: spike cusp, ???

  Black hole in the galactic center

Muon Neutrinos From the Sun



The nature of dark matter is a complex natural phenomenon.

The neutralino is a simple, elegant, compelling explanation.

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

- Tommy Gold

Dark Matter?

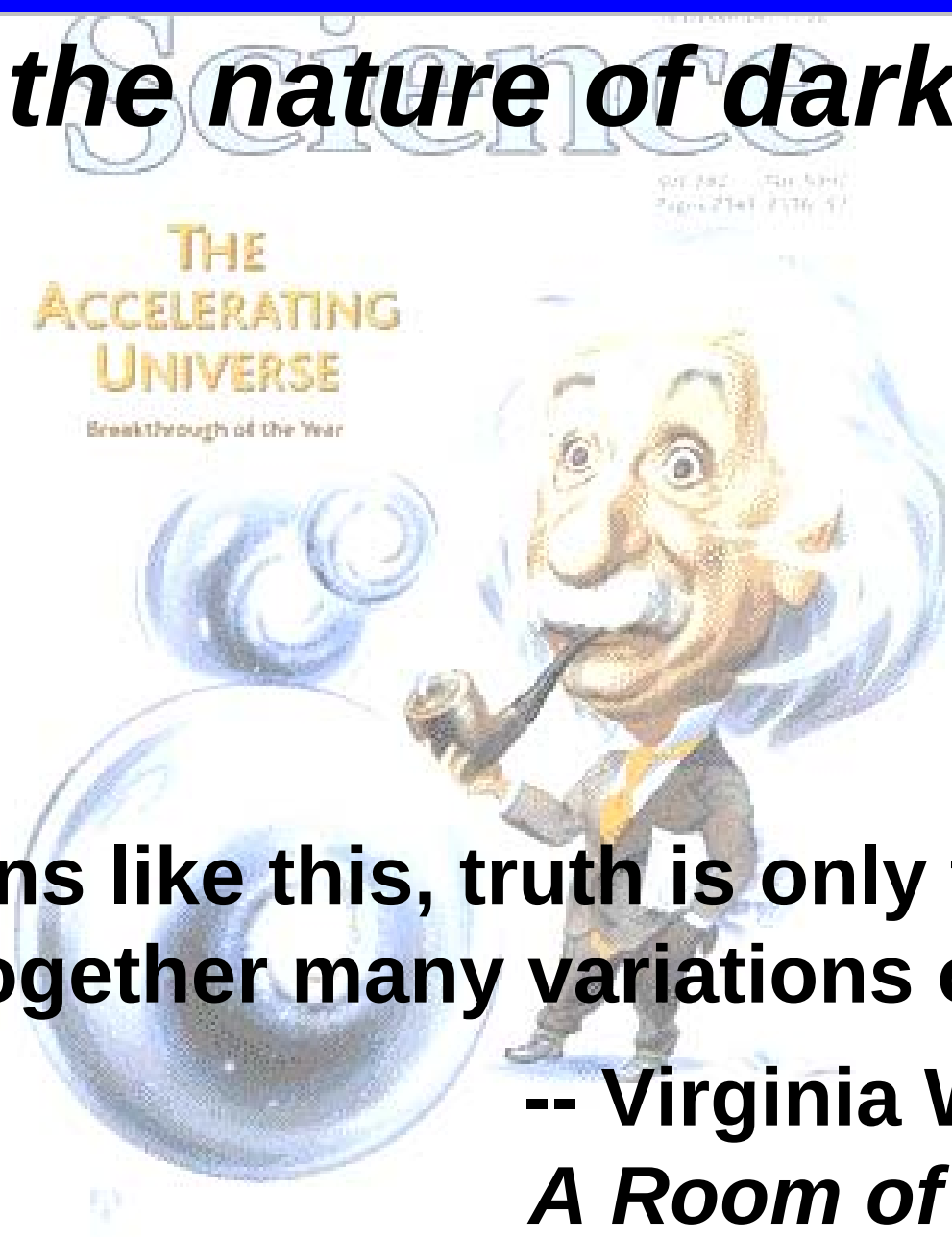
- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, axino, …) (cold dark matter)
- LKP (lightest Kaluza-Klein particle)
- axions, axion clusters
- solitons (Q-balls; B-balls; Odd-balls, Screw-balls….)
- supermassive wimpzillas

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

Interaction strength range
Noninteracting: wimpzillas
Strongly interacting: B balls

Epicycle II – Dark Energy

What is the nature of dark energy



“In questions like this, truth is only to be had by laying together many variations of error.”

