Title: Axiverse Cosmology and the Energy Scale of Inflation

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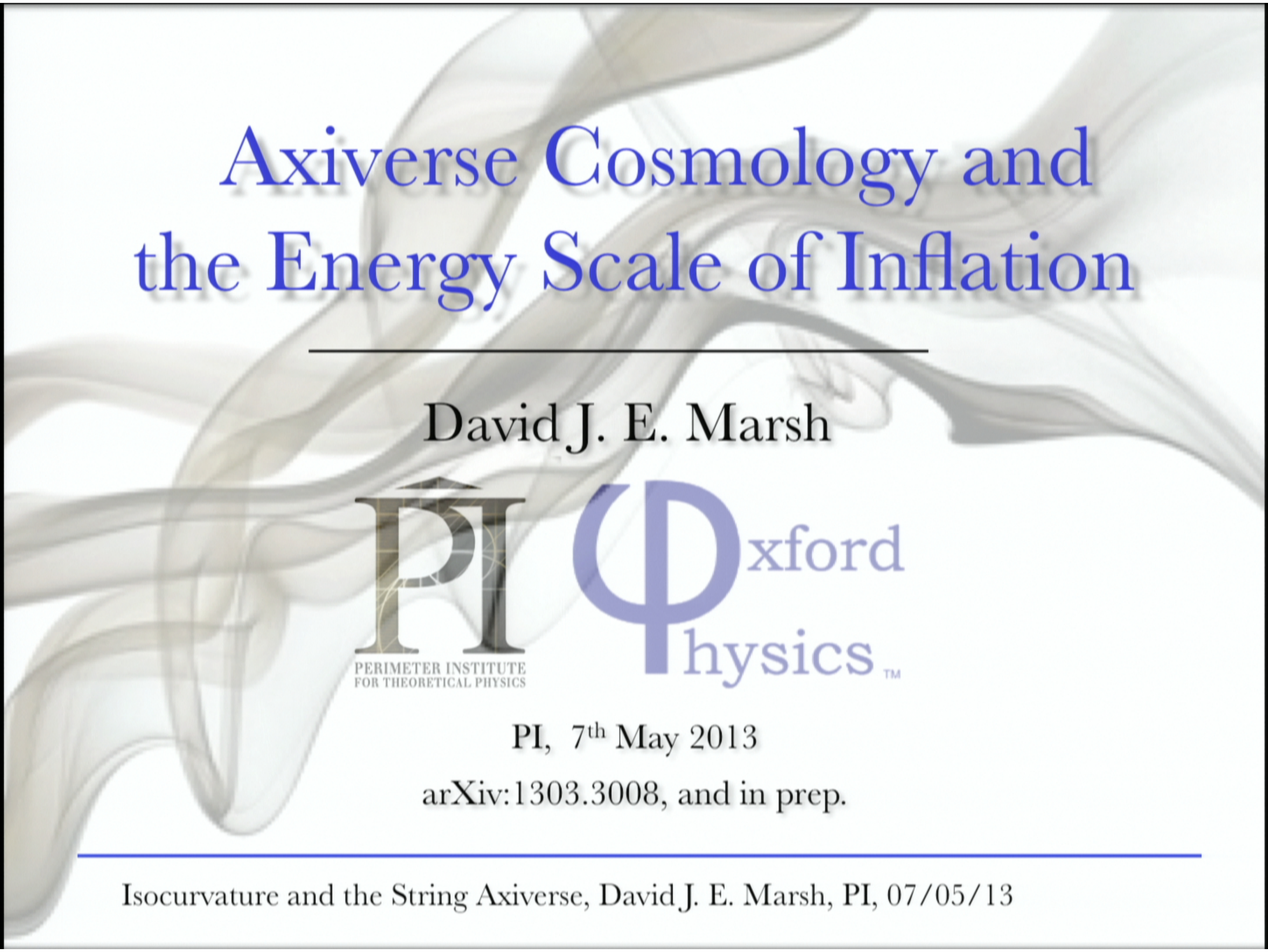
Abstract: <div>Ultra-light axions (m_a<10^{-18} eV), motivated by string theory, can be a powerful probe of the energy scale of inflation if they exist as a sub-dominant component of the Dark Matter. In contrast to heavier axions the isocurvature modes in the ultra-light axions can coexist with observable gravitational waves. Here it is shown that existing (2005) large scale structure constraints severely limit the parameter space for axion mass, density fraction and isocurvature amplitude. It is also shown that radically different CMB observables for the ultra-light axion isocurvature mode additionally reduce this space. The results of a new, accurate and efficient method to calculate this isocurvature power spectrum are presented, and can be used to constrain ultra-light axions and inflation.
</div><div>I will also present preliminary results of constraints to this model using up-to-date cosmological observations, which verify the above picture. The parameter space is interesting to explore due to a strongly mass dependent covariance matrix, motivating comparisons between Metropolis-Hastings and nested sampling. Finally I discuss fine-tuning and naturalness in these models.</div>



Axiverse Cosmology and the Energy Scale of Inflation

David J. E. Marsh

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Φxford
Φhysics™

PI, 7th May 2013

arXiv:1303.3008, and in prep.

Collaborators

Pedro G. Ferreira (Oxford)
Daniel Grin (IAS)
Renée Hlozek (Princeton)

ULA = ultralight axion

Other papers

ULA's and structure formation: PRD 82, 103528 (2010)
Forecasts for ULA's: PRD 85, 103514 (2012)
More on isocurvature: in preparation

The Principle of Plenitude: *"This best of all possible worlds will contain all possibilities, with our finite experience of eternity giving no reason to dispute nature's perfection."*

Gottfried Leibniz (1646-1716), in *Theodicee*

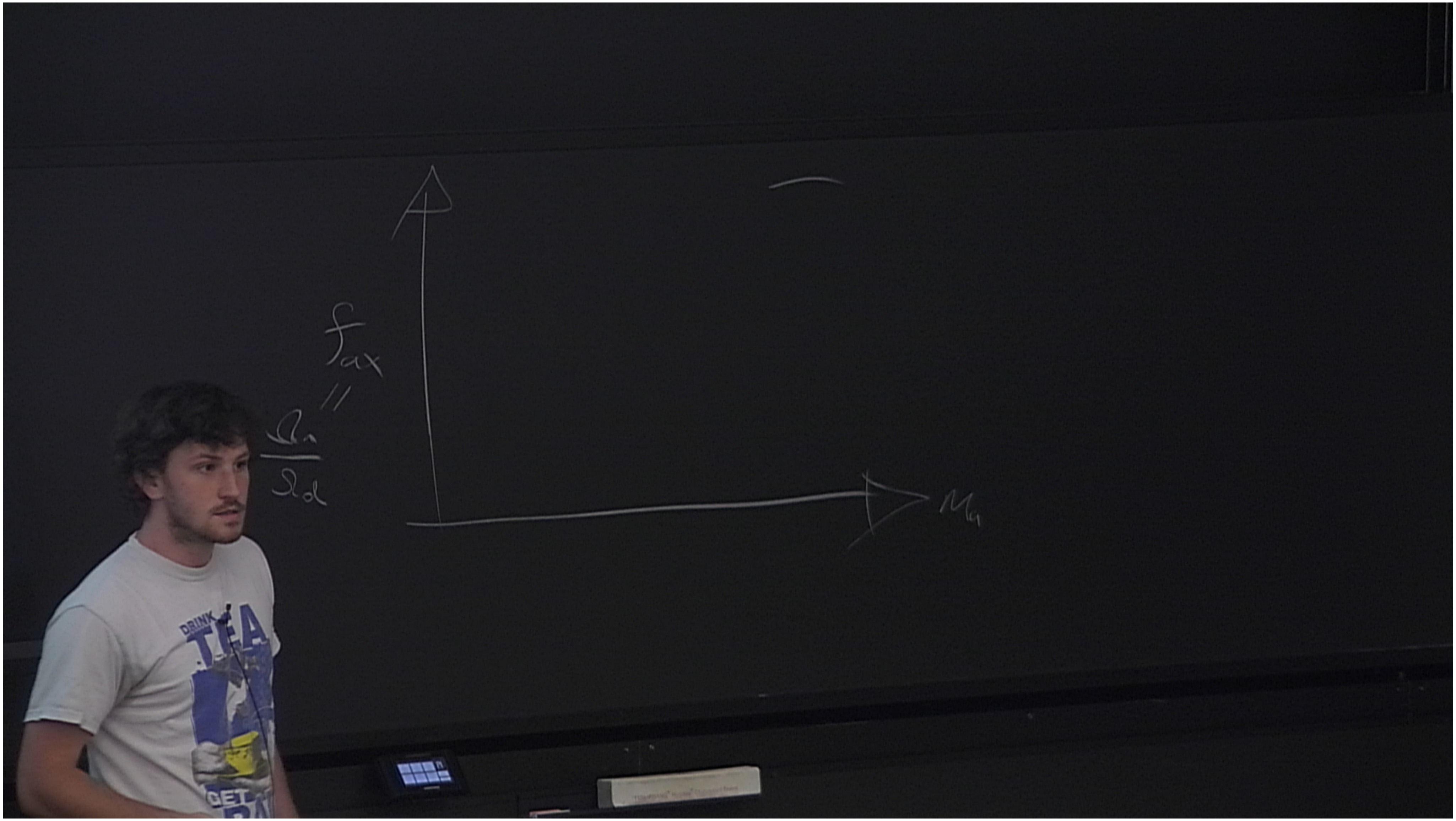
Quoted in Arvanitaki et al (2009)

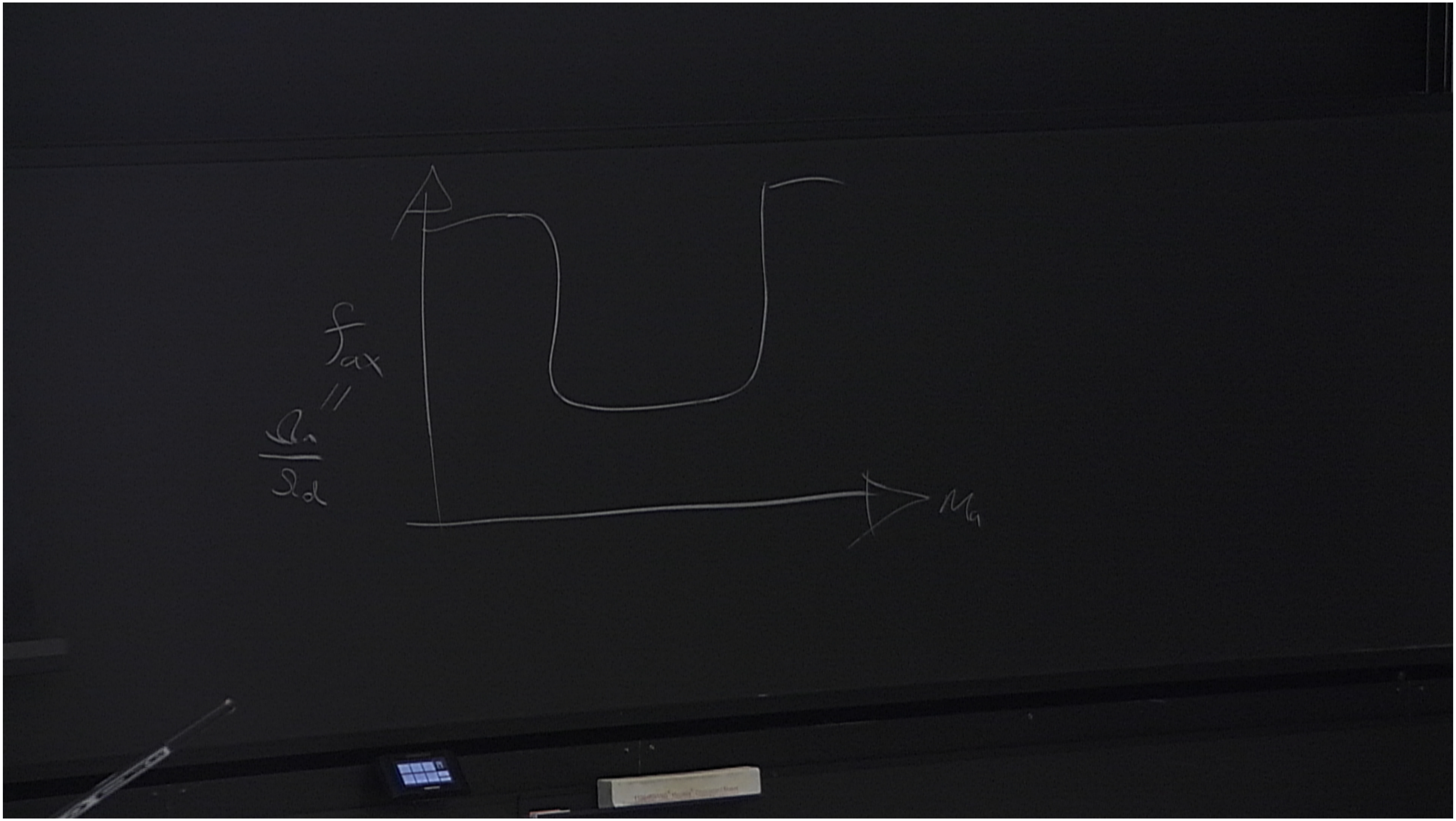
Pangloss sometimes said to Candide:

"There is a concatenation of events in this best of all possible worlds: for if you had not been kicked out of a magnificent castle for love of Miss Cunégonde–if you had not come under the Inquisition–if you had not walked over America–if you had not stabbed the Baron–if you had not lost all your sheep from the fine country of El Dorado–why, then, you would not be here, eating preserved citrons and pistachio-nuts."

"All that is very well," answered Candide, *"but let us cultivate our garden."*

Voltaire (1694-1778), in *Candide*


f_{ax}
//
$\frac{\Omega_a}{\Omega_d}$
m_a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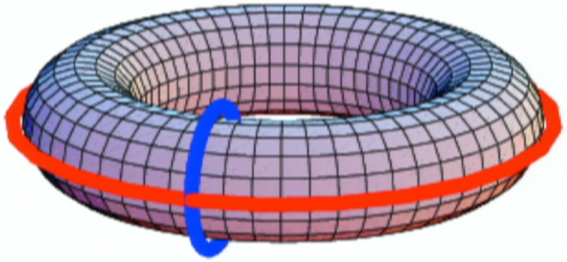
Axions in String Theory

Svrcek and Witten (2006)

- ❖ String theory has extra dimensions: compactify.
- ❖ Axions are KK zero-modes of antisymmetric tensor fields compactified on closed cycles.



Topological complexity → many axions

Isocurvature and the String Axiverse, David J. E. Marsh, PI, 07/05/13

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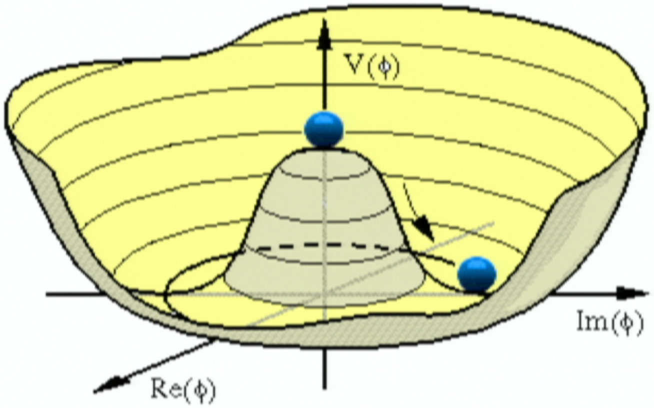
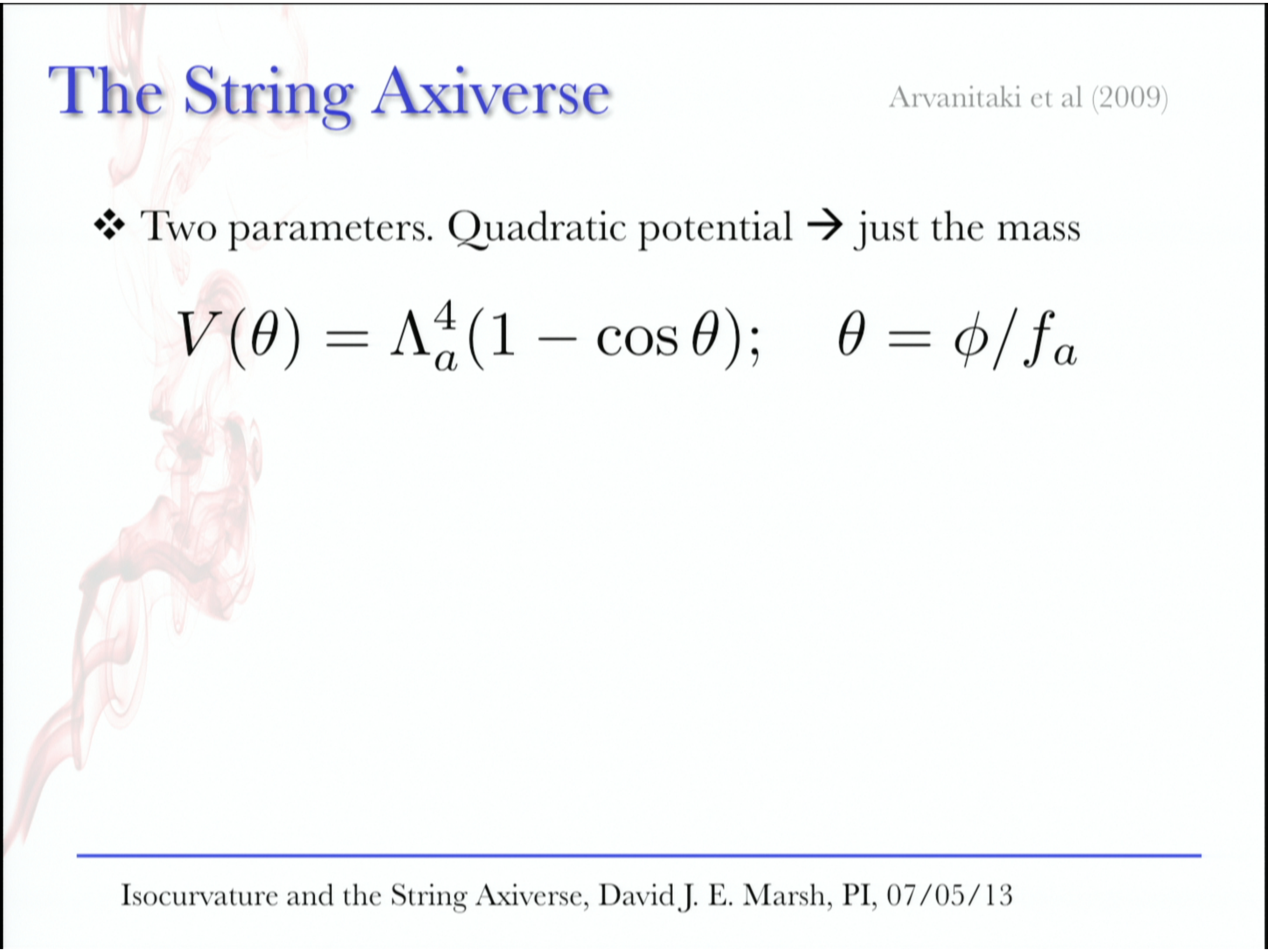


http://www.hep.ph.ic.ac.uk/cms/physics/higgs.html

- Potentials from non-perturbative physics (D-branes, instantons etc.).

many pseudo-Goldstone bosons

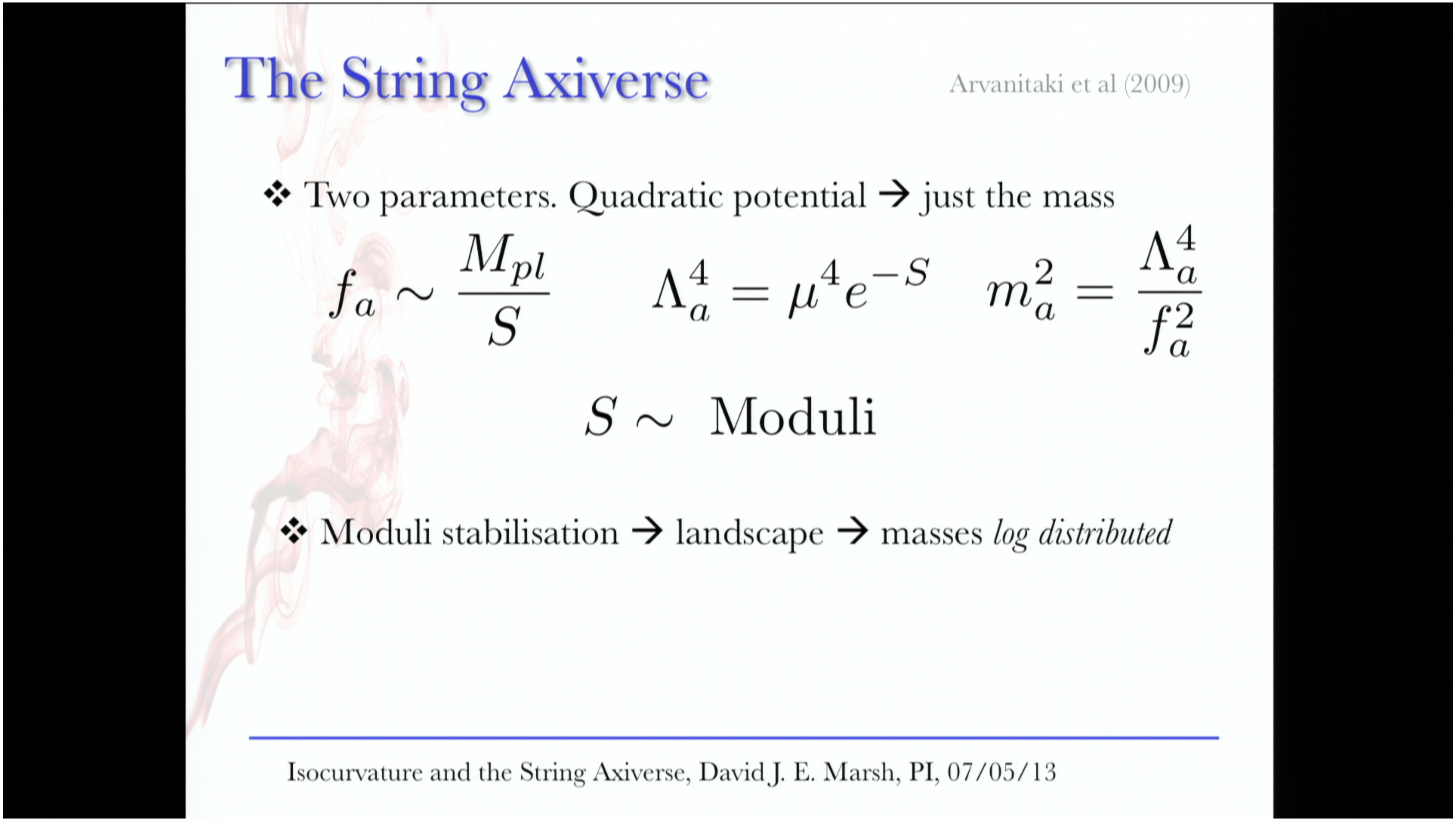


The String Axiverse

Arvanitaki et al (2009)

