Title: Discussion: Where in the Cosmos should we look for novel physics?

Speakers: Elias Kiritsis

Collection: Cosmological Frontiers in Fundamental Physics 2019

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Perimeter, September 3, 2019

DISCUSSION SESSION

Where in the Cosmos should we look for novel physics?

Coordinator:Elias Kiritsis (APC and U. of Crete)

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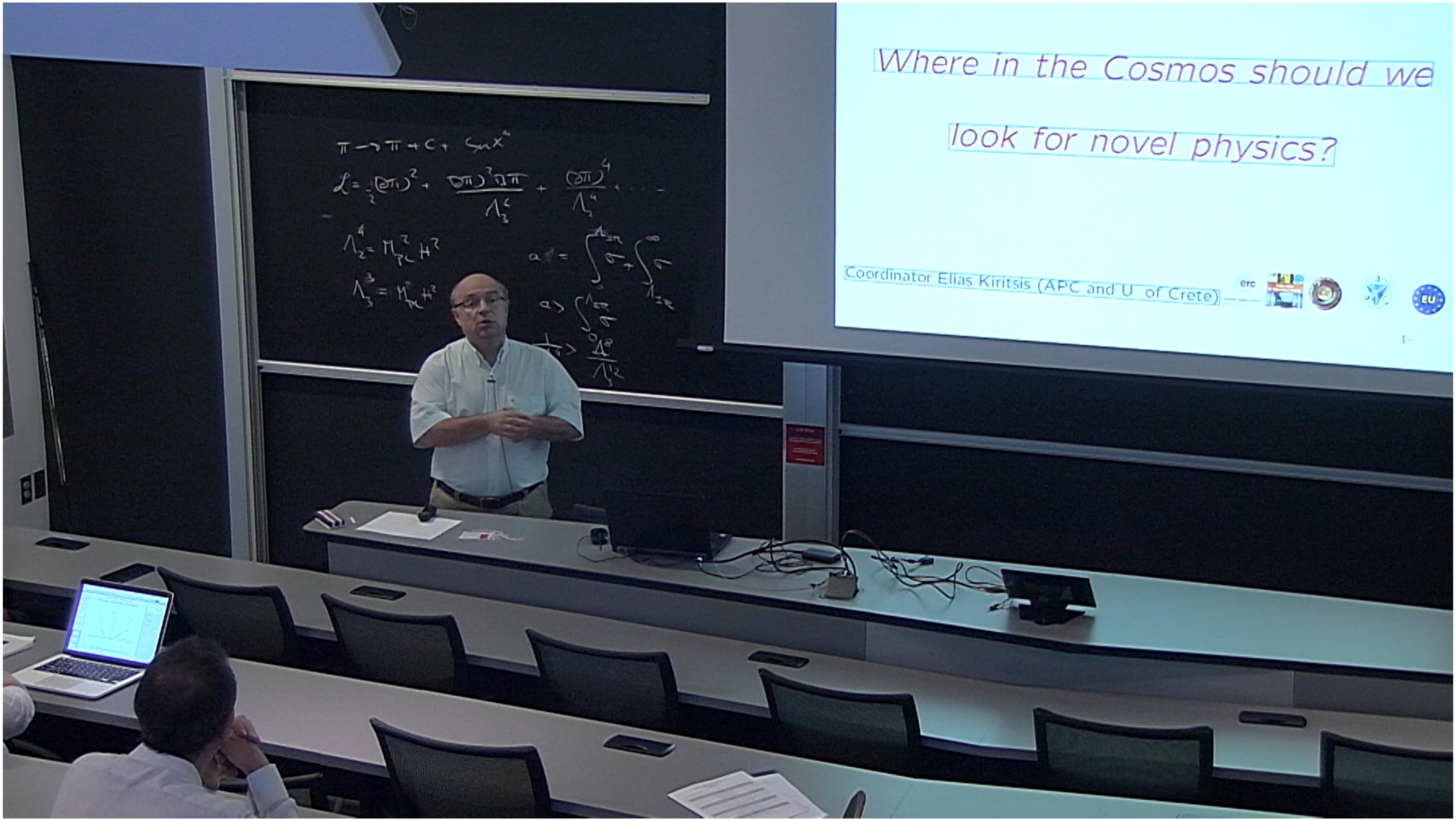
Where in the Cosmos should we
look for novel physics?
Coordinator Elias Kiritsis (APC and U. of Crete)

The interplay

- Experiment/Observation

- Theory/understanding

Theory: conceptual issues

- What is the "nature" of gravity?

- The cosmological constant and/or "dark energy" problem.

- Embedding Inflation in a "fundamental" theory.

- What is dark matter?

- How is the baryon asymmetry of the universe generated?

- And a related particle physics issue: Why is there a large hierarchy between known particle physics and gravity?


of the universe generated?
Why is there a large hierarchy be-
and gravity?

Theory: conceptual issues

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- And a related particle physics issue: Why is there a large hierarchy between known particle physics and gravity?

What is the "nature" of gravity?

- Gravity is an effective theory.

- There are good reasons to believe that the UV degrees of freedom of gravity *are not* gravitons.

- In (perturbative) string theory, gravity has a cutoff $\ll M_P$

- AdS/CFT (holography) is telling us that gravity in string theory is "composite" at high-energies: the graviton (and other fields) are composites of (generalized) gluons.

- Many argue that the high-energy physics of gravity is irrelevant for observation.

- Although this may be true, the holographic idea tells us interesting things about the low-energy theory, especially what is natural and what is not.

• For example the early universe cosmology can be described in a non-geometric formulation of "gravity"

Skederis+McFadden, Afshordi

• As another example, the dynamics in (near) de Sitter space may have stability or fine-tuning properties that are different from what low-energy gravity suggests.

• There may be constrains on gravitational physics+matter that are not obvious from the effective theory (Swampland constraints).

