Title: Can cosmology test string theory?

Date: Mar 17, 2005 11:30 AM

URL: http://pirsa.org/05030113

Abstract:

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)
w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris
hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)
w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Can Cosmology
Test String Theory?

Richard Easther (Yale)

w. Brian Greene, Will Kinney, Gary Shiu & Hiranya Peiris

hep-th/0104102, 0110226, 0204129 and astro-ph/0412613

Three Related Questions

- Do we really understand the generation of cosmological perturbations?
- Can a "minimum length" have an observable impact on cosmology?
- Can we see Planck scale physics with the cosmological microscope?

Three Related Questions

- Do we really understand the generation of cosmological perturbations?
- Can a “minimum length” have an observable impact on cosmology?
- Can we see Planck scale physics with the cosmological microscope?

Three Related Questions

- Do we really understand the generation of cosmological perturbations?
- Can a “minimum length” have an observable impact on cosmology?
- Can we see Planck scale physics with the cosmological microscope?

Three Related Questions

- Do we really understand the generation of cosmological perturbations? **YES**
- Can a “minimum length” have an observable impact on cosmology? **MAYBE**
- Can we see Planck scale physics with the cosmological microscope?

Three Related Questions

- Do we really understand the generation of cosmological perturbations? **YES**
- Can a “minimum length” have an observable impact on cosmology? **MAYBE**
- Can we see Planck scale physics with the cosmological microscope? **IF WE ARE LUCKY**

Three Related Questions

- Do we really understand the generation of cosmological perturbations? **YES**

- Can a "minimum length" have an observable impact on cosmology? **MAYBE**

- Can we see Planck scale physics with the cosmological microscope? **IF WE ARE LUCKY**

Three Related Questions

- Do we really understand the generation of cosmological perturbations? **YES**
- Can a “minimum length” have an observable impact on cosmology? **MAYBE**
- Can we see Planck scale physics with the cosmological microscope? **IF WE ARE LUCKY**

Three Related Questions

- Do we really understand the generation of cosmological perturbations?
- Can a “minimum length” have an observable impact on cosmology?
- Can we see Planck scale physics with the cosmological microscope?

What I am (Not) Doing

- Minimal stringy / Planckian modifications
  - Does string/Planck physics change cosmology?

- Feasibility study motivated by
  - High quality data (“golden age”)
  - Chance to test string / Planck physics

- Not cosmology directly based on string theory
  - Corrections to Einstein action (pre-big-bang)
  - Brane worlds / Brane-gas / Brandenberger-Vafa scenario
  - Holography
  - Stringy inflation models.

What I am (Not) Doing

- Minimal stringy / Planckian modifications
  - Does string/Planck physics change cosmology?

- Feasibility study motivated by
  - High quality data (“golden age”)
  - Chance to test string / Planck physics

- Not cosmology directly based on string theory
  - Corrections to Einstein action (pre-big-bang)
  - Brane worlds / Brane-gas / Brandenberger-Vafa scenario
  - Holography
  - Stringy inflation models.

What I am (Not) Doing

- Minimal stringy / Planckian modifications
    - Does string/Planck physics change cosmology?

- Feasibility study motivated by
    - High quality data ("golden age")
    - Chance to test string / Planck physics

- Not cosmology directly based on string theory
    - Corrections to Einstein action (pre-big-bang)
    - Brane worlds / Brane-gas / Brandenberger-Vafa scenario
    - Holography
    - Stringy inflation models.

What I am (Not) Doing

- Minimal stringy / Planckian modifications
  - Does string/Planck physics change cosmology?

- Feasibility study motivated by
  - High quality data ("golden age")
  - Chance to test string / Planck physics

- Not cosmology directly based on string theory
  - Corrections to Einstein action (pre-big-bang)
  - Brane worlds / Brane-gas / Brandenberger-Vafa scenario
  - Holography
  - Stringy inflation models.

What I am (Not) Doing

- Minimal stringy / Planckian modifications
  - Does string/Planck physics change cosmology?

- Feasibility study motivated by
  - High quality data ("golden age")
  - Chance to test string / Planck physics

- Not cosmology directly based on string theory
  - Corrections to Einstein action (pre-big-bang)
  - Brane worlds / Brane-gas / Brandenberger-Vafa scenario
  - Holography
  - Stringy inflation models.

What I am (Not) Doing

- Minimal stringy / Planckian modifications
  - Does string/Planck physics change cosmology?

- Feasibility study motivated by
  - High quality data ("golden age")
  - Chance to test string / Planck physics

- Not cosmology directly based on string theory
  - Corrections to Einstein action (pre-big-bang)
  - Brane worlds / Brane-gas / Brandenberger-Vafa scenario
  - Holography
  - Stringy inflation models.

Outline

- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

Outline

- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

Outline

- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

Outline

- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

Outline

- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

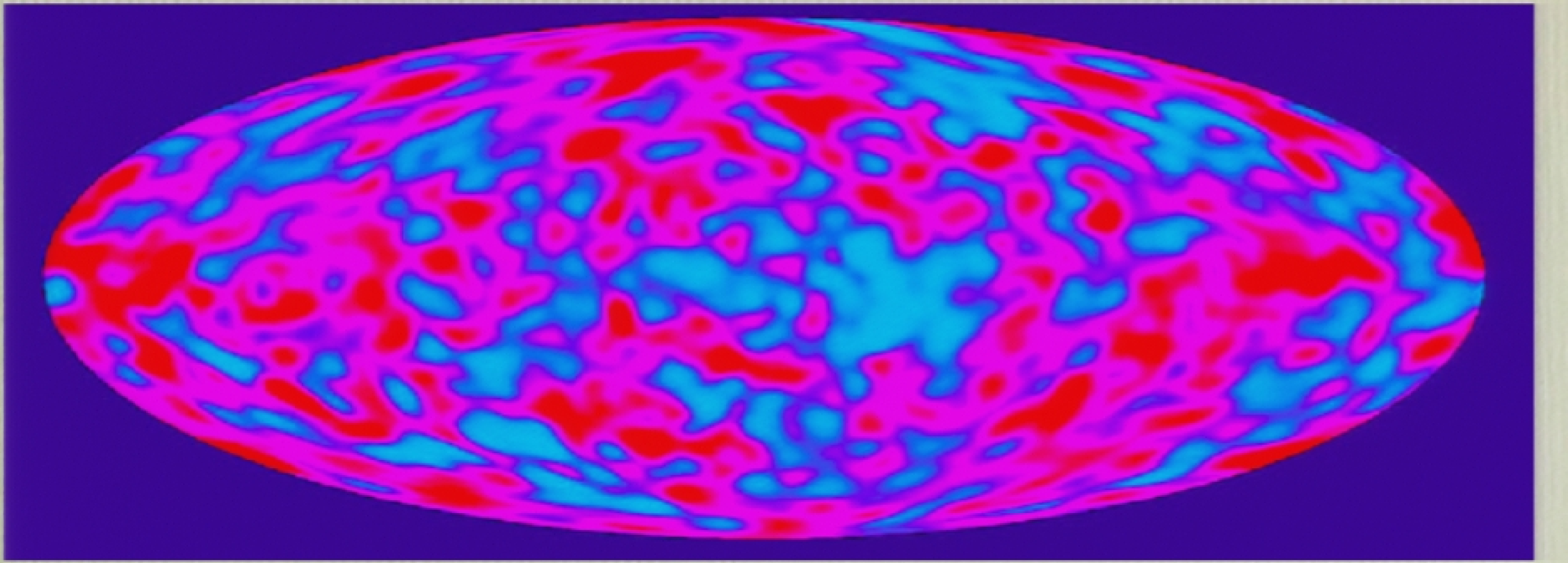
Outline

- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

Outline

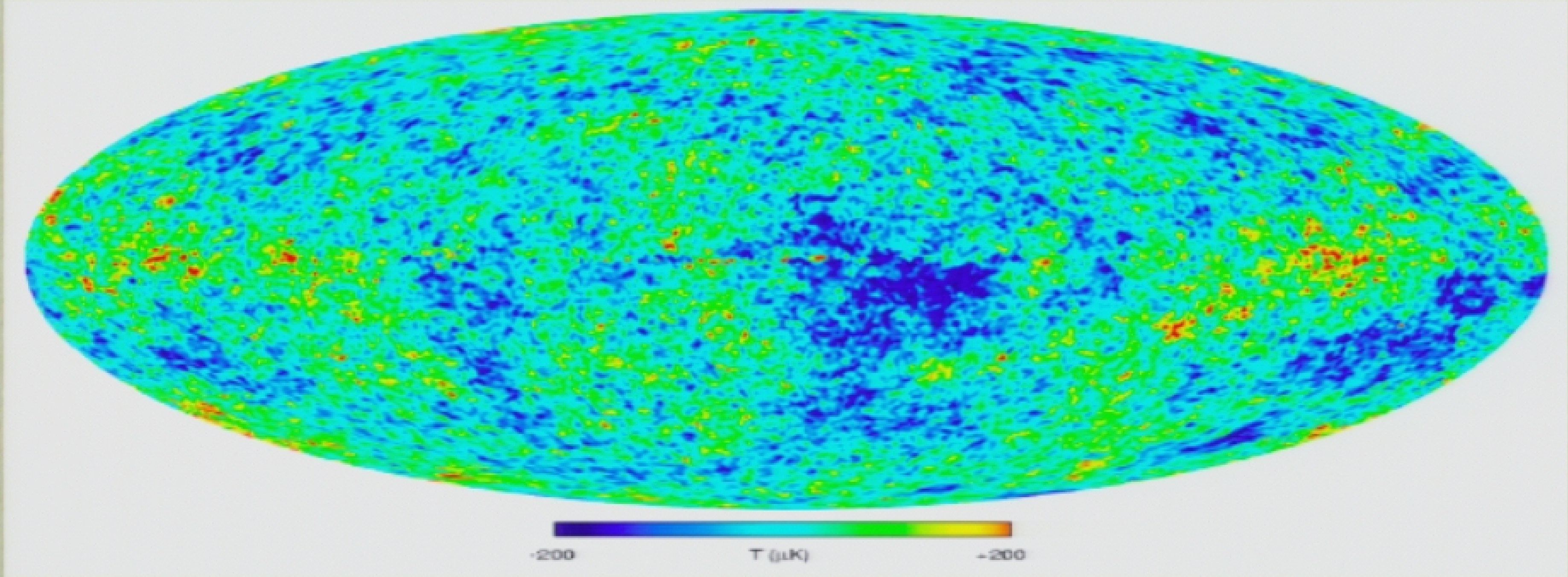
- Cosmic Microwave Background
- Inflationary perturbations: a quick review
    - The Cosmological Microscope.
- Lengthscales and Dimensional Analysis.
- Perturbations: the standard lore.
- Adding a minimum length
    - Power spectrum and observability
- Conclusions & Summary

Cosmic Microwave Background



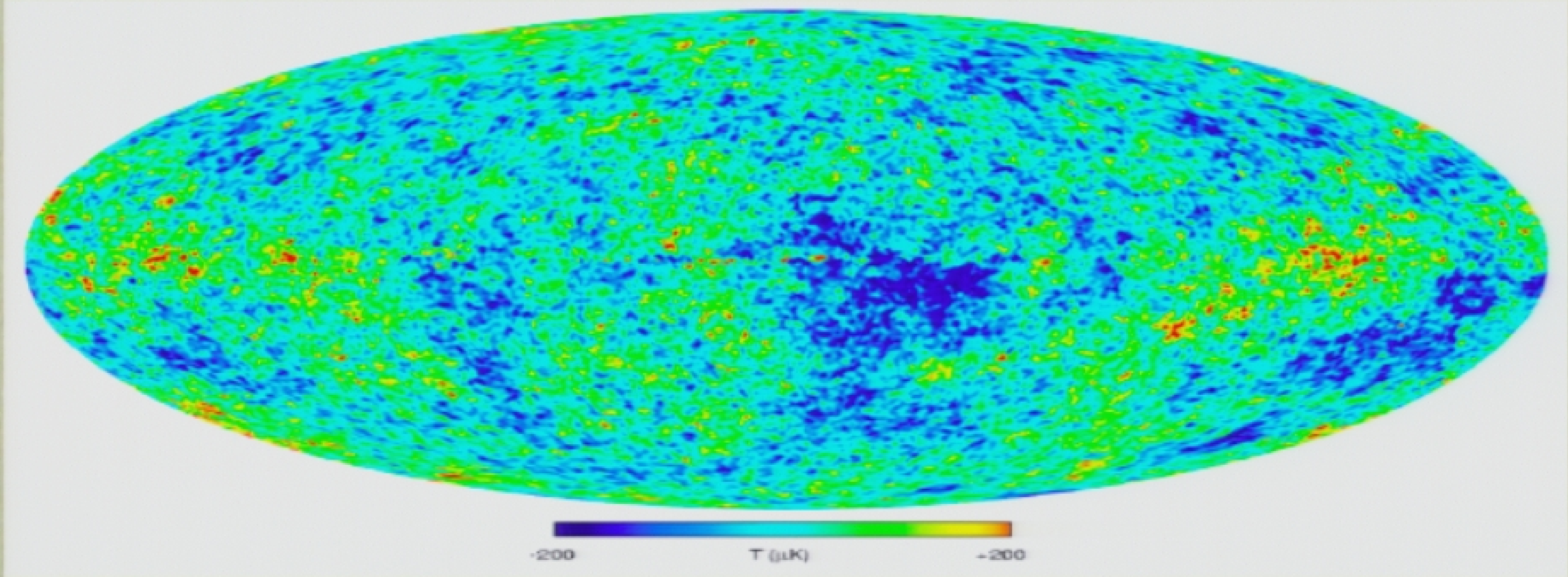
- Discovered 1965
- Every point in the sky appears to be ~2.725K
    - Almost perfect blackbody spectrum

Cosmic Microwave Background



- Discovered 1965
- Every point in the sky appears to be ~2.725K
  - Almost perfect blackbody spectrum

Cosmic Microwave Background



- Discovered 1965
- Every point in the sky appears to be ~2.725K
    - Almost perfect blackbody spectrum

Inflationary Perturbations

- Universe roughly homogeneous and isotropic
- We observe departures from smoothness
    - Galaxies and clusters of galaxies
    - Overall matter distribution
    - Microwave background anisotropies
- Inflation also predicts perturbations
    - Used to test *specific* inflationary models.
    - Physics determined by late time limit.
- Quantum mechanical origin, classical evolution.

Inflationary Perturbations

- Universe roughly homogeneous and isotropic
- We observe departures from smoothness
  - Galaxies and clusters of galaxies
  - Overall matter distribution
  - Microwave background anisotropies
- Inflation also predicts perturbations
  - Used to test *specific* inflationary models.
  - Physics determined by late time limit.
- Quantum mechanical origin, classical evolution.

Inflationary Perturbations

- Universe roughly homogeneous and isotropic
- We observe departures from smoothness
    - Galaxies and clusters of galaxies
    - Overall matter distribution
    - Microwave background anisotropies
- Inflation also predicts perturbations
    - Used to test *specific* inflationary models.
    - Physics determined by late time limit.
- Quantum mechanical origin, classical evolution.

Horizons

- Hubble length – dynamical scale, $1/H$, $H \sim \rho^{1/2}$
  - Often just called "the horizon"
  - Reduces to future light cone in de Sitter limit.
- Inflation decreases comoving Hubble length
  - Perturbations have fixed comoving length
  - Perturbations "exit horizon" and "freeze out"
  - Longest scales leave horizon earliest (small k)
- Inflation ends, Hubble length increases
  - Perturbations re-enter horizon, seed structure.

Horizons

- Hubble length – dynamical scale, $1/H$, $H \sim \rho^{1/2}$
  - Often just called “the horizon”
  - Reduces to future light cone in de Sitter limit.
- Inflation decreases comoving Hubble length
  - Perturbations have fixed comoving length
  - Perturbations “exit horizon” and “freeze out”
  - Longest scales leave horizon earliest (small k)
- Inflation ends, Hubble length increases
  - Perturbations re-enter horizon, seed structure.

Horizons

- Hubble length – dynamical scale, 1/H, H ~ $\rho^{1/2}$
  - Often just called "the horizon"
  - Reduces to future light cone in de Sitter limit.
- Inflation decreases comoving Hubble length
  - Perturbations have fixed comoving length
  - Perturbations "exit horizon" and "freeze out"
  - Longest scales leave horizon earliest (small k)
- Inflation ends, Hubble length increases
  - Perturbations re-enter horizon, seed structure.

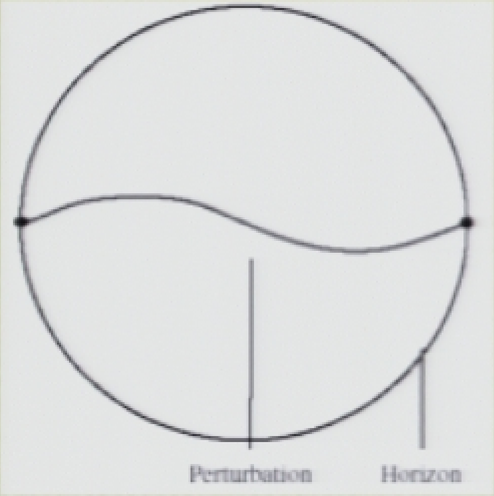
Horizons

- Hubble length – dynamical scale, $1/H$, $H \sim \rho^{1/2}$
  - Often just called “the horizon”
  - Reduces to future light cone in de Sitter limit.
- Inflation decreases comoving Hubble length
  - Perturbations have fixed comoving length
  - Perturbations “exit horizon” and “freeze out”
  - Longest scales leave horizon earliest (small k)
- Inflation ends, Hubble length increases
  - Perturbations re-enter horizon, seed structure.