-- Virginia Woolf

A Room of Ones Own

Big-Bang

Robertson-Walker metric

$a(t) = \text{cosmic scale factor}$

$k = 0, \pm 1$

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

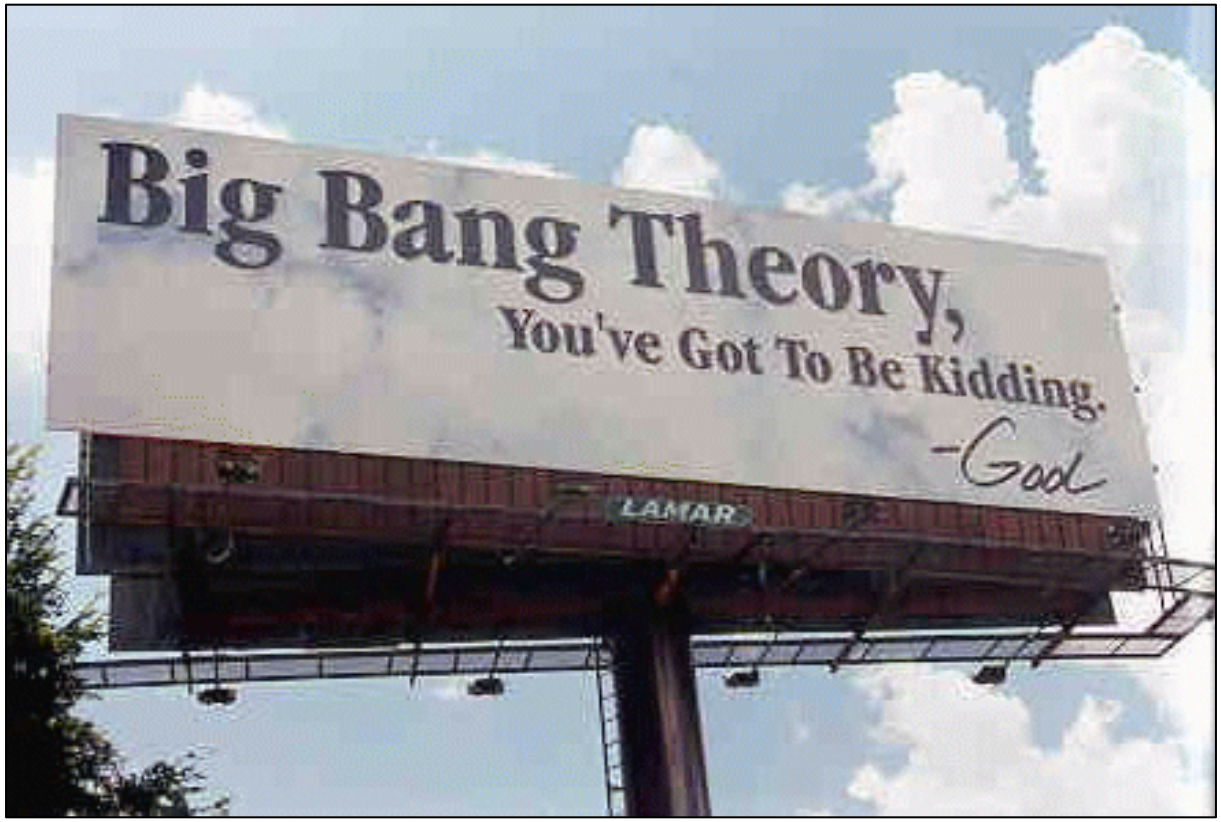
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Perfect-fluid stress tensor

