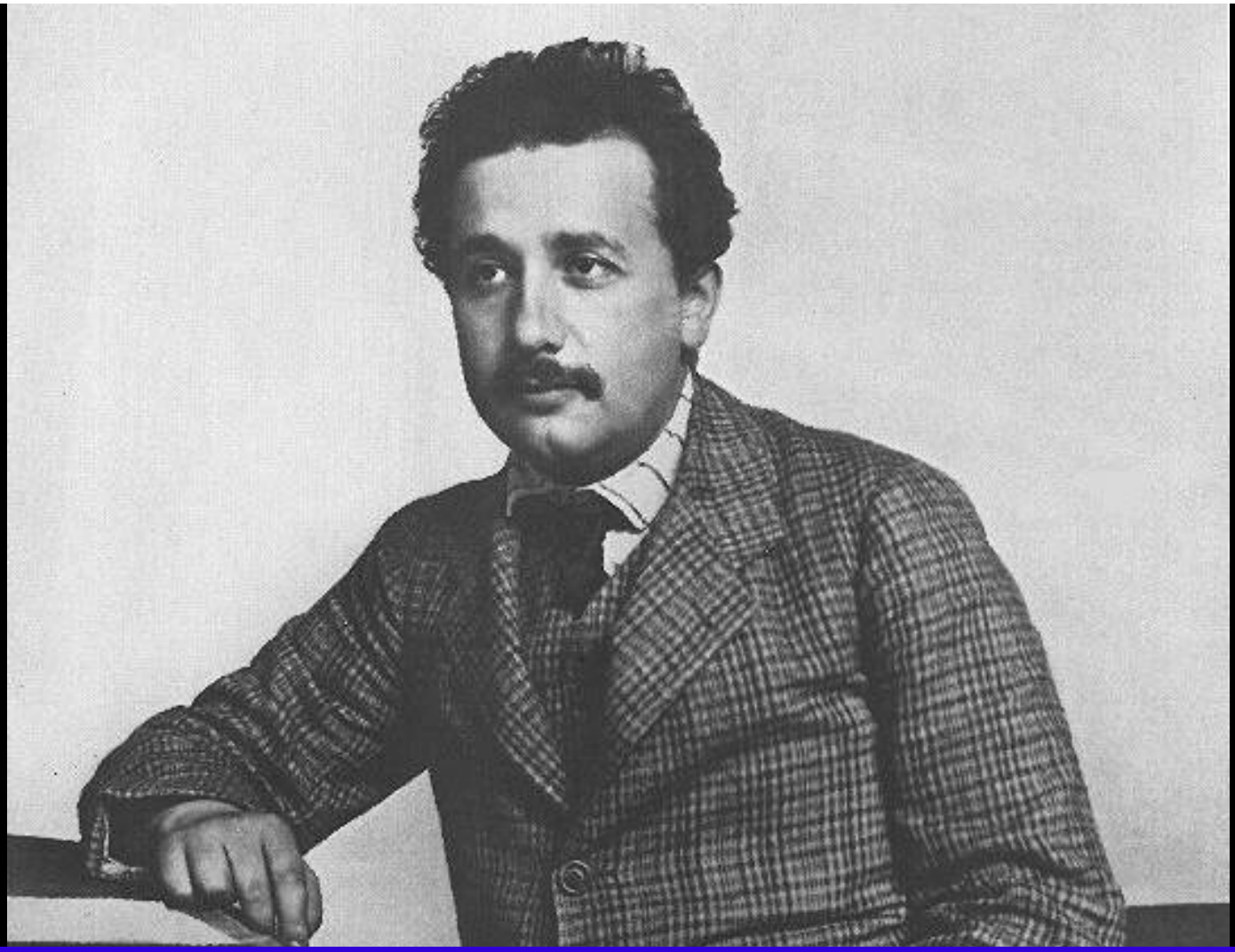
INTRODUCTION TO COSMOLOGY

Joe Silk

Oxford/IAP

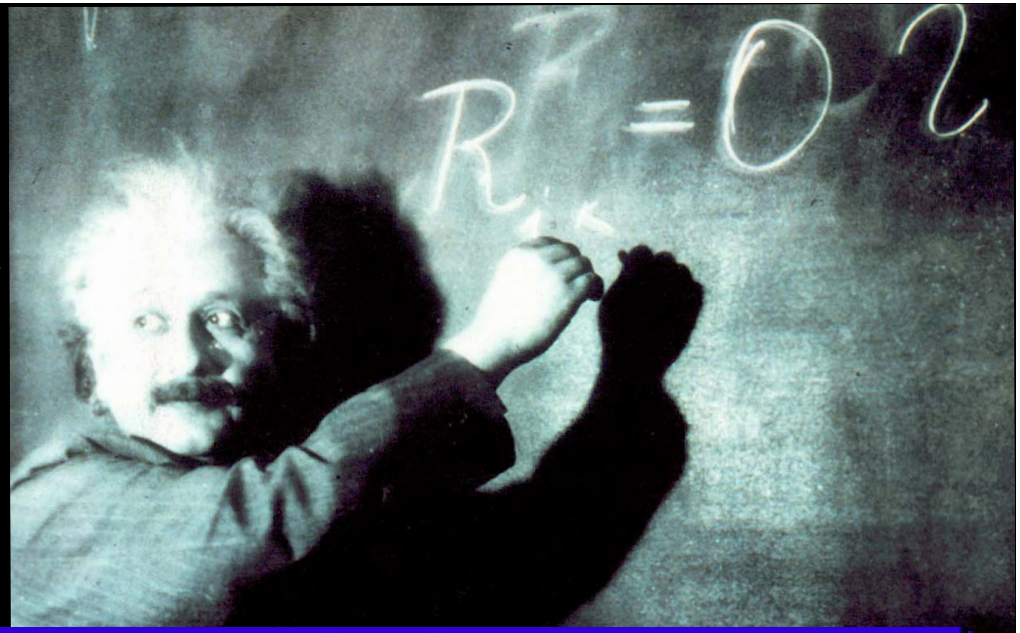
July 2011



CURVATURE = ENERGY-MOMENTUM

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

THE BIRTH OF DARK ENERGY



CURVATURE = ENERGY-MOMENTUM

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

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

COSMOLOGICAL CONSTANT OR DARK ENERGY?

Field equation: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$

Perfect fluid stress tensor: $T^{\mu}{}_{\nu} = \mathrm{diag}(\rho, -p, -p, -p)$

$$\tilde{T}^{\mu}{}_{\nu} = \mathrm{diag}(\rho_\Lambda, \rho_\Lambda, \rho_\Lambda, \rho_\Lambda) \qquad \rho_\Lambda = \Lambda / 8\pi G$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + \tilde{T}_{\mu\nu} \right)$$

In general, p=wρ with w=-1 for the cosmological constant Λ

Observational cosmology

$$\dot{R}^2 - \frac{8\pi G}{3}\rho R^2 = -kc^2$$

$$\Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2}$$

$$H^2(a) = H_0^2\left[\Omega_{\rm v} + \Omega_{\rm m}a^{-3} + \Omega_r a^{-4} - (\Omega_{\rm total} - 1)a^{-2}\right]$$

Distance measurement

$$D(z) = \int_0^z \frac{c}{H(z')}\,{\rm d}z'$$

Density fluctuation growth

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G\rho_{\rm m} - c_s^2k^2/a^2\right)$$

$$\delta \propto f(\Omega)a$$

$$f(\Omega) \simeq \tfrac{5}{2}\Omega_{\rm m}\left[\Omega_{\rm m}^{4/7} - \Omega_{\rm v} + (1 + \tfrac{1}{2}\Omega_{\rm m})(1 + \tfrac{1}{70}\Omega_{\rm v})\right]^{-1}$$

1929: Hubble obtained
slope H=530 km/sec/Mpc

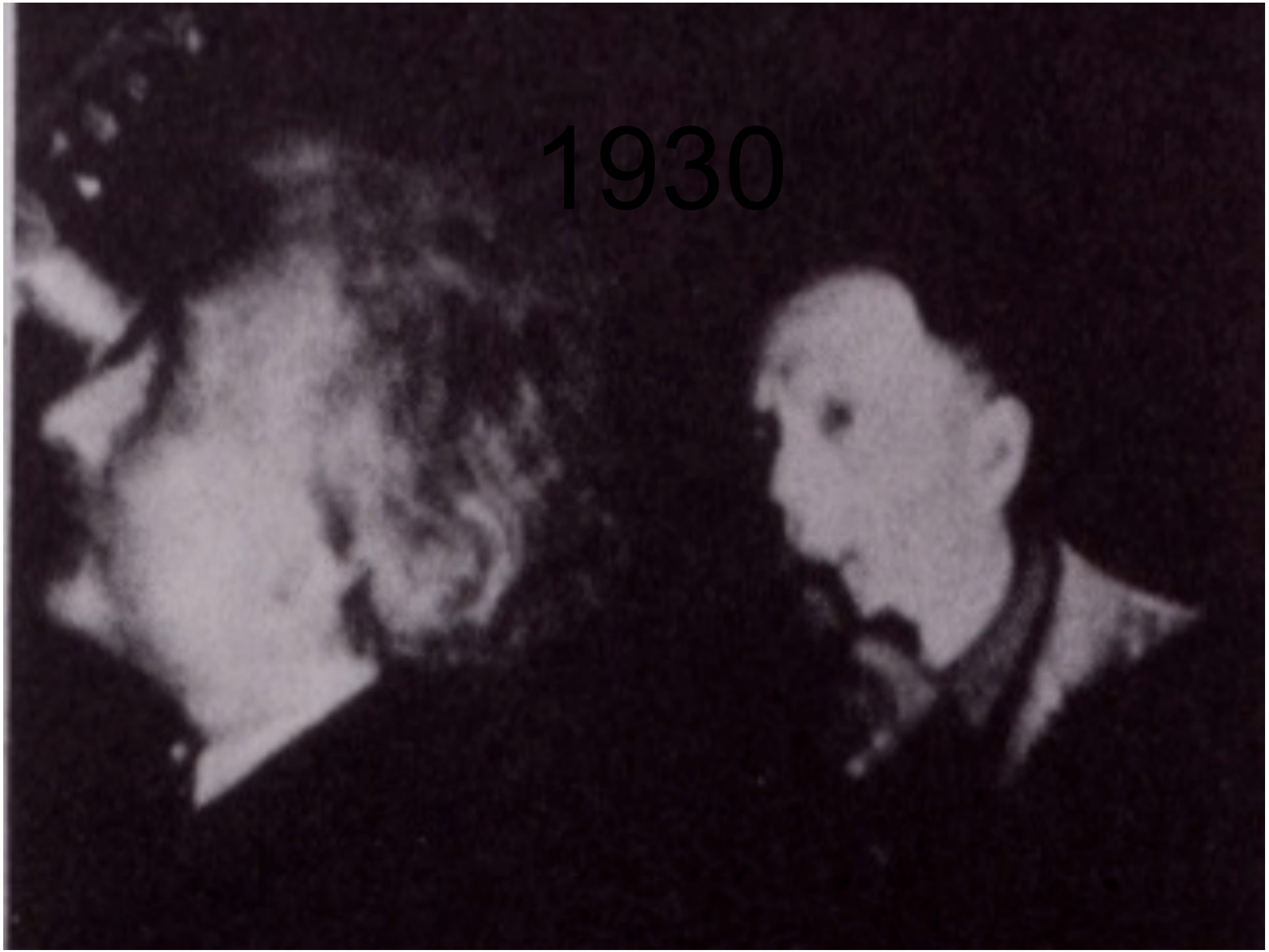
velocity

distance

10⁶ PARSECS

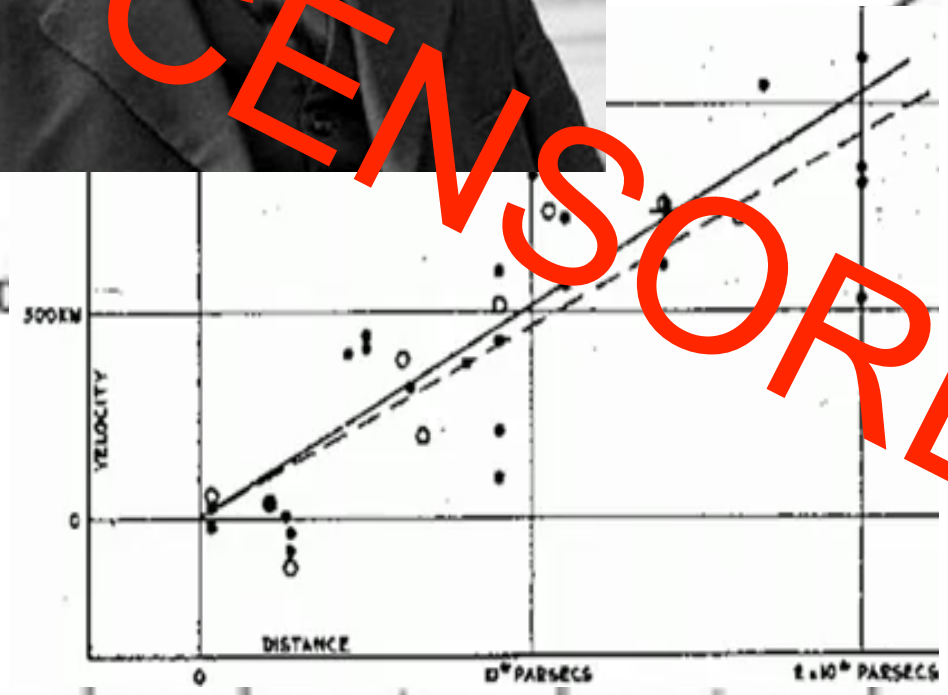
FIGURE 1

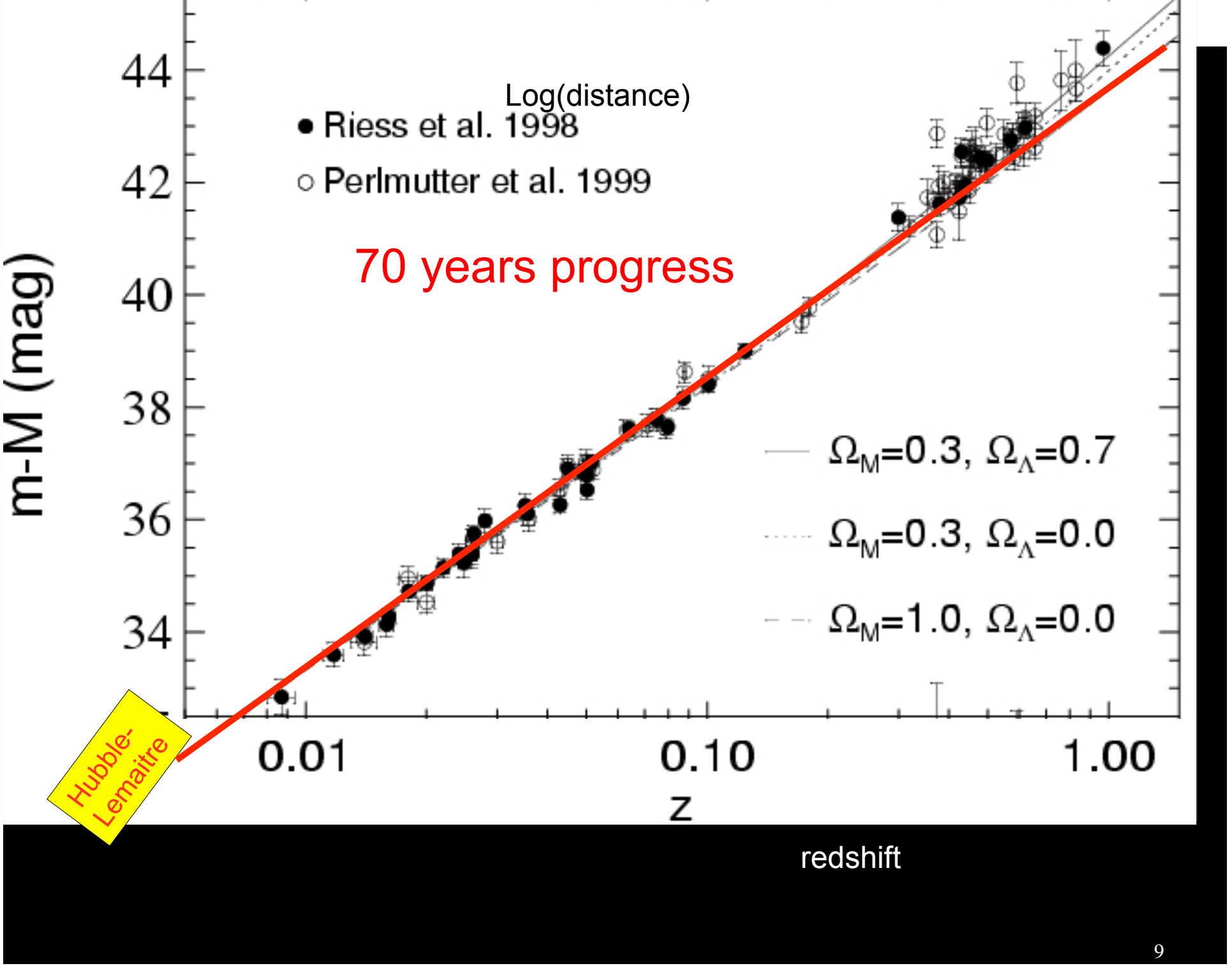
Alexander Friedmann:
1924


1930

1927: Georges Lemaitre obtained slope H=625 km/sec/Mpc

CENSORED?




Log(distance)
Riess et al. 1998
Perlmutter et al. 1999
70 years progress
m-M (mag)
44
42
40
38
36
34
0.01
0.10
1.00
z
redshift
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Hubble-Lemaitre

1949

nuclear physicists plunge in

RALPH ALPHER
GEORGE GAMOW

predicted origin of light elements
& fossil radiation

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.

February 18, 1948

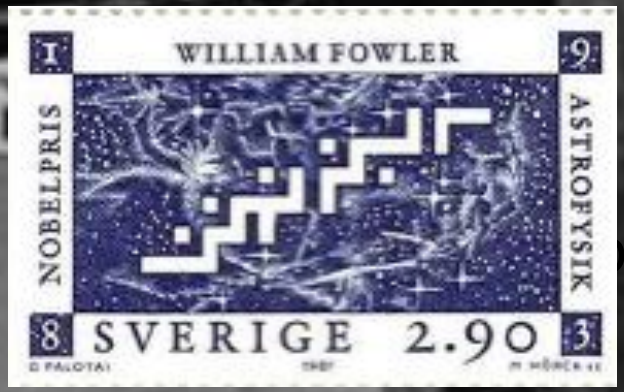
half an hour of creation...

PHYSICS TODAY
AUGUST 1950

What happened to time in the first one three

At the present epoch, in which the density of mat ter in the universe is about [illegible] g/cm³, and th temperature is only about 3°K, the density of radia tion (according to the Stefan-Boltzmann law) [illegible] Thus even now the mass-density of radiation (re lated to mass-energy equivalence law) is only abo twenty times smaller than that of matter.

