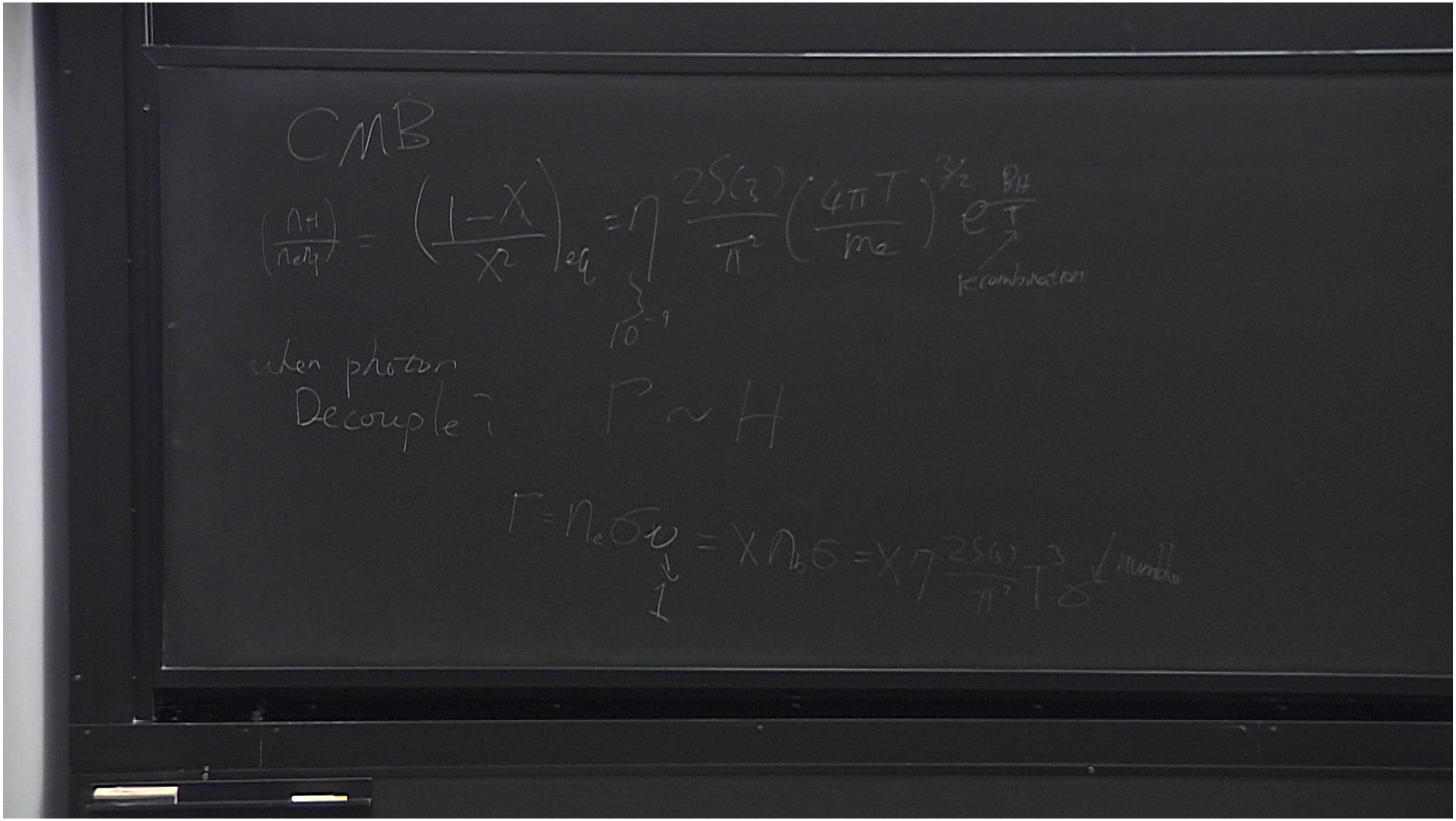
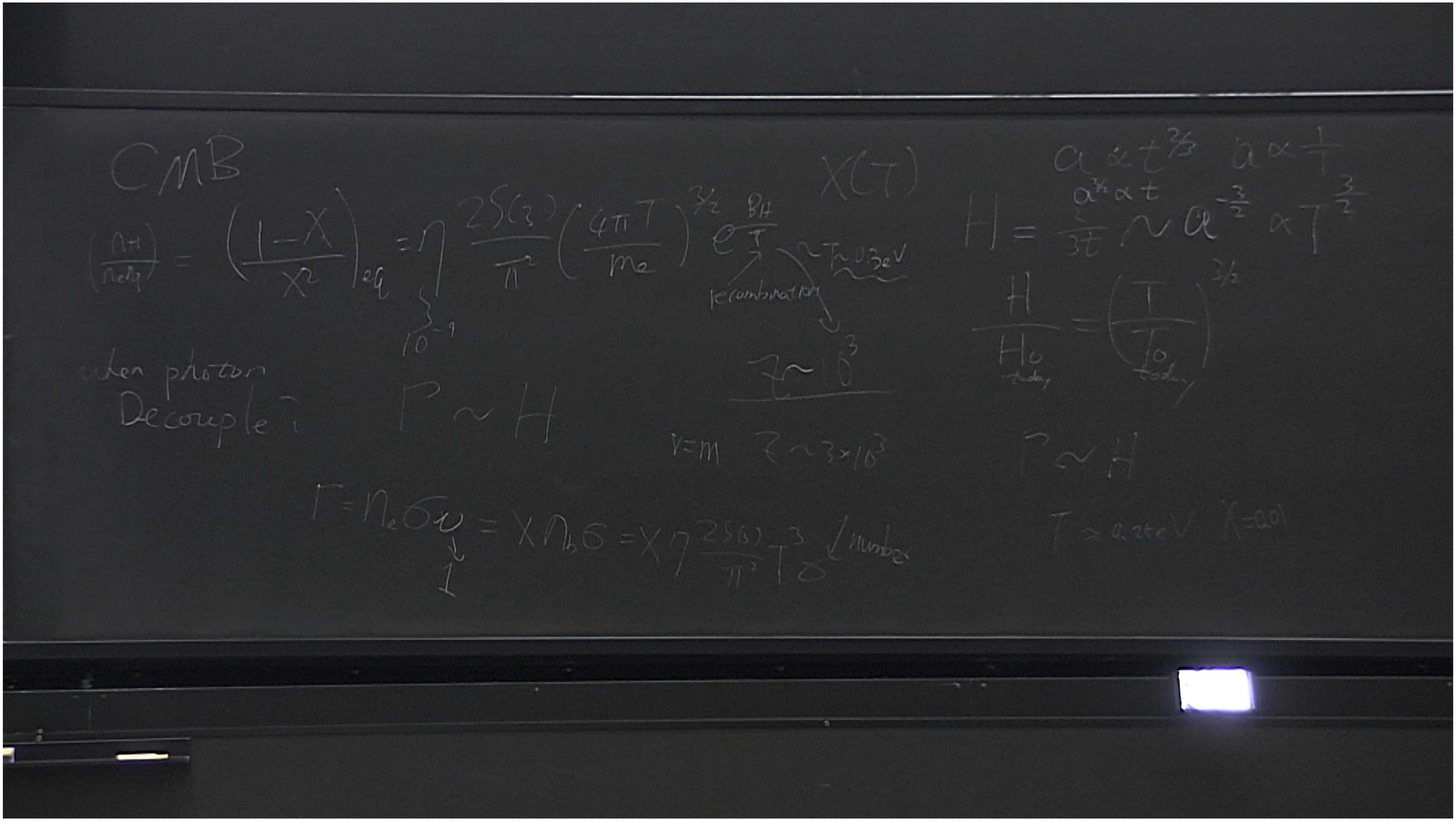
Title: PSI 2018/2019 - Cosmology Review - Lecture 9

