

Title: PSI 2016/2017 Cosmology (Review) - Lecture 7

Date: Feb 08, 2017 10:15 AM

URL: <http://pirsa.org/17020055>

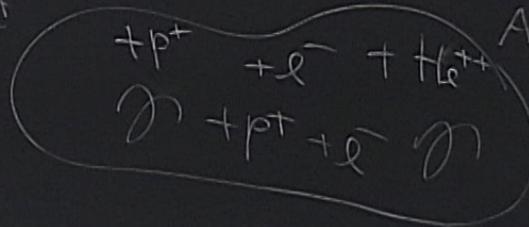
Abstract:

YESTERDAY: BBN 1 MeV (RADIATION ERA)  
FUSED  $\text{He}^{++}$

d) FIRST LOOK AT CMB

CONSIDER  $T \approx eV$  (MATTER ERA)

PLASMA



ALL PARTICLES  
ARE NON-RELATIVISTIC

RA)

- RECOMBINATION OF He:  $T \approx 5000 \text{ K}$
- RECOMBINATION OF H.



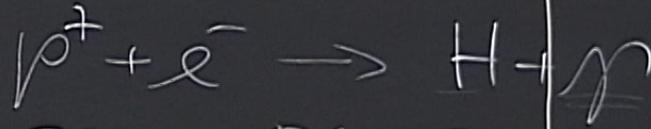
NON-EQUIL PROCESS

"CAN" MODEL BY "SAHA APPROXIMATION"

S  
RELATIVISTIC

RA)

- RECOMBINATION OF He:  $T \approx 5000 \text{ K}$
- RECOMBINATION OF H.



NON-EQUIL PROCESS

"CAN" MODEL BY "SAHA APPROXIMATION"

$$X_e = \frac{n_e}{n_b}$$

→ DENSITY OF FREE  
ELECTRONS

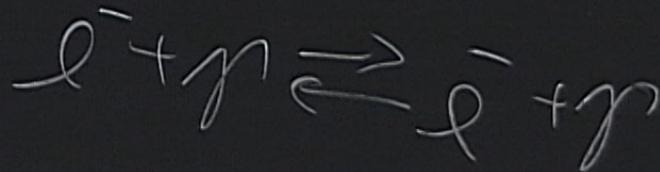
RELATIVISTIC

$$X_e \approx 0.1 \dots T_{\text{REC}} = 0.3 \text{ eV} \approx 3600 \text{ K}, z = 1320$$

→ NEUTRAL HYDROGEN

- PHOTON DECOUPLING ALTHOUGH MOST ELECTRONS ALREADY EATEN BY  $p^+$  THE REMAINING ELECTRONS STILL INTERACT

$\gamma$  ... THOMSON SCATTERING



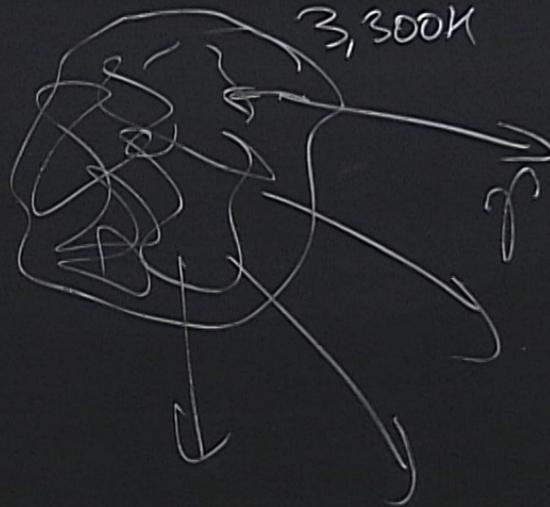
$$z = 1320$$

$$T_{DEC} \approx 0.27 \text{ eV} \approx 3,300 \text{ K}$$

$$X_e \approx 0.01$$

$$z \approx 1100$$

ELECTRONS  
AND ELECTRONS  
INTERACT



PHOTONS SUDDENLY ROAD  
FREE  
→ GET RED SHIFTED

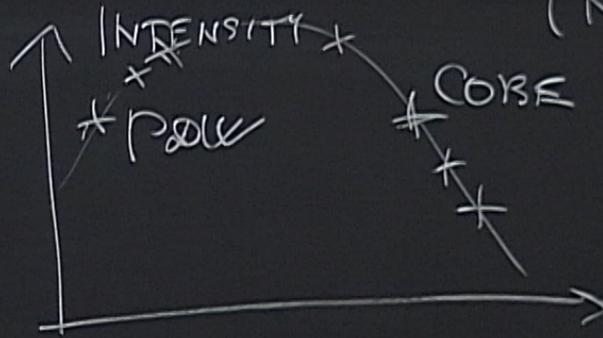
$$T_0 \sim 3 \text{ K}$$

CMB SPECTRUM

1964

PENZIOS & WILSON.