- Two parameters. Quadratic potential → just the mass

$$V(\theta) = \Lambda_a^4(1 - \cos\theta); \quad \theta = \phi/f_a$$



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$$f_a \sim \frac{M_{pl}}{S} \qquad \Lambda_a^4 = \mu^4 e^{-S} \quad m_a^2 = \frac{\Lambda_a^4}{f_a^2}$$

$$S \sim \text{ Moduli}$$

- Moduli stabilisation → landscape → masses *log distributed*

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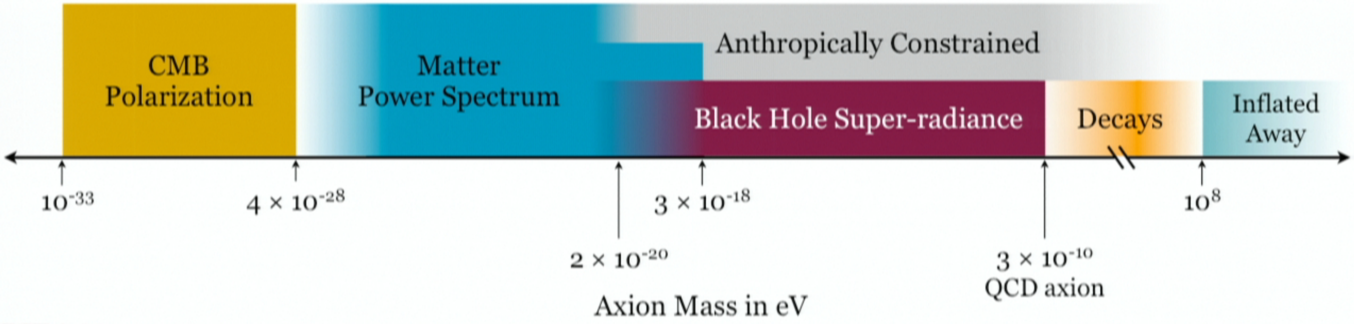

Figure: Arvanitaki et al

The String Axiverse

Physics: 3 Easy Pieces

Arvanitaki et al (2009)

- Background Evolution: Two parameters. Quadratic potential → just the mass

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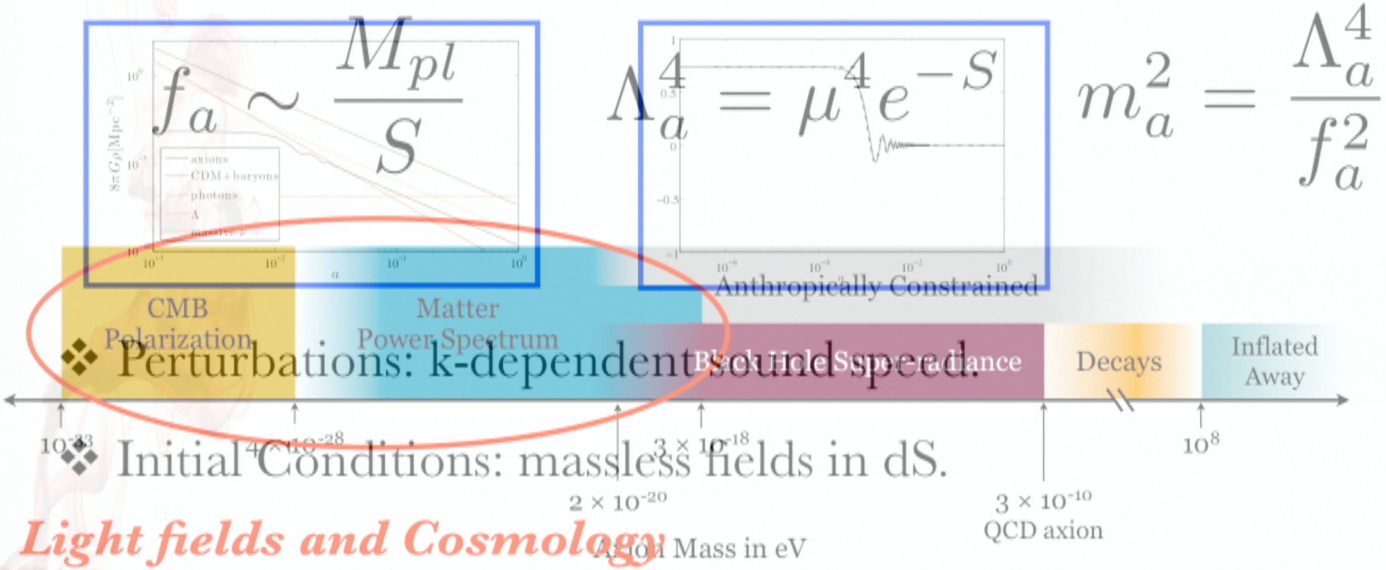

- Perturbations: k-dependent sound speed.
- Initial Conditions: massless fields in dS.

Light fields and Cosmology

Figure: Arvanitaki et al

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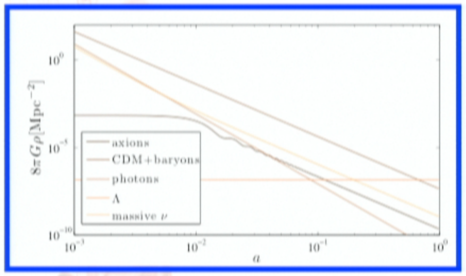
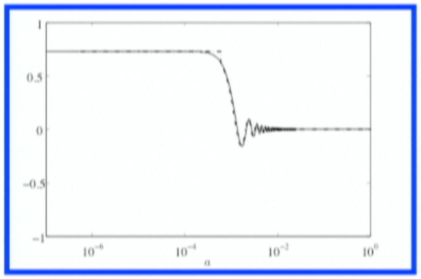
Physics: 3 Easy Pieces

- ❖ Background Evolution: two stages.





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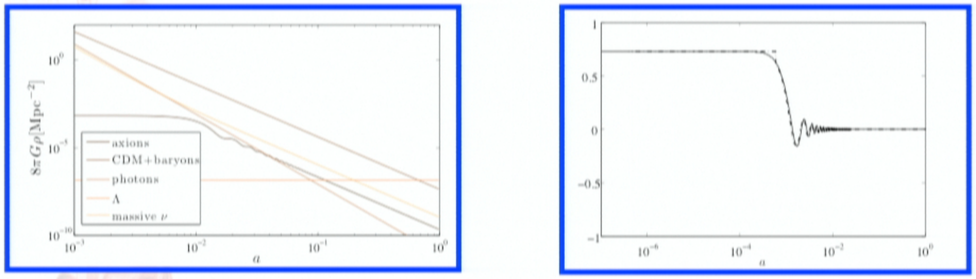

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Detect axions

Physics: 3 Easy Pieces

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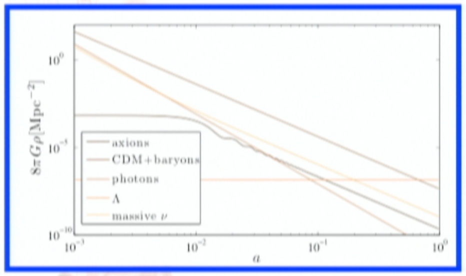

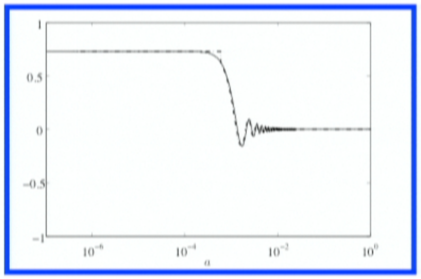

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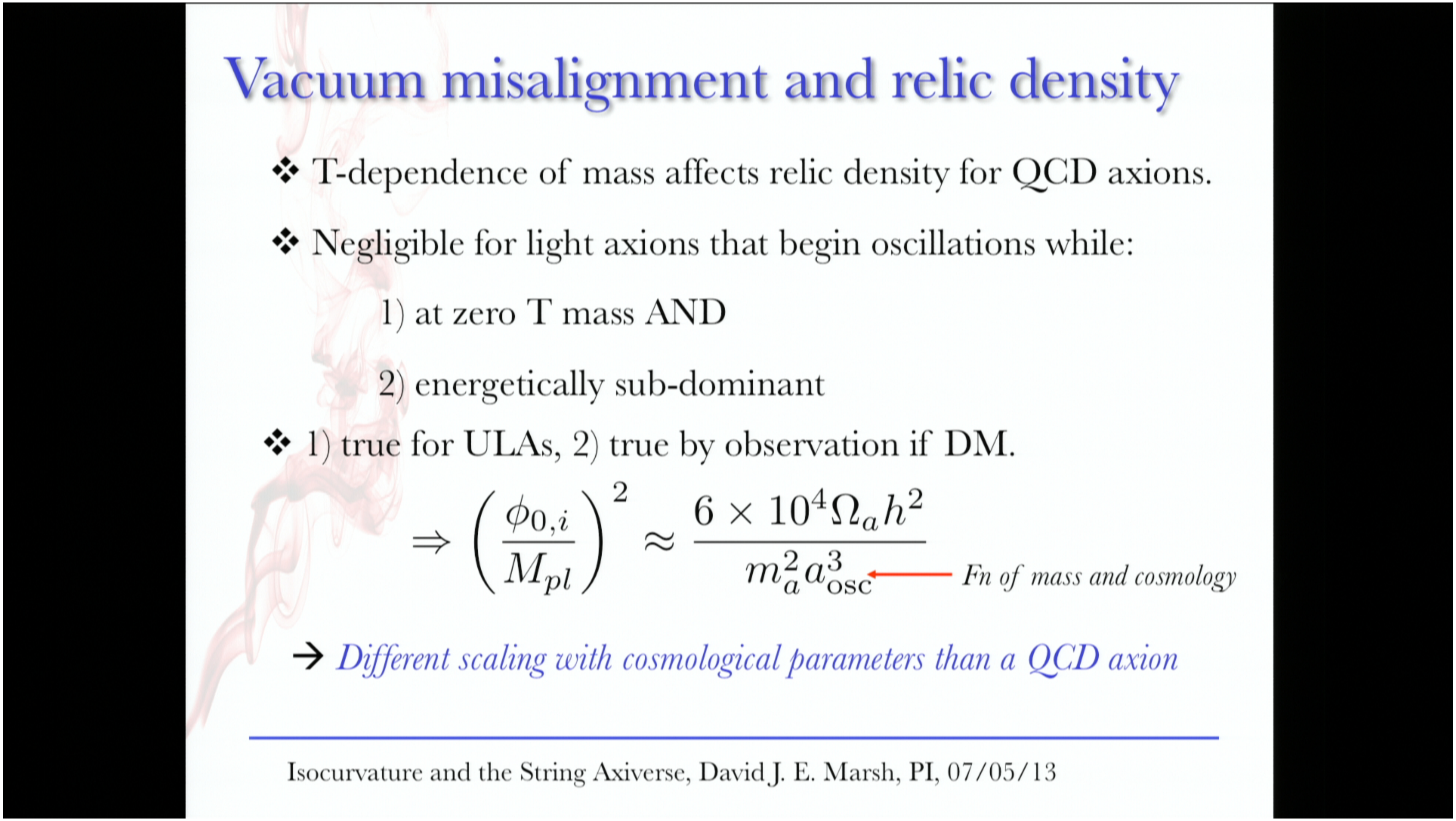
Probe inflation



Vacuum misalignment and relic density

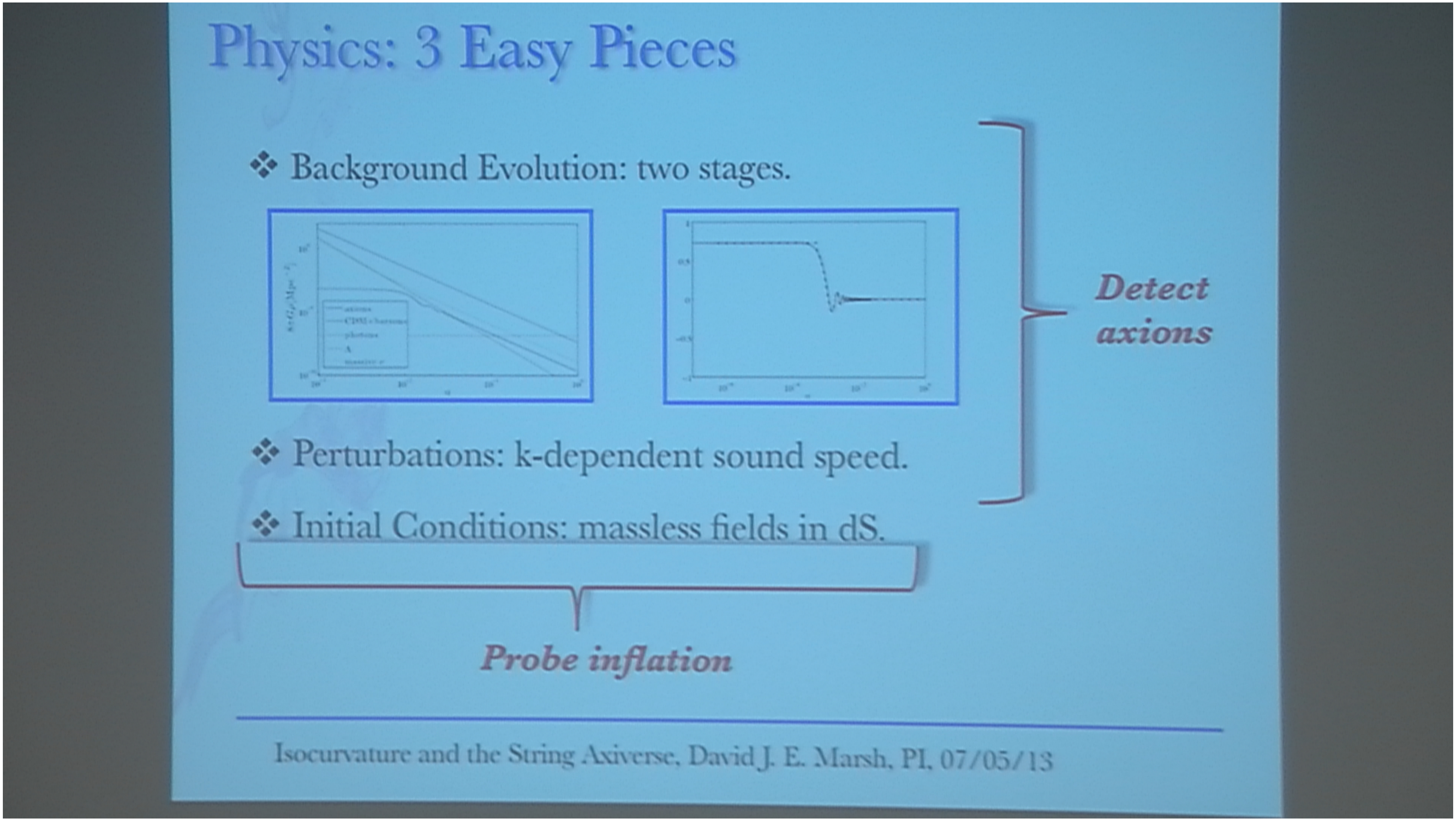
- T-dependence of mass affects relic density for QCD axions.
- Negligible for light axions that begin oscillations while:

  1) at zero T mass AND

  2) energetically sub-dominant
- 1) true for ULAs, 2) true by observation if DM.

$$\Rightarrow \left(\frac{\phi_{0,i}}{M_{pl}}\right)^2 \approx \frac{6\times 10^4\,\Omega_a h^2}{m_a^2 a_{\rm osc}^3} \longleftarrow \textit{Fn of mass and cosmology}$$

→ *Different scaling with cosmological parameters than a QCD axion*



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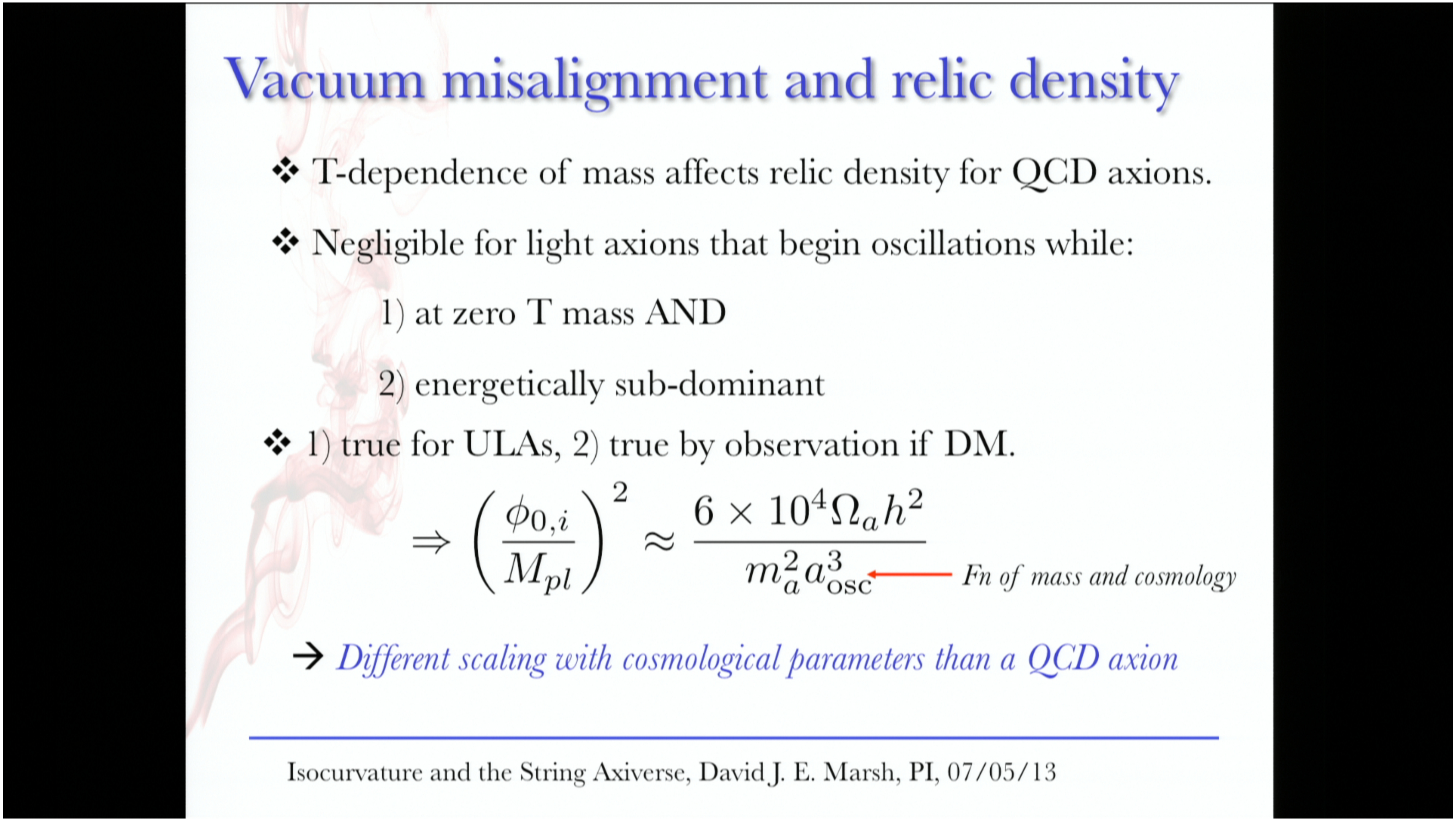