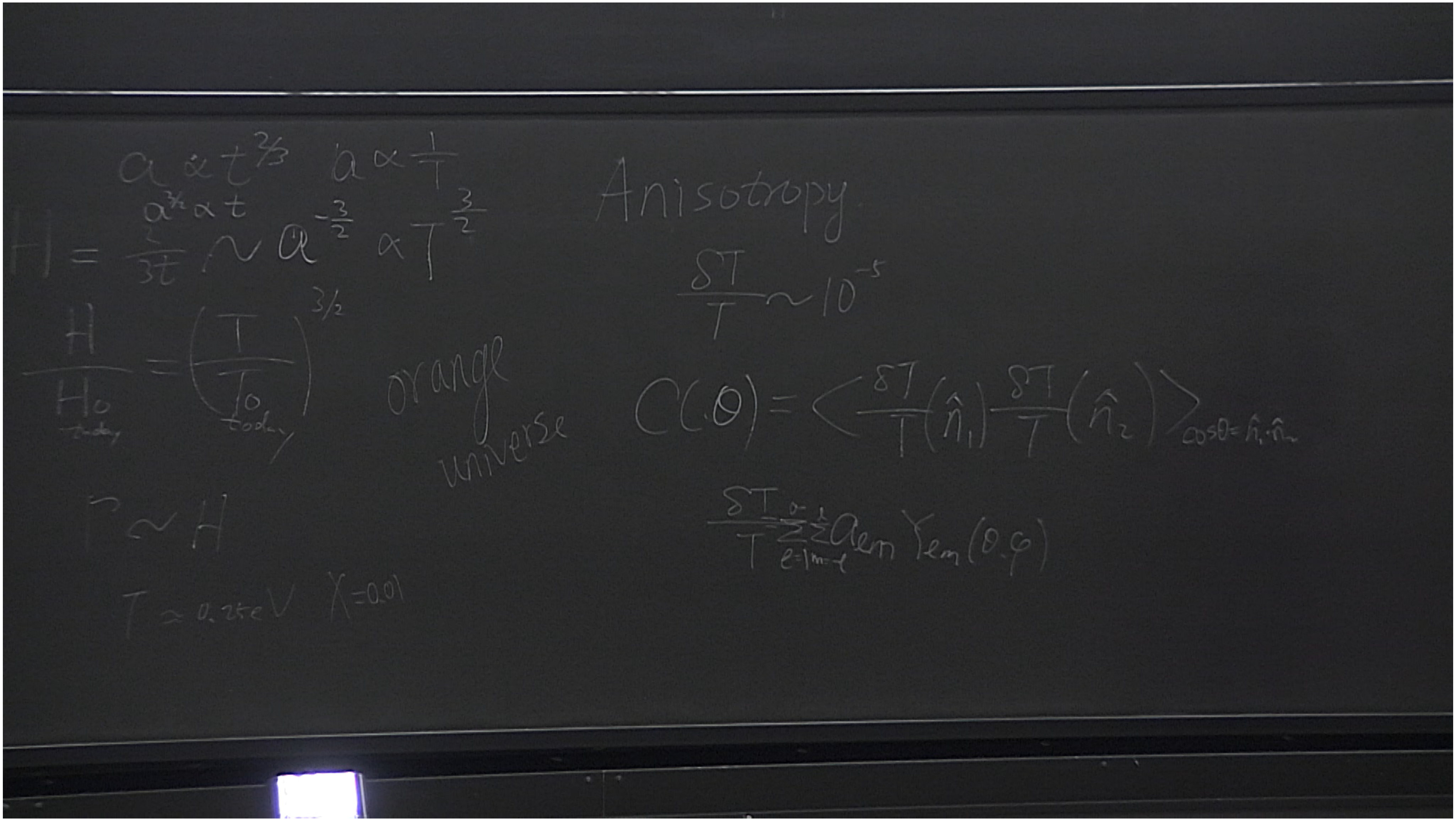
Date: Jan 17, 2019 09:00 AM

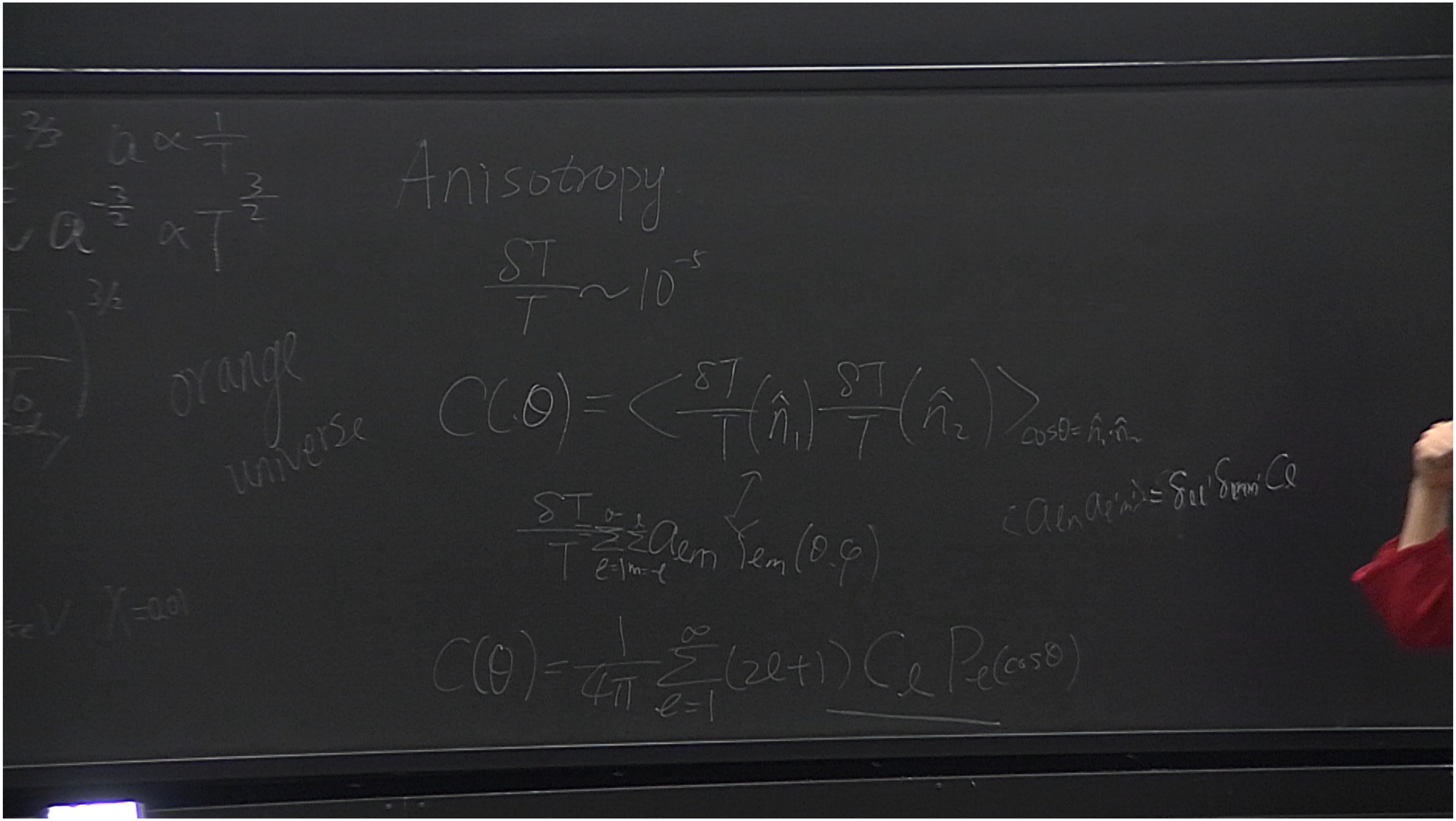
URL: http://pirsa.org/19010010

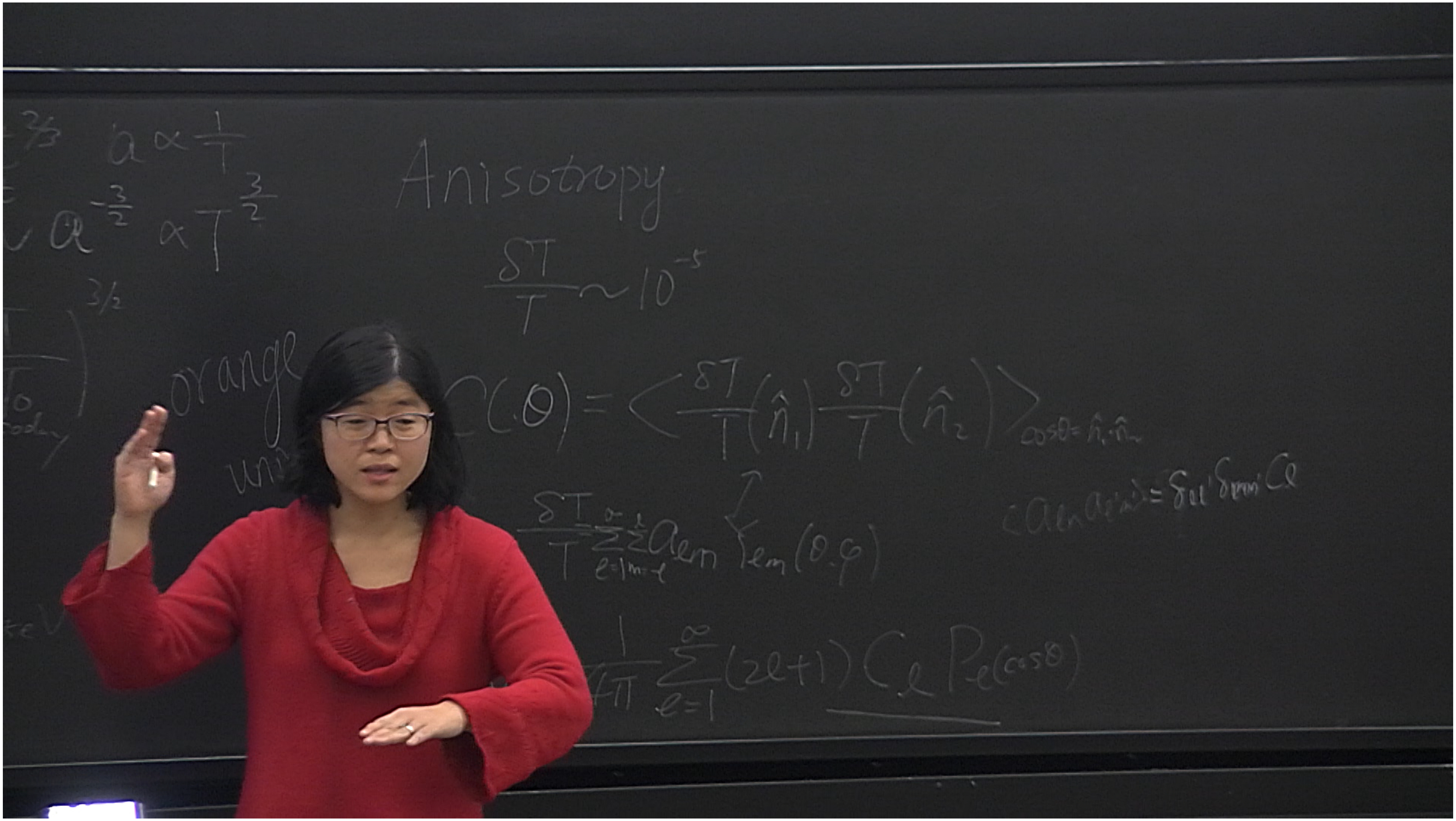
Abstract:

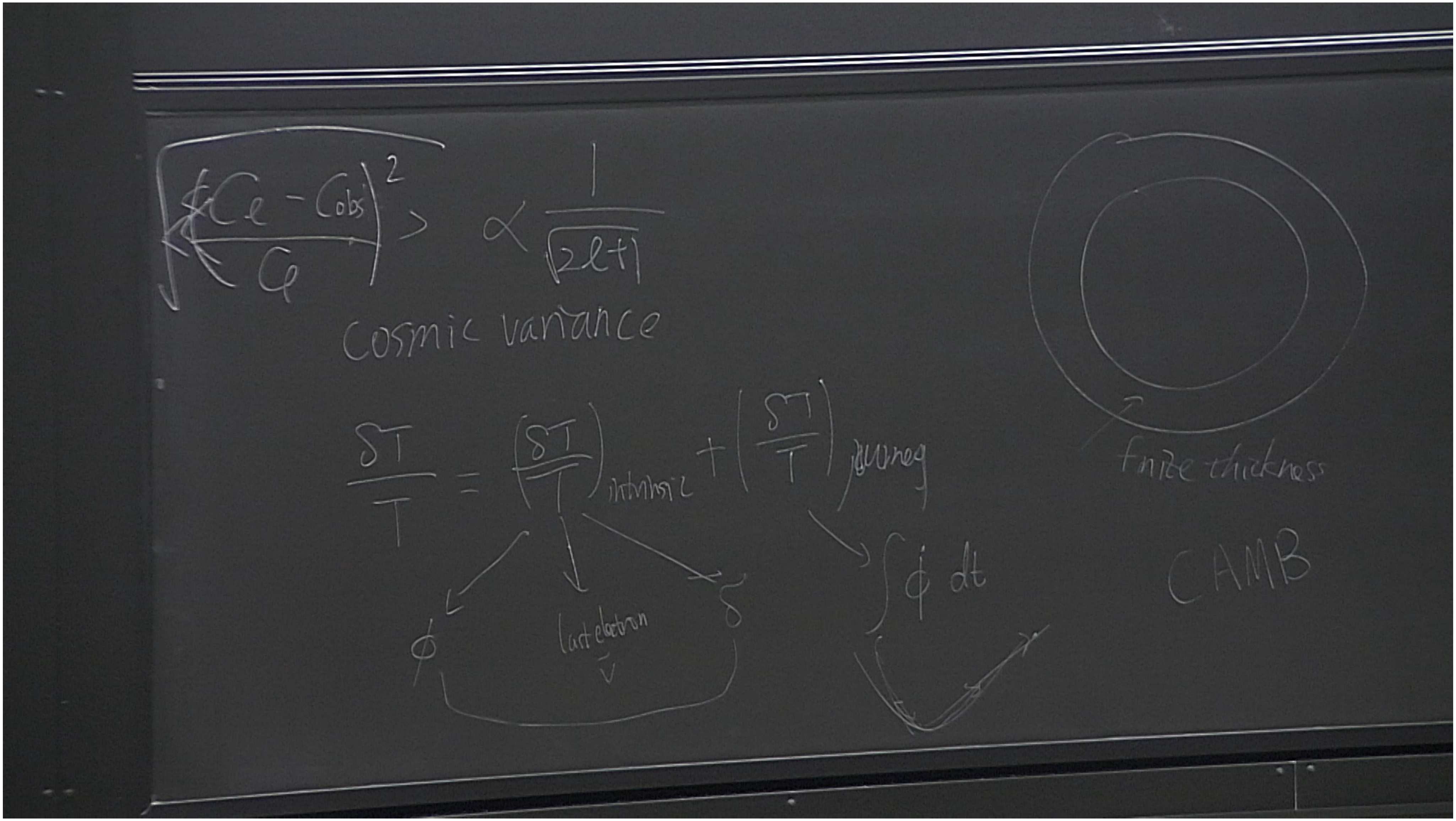

CMB
recombination
when photon
Decouple?
Γ ~ H
number

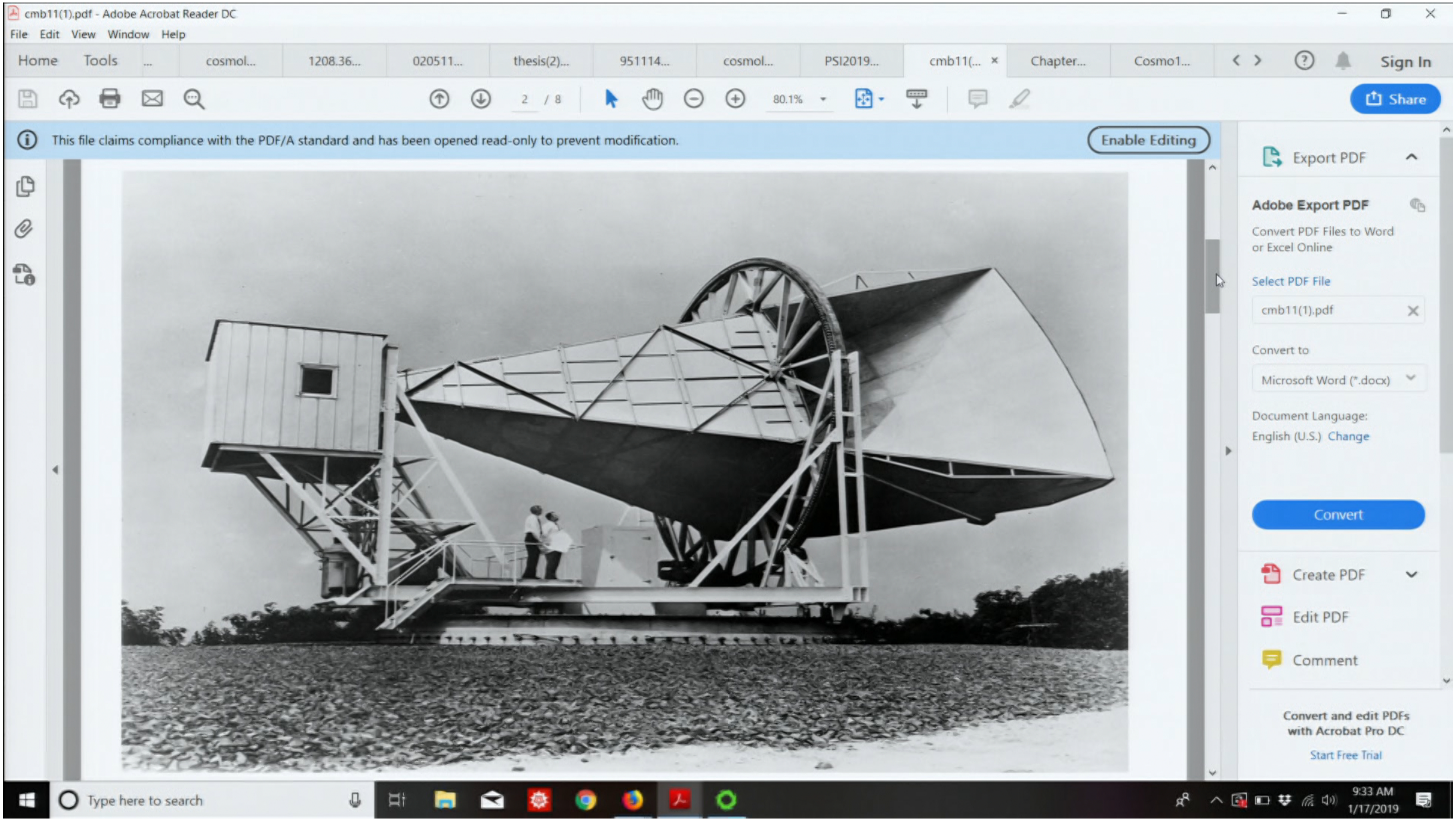

CMB
X(T)
recombination
when photon
Decouple?
Γ ~ H
Γ ~ H
today
number

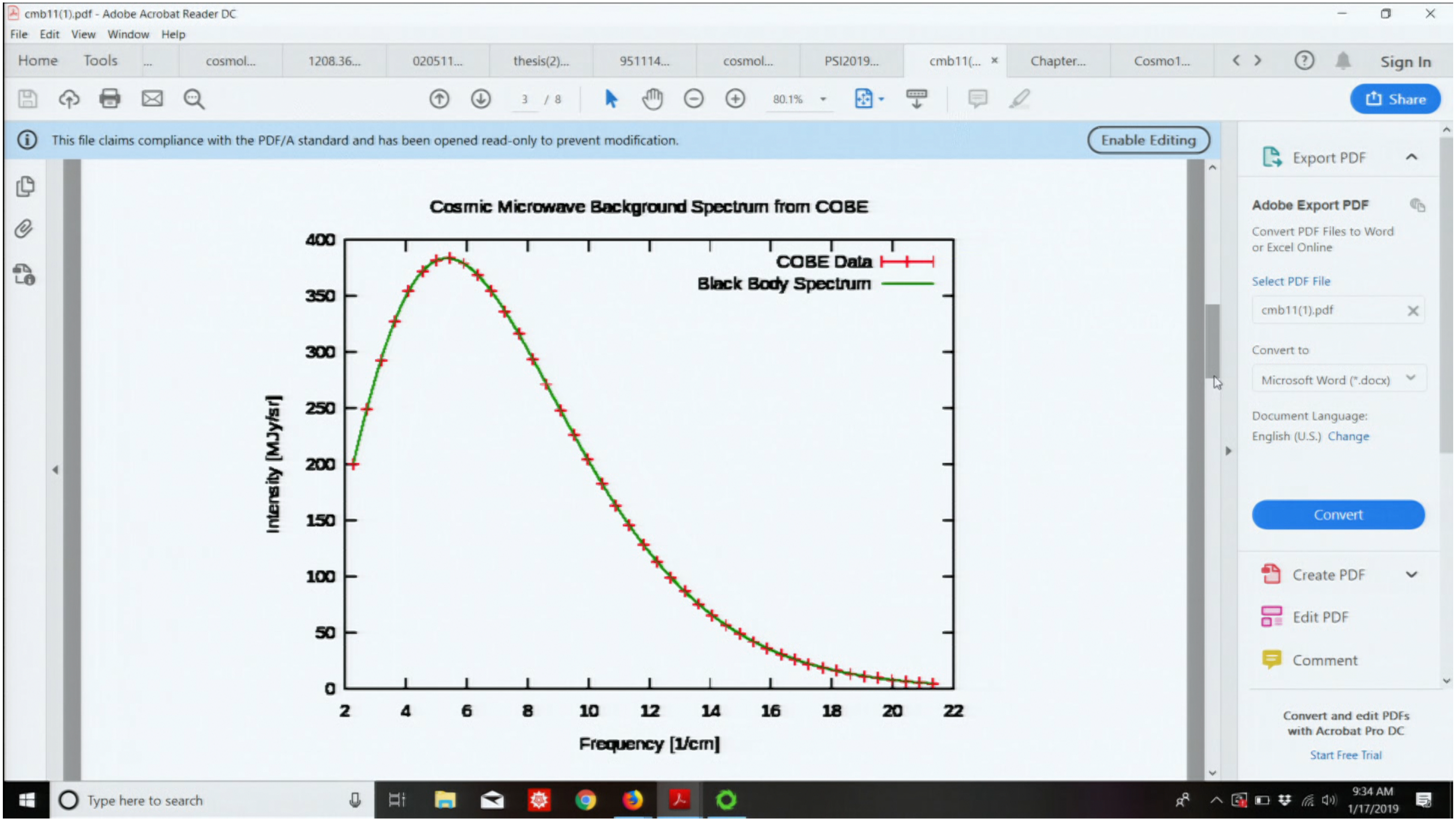

Anisotropy
orange
universe
today
today

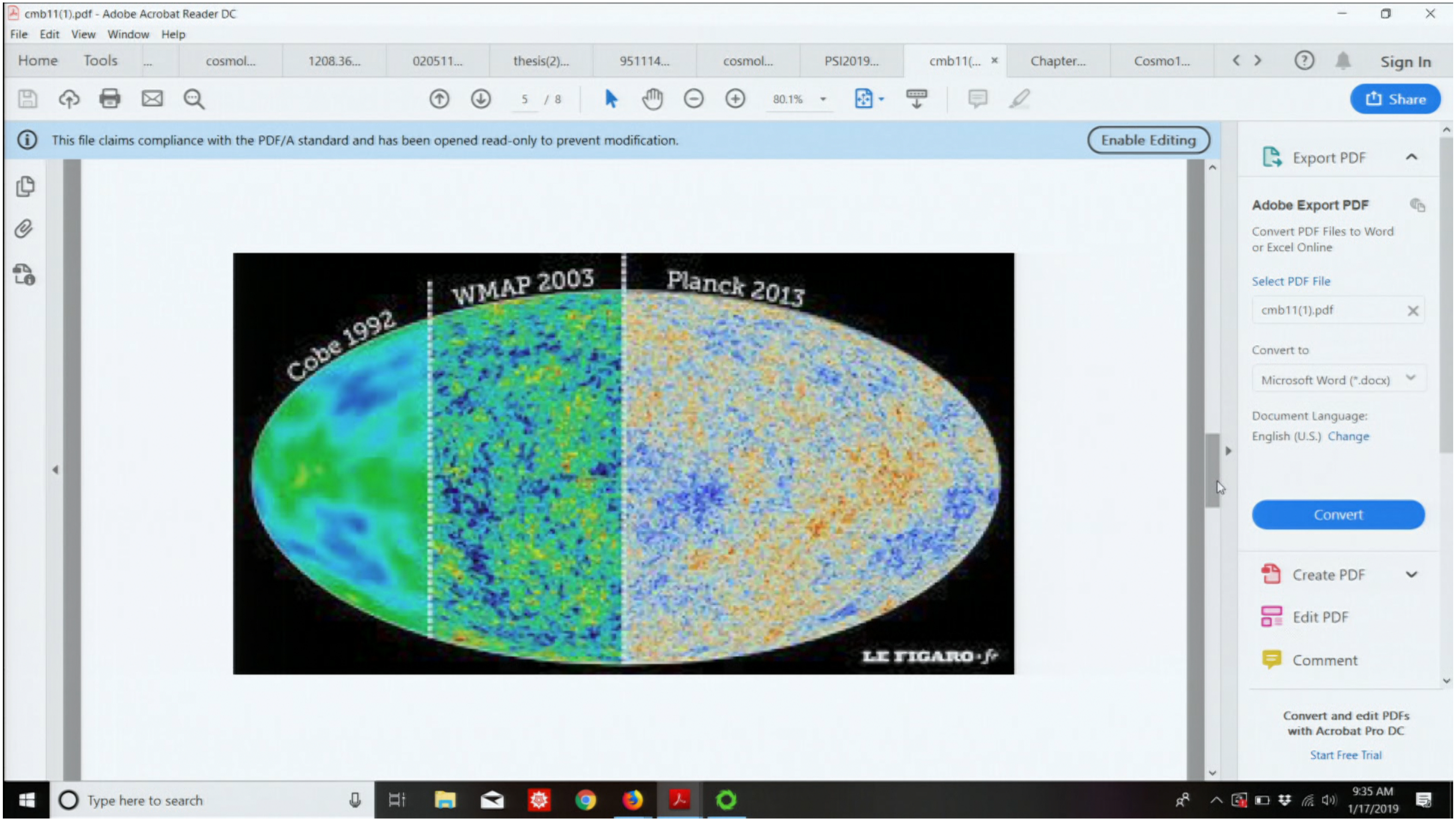

Anisotropy
$\frac{\delta T}{T} \sim 10^{-5}$
$C(\theta) = \left\langle \frac{\delta T}{T}(\hat{n}_1) \frac{\delta T}{T}(\hat{n}_2) \right\rangle_{\cos\theta = \hat{n}_1 \cdot \hat{n}_2}$
$\frac{\delta T}{T} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \varphi)$
$\langle a_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$
$C(\theta) = \frac{1}{4\pi} \sum_{\ell=1}^{\infty} (2\ell+1) C_\ell P_\ell(\cos\theta)$
orange universe
$a \propto \frac{1}{T}$
$a^{-\frac{3}{2}} \propto T^{\frac{3}{2}}$

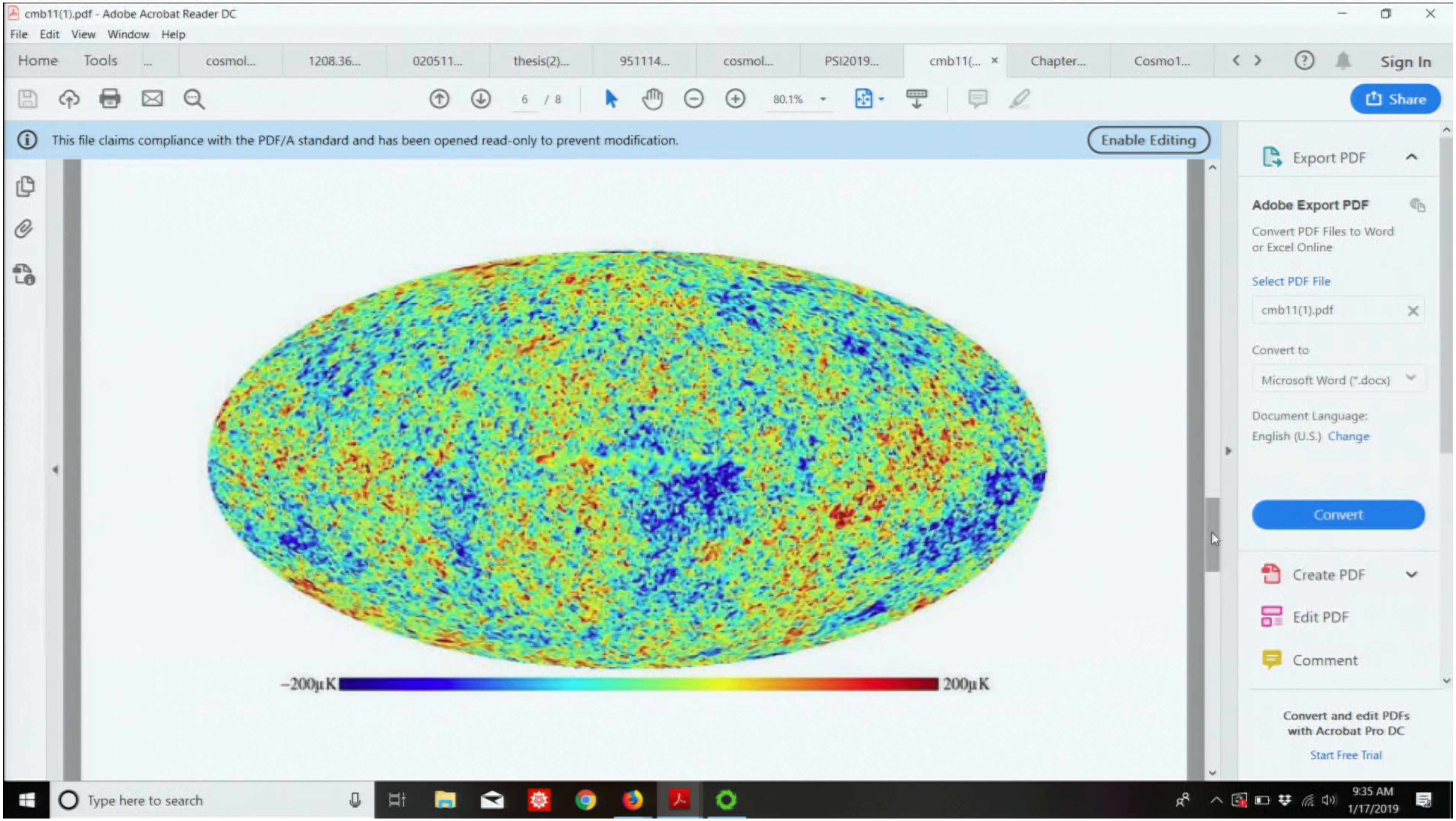

Anisotropy
$\frac{\delta T}{T} \sim 10^{-5}$
$C(\theta) = \left\langle \frac{\delta T}{T}(\hat{n}_1) \frac{\delta T}{T}(\hat{n}_2) \right\rangle_{\cos\theta = \hat{n}_1 \cdot \hat{n}_2}$
$\frac{\delta T}{T} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \varphi)$
$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$
$\sum_{\ell=1}^{\infty} (2\ell+1) C_\ell P_\ell(\cos\theta)$
orange