Vafa+Ooguri

• For example, current efforts seems to imply that pure gravity does not have a consistent UV Completion.

• There are current efforts to understand how the graviton can be composite at high energy but look featureless at low energies.

Betzios+EK+Niarchos

• In all these cases, the long distance nature of gravity seems to become different from flat space gravity, but without the problems of massive gravity.

The cosmological constant and dark energy

• This appears as the most serious fine tuning problems in physics.

There are several ideas on its resolution

• The "just so" idea (aka the anthropic resolution).

♠ Interesting recent proposal on how to test experimentally this solution

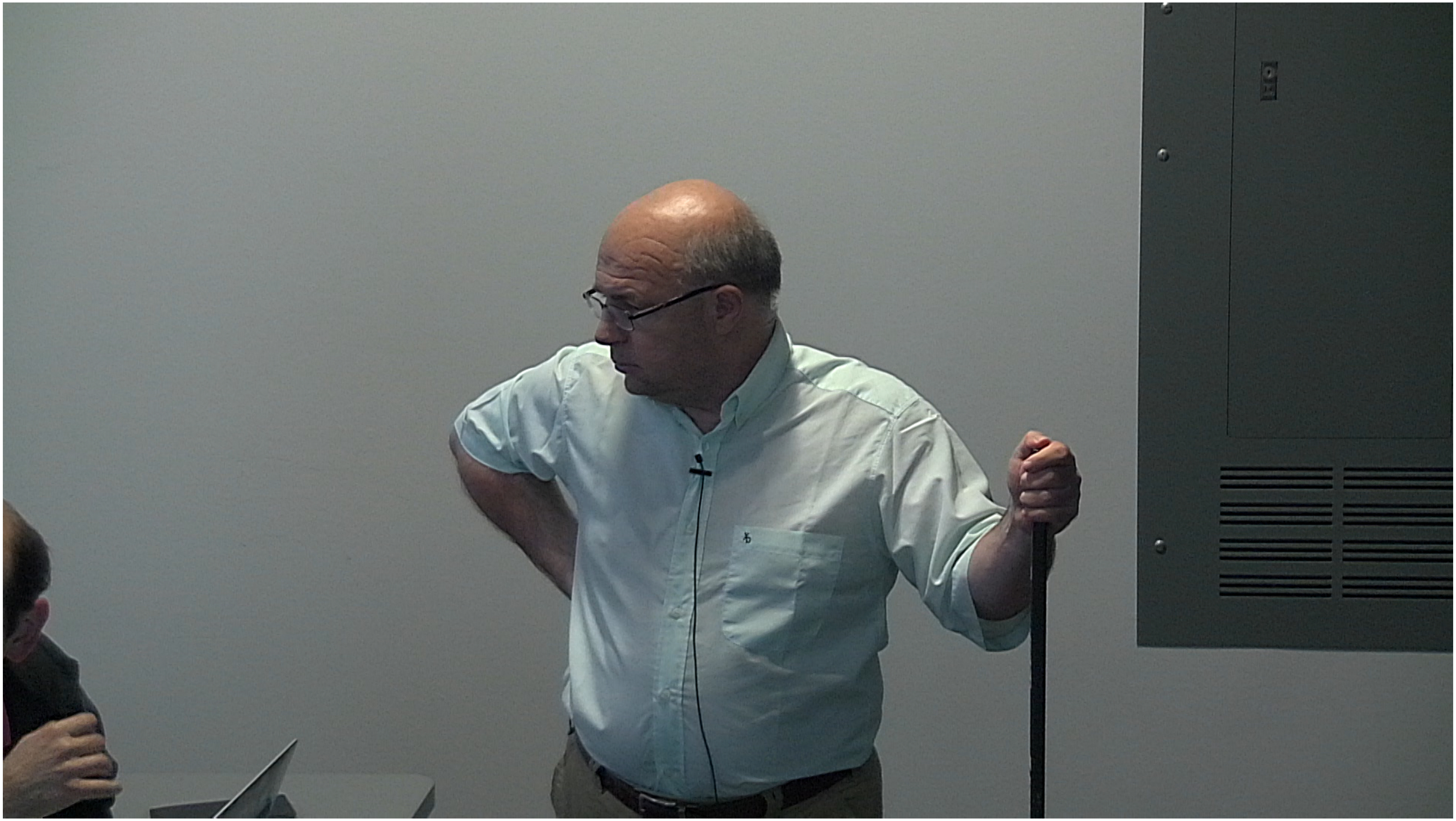
Csaki+Belazzini et al.

♠ That may require a synergy between Nuclear and particle physics (Fair) to pin down the equation of state of cold nuclear matter at high density, and GW observations of neutron star mergers.

• The "fine tuning" between two sectors, one observable and the other hidden.

see eg. Latham's talk

♠ This may be implementable in theories where gravity emerges from hidden sectors.



♠ I am not aware of possible experimental tests.

• The possibility that all masses are due to spontaneous symmetry breaking of a near conformal theory.

♠ Difficult to realize and difficult to test.

• The self-tuning mechanism of the cosmological constant.

♠ Implementable in higher-dimensional models of gravity where the SM lives on a domain wall.

Arkani-Hamed+Dimopoulos+Kaloper+Sundrum,

Kachru+Schulz+Silverstein,Burgess+Quevedo+Tasinato+Zavalla

♠ A working version was proposed recently. The graviton is ALWAYS massive on the brane.

Charmousis+EK+Nitti

♠ Interestingly, the brane-world setup is the holographic dual of emergent gravity from hidden sectors.

Inflation

- We have a working effective theory and remarkable data!

- It seems difficult to be incorporated in a fundamental theory without fine tuning.

- There are even swampland conjectures that attempt to say it is impossible! (but they apply only in weakly coupled/weakly curved setups).