(NP-76?)



$$I = \frac{2hv^3}{c} \frac{1}{e^{\frac{hv}{kT}} - 1}$$

PERFECT BLACK BODY

λ OF SLIGHTLY DIFFERENT TEMPERATURE IN VARIOUS DIRECTIONS

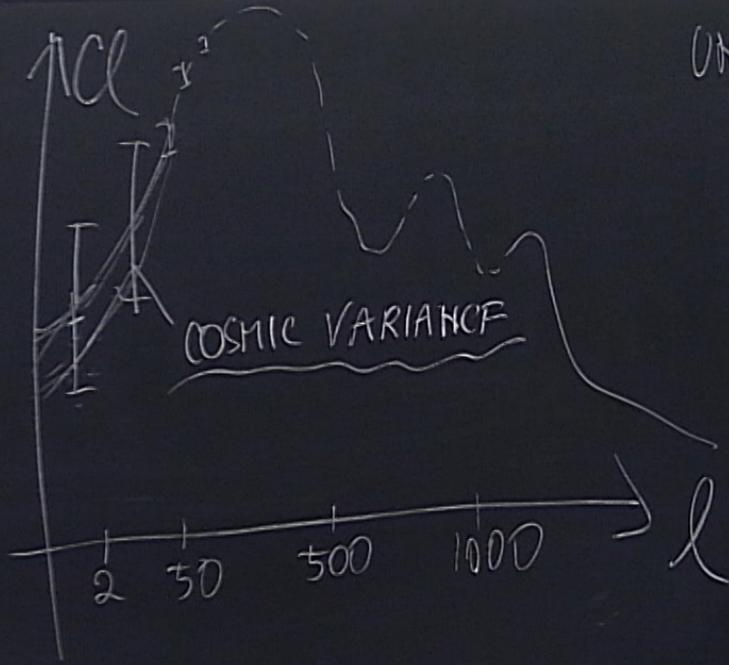
$$T_0 \sim 2.7\text{K} \quad \delta T = \frac{T - T_0}{T_0} \approx 10^{-5}$$

### • MULTIPOLE EXPANSION

EXPAND  $\delta T$  ... IN MULTIPOLE MOMENTS ON  $S^2$ .

$$\delta T(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}(\theta, \varphi)$$