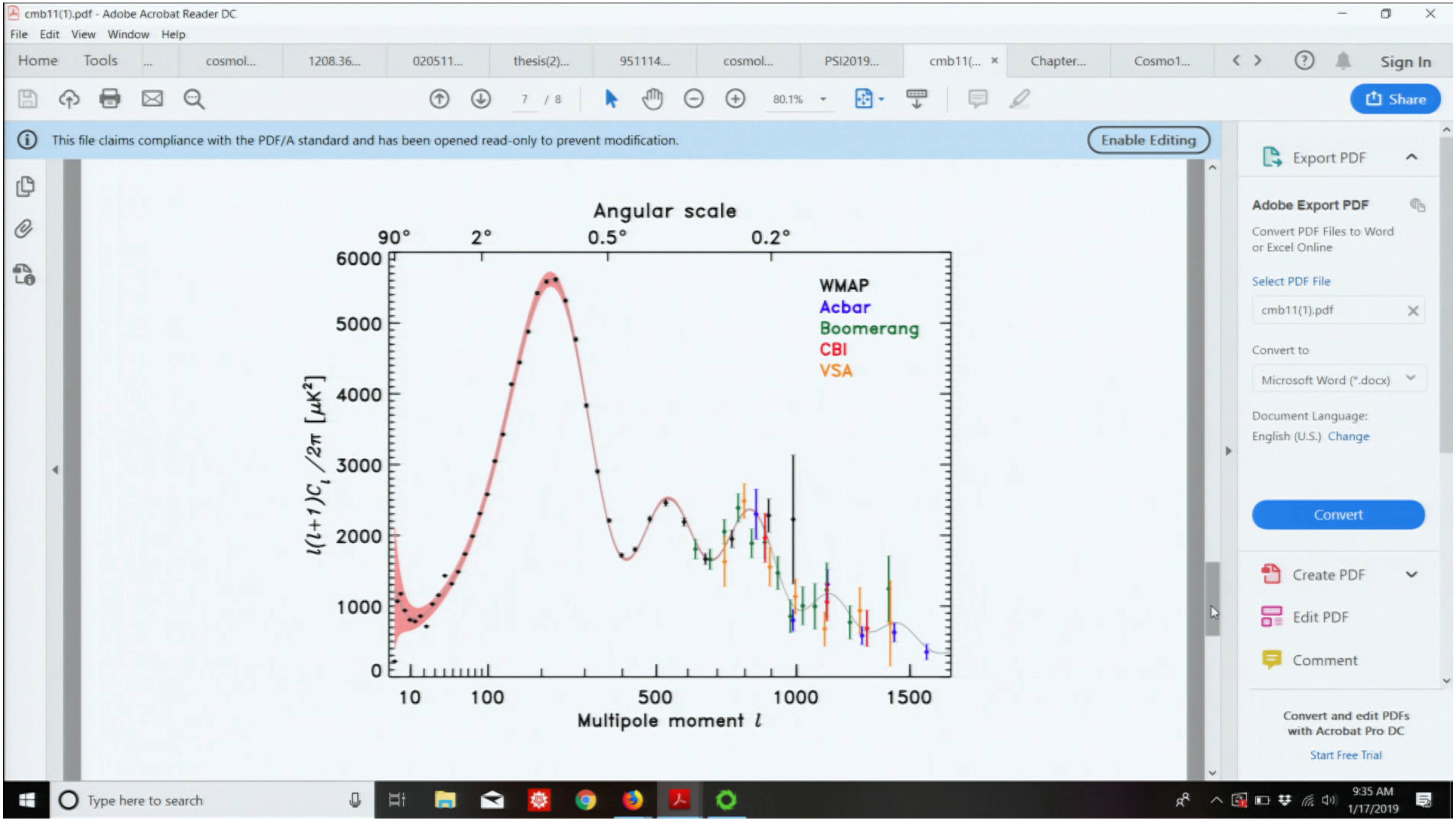

cosmic variance
intrinsic
finite thickness
CAMB

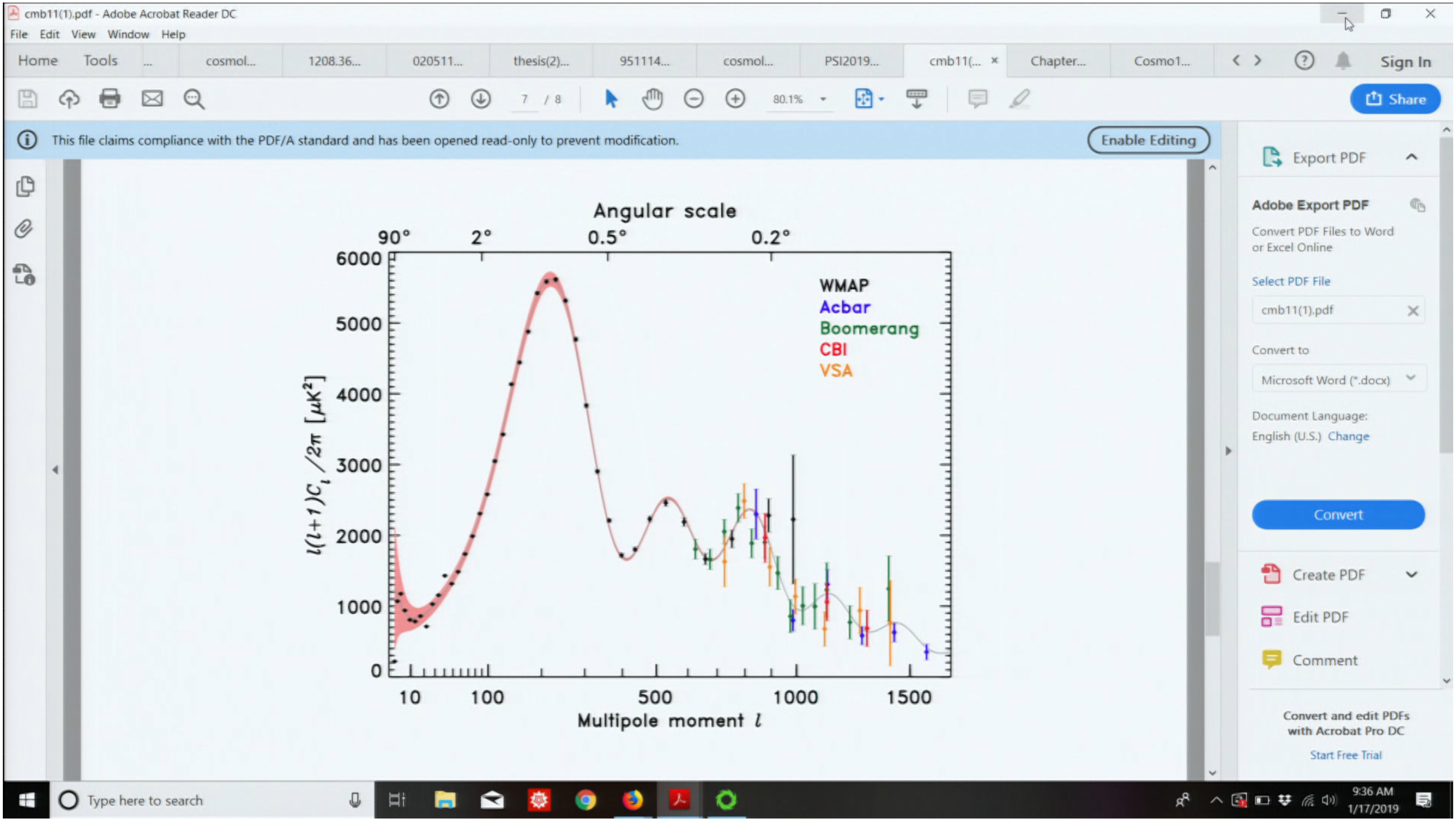

cmb11(1).pdf - Adobe Acrobat Reader DC
File Edit View Window Help
Home Tools ... cosmol... 1208.36... 020511... thesis(2)... 951114... cosmol... PSI2019... cmb11(... Chapter... Cosmo1...
Sign In
2 / 8
80.1%
Share
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Select PDF File
cmb11(1).pdf
Convert to
Microsoft Word (*.docx)
Document Language:
English (U.S.) Change
Convert
Create PDF
Edit PDF
Comment
Convert and edit PDFs with Acrobat Pro DC
Start Free Trial
Type here to search
9:33 AM
1/17/2019

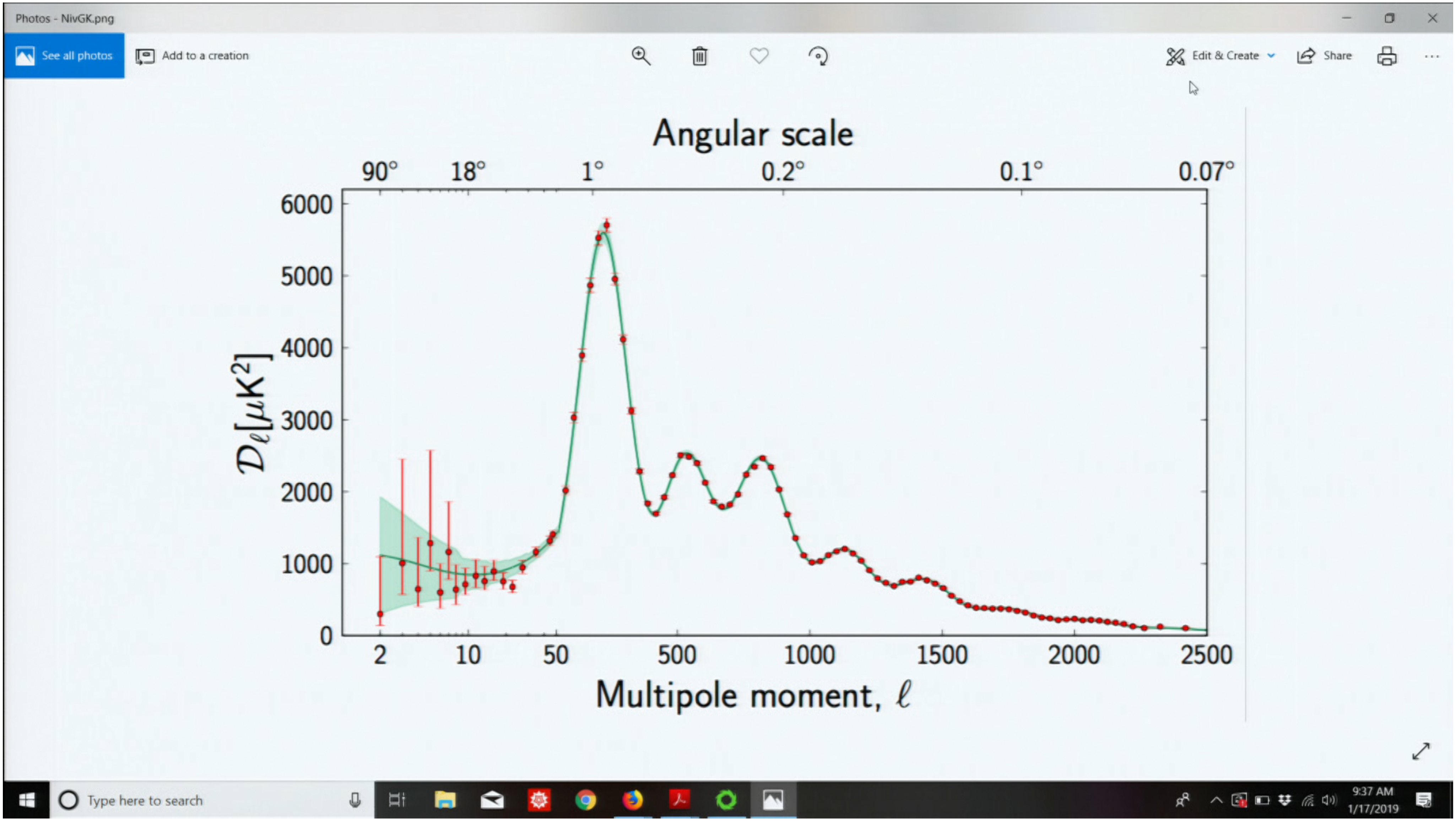

cmb11(1).pdf - Adobe Acrobat Reader DC
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
Intensity [MJy/sr]
Frequency [1/cm]
0
50
100
150
200
250
300
350
400
2
4
6
8
10
12
14
16
18
20
22
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Convert
Create PDF
Edit PDF
Comment

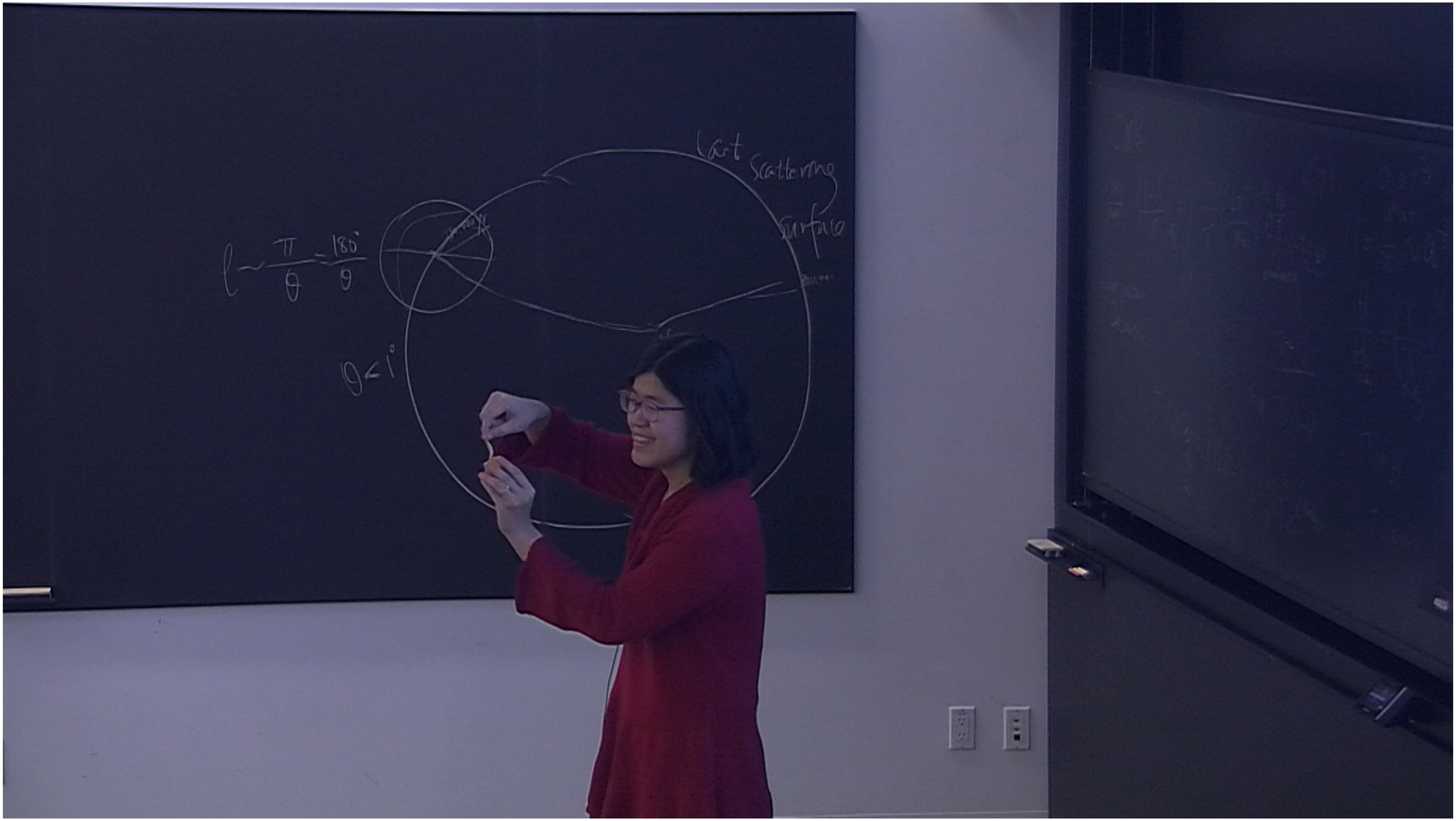

cmb11(1).pdf - Adobe Acrobat Reader DC
File Edit View Window Help
Home Tools
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Select PDF File
cmb11(1).pdf
Convert to
Microsoft Word (*.docx)
Document Language:
English (U.S.) Change
Convert
Create PDF
Edit PDF
Comment
Convert and edit PDFs with Acrobat Pro DC
Start Free Trial
Type here to search
9:35 AM
1/17/2019