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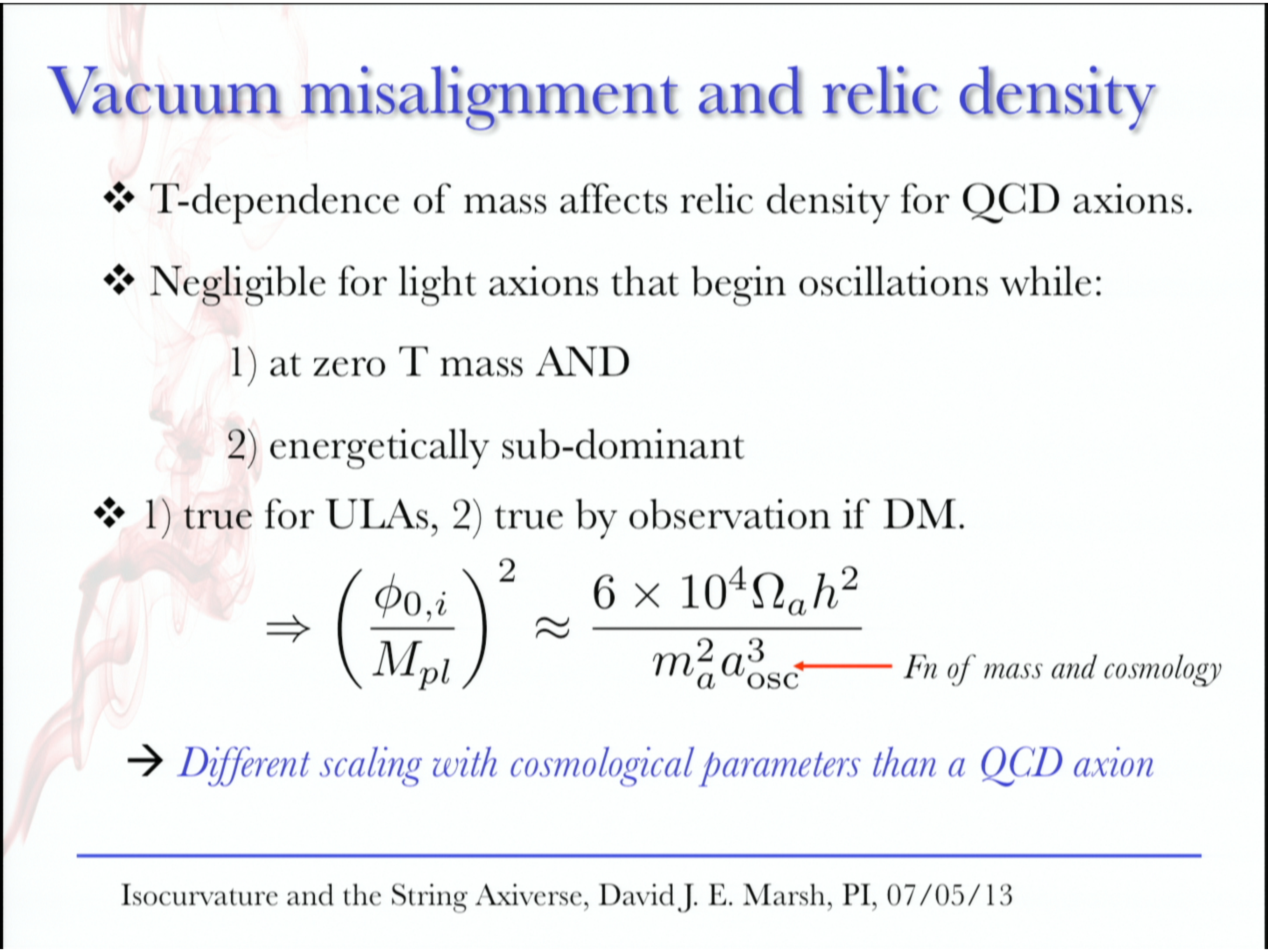

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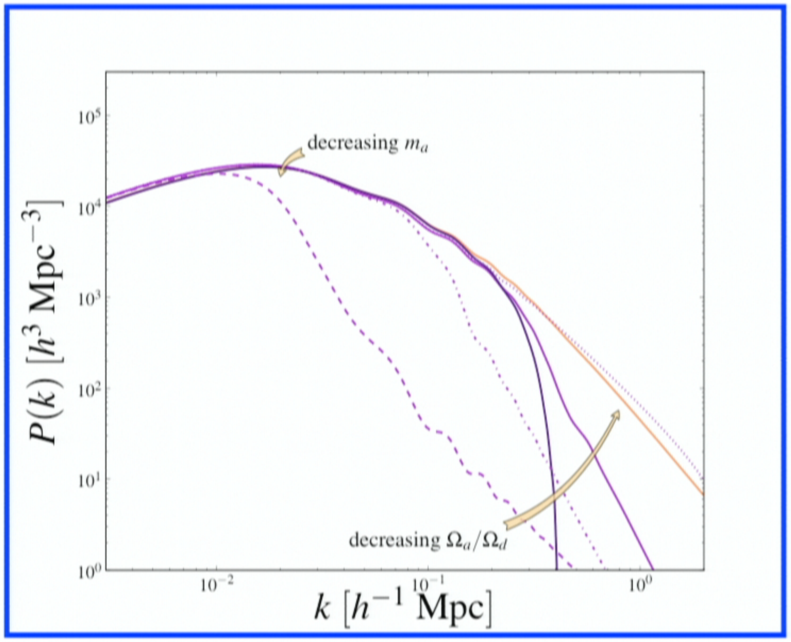
Axions as "Fuzzy" DM

Hu et al (2000)

Amendola and Barbieri (2006)

DJEM and Ferreira (2010)



- ❖ "Quantum" pressure in the sound speed leads to structure suppression: cosmological Compton wavelength.

I.C. Modes

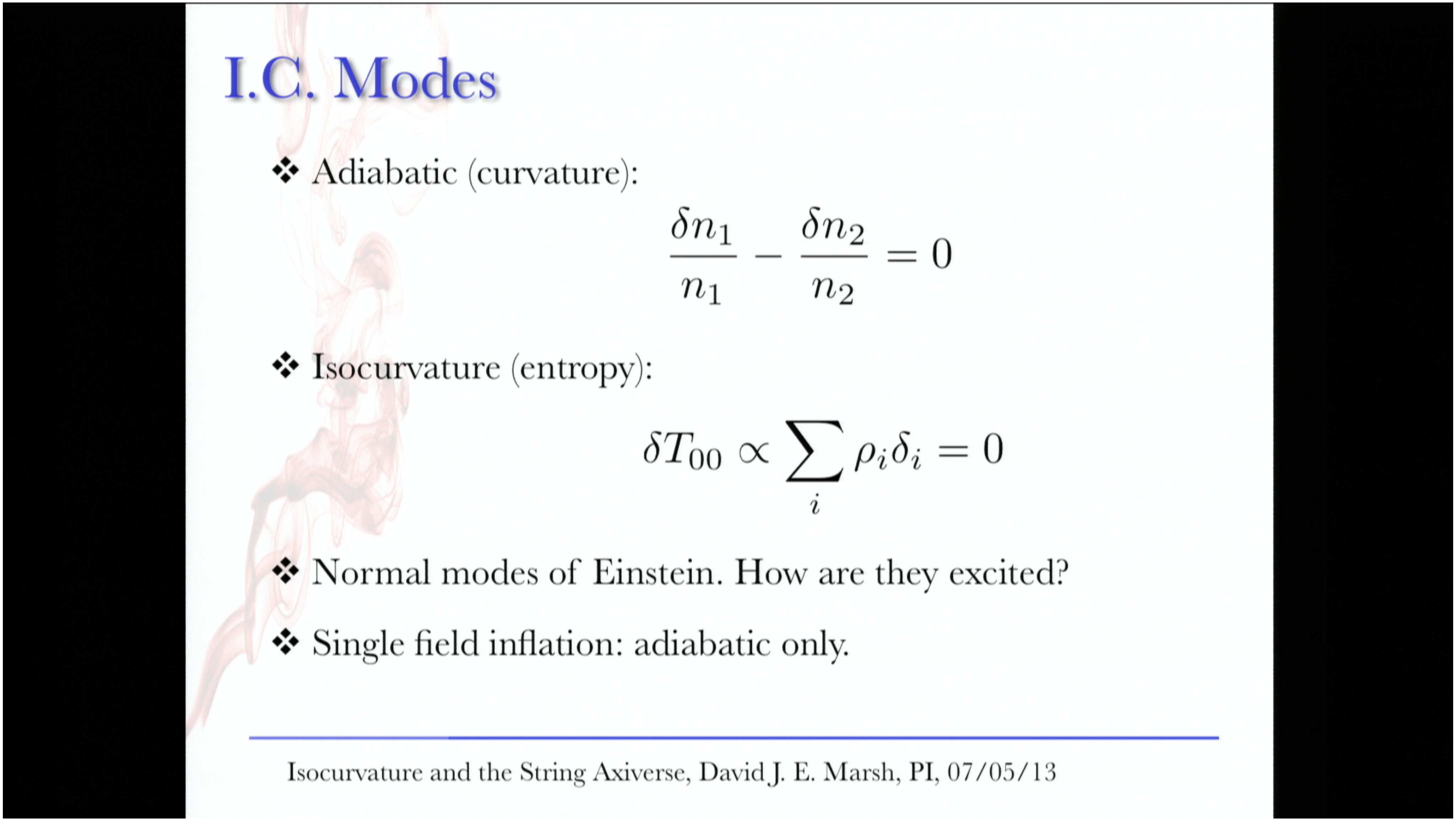
- Adiabatic (curvature):

$$\frac{\delta n_1}{n_1} - \frac{\delta n_2}{n_2} = 0$$

- Isocurvature (entropy):

$$\delta T_{00} \propto \sum_i \rho_i \delta_i = 0$$

- Normal modes of Einstein. How are they excited?
- Single field inflation: adiabatic only.



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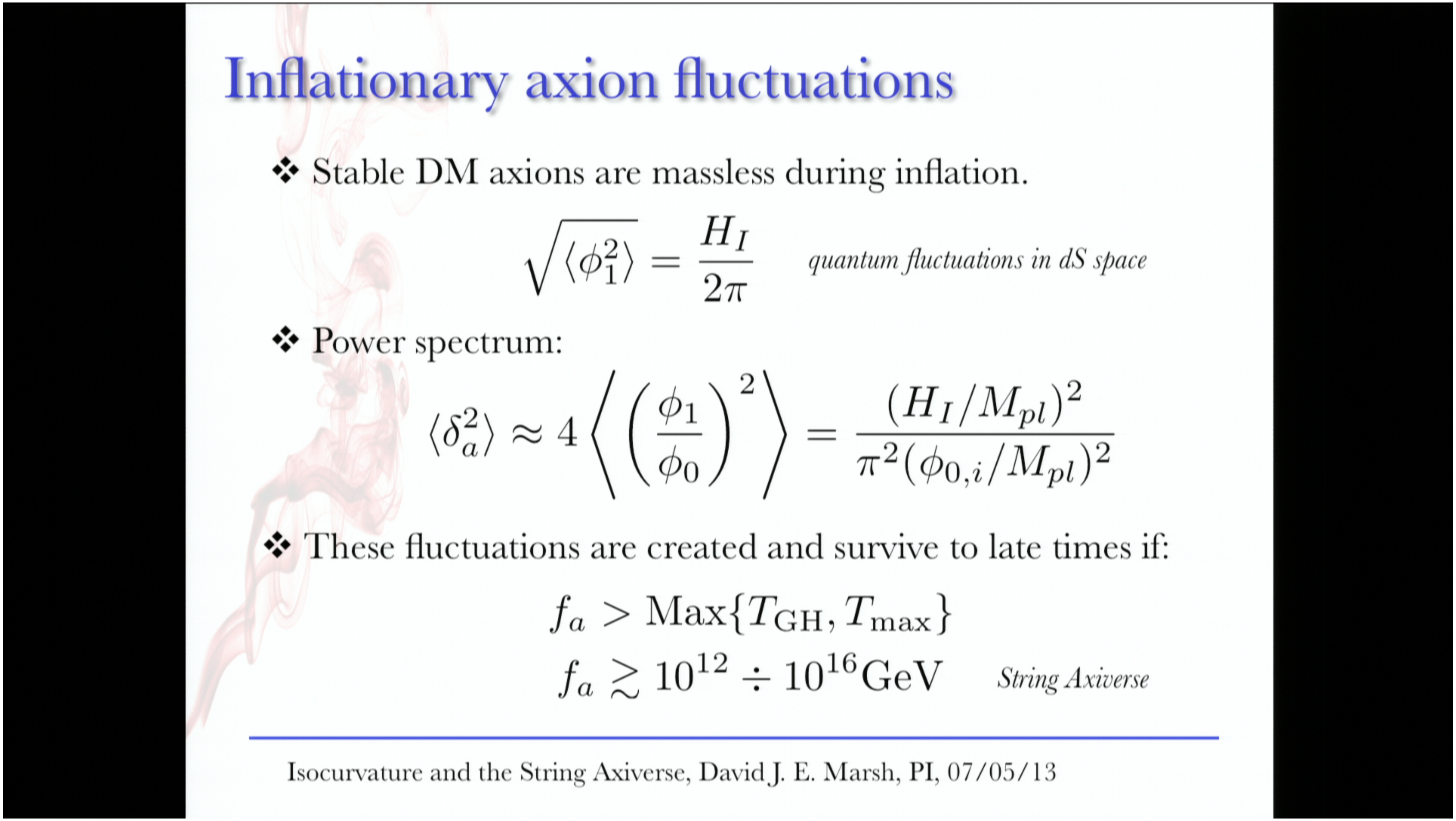


Inflationary axion fluctuations

- Stable DM axions are massless during inflation.

$$\sqrt{\langle \phi_1^2 \rangle} = \frac{H_I}{2\pi}$$ *quantum fluctuations in dS space*

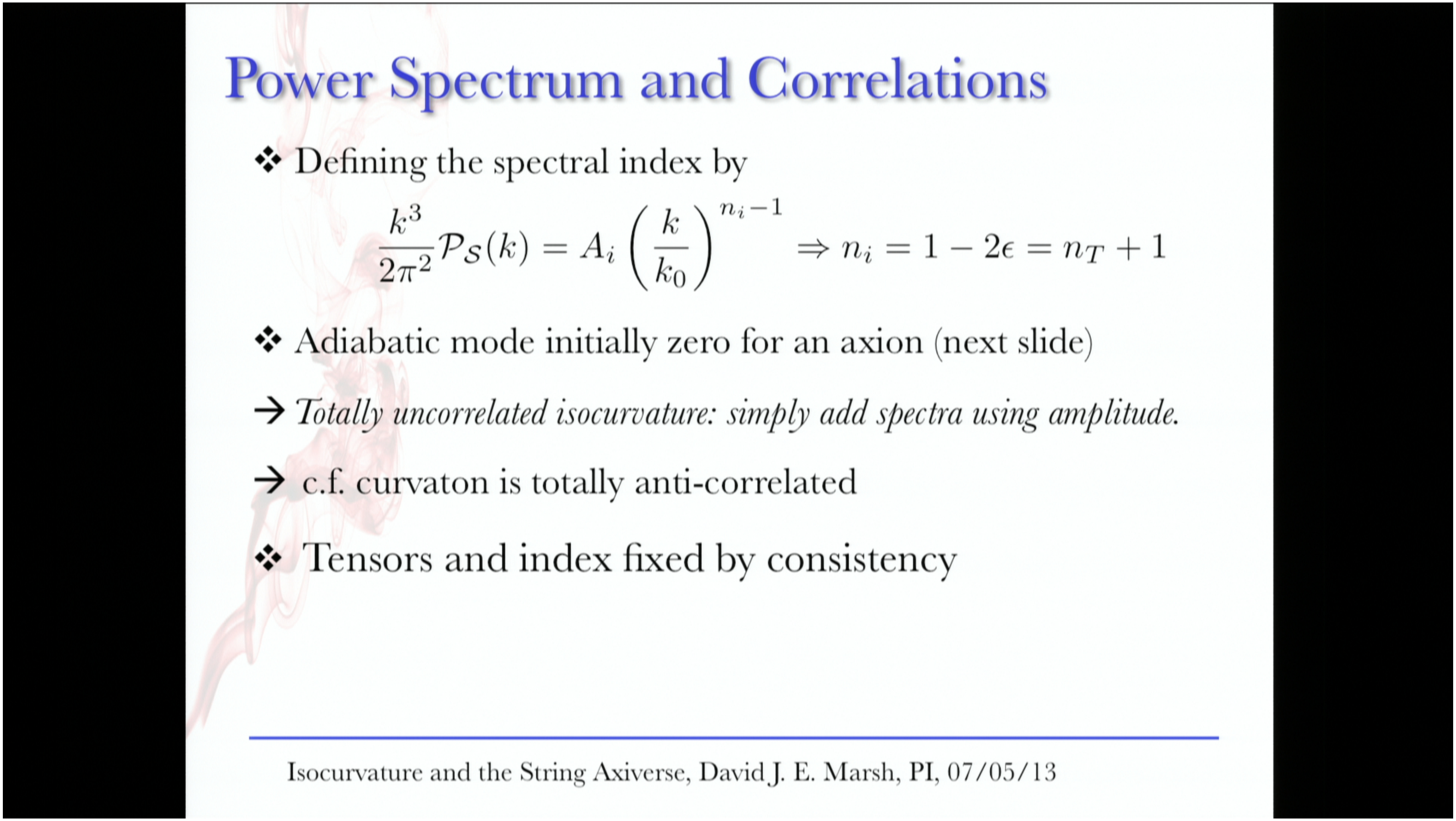
- Power spectrum:

$$\langle \delta_a^2 \rangle \approx 4 \left\langle \left(\frac{\phi_1}{\phi_0} \right)^2 \right\rangle = \frac{(H_I/M_{pl})^2}{\pi^2(\phi_{0,i}/M_{pl})^2}$$

- These fluctuations are created and survive to late times if:

$$f_a > \mathrm{Max}\{T_{\mathrm{GH}}, T_{\mathrm{max}}\}$$

$$f_a \gtrsim 10^{12} \div 10^{16}\mathrm{GeV}$$ *String Axiverse*



Power Spectrum and Correlations

- Defining the spectral index by

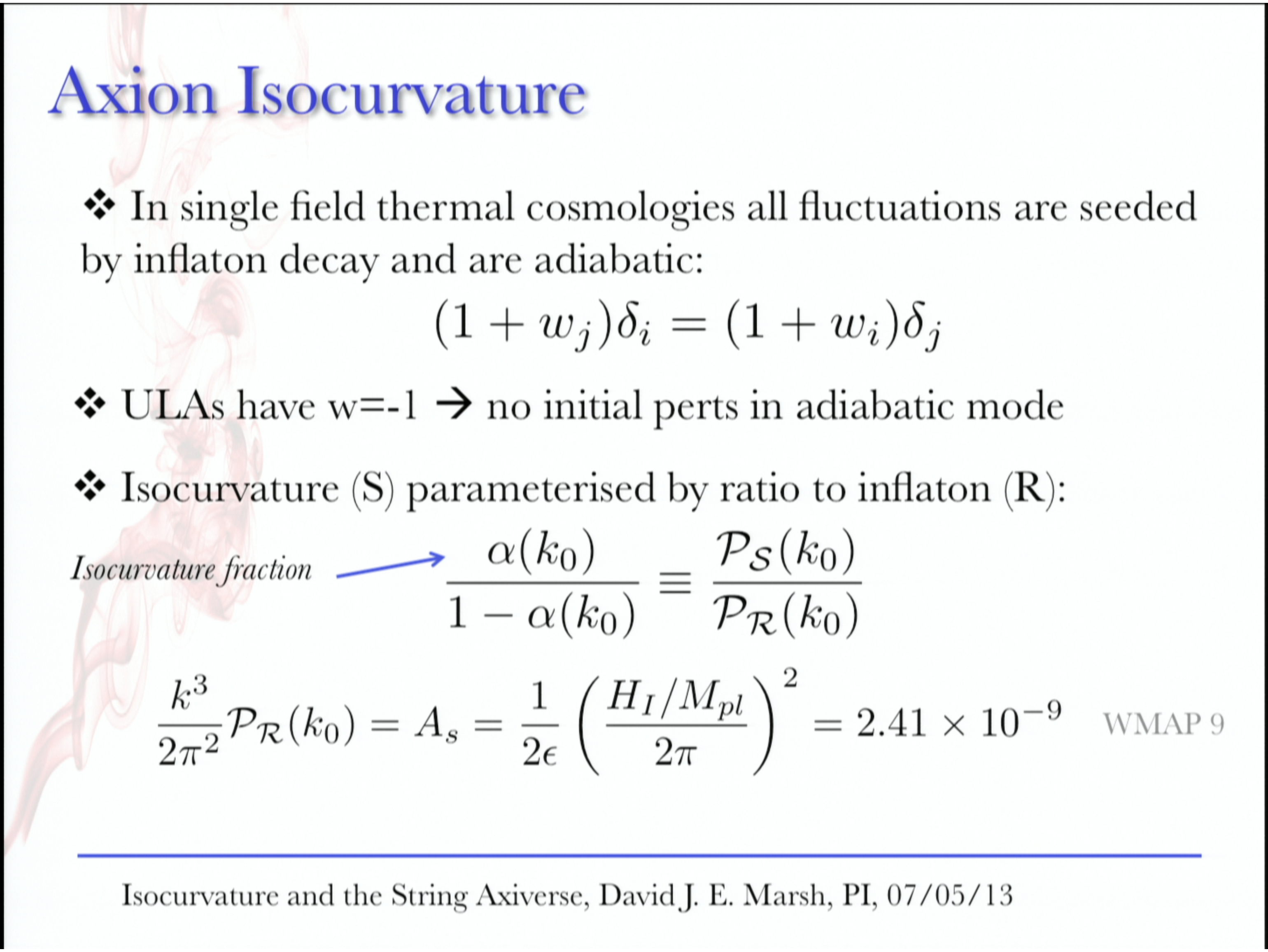
$$\frac{k^3}{2\pi^2}\mathcal{P}_{\mathcal{S}}(k) = A_i \left(\frac{k}{k_0}\right)^{n_i-1} \Rightarrow n_i = 1 - 2\epsilon = n_T + 1$$

- Adiabatic mode initially zero for an axion (next slide)