- We are missing an important datum (inflationary gravitational waves). It is crucial for determining the energy scale of inflation.

- This is one of the holy-grails of modern cosmology.

• (small) experiments that attempt to understand the (very complex) physics of the polarisation of the "background" are of paramount importance.

• There may be other observable features of inflation that may become accessible in the near of far future.

Linking them to features of the theory seems important.

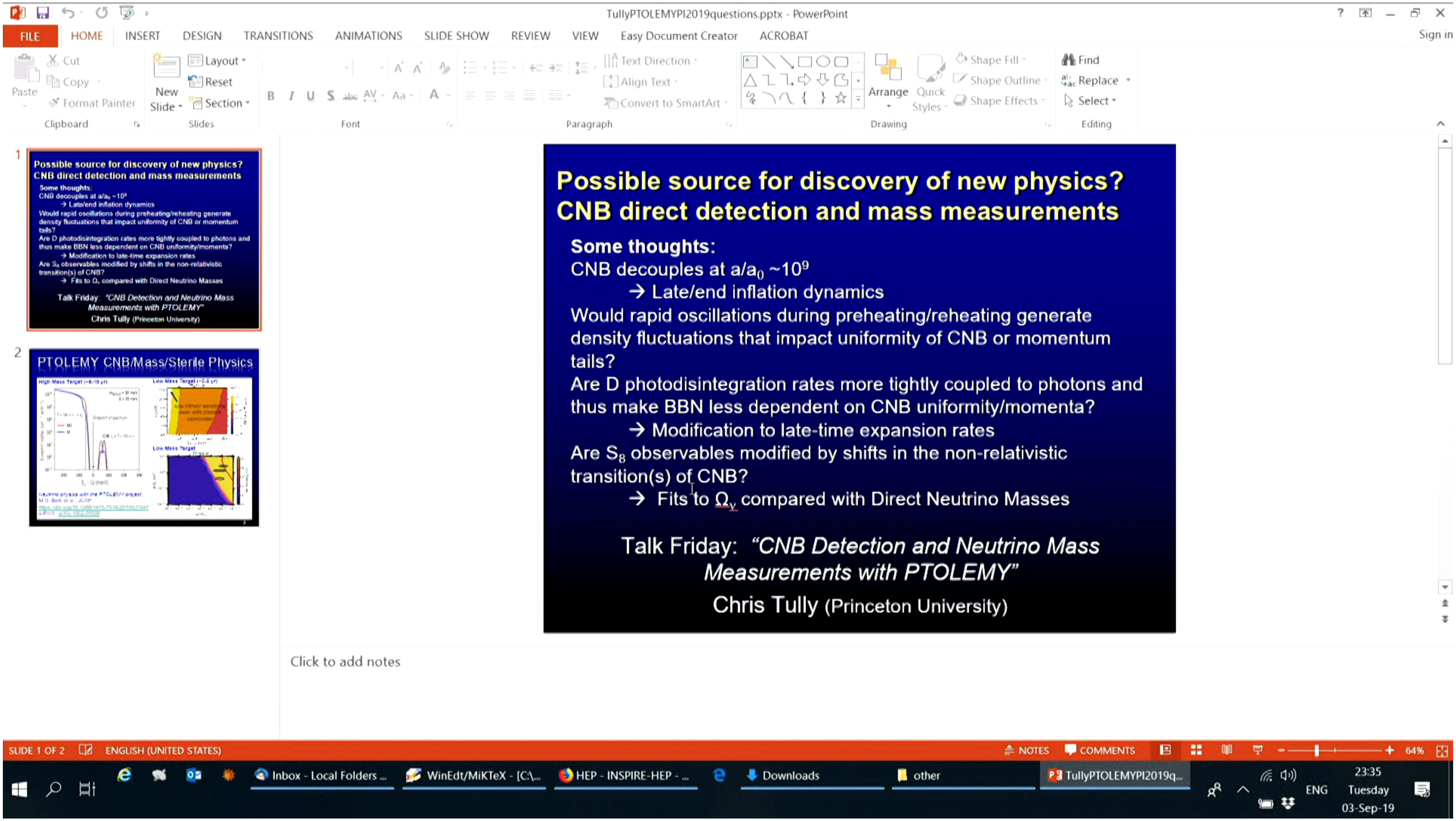
• Embedding inflation is correlated crucially with any mechanism for a small late cosmological constant.