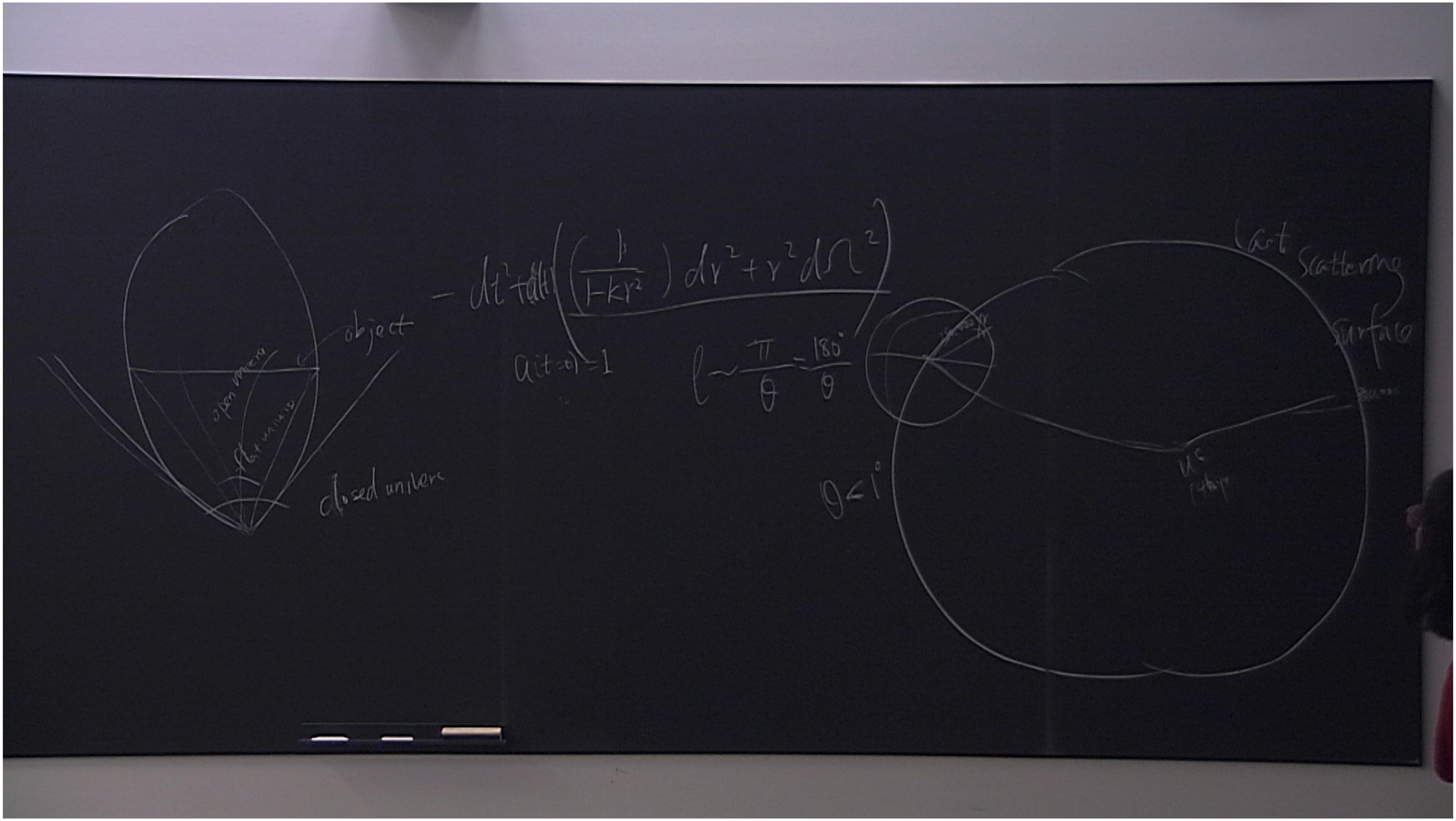

cmb11(1).pdf - Adobe Acrobat Reader DC
File Edit View Window Help
Home Tools cosmol... 1208.36... 020511... thesis(2)... 951114... cosmol... PSI2019... cmb11(... Chapter... Cosmo1...
Sign In
6 / 8
80.1%
Share
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
−200μK
200μK
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Select PDF File
cmb11(1).pdf
Convert to
Microsoft Word (*.docx)
Document Language:
English (U.S.) Change
Convert
Create PDF
Edit PDF
Comment
Convert and edit PDFs with Acrobat Pro DC
Start Free Trial
Type here to search
9:35 AM
1/17/2019

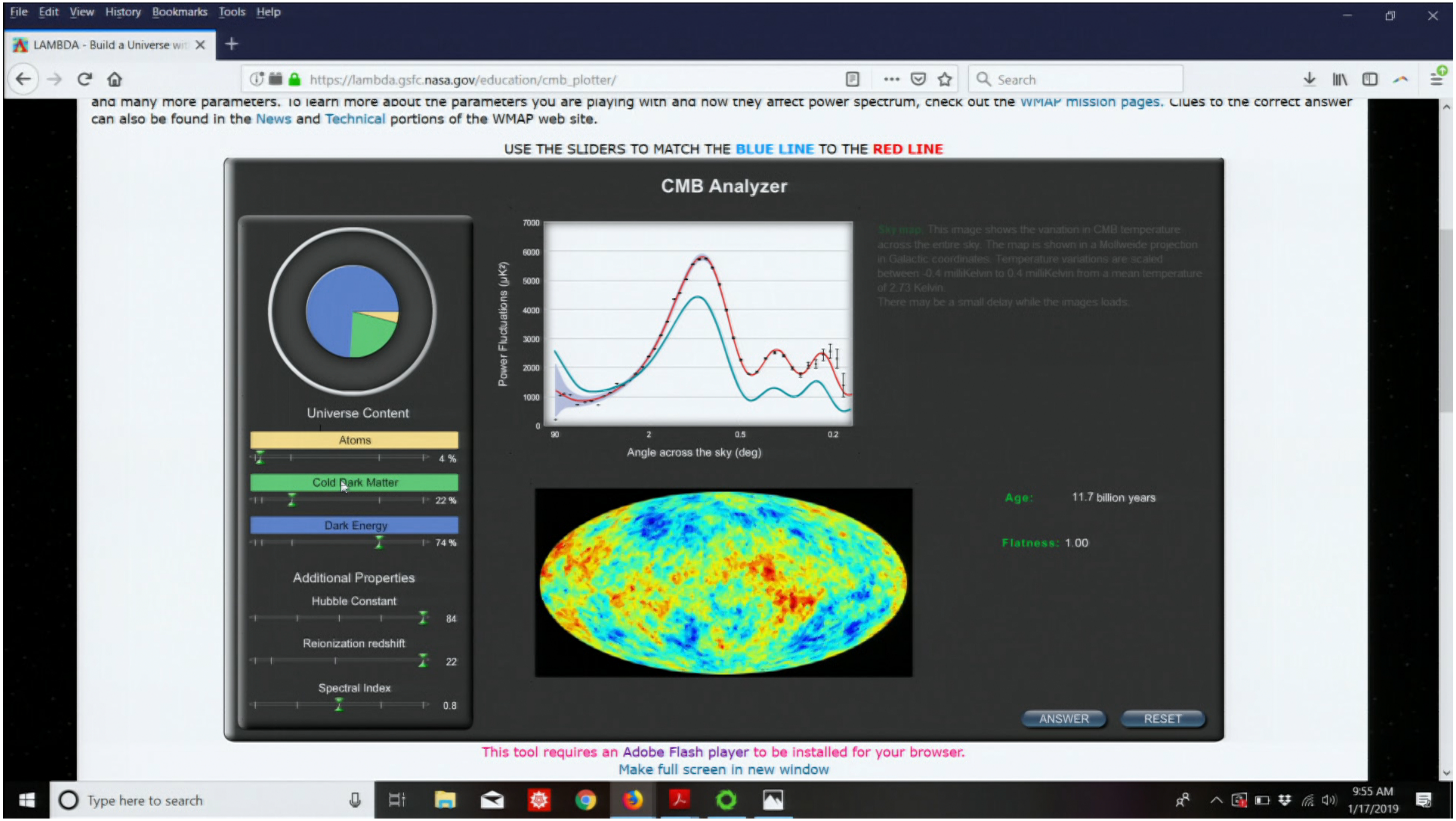

cmb11(1).pdf - Adobe Acrobat Reader DC
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
Angular scale
90°
2°
0.5°
0.2°
WMAP
Acbar
Boomerang
CBI
VSA
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l
l(l+1)C_l /2π [μK²]
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Convert
Create PDF
Edit PDF
Comment

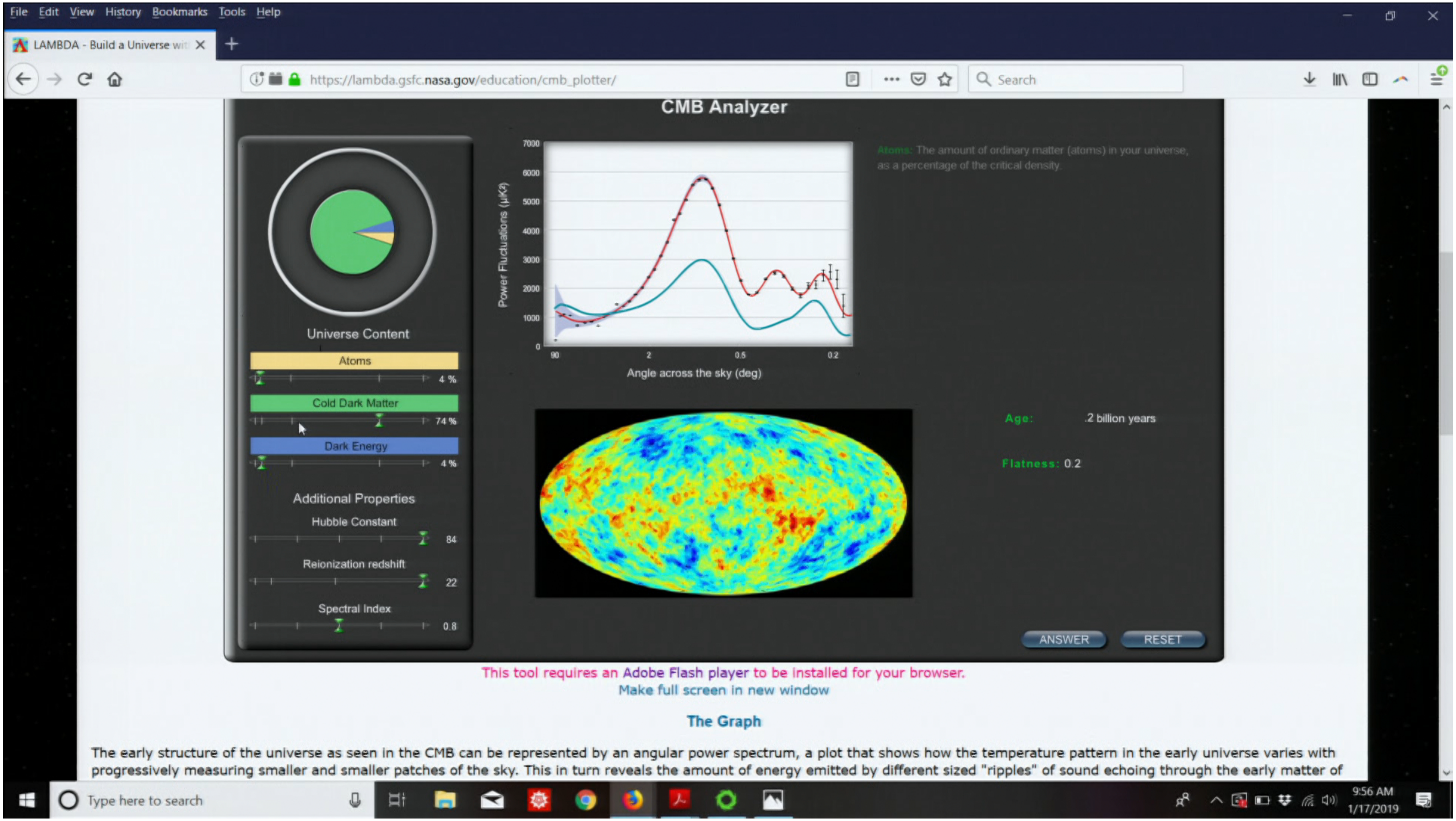

cmb11(1).pdf - Adobe Acrobat Reader DC
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
Angular scale
90°
2°
0.5°
0.2°
WMAP
Acbar
Boomerang
CBI
VSA
$l(l+1)C_l/2\pi\ [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Convert
Create PDF
Edit PDF
Comment
Convert and edit PDFs with Acrobat Pro DC
Start Free Trial

