

Title: PSI 2017/2018 - Cosmology - Lecture 7

Date: Feb 05, 2018 11:30 AM

URL: <http://pirsa.org/18020096>

Abstract:

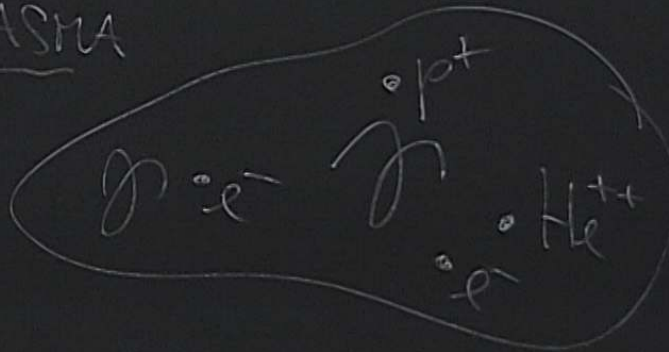
d) FIRST LOOK AT CMB

• RECOMBINATION

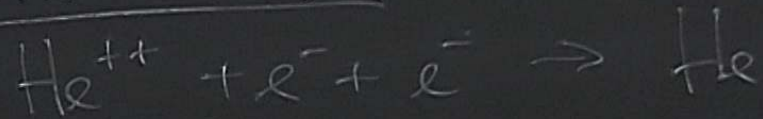
BBN: RADIATION ERA,  $T \gtrsim 1 \text{ MeV}$

CMB: MATTER ERA,  $T \approx \text{eV}$

PLASMA



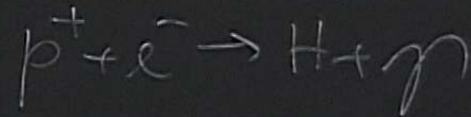
◦ RECOMBINATION OF He

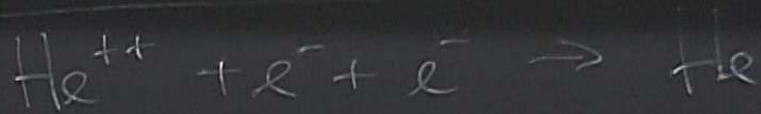


$$T = 5000 \text{ K}$$

UNIVERSE IS STILL OPAQUE

◦ RECOMBINATION OF H

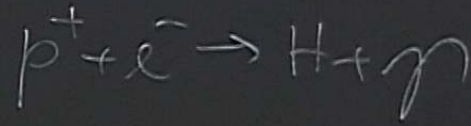




$$T = 5000 \text{ K}$$

UNIVERSE IS STILL OPAQUE

• RECOMBINATION OF H



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

IONIZATION FRACTION

SAHA APPROXIMATION (H2)

$$\underline{X_e \approx 0.1} \dots T_{\text{REC}} \approx 3600 \text{ K}$$
$$z \approx 1320$$