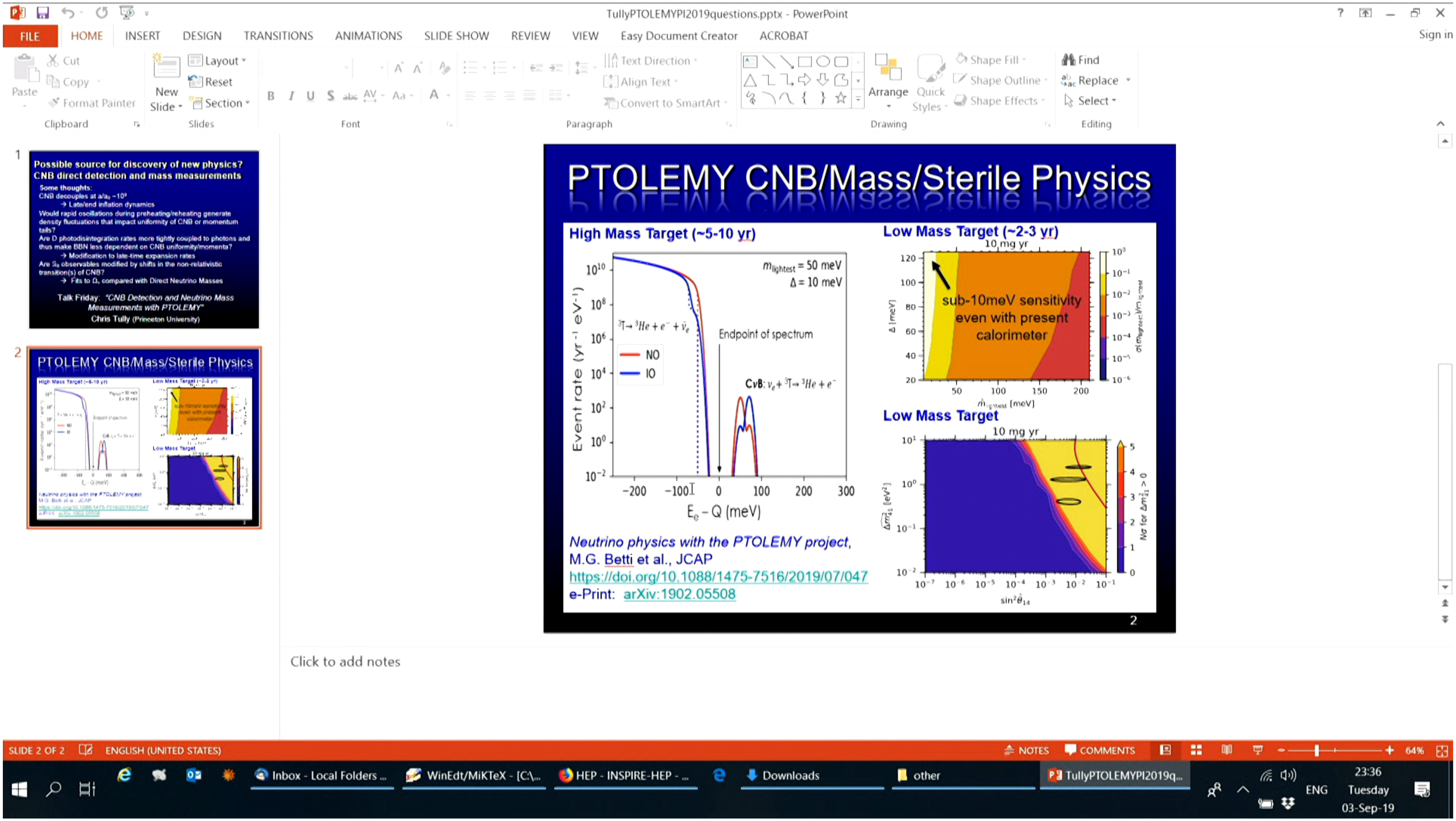
Observations

♠ We have at hand an unprecedent four windows into the universe

- EM over all frequencies
- Neutrinos (getting there).
- Cosmic radiation (particles)
- Gravitational Waves.

But, many questions demand time-consuming and costly instruments.


TullyPTOLEMYPI2019questions.pptx - PowerPoint
Possible source for discovery of new physics?
CNB direct detection and mass measurements
Some thoughts:
CNB decouples at a/a0 ~10^9
→ Late/end inflation dynamics
Would rapid oscillations during preheating/reheating generate density fluctuations that impact uniformity of CNB or momentum tails?
Are D photodisintegration rates more tightly coupled to photons and thus make BBN less dependent on CNB uniformity/momenta?
→ Modification to late-time expansion rates
Are S8 observables modified by shifts in the non-relativistic transition(s) of CNB?
→ Fits to Ων compared with Direct Neutrino Masses
Talk Friday: "CNB Detection and Neutrino Mass Measurements with PTOLEMY"
Chris Tully (Princeton University)
PTOLEMY CNB/Mass/Sterile Physics
Click to add notes
SLIDE 1 OF 2
ENGLISH (UNITED STATES)