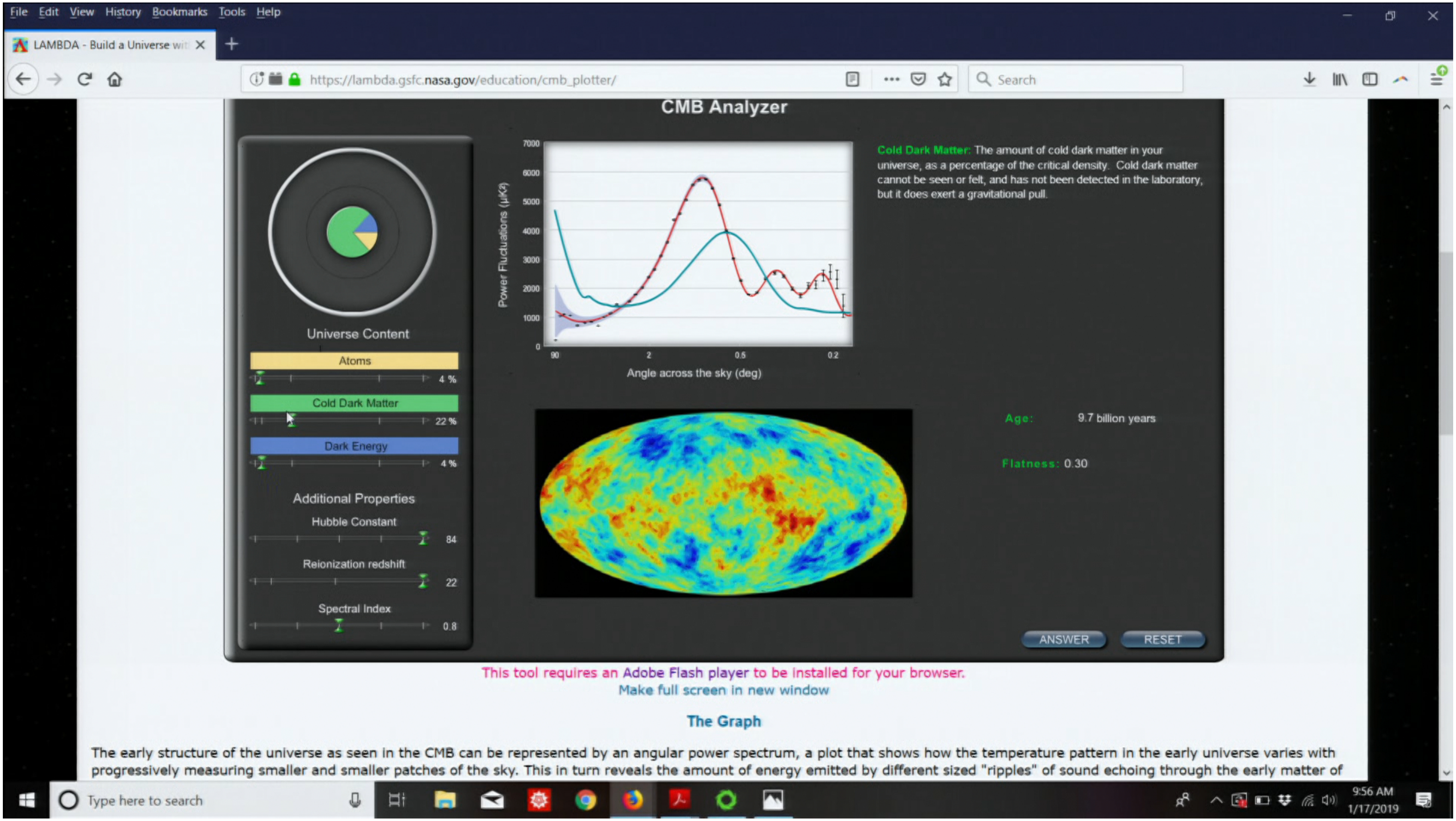

Photos - NivGK.png
See all photos
Add to a creation
Edit & Create
Share
Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell[\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ
Type here to search
9:37 AM
1/17/2019

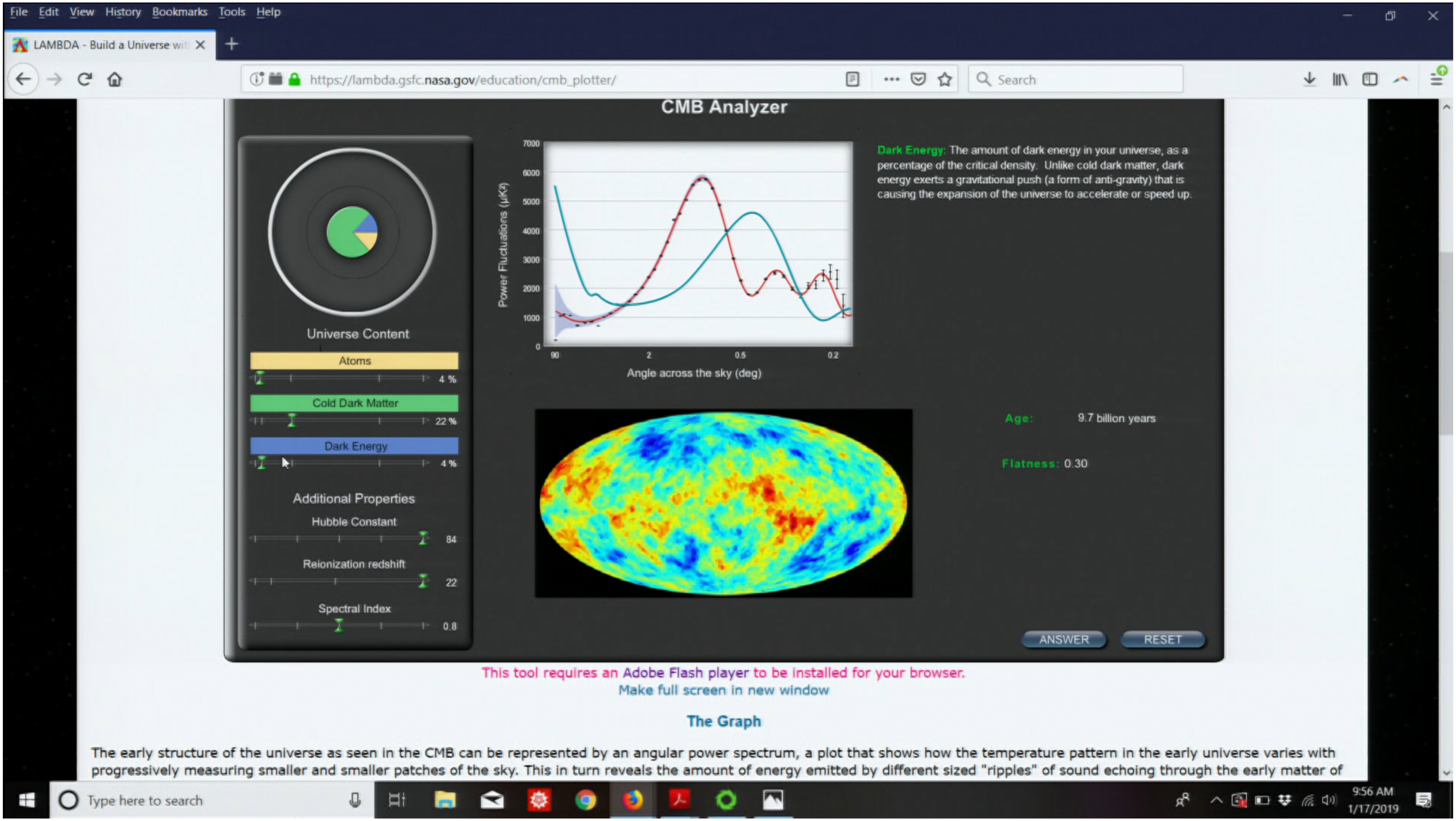

$l \sim \frac{\pi}{\theta} = \frac{180^\circ}{\theta}$
$\theta < 1^\circ$
Last scattering surface


object
closed universe
open universe
$-dt^2 + a(t)^2\left(\left(\frac{1}{1-kr^2}\right)dr^2 + r^2 d\Omega^2\right)$
$a(t=0)=1$
$l \sim \frac{\pi}{\theta} = \frac{180^\circ}{\theta}$
$\theta < 1^\circ$
last scattering surface

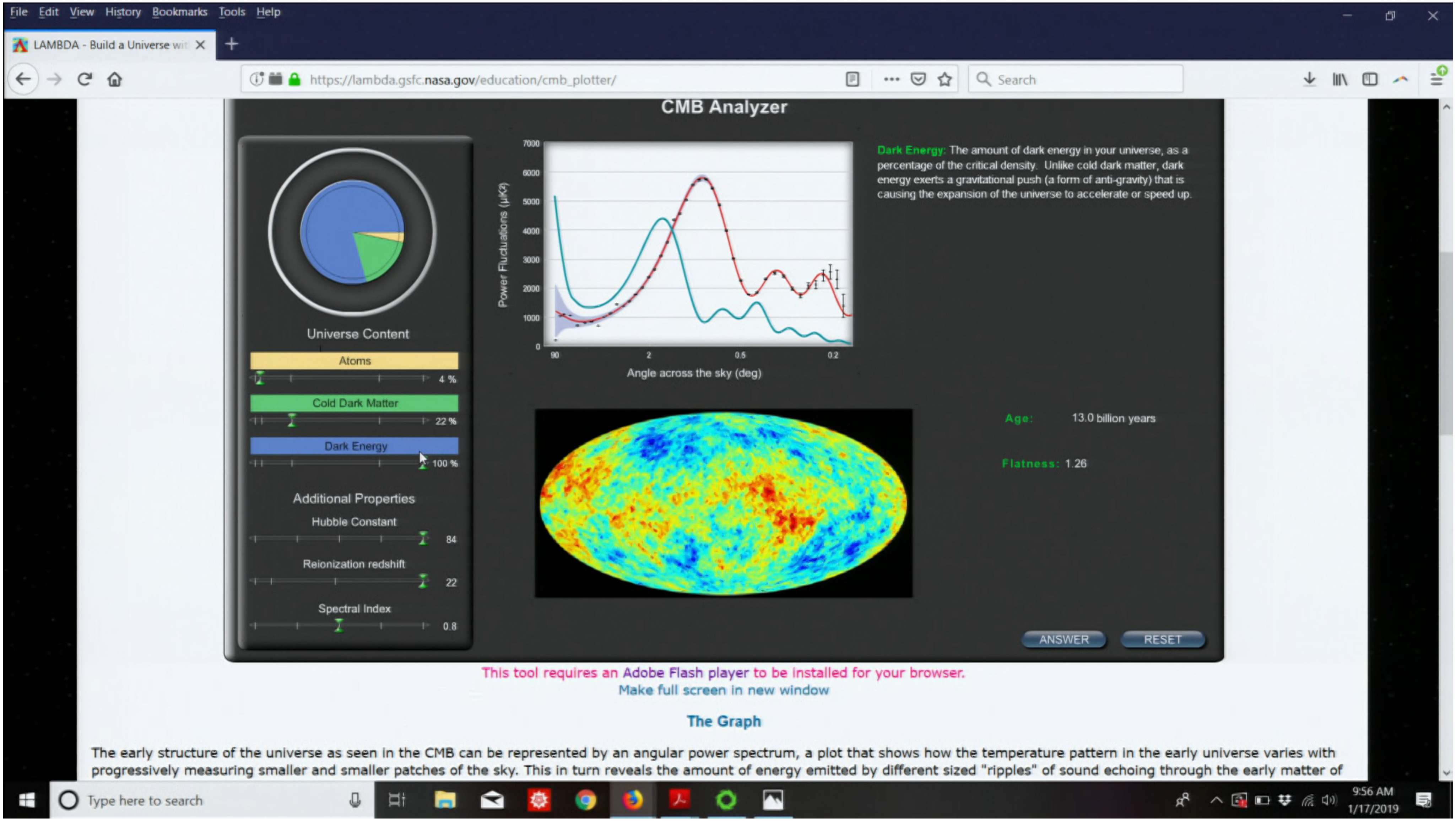

File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
and many more parameters. To learn more about the parameters you are playing with and how they affect power spectrum, check out the WMAP mission pages. Clues to the correct answer can also be found in the News and Technical portions of the WMAP web site.
USE THE SLIDERS TO MATCH THE BLUE LINE TO THE RED LINE
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
74 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
7000
6000
5000
4000
3000
2000
1000
0
90
2
0.5
0.2
Angle across the sky (deg)
Age: 11.7 billion years
Flatness: 1.00
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
Type here to search
9:55 AM
1/17/2019

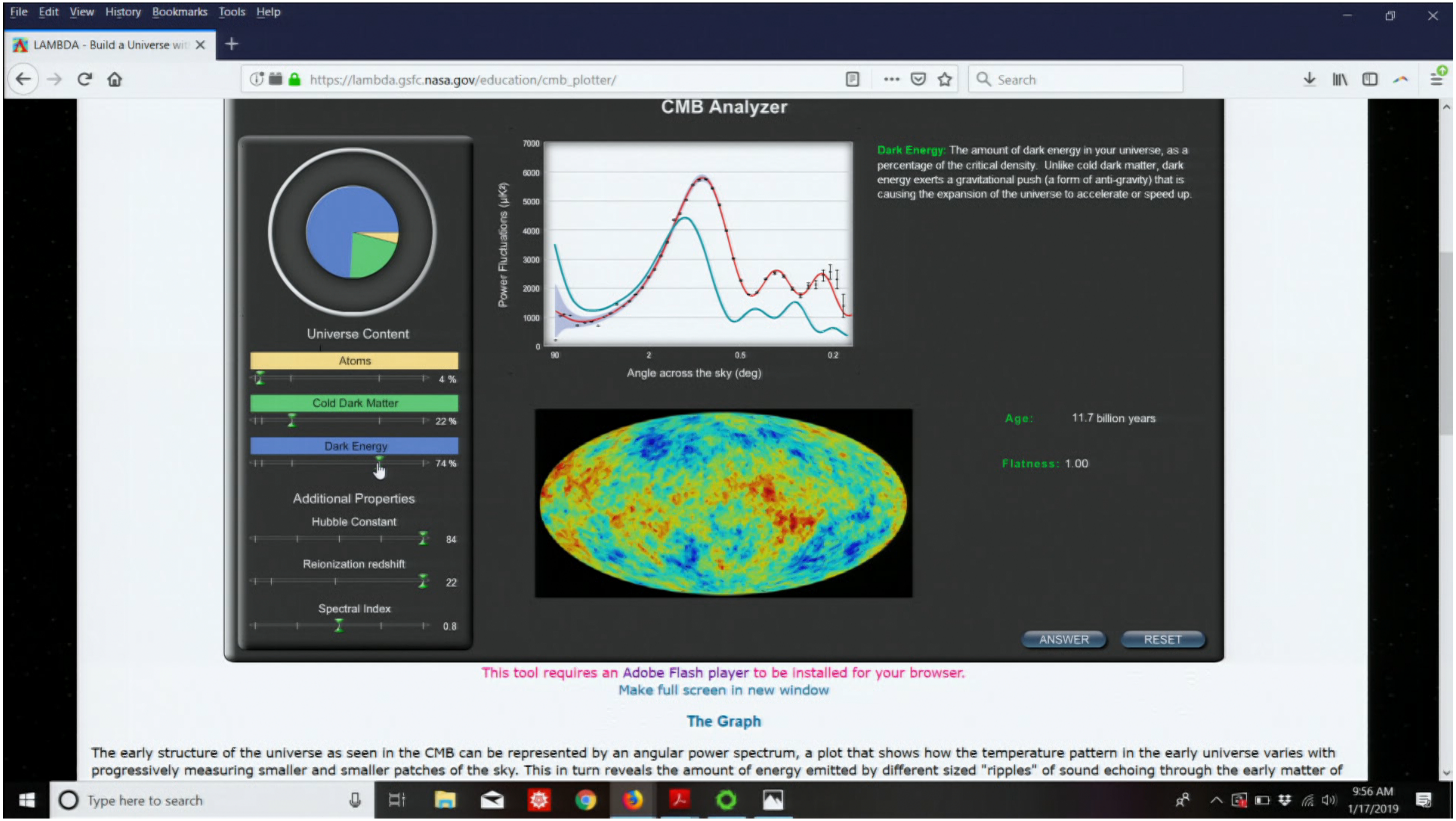

File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
74 %
Dark Energy
4 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
Angle across the sky (deg)
Atoms: The amount of ordinary matter (atoms) in your universe, as a percentage of the critical density.
Age: 2 billion years
Flatness: 0.2
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019