by George Gamow

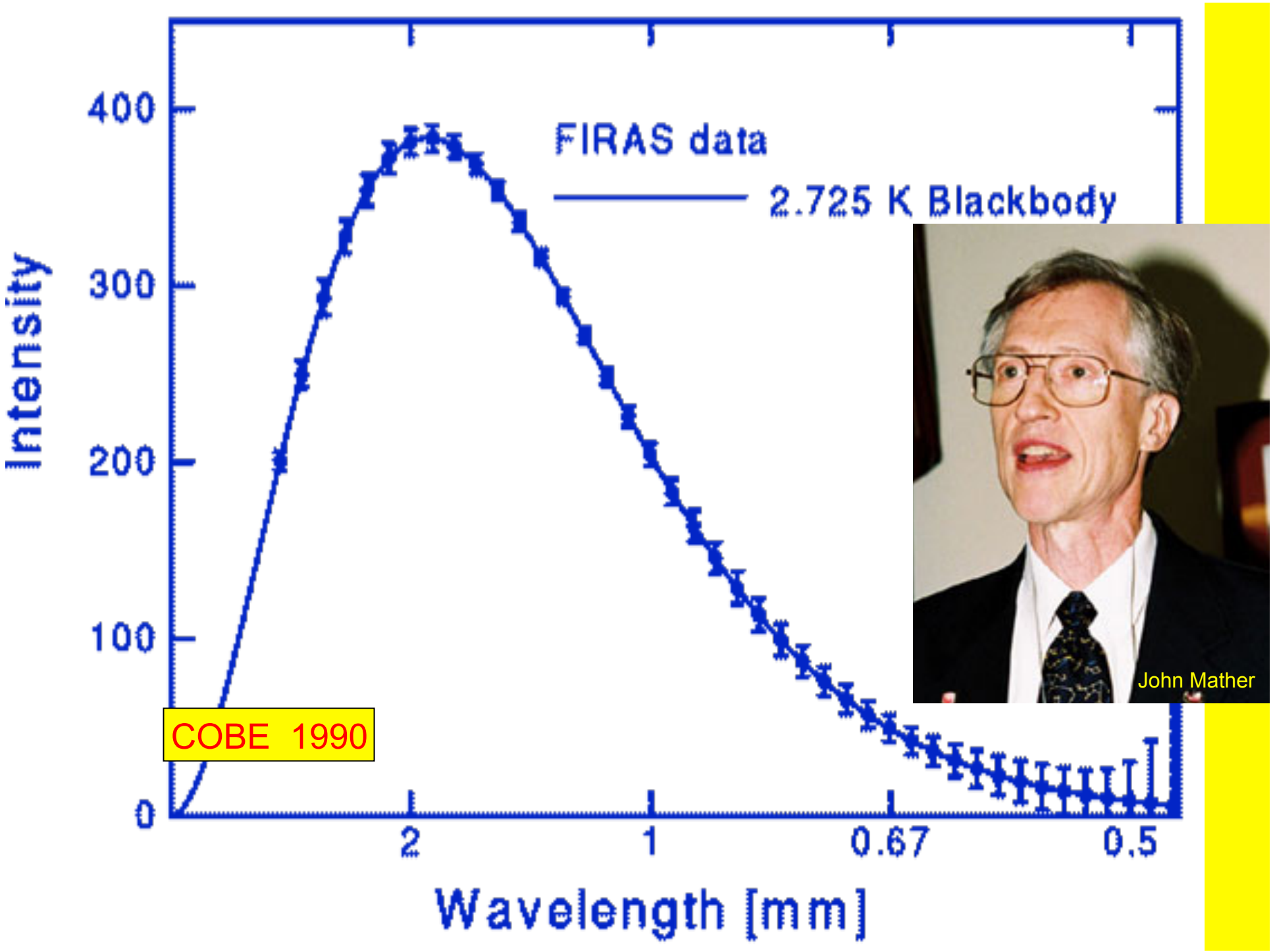


idge, Burbidge, Fo er, Ho

ROM ITS ASHES OUR SOLAR SYSTEM FORME

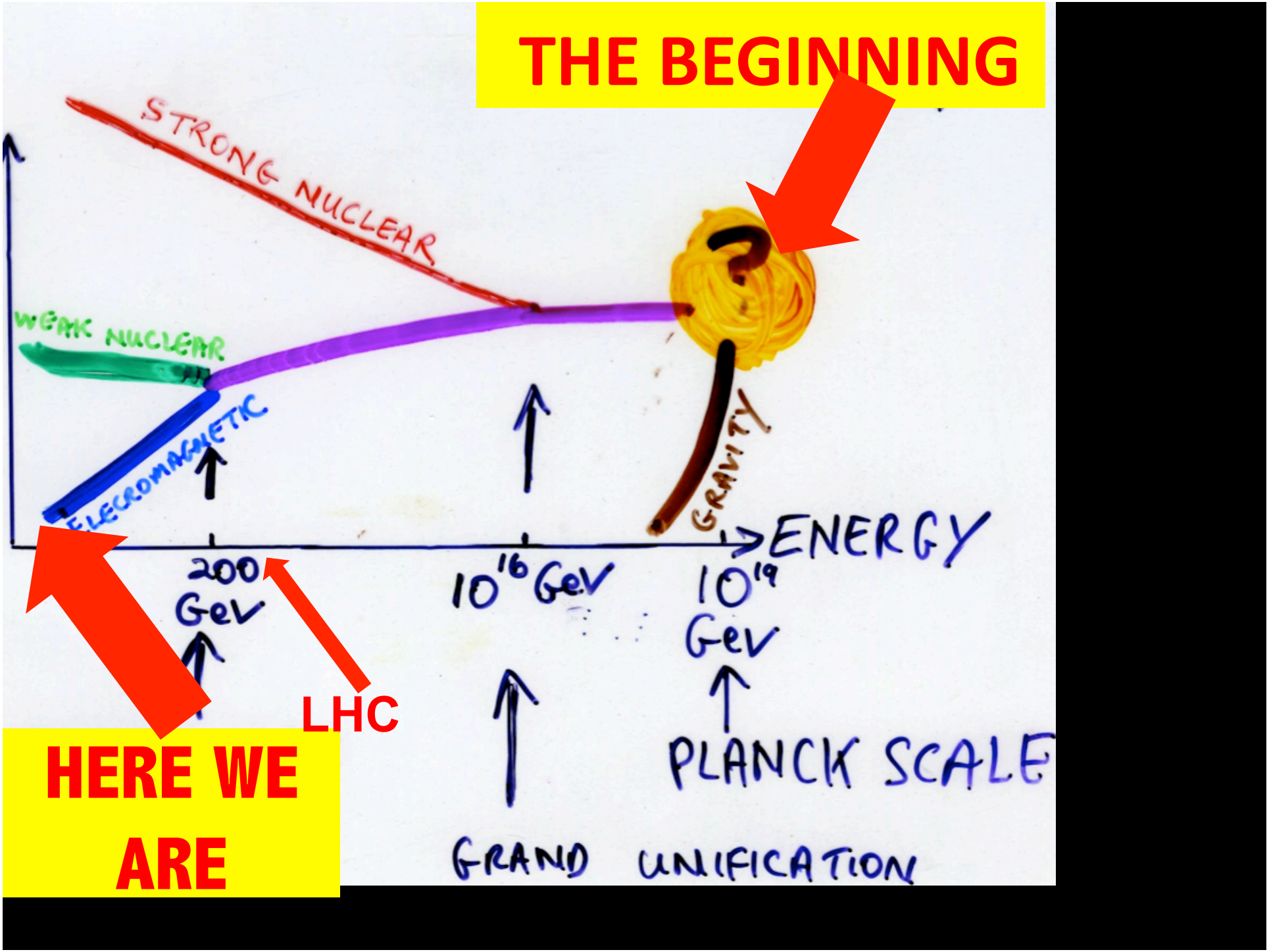
1964

RELIC RADIATION DISCOVERED BY ARNO PENZIAS AND ROBERT WILSON


FIRAS data
2.725 K Blackbody
Intensity
400
300
200
100
0
2
1
0.67
0.5
Wavelength [mm]
COBE 1990
John Mather

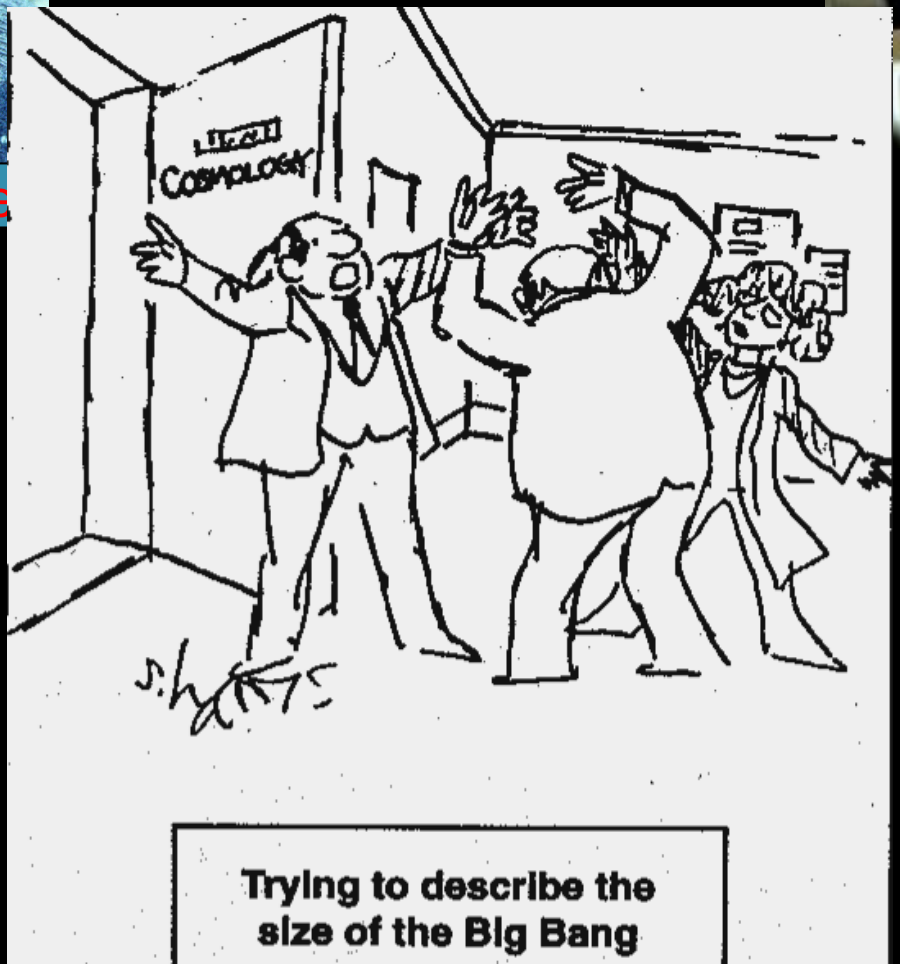
1980

particle physicists plunge in

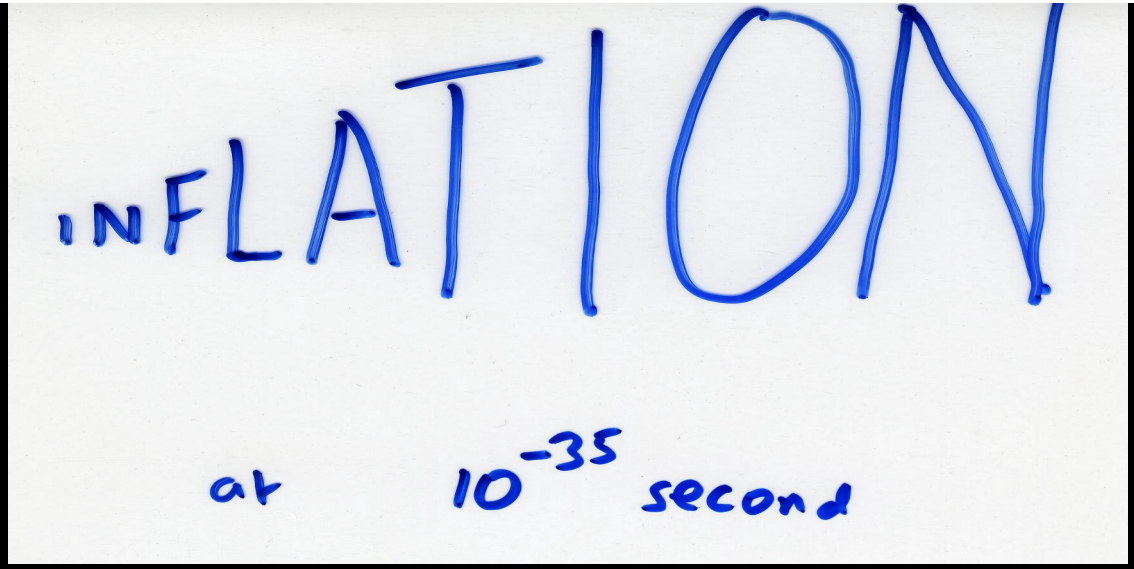

THE BEGINNING
STRONG NUCLEAR
WEAK NUCLEAR
ELECTROMAGNETIC
GRAVITY
ENERGY
200 Gev
10^{16} Gev
10^{19} Gev
LHC
HERE WE ARE
PLANCK SCALE
GRAND UNIFICATION

FROM EXPANSION TO INFLATION (1980)

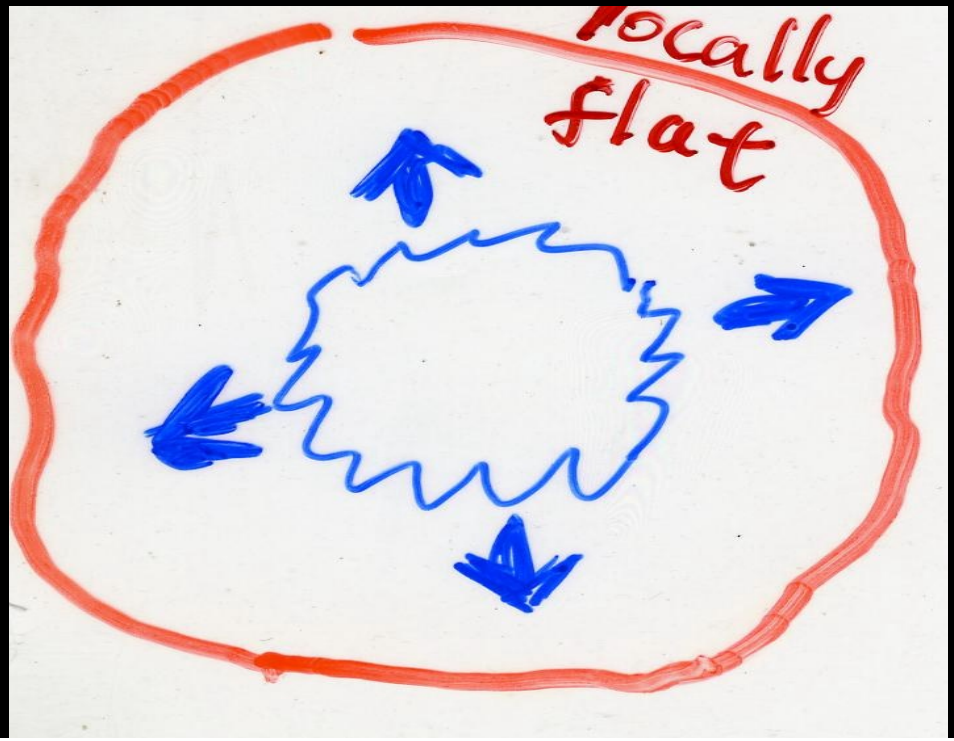
Andrei Linde

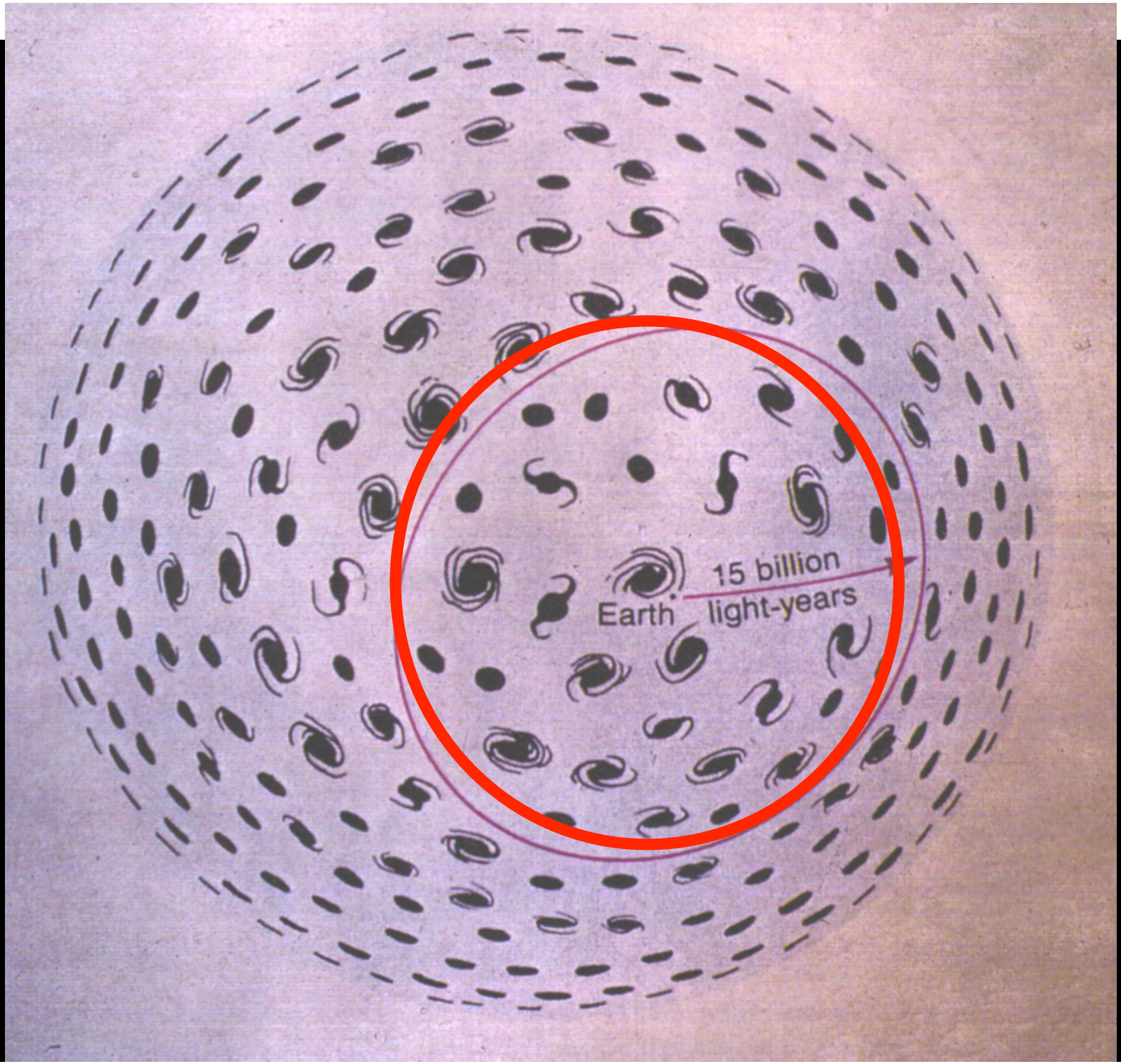


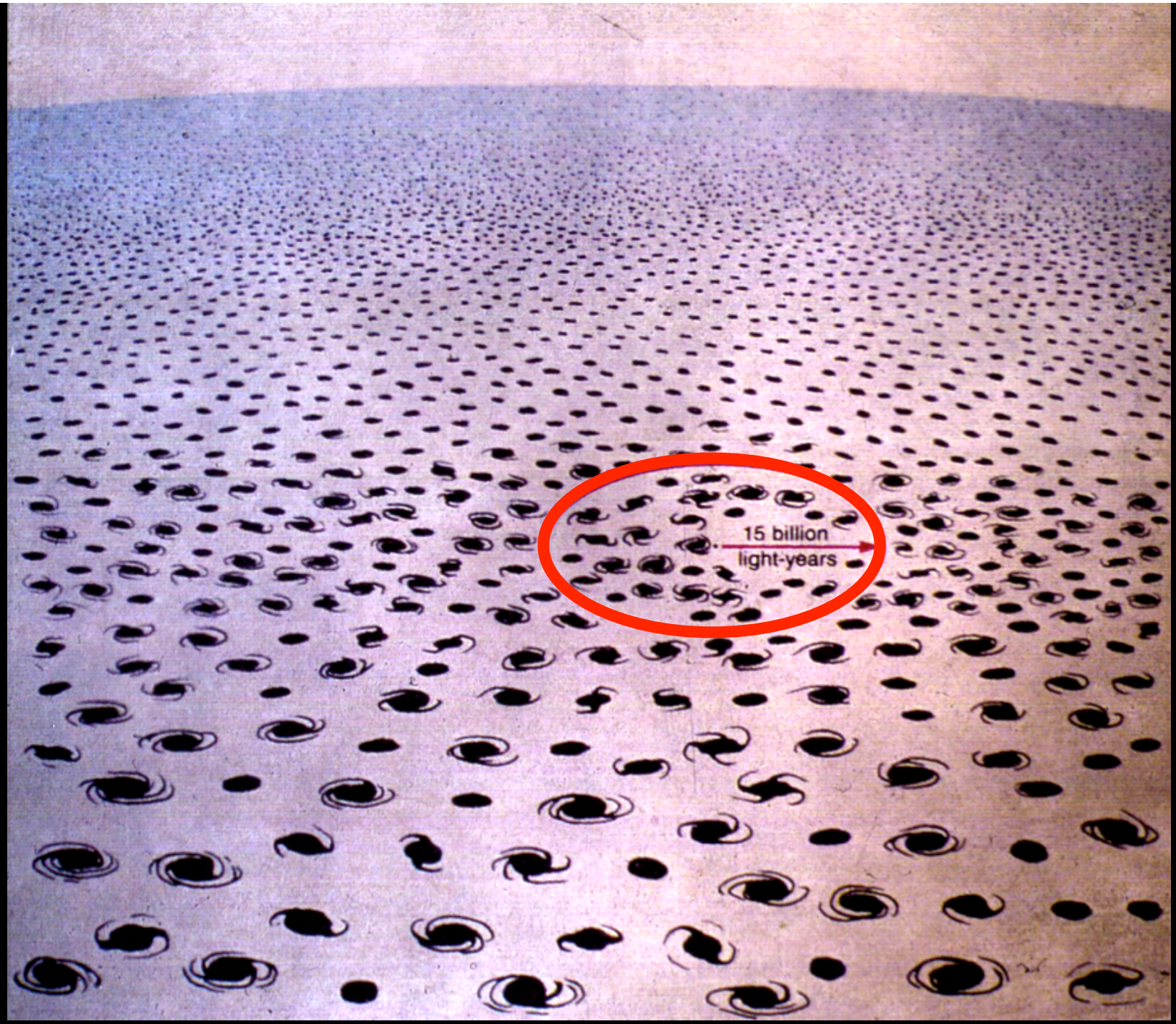
Alan Guth

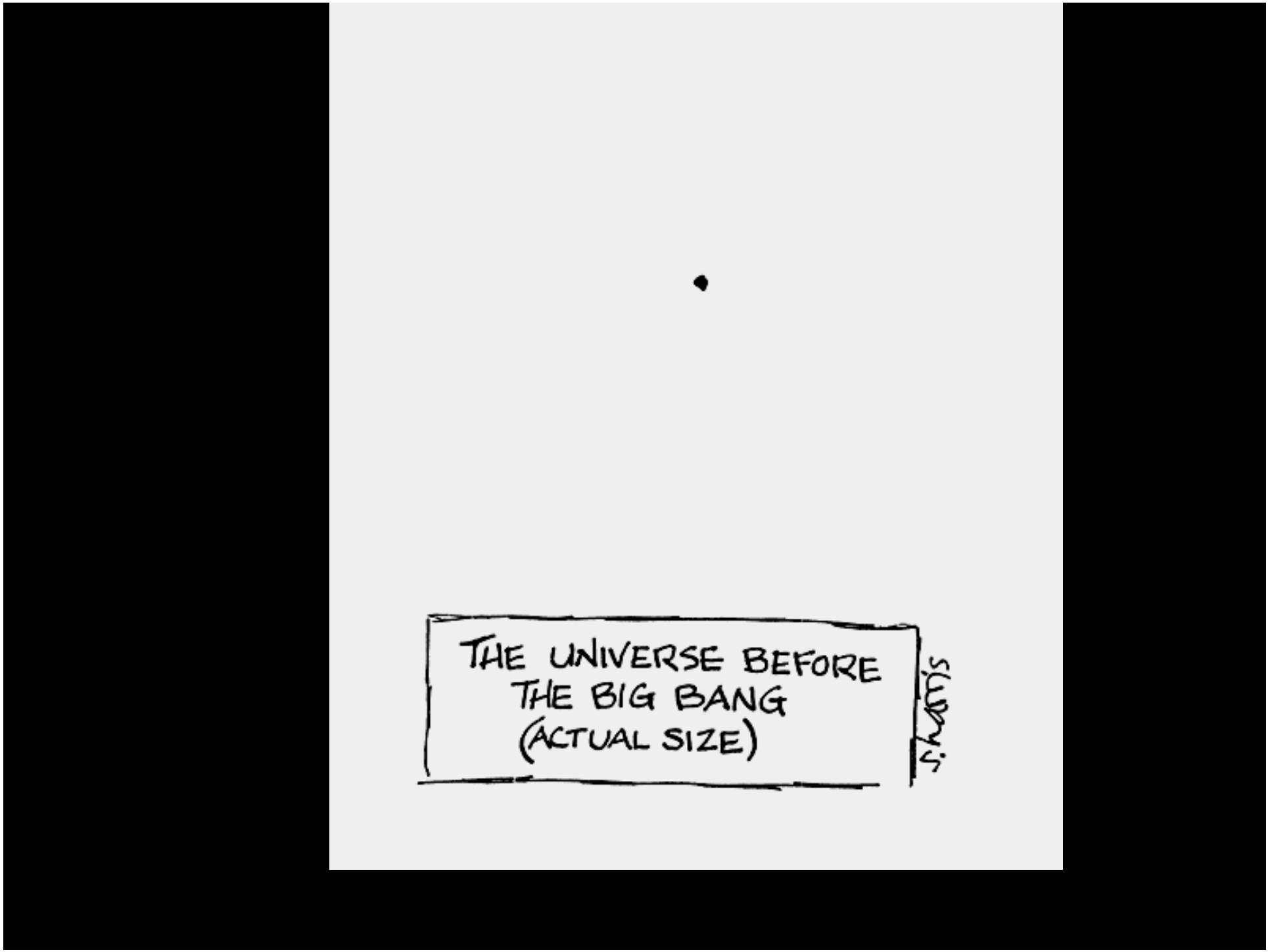


Predicts space is flat and large




15 billion
light-years
Earth


15 billion
light-years


THE UNIVERSE BEFORE
THE BIG BANG
(ACTUAL SIZE)