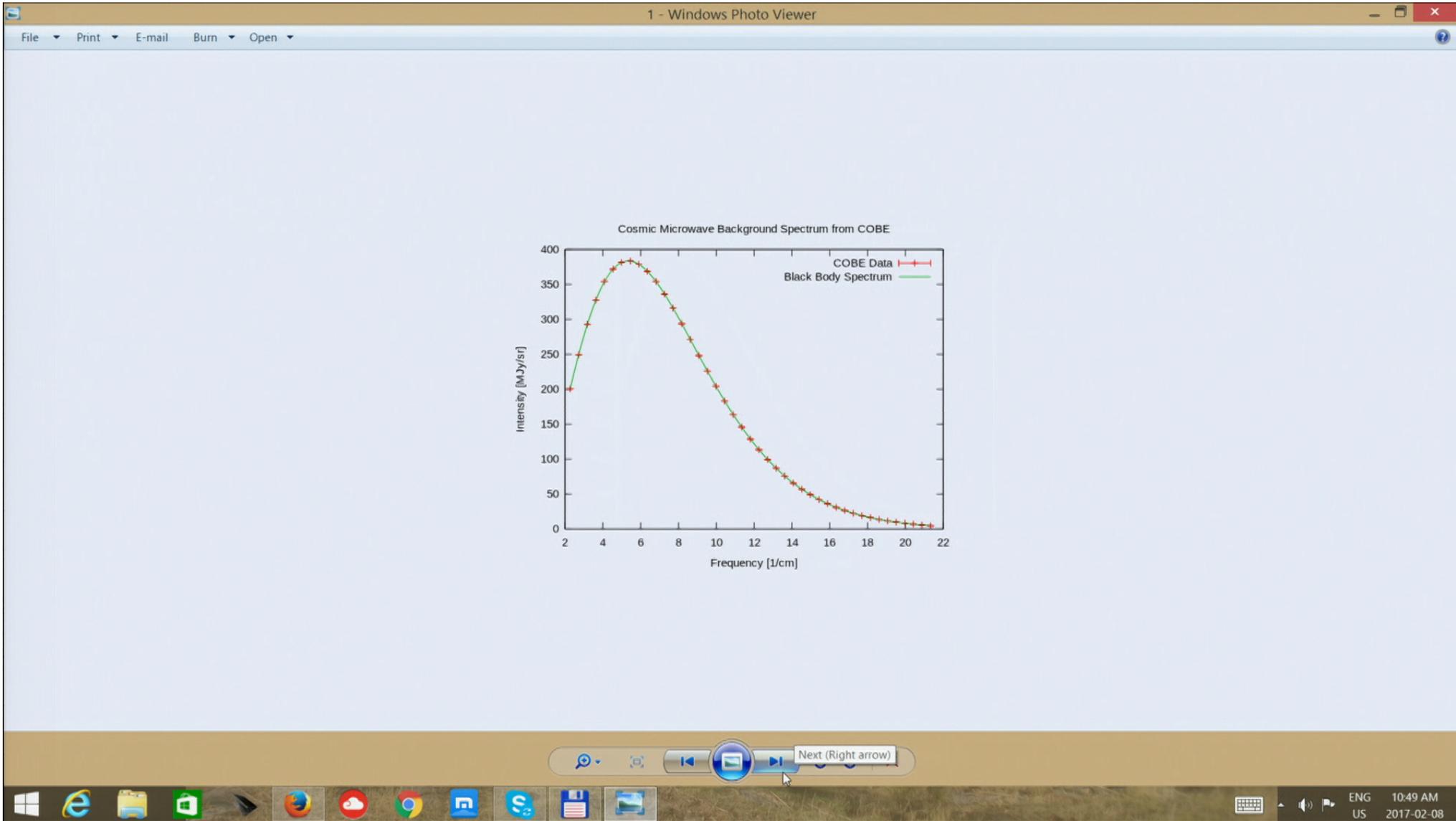
↑ EXP. COEFF