→ NEUTRAL HYDROGEN

a PHOTON DECOUPLING .. REMAINING ELECTRONS

STILL BUMP LIKE CRAZY TO  $\mathcal{D}$

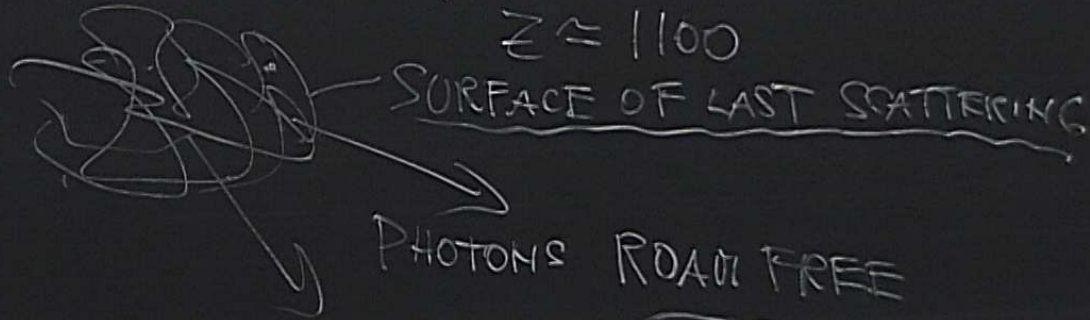
THOMSON SCATTERING

$$e^- + \gamma \rightleftharpoons e^- + \gamma$$

AT ABOUT  $X_e \approx 0.01$  THIS

STOPS...  $T_{DEC} \approx 3300K$

$z \approx 1100$



ELECTRONS

NG

$$e + \eta \rightleftharpoons e + \eta$$

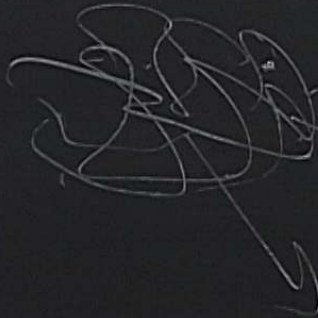
AT ABOUT  $X_e \approx 0.01$  THIS

STOPS...

$$T_{DEC} \approx 3300K$$

$$z \approx 1100$$

SURFACE OF LAST SCATTERING



PHOTONS ROAD FREE

(MOST NEVER SCATTER AGAIN)

→ REDSHIFTED

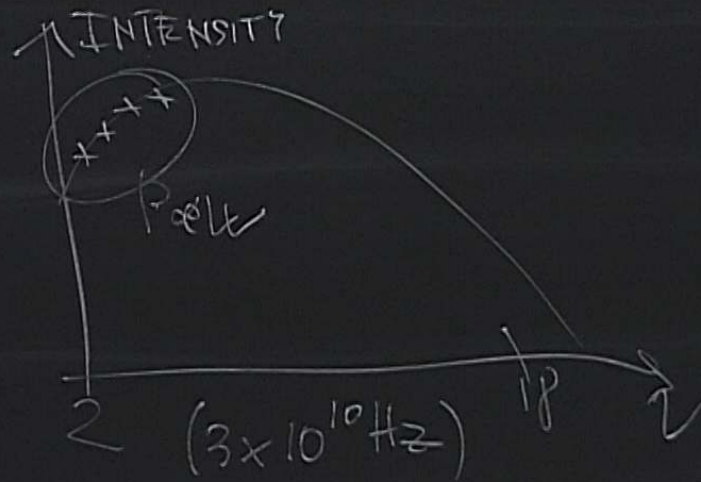
$$T \propto 3K$$

CMB RADIATION

STRONG

CMB SPECTRUM → CMB DISCOVERED - 1964. PENZIAS & WILSON  
(RADIOTELESCOPE)  
→ NP 1978.

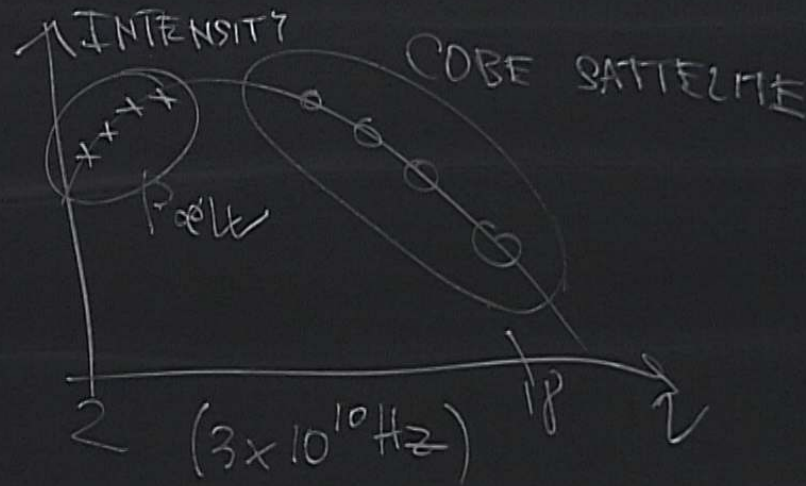
• PERFECT BLACK BODY



• CMB SPECTRUM → CMB DISCOVERED - 1964 (PENZIAS & WILSON)  
(RADIOTELESCOPE)

• PERFECT BLACK BODY → NP 1978.