→ *Totally uncorrelated isocurvature: simply add spectra using amplitude.*

→ c.f. curvaton is totally anti-correlated

- Tensors and index fixed by consistency



Axion Isocurvature

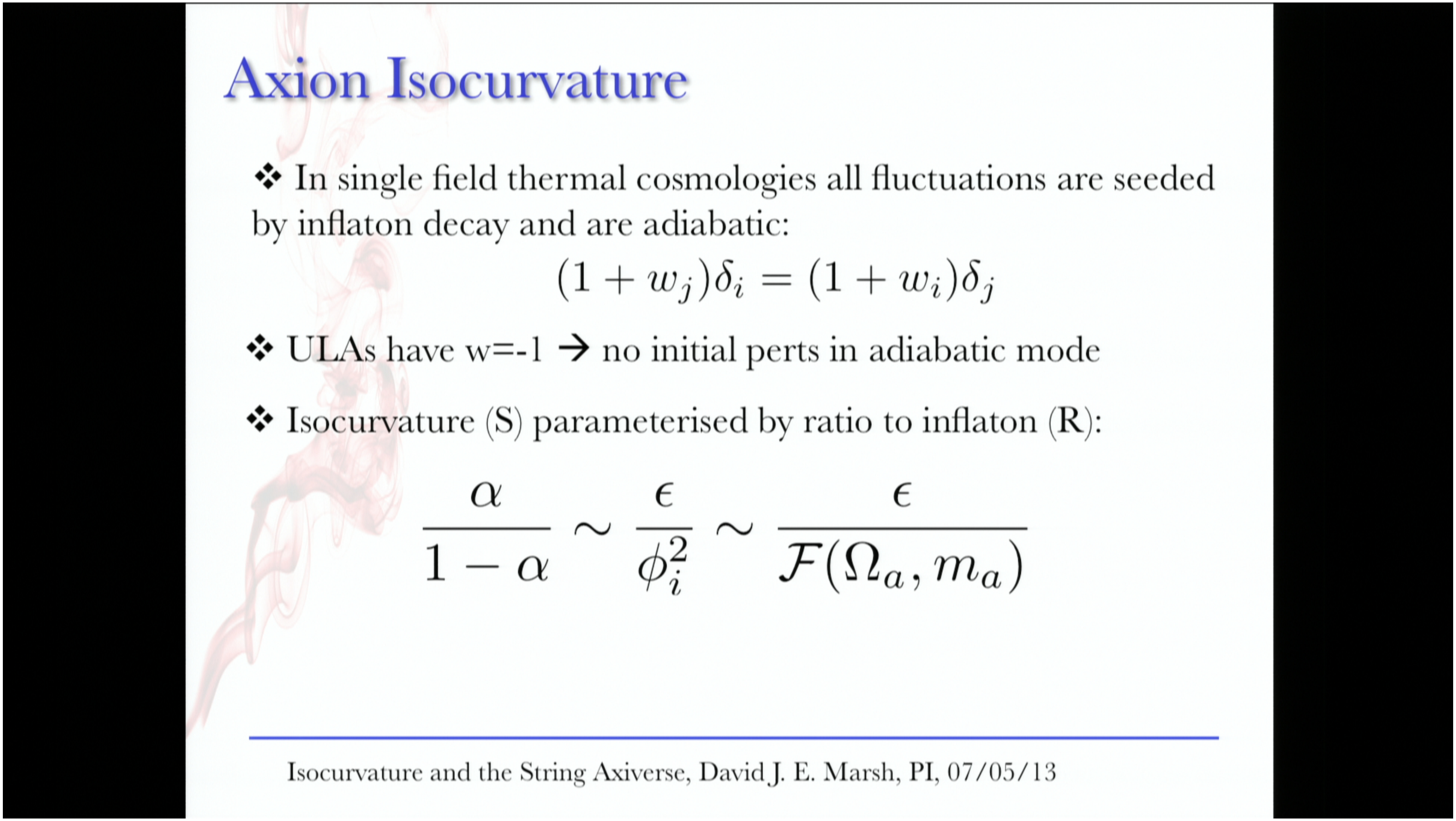
- In single field thermal cosmologies all fluctuations are seeded by inflaton decay and are adiabatic:

$$(1+w_j)\delta_i = (1+w_i)\delta_j$$

- ULAs have w=-1 → no initial perts in adiabatic mode
- Isocurvature (S) parameterised by ratio to inflaton (R):

Isocurvature fraction $\longrightarrow$ $$\frac{\alpha(k_0)}{1-\alpha(k_0)} \equiv \frac{\mathcal{P}_{\mathcal{S}}(k_0)}{\mathcal{P}_{\mathcal{R}}(k_0)}$$

$$\frac{k^3}{2\pi^2}\mathcal{P}_{\mathcal{R}}(k_0) = A_s = \frac{1}{2\epsilon}\left(\frac{H_I/M_{pl}}{2\pi}\right)^2 = 2.41\times 10^{-9}$$ WMAP 9



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$$\frac{\alpha}{1-\alpha} \sim \frac{\epsilon}{\phi_i^2} \sim \frac{\epsilon}{\mathcal{F}(\Omega_a, m_a)}$$

Isocurvature and the String Axiverse, David J. E. Marsh, PI, 07/05/13

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The Energy Scale of Inflation

$$
\begin{aligned}
H_I &= 1.5\times 10^{14}\mathrm{GeV}\left(\frac{\alpha_\mathrm{a}}{1-\alpha_\mathrm{a}}\right)^{1/2}\left(\frac{\phi_{0,\mathrm{i}}}{\mathrm{M_{pl}}}\right) \\
&\approx \begin{cases} 9.6\times 10^{11}\mathrm{GeV}\left(\frac{\alpha_\mathrm{CDM}}{0.047}\right)^{1/2}\left(\frac{\Omega_\mathrm{a}}{0.233}\right)^{-1/2}\left(\frac{\mathrm{m_a}}{10^{-22}\mathrm{eV}}\right)^{-1/4} & \text{if } a_\mathrm{osc} < a_\mathrm{eq}\,, \\ 2.4\times 10^{13}\mathrm{GeV}\left(\frac{\alpha_\mathrm{CDM}}{0.047}\right)^{1/2}\left(\frac{\Omega_\mathrm{a}}{0.233}\right)^{-1/2} & \text{if } a_\mathrm{osc} > a_\mathrm{eq}\,, \end{cases}
\end{aligned}
$$

Compare to Planck tensor and isocurvature:

$$\alpha_\mathrm{CDM} < 0.039 \longrightarrow H_I < 10^7\mathrm{GeV}(\mathrm{f_a}/10^{11}\mathrm{GeV})^{0.408}$$

$$r < 0.11 \longrightarrow H_I < 5.53\times 10^{12}\mathrm{GeV}$$

WMAP for QCD

WMAP 5 Appendix is great!

- ❖ QCD relic abundance depends on f_a, θ_i and γ

→ So do isocurvature constraints

$$\alpha_{\rm CDM} < 0.047, (95\%{\rm C.L.})$$

WMAP 9
+eCMB+BAO+H0

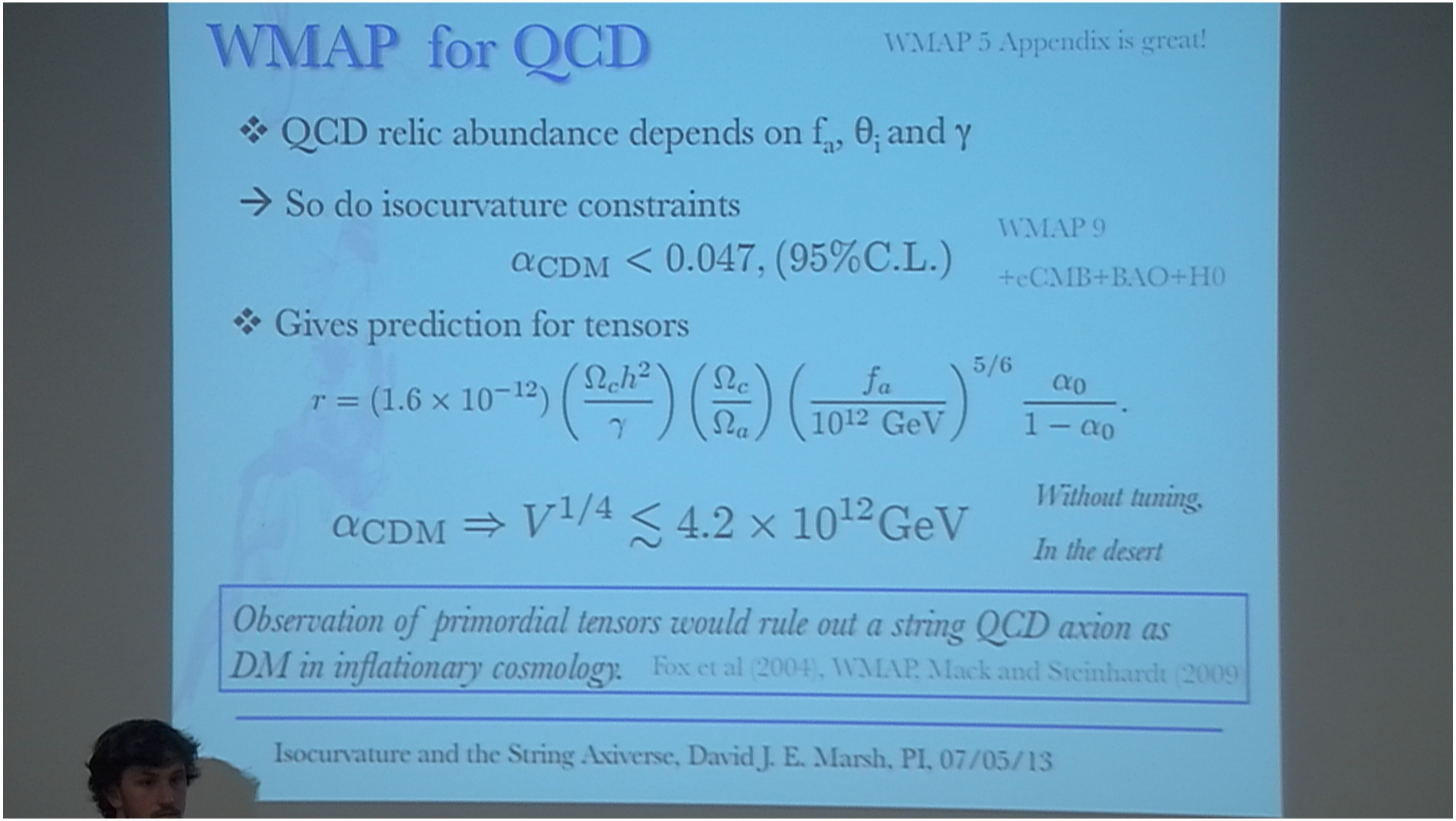
- ❖ Gives prediction for tensors

$$r = (1.6 \times 10^{-12}) \left(\frac{\Omega_c h^2}{\gamma}\right) \left(\frac{\Omega_c}{\Omega_a}\right) \left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{5/6} \frac{\alpha_0}{1-\alpha_0}.$$

$$\alpha_{\rm CDM} \Rightarrow V^{1/4} \lesssim 4.2 \times 10^{12}{\rm GeV}$$

Without tuning,
In the desert

Observation of primordial tensors would rule out a string QCD axion as DM in inflationary cosmology. Fox et al (2004), WMAP, Mack and Steinhardt (2009)



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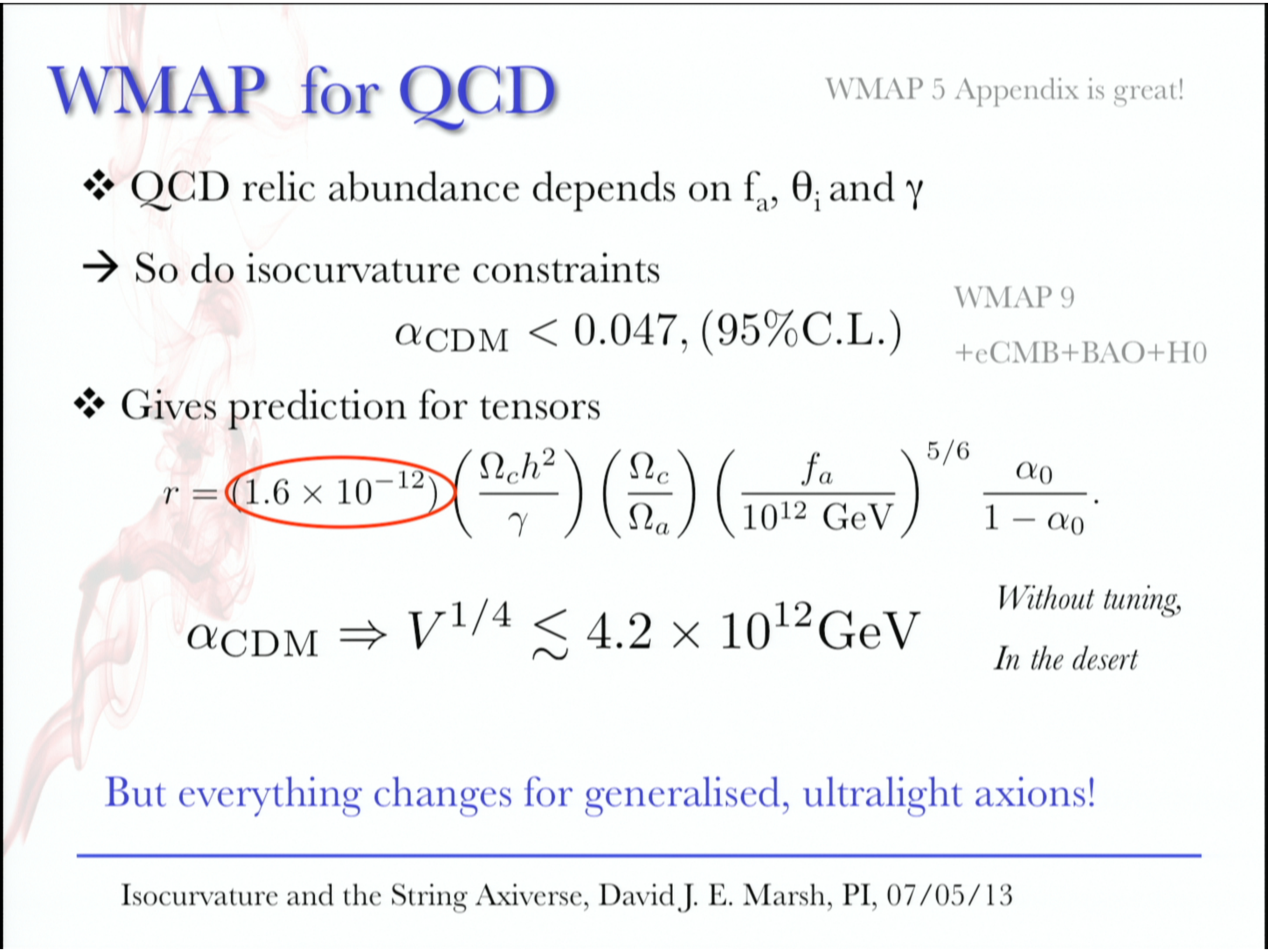

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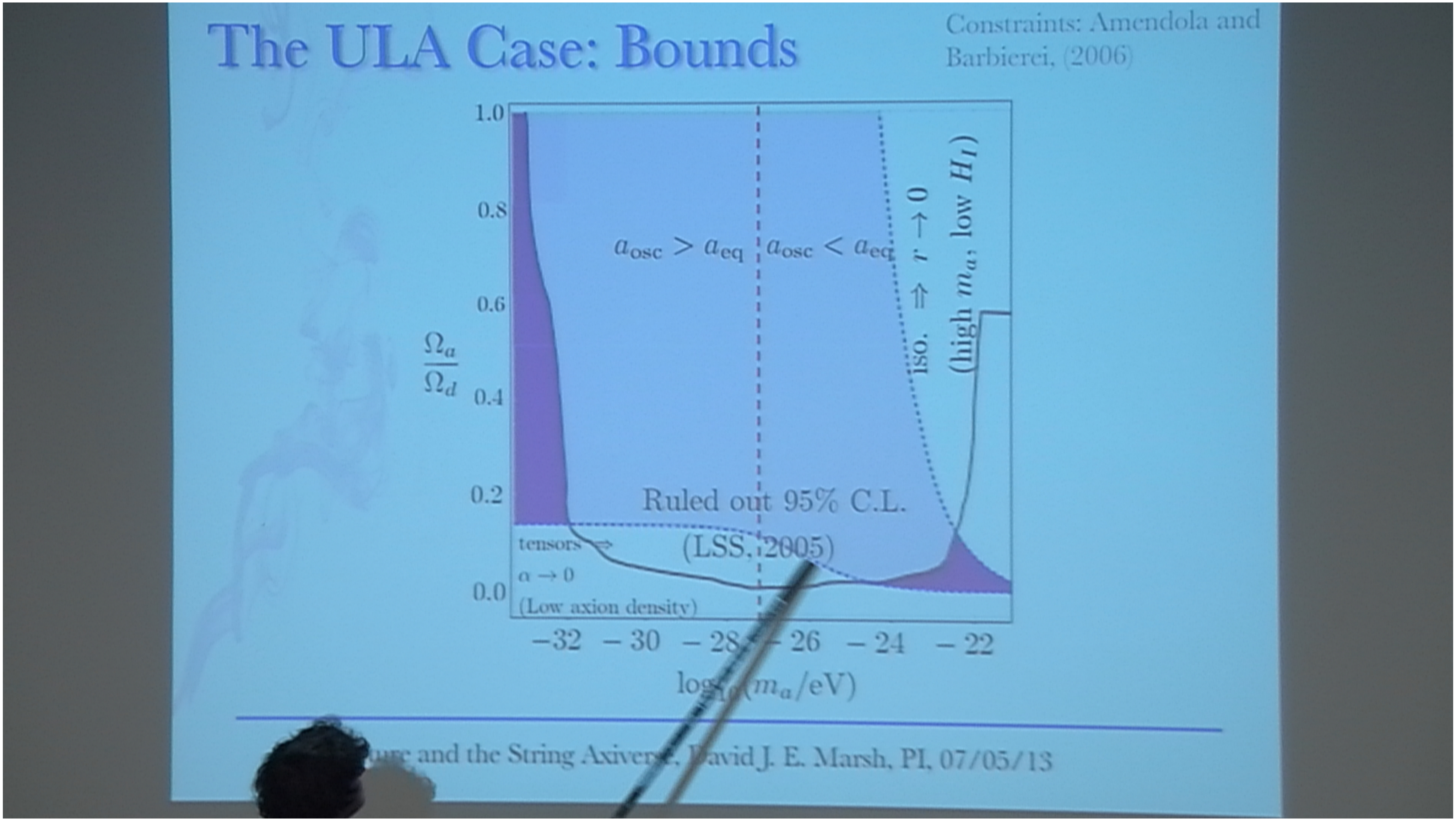
But everything changes for generalised, ultralight axions!



The ULA Case: Bounds

Constraints: Amendola and Barbiercei, (2006)

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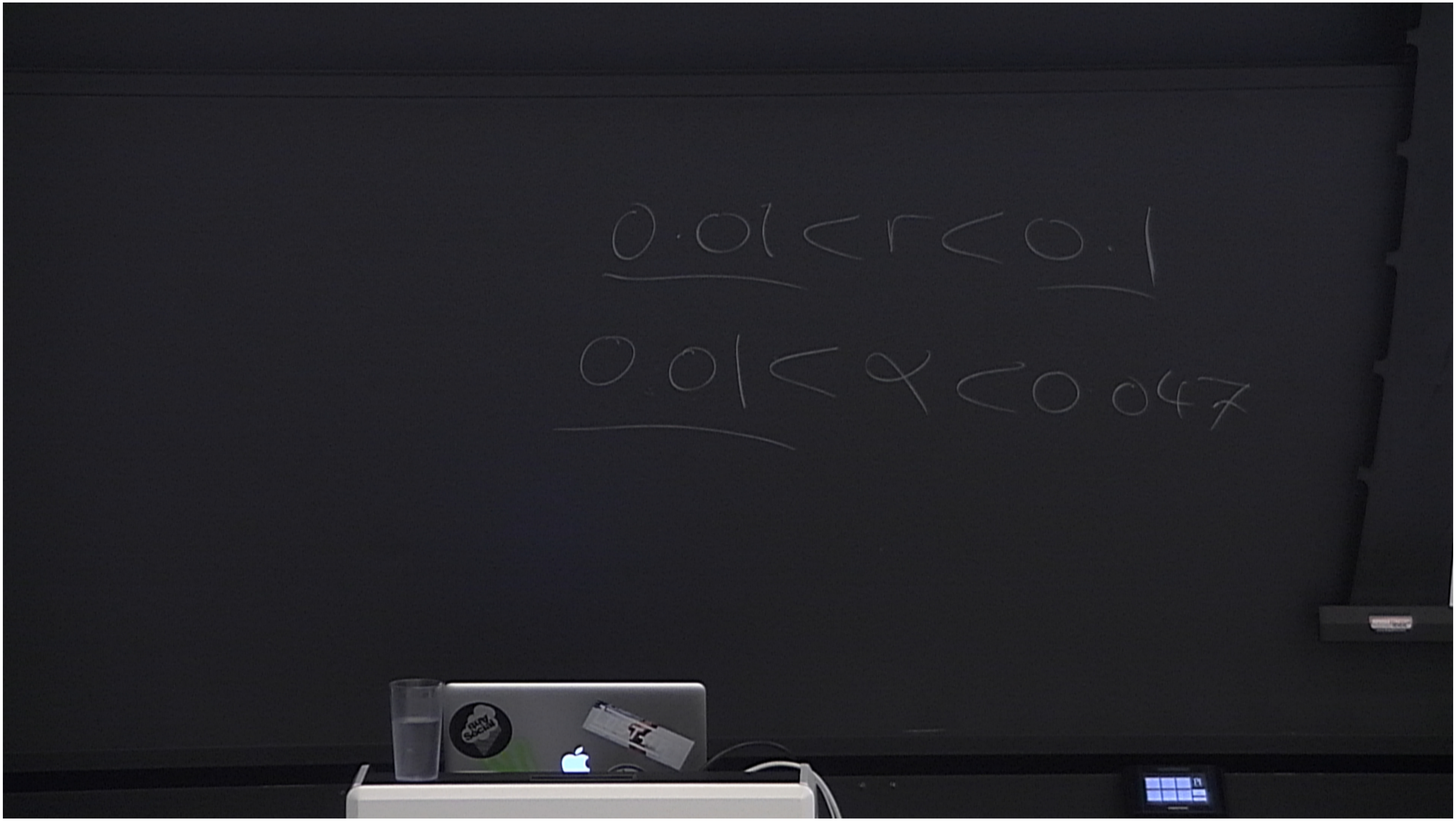