TullyPTOLEMYPI2019questions.pptx - PowerPoint
PTOLEMY CNB/Mass/Sterile Physics
High Mass Target (~5-10 yr)
Low Mass Target (~2-3 yr)
10 mg yr
sub-10meV sensitivity even with present calorimeter
Low Mass Target
10 mg yr
Endpoint of spectrum
NO
IO
Event rate (yr⁻¹ eV⁻¹)
E_e − Q (meV)
Neutrino physics with the PTOLEMY project,
M.G. Betti et al., JCAP
https://doi.org/10.1088/1475-7516/2019/07/047
e-Print: arXiv:1902.05508
Possible source for discovery of new physics?
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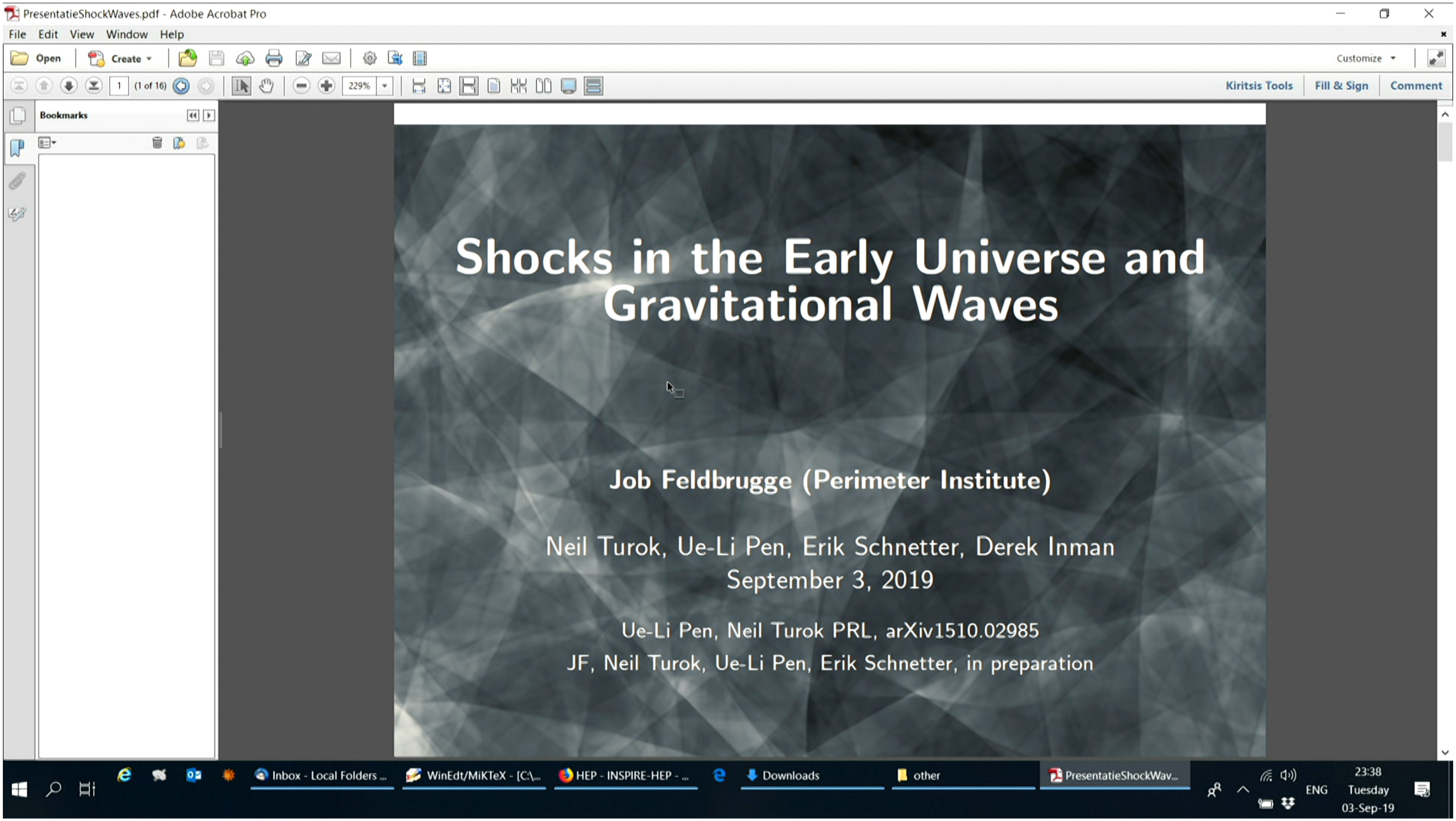
SLIDE 2 OF 2


Shocks in the Early Universe and Gravitational Waves
Job Feldbrugge (Perimeter Institute)
Neil Turok, Ue-Li Pen, Erik Schnetter, Derek Inman
September 3, 2019
Ue-Li Pen, Neil Turok PRL, arXiv1510.02985
JF, Neil Turok, Ue-Li Pen, Erik Schnetter, in preparation

Formation of shocks

Simple model of the early universe:

- Flat FLRW cosmology
- Small growing (nearly) conformal perturbations

In a radiation fluid, shocks form after $\sim \epsilon^{-1}$ oscillations, with ϵ the rms fractional density perturbation. Typically $\epsilon \sim 10^{-4}$ - 10^{-1}.

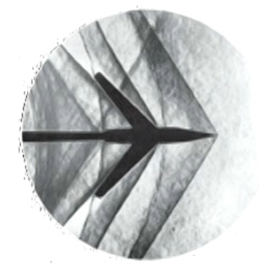
This can lead to

- Gravitational waves
- Out of equilibrium
- Vorticity
- Entropy

which are protected in linear perturbation theory.

Time window

Shocks form when the shock width $<$ steepening scale.



- In a radiation fluid, the shock width is

$$L_s = 9\sqrt{2}\eta/(\epsilon\rho)$$

with η the shear viscosity.

- Steepening takes place at scales $\epsilon\ H^{-1}$, with H the Hubble parameter
- While $T > 100 GeV$, the viscosity $\eta \sim 400\ T^3$
- During neutrino decoupling $\eta \sim v^4/T^5$ with v the Higgs field vev

Time window:

- For $\epsilon = 10^{-4}$: shocks form while $10^7 GeV < T < 1 GeV$
- For $\epsilon = 10^{-1}$: shocks form while $10^{13} GeV < T < 100 MeV$

Non-linearities in equation of motion

The energy-momentum tensor

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + pg^{\mu\nu} = \frac{4}{3}\rho u^\mu u^\nu + \frac{1}{3}\rho g^{\mu\nu}, \quad u_\mu u^\nu = -1,$$

with $\eta^{\mu\nu} = \text{diag}(-1, 1, 1, 1)$, $P = \frac{1}{3}\rho$, $c_s = \frac{c}{\sqrt{3}}$

Equations of motion

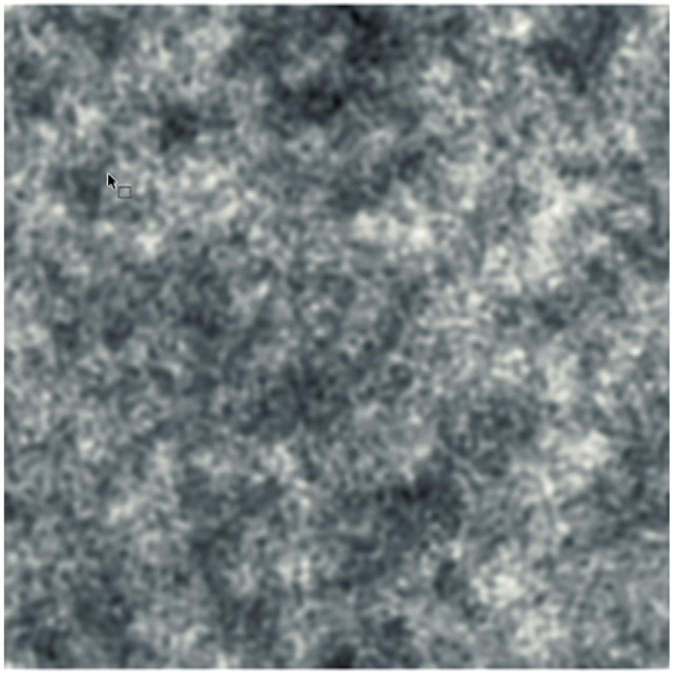
$$0 = \rho(\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v}) + \frac{1}{4}(1 - \mathbf{v}^2)(\nabla\rho + \mathbf{v}\partial_t\rho),$$