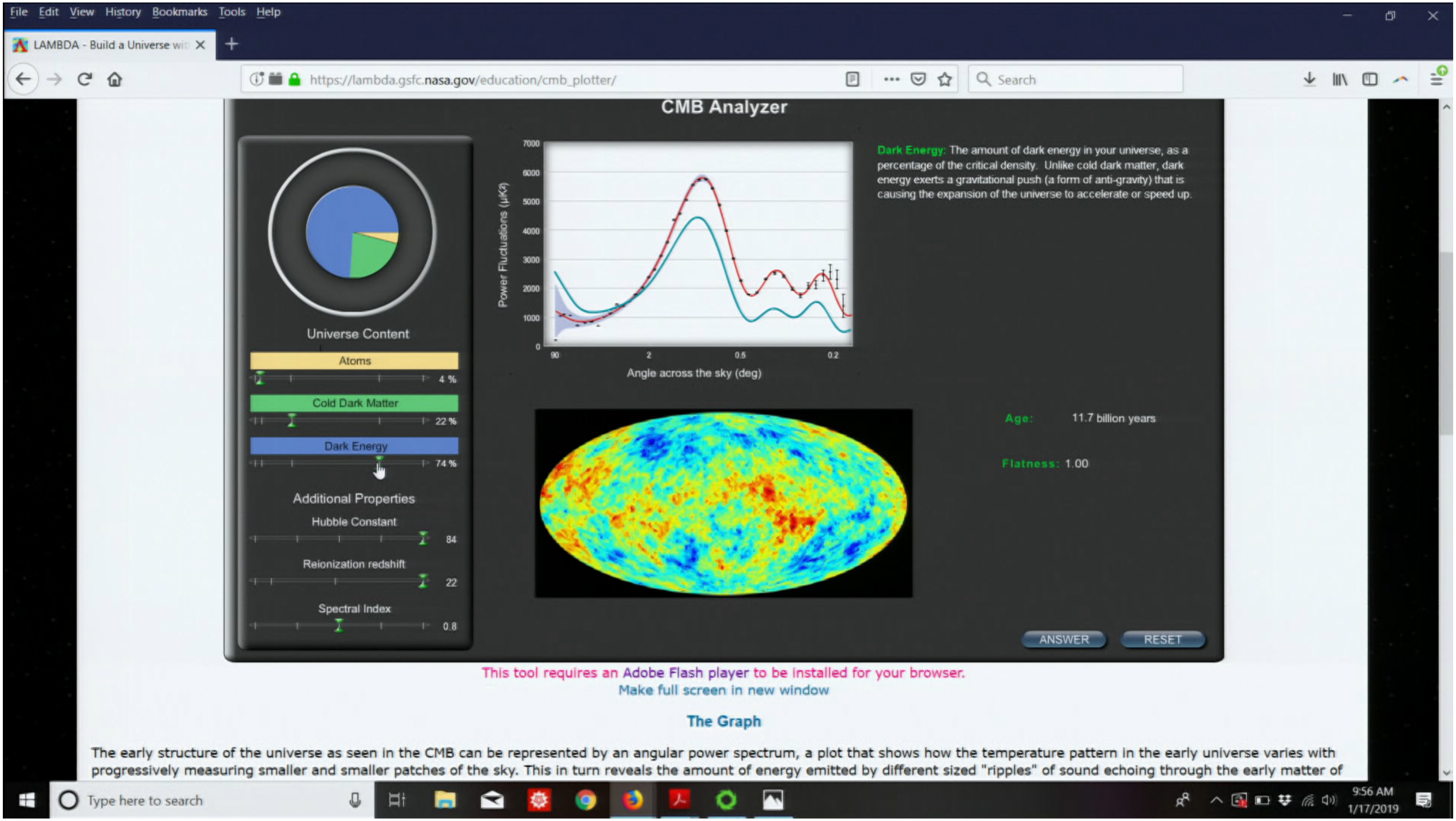

File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
4 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
Angle across the sky (deg)
Cold Dark Matter: The amount of cold dark matter in your universe, as a percentage of the critical density. Cold dark matter cannot be seen or felt, and has not been detected in the laboratory, but it does exert a gravitational pull.
Age: 9.7 billion years
Flatness: 0.30
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019

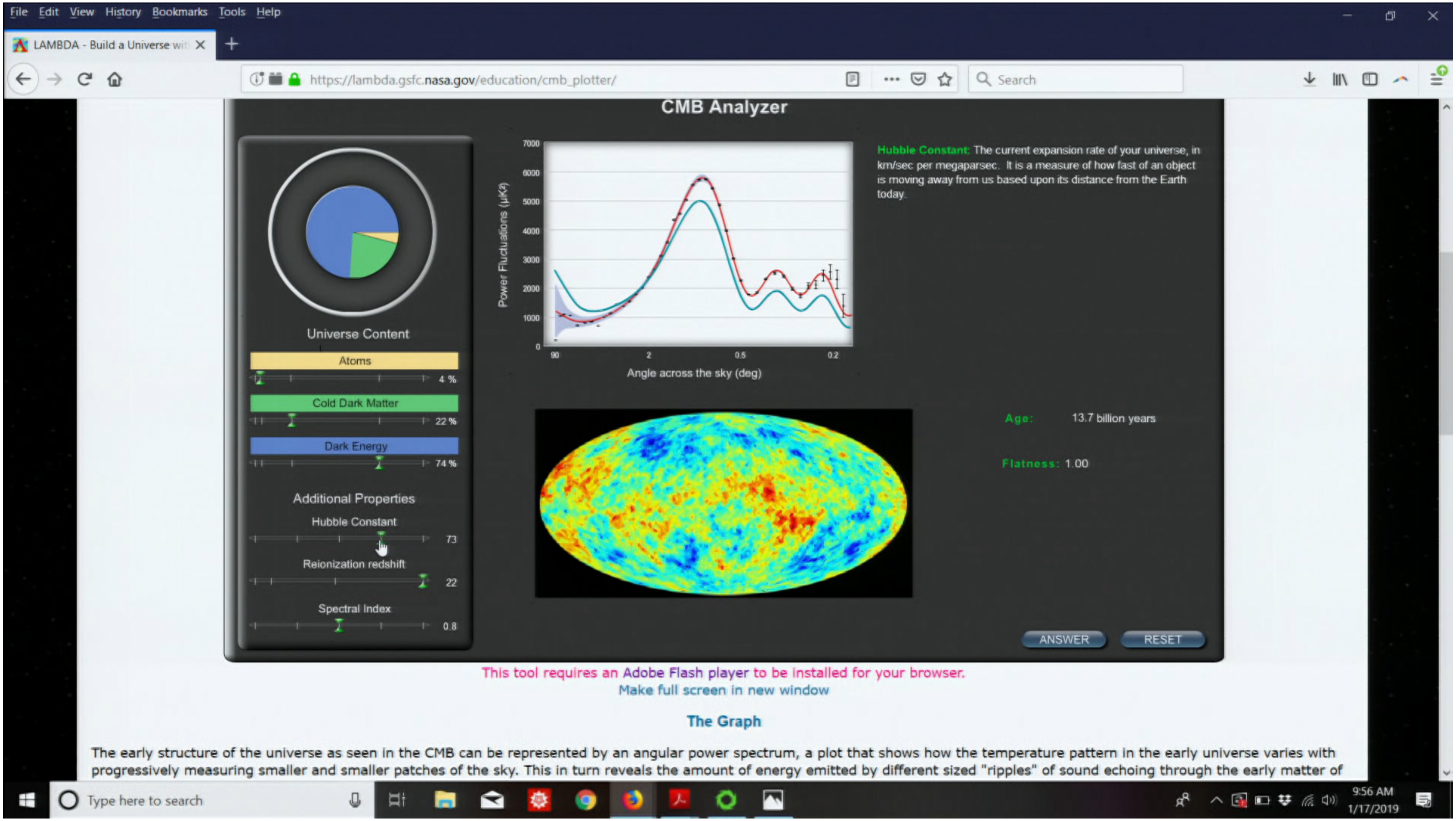


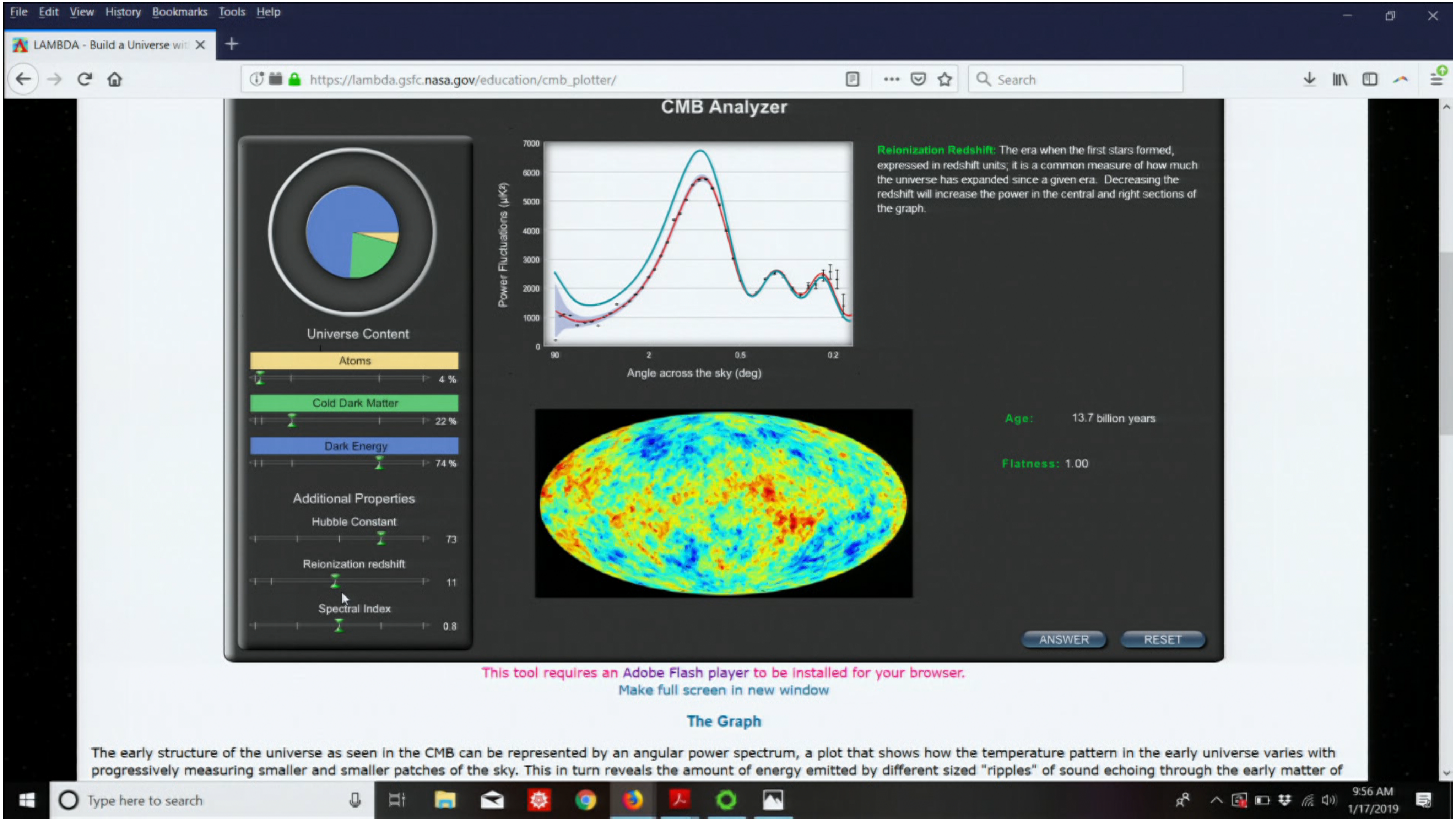
File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wit
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
4 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
Angle across the sky (deg)
Dark Energy: The amount of dark energy in your universe, as a percentage of the critical density. Unlike cold dark matter, dark energy exerts a gravitational push (a form of anti-gravity) that is causing the expansion of the universe to accelerate or speed up.
Age: 9.7 billion years
Flatness: 0.30
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019