$\rho =$ energy density

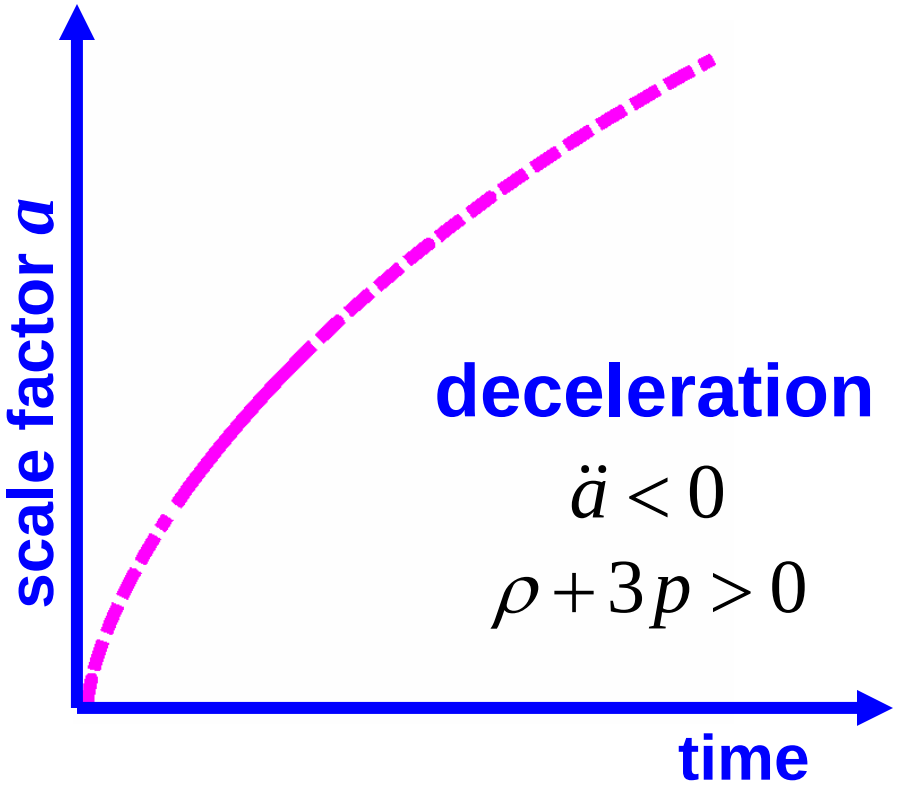
$p =$ pressure

$$T^{\mu}{}_{\nu} = \text{diag}(\rho, p, p, p)$$



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

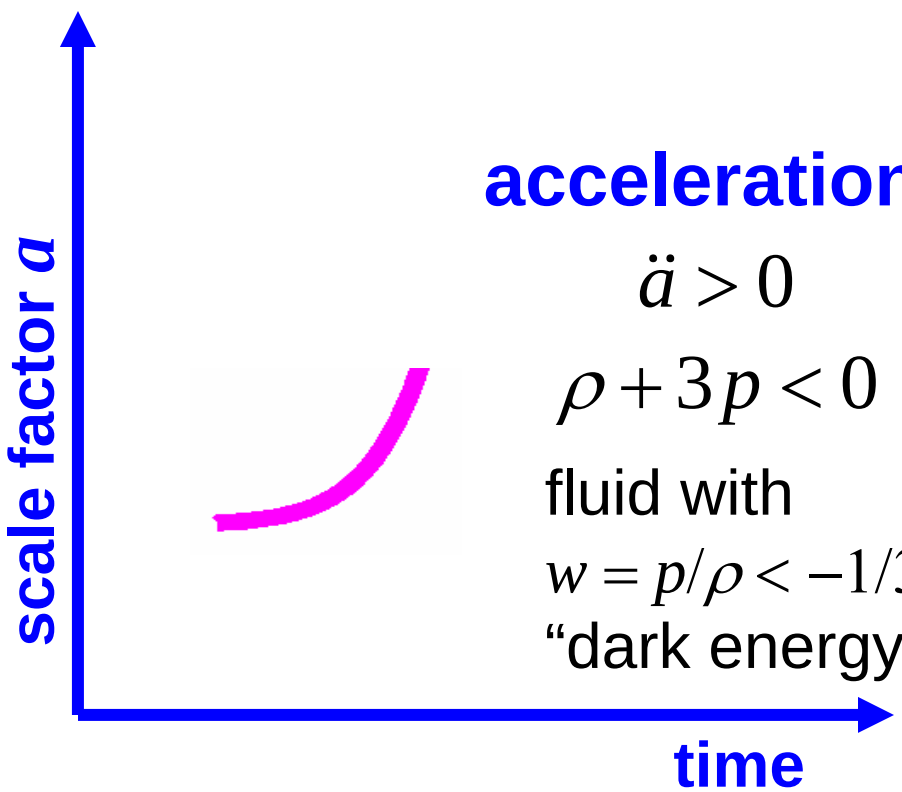
$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + 3p\right)$$