$$0 = \partial_t(\rho^{3/4}\gamma_v) + \nabla \cdot (\rho^{3/4}\gamma_v \mathbf{v}),$$

with $u^\mu = \gamma_v(1, \mathbf{v})$ and $\gamma_v = (1 - \mathbf{v}^2)^{-\frac{1}{2}}$.

Three-dimensional simulations

A 1024^3 simulation with $\epsilon = 0.1$.



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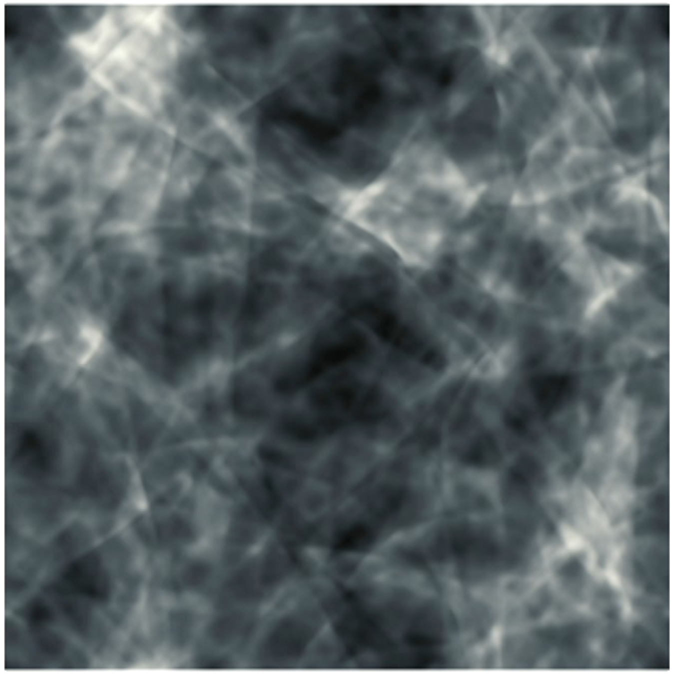
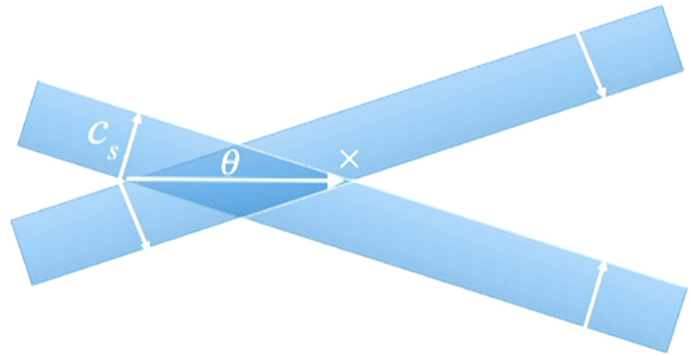


Gravitational Cherenkov radiation



The intersection point moves with

$$v_x = \frac{c_s}{\sin\theta}.$$

Faster than speed of light when

$$\theta < \sin^{-1}\left(\frac{c_s}{c}\right) \approx 35^\circ.$$

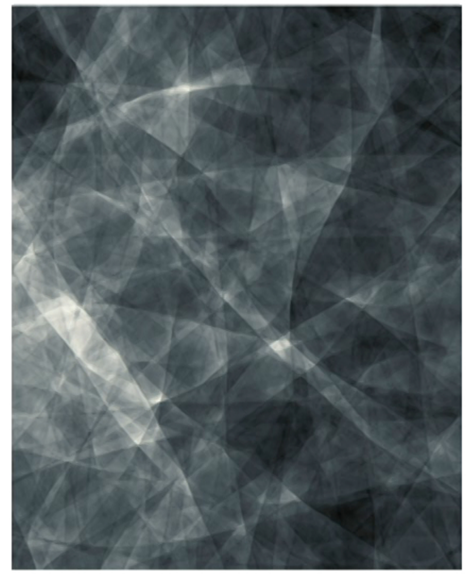
This leads to gravitational radiation.

Summary

Shock waves in the early universe:

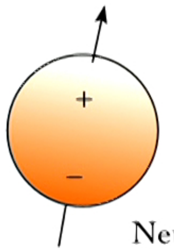
- The early universe contained shock waves $10^7 GeV < T < 1 GeV$, for $\epsilon = 10^{-4}$
- Gravitational waves
- Vorticity
- Entropy

Detailed numerical calculations are in progress.



Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron
EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

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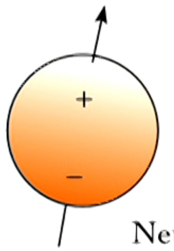


$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

Solution:

$\theta_s \propto a(x,t)$ is a dynamical field, an axion

Axion mass from QCD:

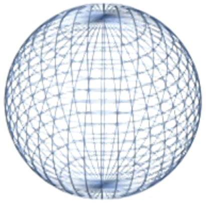
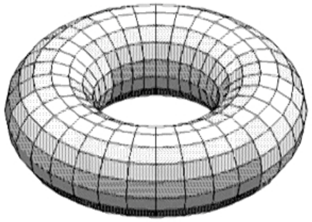
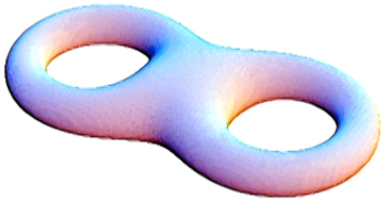
$$\mu_a \sim 6 \times 10^{-11}\ \mathrm{eV}\ \frac{10^{17}\ \mathrm{GeV}}{f_a} \sim (3\ \mathrm{km})^{-1}\ \frac{10^{17}\ \mathrm{GeV}}{\mathrm{f_a}}$$

f_a : axion decay constant

Elements of String Theory

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

- Extra dimensions
- Gauge fields
- Topology

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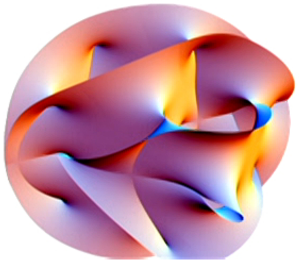

Elements of String Theory

AA, Dimopoulos, Dubovsky, March-Russell, and Kaloper (2009)

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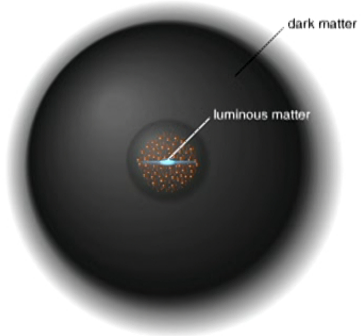
Give rise to a plenitude of massless particles in our Universe

A Plenitude of (Almost) Massless Particles

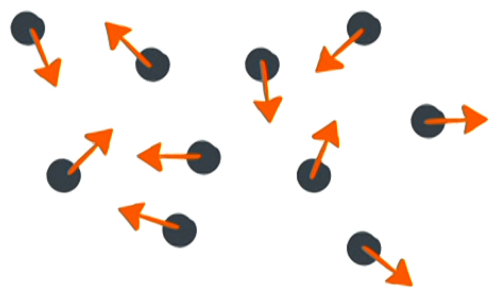
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Usually we think of ...



like a WIMP

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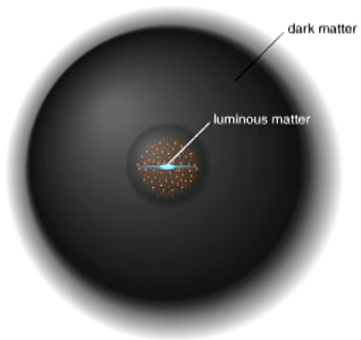

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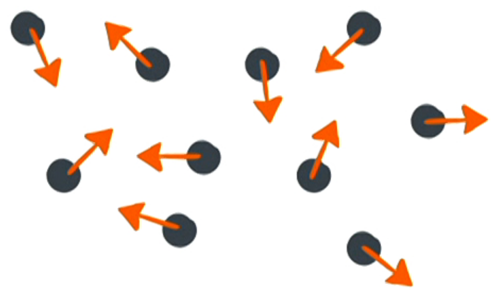
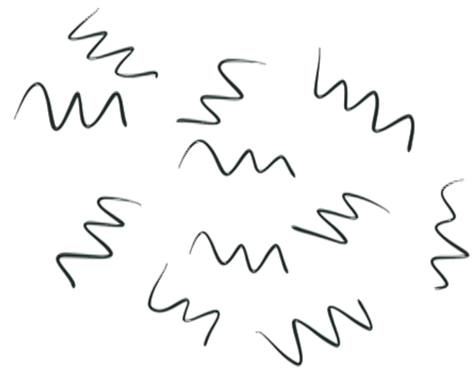


like a WIMP

instead of…



$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

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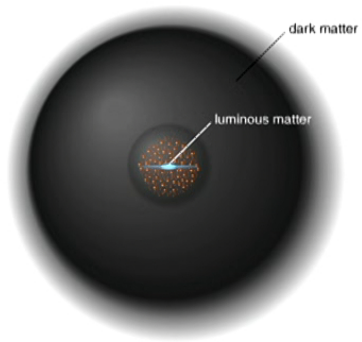

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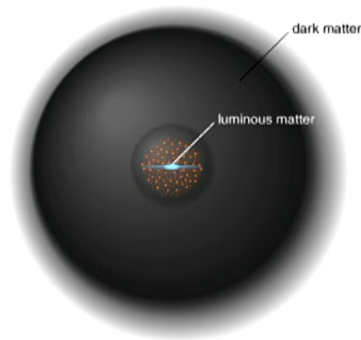
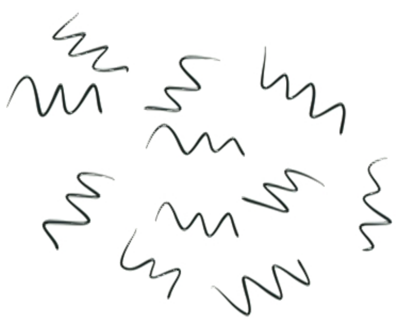
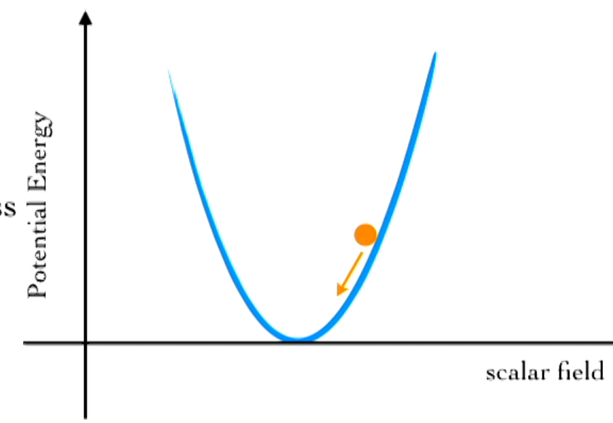