$$\underline{0.01} < r < \underline{0.1}$$

$$\underline{0.01} < \alpha < 0.047$$

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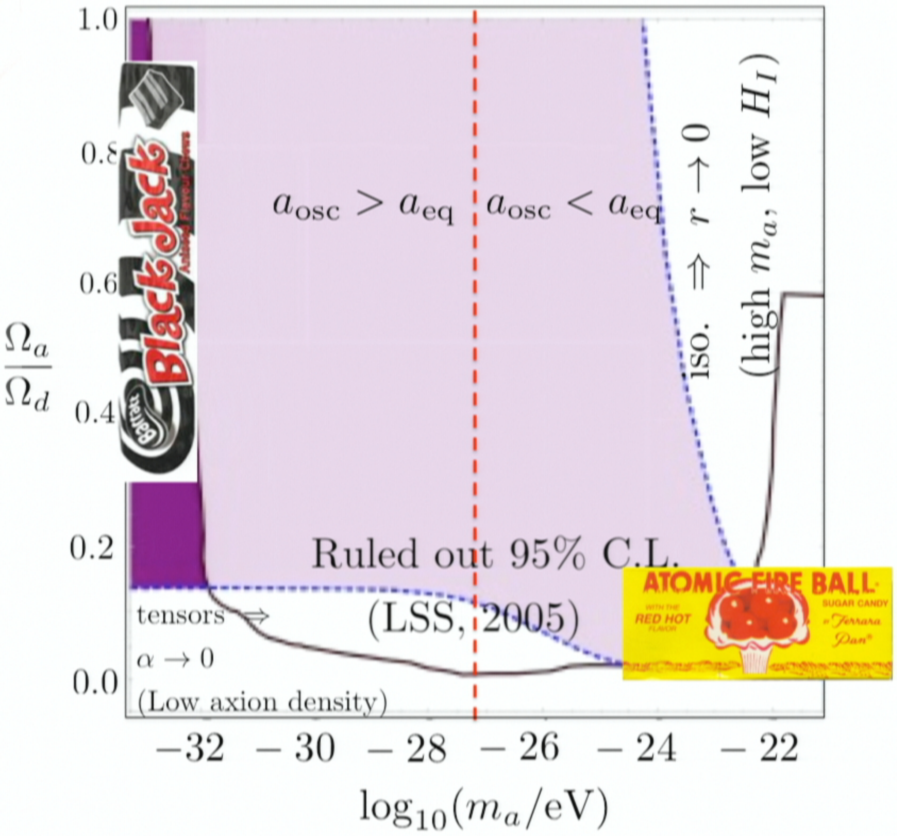
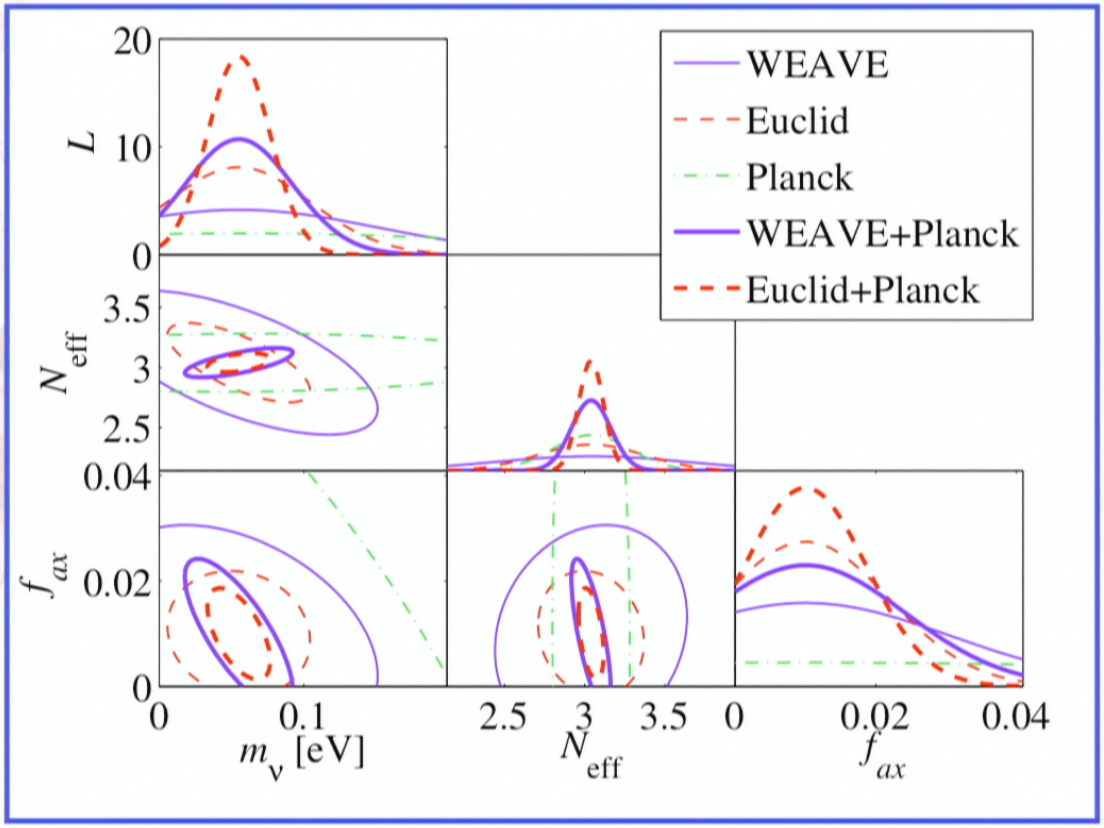


Forecasts at low mass

DJEM et al (2011)

Macaulay et al (in prep.)



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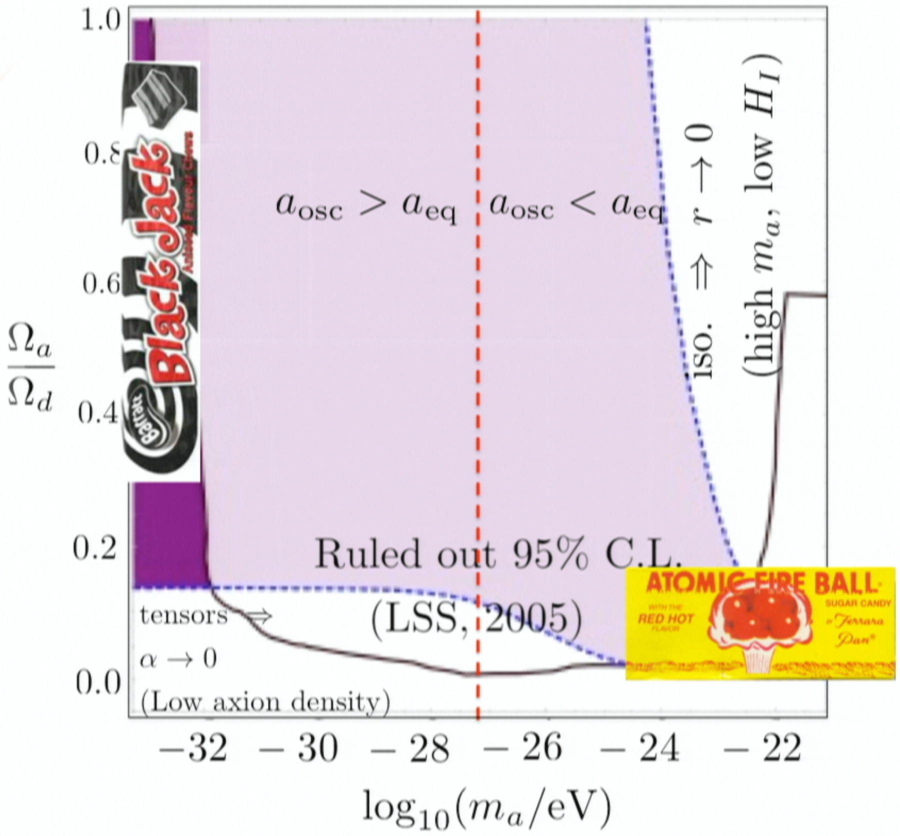

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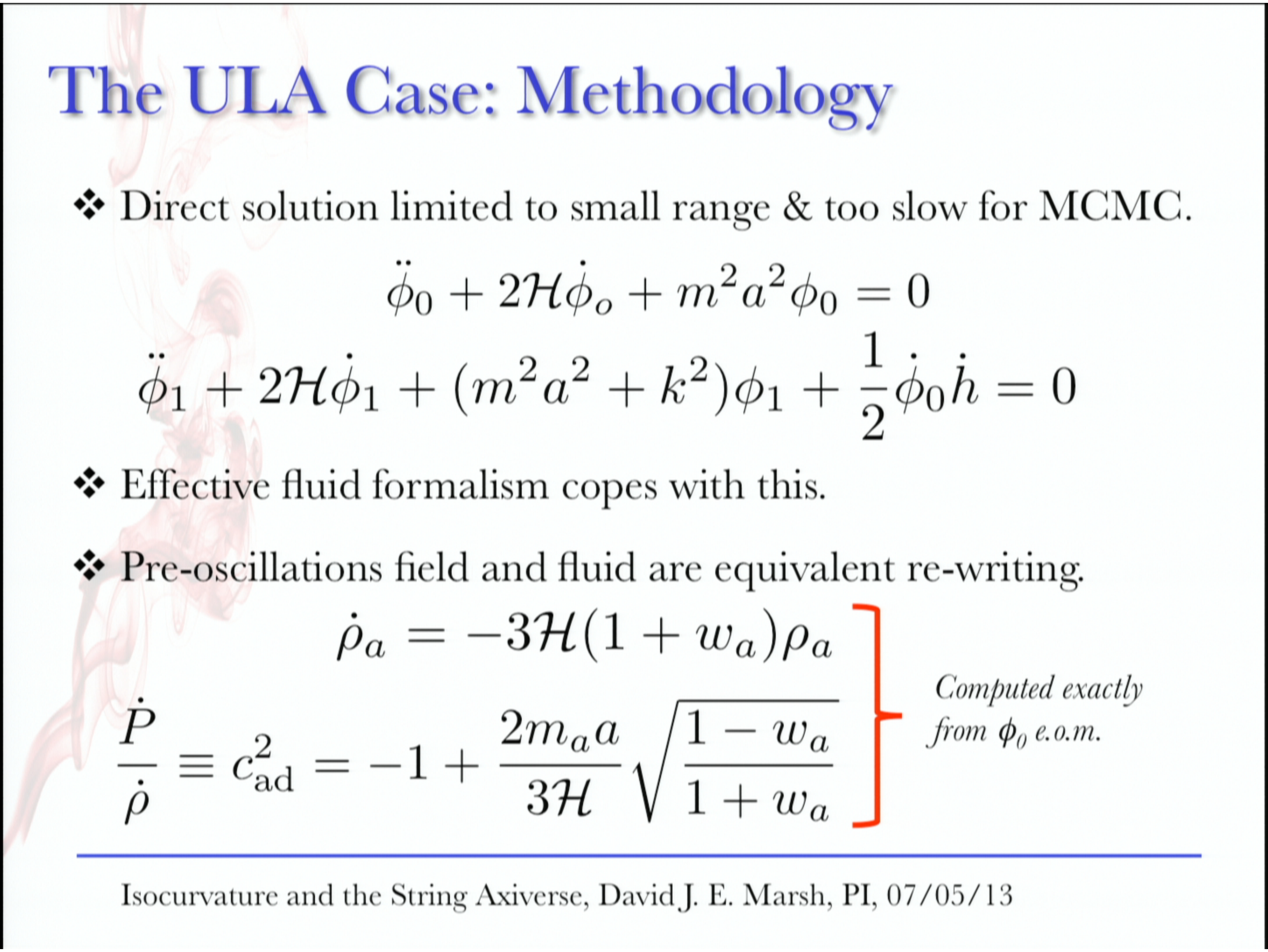


The ULA Case: Methodology

- Direct solution limited to small range & too slow for MCMC.

$$\ddot{\phi}_0 + 2\mathcal{H}\dot{\phi}_o + m^2a^2\phi_0 = 0$$

$$\ddot{\phi}_1 + 2\mathcal{H}\dot{\phi}_1 + (m^2a^2 + k^2)\phi_1 + \frac{1}{2}\dot{\phi}_0\dot{h} = 0$$

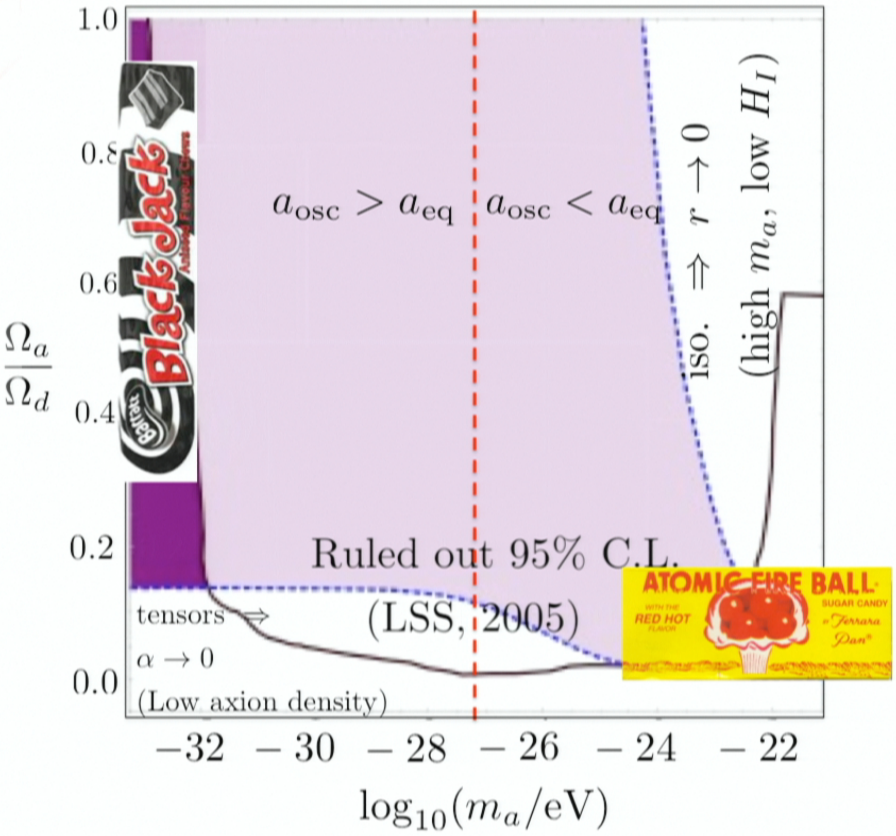
- Effective fluid formalism copes with this.
- Pre-oscillations field and fluid are equivalent re-writing.

$$\left.\begin{aligned} \dot{\rho}_a &= -3\mathcal{H}(1+w_a)\rho_a \\ \frac{\dot{P}}{\dot{\rho}} \equiv c_{\rm ad}^2 &= -1 + \frac{2m_a a}{3\mathcal{H}}\sqrt{\frac{1-w_a}{1+w_a}} \end{aligned}\right\}$$

Computed exactly from ϕ_0 e.o.m.

The ULA Case: Bounds

Constraints: Amendola and Barbierei, (2006)



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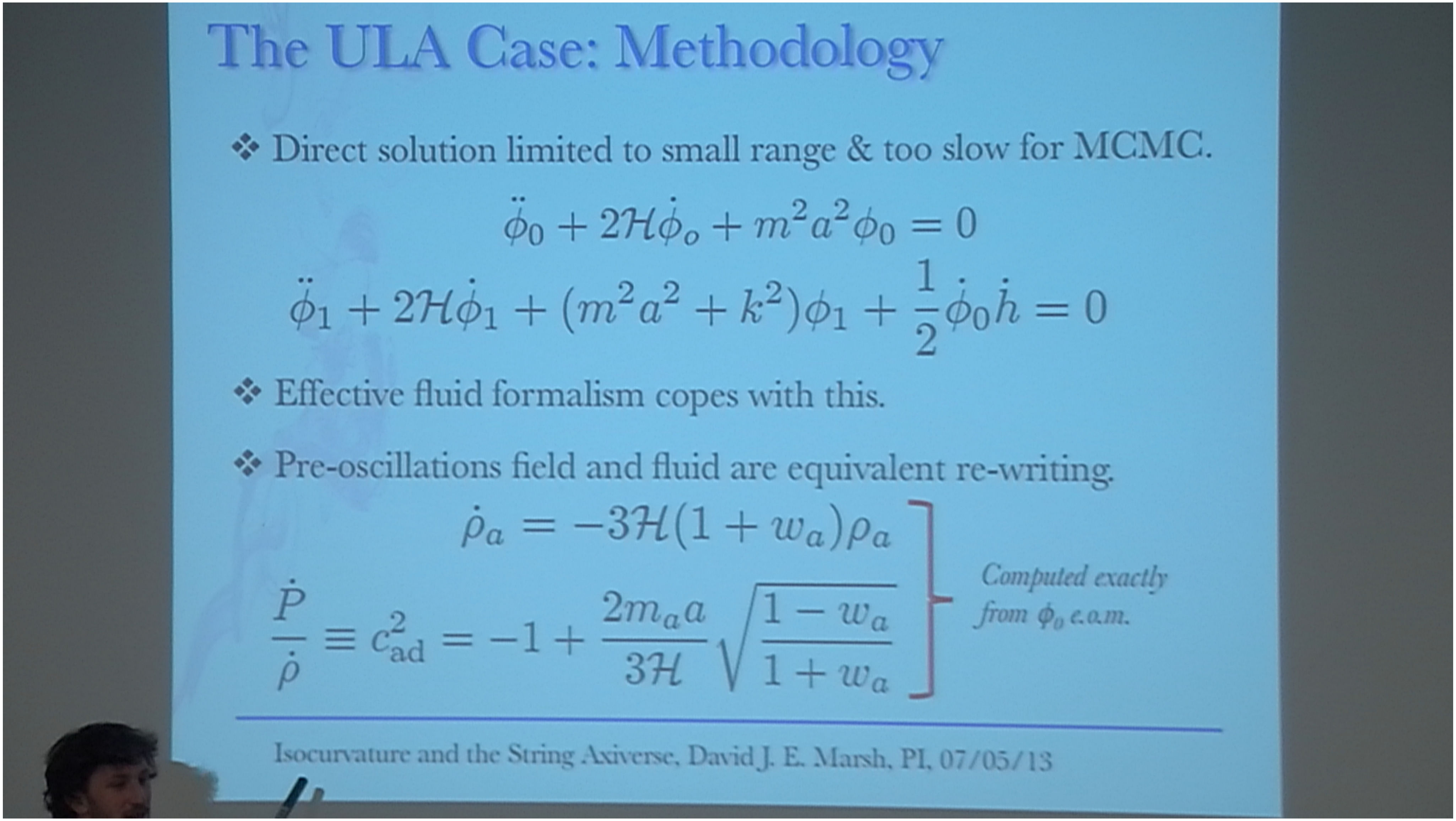

The ULA Case: Methodology

- Direct solution limited to small range & too slow for MCMC.

$$\ddot{\phi}_0 + 2\mathcal{H}\dot{\phi}_o + m^2a^2\phi_0 = 0$$

$$\ddot{\phi}_1 + 2\mathcal{H}\dot{\phi}_1 + (m^2a^2 + k^2)\phi_1 + \frac{1}{2}\dot{\phi}_0\dot{h} = 0$$

- Effective fluid formalism copes with this.
- Pre-oscillations field and fluid are equivalent re-writing.

$$\left.\begin{aligned} \dot{\rho}_a &= -3\mathcal{H}(1+w_a)\rho_a \\ \frac{\dot{P}}{\dot{\rho}} \equiv c^2_{\rm ad} &= -1 + \frac{2m_a a}{3\mathcal{H}}\sqrt{\frac{1-w_a}{1+w_a}} \end{aligned}\right]$$

Computed exactly from ϕ_0 e.o.m.