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



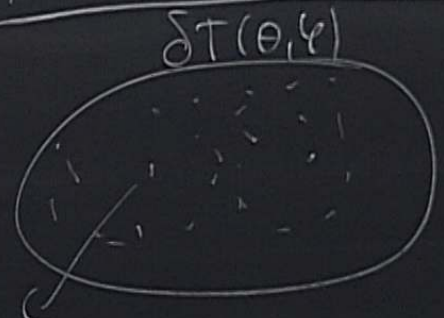
PENZIAS & WILSON  
(RADIOTELESCOPE)  
1978.

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

EACH DIRECTION  
SLIGHTLY DIFFERENT  
TEMPERATURE

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

MULTIPOLE EXPANSION: EXPAND  $\delta T$  ON  $S^2$ .



TINY FLUCTUATIONS

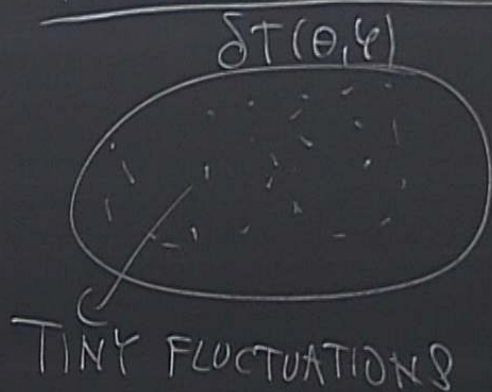


(RADIO TELESCOPE)  
1978.

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

EACH DIRECTION  
SLIGHTLY DIFFERENT  
TEMPERATURE

MULTIPOLE EXPANSION: EXPAND  $\delta T$  ON  $S^2$ .



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

↑  
SPHERICAL HARM.  
EXPANSION COEFF.

