Cosmology and the String Axiverse

David Marsh

with Pedro Ferreira

University of Edinburgh, 12/01/11

Based on Phys. Rev. D 82, 103528 (2010)

arXiv: 1009.3501

Oxford Physics ™

Outline

- Motivation: the "String Axiverse"
- Setup: cosmological pertubations
- Results: power spectra
- Conclusions/Outlook

Axions

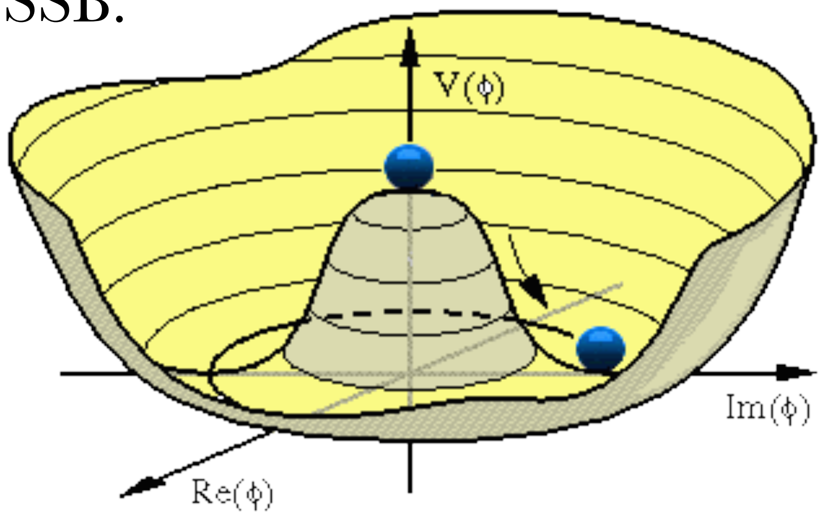
The strong CP problem:

$$\mathcal{L} \sim \theta \tilde{F}^{\mu\nu} F_{\mu\nu} \equiv \theta \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} F_{\mu\nu}$$

$$\theta = \theta_T + \theta_M \qquad \theta \lesssim 10^{-10}$$

The Peccei-Quinn mechanism: SSB.

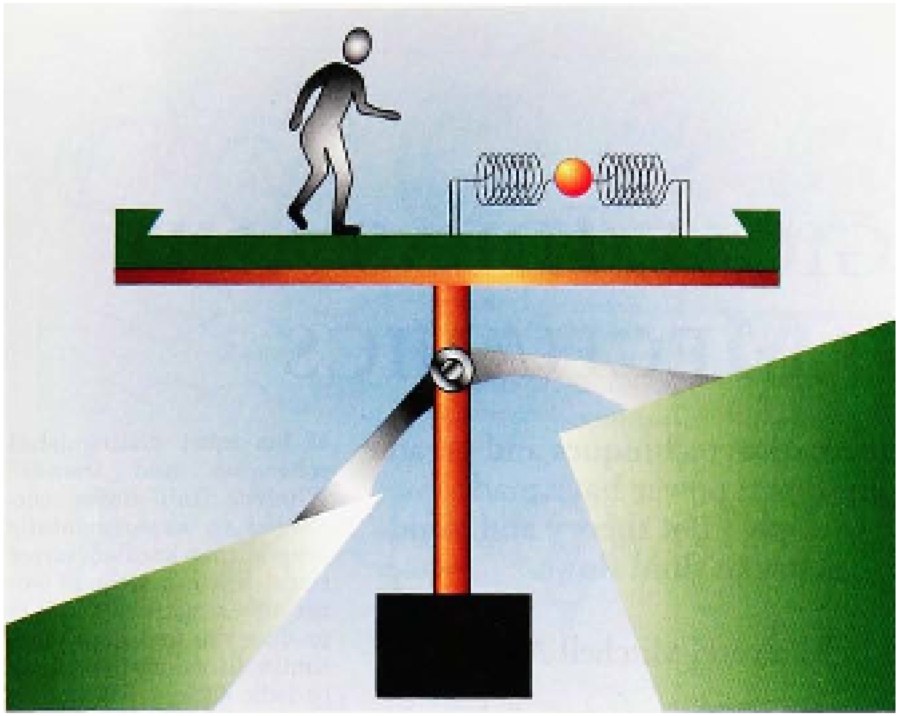
Instantons tilt the hat, making the axion a pseudo Goldstone-boson.