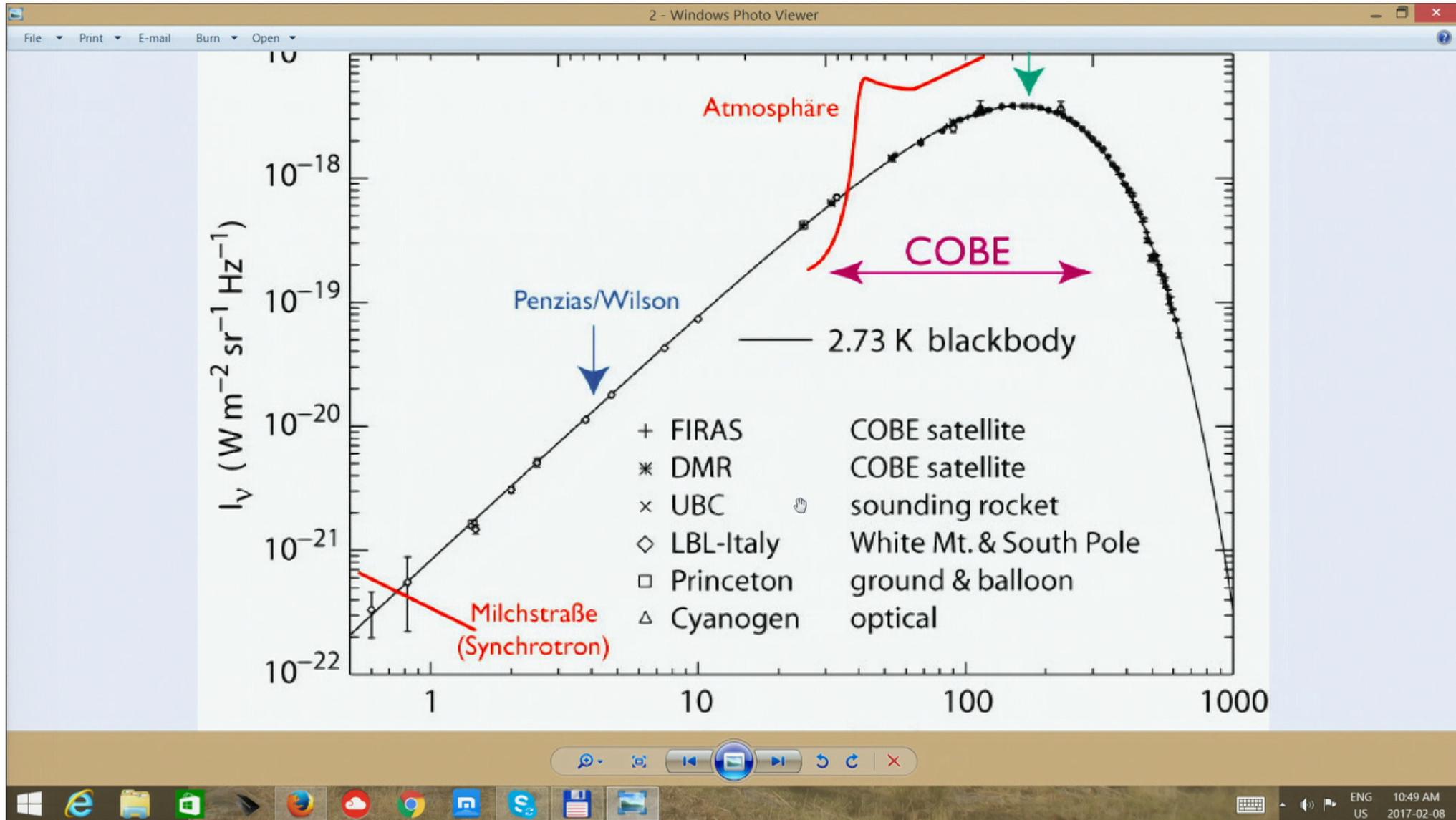


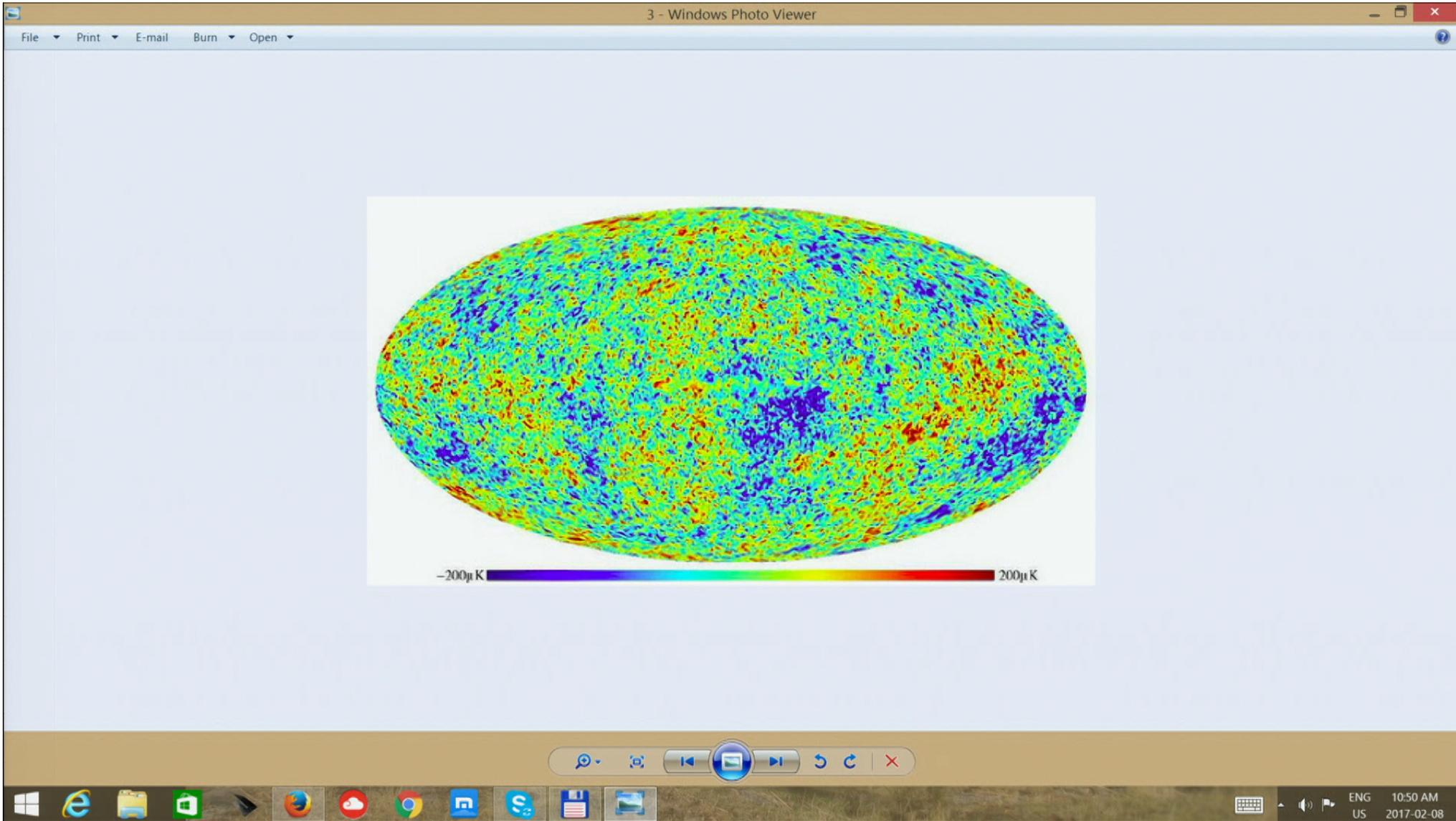
UNIVERSE... 6 PARAMETERS  
 $Jl_b \dots$