deceleration

$$\ddot{a} < 0$$

$$\rho + 3p > 0$$



acceleration

$$\ddot{a} > 0$$

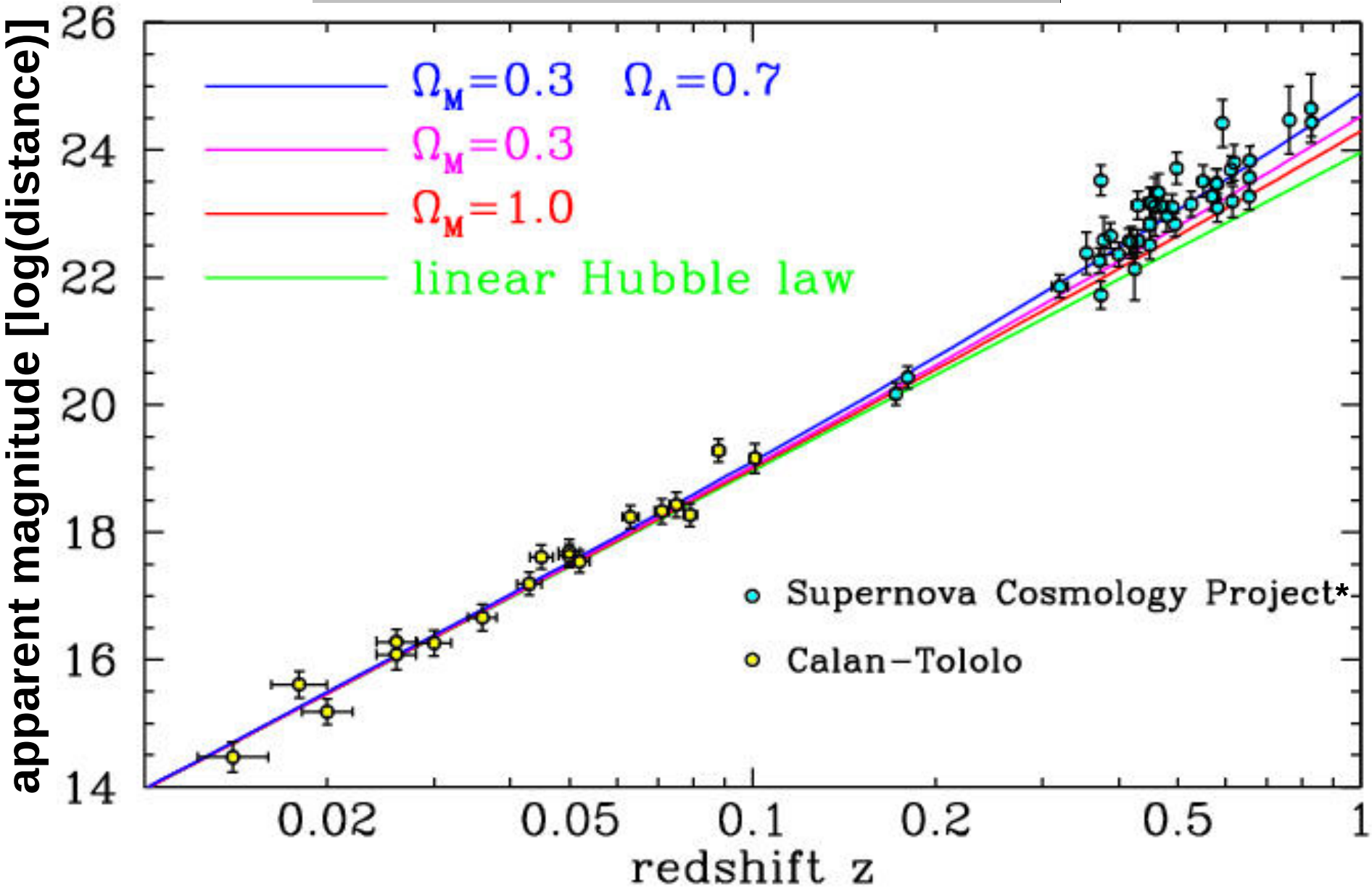
$$\rho + 3p < 0$$

fluid with

$w = p/\rho < -1/3$

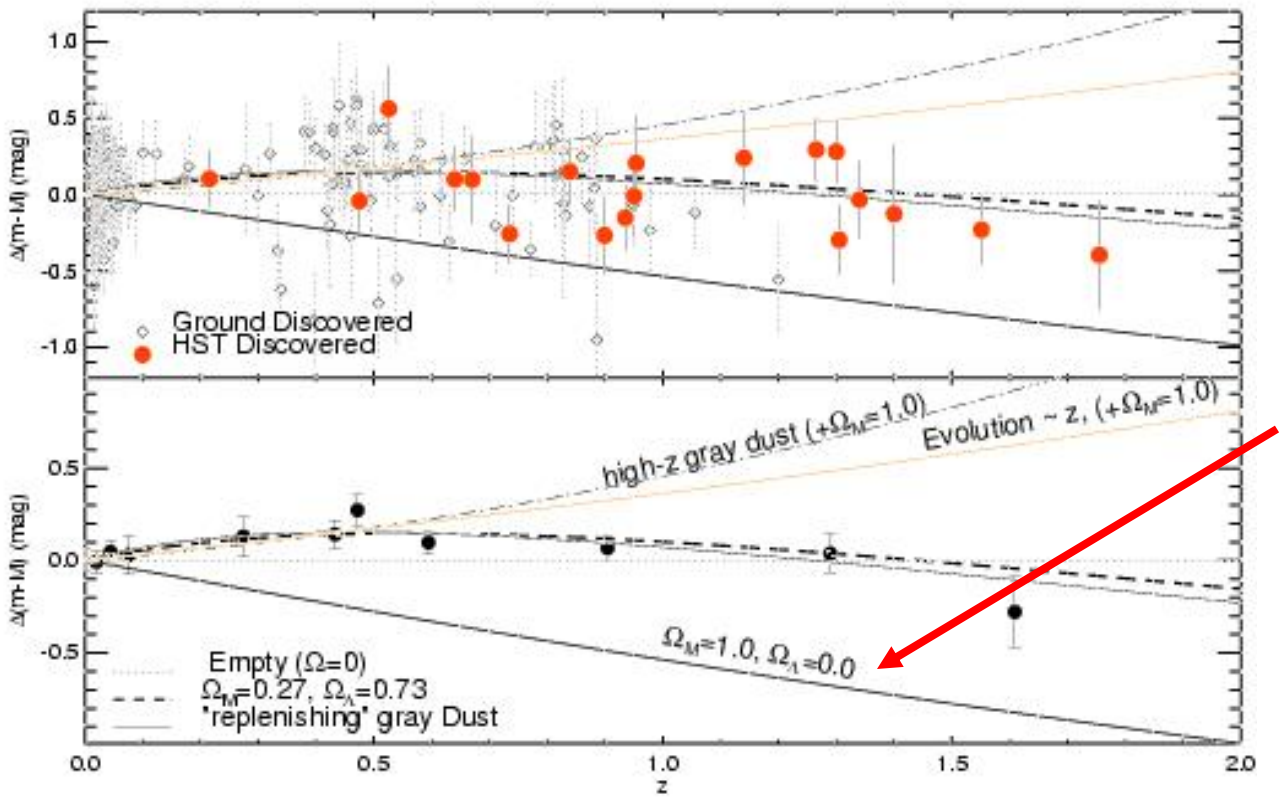
“dark energy”

Type Ia supernova



High-z SNe are fainter than expected in the Einstein-deSitter model

Riess et al. (2004)



Einstein-de Sitter: flat, matter-dominated model (maximum theoretical bliss)

cosmological constant, some changing non-zero vacuum energy, or some unknown systematic effect(s)