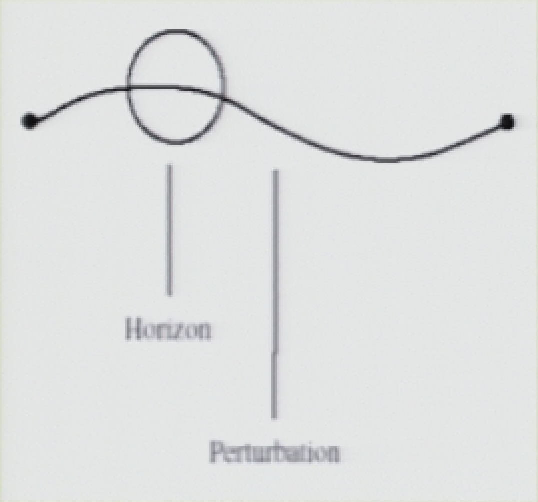
Perturbation Generation

Mode creation

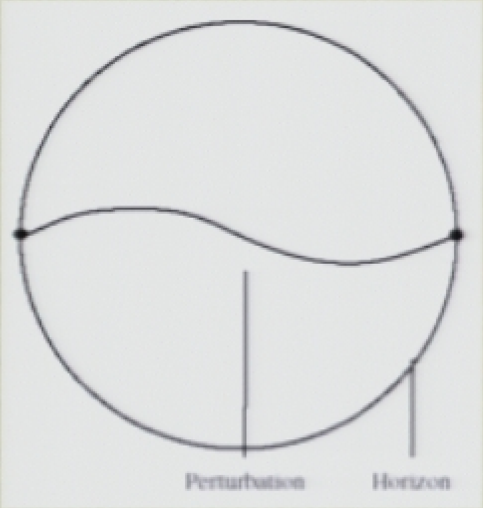
Horizon exit



End of inflation



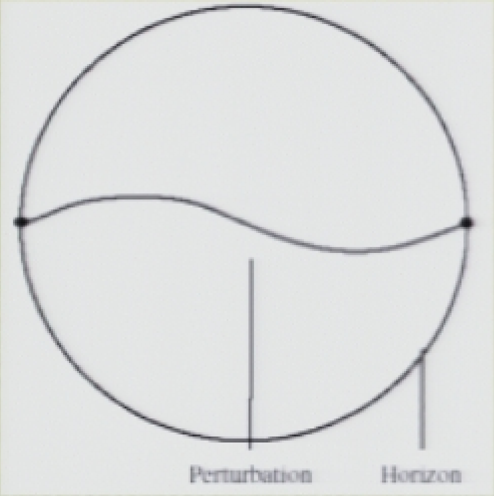
Re-entry



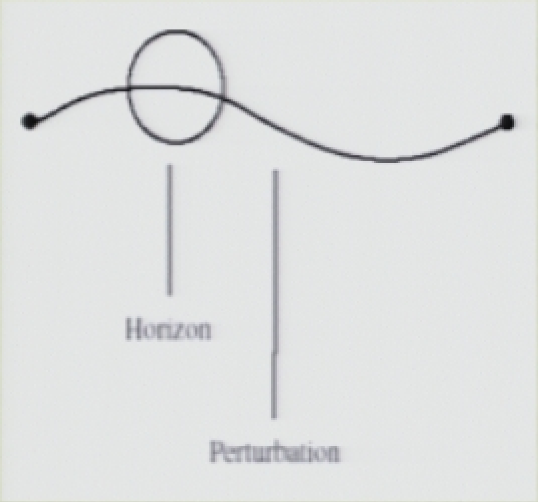
Perturbation Generation

Mode creation

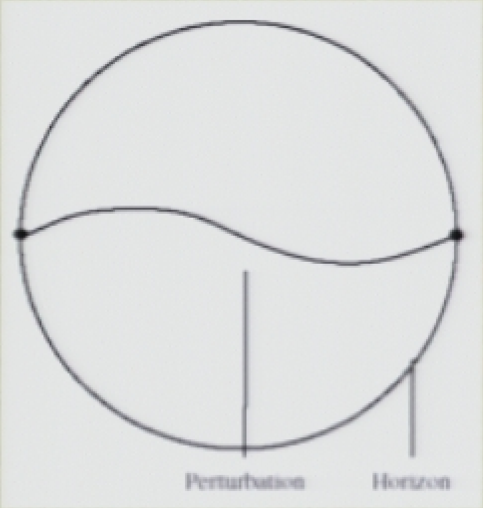
Horizon exit



End of inflation

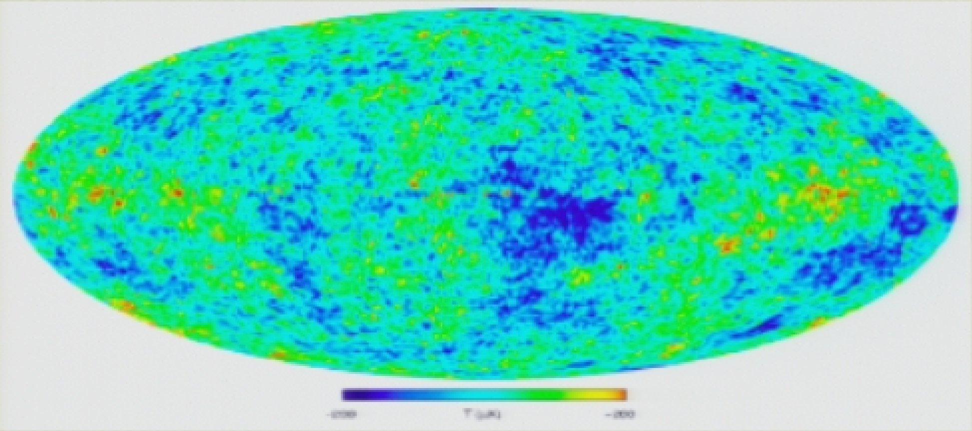


Re-entry

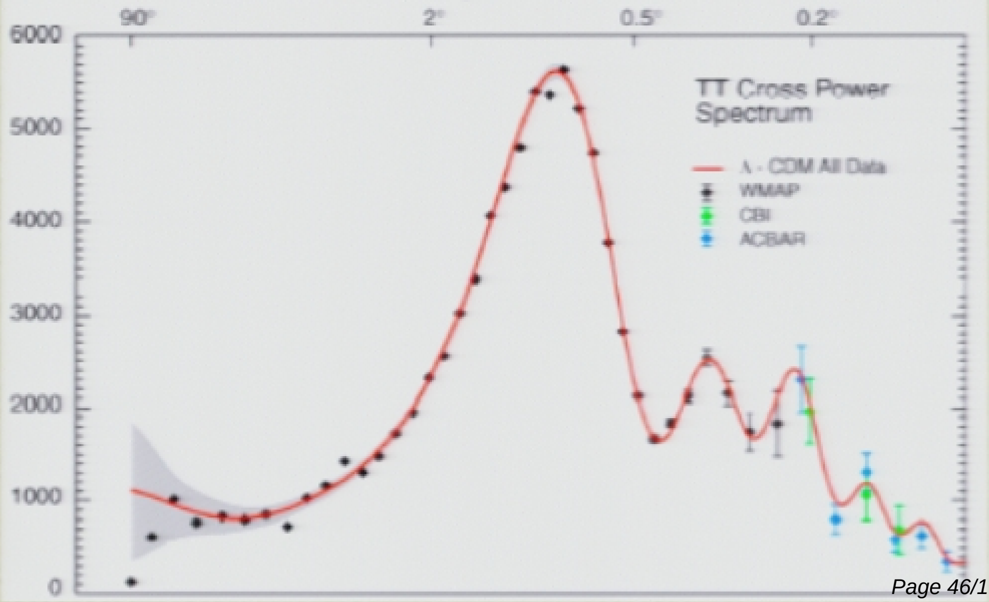


Observation Meets Theory

- Observe CMB:
    - eg WMAP

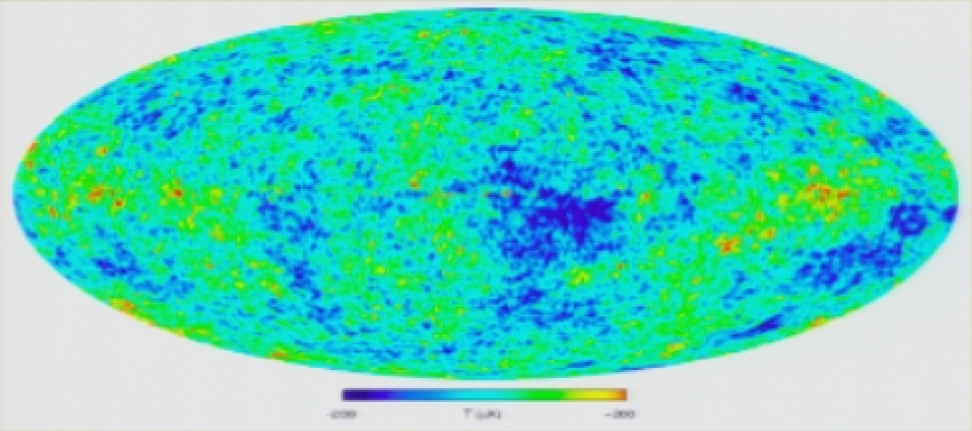


- Extract spectrum:
    - WMAP

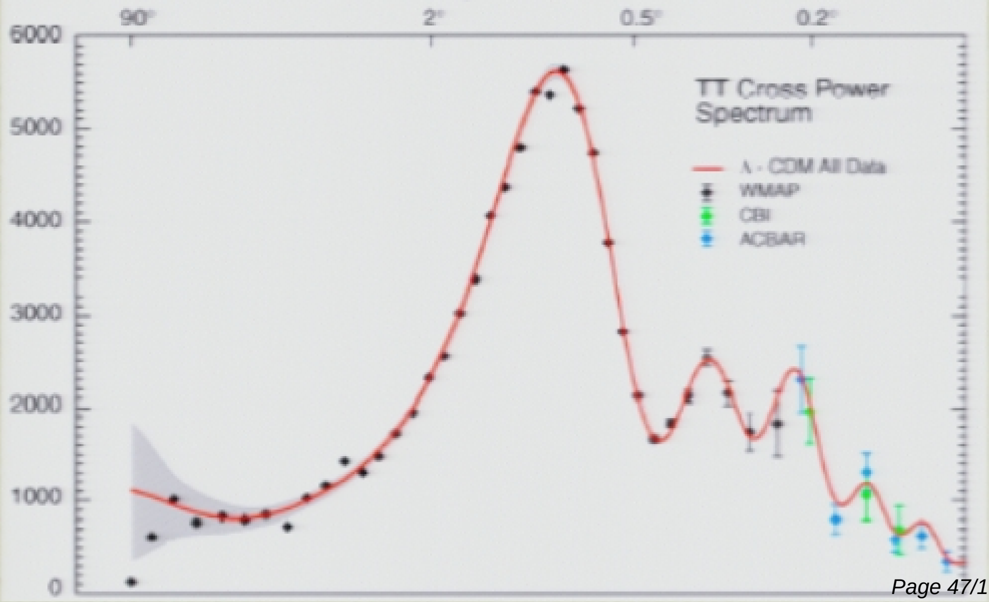


Observation Meets Theory

- Observe CMB:
  - eg WMAP

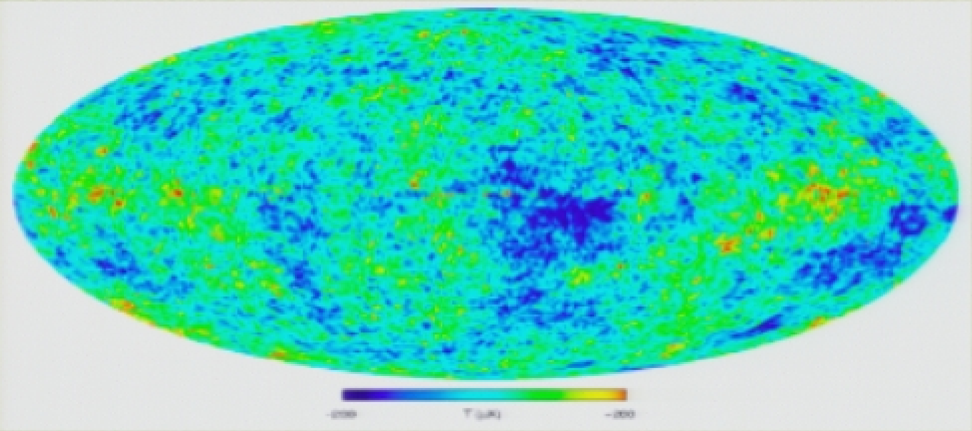


- Extract spectrum:
  - WMAP

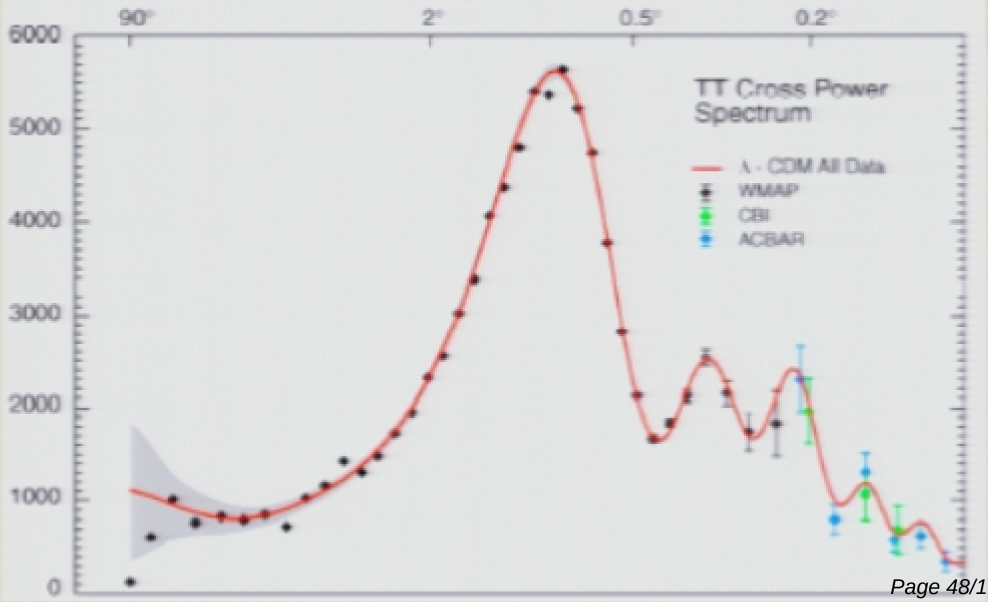


Observation Meets Theory

- Observe CMB:
    - eg WMAP

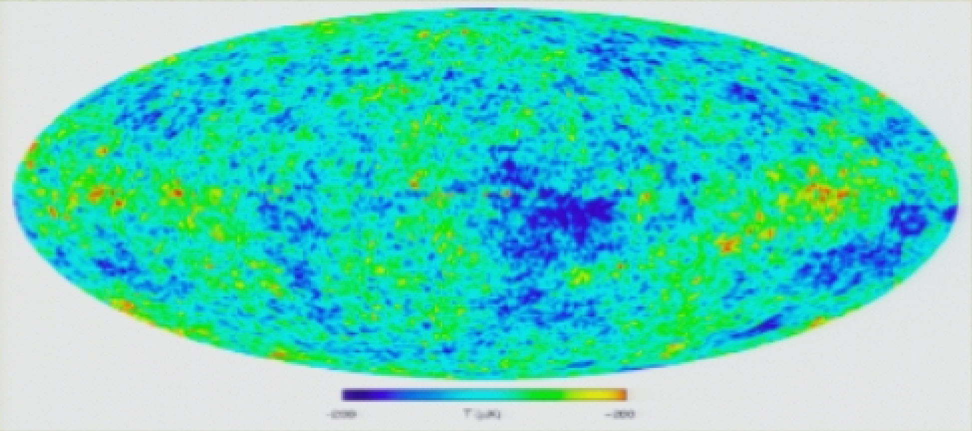


- Extract spectrum:
    - WMAP

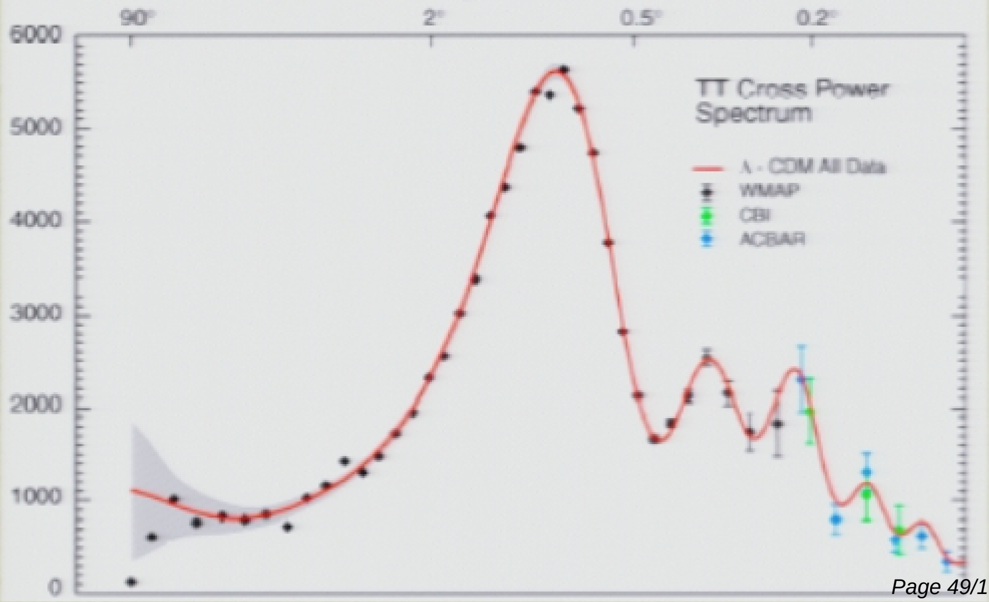


Observation Meets Theory

- Observe CMB:
  - eg WMAP

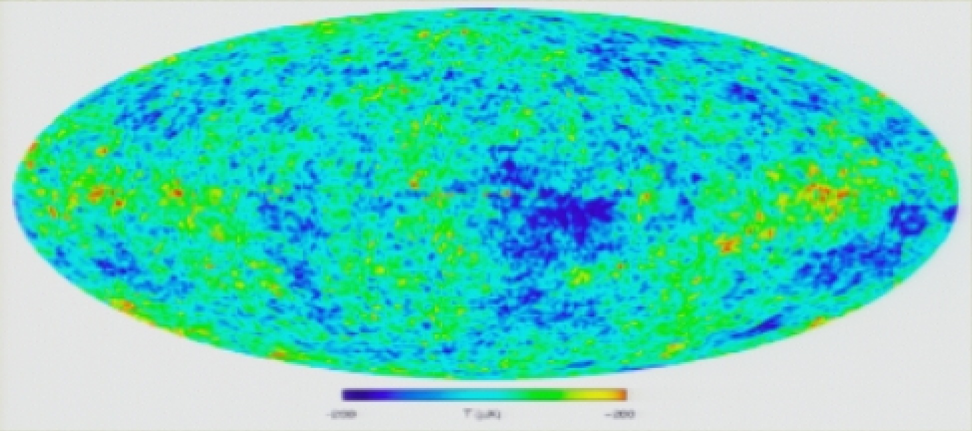


- Extract spectrum:
  - WMAP

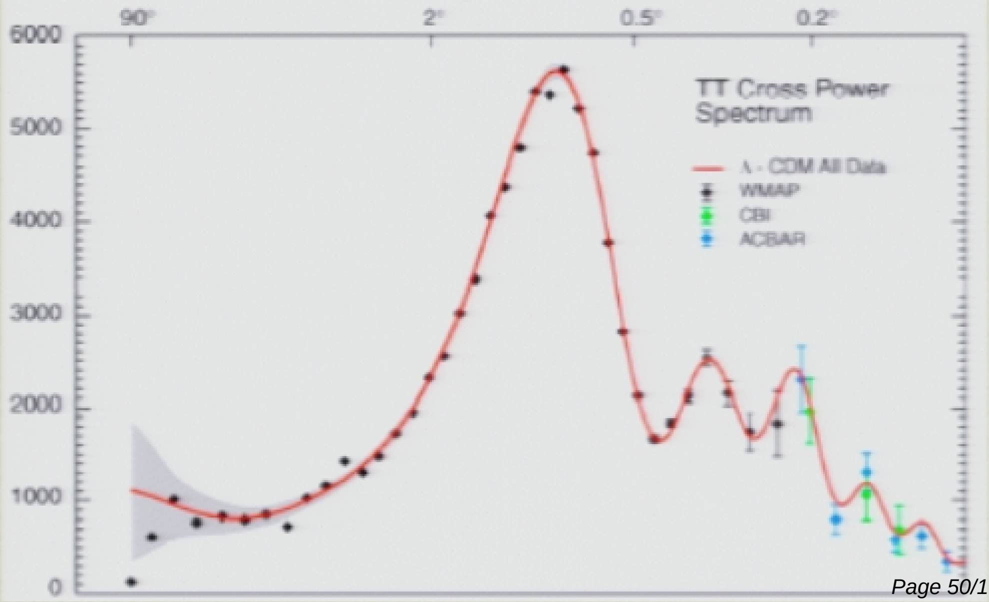


Observation Meets Theory

- Observe CMB:
  - eg WMAP

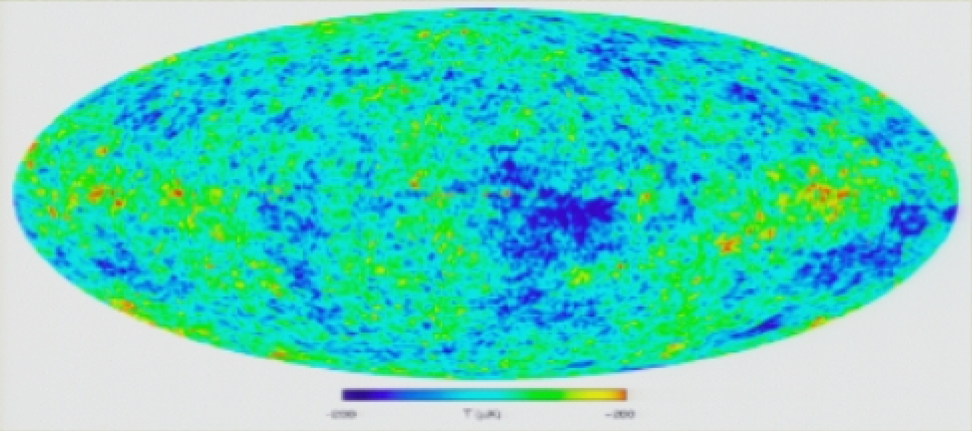


- Extract spectrum:
  - WMAP

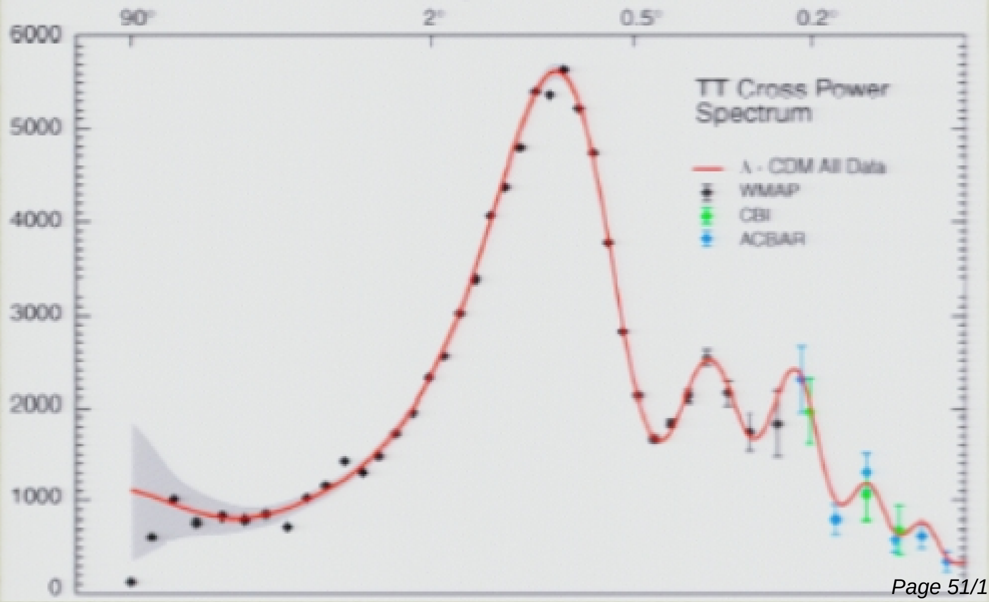


Observation Meets Theory

- Observe CMB:
  - eg WMAP

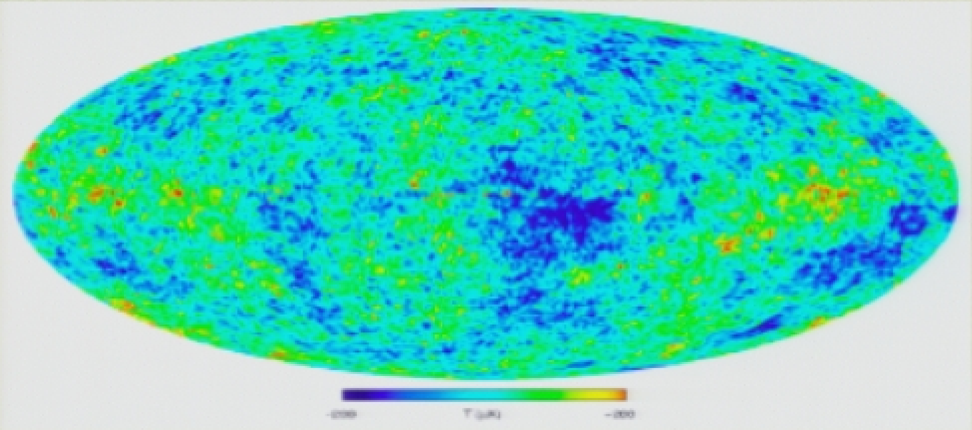


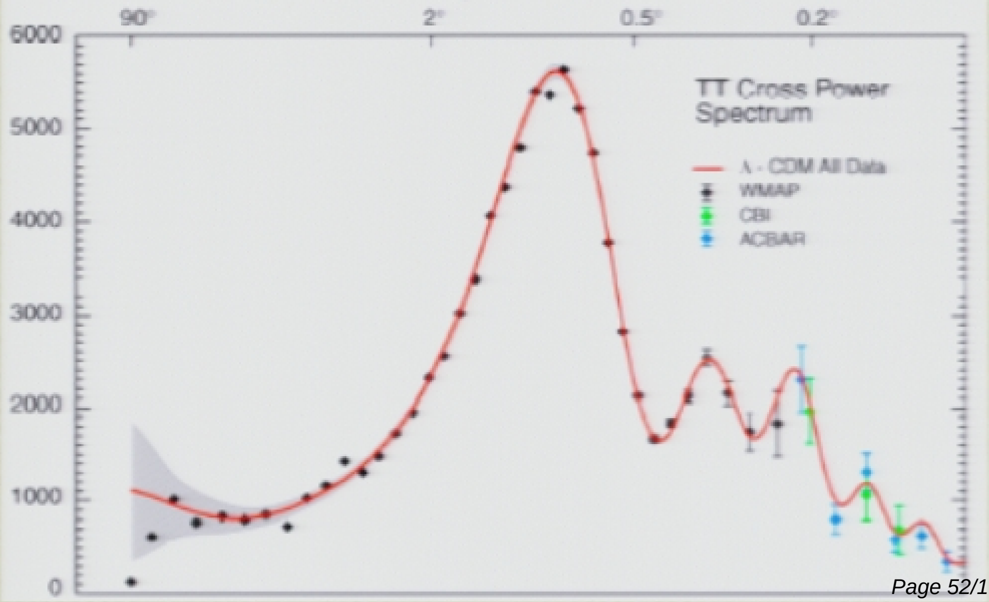
- Extract spectrum:
  - WMAP



Observation Meets Theory

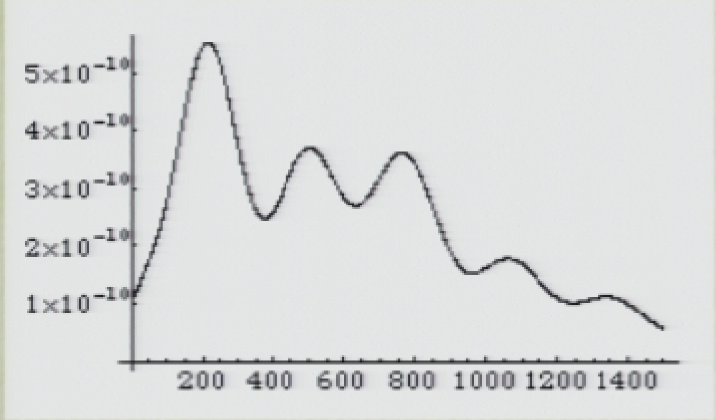
- Observe CMB:
  - eg WMAP





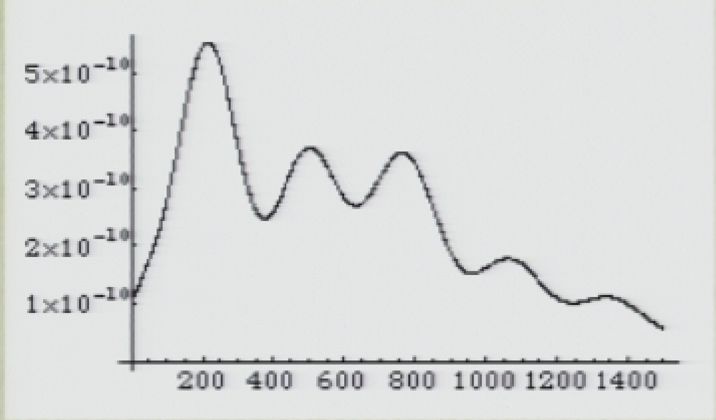
- Extract spectrum:
  - WMAP

Theoretical Predictions



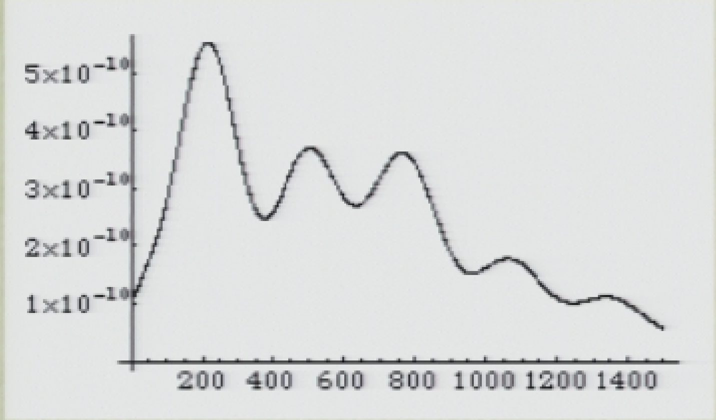
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P\propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



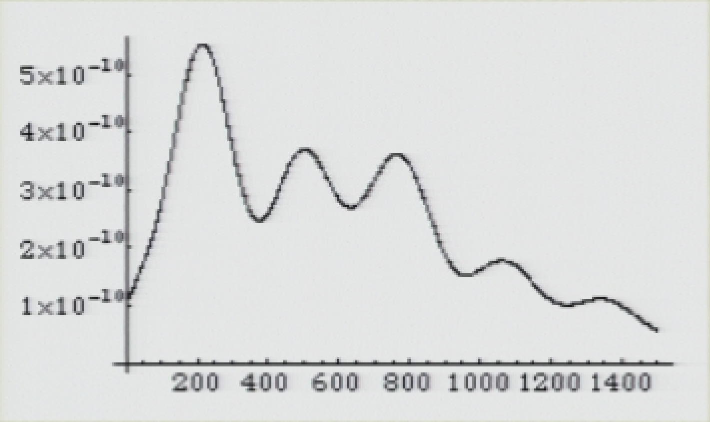
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



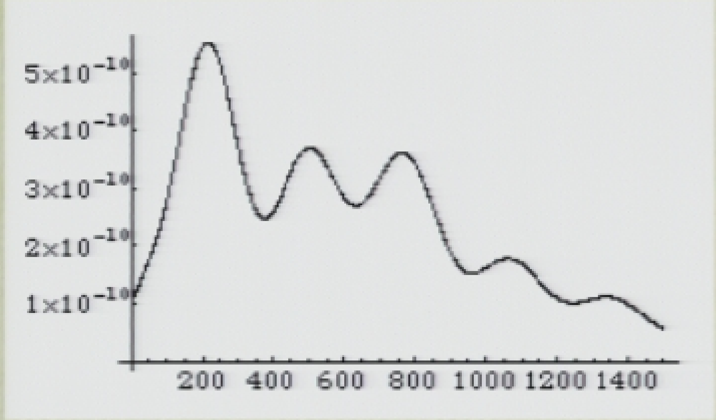
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



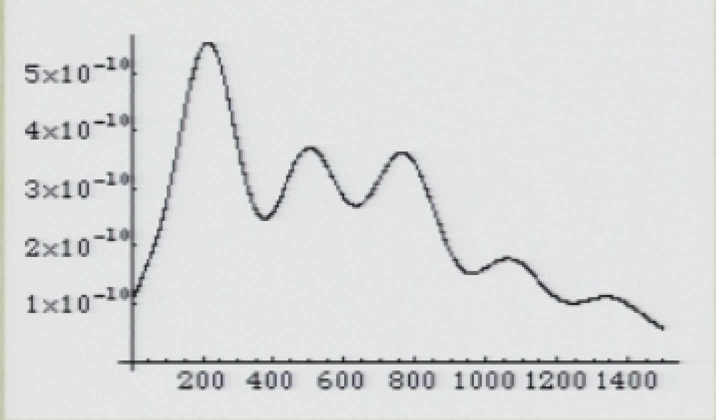
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