• FIX  $l$ ,  $(2l+1)$   $a_{lm}$ 's

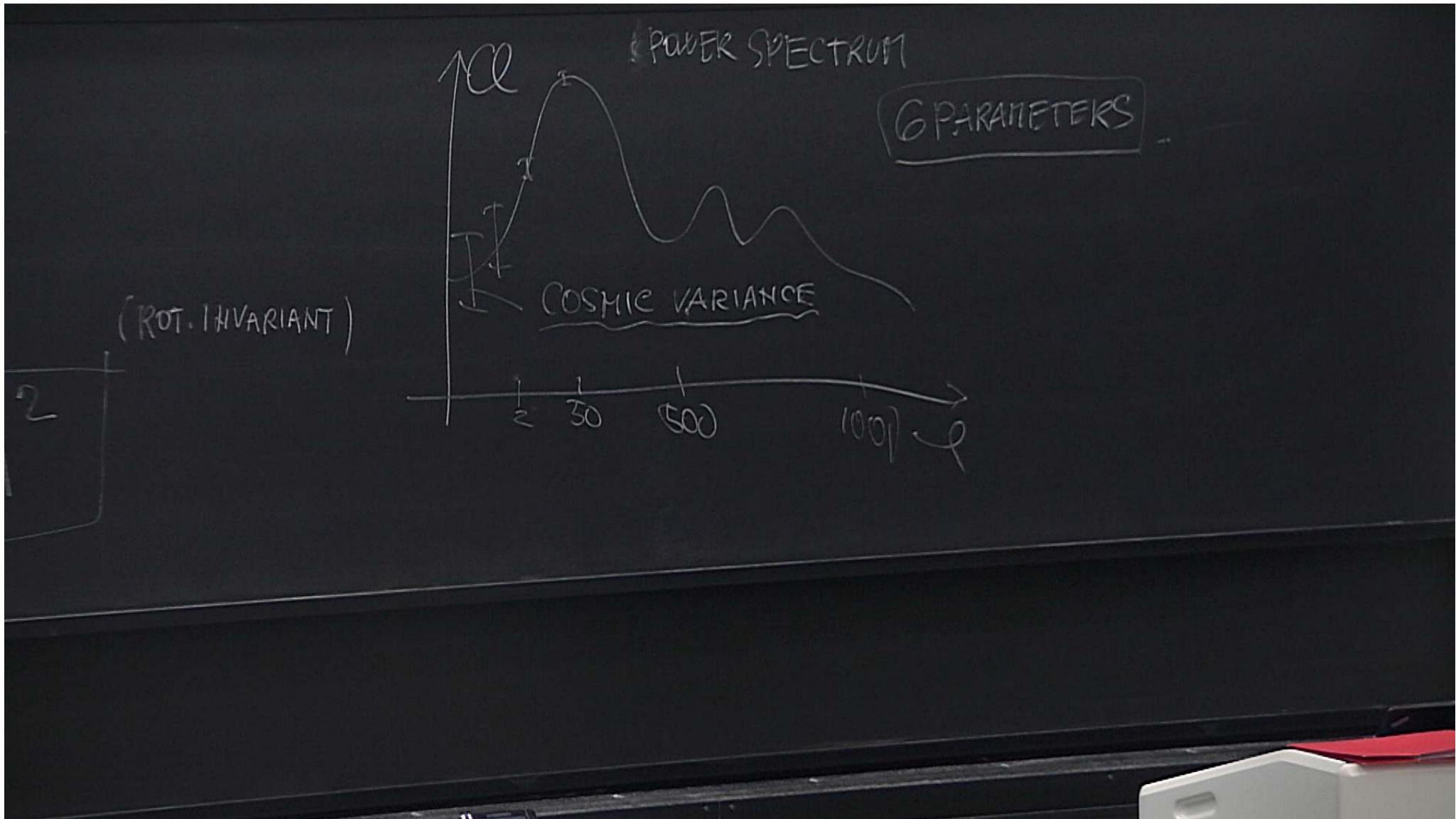
• ANGULAR SCALE ON THE SKY

$$\Theta \sim \pi/l$$

• POWER SPECTRUM  $C_l$

(ROT. INVARIANT)

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^l |a_{lm}|^2$$



**Homework 2**

The graph shows the ionization fraction  $X_e$  as a function of redshift  $z$ . The y-axis is logarithmic, ranging from  $10^{-3}$  to  $1$ . The x-axis is also logarithmic, ranging from  $10^3$  to  $10^2$ . The curve starts at  $X_e = 1$  for  $z > 10^3$ , indicating a fully ionized plasma. At  $z \approx 10^3$ , recombination occurs, and the ionization fraction drops sharply. This transition is labeled 'recombination' and 'decoupling', with 'CMB' (Cosmic Microwave Background) noted below the curve. The Saha equation is indicated by a dashed line at the transition point. For  $z < 10^2$ , the ionization fraction levels off at  $X_e \approx 10^{-3}$ , labeled 'Boltzmann' and 'neutral H'. Energy values of  $1 \text{ eV}$  and  $0.1 \text{ eV}$  are marked at the top of the graph.

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### Cosmic Microwave Background Spectrum from COBE

| Frequency [1/cm] | Intensity [MJy/sr] |
|------------------|--------------------|
| 2.0              | 200                |
| 3.0              | 290                |
| 4.0              | 350                |
| 5.0              | 380                |
| 6.0              | 380                |
| 7.0              | 360                |
| 8.0              | 320                |
| 9.0              | 270                |
| 10.0             | 210                |
| 11.0             | 160                |
| 12.0             | 120                |
| 13.0             | 90                 |
| 14.0             | 70                 |
| 15.0             | 55                 |
| 16.0             | 45                 |
| 17.0             | 38                 |
| 18.0             | 32                 |
| 19.0             | 28                 |
| 20.0             | 25                 |
| 21.0             | 22                 |
| 22.0             | 20                 |

SLIDE 3 OF 8 ENGLISH (CANADA) NOTES COMMENTS 116%

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**Wavelength (cm)**

**Frequency (GHz)**

**$I_\nu$  ( $\text{W m}^{-2} \text{sr}^{-1} \text{Hz}^{-1}$ )**

**2.73 K blackbody**

**Atmosphäre**

**COBE**

**1.7 mm**

**Milchstraße (Synchrotron)**

**Penzias/Wilson**

|             |                        |
|-------------|------------------------|
| + FIRAS     | COBE satellite         |
| * DMR       | COBE satellite         |
| x UBC       | sounding rocket        |
| ◇ LBL-Italy | White Mt. & South Pole |
| □ Princeton | ground & balloon       |
| △ Cyanogen  | optical                |