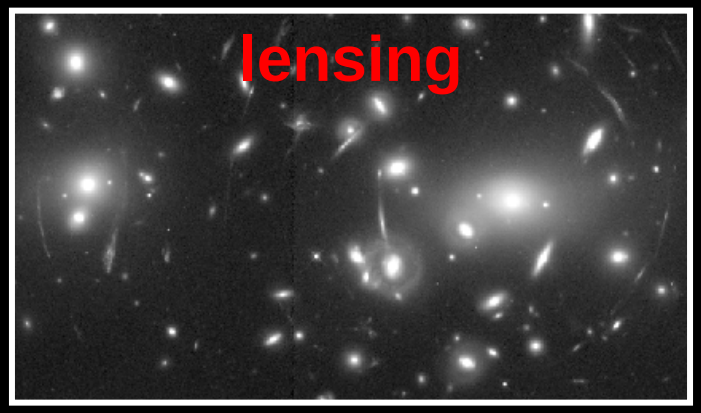
<u>The case for Λ:</u>

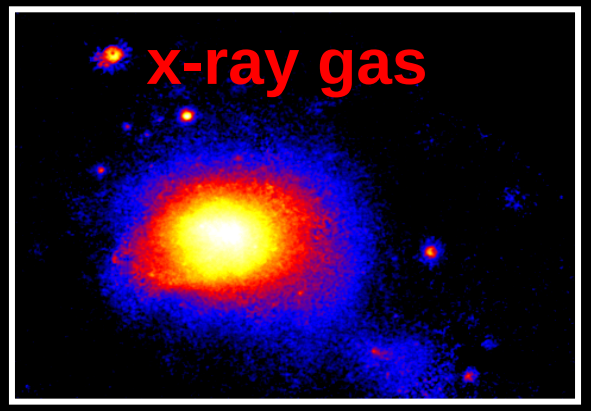
1) Hubble diagram $d_L(z)$

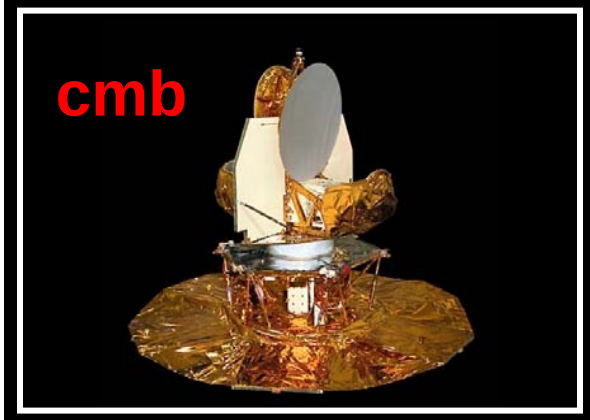
2) subtraction

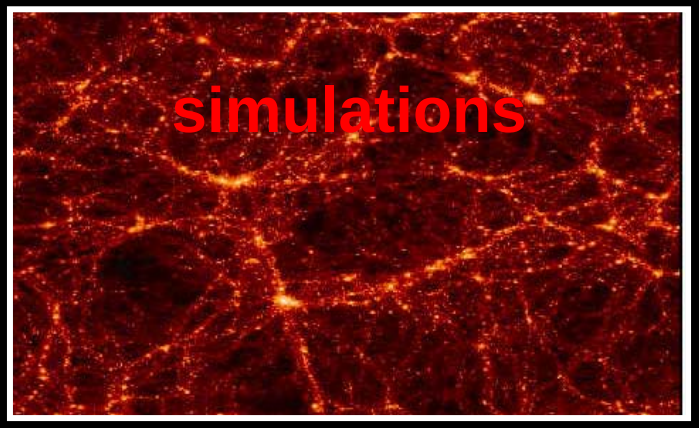
Subtraction

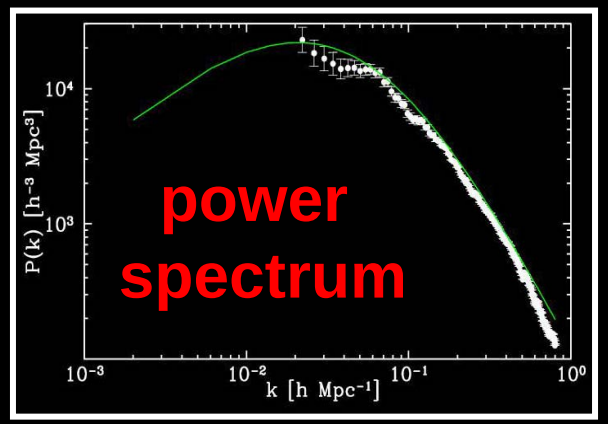
$$\Omega_i \equiv \rho_i / \rho_C \qquad \rho_C \equiv 3H_0^2 / 8\pi G$$