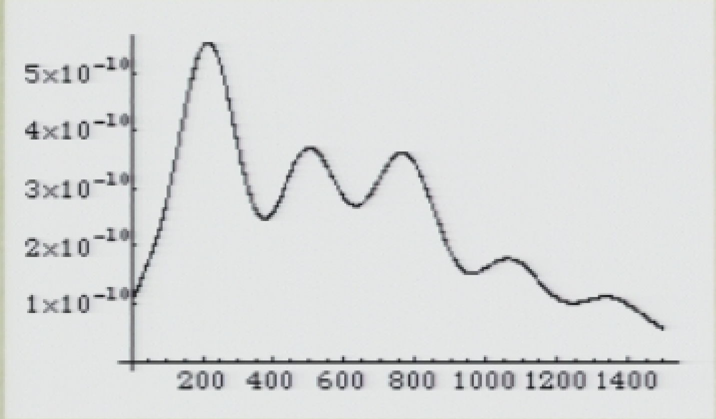
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



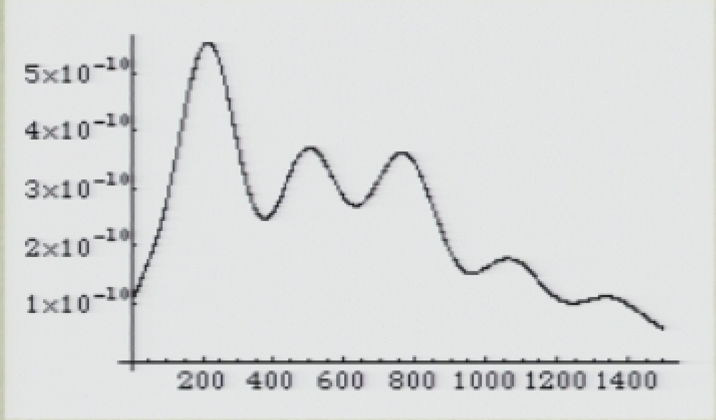
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



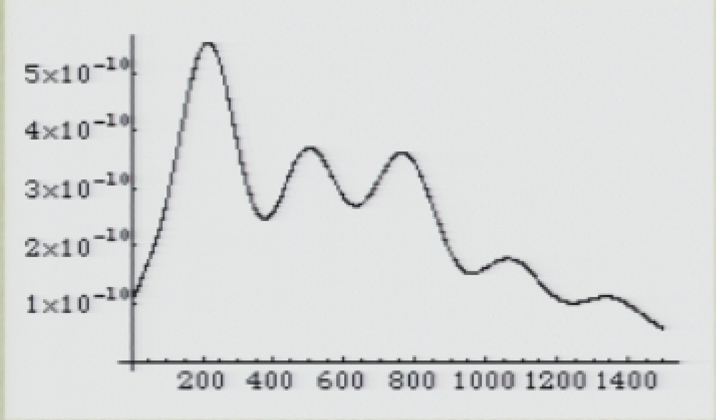
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P\propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



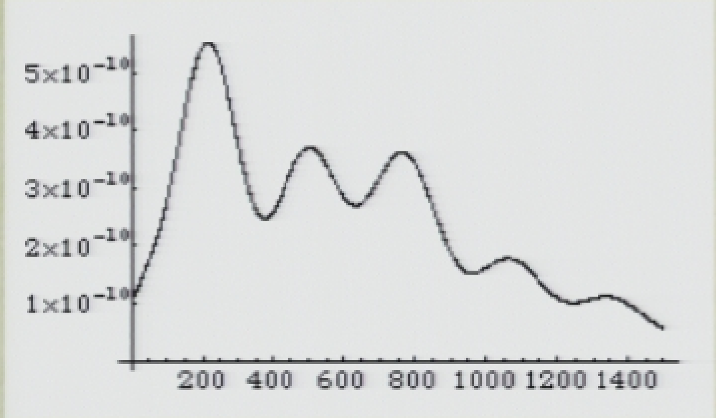
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



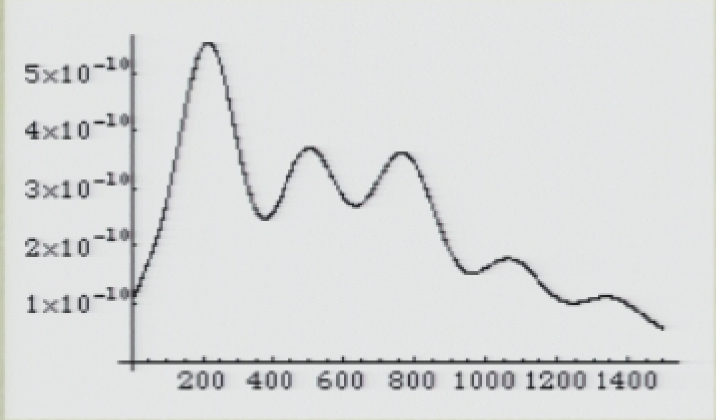
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



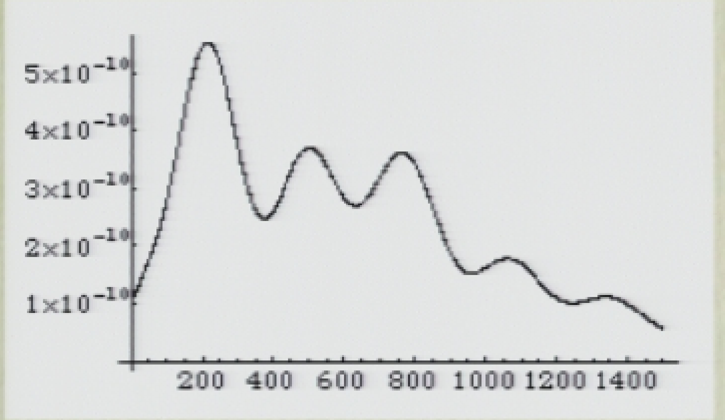
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



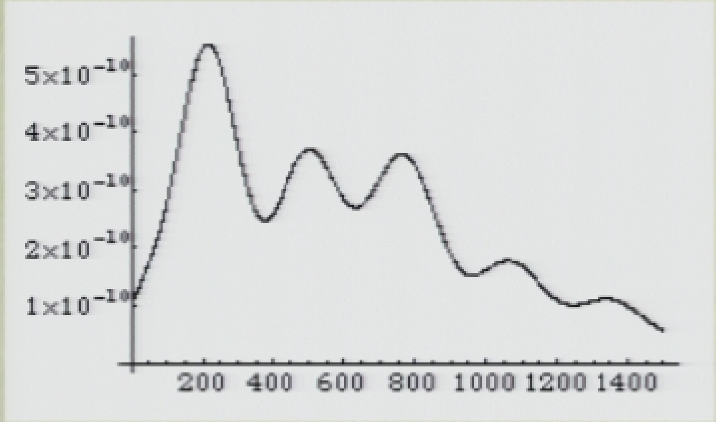
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



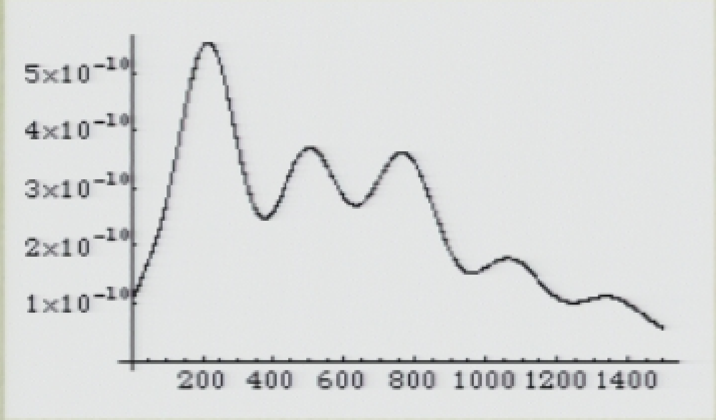
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



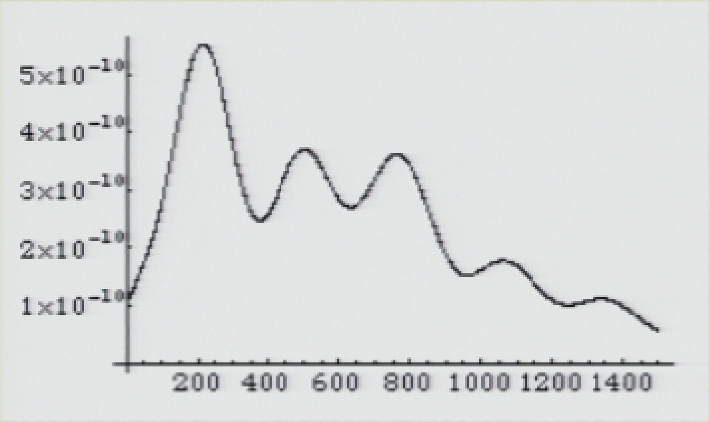
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



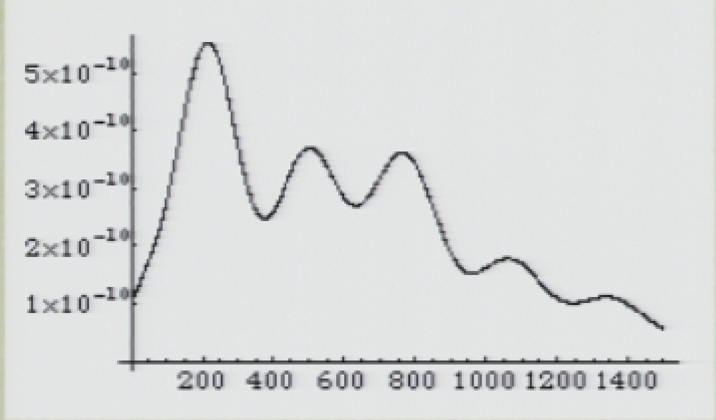
- Predict spectrum:
    - via CMBfast
    - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
    - (Usually) just two parameters, plus tensors.
    - Effects we study modify underlying spectrum.

Theoretical Predictions



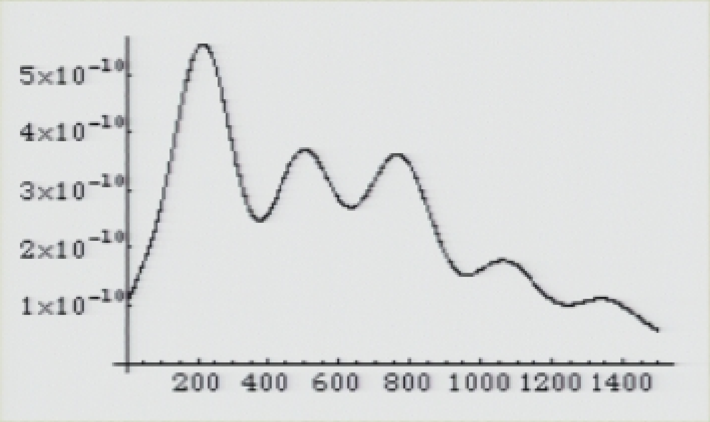
- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Theoretical Predictions



- Predict spectrum:
  - via CMBfast
  - Baryon fraction, dark matter, Hubble constant, cosmological constant, spatial curvature ...
- Underlying spectrum - $P \propto k^{n-1}$
  - (Usually) just two parameters, plus tensors.
  - Effects we study modify underlying spectrum.

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: T_{reheat} ~10^{15} GeV
- T_{Planck} =10^{19} GeV, l_{Planck} = $1/T_{Planck}$
  - 1GeV= 10^{13}K, 1ly = 10^{18} cm
- Today: visible universe is
  - 10^{10}ly = 10^{61} l_{Planck}, T=2.7K
  - a_{today} /a_{end} = T_{end} /T_{reheat} = 10^{28}
- Longest perturbations grow
  - >e^{60} = 10^{26} during inflation, 10^{28} afterward
  - Total growth at least 10^{54}
- Long scales almost always subplanckian

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: T_{reheat} ~10^{15} GeV
- T_{Planck} =10^{19} GeV, l_{Planck} = $1/T_{Planck}$
  - 1GeV= 10^{13}K, 1ly = 10^{18} cm
- Today: visible universe is
  - 10^{10}ly = 10^{61} l_{Planck}, T=2.7K
  - a_{today} /a_{end} = T_{end} /T_{reheat} = 10^{28}
- Longest perturbations grow
  - >e^{60} = 10^{26} during inflation, 10^{28} afterward
  - Total growth at least 10^{54}
- Long scales almost always subplanckian

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: T_{reheat} ~10^{15} GeV
- T_{Planck} =10^{19} GeV, l_{Planck} = $1/T_{Planck}$
    - 1GeV= 10^{13}K, 1ly = 10^{18} cm
- Today: visible universe is
    - 10^{10}ly = 10^{61} l_{Planck}, T=2.7K
    - a_{today} /a_{end} = T_{end} /T_{reheat} = 10^{28}
- Longest perturbations grow
    - >e^{60} = 10^{26} during inflation, 10^{28} afterward
    - Total growth at least 10^{54}
- Long scales almost always subplanckian

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: $T_{reheat} \sim 10^{15}$ GeV
- $T_{Planck} = 10^{19}$ GeV, $l_{Planck} = 1/T_{Planck}$
  - $1\text{GeV} = 10^{13}\text{K}$, $1\text{ly} = 10^{18}$ cm
- Today: visible universe is
  - $10^{10}\text{ly} = 10^{61}\ l_{Planck}$, $T=2.7\text{K}$
  - $a_{today} / a_{end} = T_{end} / T_{reheat} = 10^{28}$
- Longest perturbations grow
  - $> e^{60} = 10^{26}$ during inflation, 10^{28} afterward
  - Total growth at least 10^{54}
- Long scales almost always subplanckian

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: T_{reheat} ~10^{15} GeV
- $T_{Planck} = 10^{19}$ GeV, $l_{Planck} = 1/T_{Planck}$
  - 1GeV$= 10^{13}$K, 1ly $= 10^{18}$ cm
- Today: visible universe is
  - 10^{10}ly $= 10^{61}$ l_{Planck}, $T=2.7$K
  - $a_{today} / a_{end} = T_{end} / T_{reheat} = 10^{28}$
- Longest perturbations grow
  - $>e^{60} = 10^{26}$ during inflation, 10^{28} afterward
  - Total growth at least 10^{54}
- Long scales almost always subplanckian

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: T_{reheat} ~10^{15} GeV
- $T_{Planck} = 10^{19}$ GeV, $l_{Planck} = 1/T_{Planck}$
  - $1GeV = 10^{13}K$, $1ly = 10^{18}$ cm
- Today: visible universe is
  - $10^{10}ly = 10^{61}\ l_{Planck}$, $T=2.7K$
  - $a_{today} / a_{end} = T_{end} / T_{reheat} = 10^{28}$
- Longest perturbations grow
  - $>e^{60} = 10^{26}$ during inflation, 10^{28} afterward
  - Total growth at least 10^{54}
- Long scales almost always subplanckian

Scales in Inflation

- Inflation occurs at GUT scale (or lower)
- Final temperature: $T_{reheat} \sim 10^{15}$ GeV
- $T_{Planck} = 10^{19}$ GeV, $l_{Planck} = 1/T_{Planck}$
  - 1GeV= 10^{13}K, 1ly = 10^{18} cm
- Today: visible universe is
  - 10^{10}ly = 10^{61} l_{Planck}, T=2.7K
  - $a_{today} / a_{end} = T_{end} / T_{reheat} = 10^{28}$
- Longest perturbations grow
  - $>e^{60} = 10^{26}$ during inflation, 10^{28} afterward
  - Total growth at least 10^{54}
- Long scales almost always subplanckian

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
    - Quantum gravity / Planck scale 10^{19} GeV
    - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
    - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
    - Impact of fundamental scale ~ $(H/M)^n$
    - Key question: is n = 1 or n =2? (and prefactor?)
    - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{inflation}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale $\sim 10^{15}$ GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale $\sim (H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
    - Quantum gravity / Planck scale 10^{19} GeV
    - String scale up to 2 orders of magnitude lower?
- Inflationary scale $\sim 10^{15}$ GeV
    - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
    - Impact of fundamental scale $\sim (H/M)^n$
    - Key question: is n = 1 or n =2? (and prefactor?)
    - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2}$ ~ H (Hubble scale), $L_{\text{inflation}}$ ~ 1/H
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{\text{inflation}} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
    - Quantum gravity / Planck scale 10^{19} GeV
    - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
    - $\rho^{1/2}$ ~ H (Hubble scale), $L_{inflation}$ ~ 1/H
- Dimensionless combination: H/M
    - Impact of fundamental scale ~ $(H/M)^n$
    - Key question: is n = 1 or n =2? (and prefactor?)
    - Possibly a 1% effect??

1) String Theory v. Dimensional Analysis

- Does this have observational consequences?
- Assume a fundamental mass scale, M
  - Quantum gravity / Planck scale 10^{19} GeV
  - String scale up to 2 orders of magnitude lower?
- Inflationary scale ~ 10^{15} GeV
  - $\rho^{1/2} \sim H$ (Hubble scale), $L_{inflation} \sim 1/H$
- Dimensionless combination: H/M
  - Impact of fundamental scale ~ $(H/M)^n$
  - Key question: is n = 1 or n =2? (and prefactor?)
  - Possibly a 1% effect??

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can’t do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

2) String Theory and Perturbations: Case Study

- Can't do *ab initio* perturbations in string theory.
- Introduce minimum length via anstatz.
  - Can modify evolution (n=2, typically)
  - Or initial conditions (n=1, typically)
- See: Schalm, Shiu van der Schaar, Greene
  - Effective field theory approach
  - Trans-planck physics introduced via high dimensional operators
  - UV completion of GR unknown
  - Initial conditions specified on surface, n=1.

Modulated Spectrum

- Standard calculation:

$$u_k'' + \left(k^2 - \frac{z''}{z}\right) u_k = 0$$

$$u_k \sim \frac{1}{\sqrt{2k}} e^{-ik\eta}, \quad \eta \to -\infty$$

- Initial conditions guarantee bosonic statistics for fluctuations
  - Fixed at arbitrarily small scales.

Initial Conditions Ansatz

- Power law solution; generalize to slow roll

$$u_k = \frac{\sqrt{-\pi\eta}}{2}\left[C_+ H_\nu(-k\eta) + C_- H_\nu^\star(-k\eta)\right]$$

$$u_k(\eta_k) = \frac{1}{\sqrt{2k}} e^{-i\eta_k}$$

$$C_- \neq 0, \quad C_- \sim \frac{H}{M}$$

- Mode created in Minkowski space, at finite time.
  - Extract power spectrum from late time limit.
  - Details in EGKS-III

Initial Conditions Ansatz

- Power law solution; generalize to slow roll

$$u_k = \frac{\sqrt{-\pi\eta}}{2}\left[C_+ H_\nu(-k\eta) + C_- H_\nu^\star(-k\eta)\right]$$

$$u_k(\eta_k) = \frac{1}{\sqrt{2k}} e^{-i\eta_k}$$

$$C_- \neq 0, \quad C_- \sim \frac{H}{M}$$

- Mode created in Minkowski space, at finite time.
  - Extract power spectrum from late time limit.
  - Details in EGKS-III

Initial Conditions Ansatz

- Power law solution; generalize to slow roll

$$u_k = \frac{\sqrt{-\pi\eta}}{2}\left[C_+ H_\nu(-k\eta) + C_- H_\nu^\star(-k\eta)\right]$$

$$u_k(\eta_k) = \frac{1}{\sqrt{2k}} e^{-i\eta_k}$$

$$C_- \neq 0, \quad C_- \sim \frac{H}{M}$$

- Mode created in Minkowski space, at finite time.
  - Extract power spectrum from late time limit.
  - Details in EGKS-III

Modulated Spectrum

$$P_{TP} = \left\{1 + \left(\frac{H_*}{M}\right)\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{M}{H_*}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]\right\} P$$

Modulated Spectrum

$$P_{TP} = \left\{1 + \left(\frac{H_*}{M}\right)\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{M}{H_*}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]\right\} P$$

Modulated Spectrum

$$P_{TP} = \left\{1+\left(\underset{\substack{\uparrow \\ \text{Amplitude}}}{\frac{H_*}{M}}\right)\left(\frac{k}{k_*}\right)^{-\varepsilon}\sin\left[\frac{2}{1-\varepsilon}\left(\frac{M}{H_*}\right)\left(\frac{k}{k_*}\right)^{\varepsilon}+\phi\right]\right\}P$$

Modulated Spectrum

$$P_{TP} = \left\{ 1 + \underset{\substack{\uparrow \\ \textbf{Amplitude}}}{\left(\frac{H_*}{M}\right)} \left(\frac{k}{k_*}\right)^{-\varepsilon} \underset{\substack{\uparrow \\ \textbf{Modulation}}}{\sin} \left[\frac{2}{1-\varepsilon} \left(\frac{M}{H_*}\right) \left(\frac{k}{k_*}\right)^{\varepsilon} + \phi \right] \right\} P$$

Modulated Spectrum

$$P_{TP} = \left\{1 + \left(\frac{H_*}{M}\right)\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{M}{H_*}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]\right\} P$$

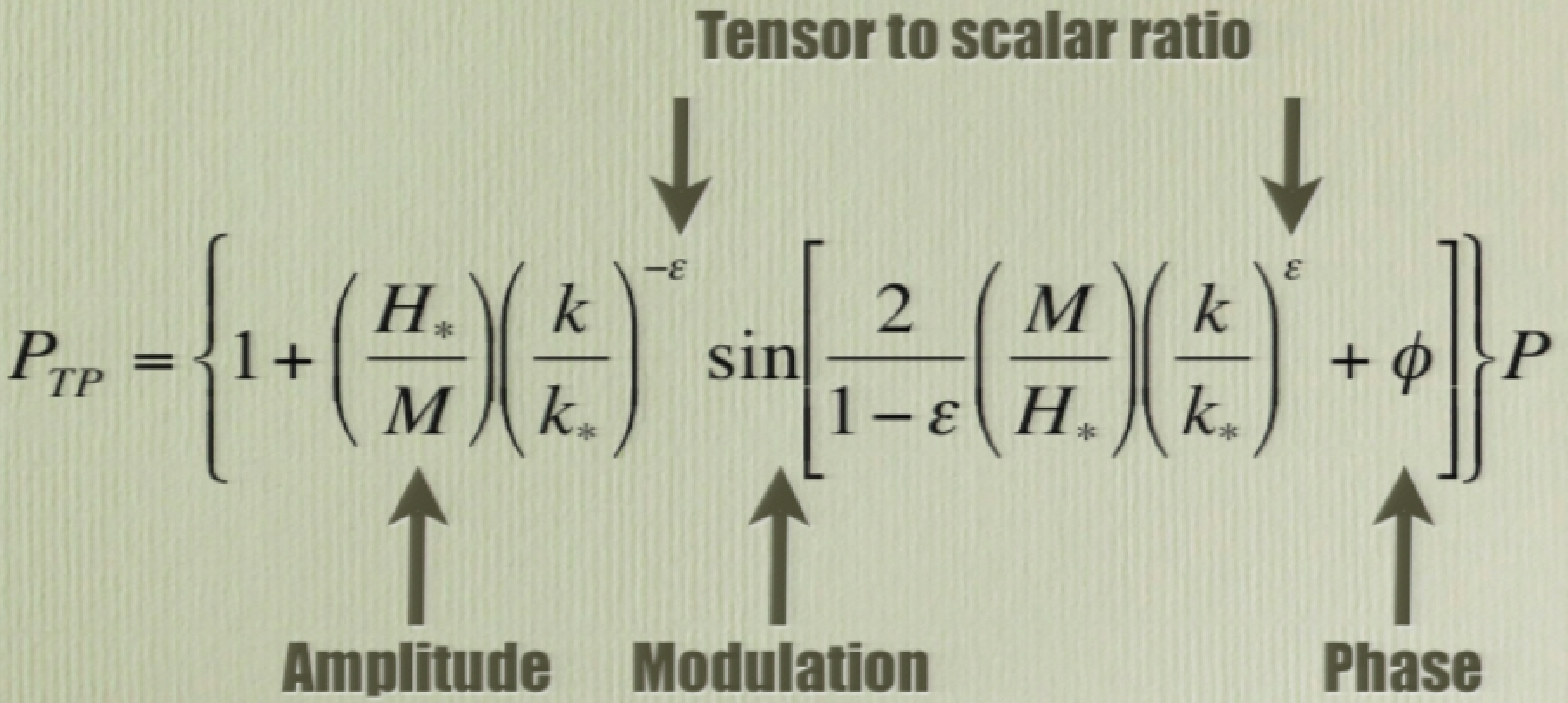
Amplitude **Modulation** **Phase**

Modulated Spectrum

$$P_{TP} = \left\{ 1 + \left(\frac{H_*}{M}\right)\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{M}{H_*}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]\right\} P$$