Naive expectation :

in a static medium : $t_{inst} \sim 1/\sqrt{G\rho}$ and $\frac{\delta\rho}{\rho} \sim e^{t/t_{inst}}$

dispersion relation: $\omega^2 = k^2 v_s^2 - 4\pi G\rho$ (Jeans instability)

for $\delta\rho \sim \exp i(\omega t - kx)$

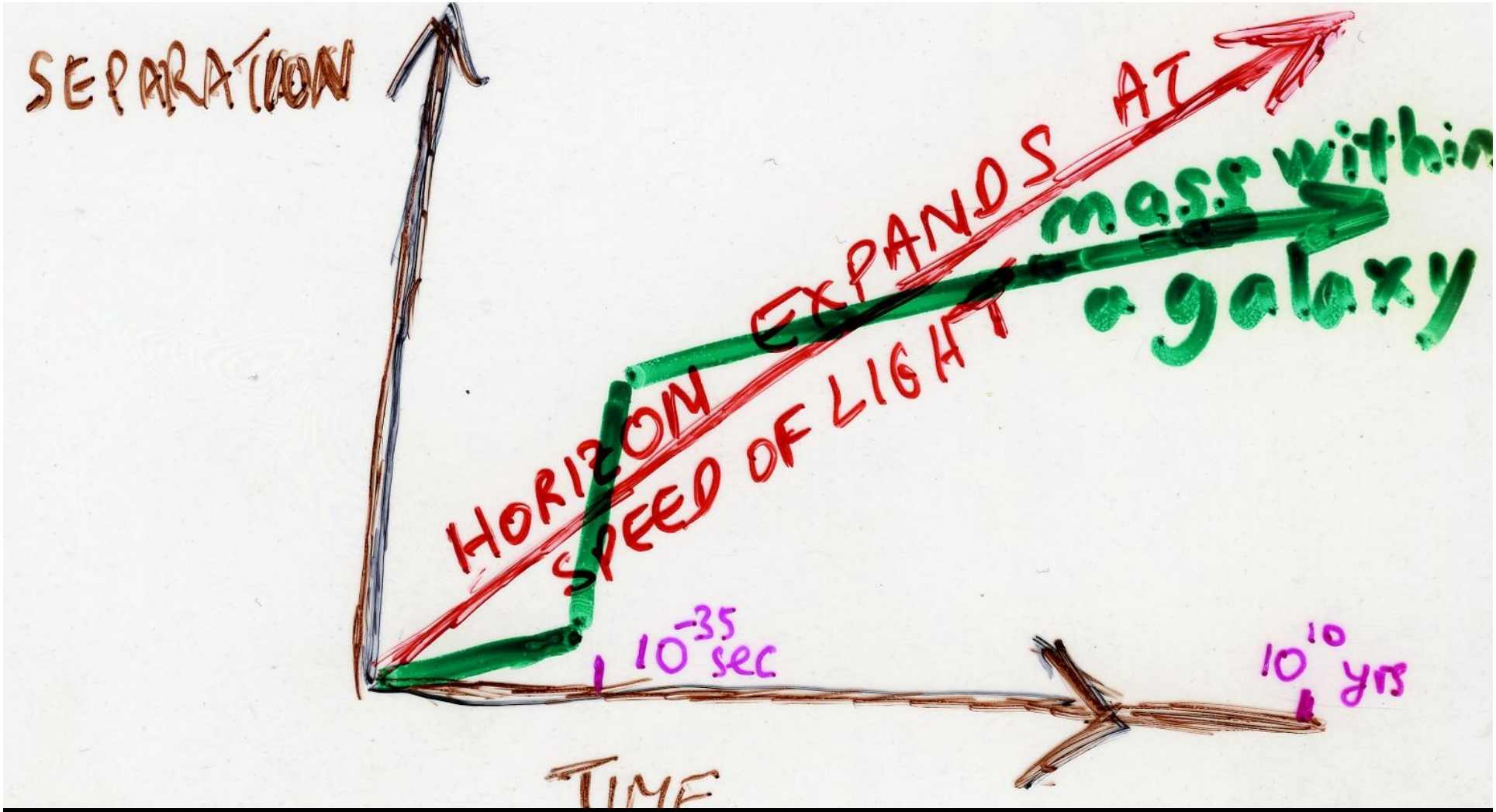
with $\rho \propto t^{-2}$, expect power-law growth rate

Need initial density fluctuations in order to form structure!

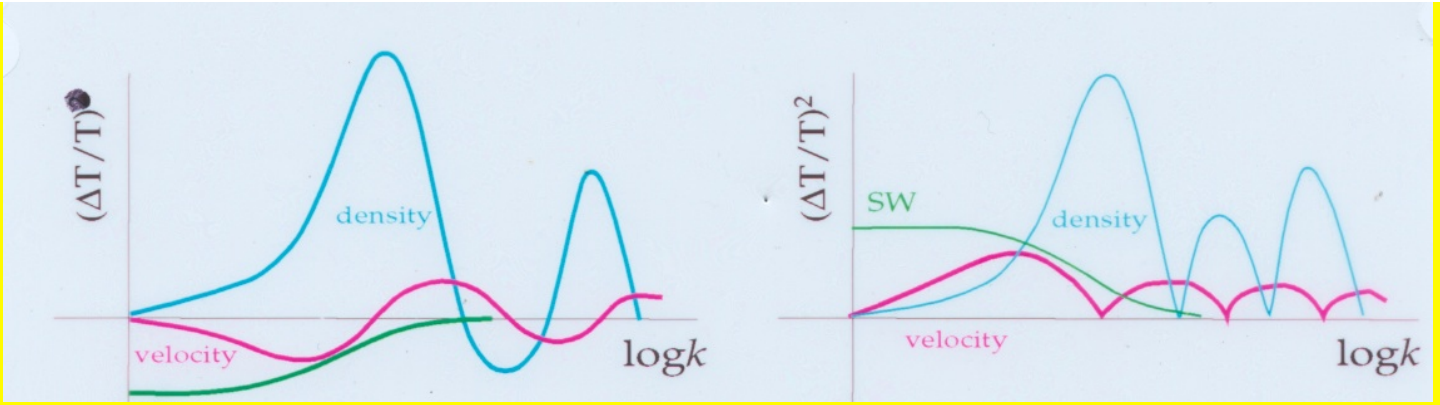
intrinsic potential doppler

$$\left|\frac{\delta T}{T}\right| = \left| \frac{1}{3}\frac{\delta\rho}{\rho} + \delta\varphi - \hat{r}\cdot v \right|$$

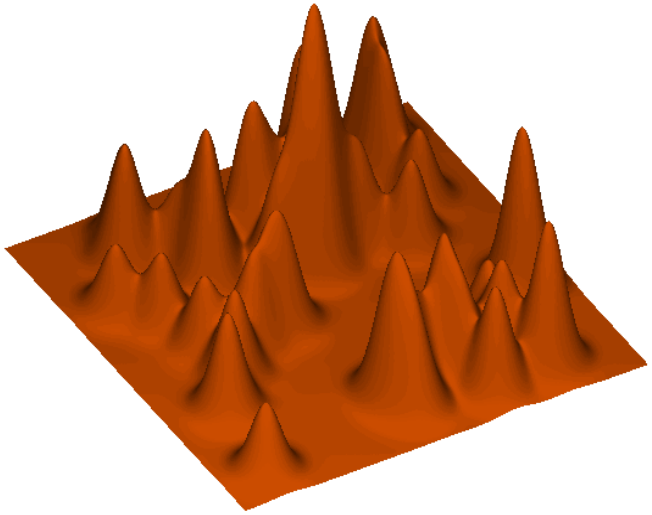
$$-\frac{1}{3}\delta\varphi$$

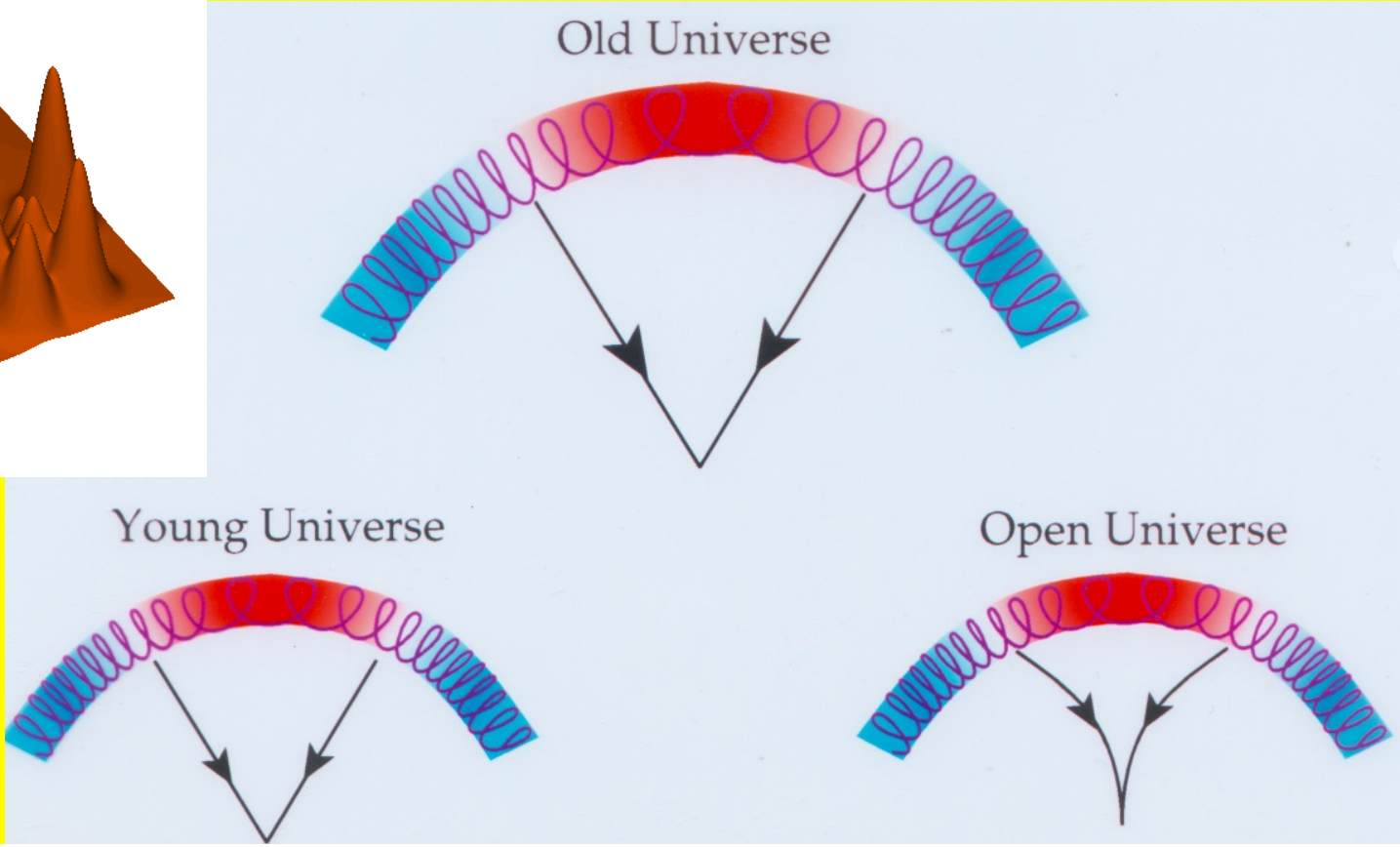


Inflation predicts thermal fluctuations

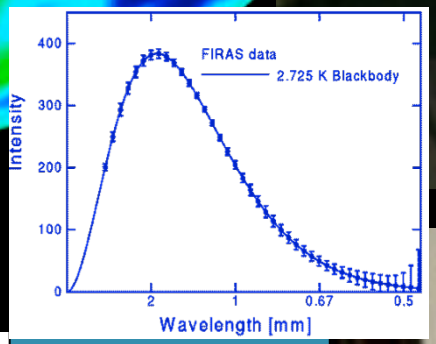


measure space curvature: dark matter plus dark energy once we know the age of the universe