SLIDE 4 OF 8

ENGLISH (CANADA)

NOTES COMMENTS

116%

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Cobe 1992 WMAP 2003 Planck 2013

LE FIGARO

SLIDE 5 OF 8 ENGLISH (CANADA)

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6 [No Title]

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-200  $\mu$ K 200  $\mu$ K

SLIDE 6 OF 8 ENGLISH (CANADA)

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Angular scale

90° 2° 0.5° 0.2°

6000  
5000  
4000  
3000  
2000  
1000  
0

$l(l+1)C_l / 2\pi$  [ $\mu K^2$ ]

WMAP  
Acbar  
Boomerang  
CBI  
VSA

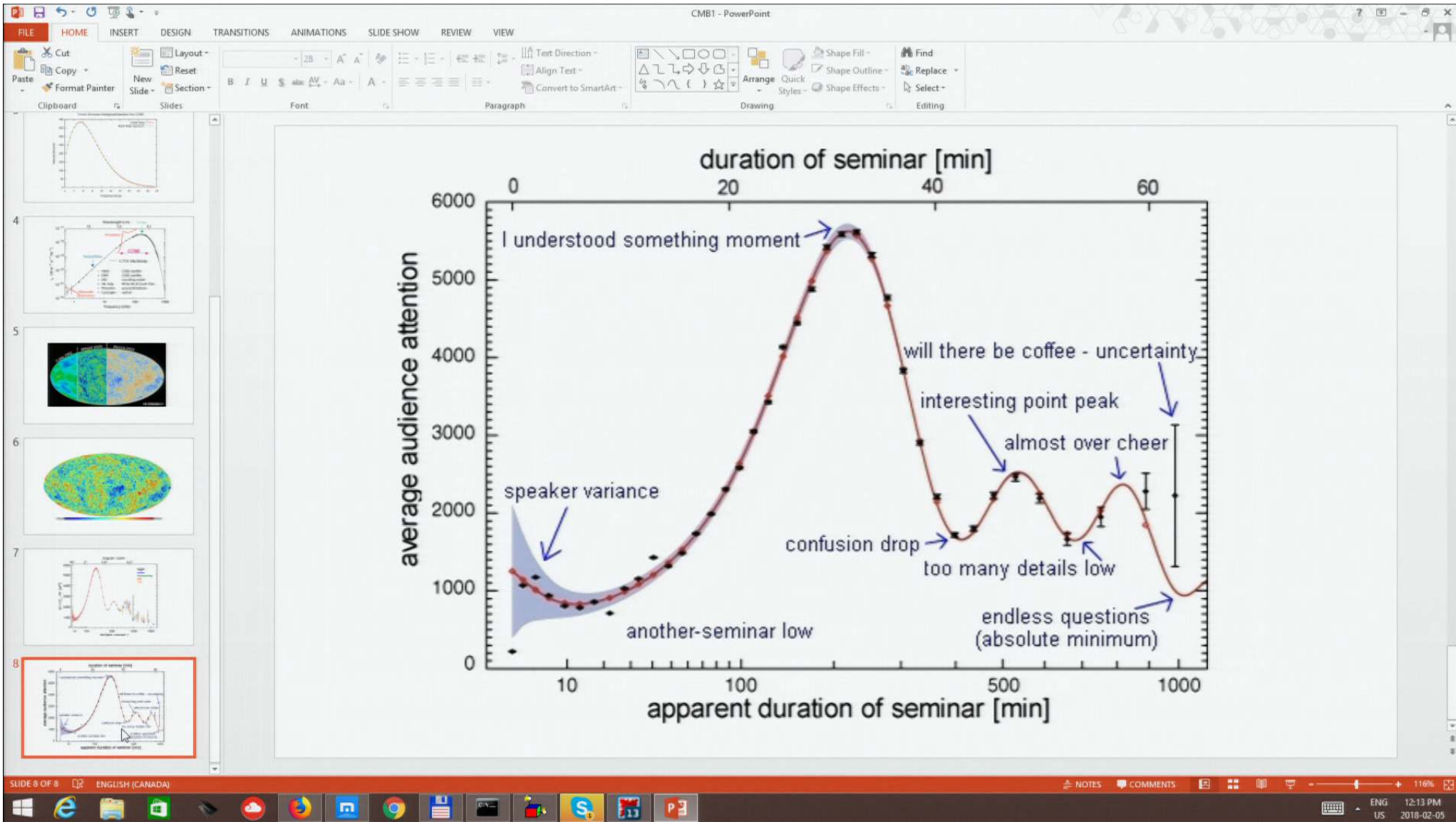
10 100 500 1000 1500

Multipole moment  $l$

SLIDE 7 OF 8 ENGLISH (CANADA)