Amplitude **Modulation** **Phase**

Modulated Spectrum



Tensor to scalar ratio

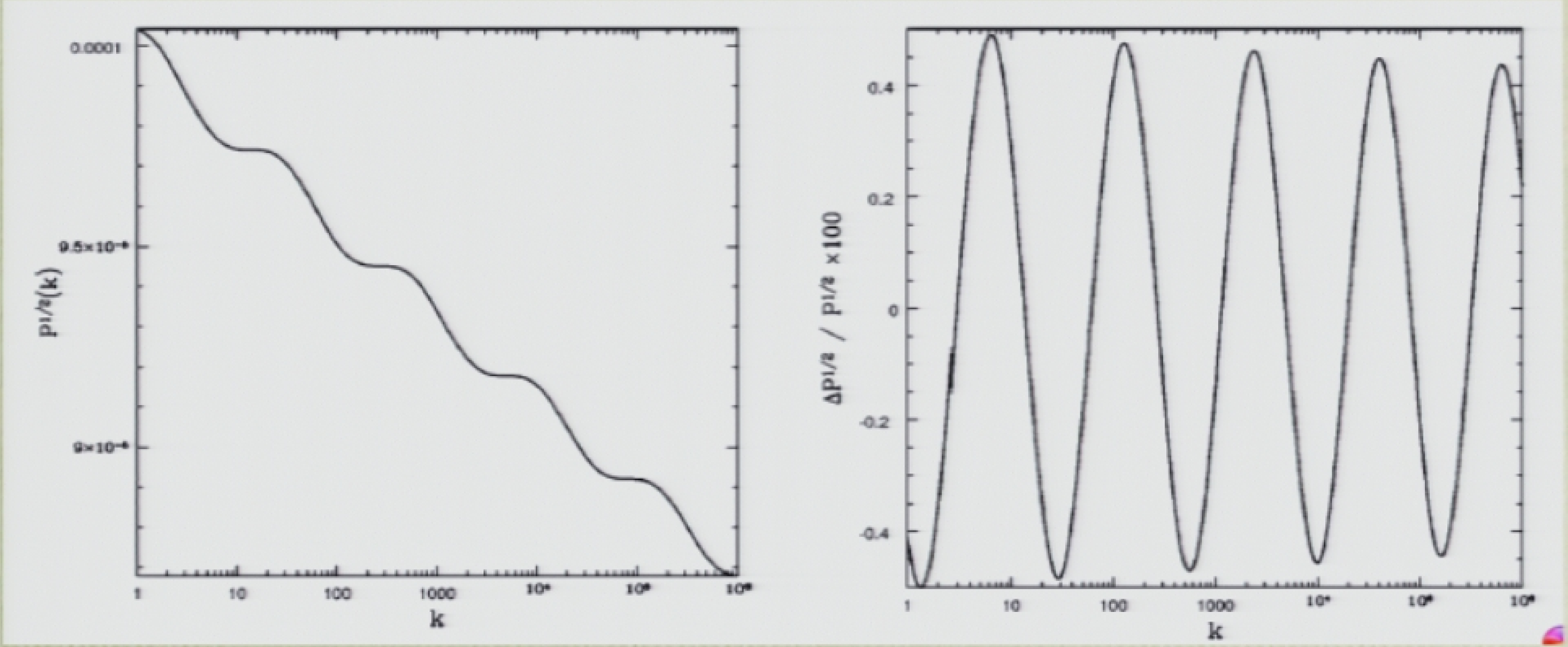
$$P_{TP} = \left\{1 + \left(\frac{H_*}{M}\right)\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{M}{H_*}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]\right\} P$$

Amplitude

Modulation

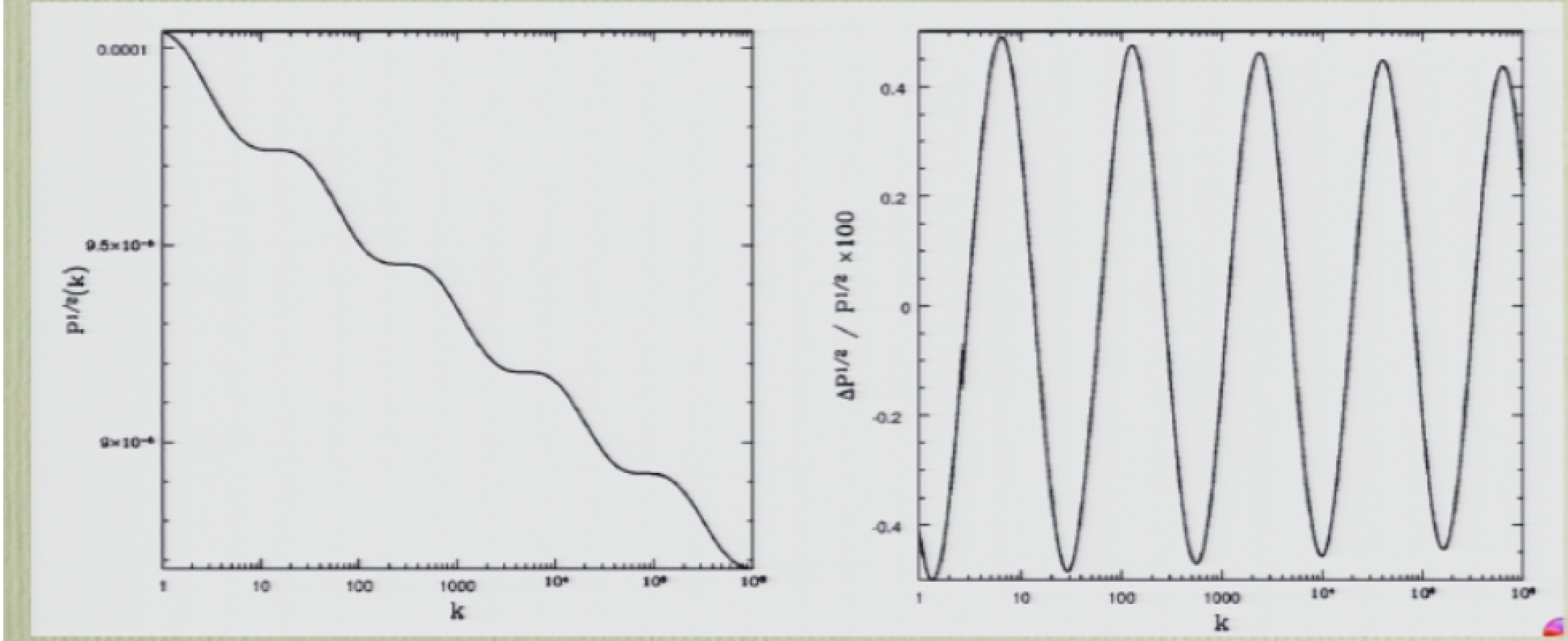
Phase

Modulated Spectrum



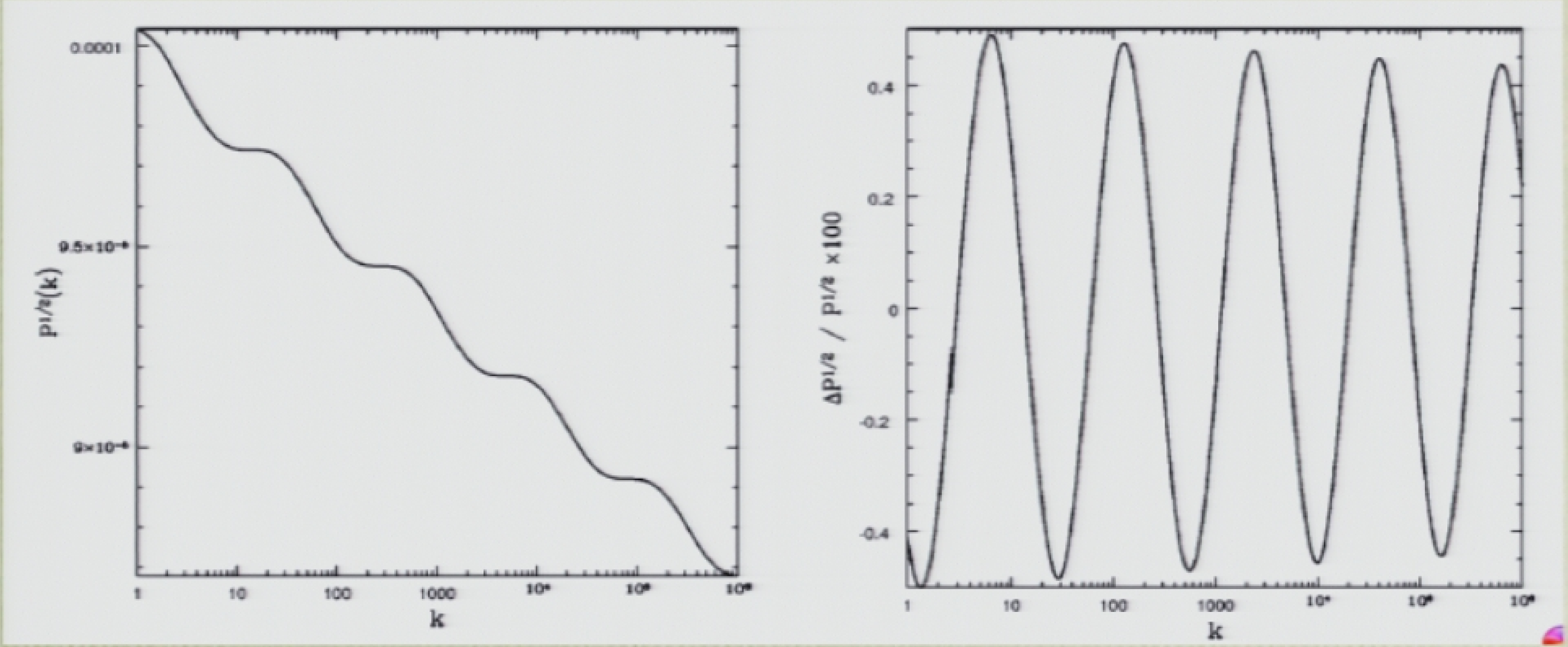
- $p=100$, $\varepsilon = .01$, $H/M = 100$
- Tensor to scalar ratio expected: H changes slowly.

Modulated Spectrum



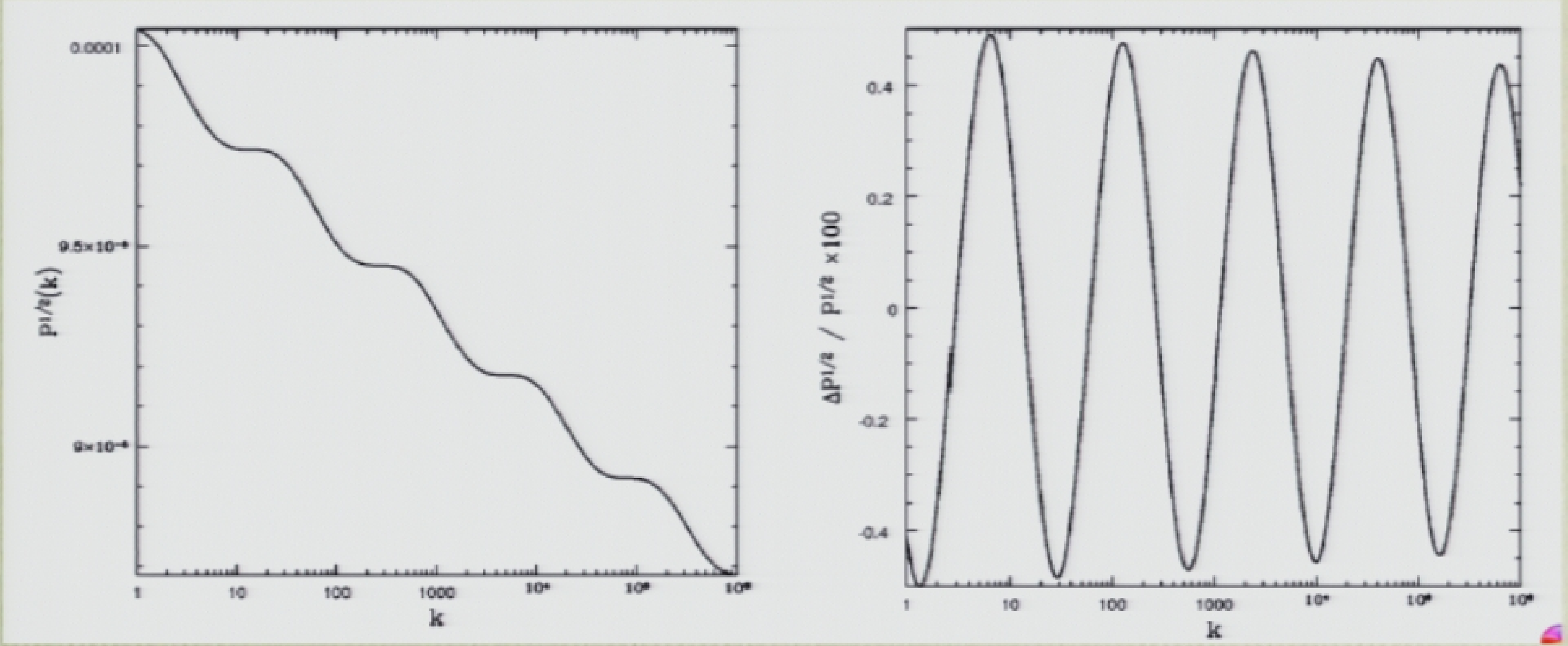
- p=100, ε = .01, H/M = 100
- Tensor to scalar ratio expected: H changes slowly.

Modulated Spectrum



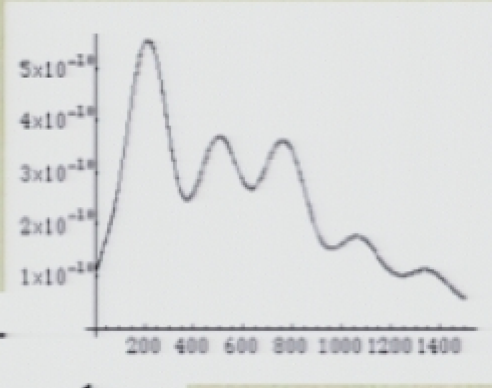
- p=100, ε = .01, H/M = 100
- Tensor to scalar ratio expected: H changes slowly.

Modulated Spectrum

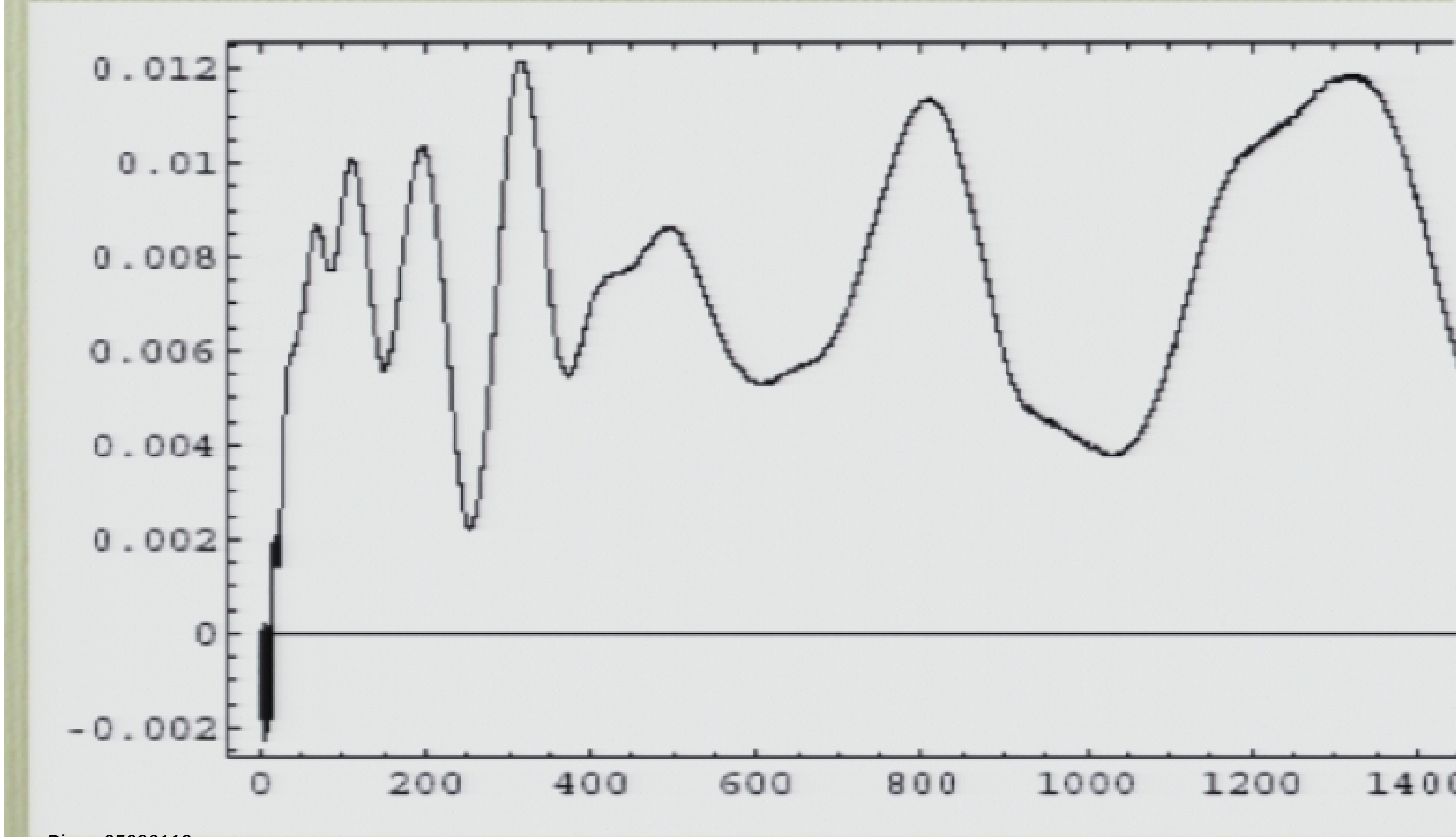


- $p=100$, $\varepsilon = .01$, $H/M = 100$
- Tensor to scalar ratio expected: H changes slowly.

Impact on C_l

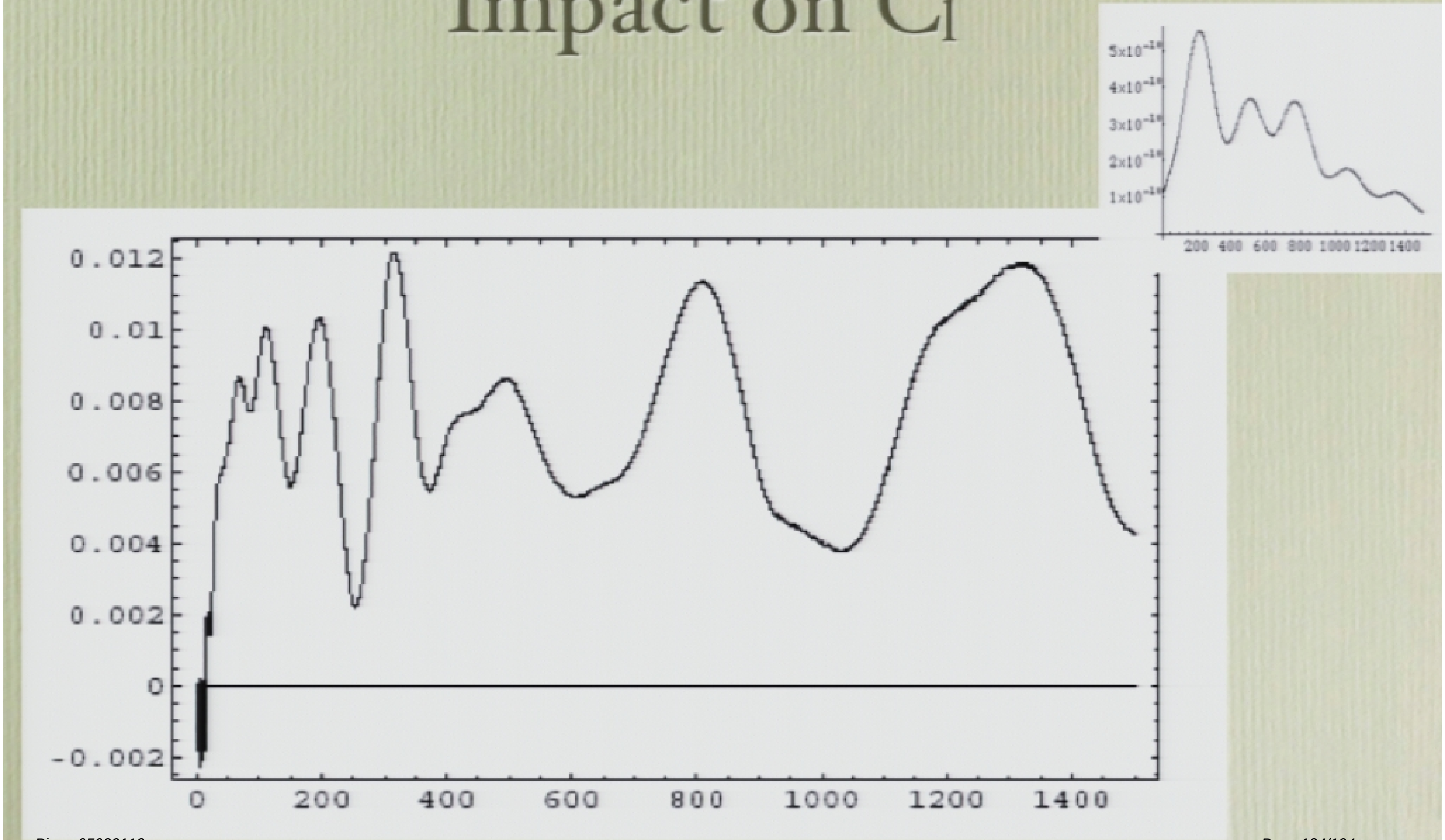


5×10^{-10}
4×10^{-10}
3×10^{-10}
2×10^{-10}
1×10^{-10}
200
400
600
800
1000
1200
1400

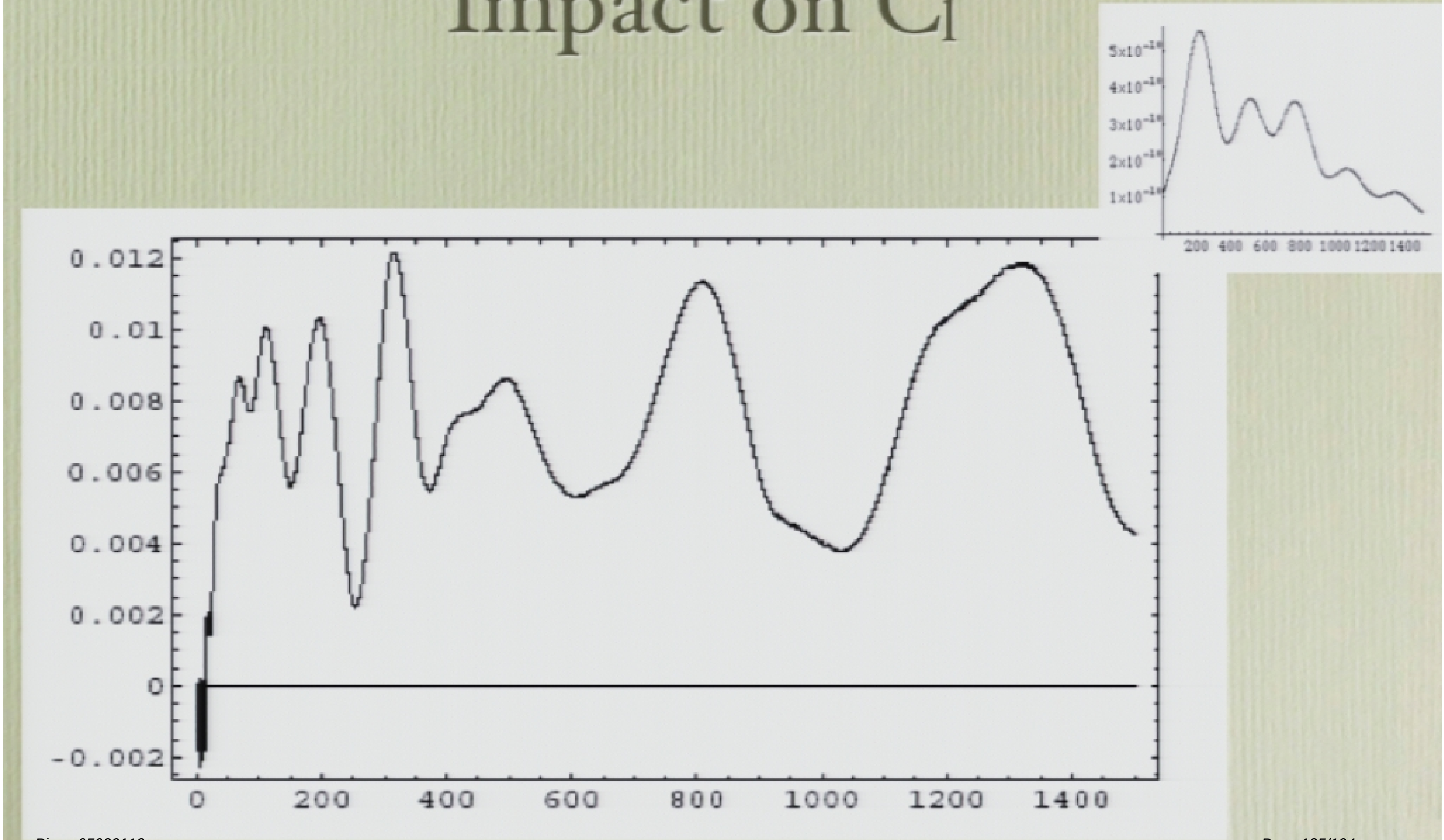


0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
200
400
600
800
1000
1200
1400