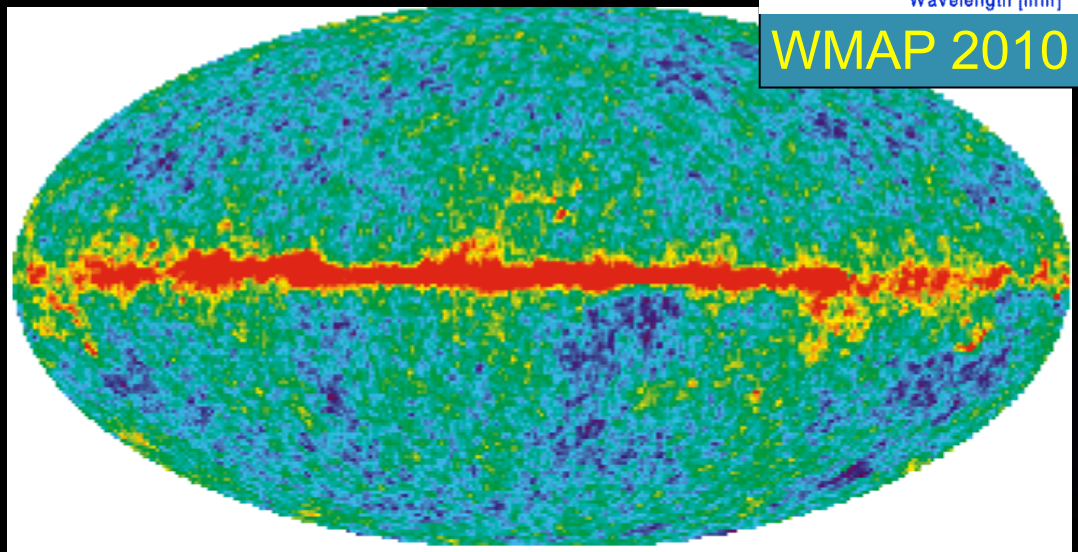




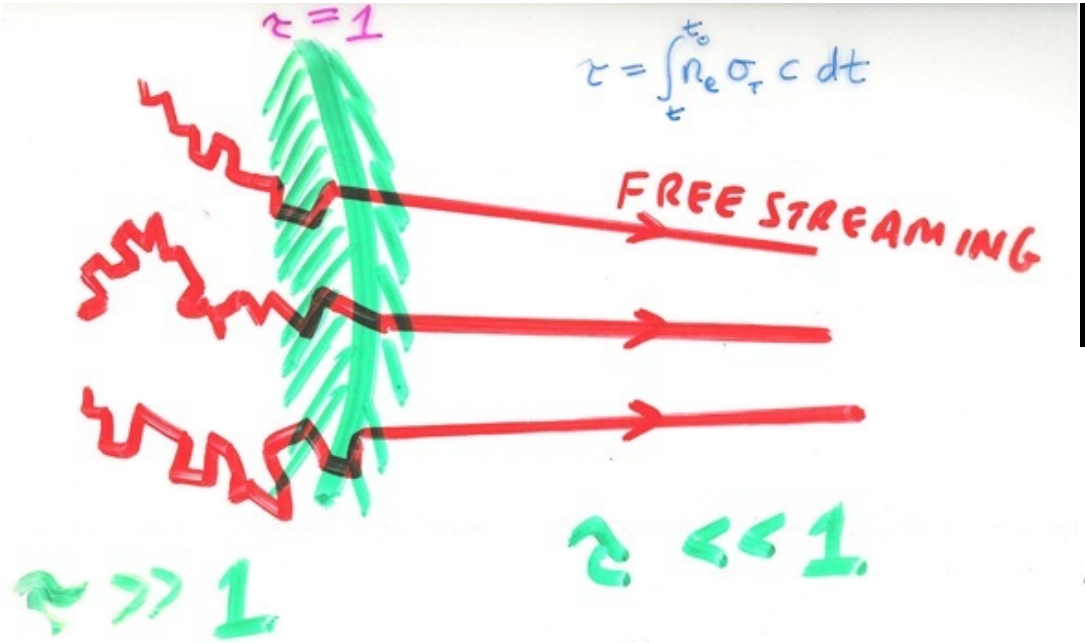
COBE 1992



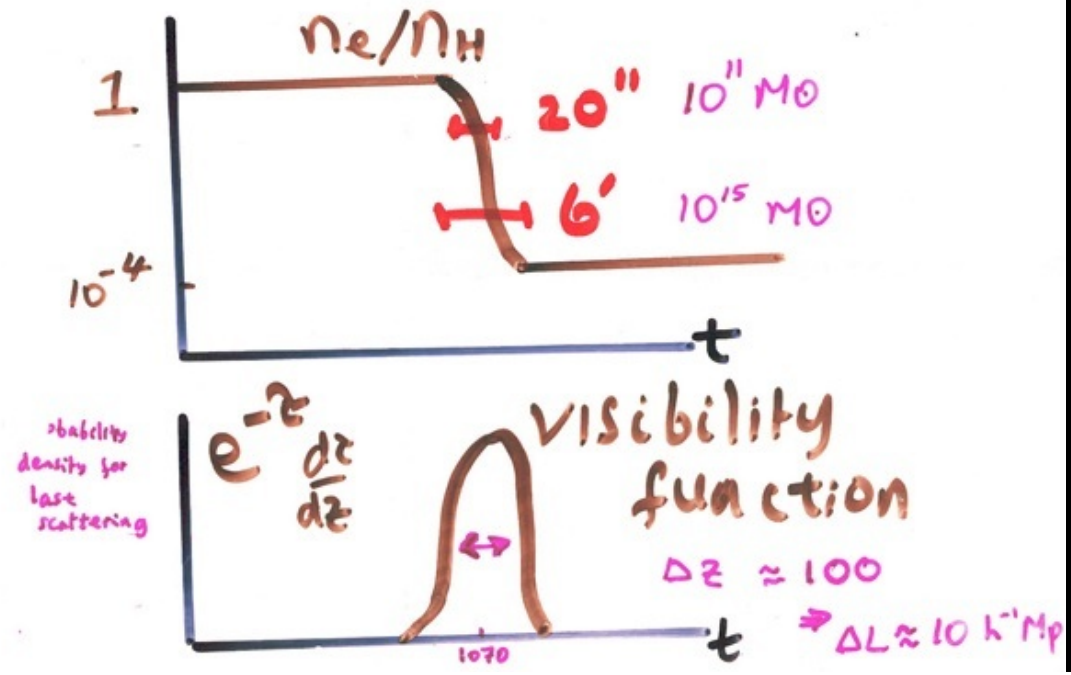
WMAP 2010

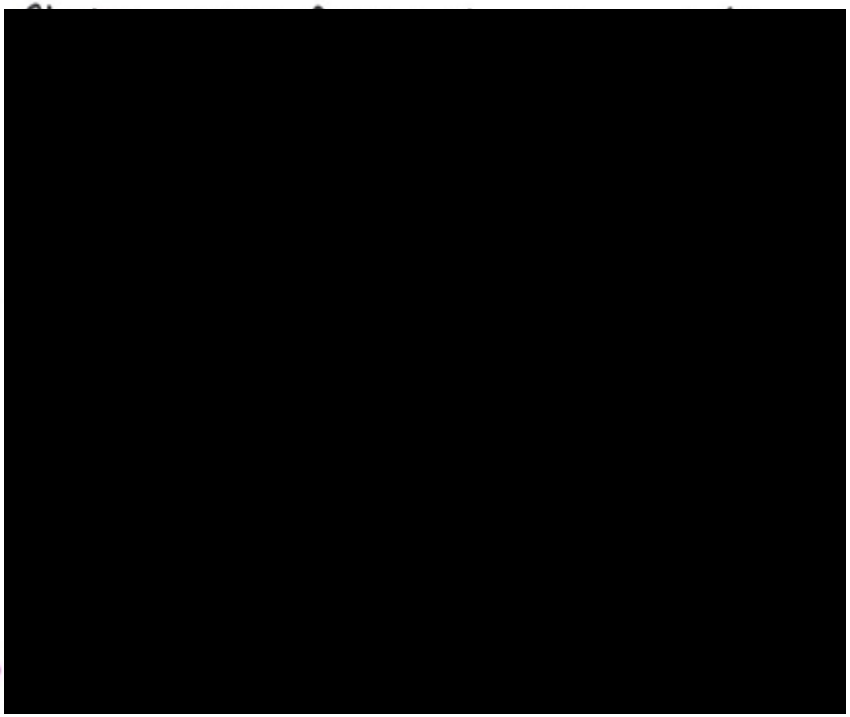


George Smoot John Mather
STOCKHOLM 2006


τ = 1
$\tau = \int_t^{t_0} n_e \sigma_T c\, dt$
FREE STREAMING
τ << 1
τ >> 1


BARYONS
PHOTONS
LEAK OUT

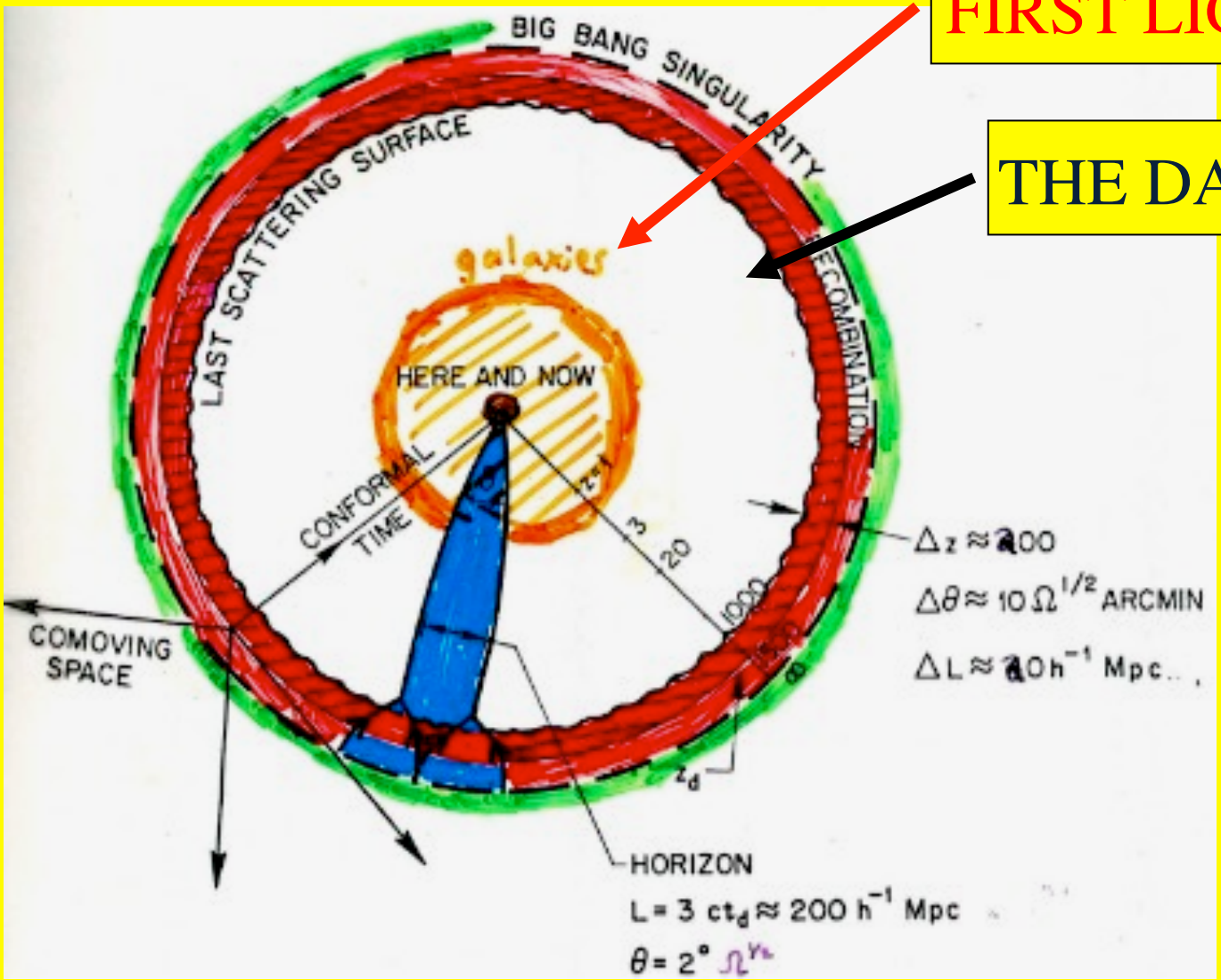

ne/nH
1
10^{-4}
20"
10^{11} MO
6'
10^{15} MO
t
probability density for last scattering
$e^{-\tau} \frac{d\tau}{dz}$
visibility function
Δz ≈ 100
ΔL ≈ 10 h⁻¹ Mp
1070
t



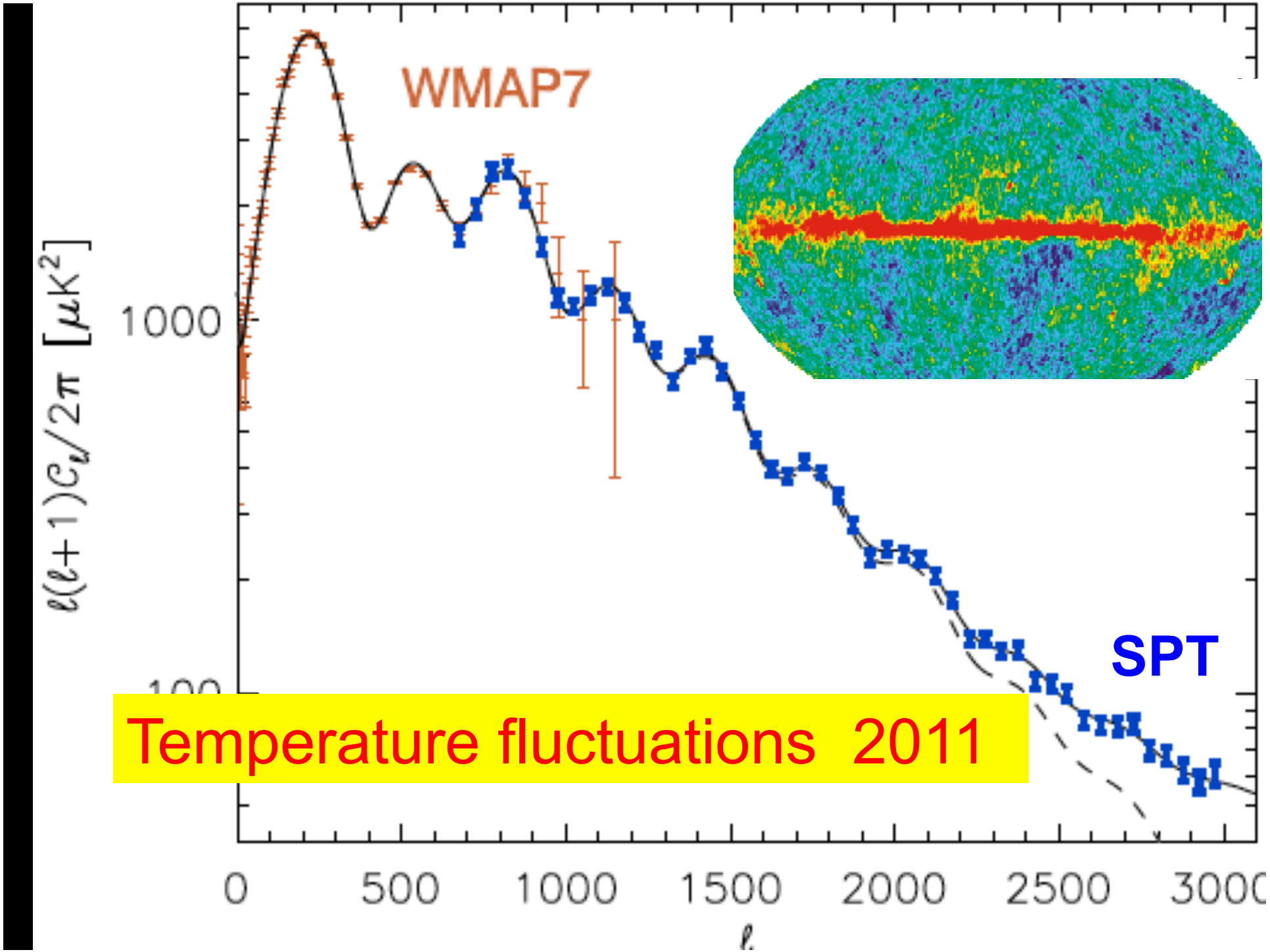
A SPACE-TIME DIAGRAM OF THE UNIVERSE

FIRST LIGHT

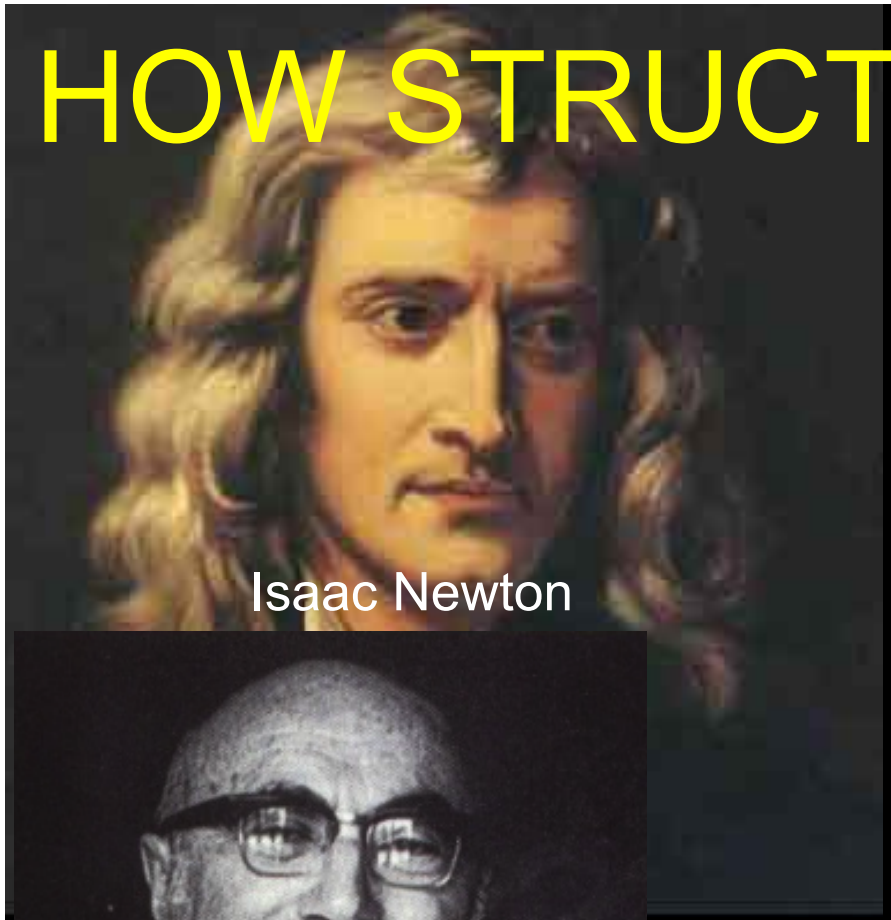
THE DARK AGES



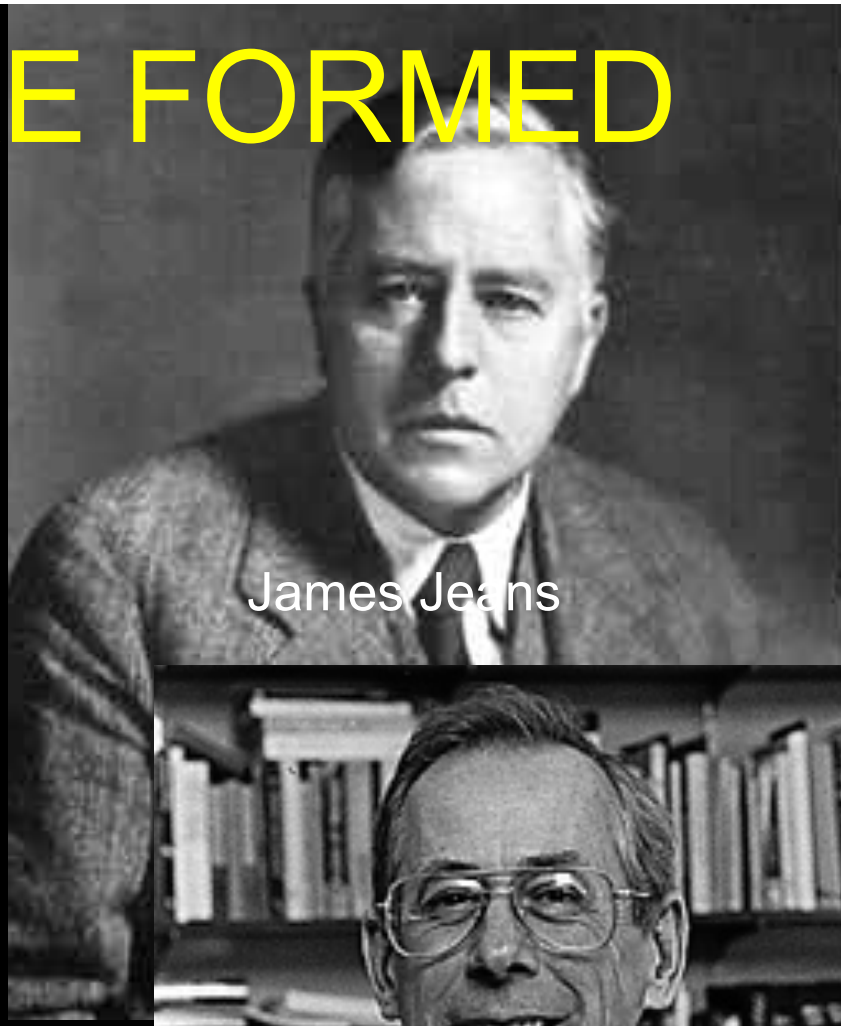
ON ANGULAR SCALES ABOVE A DEGREE, WE ARE VIEWING QUANTUM FLUCTUATIONS IN THE SKY!


WMAP7
SPT
Temperature fluctuations 2011
$\ell(\ell+1)C_\ell/2\pi$ [μK^2]
1000
0
500
1000
1500
2000
2500
3000
ℓ

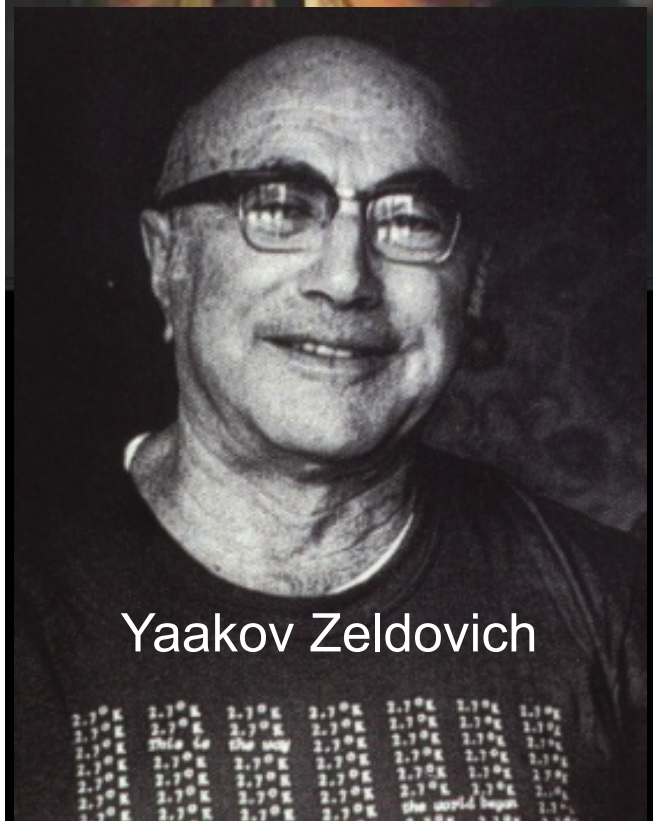
HOW STRUCTURE FORMED



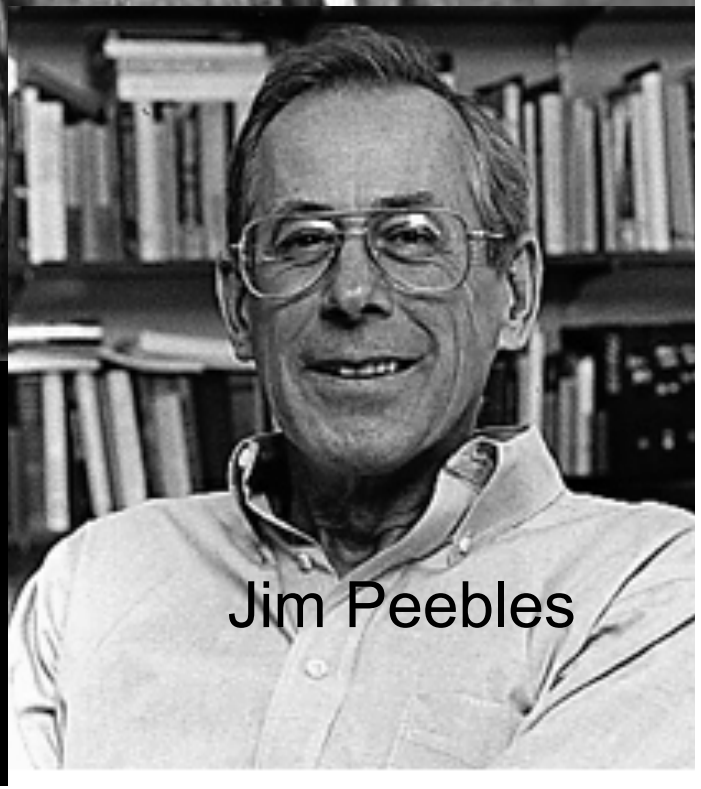
Isaac Newton



James Jeans



Yaakov Zeldovich



Jim Peebles

if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space.And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.

if the sun at rest were an opaque body like the planets or the planets lucid bodies like the sun, how he alone should be changed into a shining body whilst all they continue opaque, or all they be changed into opaque ones whilst he remains unchanged, I do not think explicable by mere natural causes, but am forced to ascribe it to the counsel and contrivance of a voluntary Agent.

Isaac Newton, letter to Richard Bentley, December 10, 1692

James Jeans:

"We have found that as Newton first conjectured….

All celestial bodies originate by a process of fragmentation of nebulae out of chaos, of stars out of nebulae, of planets out of stars and satellites out of planets."