NOTES COMMENTS

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• WHY DO COSMOLOGISTS THINK THERE IS DM?

• 1930's ZWICKY: STUDIED CLUSTER OF GALAXIES



• THOMSON SCATTERING

STATISTICALLY STEADY, SPHERICAL, SELF-GRAV SYSTEM  
OF N OBJECTS OF AVERAGE MASS m.

STATISTICALLY STEADY, SPHERICAL, SELF-GRAV SYSTEM  
OF N OBJECTS OF AVERAGE MASS m, AVERAGE  
ORBITAL VELOCITY v

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

STATISTICALLY STEADY, SPHERICAL, SELF-GRAV SYSTEM  
OF  $N$  OBJECTS OF AVERAGE MASS  $\underline{m}$ , AVERAGE  
ORBITAL VELOCITY  $\underline{v}$

$$E = \frac{1}{2} N m v^2, \quad U = - \binom{N}{2} \frac{G m^2}{r}$$

VIRIALS THEOREM:  $E = - \frac{U}{2}$

TOTAL DYNAMICAL MASS

$$M = N m$$

PHOTONS ROAM FREE (MOST NEVER SCATTER)

STATISTICALLY STEADY, SPHERICAL, SELF-GRAV SYSTEM  
 OF  $N$  OBJECTS OF AVERAGE MASS  $\underline{m}$ , AVERAGE  
 ORBITAL VELOCITY  $\underline{v}$

$$E = \frac{1}{2} N m v^2, \quad U = - \binom{N}{2} \frac{G m^2}{r}$$

VIRIALS THEOREM:  $E = - \frac{U}{2} = \frac{1}{2} N m v^2 = + \frac{1}{2} \frac{N N}{2} \frac{G m^2}{r}$

TOTAL DYNAMICAL MASS

$$M = N m$$

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

PHOTONS ROAM FREE (MOST NEVER SCATTER)

STATISTICALLY STEADY, SPHERICAL, SELF-GRAV SYSTEM  
 OF  $N$  OBJECTS OF AVERAGE MASS  $\underline{m}$ , AVERAGE  
 ORBITAL VELOCITY  $\underline{v}$

$$E = \frac{1}{2} N m v^2, \quad U = - \binom{N}{2} \frac{G m^2}{r}$$

VIRIALS THEOREM:  $E = - \frac{U}{2} = \frac{1}{2} N m v^2 = + \frac{1}{2} \frac{N N}{2} \frac{G m^2}{r}$