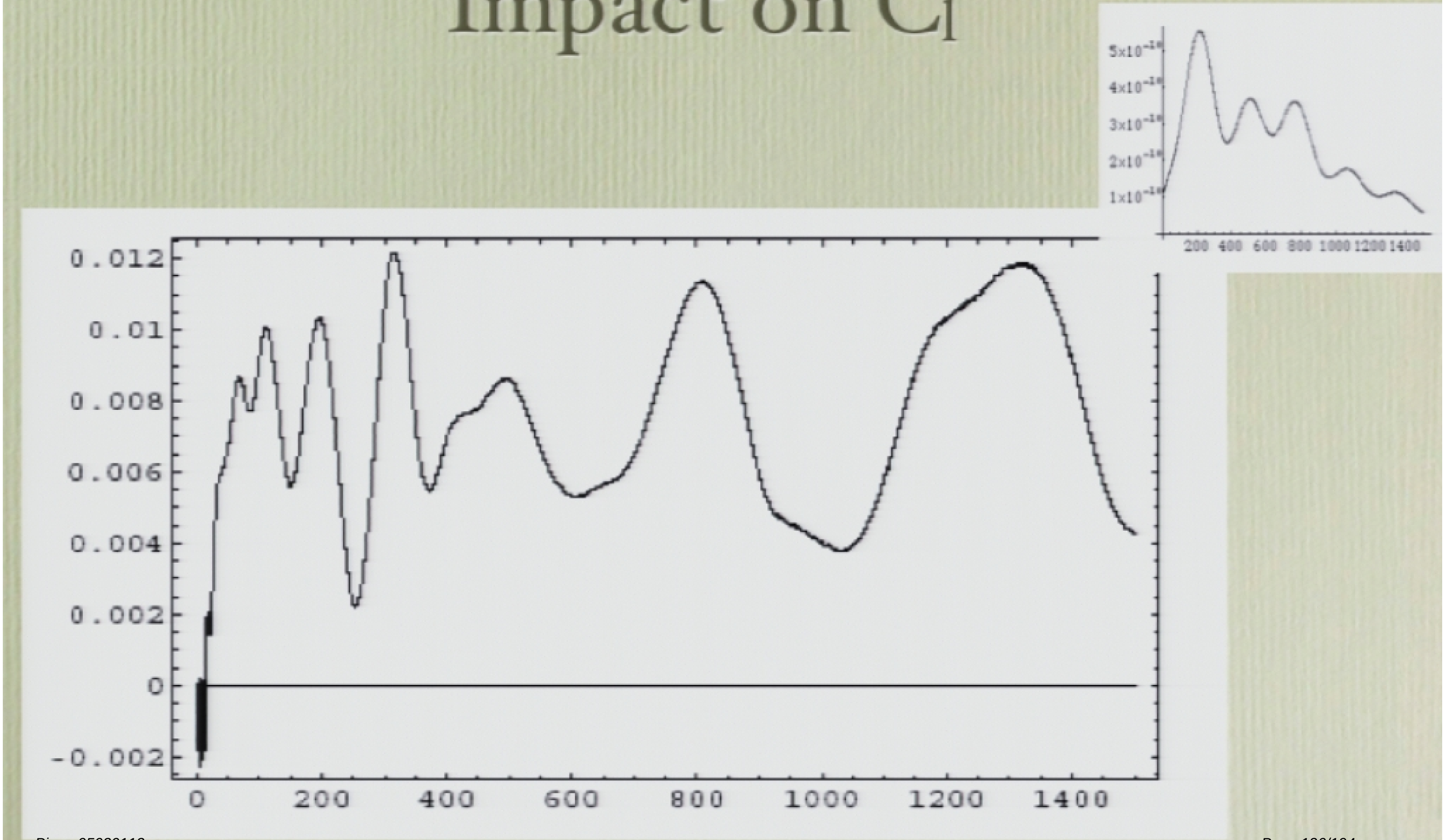
Impact on C_l


0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
200
400
600
800
1000
1200
1400
5×10^{-10}
4×10^{-10}
3×10^{-10}
2×10^{-10}
1×10^{-10}
200
400
600
800
1000
1200
1400

Impact on C_l

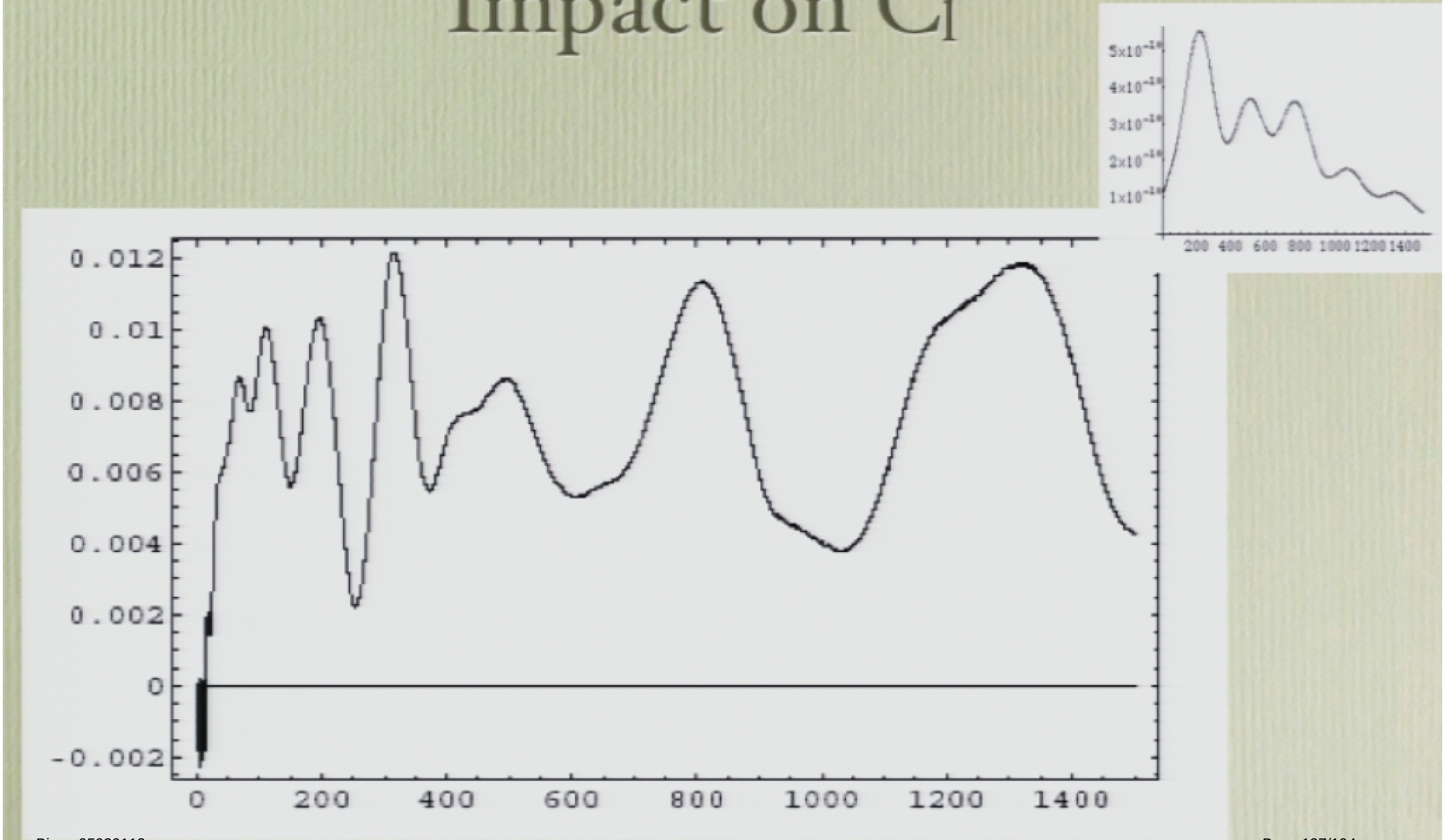

0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
200
400
600
800
1000
1200
1400
5x10⁻¹⁰
4x10⁻¹⁰
3x10⁻¹⁰
2x10⁻¹⁰
1x10⁻¹⁰
200
400
600
800
1000
1200
1400

Impact on C_l



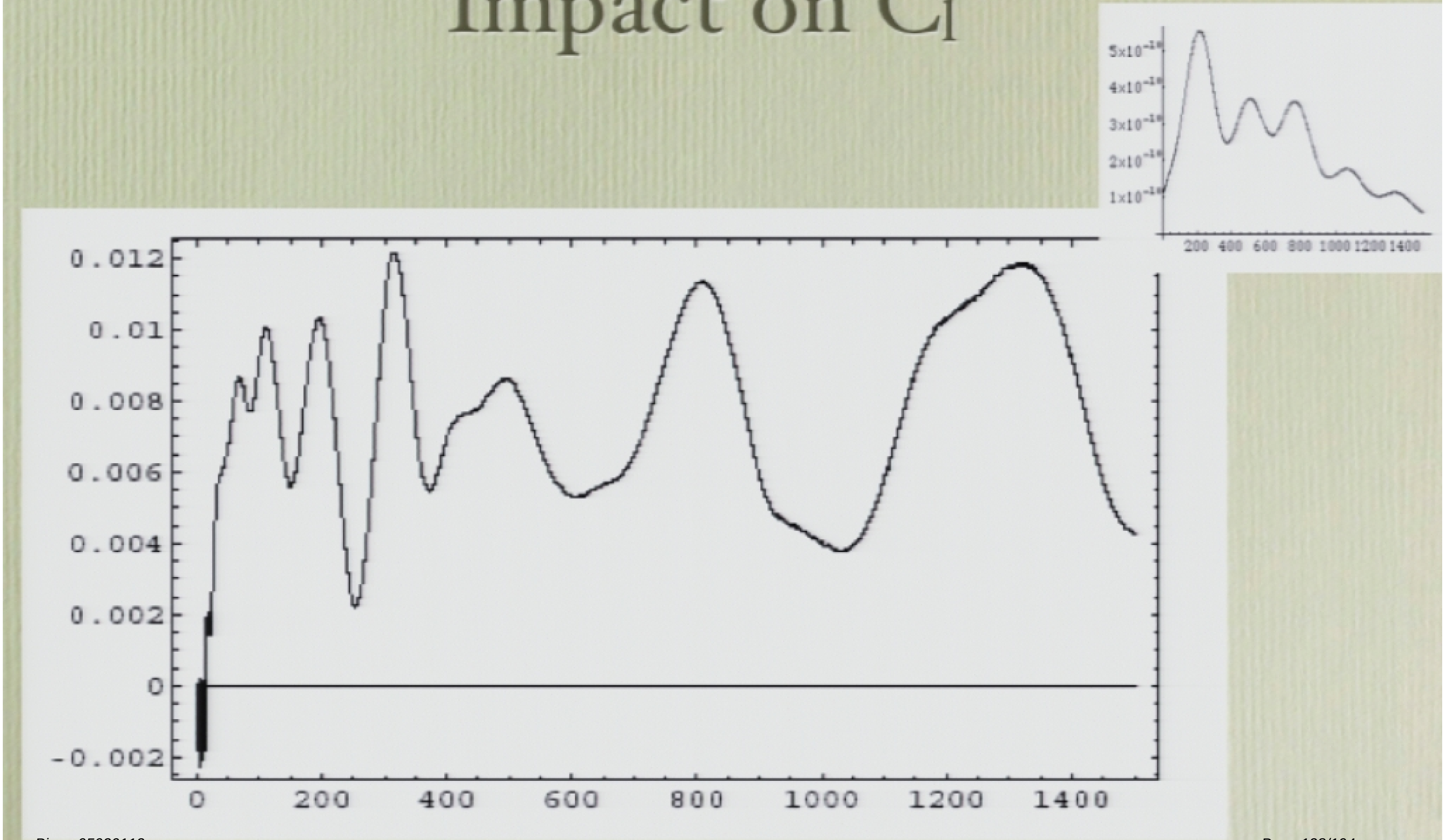
5x10^-10
4x10^-10
3x10^-10
2x10^-10
1x10^-10
200
400
600
800
1000
1200
1400
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
200
400
600
800
1000
1200
1400

Impact on C_l



0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
200
400
600
800
1000
1200
1400
5×10^{-10}
4×10^{-10}
3×10^{-10}
2×10^{-10}
1×10^{-10}
200
400
600
800
1000
1200
1400

Impact on C_l


5x10
4x10
3x10
2x10
1x10
200
400
600
800
1000
1200
1400
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
200
400
600
800
1000
1200
1400

Computational Strategy

- Look at synthetic CMB datasets
  - Cosmic variance, noise free, weak lensing
  - l<2000, {TT,TE,EE,BB}
- Assume central values from WMAP
  - Allow late time parameters to float.
  - Vary spectral index, running, tensor to scalar ratio, trans-Planck parameters.
- Multiple peaks in probability space
  - Fisher matrix calculation
  - Grid search
  - Monte Carlo Markov chains (MCMC)

Computational Strategy

- Look at synthetic CMB datasets
  - Cosmic variance, noise free, weak lensing
  - l<2000, {TT,TE,EE,BB}
- Assume central values from WMAP
  - Allow late time parameters to float.
  - Vary spectral index, running, tensor to scalar ratio, trans-Planck parameters.
- Multiple peaks in probability space
  - Fisher matrix calculation
  - Grid search
  - Monte Carlo Markov chains (MCMC)

Markov Chain Results

- Fisher matrix computed at a point in parameter space: already critiqued in this context.

- Grid search too slow with many parameters

- Markov chains are fast
  - Linear with # of parameters
  - Well understood / easy to implement
  - Standard tool in CMB physics today

- Computationally demanding problem

Markov Chain Results

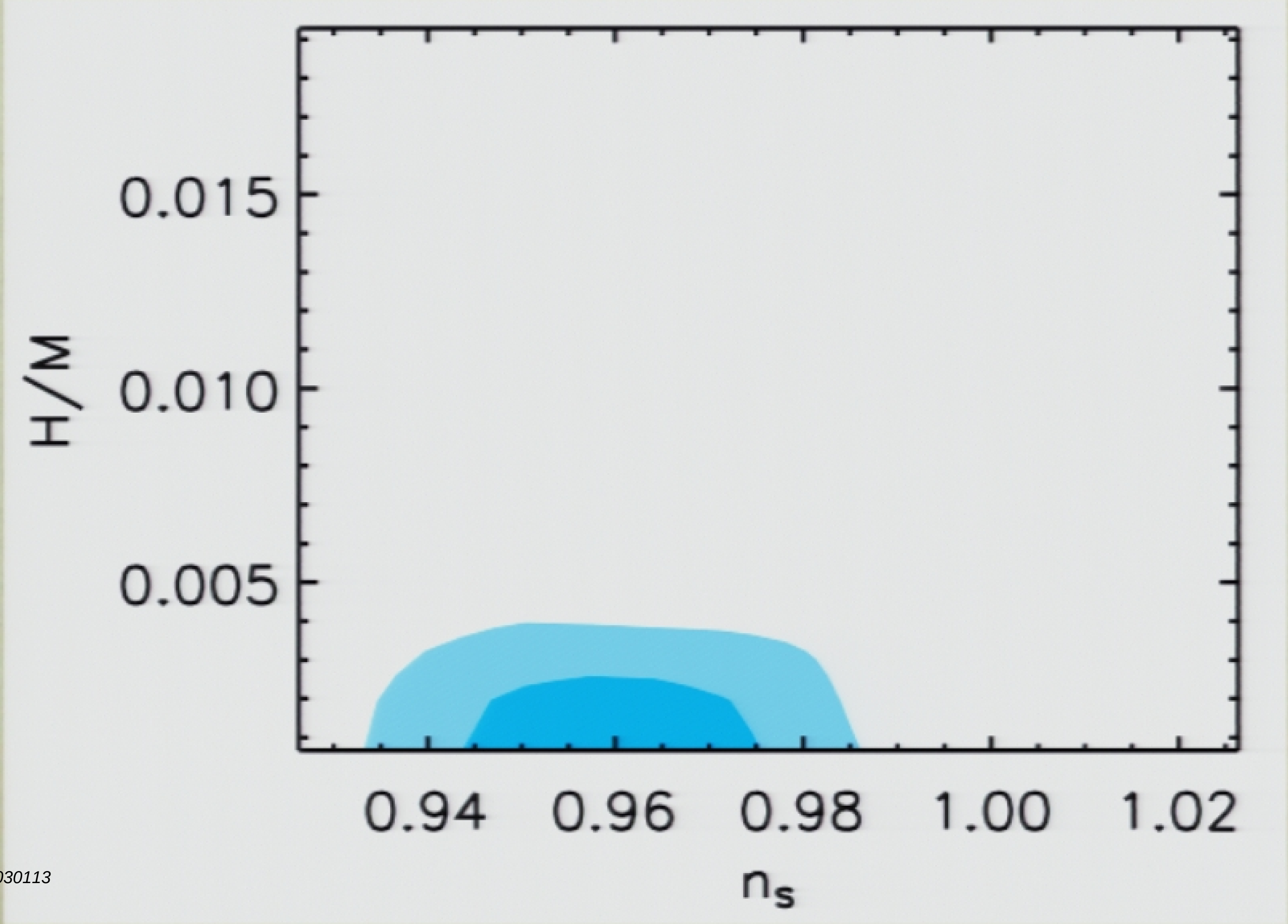
- Fisher matrix computed at a point in parameter space: already critiqued in this context.

- Grid search too slow with many parameters

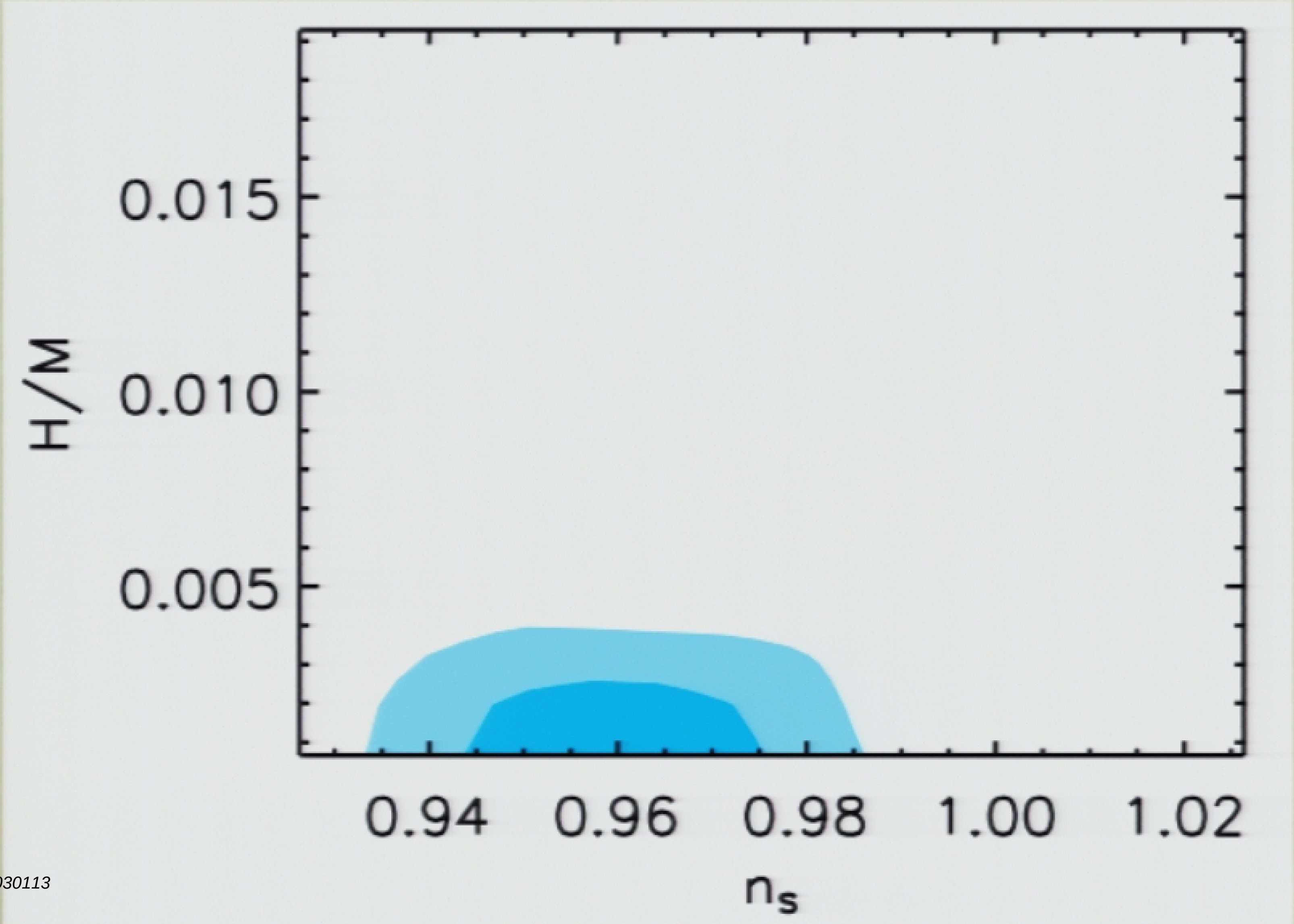
- Markov chains are fast
  - Linear with # of parameters
  - Well understood / easy to implement
  - Standard tool in CMB physics today