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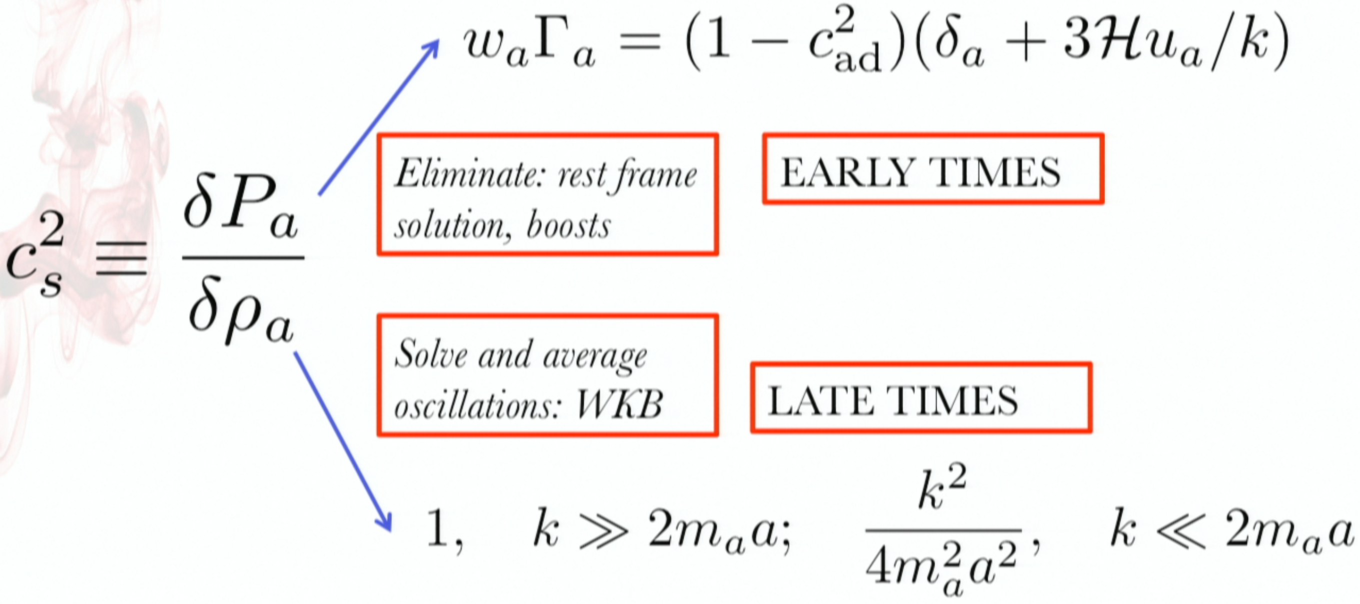
The ULA Case: Methodology

- Subtlety: frozen field w=-1 gives (apparent) divergences.
- Perturbations: continuity+Euler, with entropy perts. Hu (1998)



$$w_a\Gamma_a = (1 - c_{\rm ad}^2)(\delta_a + 3\mathcal{H}u_a/k)$$

Eliminate: rest frame solution, boosts

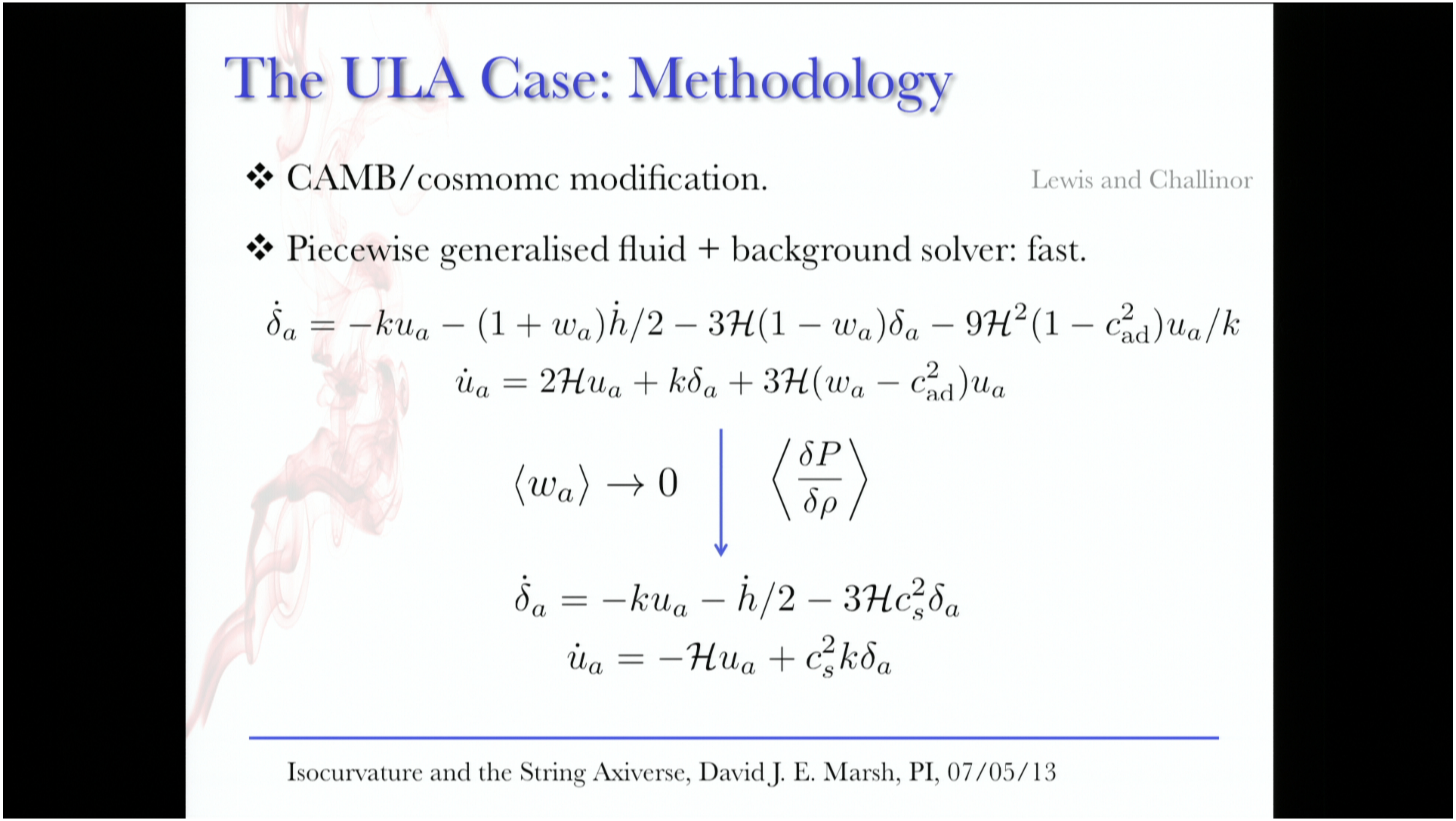
EARLY TIMES

$$c_s^2 \equiv \frac{\delta P_a}{\delta \rho_a}$$

Solve and average oscillations: WKB

LATE TIMES

$$1, \quad k \gg 2m_a a; \quad \frac{k^2}{4m_a^2 a^2}, \quad k \ll 2m_a a$$



The ULA Case: Methodology

- CAMB/cosmomc modification. Lewis and Challinor
- Piecewise generalised fluid + background solver: fast.

$$\dot{\delta}_a = -ku_a - (1+w_a)\dot{h}/2 - 3\mathcal{H}(1-w_a)\delta_a - 9\mathcal{H}^2(1-c_{\rm ad}^2)u_a/k$$

$$\dot{u}_a = 2\mathcal{H}u_a + k\delta_a + 3\mathcal{H}(w_a - c_{\rm ad}^2)u_a$$

$$\langle w_a \rangle \to 0 \quad \Big\downarrow \quad \left\langle \frac{\delta P}{\delta \rho} \right\rangle$$

$$\dot{\delta}_a = -ku_a - \dot{h}/2 - 3\mathcal{H}c_s^2\delta_a$$

$$\dot{u}_a = -\mathcal{H}u_a + c_s^2 k\delta_a$$

ULAs versus CDM axions

❖ Normalisation effects parameter dependence.

❖ CDM axions are indistinguishable from WIMPs etc

→ Single fluid normalisation

$$\delta_d = 1 \Rightarrow \mathcal{P}_\mathcal{S} = (\Omega_a/\Omega_d)^2 \mathcal{P}_a$$

Commonly used

❖ ULAs are distinct in their clustering

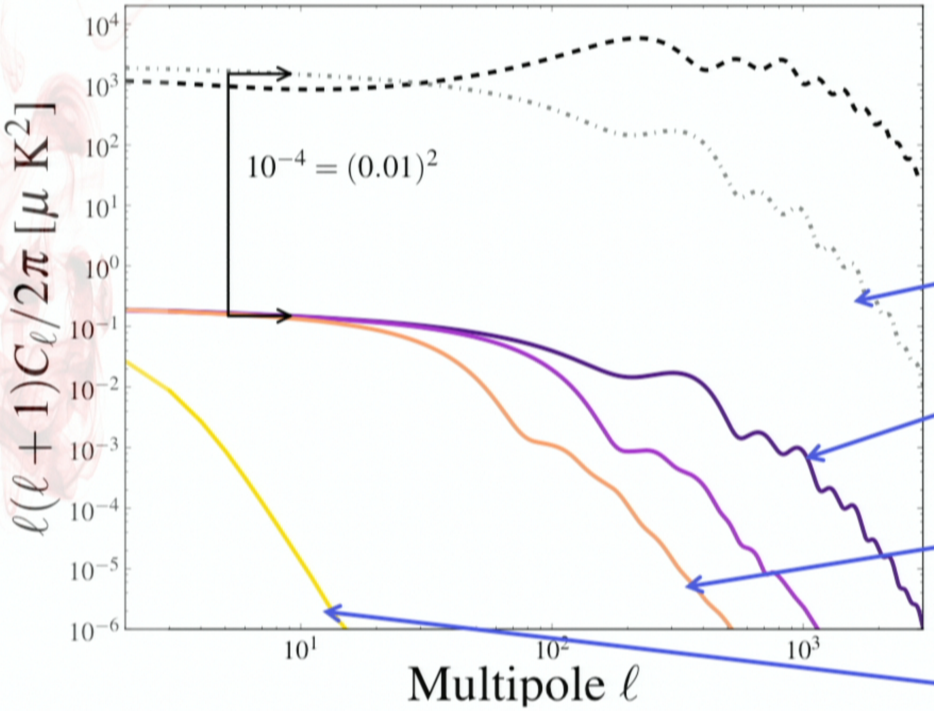
→ Separate fluid normalisation

$$\delta_a = 1 \Rightarrow \mathcal{P}_\mathcal{S} = \mathcal{P}_a$$

Necessary for light DM

$$\Rightarrow \frac{\alpha_a}{1-\alpha_a} = \frac{8\epsilon}{(\phi_{0,i}/M_{pl})^2} = \left(\frac{\Omega_d}{\Omega_a}\right)^2 \frac{\alpha_{\rm CDM}}{1-\alpha_{\rm CDM}}$$

Isocurvature TT: norm. and suppression



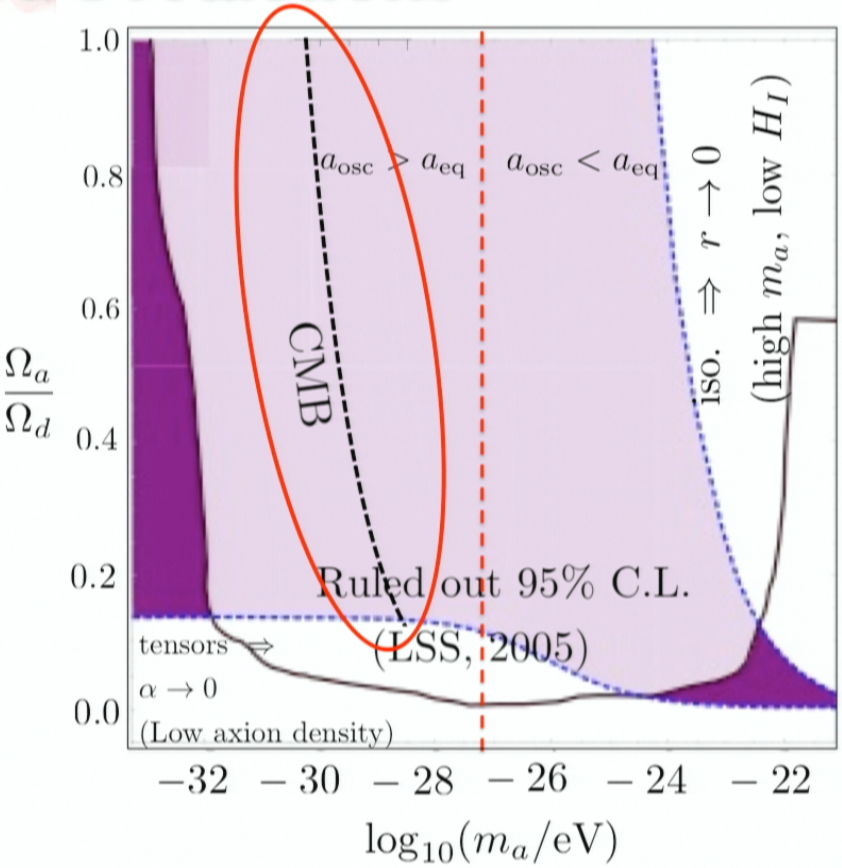
100% CDM

1% ~10^{-20}eV

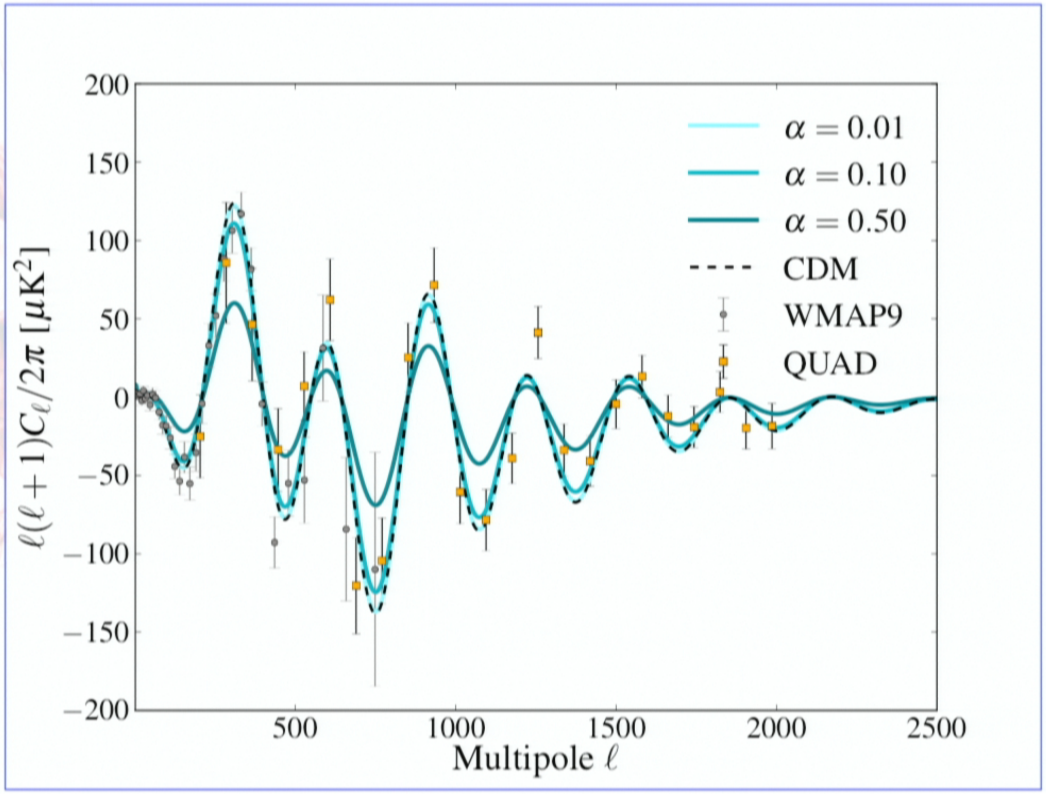
1% 10^{-29}eV

1% 10^{-32} eV

Modified Predictions



Isocurvature polarisation



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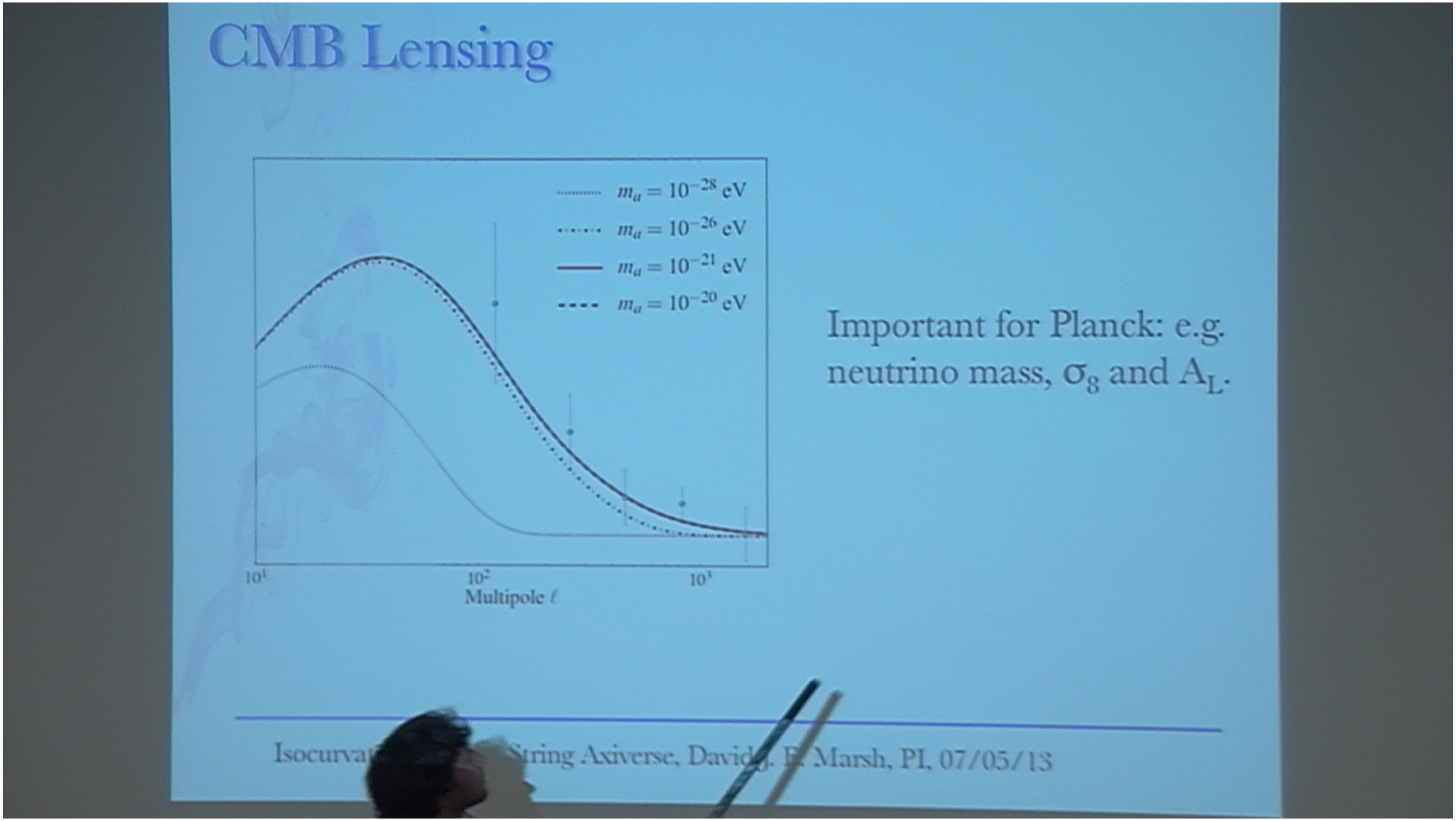

CMB Lensing

Important for Planck: e.g. neutrino mass, σ_8 and A_L.

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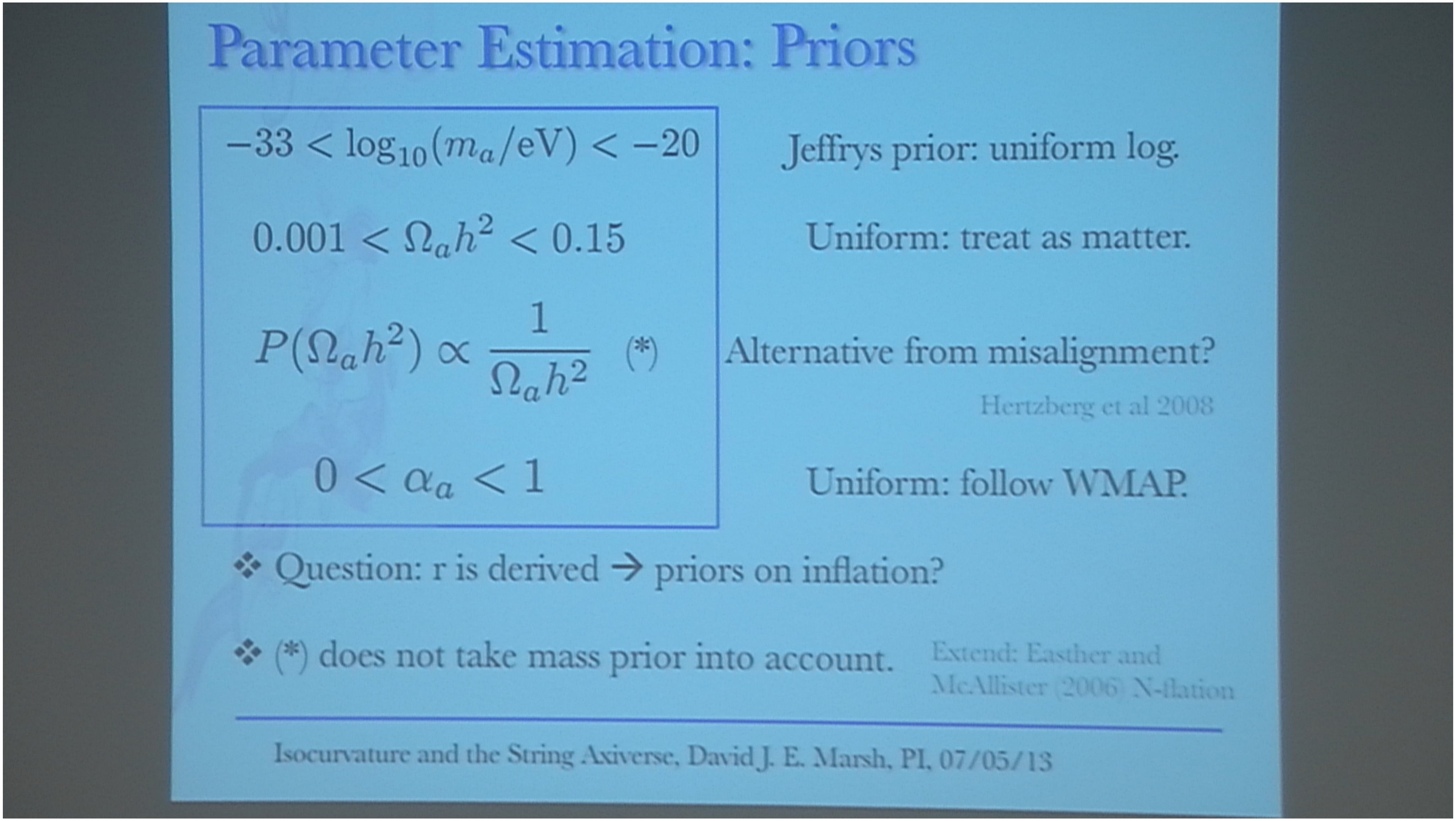


Parameter Estimation: Priors

$-33 < \log_{10}(m_a/\mathrm{eV}) < -20$ Jeffrys prior: uniform log.