Criterion for gravitational stability found by Jeans (1902):

pressure opposes collapse:

sound waves must cross region to communicate pressure changes before collapse

ASSUMPTIONS

FRW metric

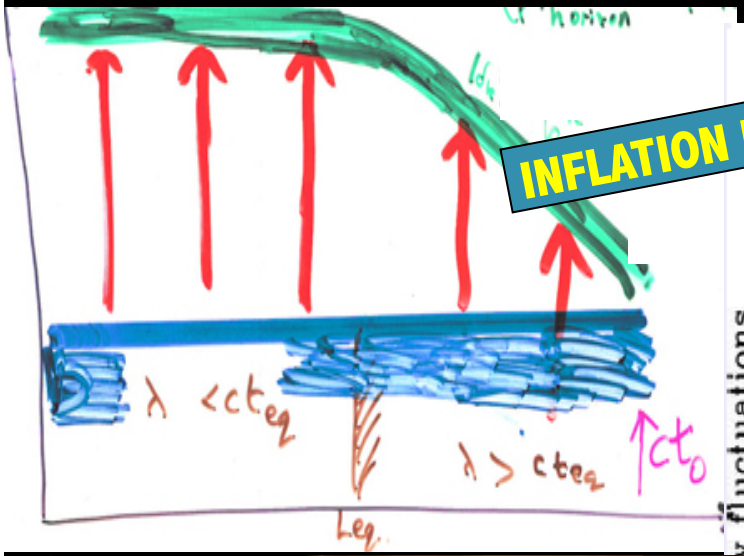
Friedmann-Lemaître cosmology

primordial density fluctuations

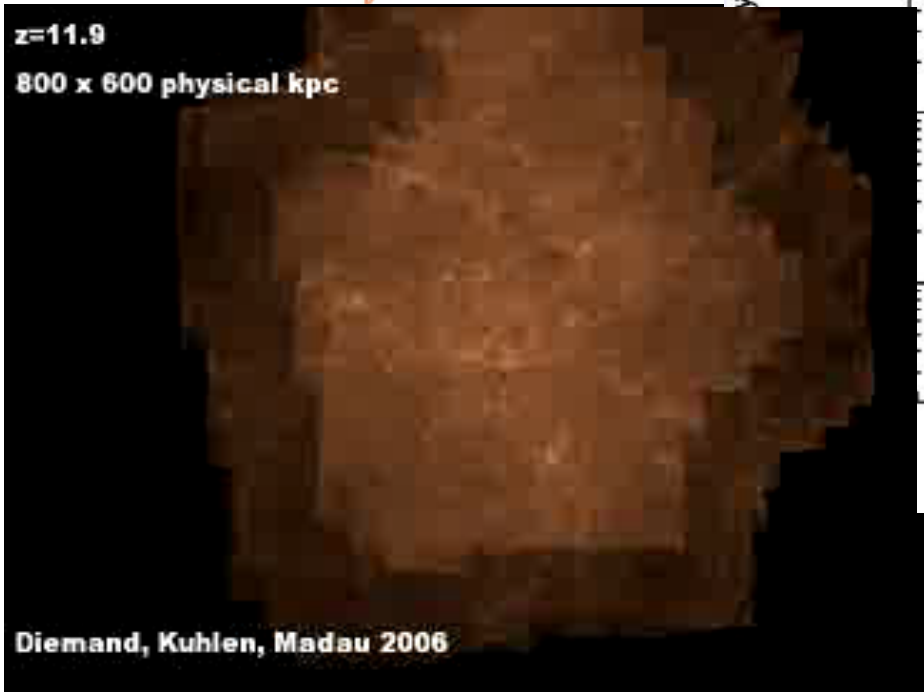
are

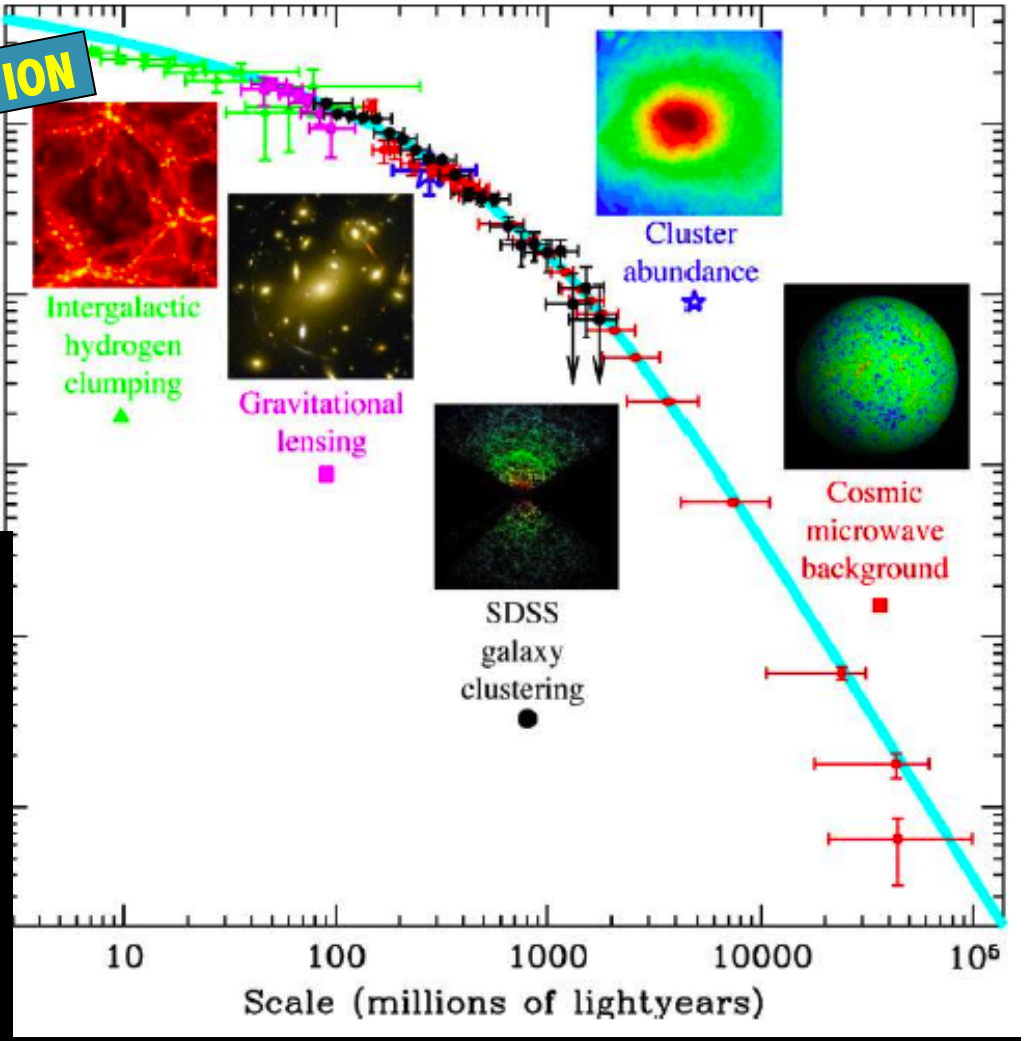
- gaussian
- nearly scale-invariant metric perturbations
- adiabatic mode

FROM INFLATIONARY DENSITY FLUCTUATIONS TO GALAXIES

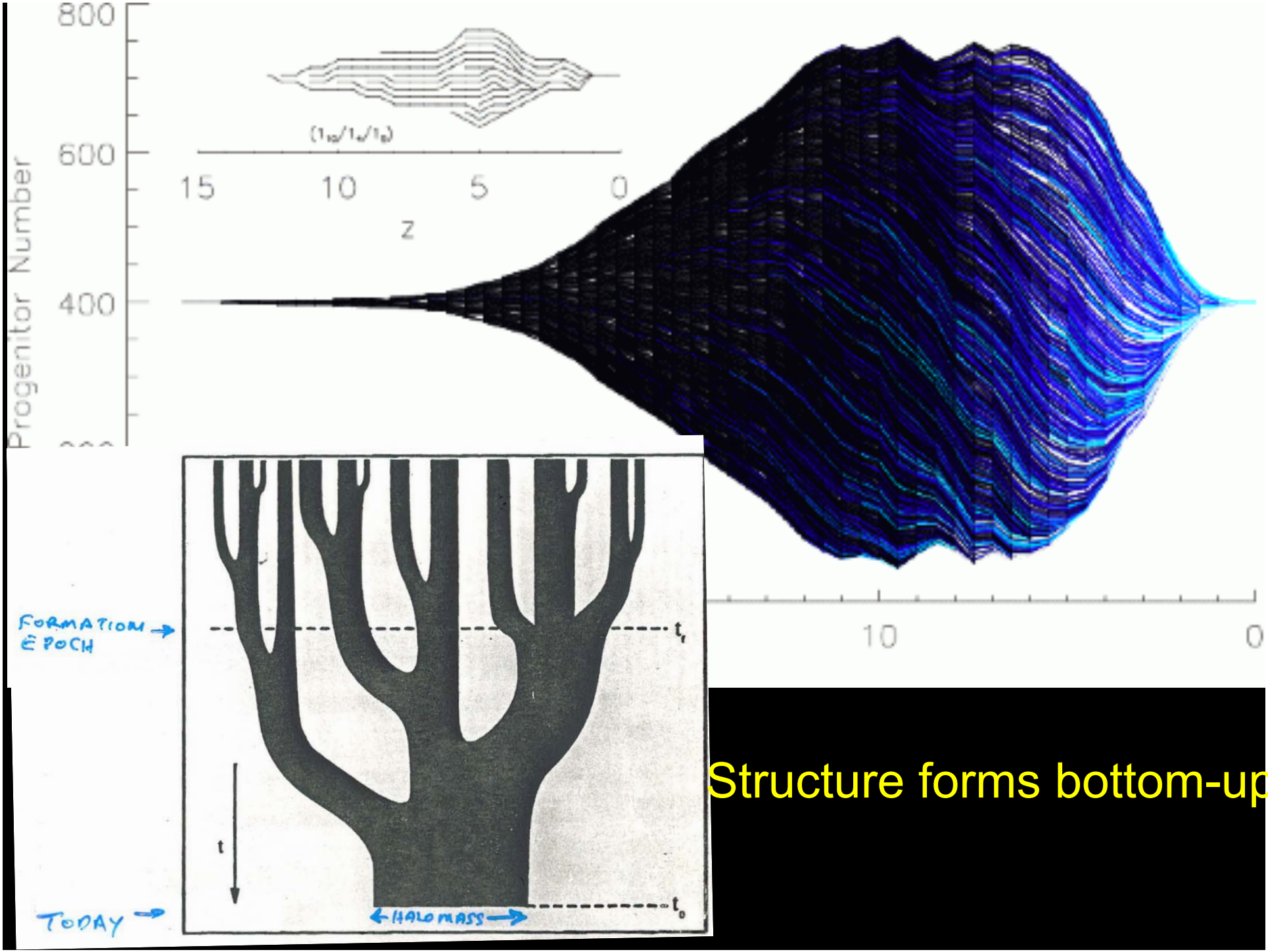


INFLATION PREDICTION

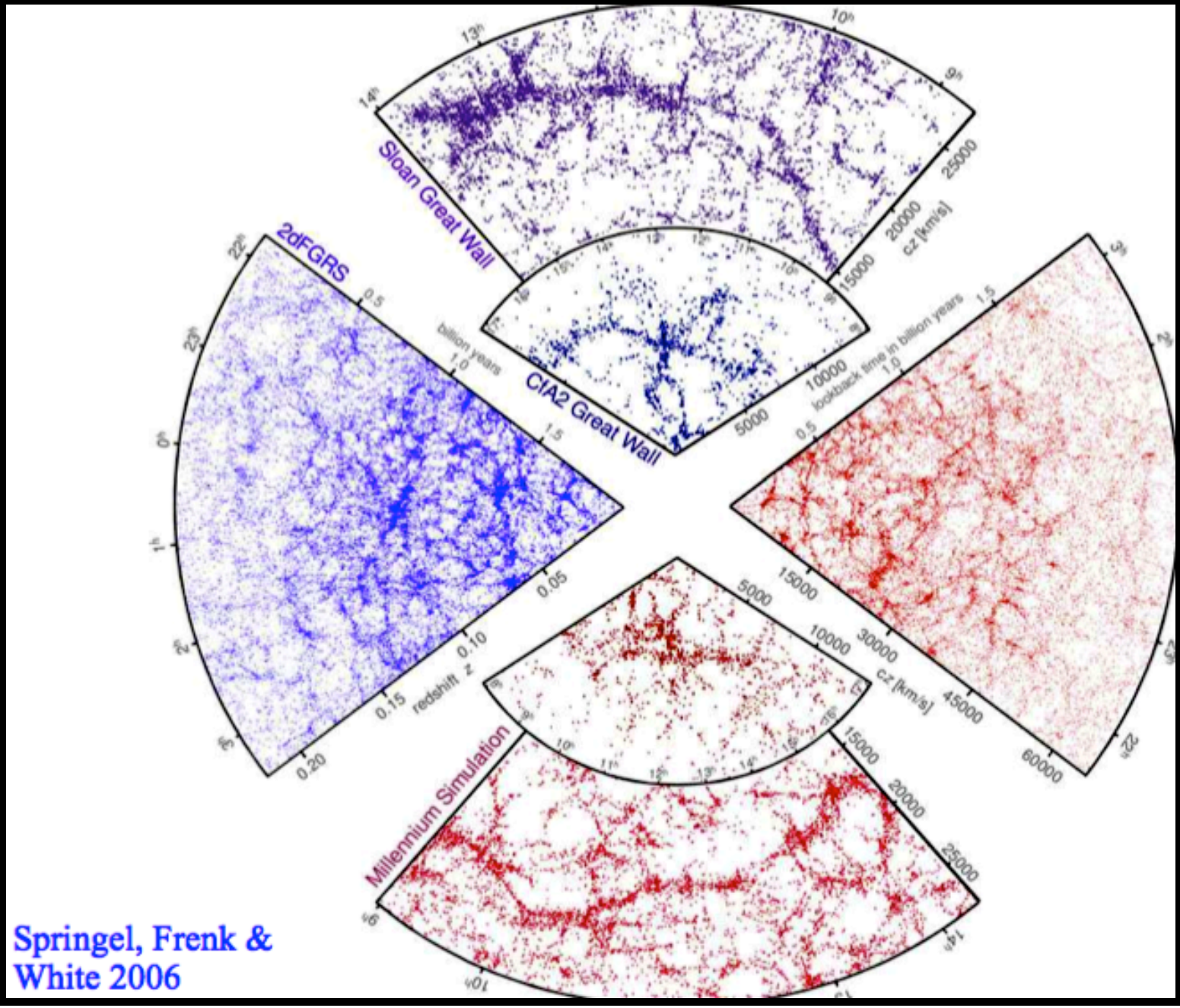




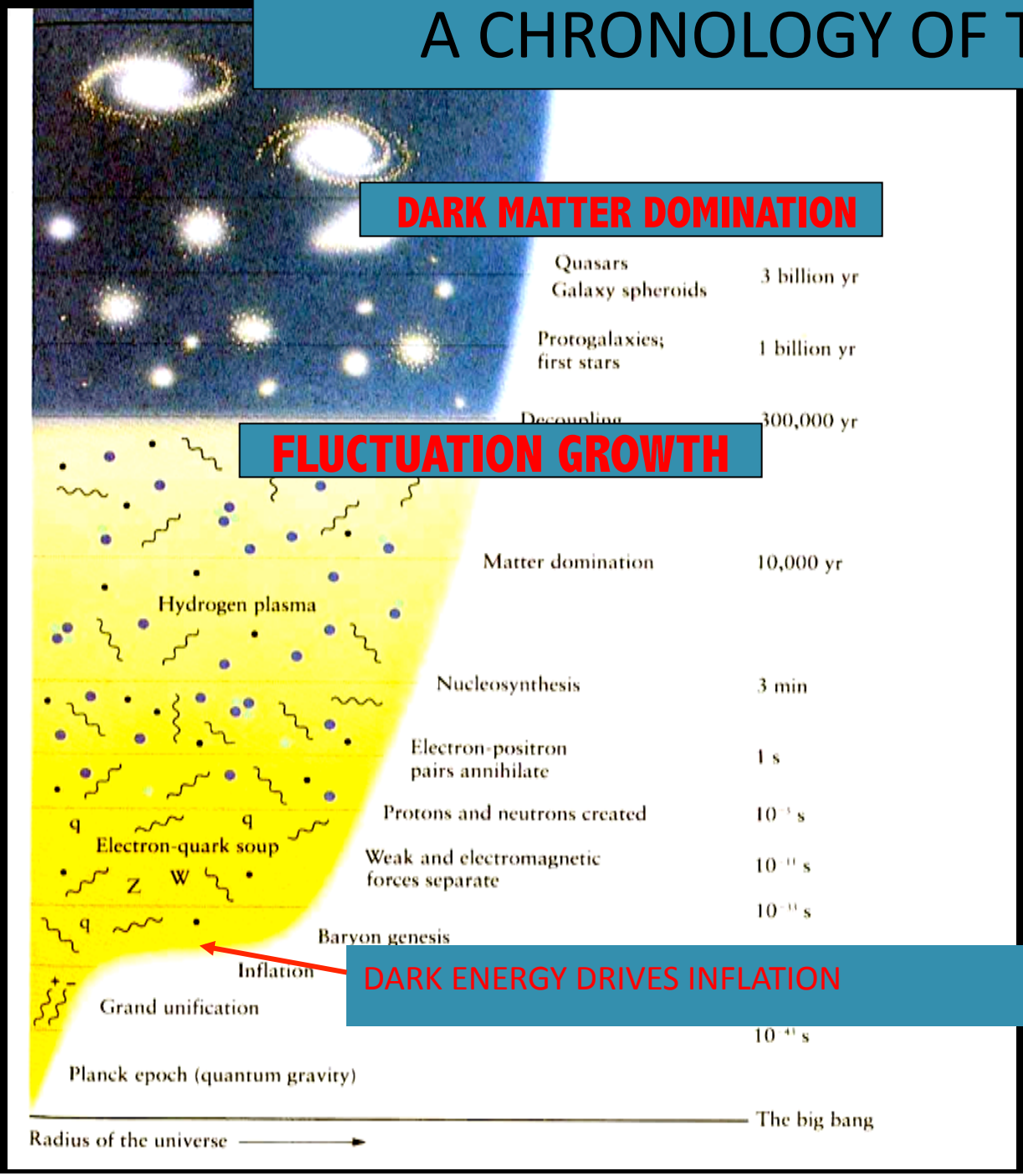
Tegmark 2004


800
600
400
Progenitor Number
15
10
5
0
z
10
0
FORMATION EPOCH
TODAY
HALO MASS
t
t_f
t_0
Structure forms bottom-up