- Computationally demanding problem

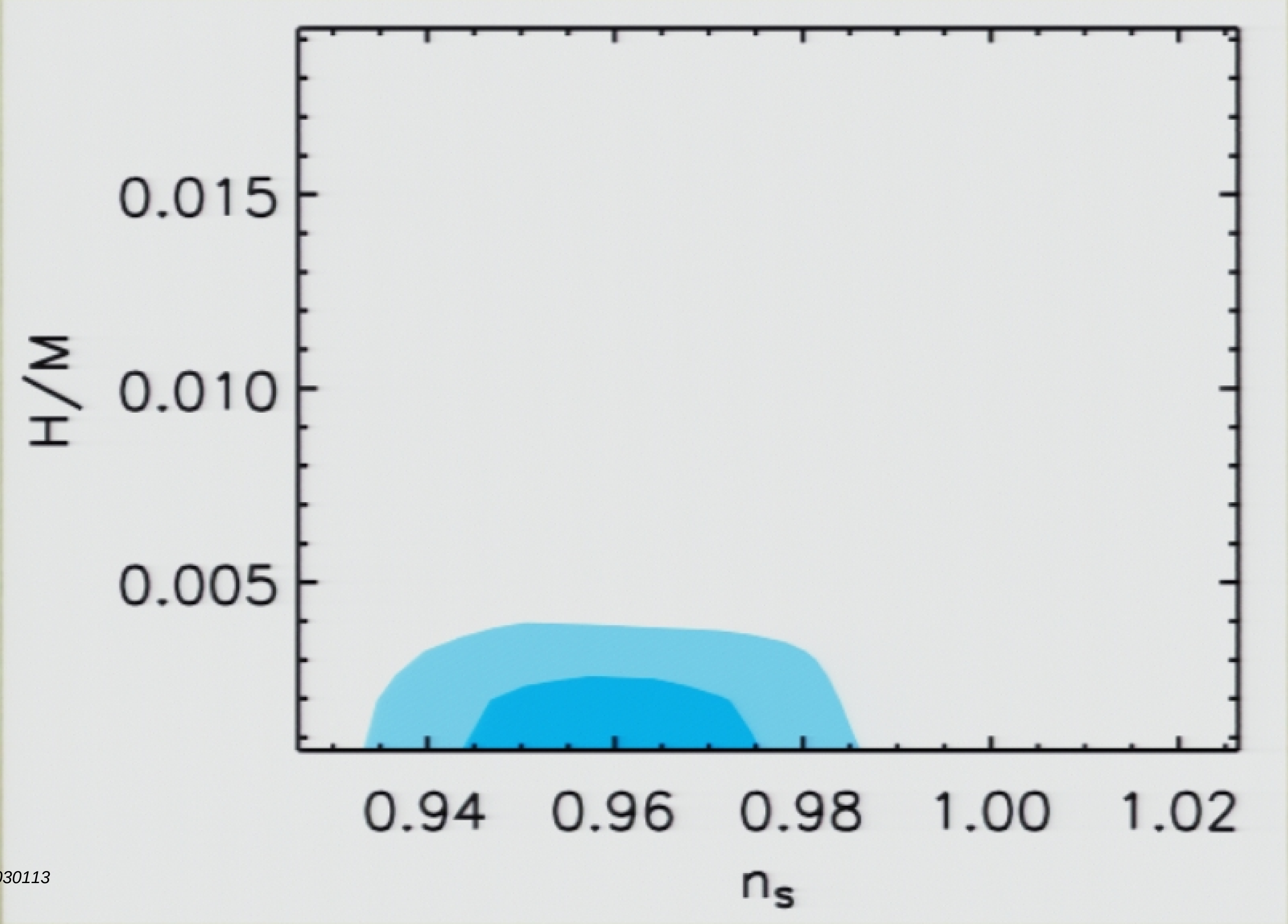
r=0.15; H/M < 0.004



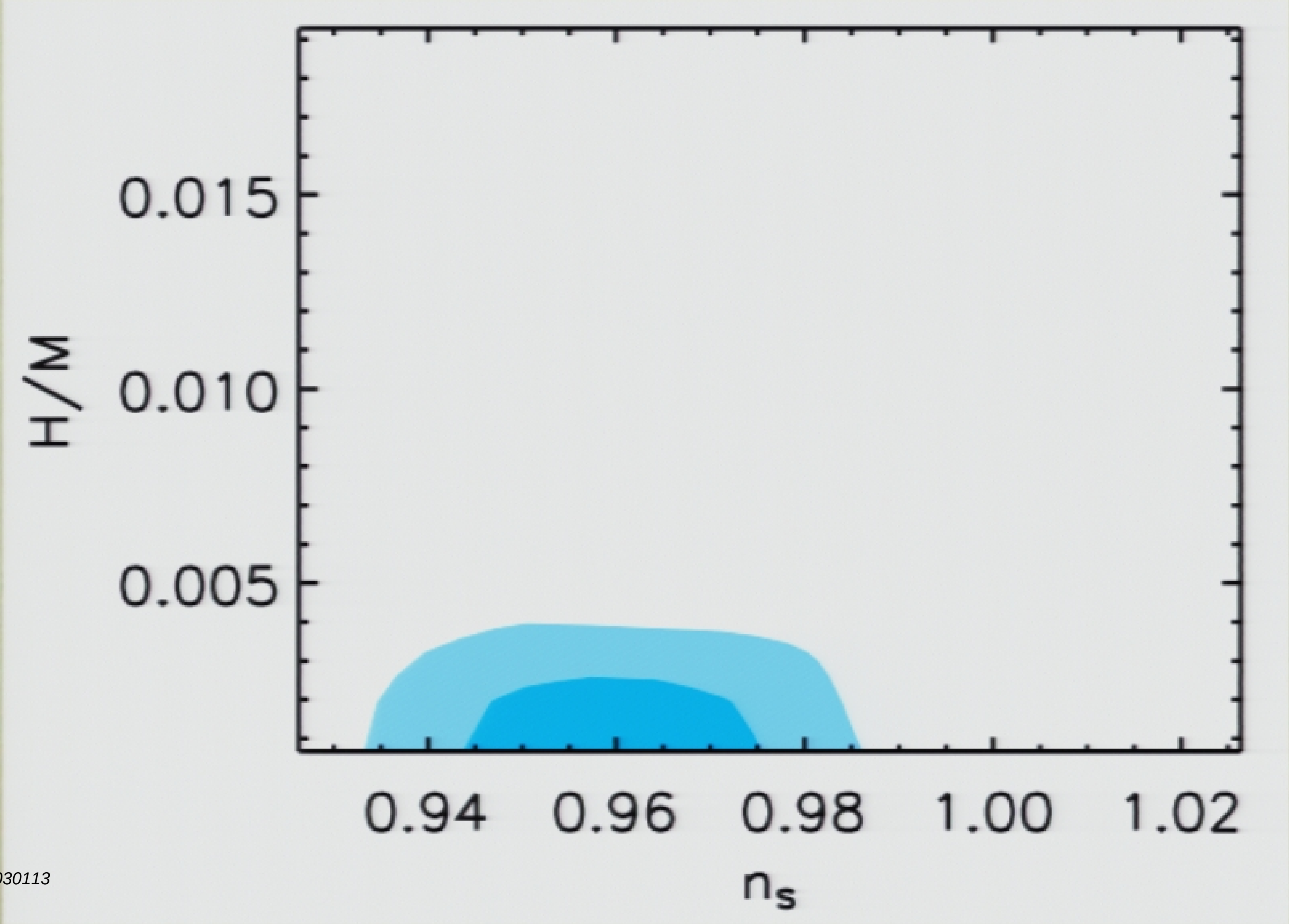
r=0.15; H/M < 0.004



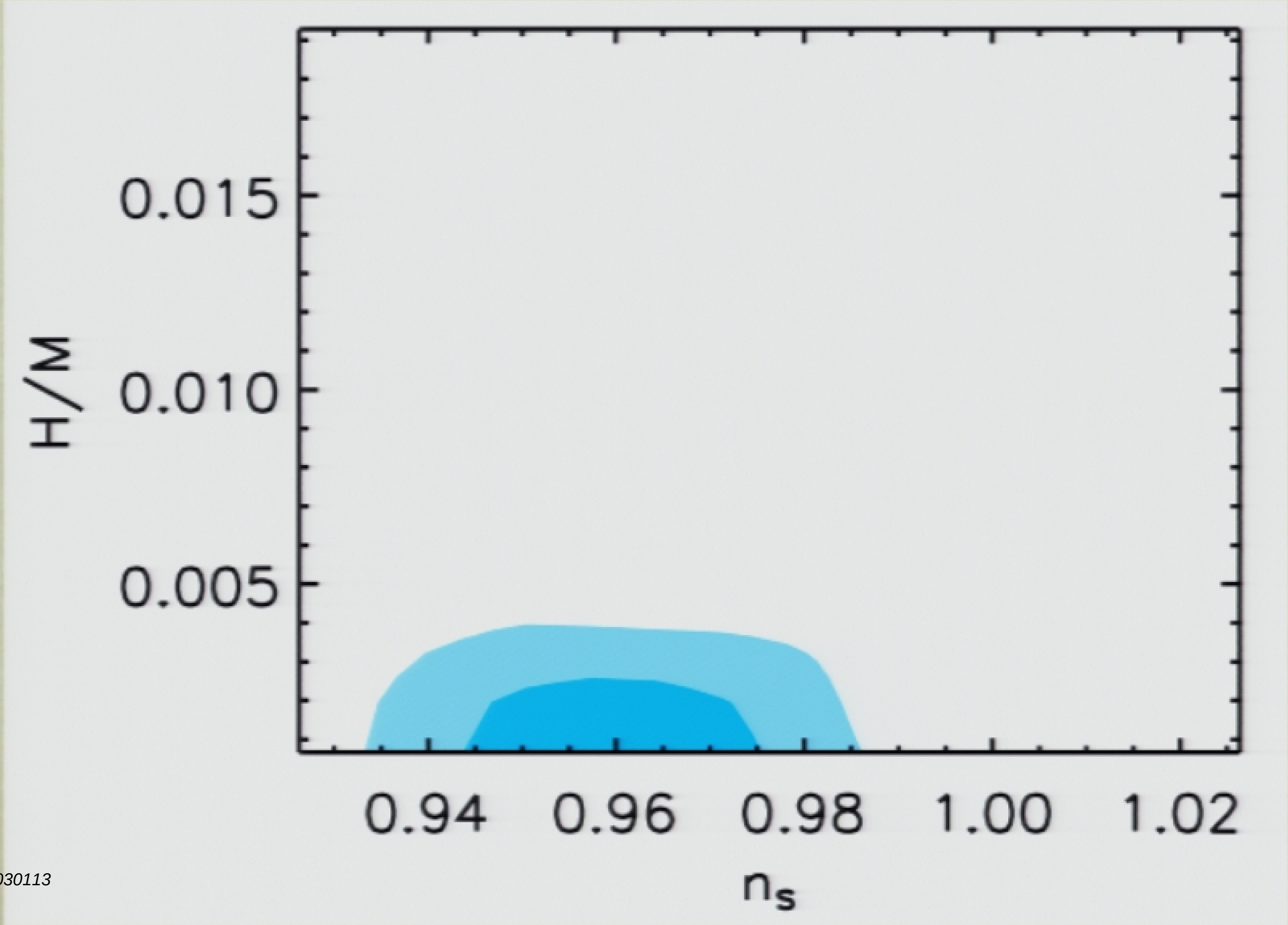
$r=0.15$; $H/M < 0.004$



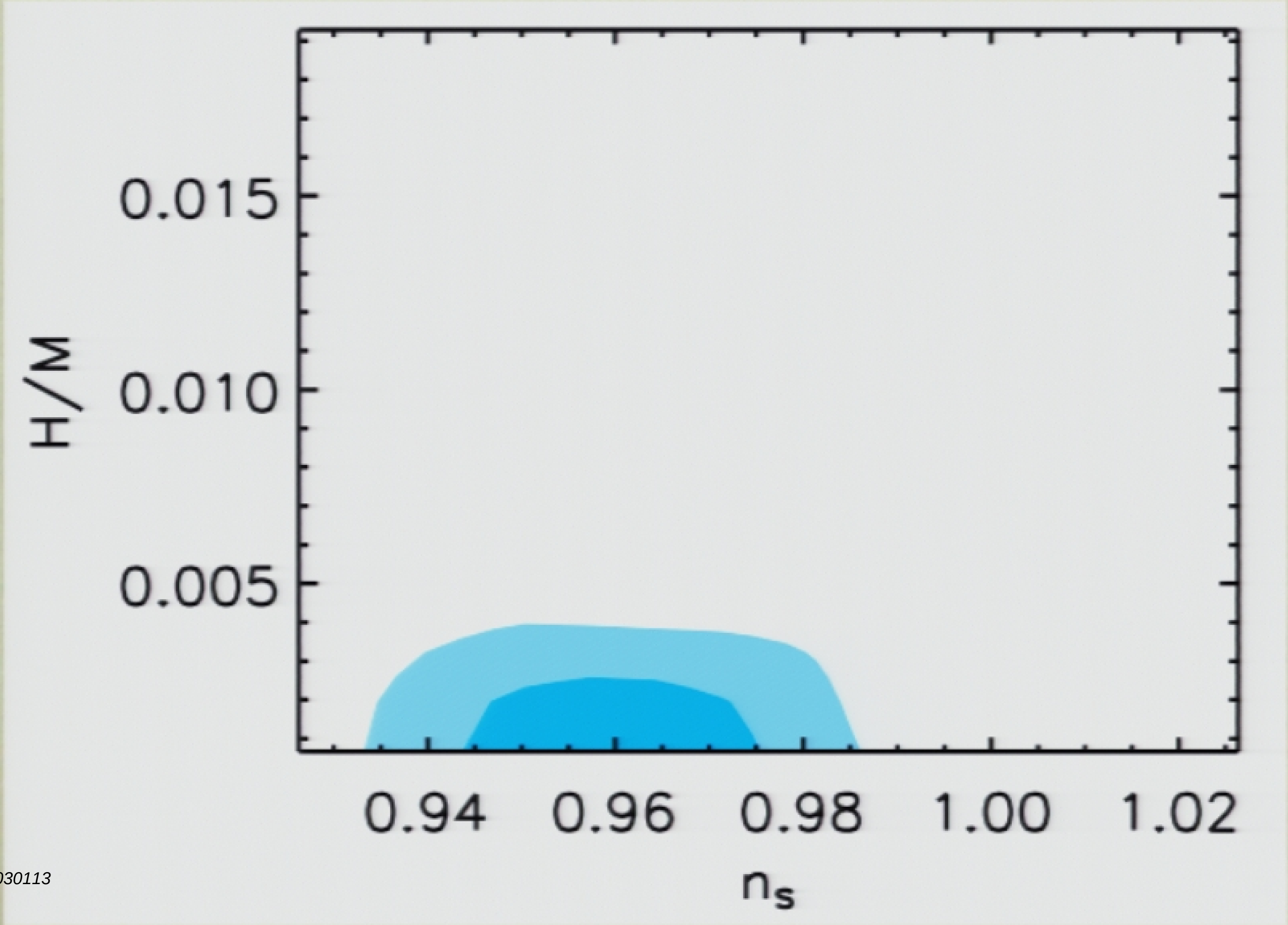
r=0.15; H/M < 0.004



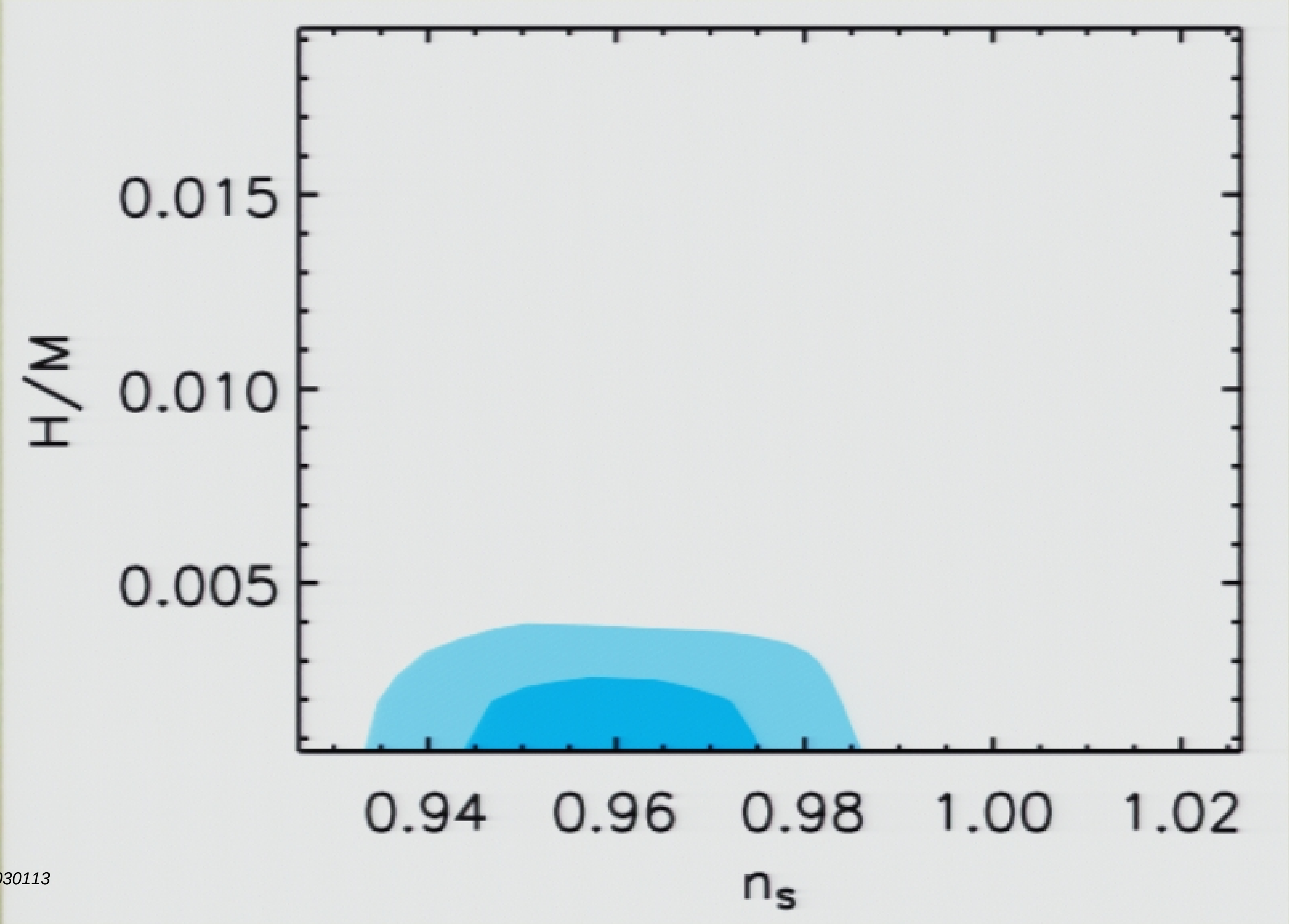
$r=0.15$; $H/M < 0.004$



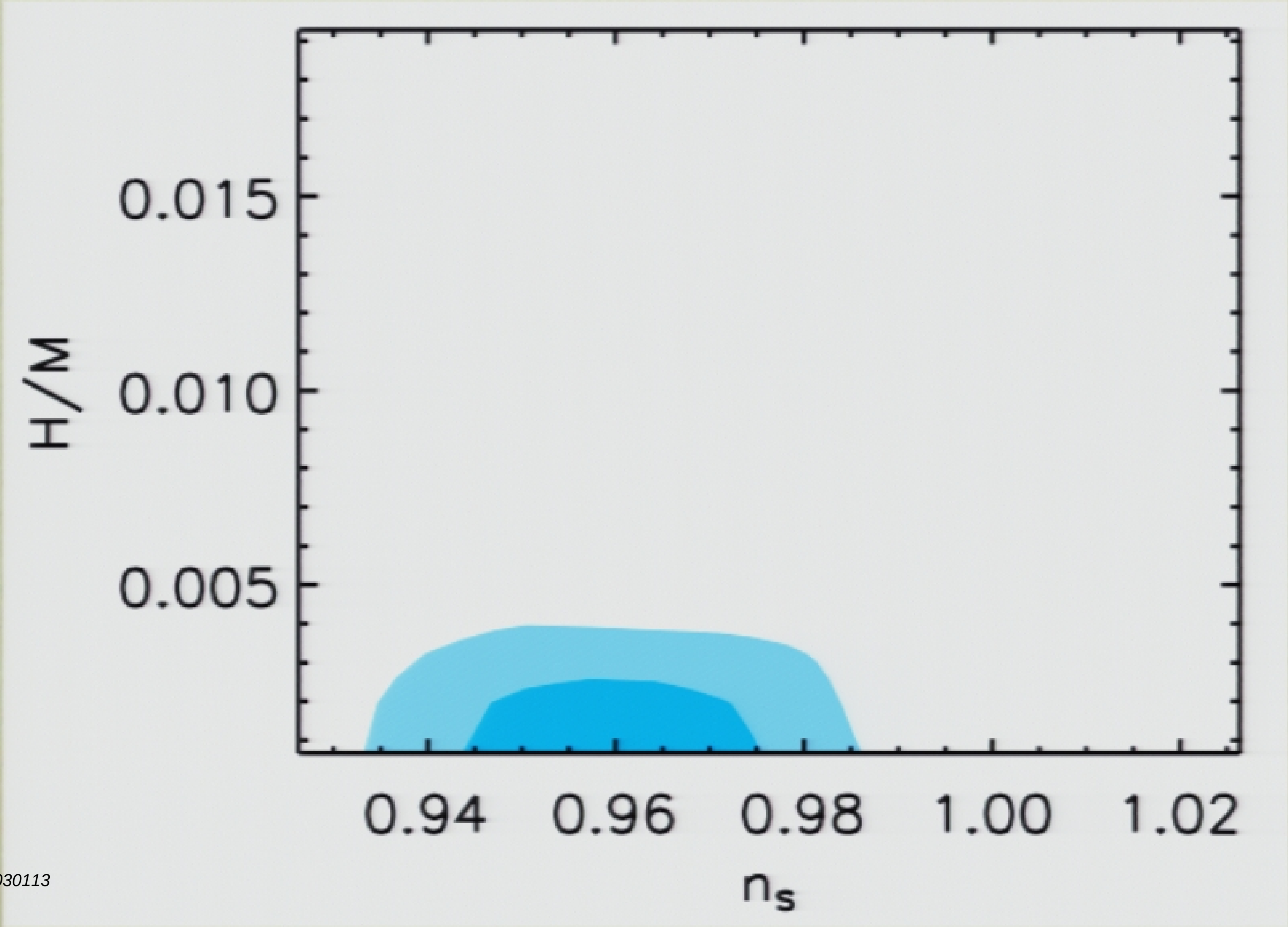
$r = 0.15$; $H/M < 0.004$



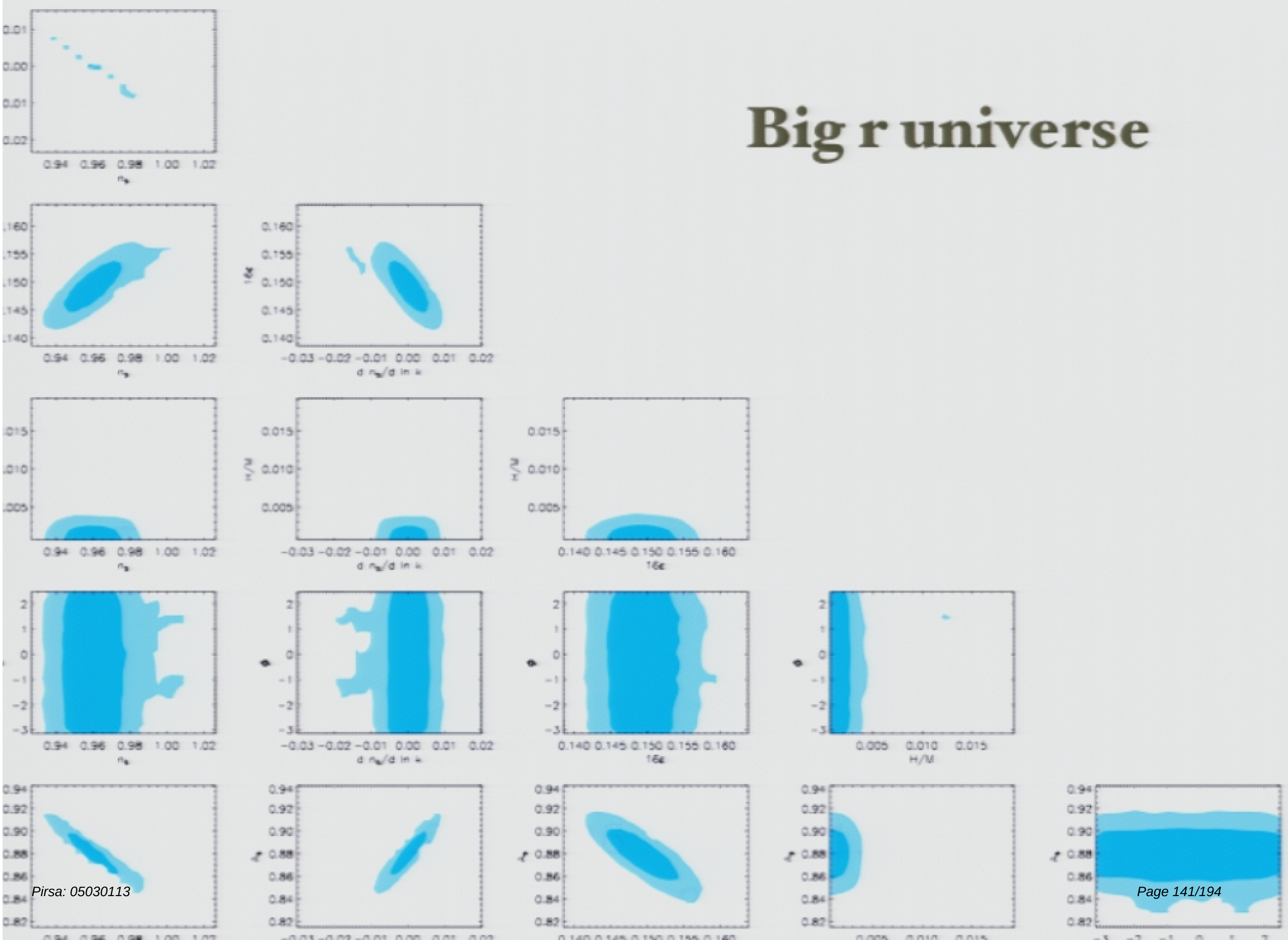
r=0.15; H/M < 0.004



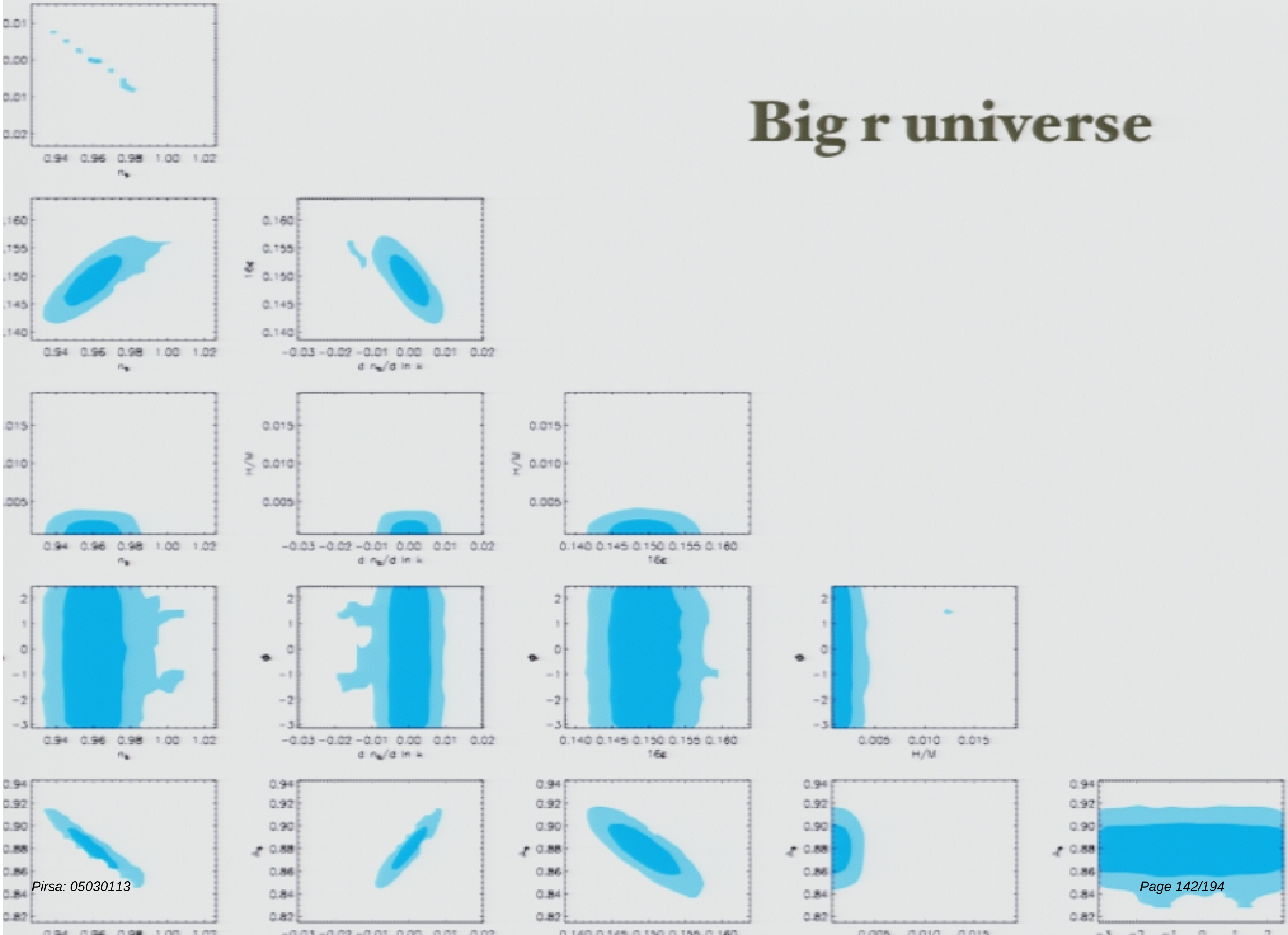
r=0.15; H/M < 0.004



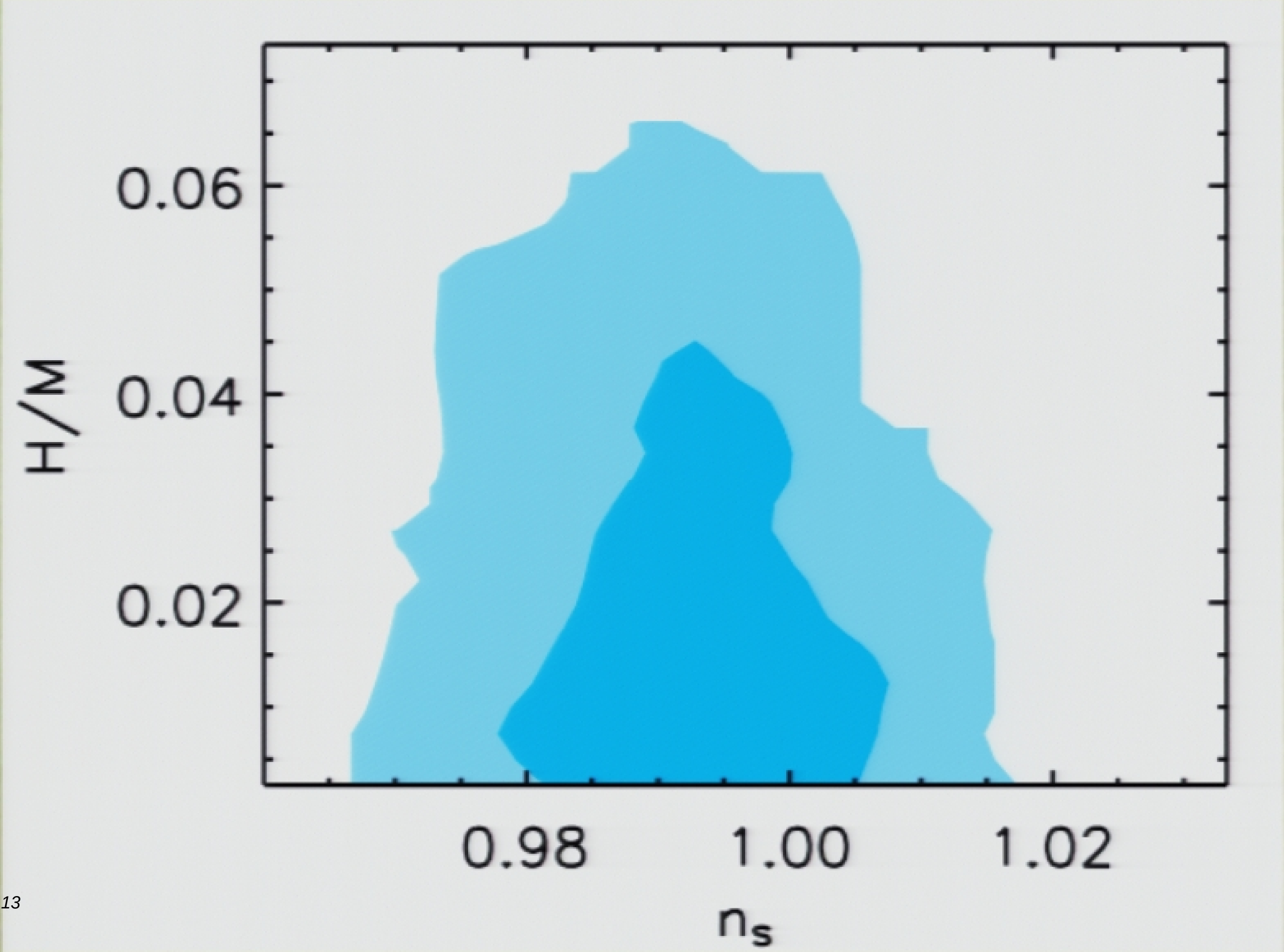
Big r universe



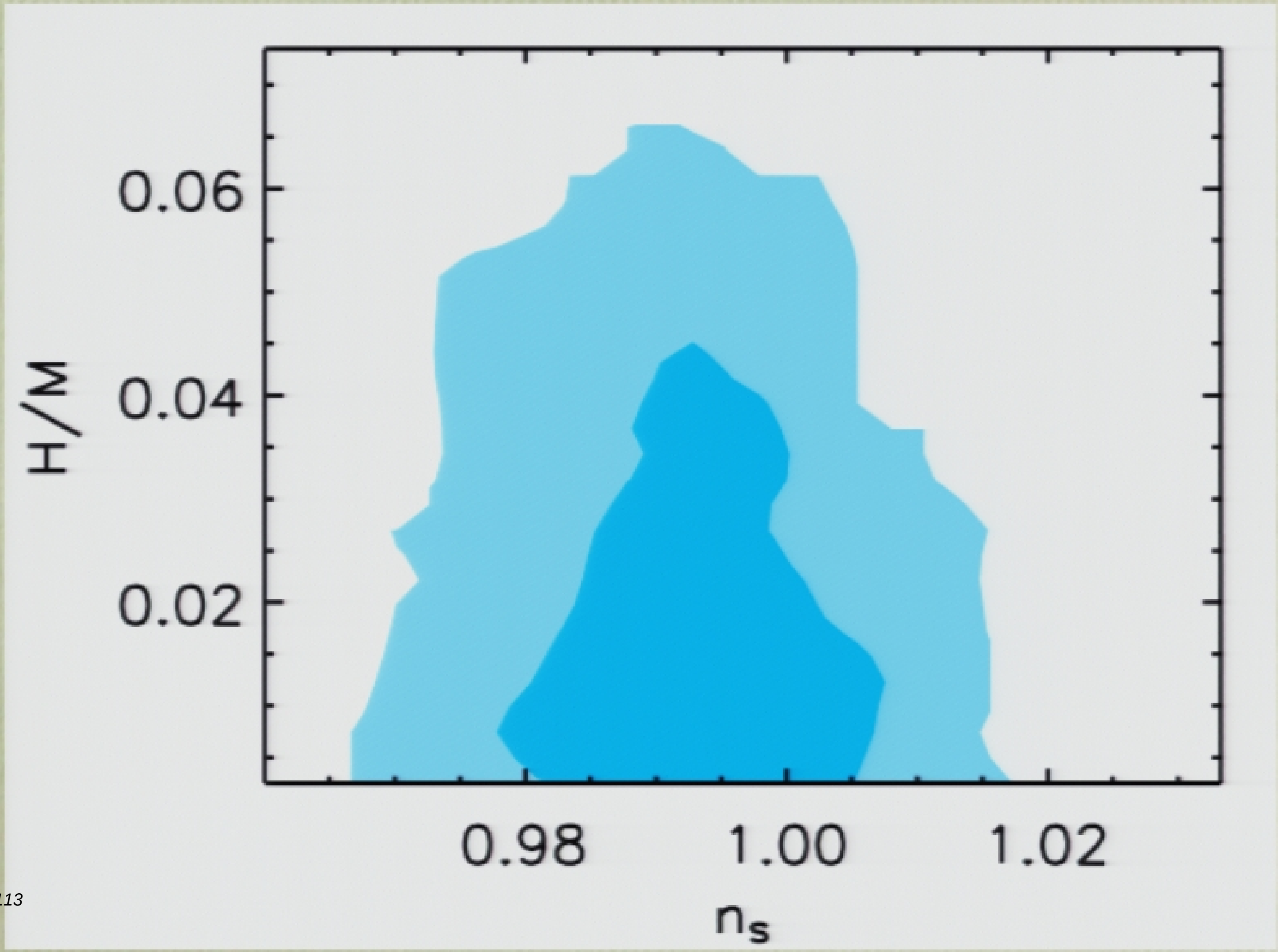
Big r universe



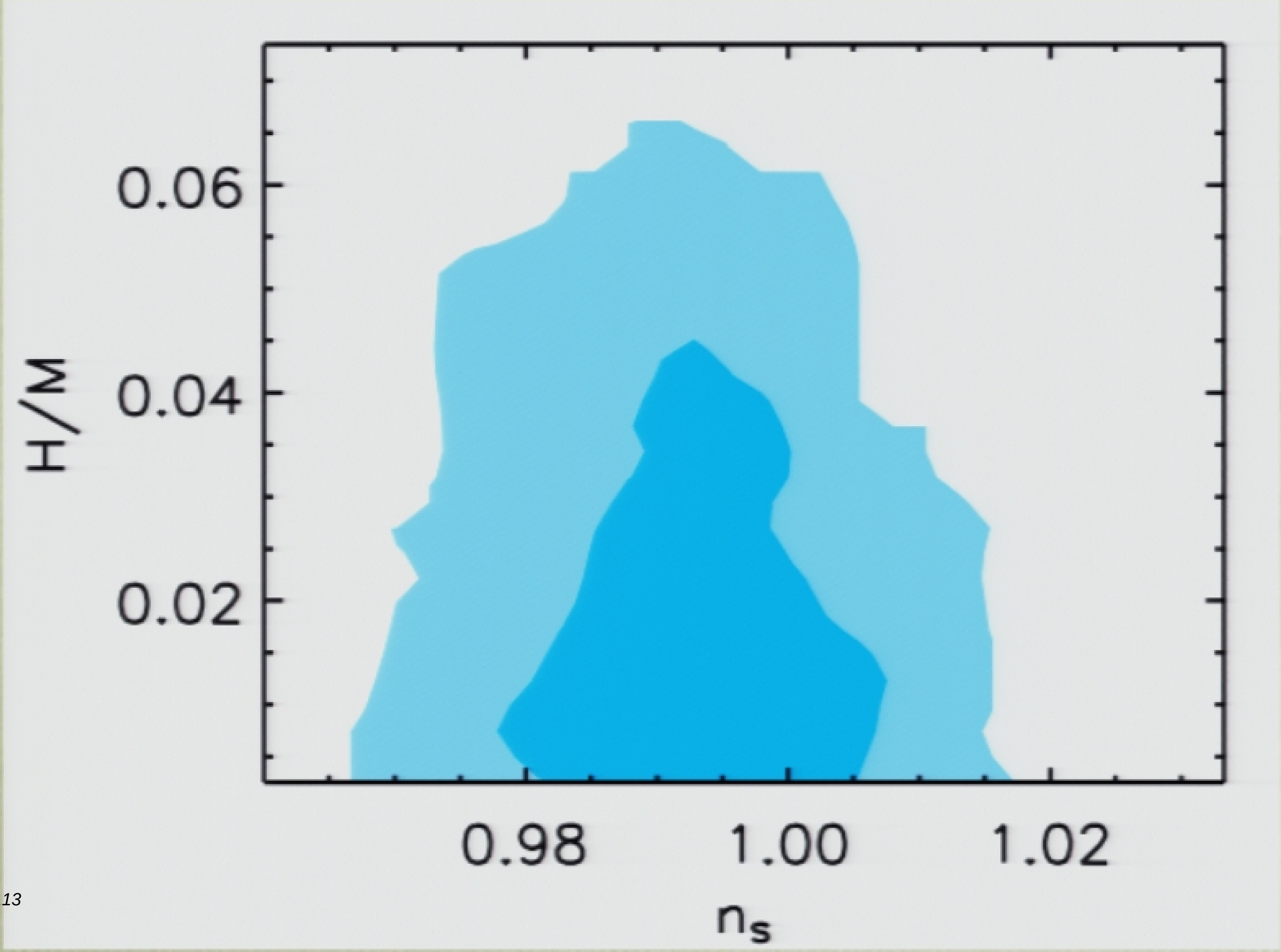
r=0.00013; H/M<0.06



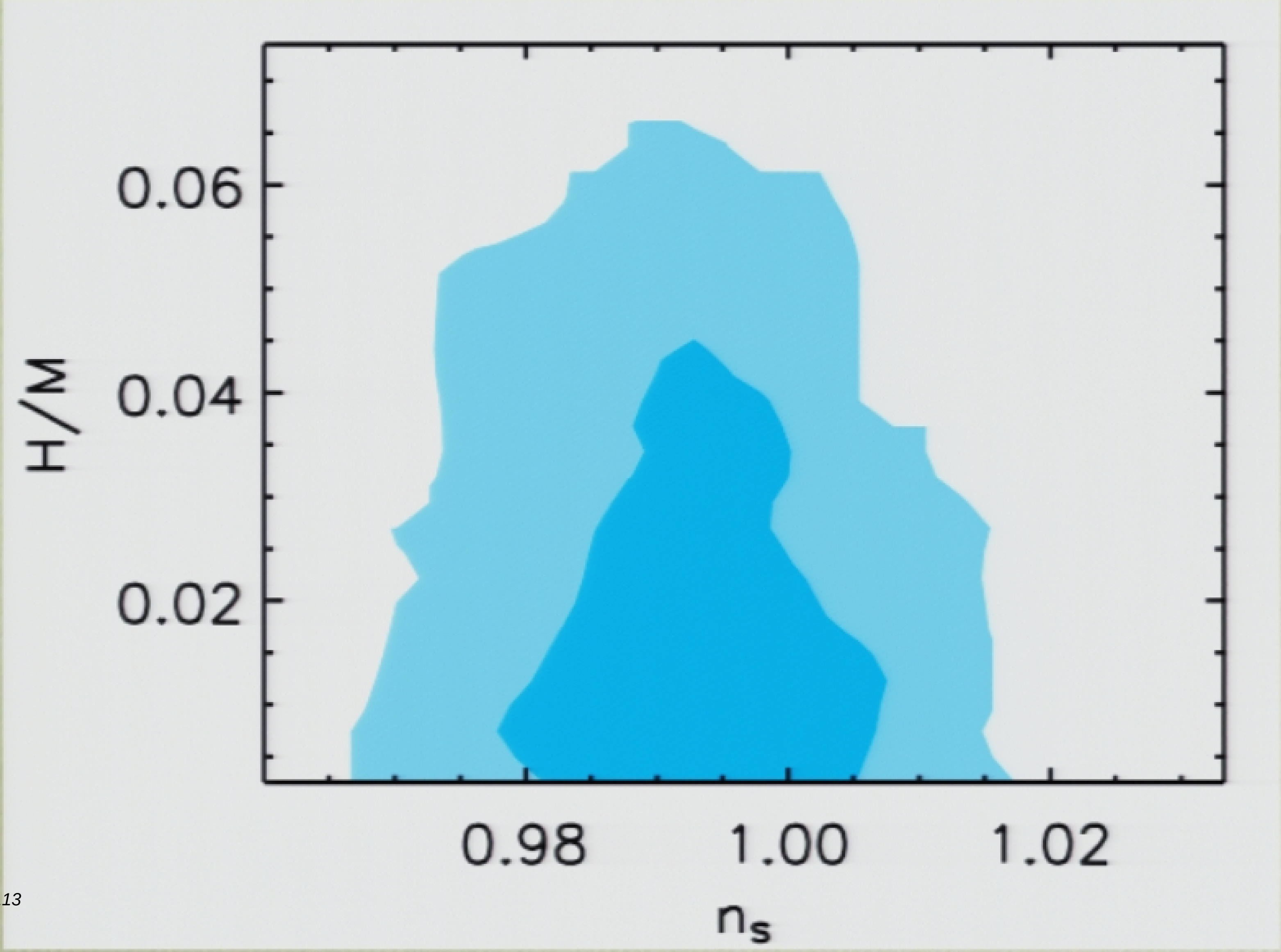
$r=0.00013$; $H/M<0.06$



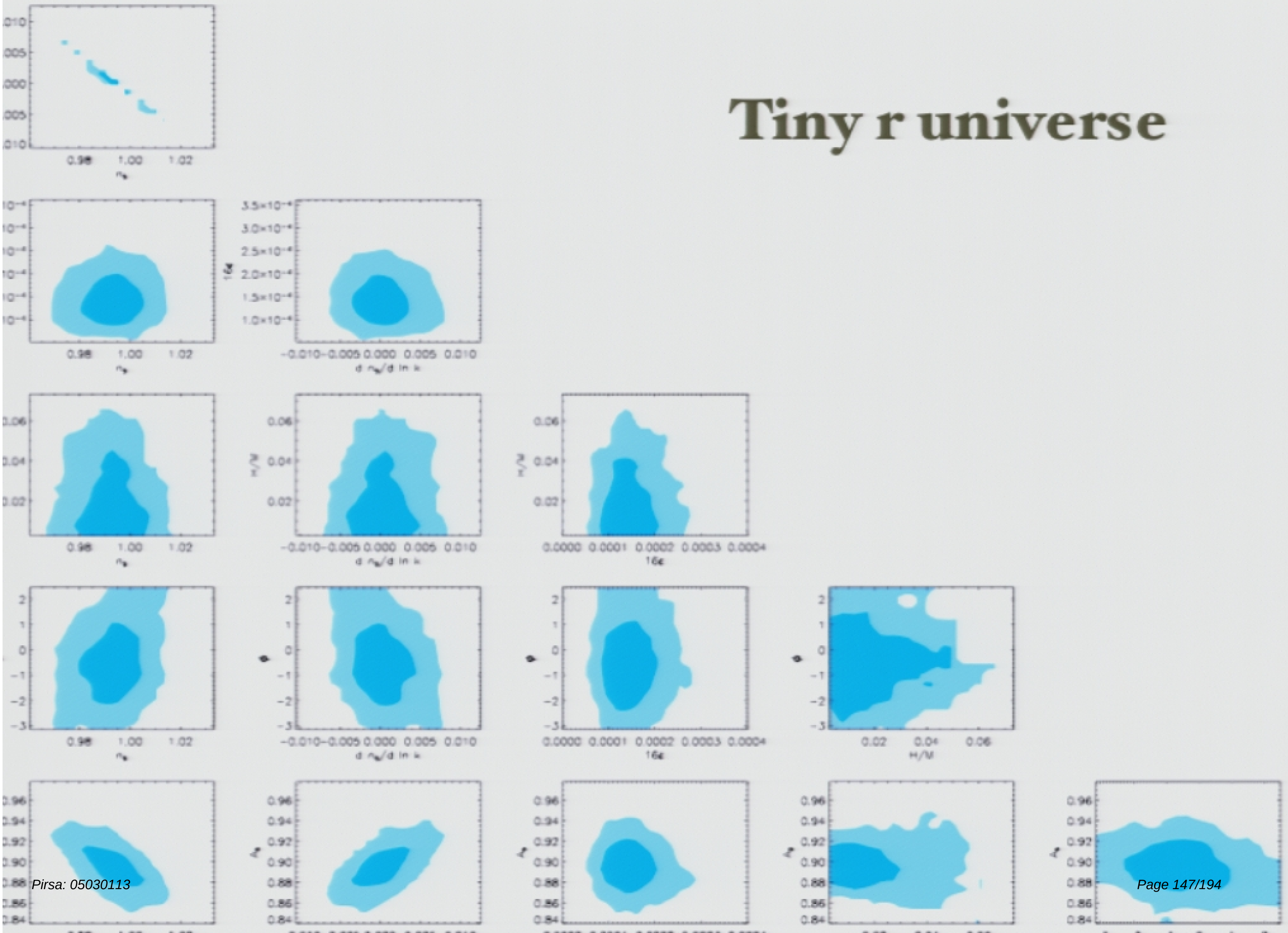
r=0.00013; H/M<0.06



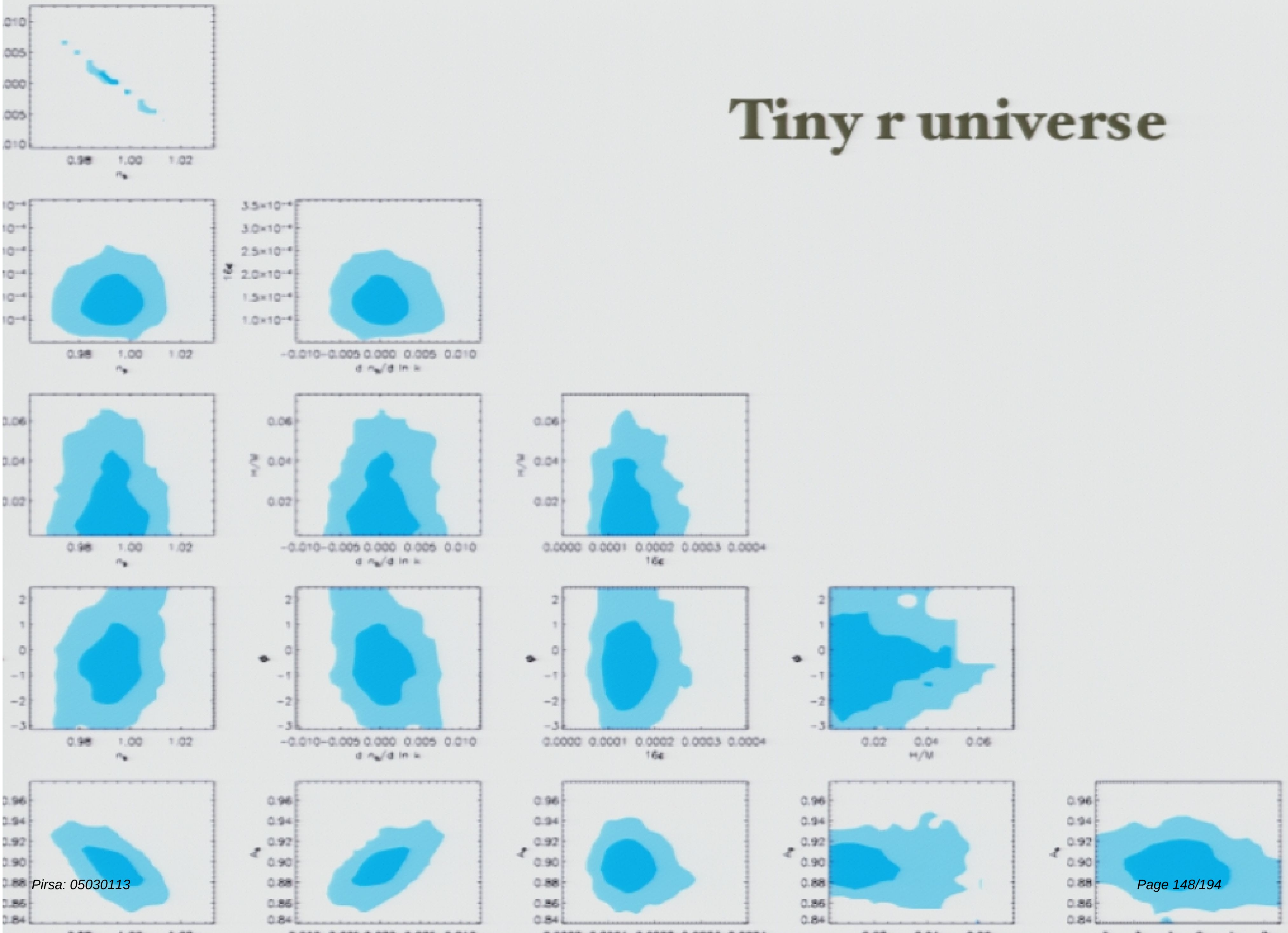
r=0.00013; H/M<0.06



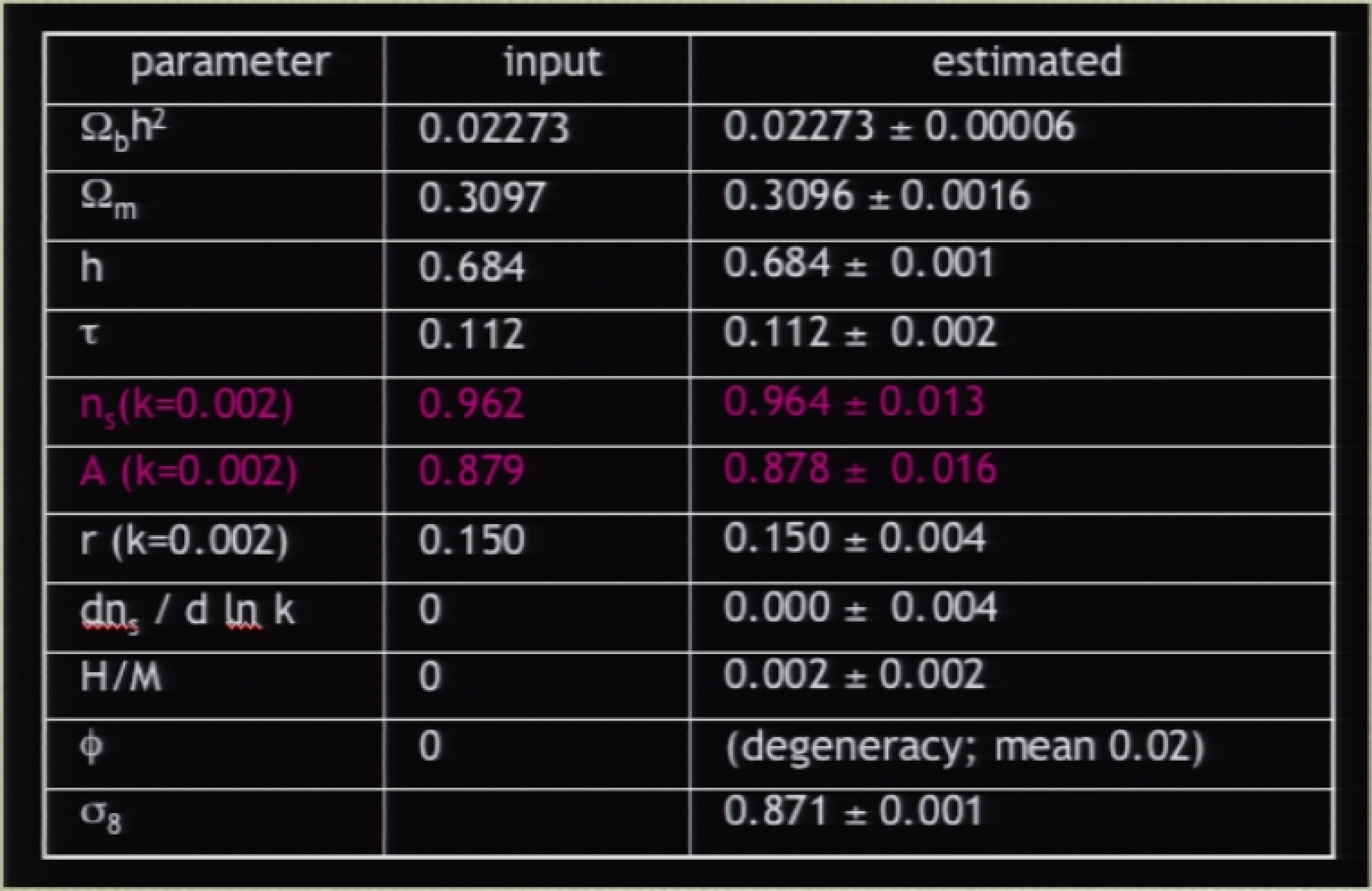
Tiny r universe



Tiny r universe

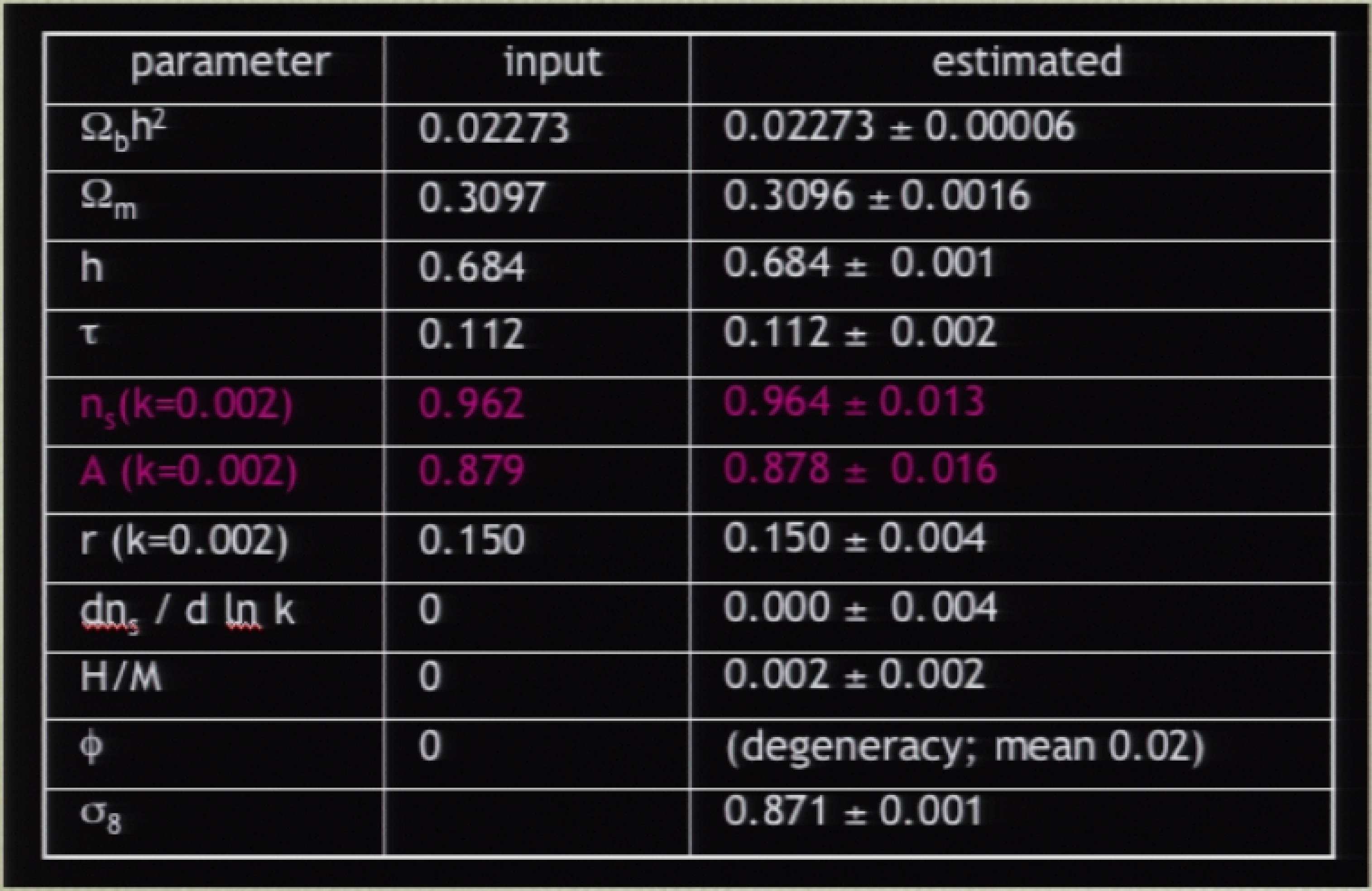


Parameter Recovery



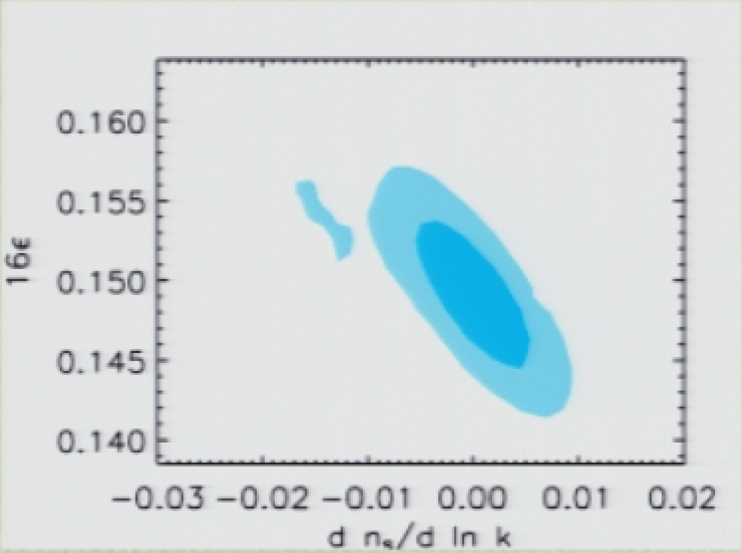
parameter	input	estimated
$\Omega_b h^2$	0.02273	0.02273 ± 0.00006
Ω_m	0.3097	0.3096 ± 0.0016
h	0.684	0.684 ± 0.001
τ	0.112	0.112 ± 0.002
n_s(k=0.002)	0.962	0.964 ± 0.013
A (k=0.002)	0.879	0.878 ± 0.016
r (k=0.002)	0.150	0.150 ± 0.004
dn_s / d ln k	0	0.000 ± 0.004
H/M	0	0.002 ± 0.002
ϕ	0	(degeneracy; mean 0.02)
σ_8		0.871 ± 0.001

Parameter Recovery



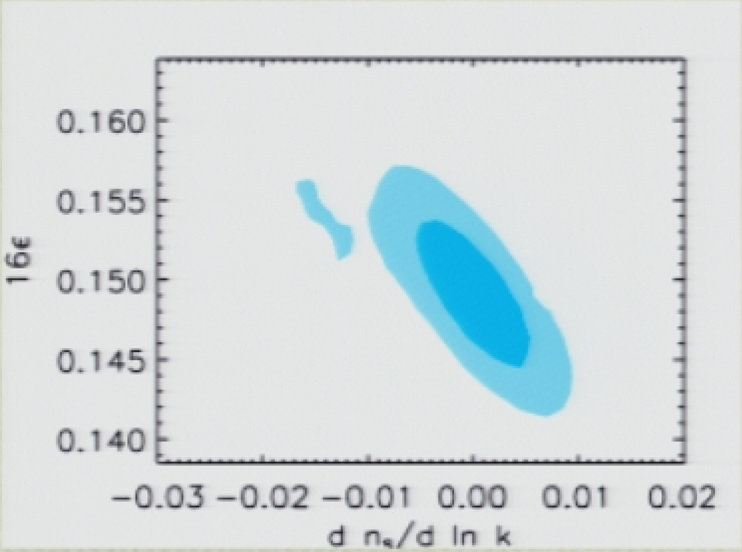
parameter	input	estimated
$\Omega_b h^2$	0.02273	0.02273 ± 0.00006
Ω_m	0.3097	0.3096 ± 0.0016
h	0.684	0.684 ± 0.001
τ	0.112	0.112 ± 0.002
n_s(k=0.002)	0.962	0.964 ± 0.013
A (k=0.002)	0.879	0.878 ± 0.016
r (k=0.002)	0.150	0.150 ± 0.004
dn_s / d ln k	0	0.000 ± 0.004
H/M	0	0.002 ± 0.002
ϕ	0	(degeneracy; mean 0.02)
σ_8		0.871 ± 0.001

Islands in Parameter Space



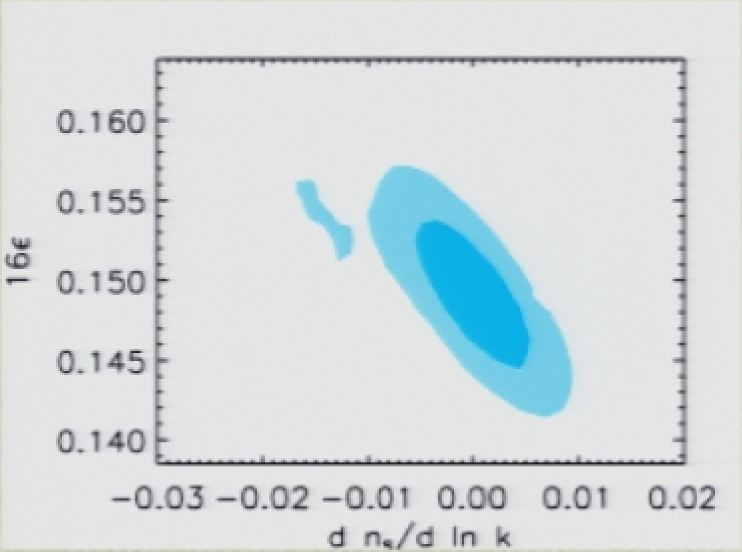
- Real effect
- Also seen by Okamoto & Lim
- Problem for MCMC analysis
  - Chain trapped in local maxima of likelihood space.
  - We had hoped multi-parameter fit would smear them out.
- Understood semi-analytically as “beating” from oscillatory spectrum.

Islands in Parameter Space



- Real effect
- Also seen by Okamoto & Lim
- Problem for MCMC analysis
  - Chain trapped in local maxima of likelihood space.
  - We had hoped multi-parameter fit would smear them out.
- Understood semi-analytically as "beating" from oscillatory spectrum.