$0.001 < \Omega_a h^2 < 0.15$ Uniform: treat as matter.

$P(\Omega_a h^2) \propto \dfrac{1}{\Omega_a h^2}$ (*) Alternative from misalignment?

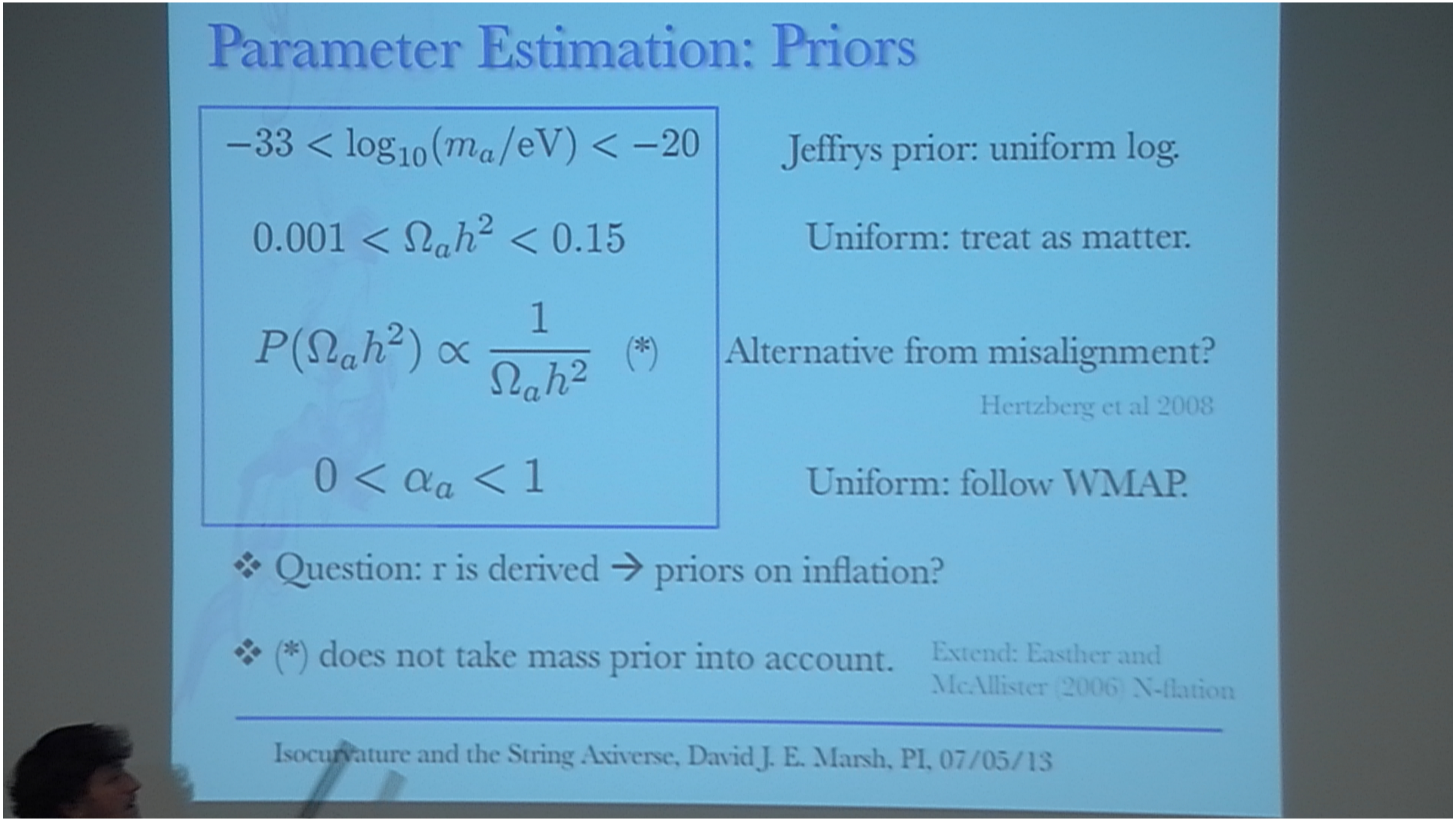
Hertzberg et al 2008

$0 < \alpha_a < 1$ Uniform: follow WMAP.

- Question: r is derived → priors on inflation?
- (*) does not take mass prior into account.

Extend: Easther and McAllister (2006) N-flation

Isocurvature and the String Axiverse, David J. E. Marsh, PI, 07/05/13



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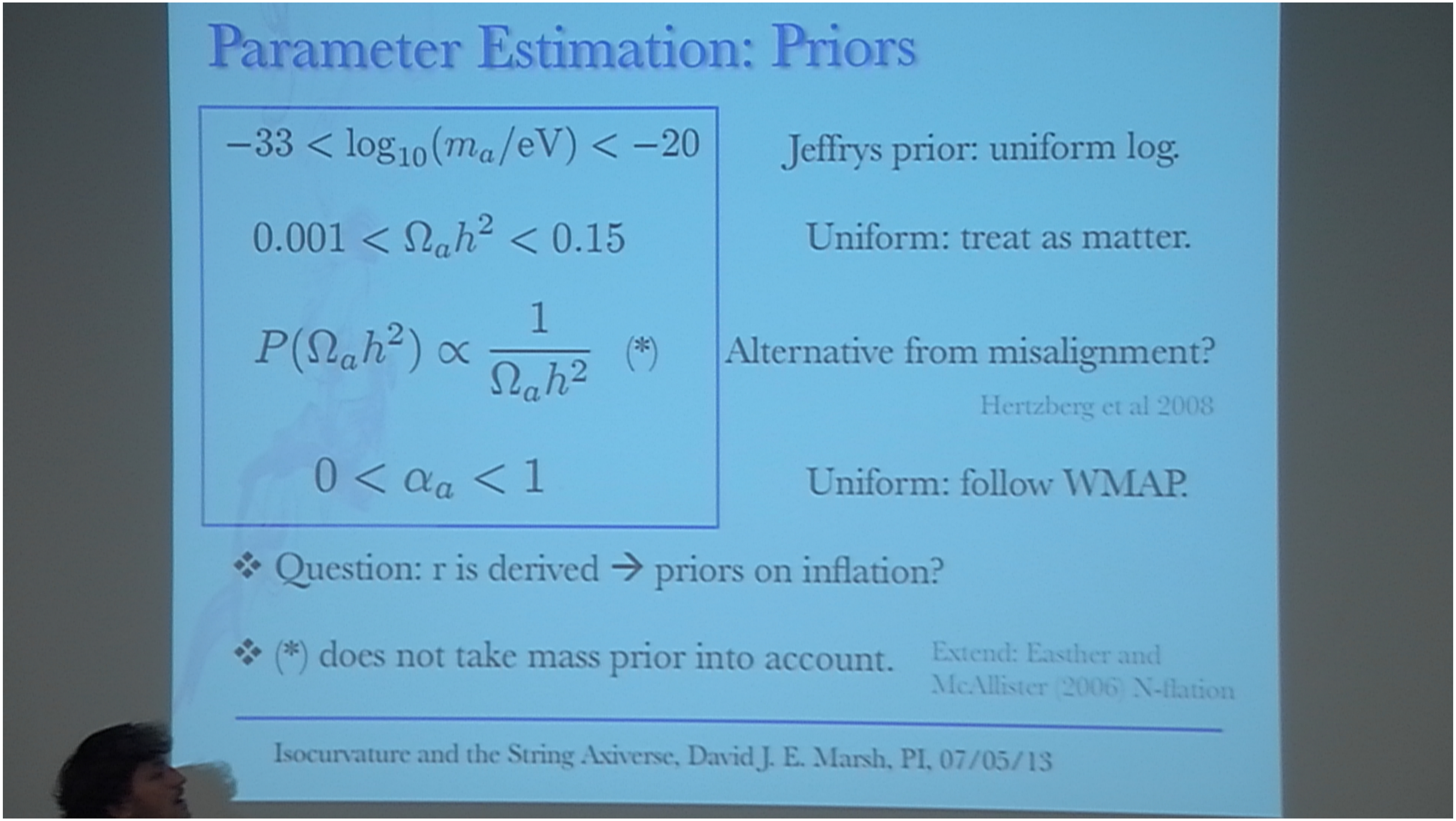

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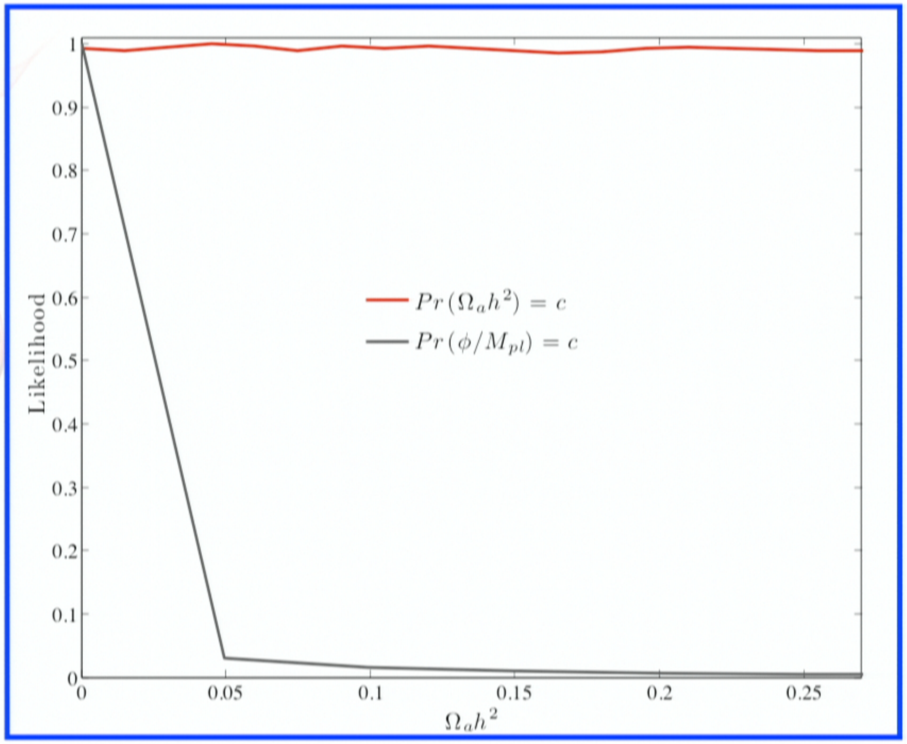
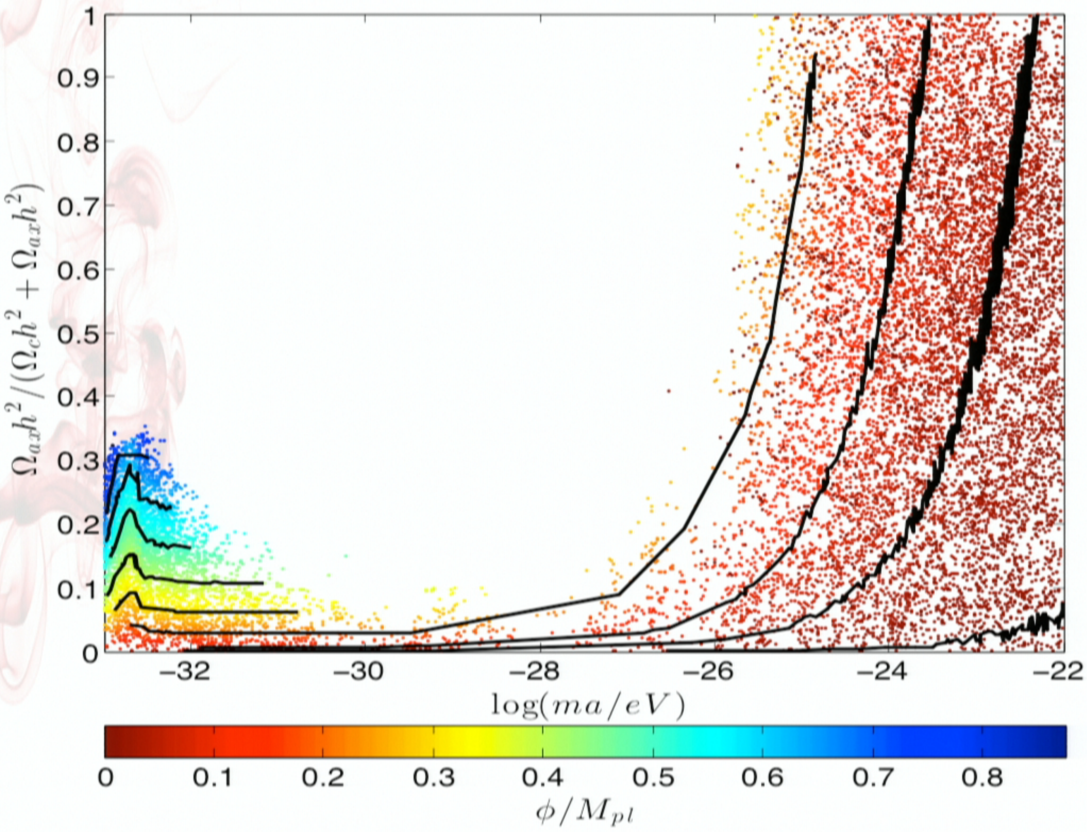


Fine Tuning?



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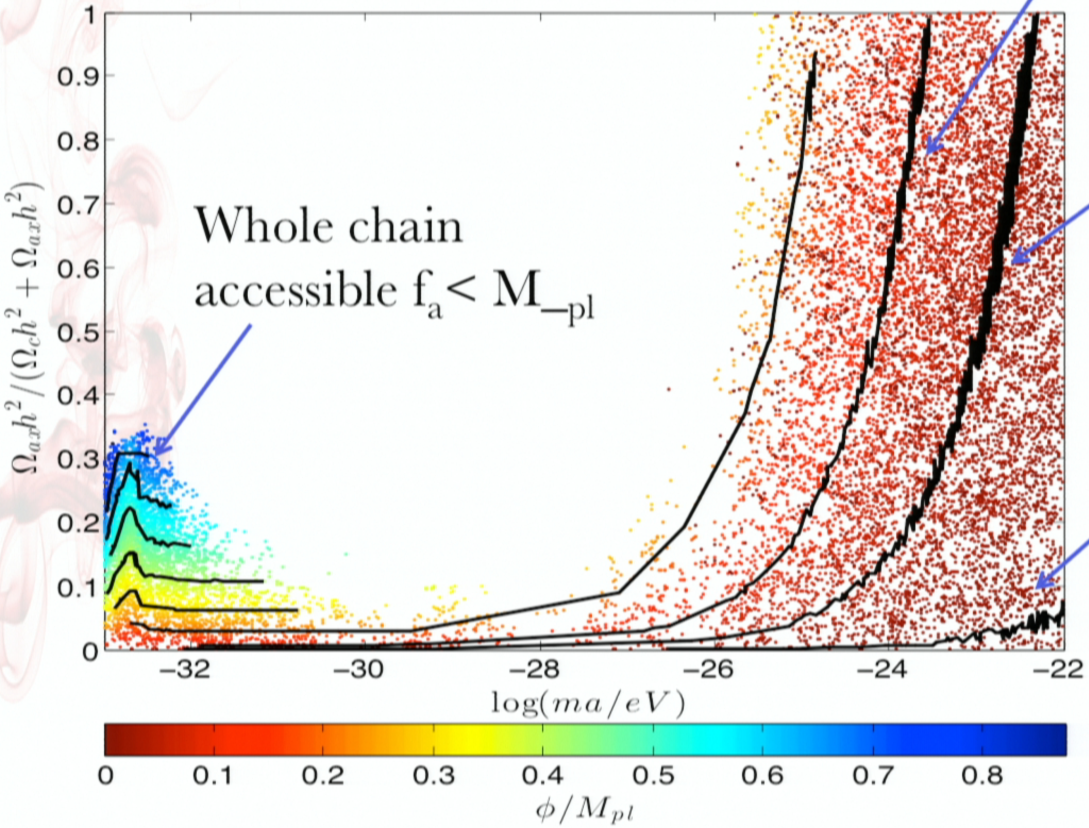
Fine Tuning?



Whole chain accessible $f_a < M\_{pl}$

0.1

0.05

0.01: interesting region natural for GUT f_a

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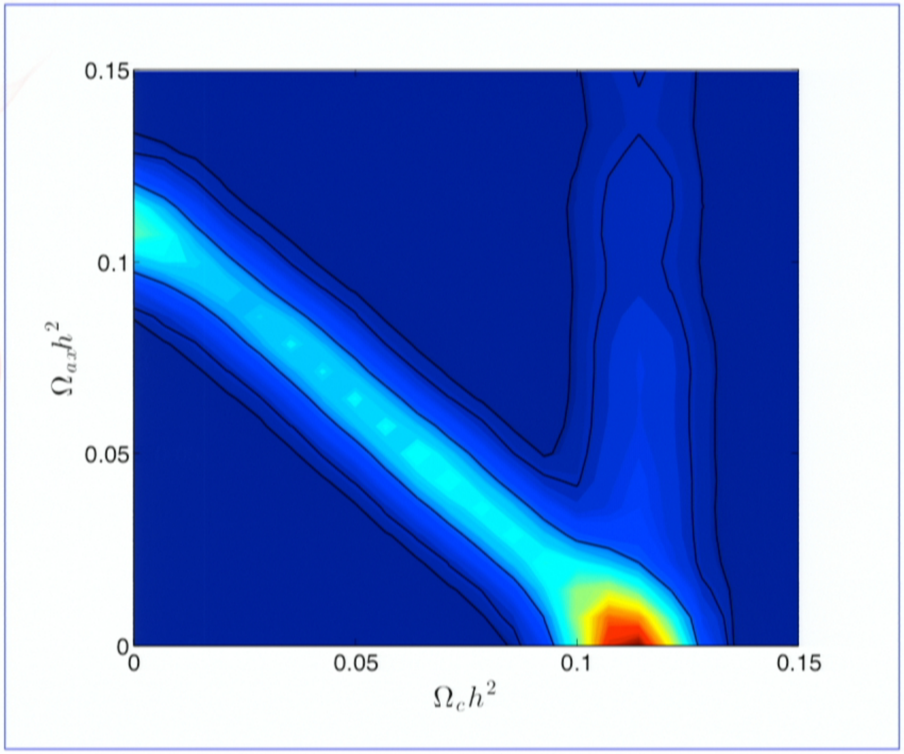
Covariance: why is MCMC hard?