virtual universe versus observed universe

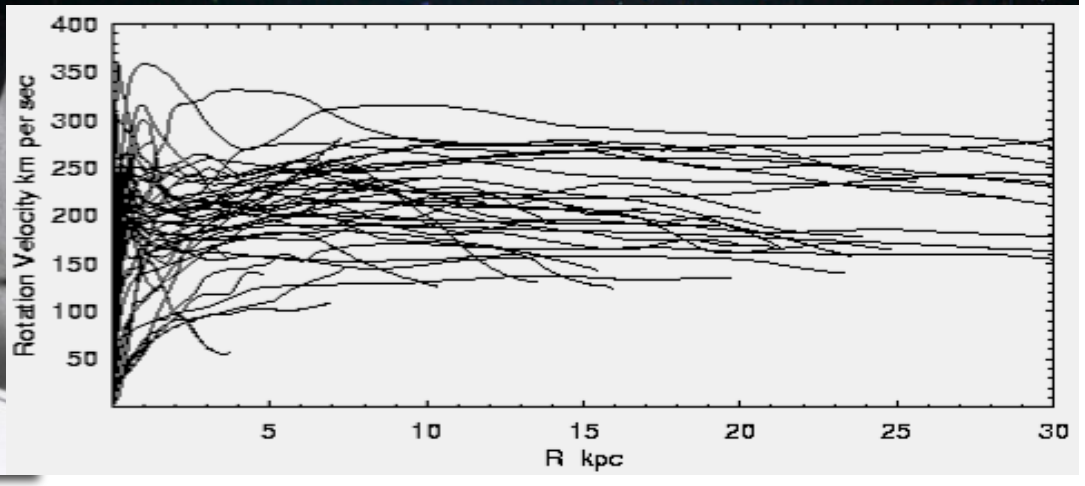


A CHRONOLOGY OF THE UNIVERSE

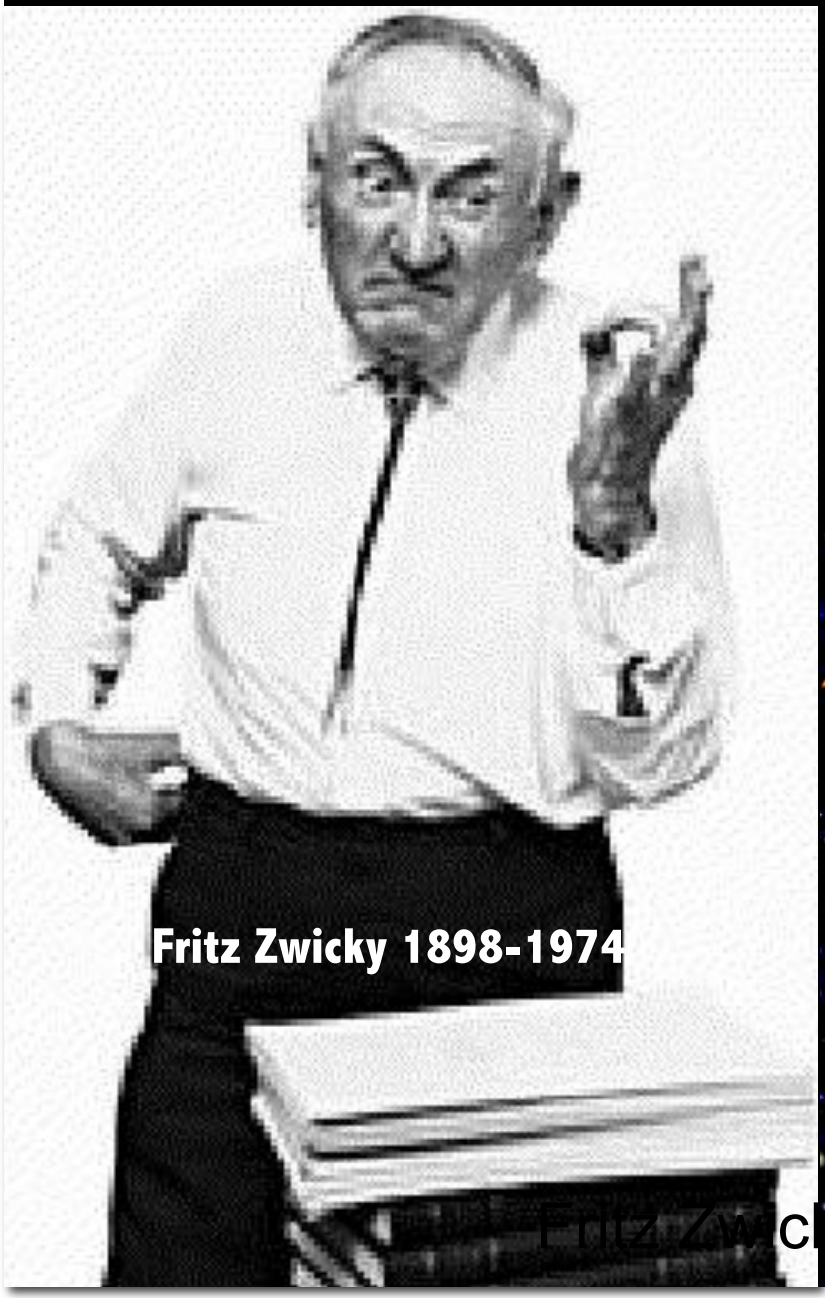


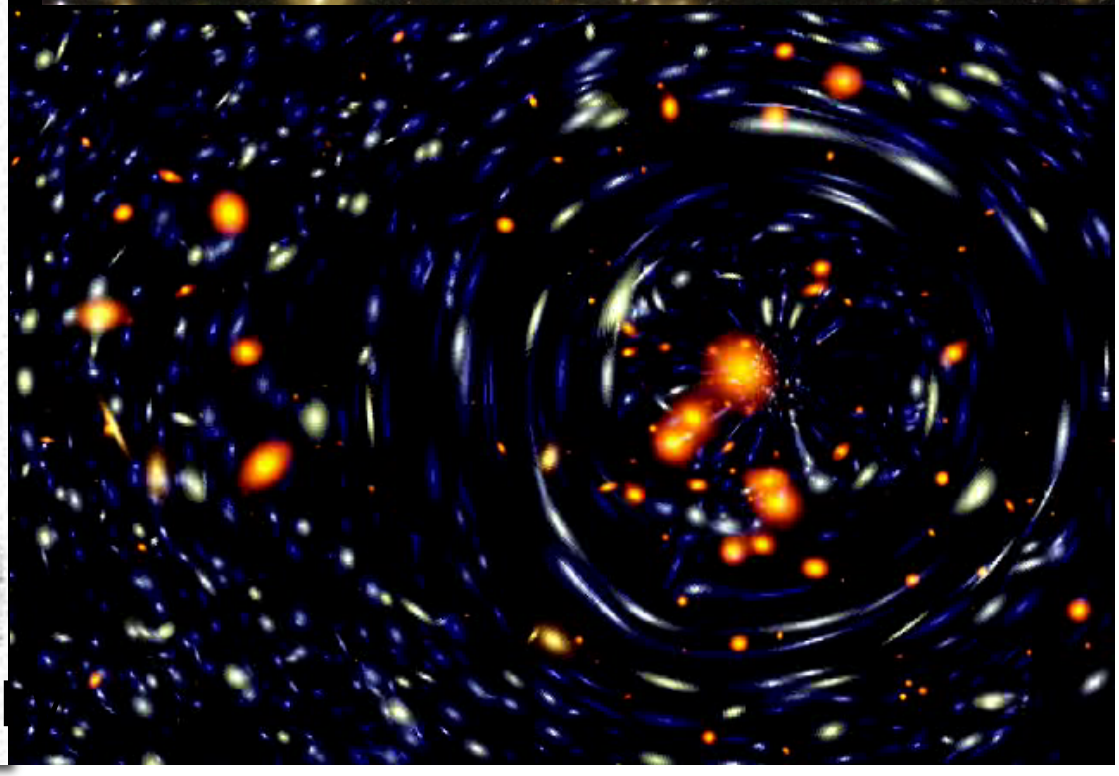
Dark Matter in Galaxies

Vera Rubin 1928-



Dark Matter in Galaxy Clusters

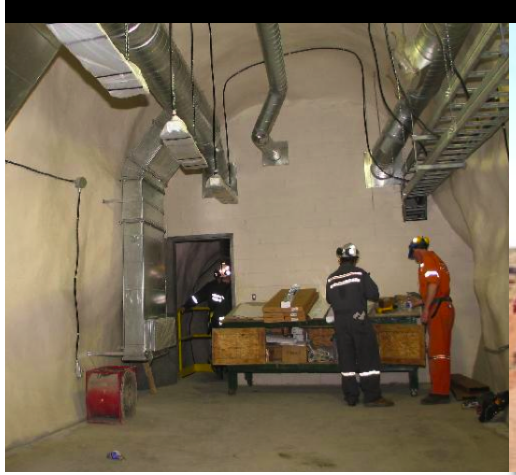


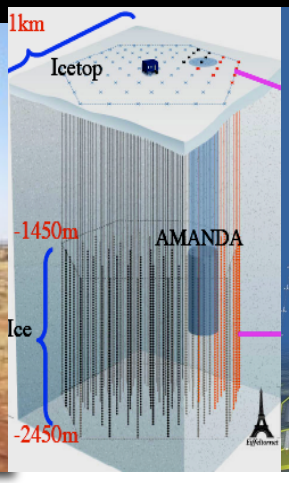


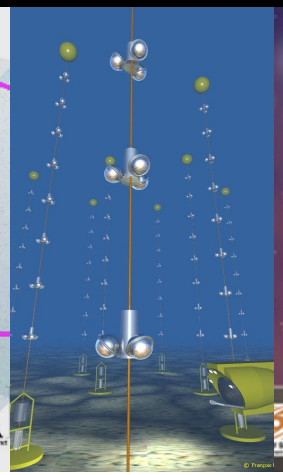
Most of the matter in the universe is dark!

Dark matter is not ordinary matter

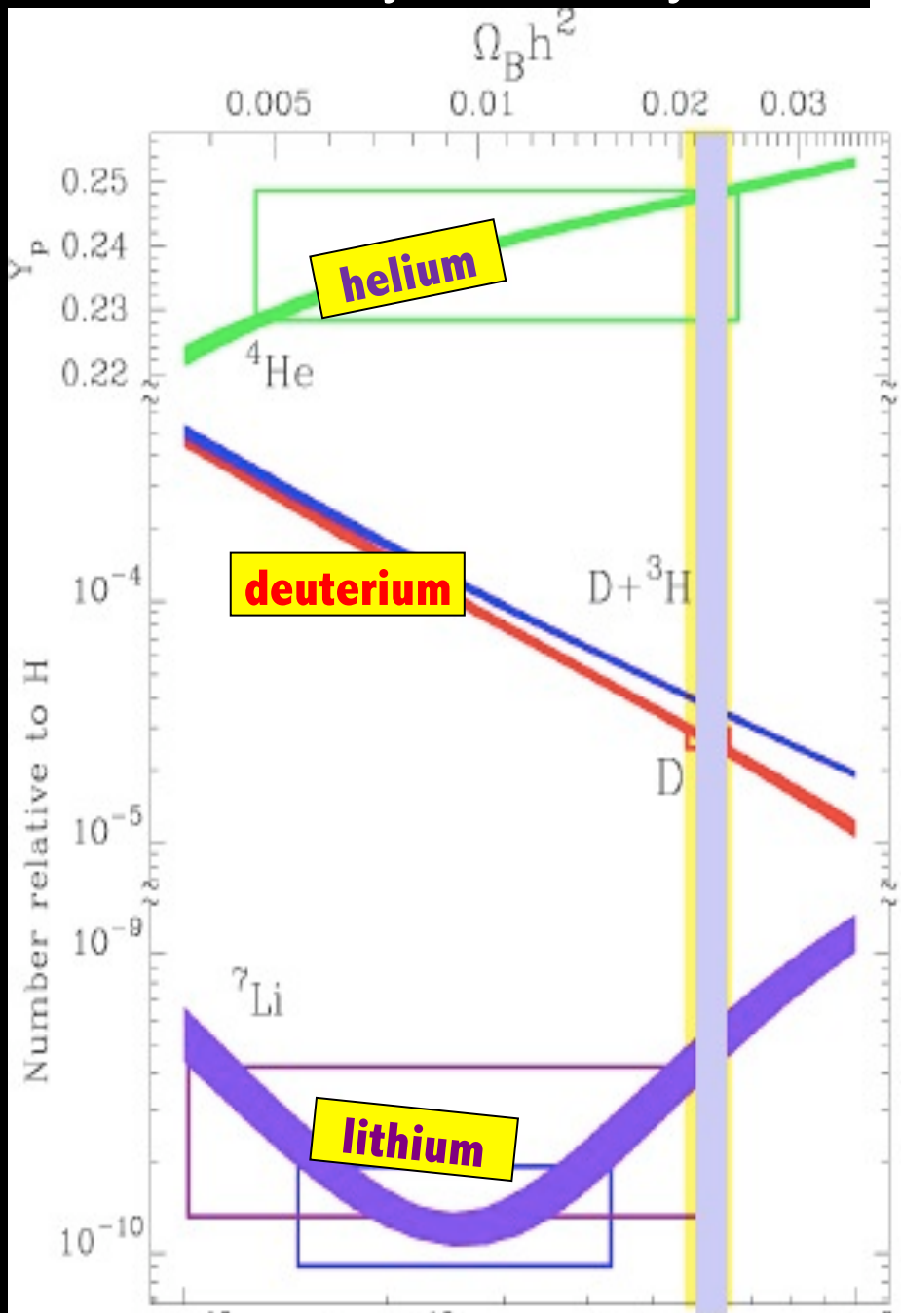
It's a weakly interacting elementary particle that we have yet to identify. This has led to a new discipline: Particle Astrophysics

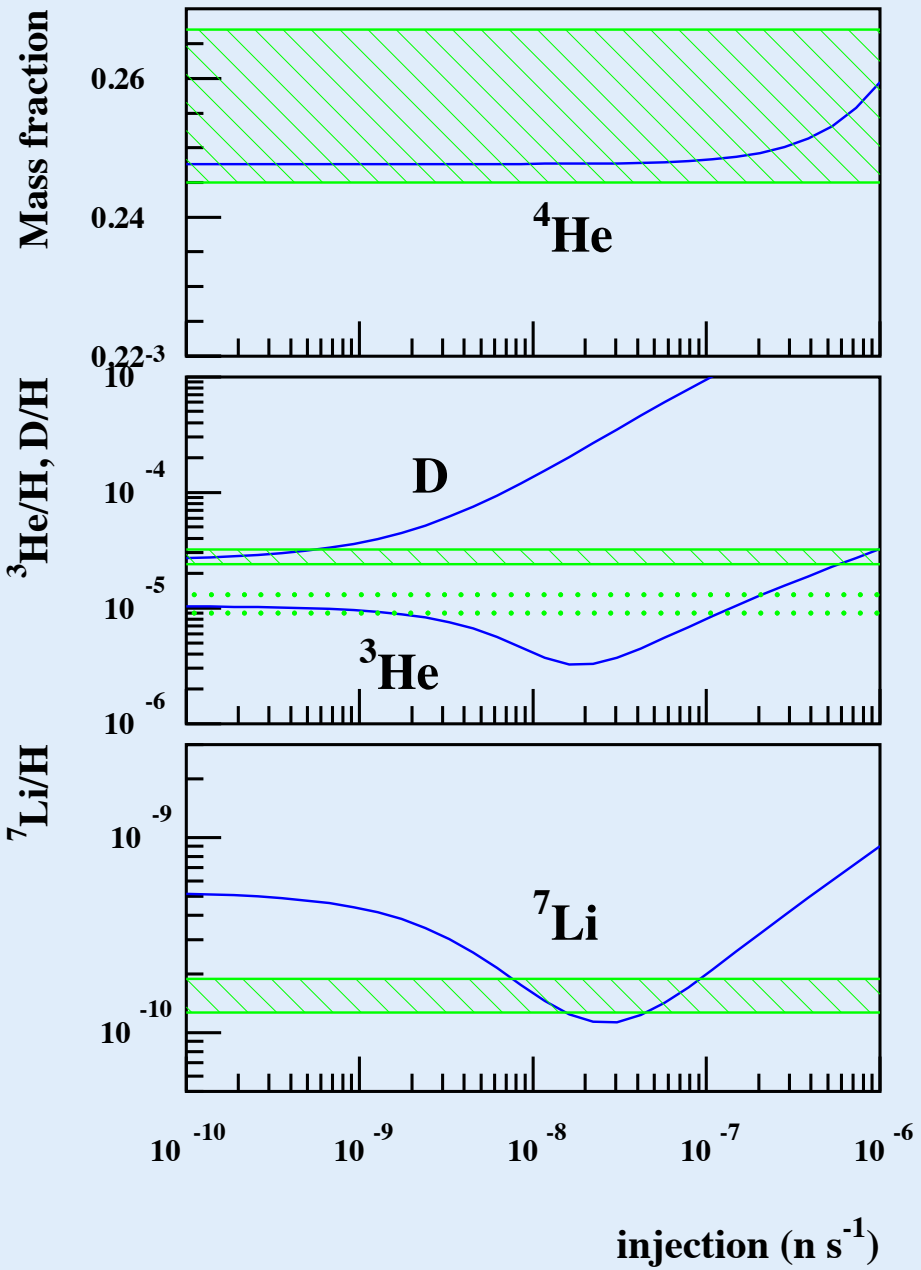






Dark matter is not baryons





Injecting neutrons destroys lithium but at a price

Coq 2011

primordial neutrinos as hot dark matter

$\Omega_\nu h^2 = \Sigma m_\nu / 92\ eV$

Hubble parameter h= 0.65 (65 km/s/Mpc)

$\Omega_\nu < 0.20$

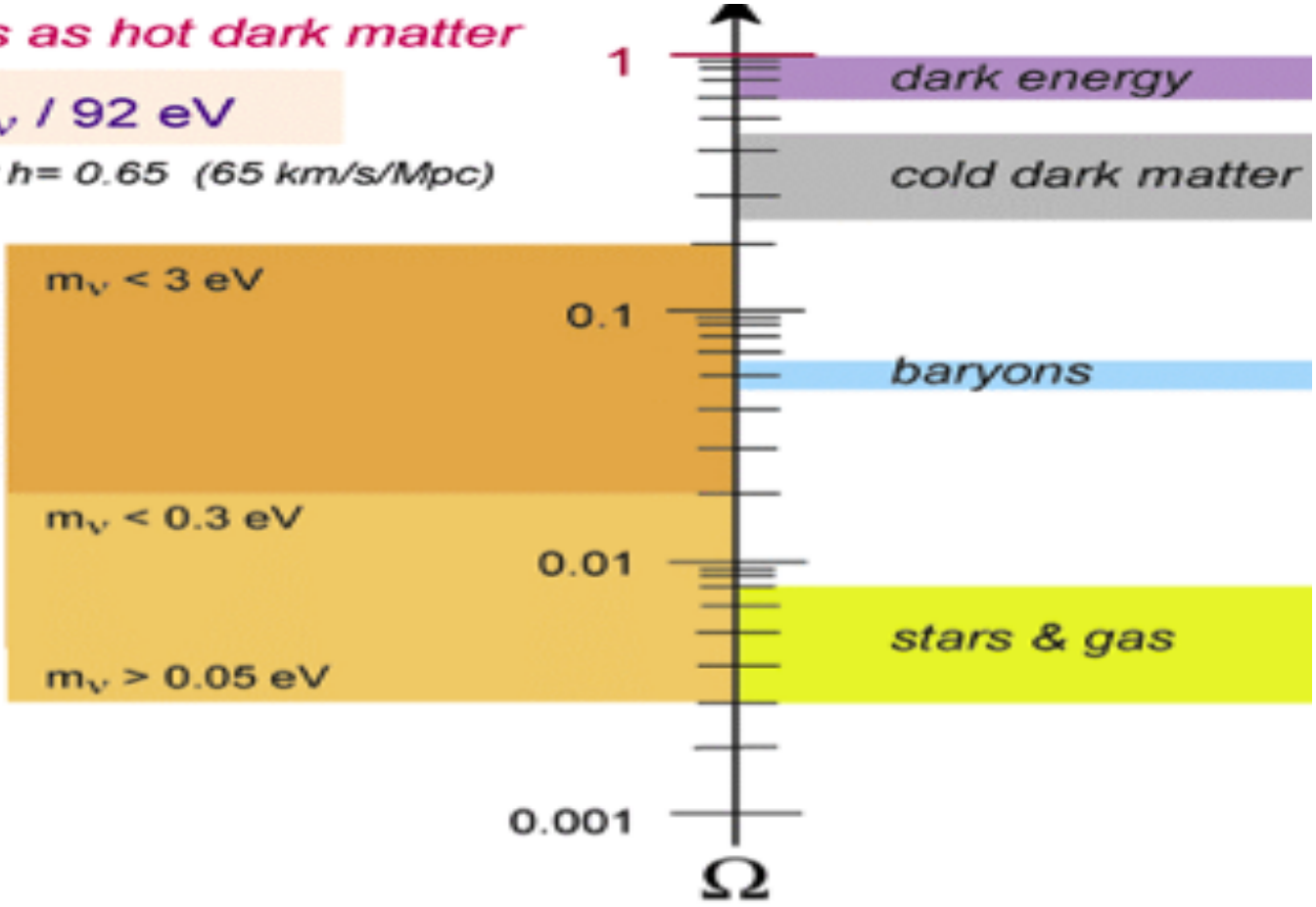
structure formation
tritium experiments

$\Omega_\nu < 0.02$

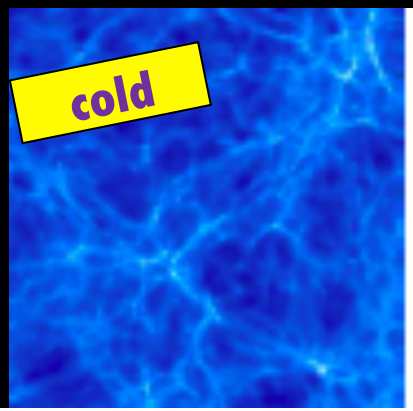
KATRIN sensitivity

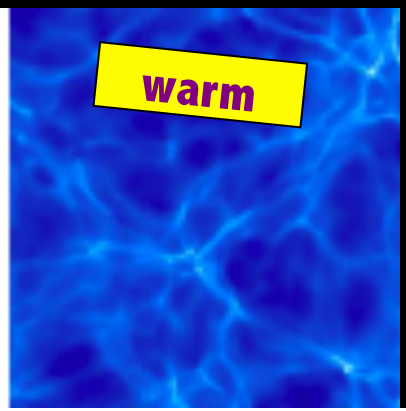
$\Omega_\nu > 0.003$

Super-Kamiokande



Dark matter is not neutrinos



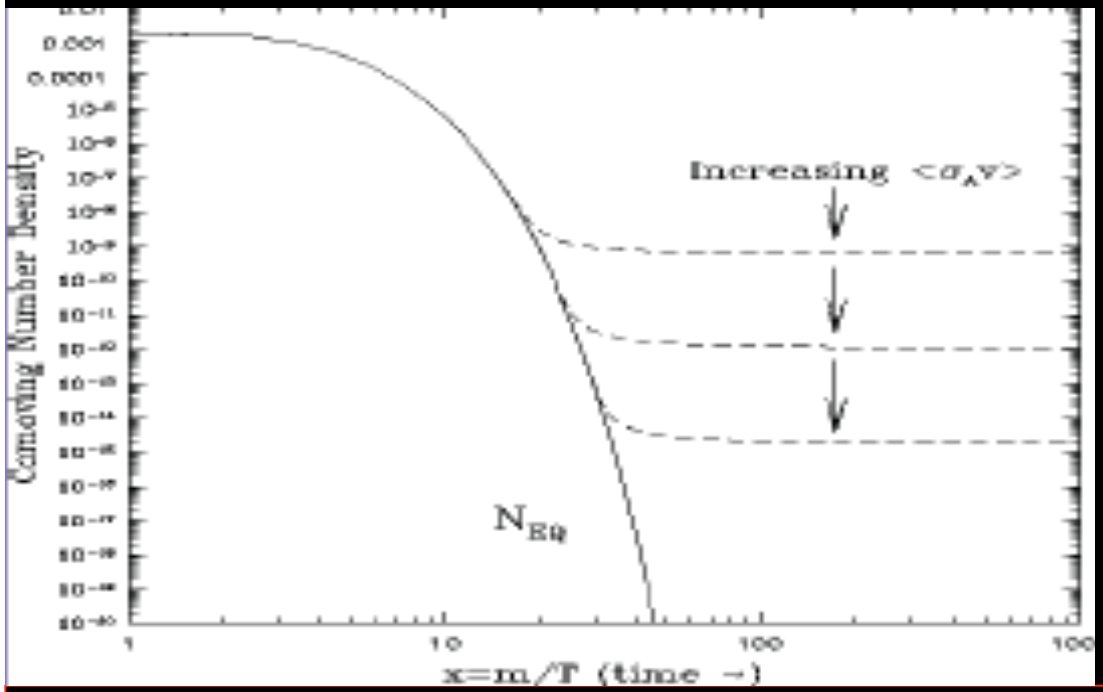


Dark matter "most likely" is a weakly interacting (massive?) particle

Eg WIMP (or LSP) motivated by theory of supersymmetry

Favoured SUSY candidate is a WIMP in mass range 0.01-10 TeV

The WIMP miracle: relic abundance if $\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3/s $\sim 1/\Omega_x$



Occasionally annihilate today
In the halo to energetic particles: ν,γ,pbar,e^+

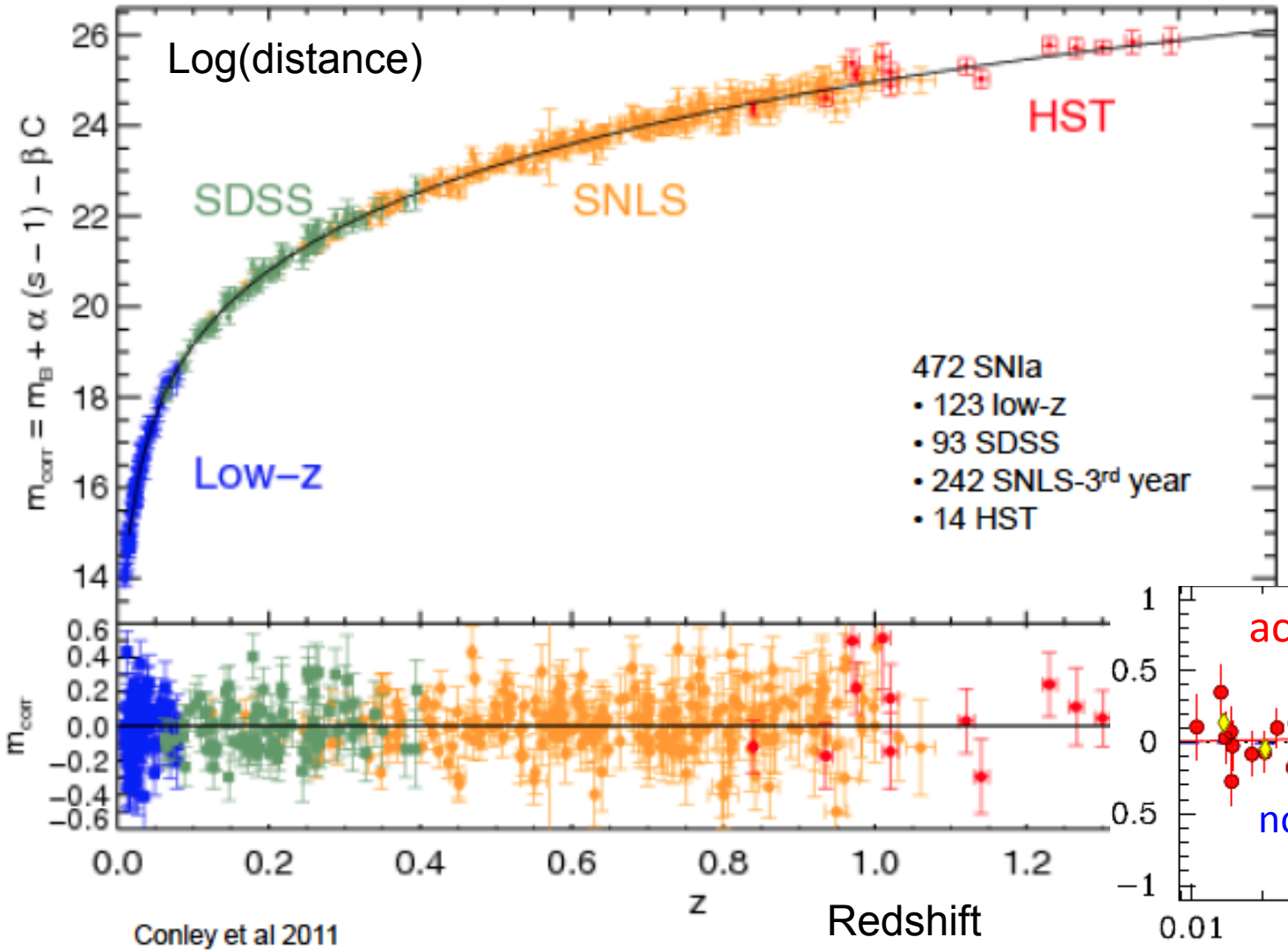
Astrophysical probes complement collider experiments

Dark energy accelerates…

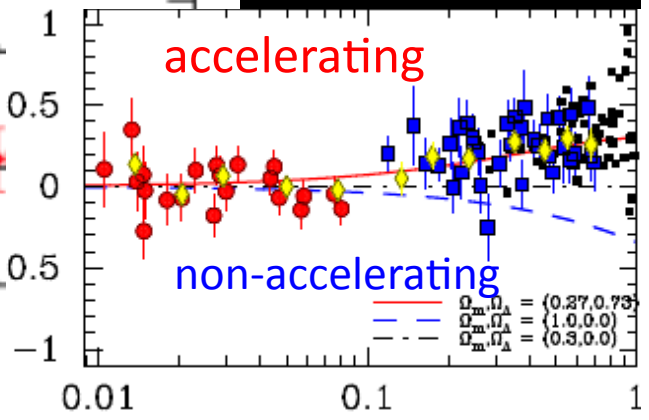
we measure **dark matter minus dark energy**

Distant type Ia supernovae are too faint!