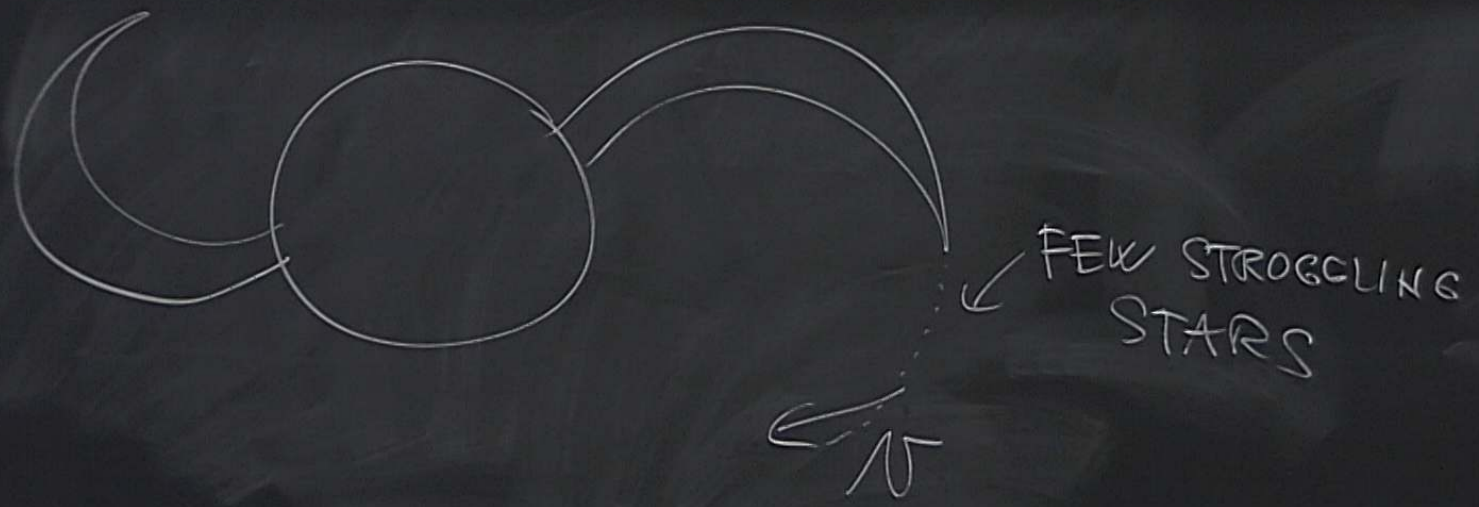
TOTAL DYNAMICAL MASS

$$M = N m = \frac{2 r v^2}{G} \approx 10 \times M_{\text{LUMINOUS}} \quad M = \frac{2 r v^2}{N G}$$

PHOTONS ROAM FREE (MOST NEVER SCATTER)

$$v = \frac{GM}{r}$$

1970's VERA RUBIN .. STUDIED GALAXY ROTATION CURVES



$$M = 10^6 M_{\odot} = \frac{10^6 \times 2 \times 10^{30} \text{ kg}}{G} \approx 10^6 M_{\text{SOLAR}}$$

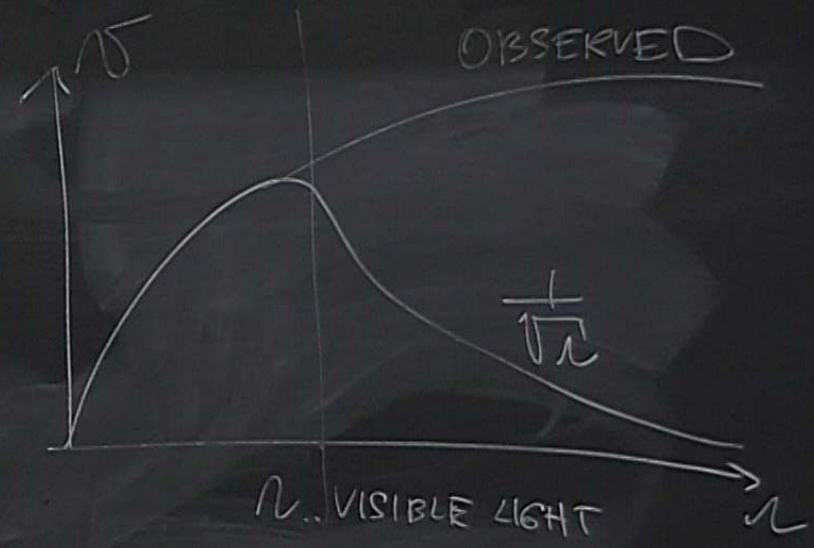
NG

CURVES

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

OUTSIDE OF MATTER -  $M(r) = \text{CONST}$

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



- ANGULAR SCALE ON THE SKY

$$\Omega \approx \pi/2$$

## DM IS NOT BARYONS

- ONE REASON IS BBN:

$$\eta = \frac{n_b}{n_{\gamma}} = 10^{-9} \quad \dots \text{CONSERVED}$$

$$= \frac{(n_b)_{\text{NOW}}}{(n_{\gamma})_{\text{NOW}}}$$

$\Rightarrow M_{\text{BARYONS}} = \text{ALL SHINING BARYONS}$