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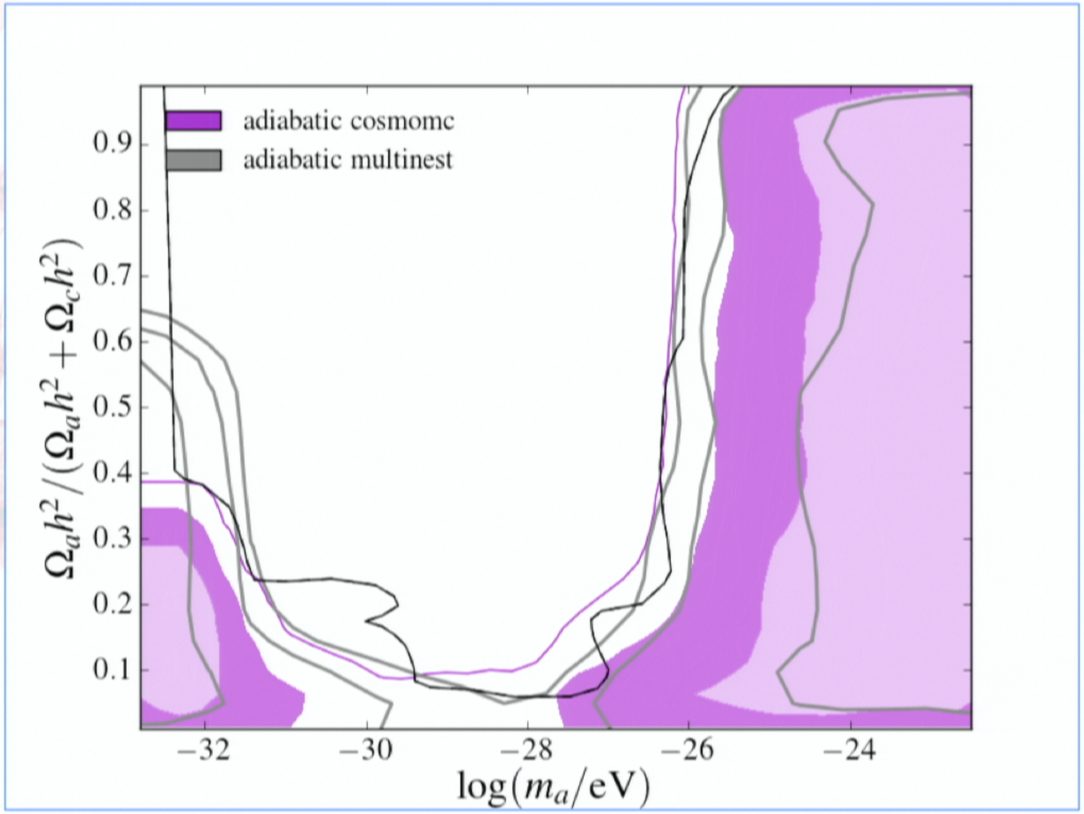
MCMC vs Multinest



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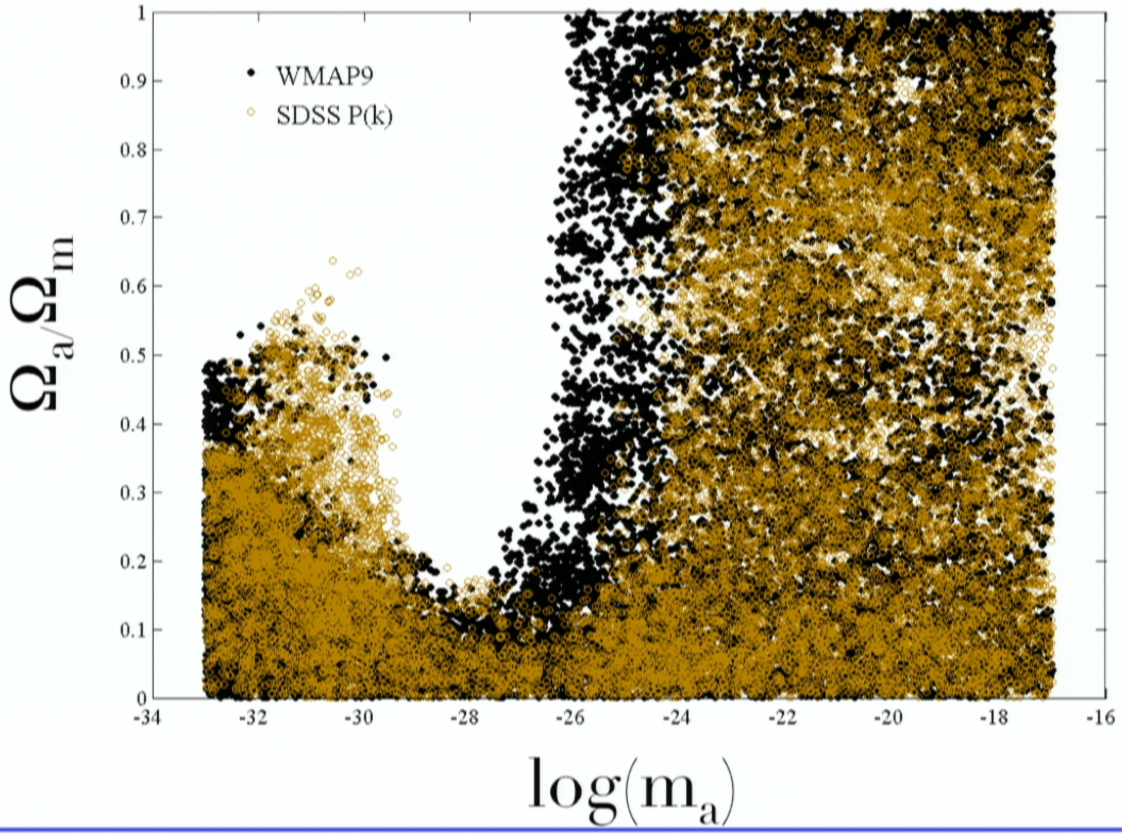
LSS vs CMB



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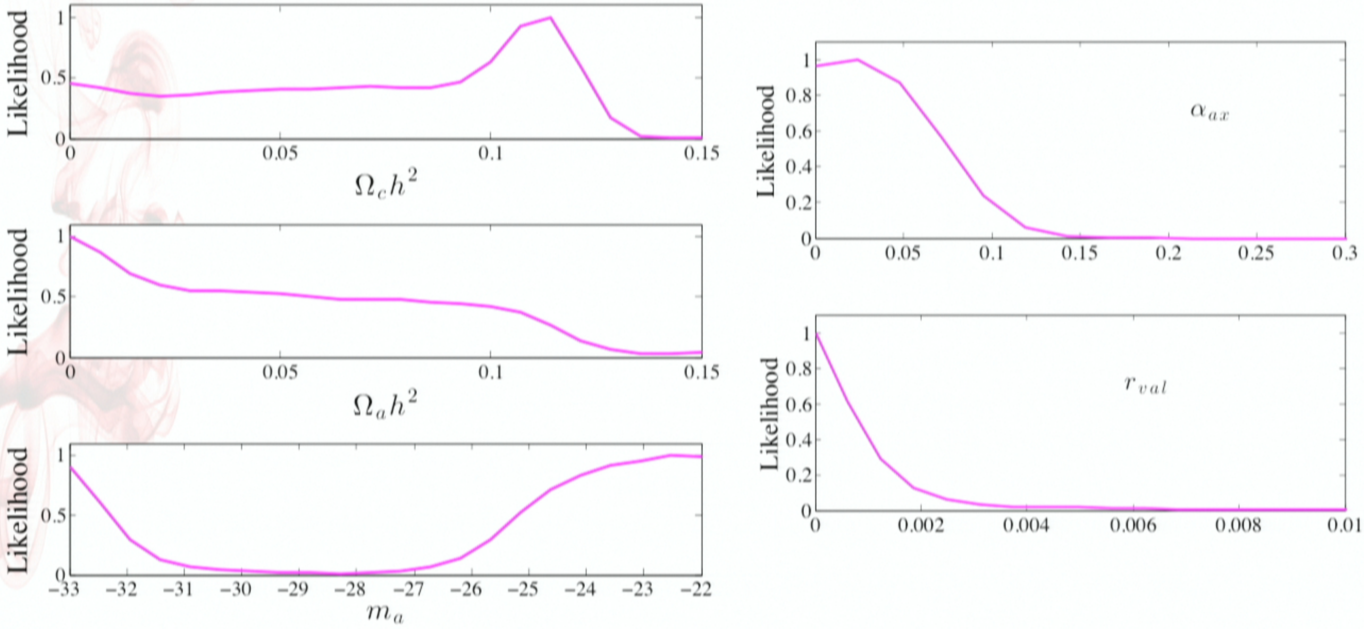
(Preliminary) Results

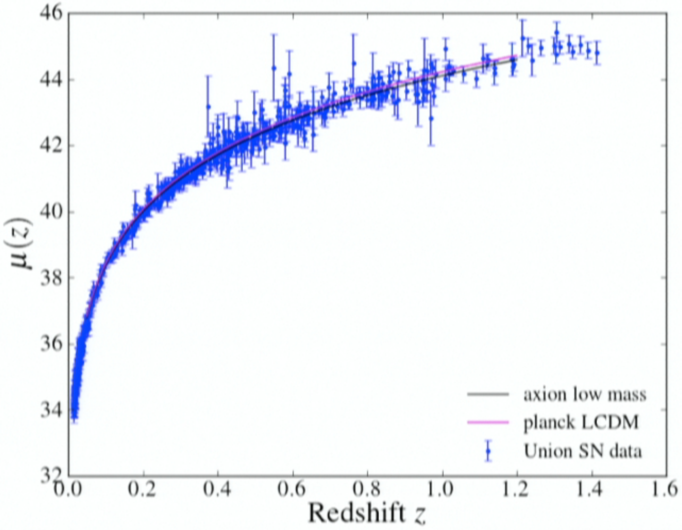


Outlook

- Results: May. Planck: summer.
- Distance indicators: low mass case.
- No CDM: preferred scale?
- Axions in halos: catch 22?

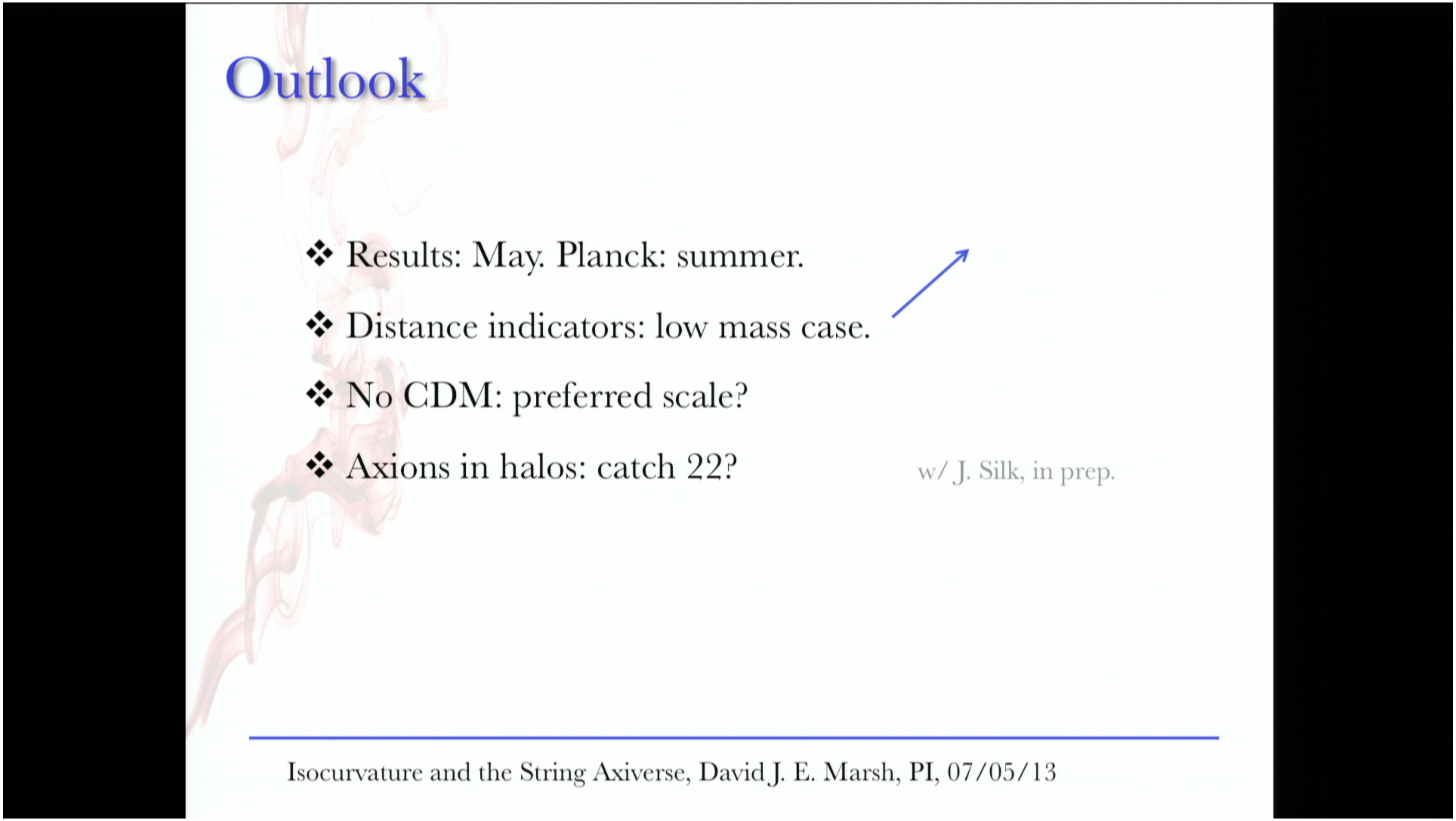
w/ J. Silk, in prep.

Outlook



- ❖ Results: May. Plan
- ❖ Distance indicator
- ❖ No CDM: preferr
- ❖ Axions in halos: catch 22.

w/ J. Silk, in prep.



Outlook

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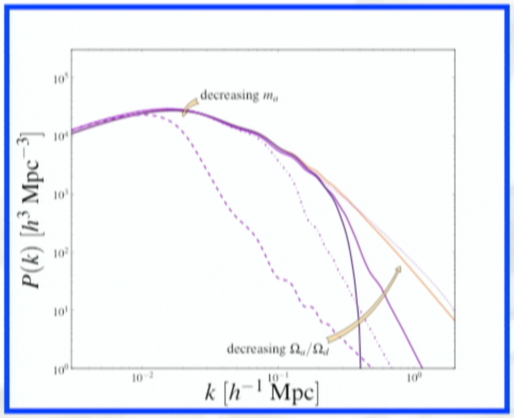
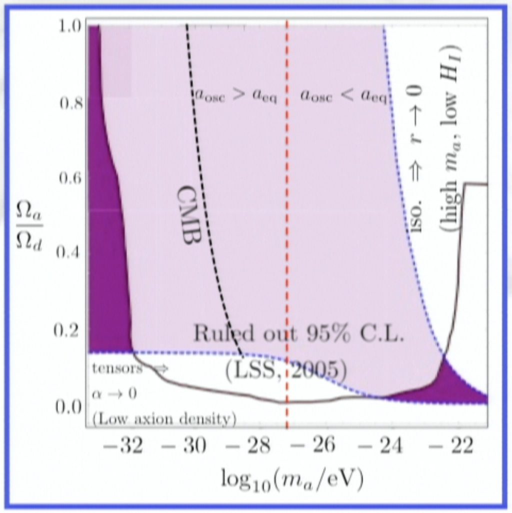
Isocurvature and the String Axiverse, David J. E. Marsh, PI, 07/05/13

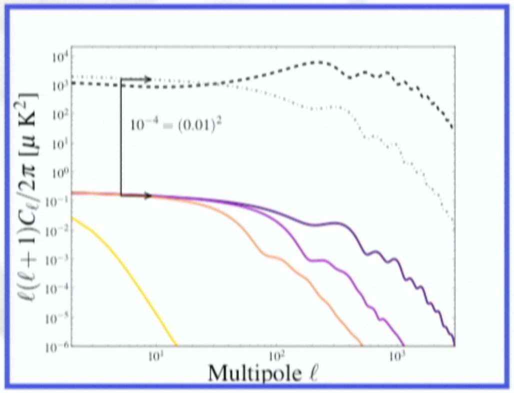
Summary



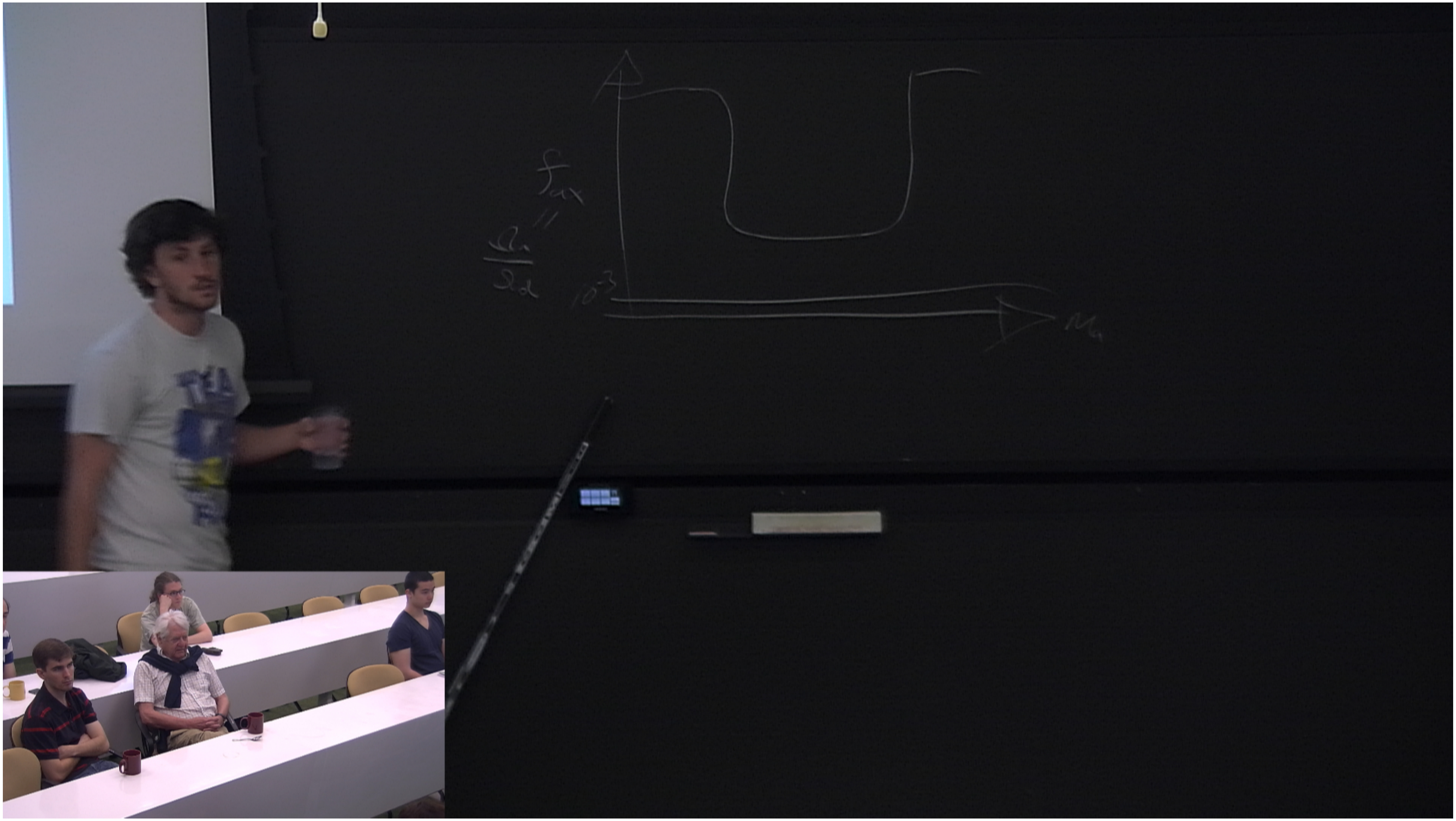
$P(k)$ $[h^3\,\mathrm{Mpc}^{-3}]$
10^0
10^1
10^2
10^3
10^4
10^5
decreasing m_a
decreasing Ω_a/Ω_d
10^{-2}
10^{-1}
10^0
k $[h^{-1}\,\mathrm{Mpc}]$

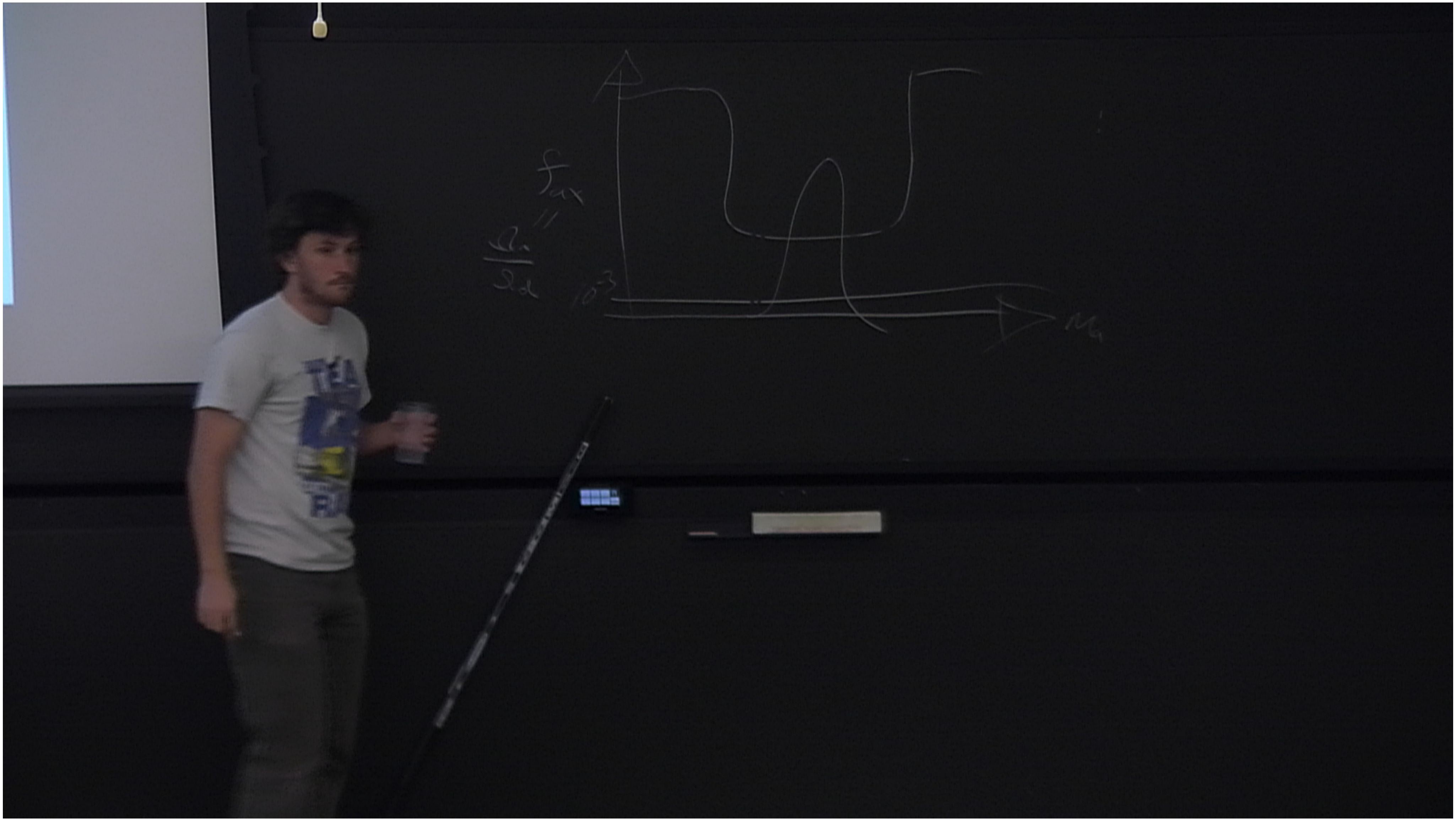


$\frac{\Omega_a}{\Omega_d}$
1.0
0.8
0.6
0.4
0.2
0.0
$a_{\mathrm{osc}} > a_{\mathrm{eq}}$
$a_{\mathrm{osc}} < a_{\mathrm{eq}}$
CMB
iso. $\Rightarrow r \to 0$
(high m_a, low H_I)
Ruled out 95% C.L.
(LSS, 2005)
tensors $\Rightarrow$
$\alpha \to 0$
(Low axion density)
-32
-30
-28
-26
-24
-22
$\log_{10}(m_a/\mathrm{eV})$



$\ell(\ell+1)C_\ell/2\pi$ $[\mu\,\mathrm{K}^2]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$10^{-4} = (0.01)^2$
10^1
10^2
10^3
Multipole ℓ


f_{ax}
$=$
$\frac{\Omega_a}{\Omega_d}$
10^{-3}
m_a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10^{-3}
m_a