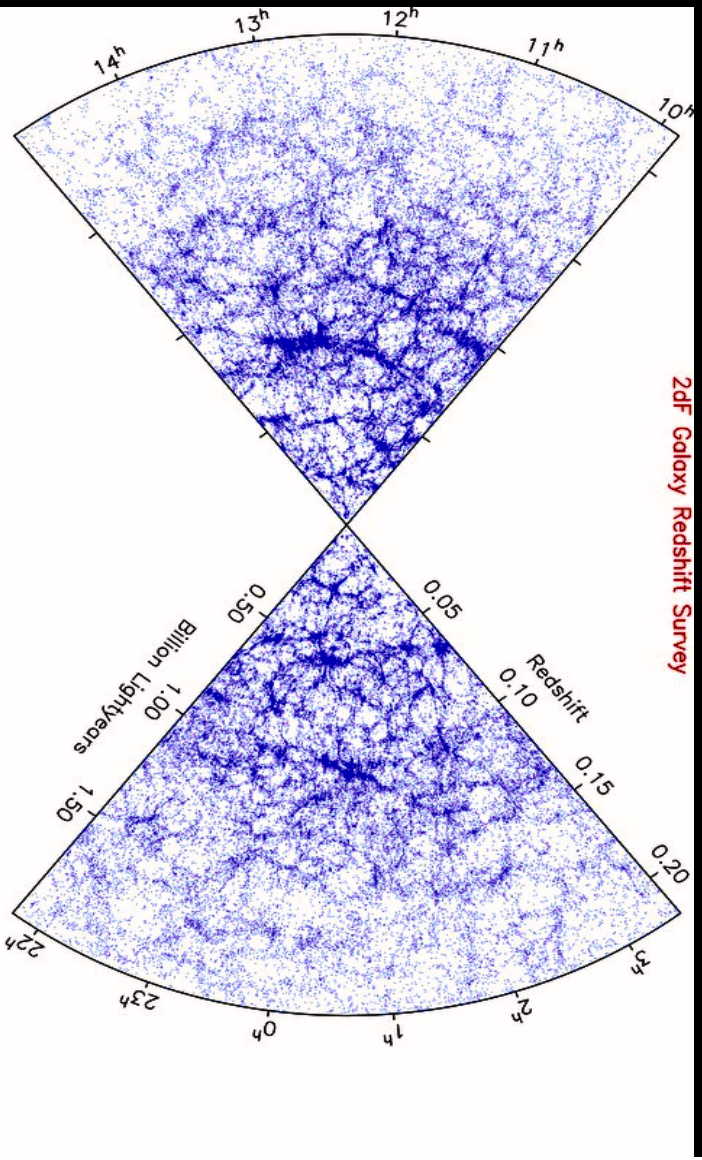
Hubble diagram SNIa

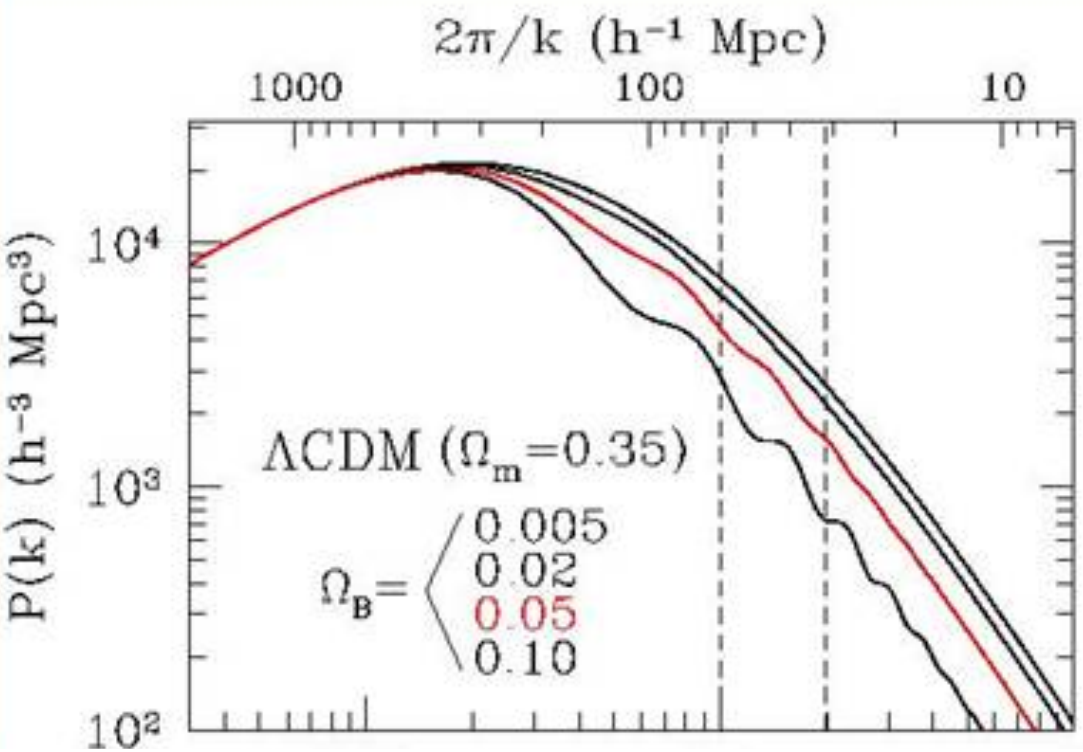


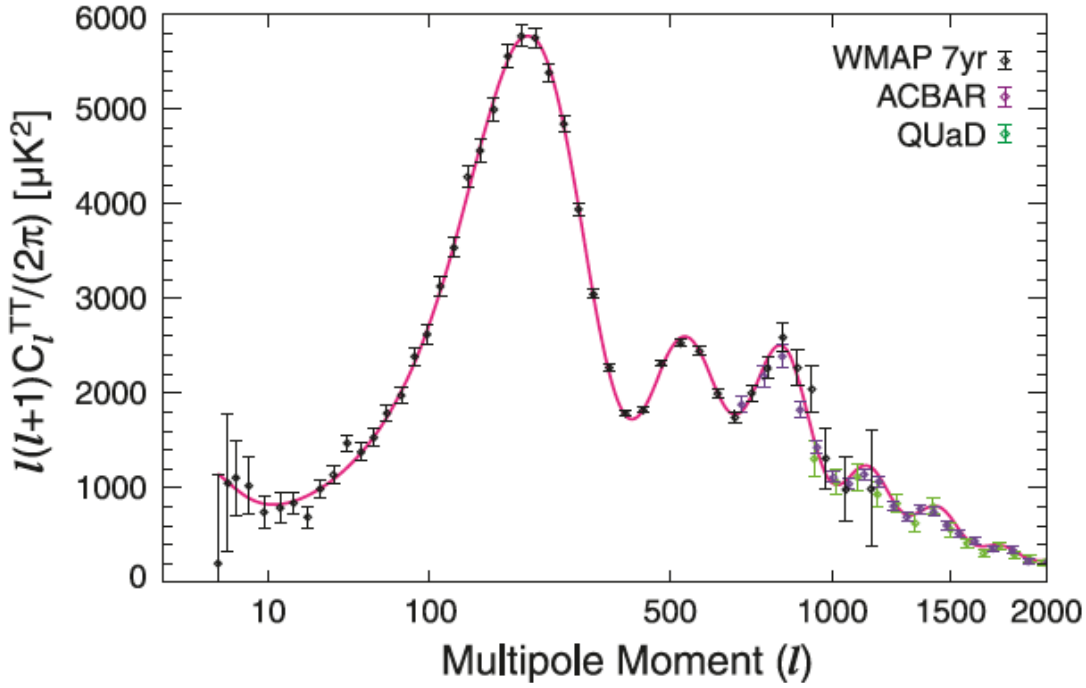
Freedman al. 2009

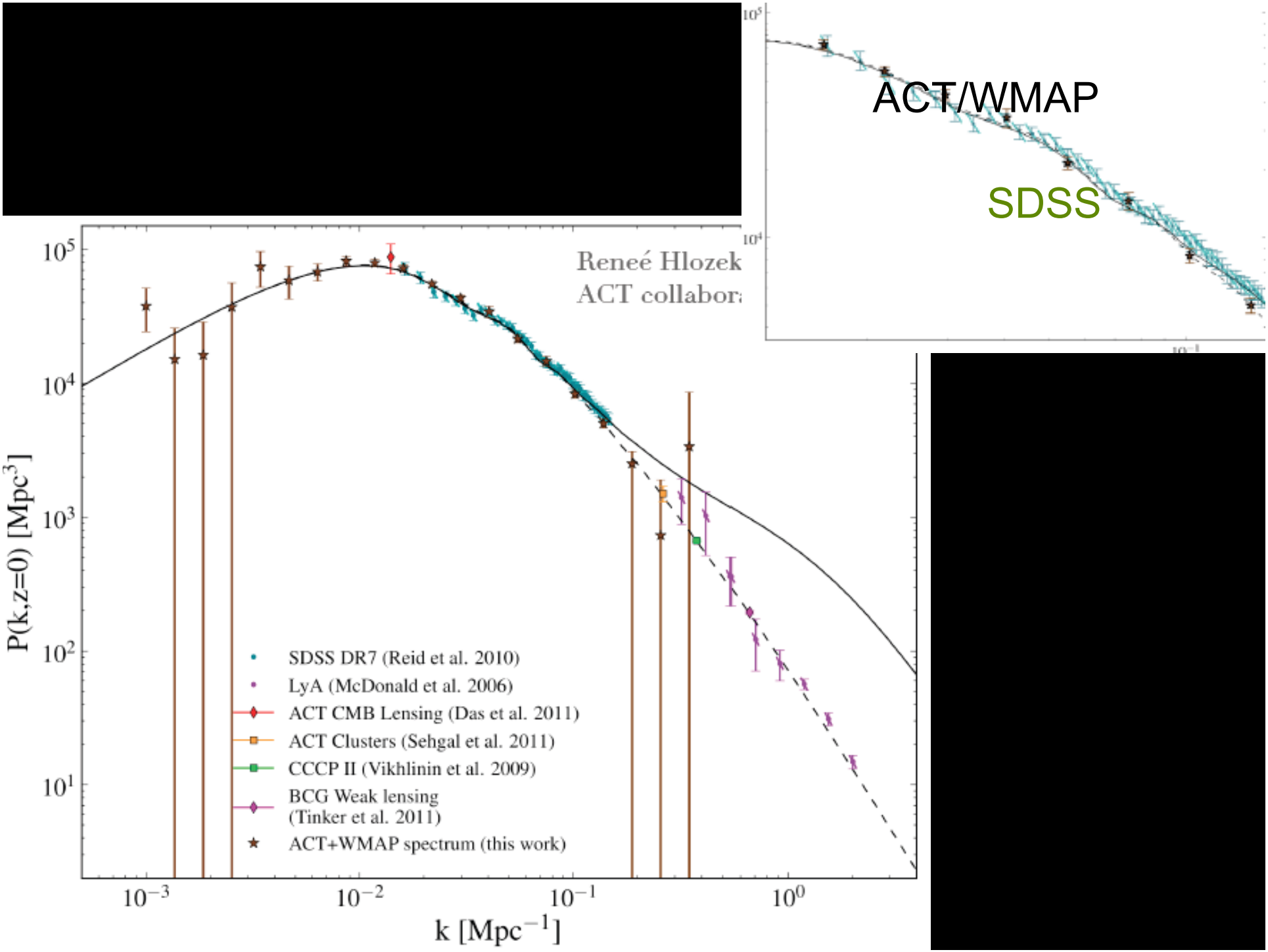


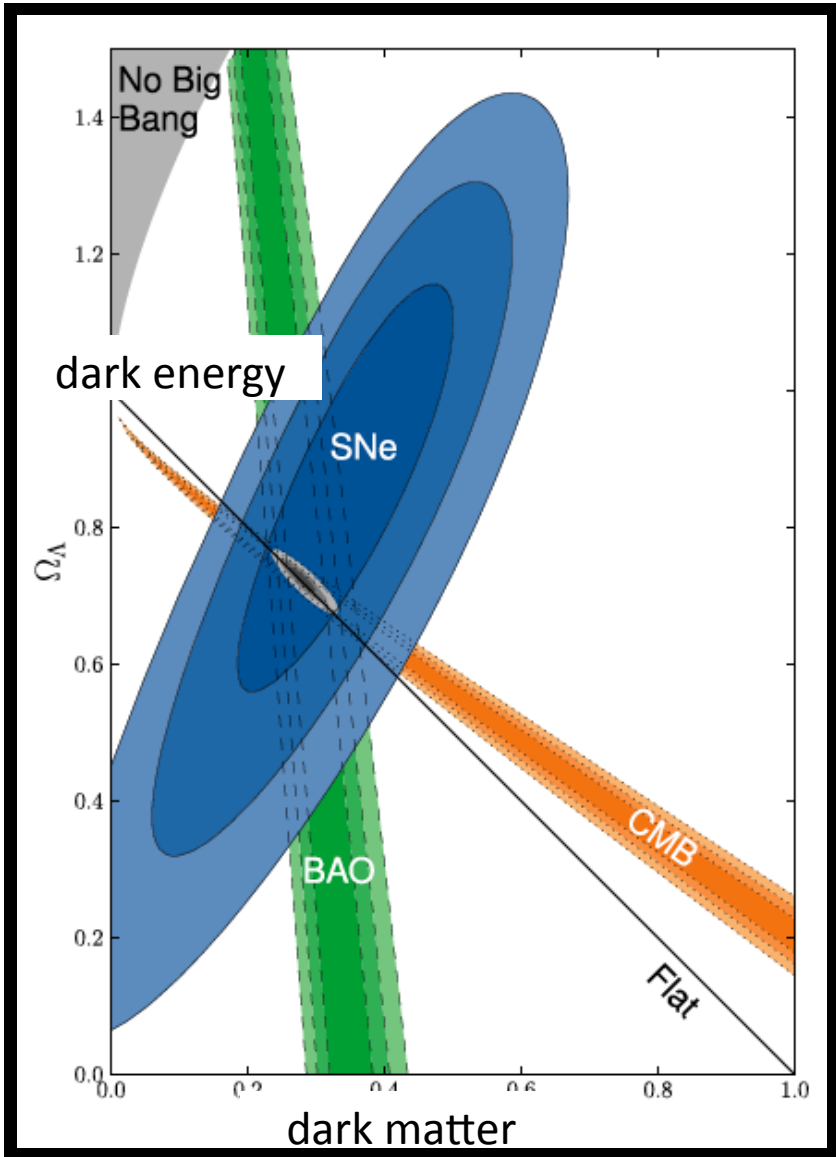
Dark matter distorts redshift space

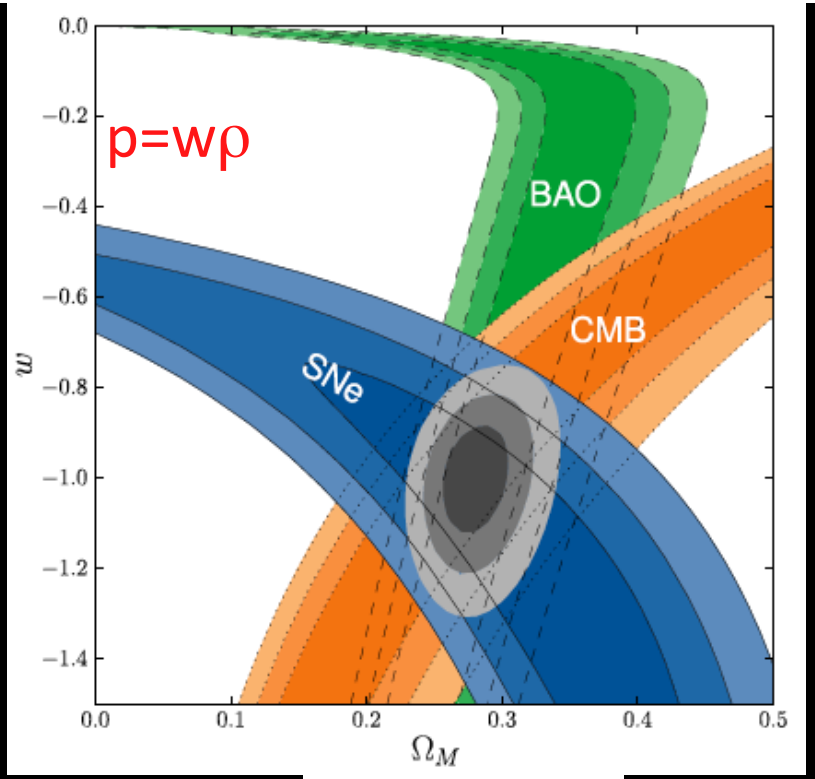







ACT/WMAP
SDSS
Reneé Hlozek
ACT collabor
P(k,z=0) [Mpc^3]
k [Mpc^{-1}]
SDSS DR7 (Reid et al. 2010)
LyA (McDonald et al. 2006)
ACT CMB Lensing (Das et al. 2011)
ACT Clusters (Sehgal et al. 2011)
CCCP II (Vikhlinin et al. 2009)
BCG Weak lensing
(Tinker et al. 2011)
ACT+WMAP spectrum (this work)





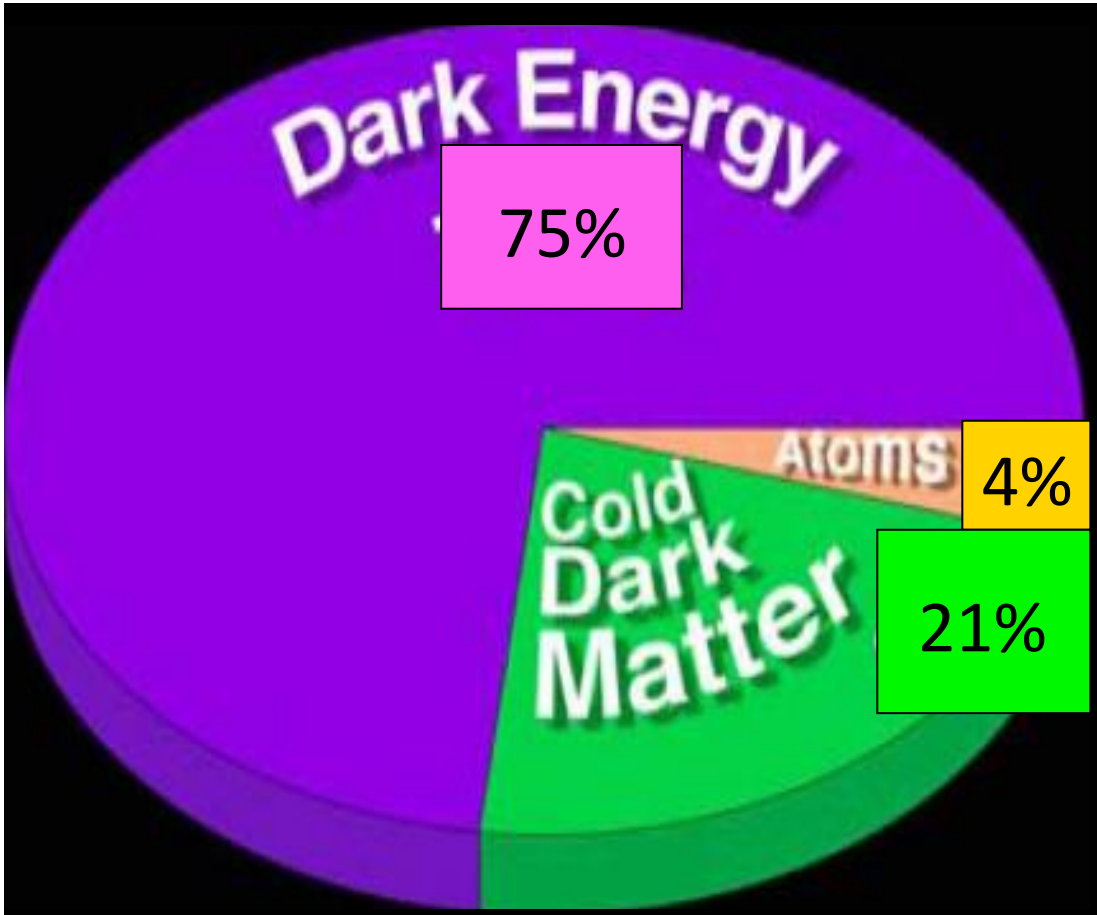
Amanullah et al 2010

Large-scale structure (BAO): DM

CMB fluctuations: DM +DE

Supernovae: DM - DE

Most of the energy in the universe is dark!