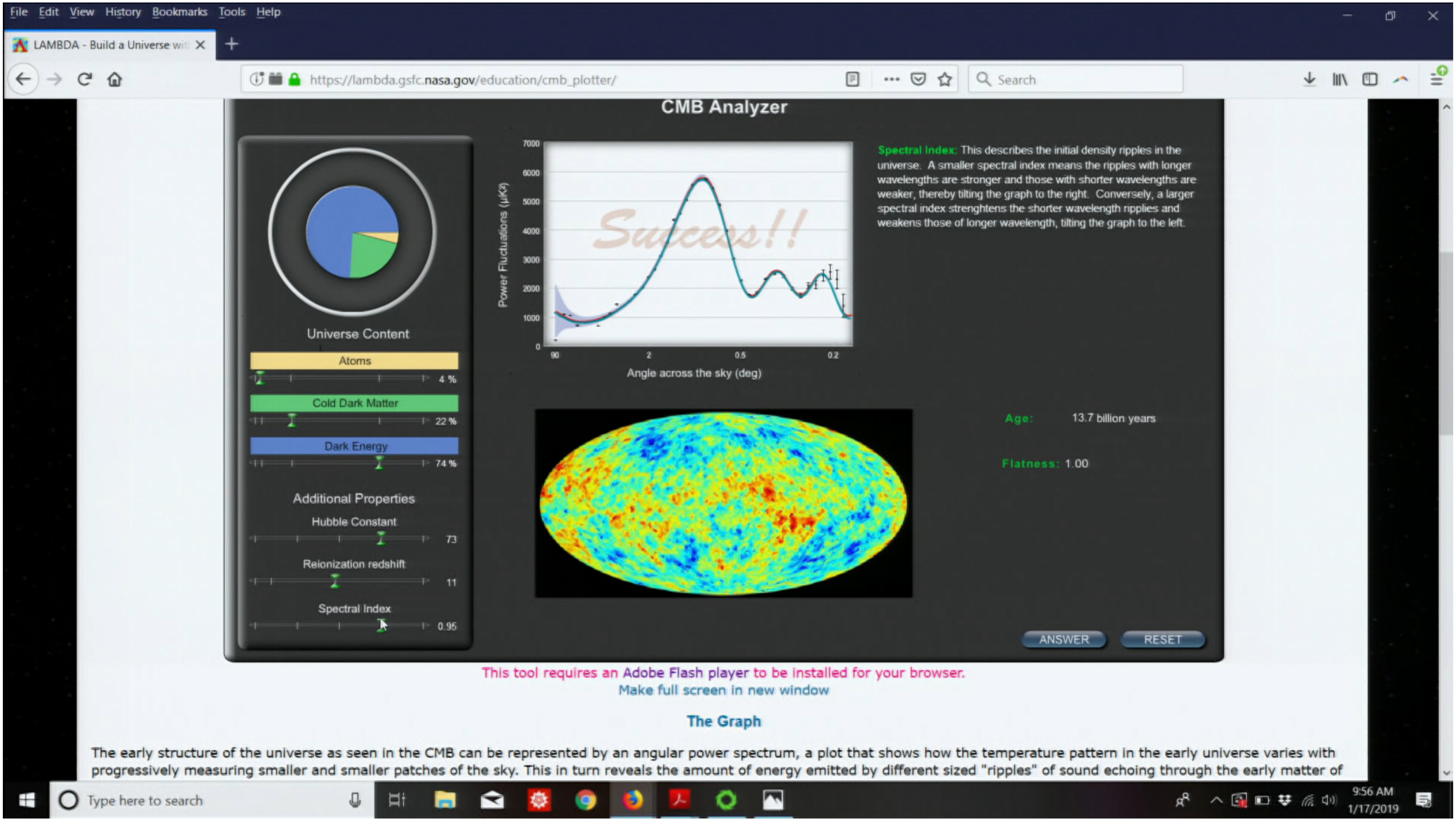

File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
100 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
7000
6000
5000
4000
3000
2000
1000
0
90
2
0.5
0.2
Angle across the sky (deg)
Dark Energy: The amount of dark energy in your universe, as a percentage of the critical density. Unlike cold dark matter, dark energy exerts a gravitational push (a form of anti-gravity) that is causing the expansion of the universe to accelerate or speed up.
Age: 13.0 billion years
Flatness: 1.26
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019

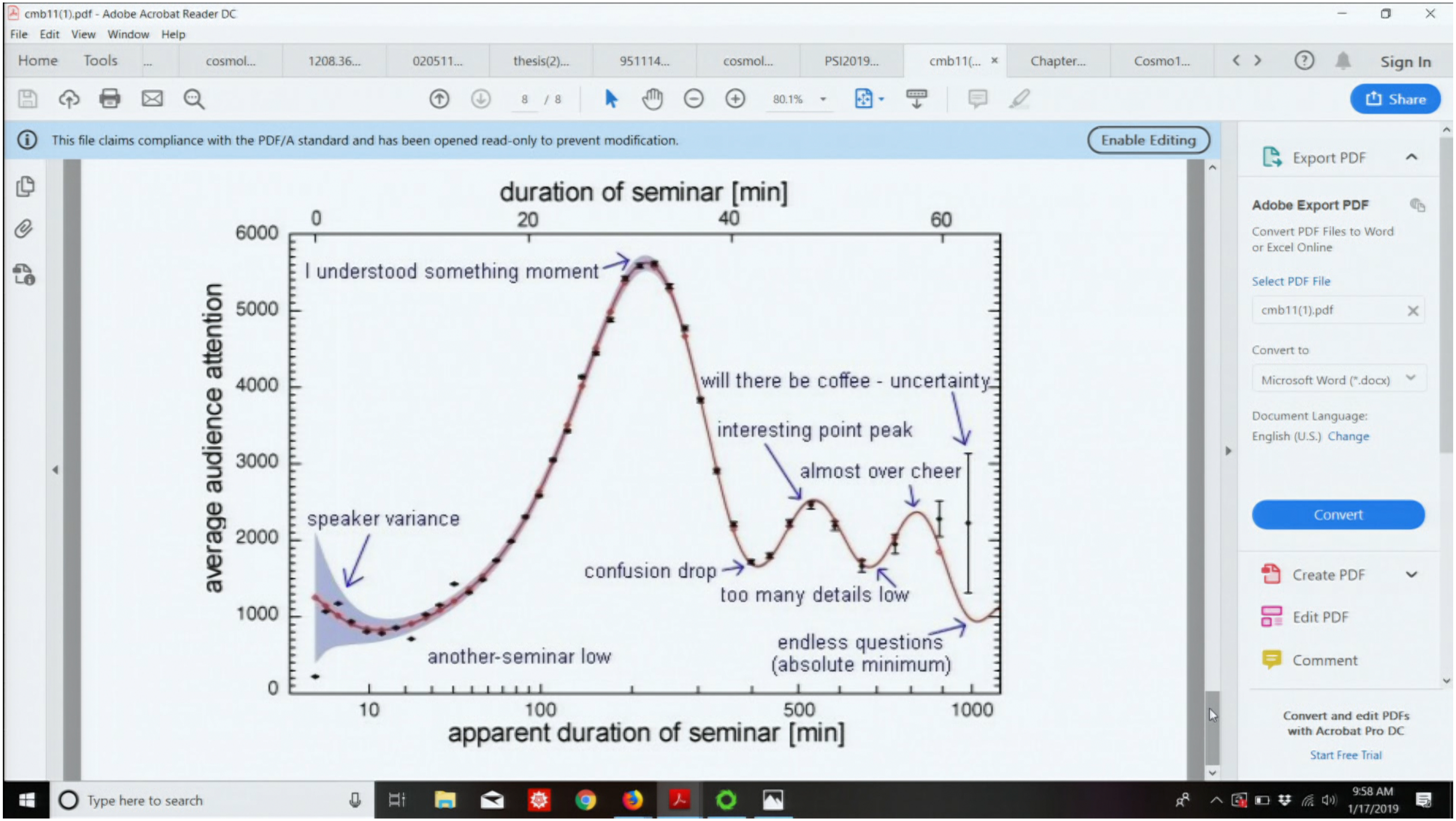

File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
74 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
7000
6000
5000
4000
3000
2000
1000
0
90
2
0.5
0.2
Angle across the sky (deg)
Dark Energy: The amount of dark energy in your universe, as a percentage of the critical density. Unlike cold dark matter, dark energy exerts a gravitational push (a form of anti-gravity) that is causing the expansion of the universe to accelerate or speed up.
Age: 11.7 billion years
Flatness: 1.00
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019

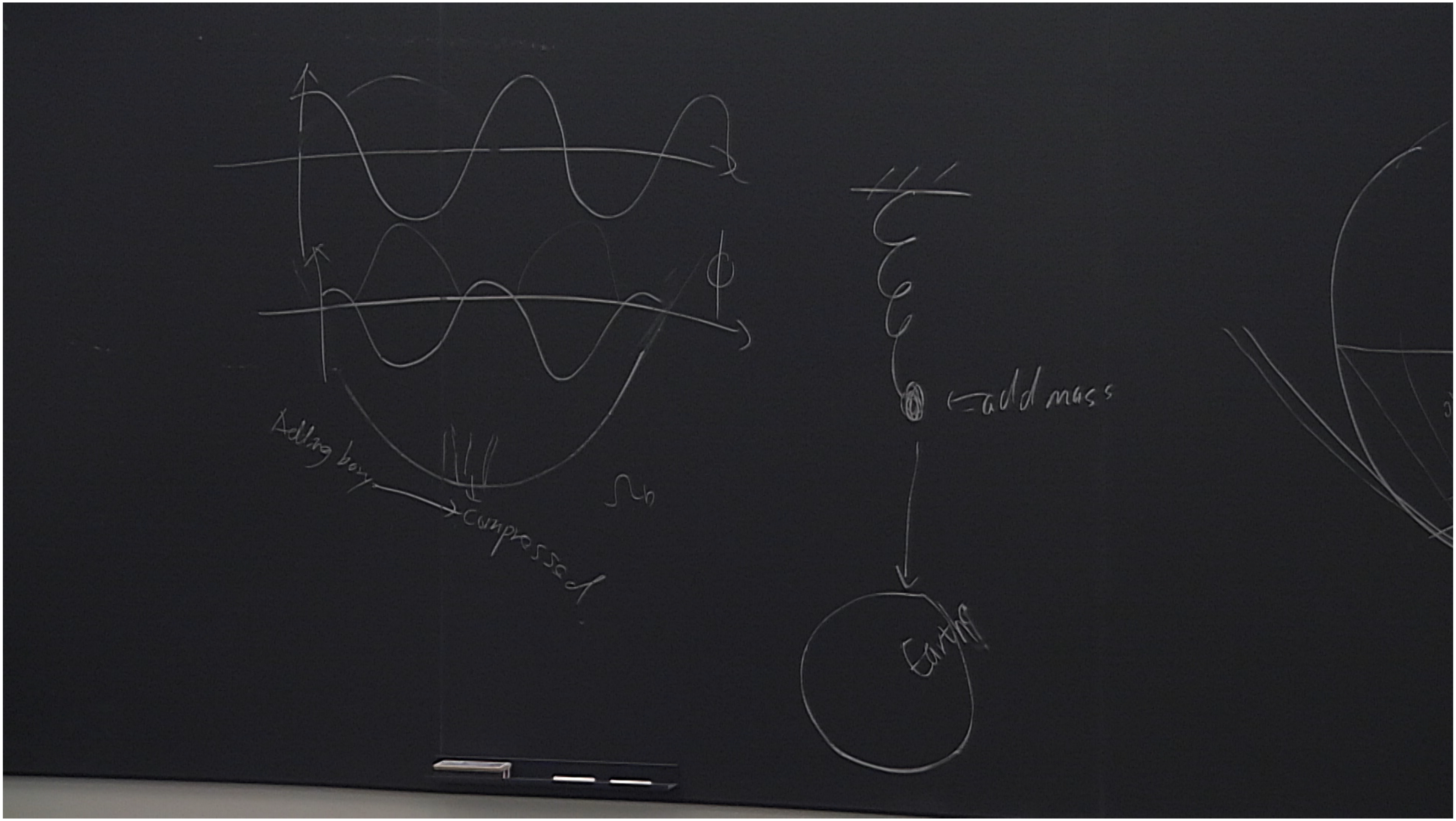

File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
74 %
Additional Properties
Hubble Constant
84
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK2)
7000
6000
5000
4000
3000
2000
1000
0
90
2
0.5
0.2
Angle across the sky (deg)
Dark Energy: The amount of dark energy in your universe, as a percentage of the critical density. Unlike cold dark matter, dark energy exerts a gravitational push (a form of anti-gravity) that is causing the expansion of the universe to accelerate or speed up.
Age: 11.7 billion years
Flatness: 1.00
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019


File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
74 %
Additional Properties
Hubble Constant
73
Reionization redshift
22
Spectral Index
0.8
Power Fluctuations (μK²)
7000
6000
5000
4000
3000
2000
1000
0
90
2
0.5
0.2
Angle across the sky (deg)
Hubble Constant: The current expansion rate of your universe, in km/sec per megaparsec. It is a measure of how fast of an object is moving away from us based upon its distance from the Earth today.
Age: 13.7 billion years
Flatness: 1.00
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019


File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
74 %
Additional Properties
Hubble Constant
73
Reionization redshift
11
Spectral Index
0.8
Power Fluctuations (μK²)
Angle across the sky (deg)
Reionization Redshift: The era when the first stars formed, expressed in redshift units; it is a common measure of how much the universe has expanded since a given era. Decreasing the redshift will increase the power in the central and right sections of the graph.
Age: 13.7 billion years
Flatness: 1.00
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019


File Edit View History Bookmarks Tools Help
LAMBDA - Build a Universe wi
https://lambda.gsfc.nasa.gov/education/cmb_plotter/
Search
CMB Analyzer
Universe Content
Atoms
4 %
Cold Dark Matter
22 %
Dark Energy
74 %
Additional Properties
Hubble Constant
73
Reionization redshift
11
Spectral Index
0.95
Power Fluctuations (μK²)
Success!!
Angle across the sky (deg)
Spectral Index: This describes the initial density ripples in the universe. A smaller spectral index means the ripples with longer wavelengths are stronger and those with shorter wavelengths are weaker, thereby tilting the graph to the right. Conversely, a larger spectral index strenghtens the shorter wavelength ripples and weakens those of longer wavelength, tilting the graph to the left.
Age: 13.7 billion years
Flatness: 1.00
ANSWER
RESET
This tool requires an Adobe Flash player to be installed for your browser.
Make full screen in new window
The Graph
The early structure of the universe as seen in the CMB can be represented by an angular power spectrum, a plot that shows how the temperature pattern in the early universe varies with progressively measuring smaller and smaller patches of the sky. This in turn reveals the amount of energy emitted by different sized "ripples" of sound echoing through the early matter of
Type here to search
9:56 AM
1/17/2019


cmb11(1).pdf - Adobe Acrobat Reader DC
File Edit View Window Help
Home Tools
This file claims compliance with the PDF/A standard and has been opened read-only to prevent modification.
Enable Editing
duration of seminar [min]
0 20 40 60
6000
5000
4000
3000
2000
1000
0
average audience attention
I understood something moment
will there be coffee - uncertainty
interesting point peak
almost over cheer
speaker variance
confusion drop
too many details low
endless questions
(absolute minimum)
another-seminar low
10 100 500 1000
apparent duration of seminar [min]
Export PDF
Adobe Export PDF
Convert PDF Files to Word or Excel Online
Select PDF File
cmb11(1).pdf
Convert to
Microsoft Word (*.docx)
Document Language:
English (U.S.) Change
Convert
Create PDF
Edit PDF
Comment
Convert and edit PDFs with Acrobat Pro DC
Start Free Trial
Type here to search
9:58 AM
1/17/2019



ϕ
x
add mass
Earth
compressed