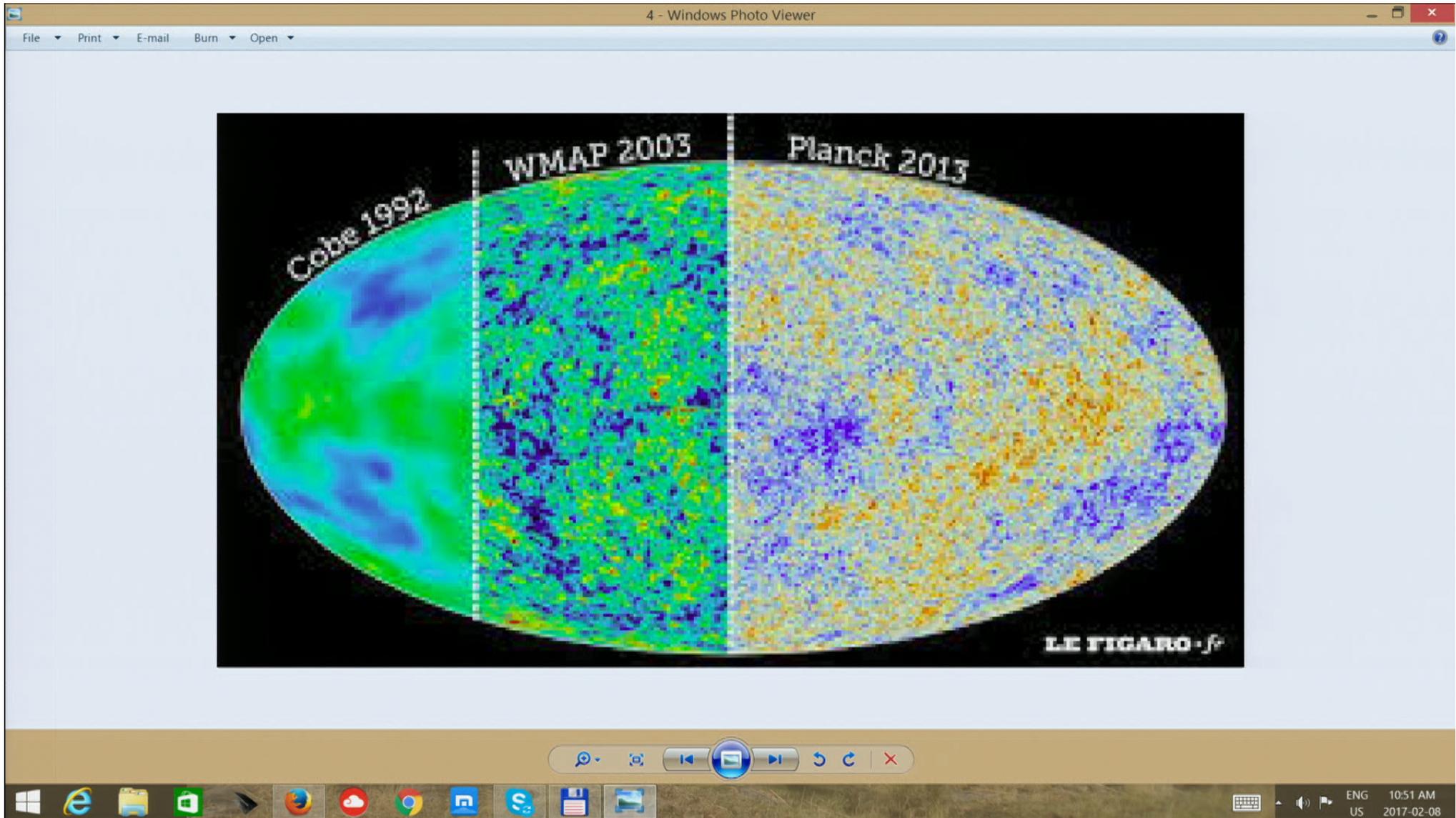


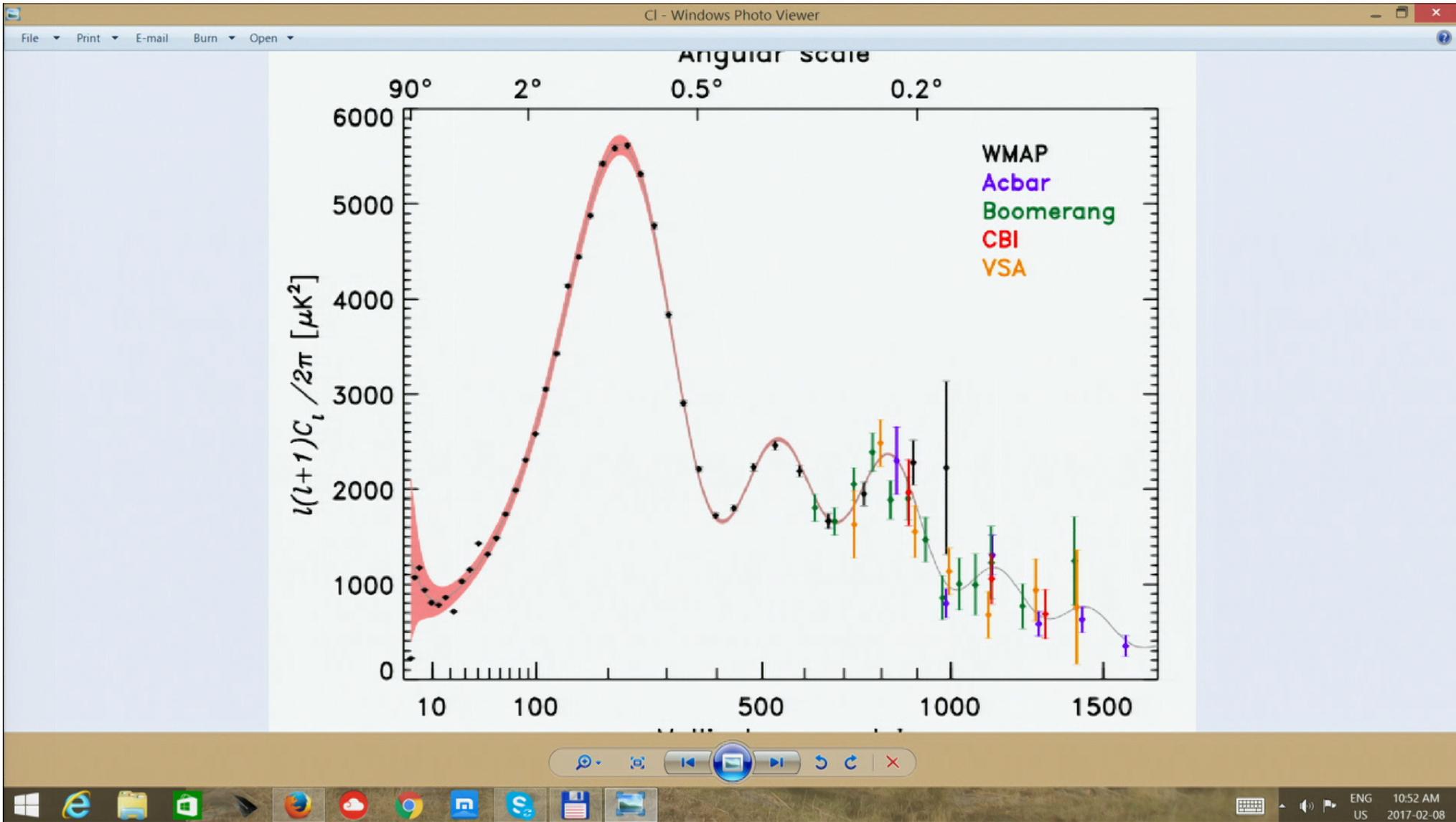


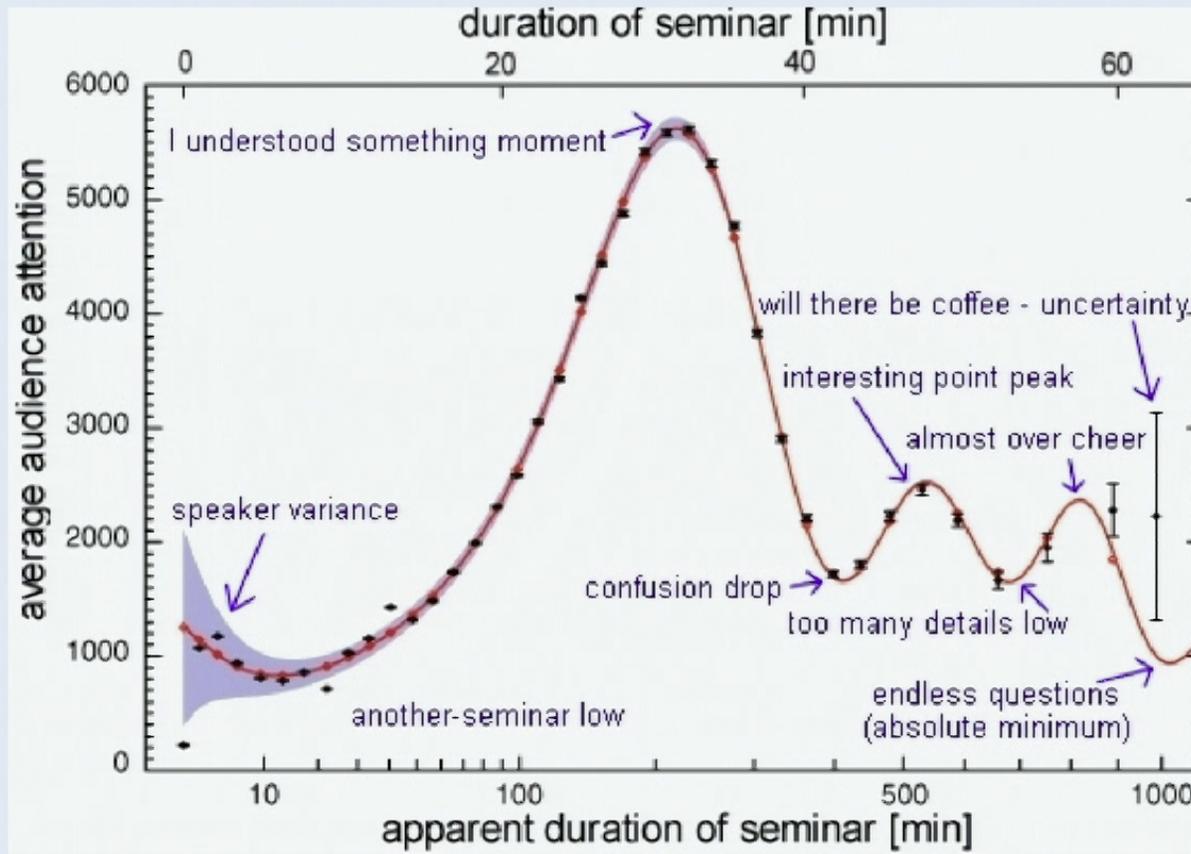








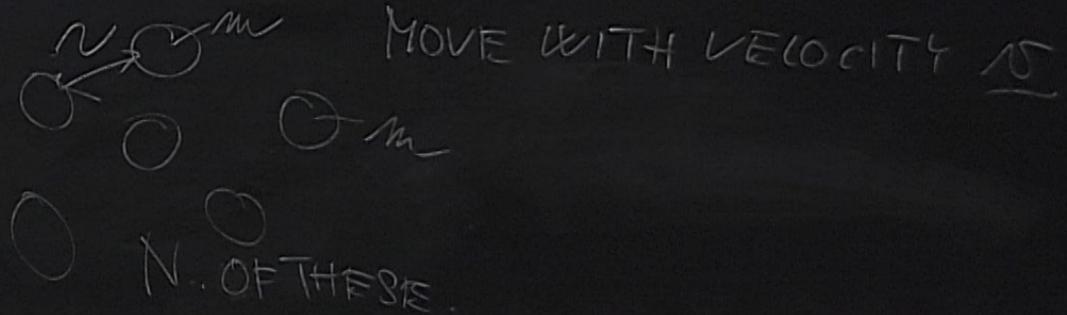




e) DARK MATTER

(?) WHY WE THINK THERE IS DM?

ALREADY IN 1930' . . . FRITZ ZWICKY  
LOOKED AT CLUSTER OF GALAXIES.



GET RED SHIFTED

$$E = \frac{1}{2} N m v^2$$

$$U = - \binom{N}{2} \frac{G m^2}{r}$$

VIRIAL THEOREM