observe

$$\rho_{\rm vac} \approx 10^{-10}\,{\rm eV}^4$$

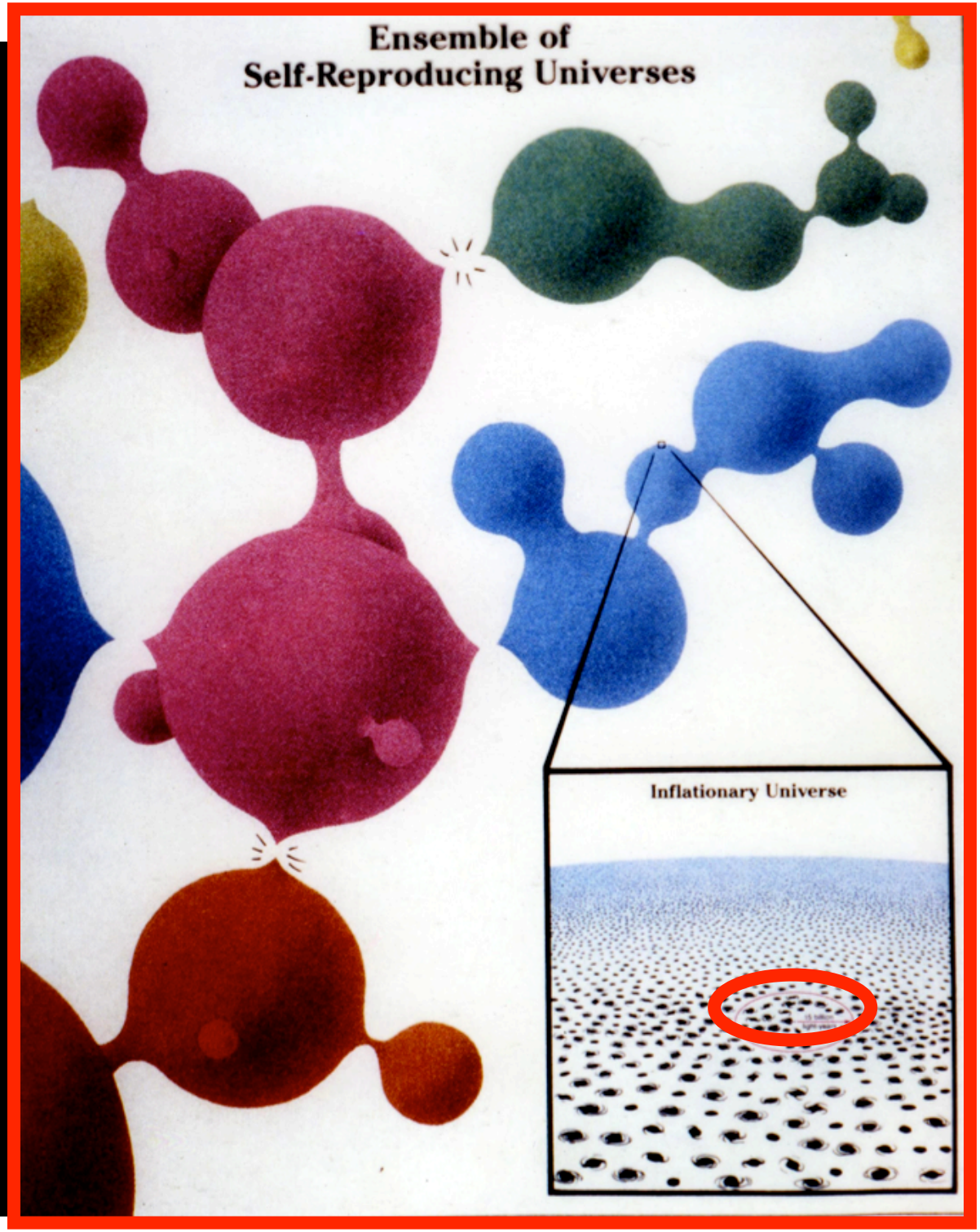
predict

$$M \sim M_{Planck} = G^{-1/2} = 10^{28}\ {\rm eV} \Rightarrow \rho_{vac} \sim 10^{112}\,{\rm eV}^4$$

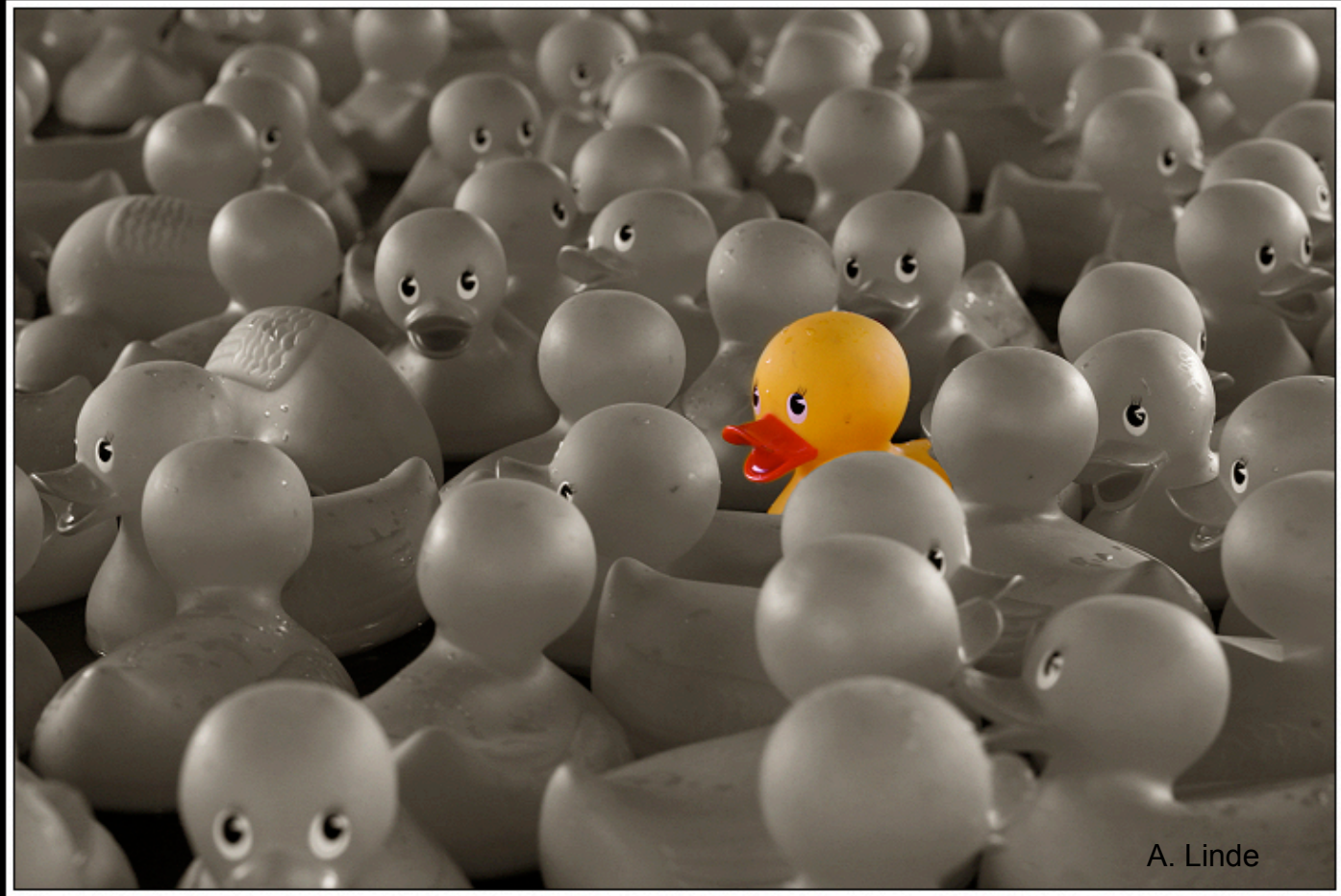
One of the greatest problems in physics!

Eternal inflation produces a nearly infinite number of inaccessible universes

Motivates multiverse explanation of why dark energy is so small

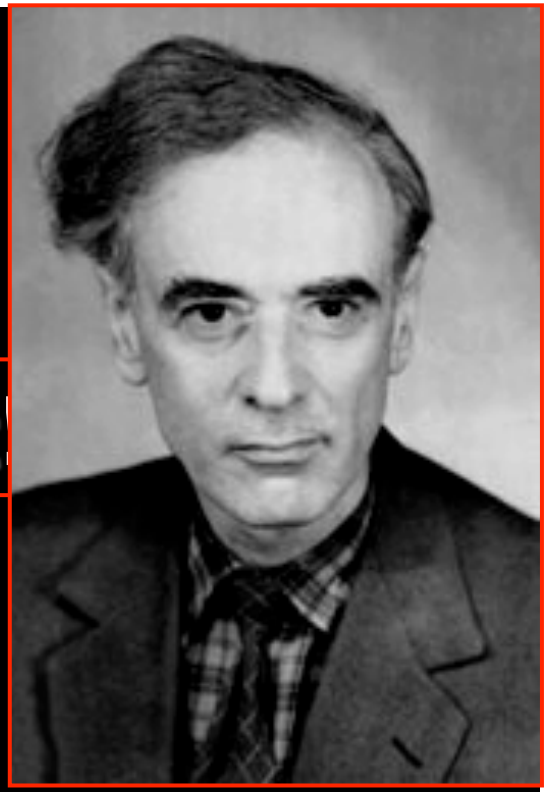


We live in one tiny pocket where the value of the cosmological constant is consistent with our kind of life **Leonard Susskind**



The multiverse theory can't make any predictions … it can explain anything…
George Ellis

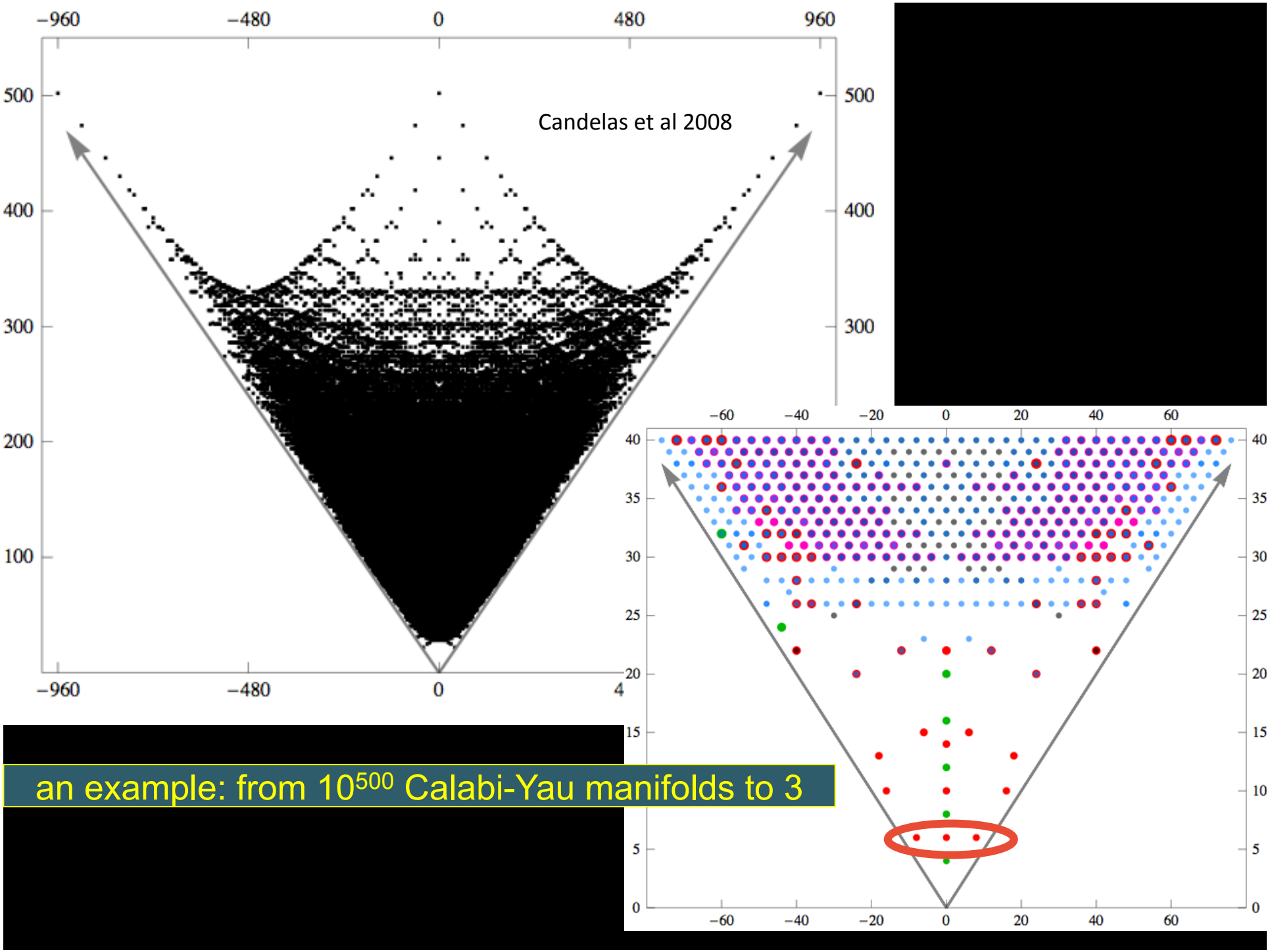
Landau on Cosmologists



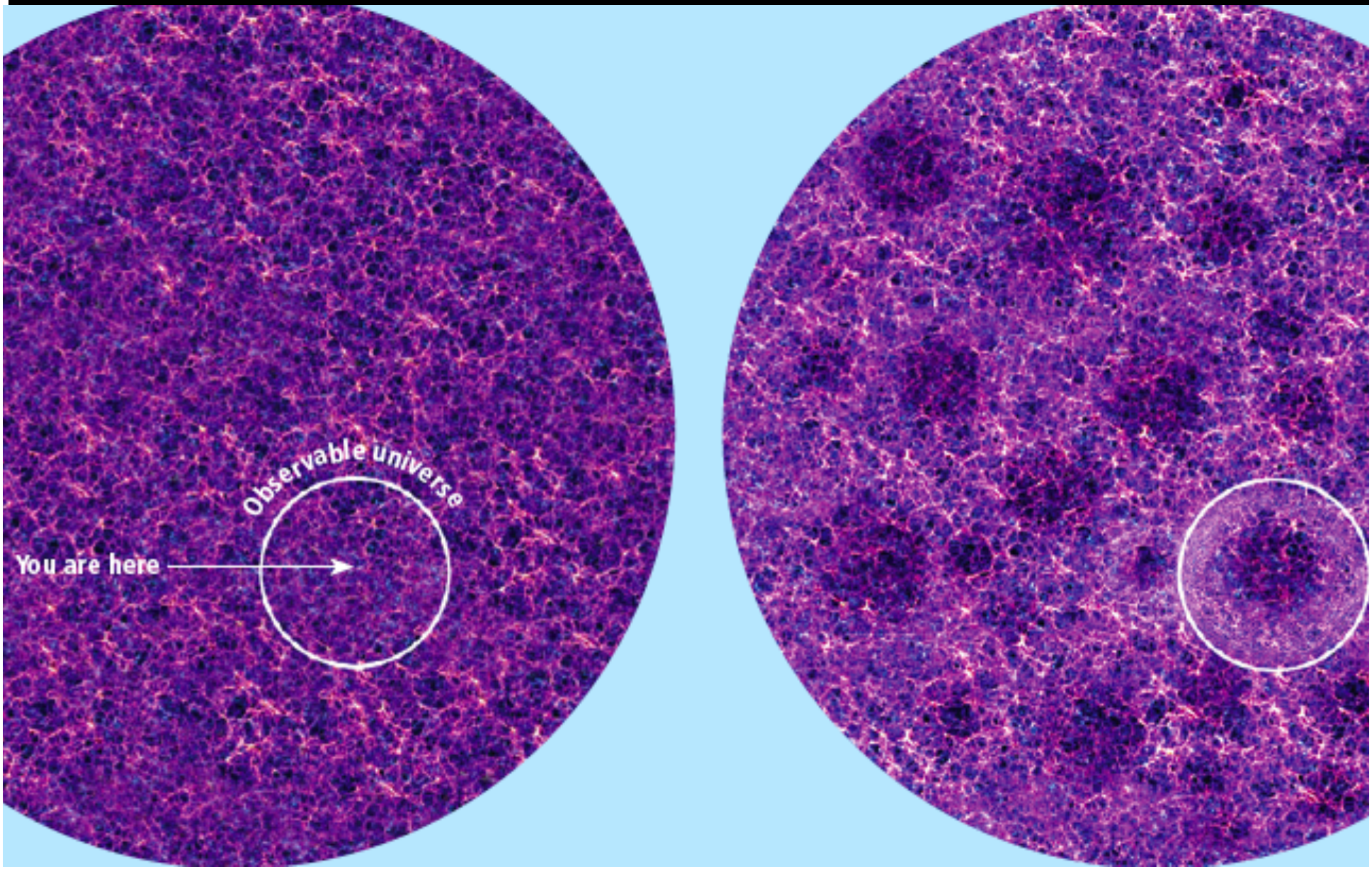
Often in Error, Never in Doubt!

Alternatives:
we may hope for a fundamental physics theory of dark energy.....

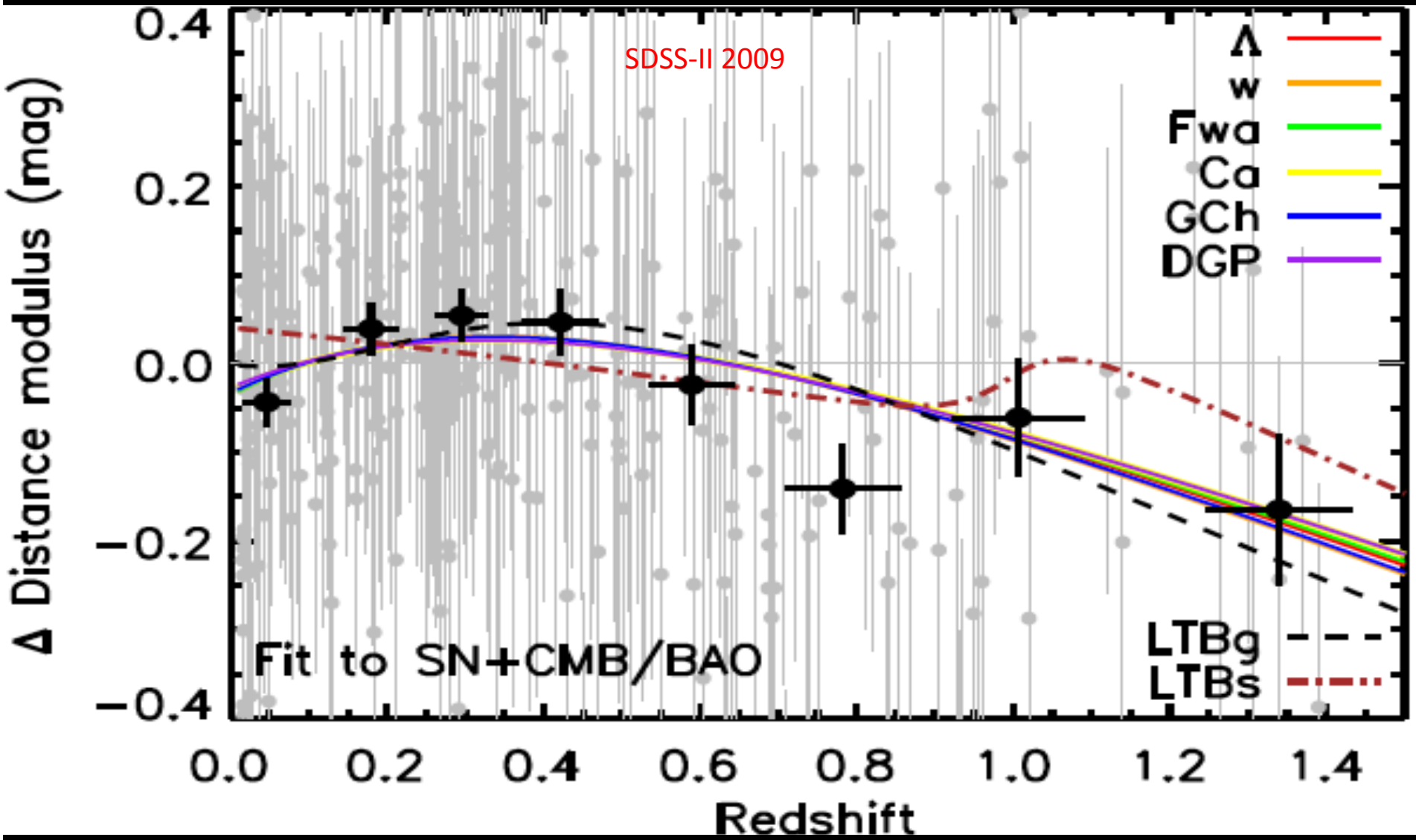
or seek an astrophysical explanation


Candelas et al 2008
an example: from 10^{500} Calabi-Yau manifolds to 3

Clifton & Ferreira 2008



CAN REPLACE ACCELERATION BY A GIANT LOCAL VOID
in Lemaitre-Tolman-Bondi model



Which hypothesis is more “fine-tuned”?

THE FUTURE FOR DARK ENERGY