$\Omega_{\mathrm{TOTAL}} = 1$ **(CMB),** $\Omega_M = 0.27,$ $1 - 0.27 = 0.73$

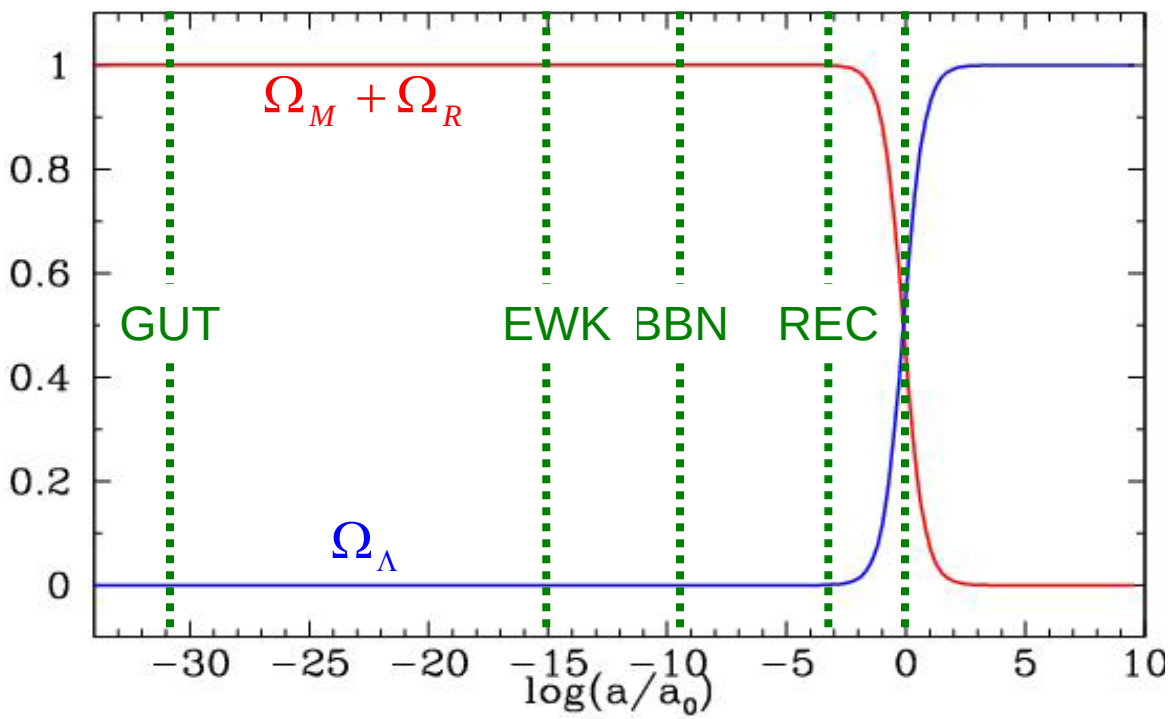
Cosmo-illogical constant?

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

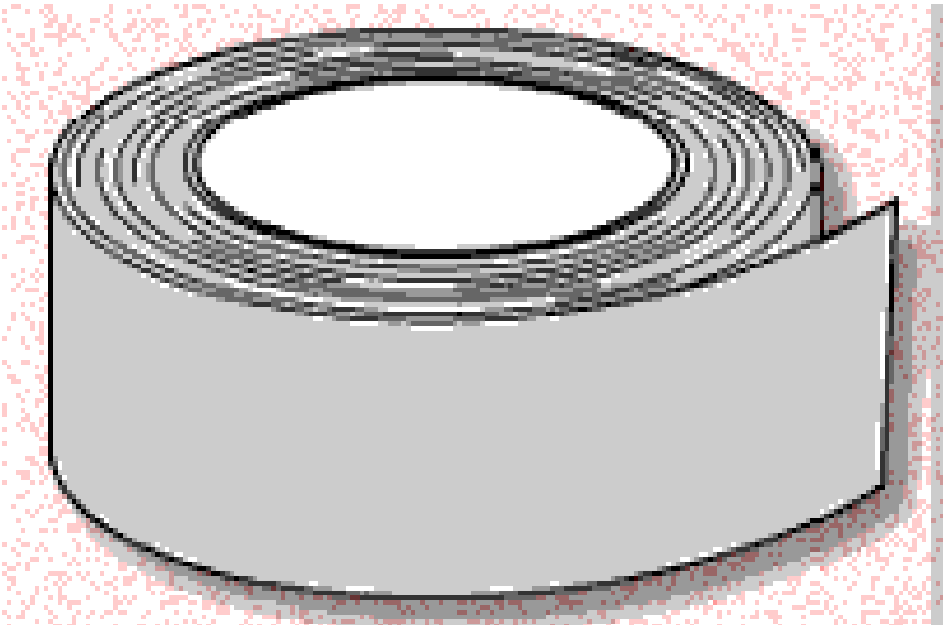
$$\rho_\Lambda \sim 10^{-30}\,\mathrm{g\ cm^{-3}} \sim \left(10^{-4}\ \mathrm{eV}\right)^4 \sim \left(10^{-3}\ \mathrm{cm}\right)^{-4}$$