Islands in Parameter Space



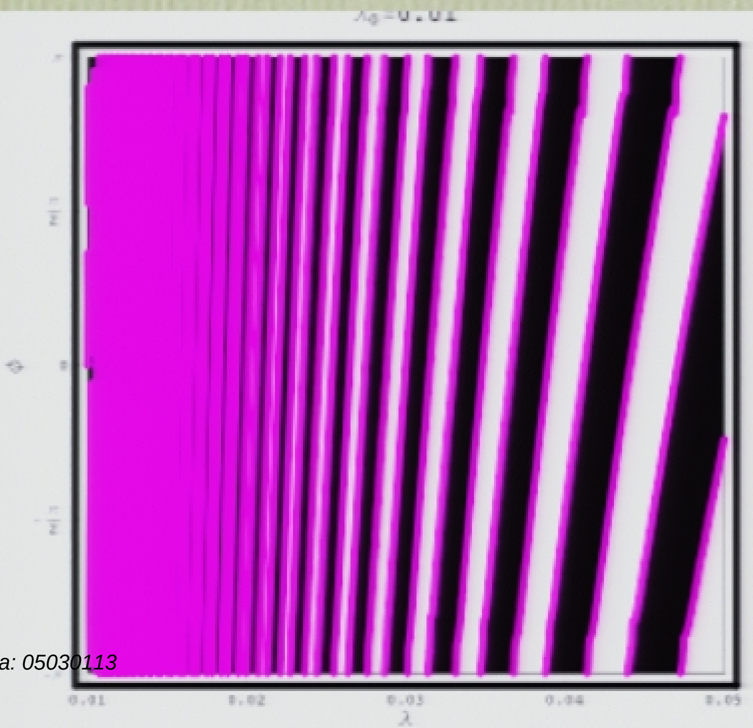
- Real effect
- Also seen by Okamoto & Lim
- Problem for MCMC analysis
  - Chain trapped in local maxima of likelihood space.
  - We had hoped multi-parameter fit would smear them out.
- Understood semi-analytically as "beating" from oscillatory spectrum.

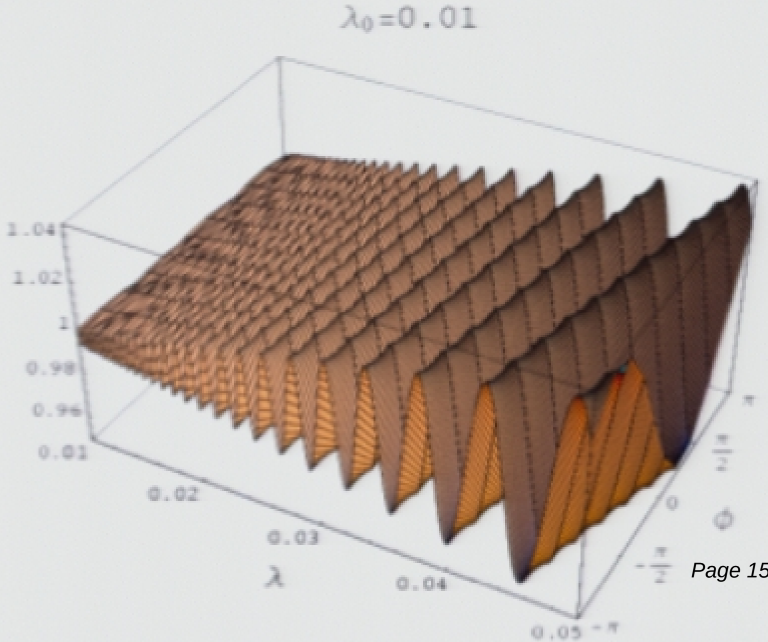
Semi-analytic understanding

$$\Delta(k,\lambda,\phi,\varepsilon)=1+\lambda\left(\frac{k}{k_*}\right)^{-\varepsilon}\sin\left[\frac{2}{1-\varepsilon}\left(\frac{1}{\lambda}\right)\left(\frac{k}{k_*}\right)^{\varepsilon}+\phi\right]$$

$$I=\frac{\int_{0.001}^{0.1}\Delta(k,\lambda,\phi,\varepsilon_0)\,\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,dk}{\int_{0.001}^{0.1}\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,dk}$$

λ=(H/M)



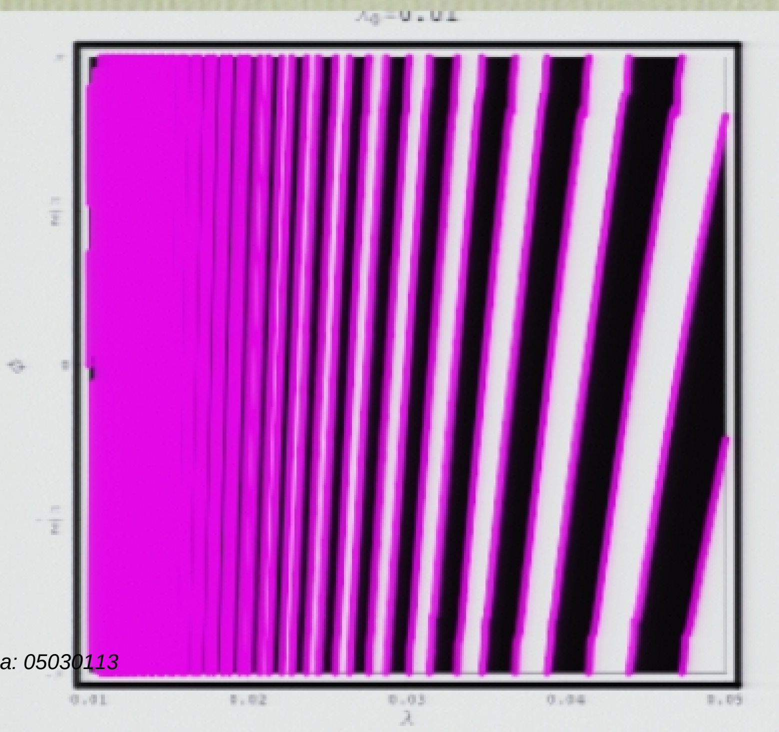


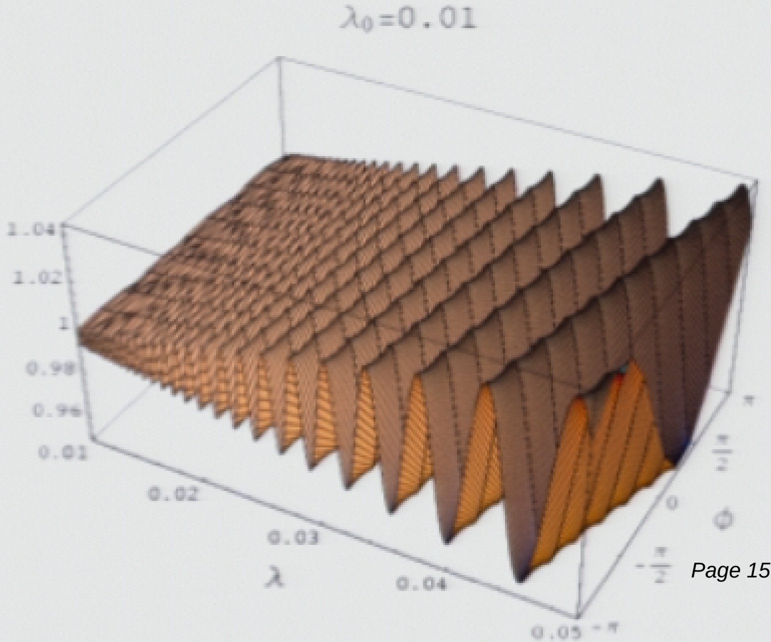
Semi-analytic understanding

$$\Delta(k,\lambda,\phi,\varepsilon) = 1 + \lambda\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{1}{\lambda}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]$$

$$I = \frac{\int_{0.001}^{0.1} \Delta(k,\lambda,\phi,\varepsilon_0)\,\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,dk}{\int_{0.001}^{0.1} \Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,dk}$$

λ=(H/M)



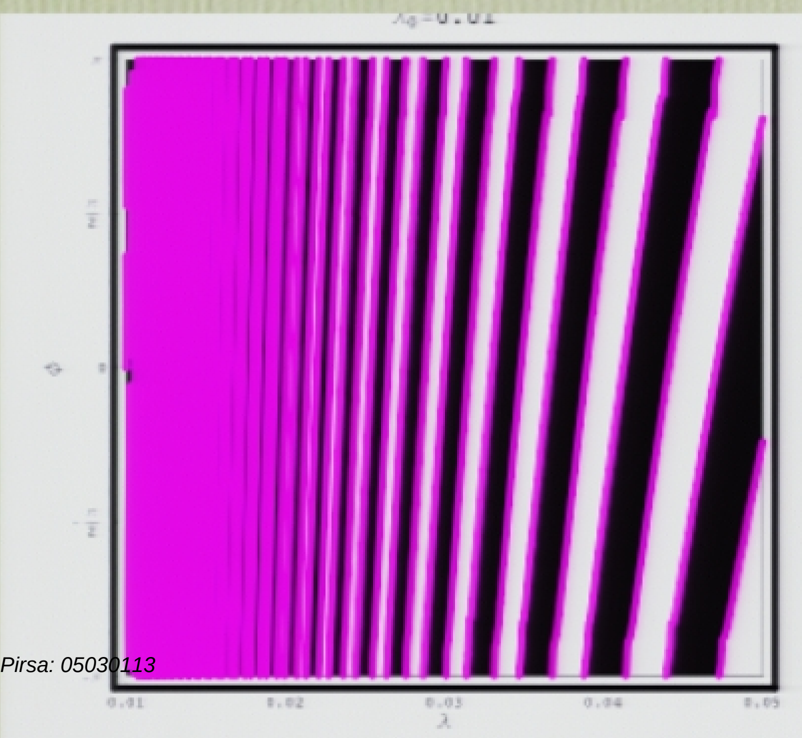


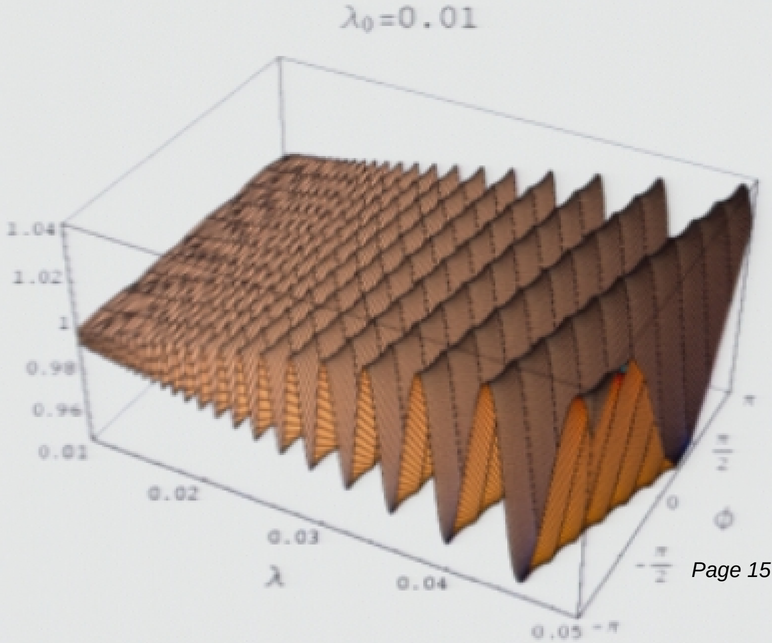
Semi-analytic understanding

$$\Delta(k,\lambda,\phi,\varepsilon) = 1 + \lambda\left(\frac{k}{k_*}\right)^{-\varepsilon} \sin\left[\frac{2}{1-\varepsilon}\left(\frac{1}{\lambda}\right)\left(\frac{k}{k_*}\right)^{\varepsilon} + \phi\right]$$

$$I = \frac{\int_{0.001}^{0.1} \Delta(k,\lambda,\phi,\varepsilon_0)\,\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,dk}{\int_{0.001}^{0.1} \Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,\Delta(k,\lambda_0,\phi_0,\varepsilon_0)\,dk}$$

λ=(H/M)





Conclusions and Summary

- Probed possible generic effects of string theory / quantum gravity on cosmology
  - Feasibility study only.
  - Tells us that the problem is worth closer inspection

Conclusions and Summary

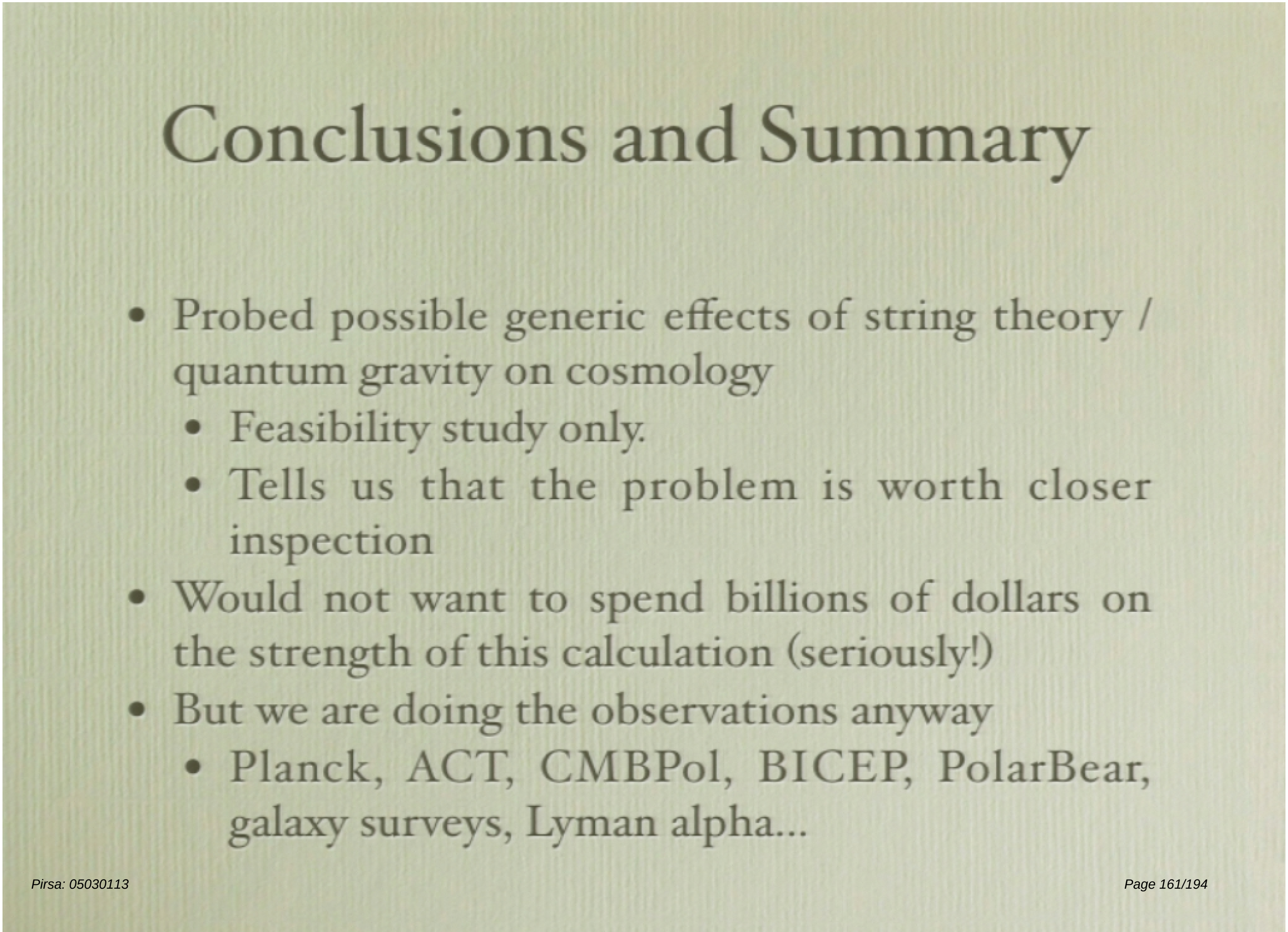
- Probed possible generic effects of string theory / quantum gravity on cosmology
  - Feasibility study only.
  - Tells us that the problem is worth closer inspection
- Would not want to spend billions of dollars on the strength of this calculation (seriously!)