$$E = - \frac{U}{2}$$

$$\frac{1}{2} N m v^2 = + \frac{1}{2} \frac{N(N-1)}{2} \frac{G m^2}{r}$$

$$m = \frac{2 r v^2}{G N (N-1)}$$

TOTAL MASS

$$M = N m = \frac{2 r v^2}{G N}$$

$$\approx 10 \times M_{\text{LUMINOUS}}$$

CITY v

END  
RIDE

$$\psi(\theta, \phi) = \sum_{l=0}^{\infty} \sum_m \frac{a_{lm}}{r} Y_{lm}(\theta, \phi)$$

- 1970's VERA RUBIN ... STUDIED GALAXY ROTATION CURVES  
KEPPLER'S:



ROTATION CURVES

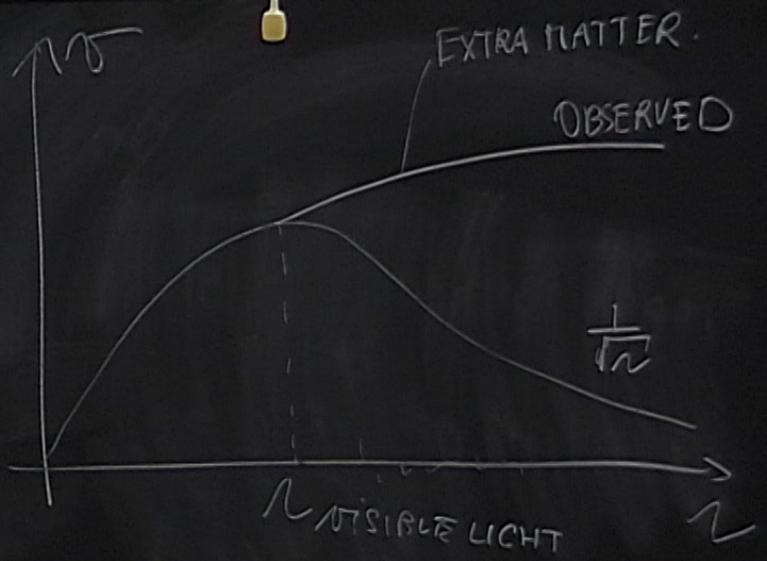
KEPPLER'S:

$$\frac{GM(r)}{r^2} = \frac{v^2}{r}$$

⇒ OUTSIDE OF MATTER  
M = CONST.

$$v \propto \frac{1}{\sqrt{r}}$$

STARS



# DM IS NOT BARYONS

BBN DEPENDS  $\eta = \frac{M_b}{M_{\text{pl}}} \sim 10^{-9}$

CONSERVED IN TIME.

WE KNOW  $(M_p)$ ,  $(M_b)$  TODAY

CAN SHOW THAT ALL THE BARYONS  
ARE SHINING MATTER.