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

Illogical timing (why now?):



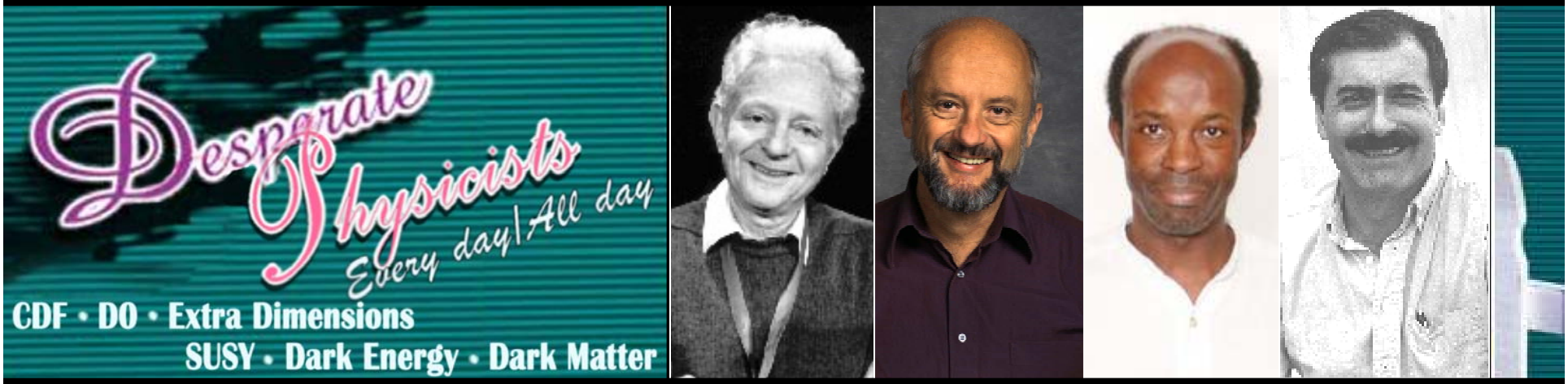
Practical Tools for Dark Energy



anthropic principle

scalar fields

How Far Will They Go?



How Far Will They Go?

Take sides!

- Can't hide from the data – ΛCDM too good to ignore
  - SNIa
  - Subtraction: $1.0 - 0.3 = 0.7$
  - Age
  - Large-scale structure
  - …

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

$$3H^2 + k/a^2 \neq 8\pi G\,\rho_{\mathrm{MATTER}} \rightarrow G_{00} \neq 8\pi G\,T_{00}\text{(matter)}$$

- Dark energy, ρ_Λ (modify <u>right-hand side</u> of Einstein equations)
  - Constant ("just" Λ)
  - Not constant (dynamics driven by scalar field: $M \sim 10^{-33}$ eV)
- Gravity (modify <u>left-hand side</u> of Einstein equations)
  - Beyond Einstein (non-GR: branes, *etc*.)
  - (Just) Einstein (GR: back reaction of inhomogeneities)

- 10^{-33} **eV scalar fields!!!**
- **modification of gravity**
- **extra dimensions**
- **branes and bulk**
- **Lorentz violating vector fields**
- **Friedmann equation incomplete**
-
-
-
- **(then there are the crazy ideas)**

The nature of dark energy is a complex natural phenomenon.

There are no simple, elegant, compelling explanations.

The Dark Side of the Universe

96% of the Universe Is Dark!

Dark Matter and Dark Energy

FNAL Summer Students, August 2006
Rocky Kolb, Astronomy & Astrophysics