Conclusions and Summary

- Probed possible generic effects of string theory / quantum gravity on cosmology
  - Feasibility study only.
  - Tells us that the problem is worth closer inspection
- Would not want to spend billions of dollars on the strength of this calculation (seriously!)

Conclusions and Summary

- Probed possible generic effects of string theory / quantum gravity on cosmology
  - Feasibility study only.
  - Tells us that the problem is worth closer inspection
- Would not want to spend billions of dollars on the strength of this calculation (seriously!)



Conclusions and Summary

- Probed possible generic effects of string theory / quantum gravity on cosmology
  - Feasibility study only.
  - Tells us that the problem is worth closer inspection
- Would not want to spend billions of dollars on the strength of this calculation (seriously!)
- But we are doing the observations anyway
  - Planck, ACT, CMBPol, BICEP, PolarBear, galaxy surveys, Lyman alpha...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.

- Impact of "minimum length" small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al*.
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of "minimum length" small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of "minimum length" small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al*.
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of "minimum length" small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
  - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
    - But stringy effects still much closer to the surface in cosmology than in particle physics.
    - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
    - Everyone agrees H/M is the key quantity.
    - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
    - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al.*
    - Comparison with data...

- Impact of “minimum length” small for any reasonable parameter choice.
  - But stringy effects still much closer to the surface in cosmology than in particle physics.
  - Basic inflationary predictions are safe.
- Results depend on assumptions about initial conditions and overall model.
  - Everyone agrees H/M is the key quantity.
  - Argument is over exponent (and prefactor).
- Effective field theory approach powerful tool.
  - Ongoing work comparing our spectrum to lowest order correction from Schalm *et al*.
  - Comparison with data...