Decreasing DM Mass



Equivalent to a Scalar Wave

Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1\ eV/c^2$

we can talk about DM $\phi(x,t)$ and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

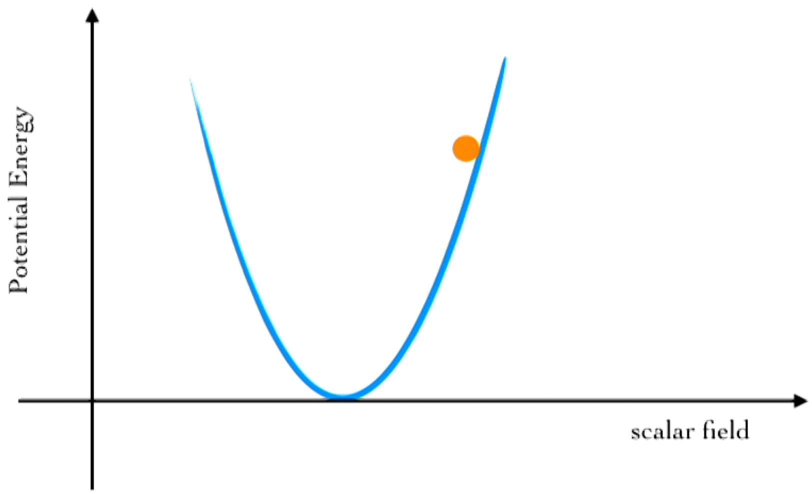
$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

Light Scalar Dark Matter

- Just like a harmonic oscillator

$$\ddot{\phi} + 3\ H\ \dot{\phi} + m_\phi^2 \phi = 0$$

$$\ddot{x} + \gamma\ \dot{x} + \omega^2 x = 0$$

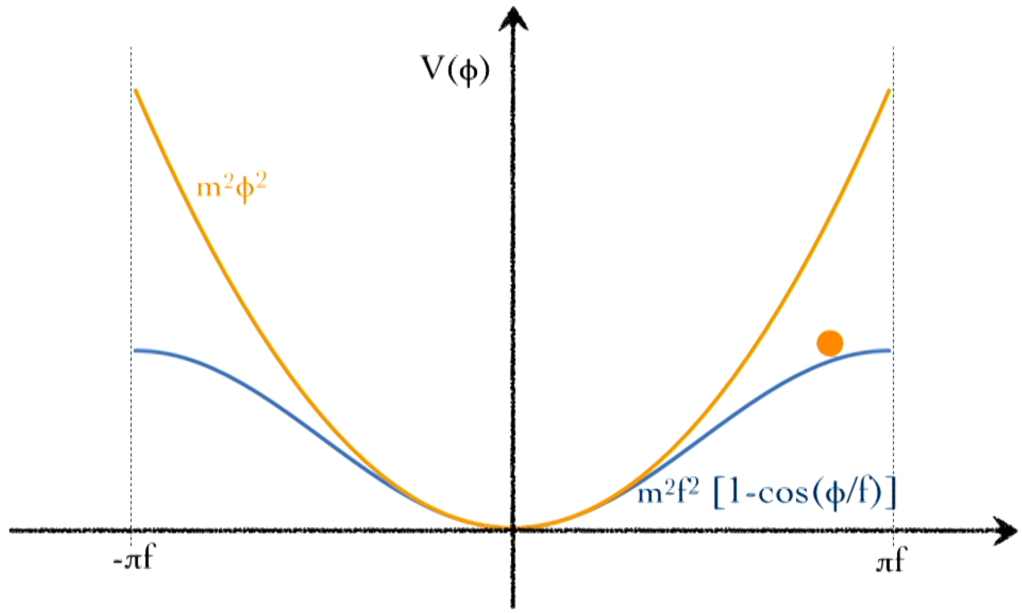


Frozen when:
Hubble > m_ϕ

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Axion Dark Matter and the Large Misalignment Mechanism



Axions generically have attractive self-interactions

Axion self-interactions affect evolution at H~ m

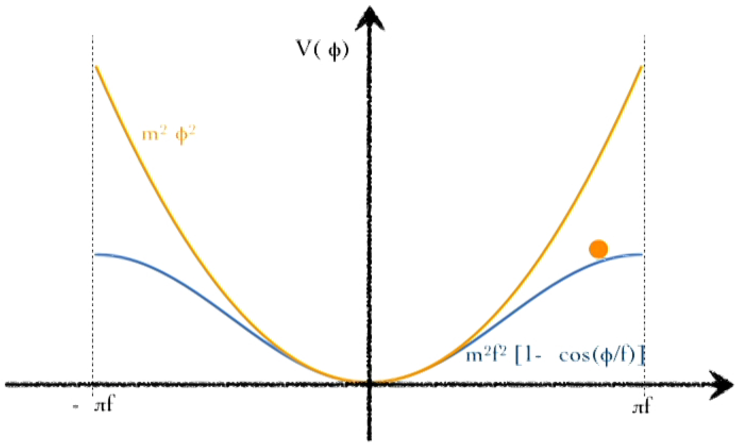
Structure growth due to axion self-interactions

Attractive self-interactions boost scales of size

$\lambda^{*} \sim 2\pi/m$ at the time of oscillation

corresponding today to:

$$0.69\,\mathrm{Mpc}\sqrt{10^{-22}\,\mathrm{eV}/m}$$



or mass of:

$$M_s^* = \frac{4\pi\rho_{\rm DM}^0}{3}\left(\frac{\lambda_*}{2}\right)^3 \approx 5\times10^9\,\mathrm{M}_\odot\left[\frac{10^{-22}\,\mathrm{eV}}{m}\right]^{3/2}$$