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

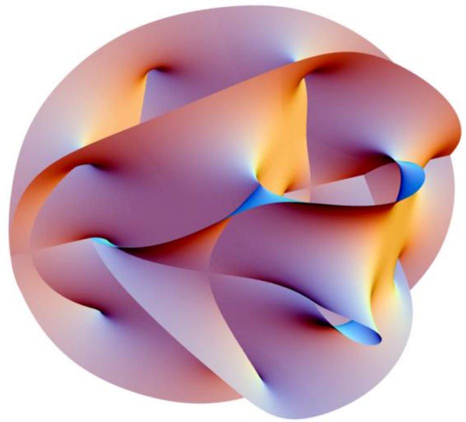
An analogy: Sikivie (Physics Today: Dec. '96)

- You observe a flat table in a room with a slanted floor. How?
- You propose a mechanism to straighten it accurately: gravity.
- The required accuracy implies a long arm and heavy weight.
- How can you test this? Look for relic oscillations from production.



Axions in String Theory

Svrcek and Witten: arxiv:hep-th/0605206



Axions arise from the existence of closed cycles in the compact space: typically hundreds. Instantons act on these cycles with action S.

$$\mathcal{L} = \frac{f_a^2}{2}(\partial\theta)^2 - \Lambda^4 U(\theta)$$

$$f_a \sim \frac{M_{pl}}{S} \qquad\qquad \Lambda^4 \sim \mu^4 e^{-S}$$

$f_a \sim 10^{16}\,\mathbf{GeV}$ → Strong variation of the mass

The String Axiverse

Arvanitaki et al: arXiv:0905.4720

Archarya et al: arXiv:1004.5138

"String theory suggests the simultaneous presence of many ultralight axions, possibly populating each decade of mass down to the Hubble scale 10^{-33}eV"

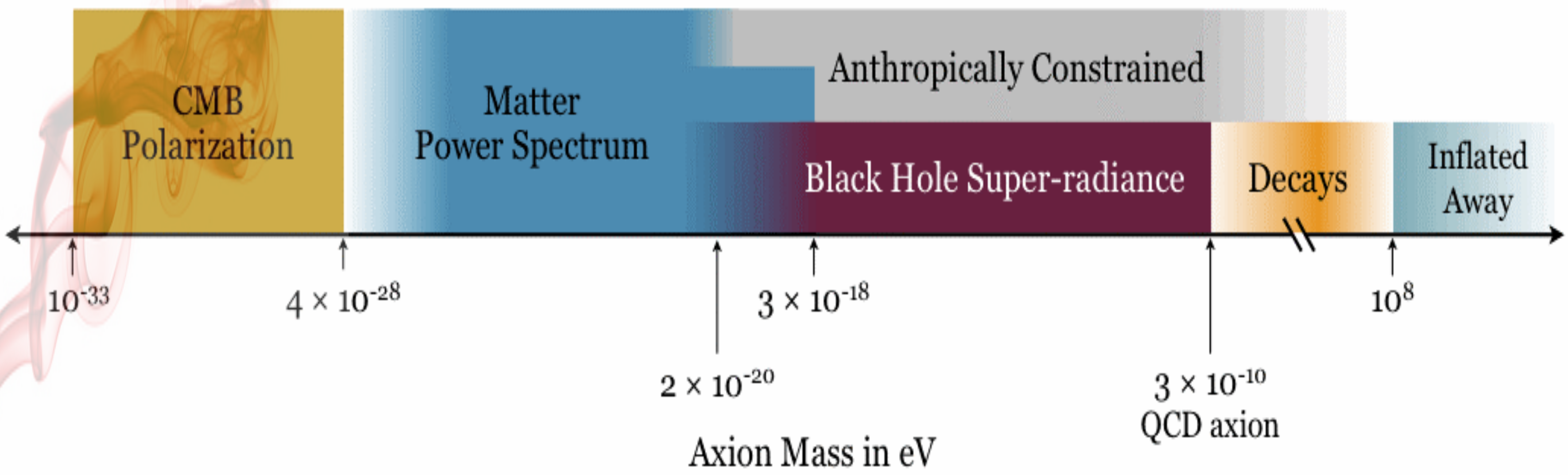


Figure: Arvanitaki et al

Axions as Dark Matter

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

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

❖ Hubble friction: non-thermally produced at late times.

❖ Fine tuning: fractional density depends on initial misalignment and mass.

❖ Axions and inflation.

Mack and Steinhardt: arXiv:0911.0418, Tegmark et al: arXiv: 0511774, Hertzberg et al: arXiv: 0807.1726v2

❖ Direct detection: unimportant for this scenario.

Cold and Fuzzy Dark Matter

Hu et al arXiv:astro-ph/0003365v2

- ❖ Ordinary CDM has too much "small scale power".

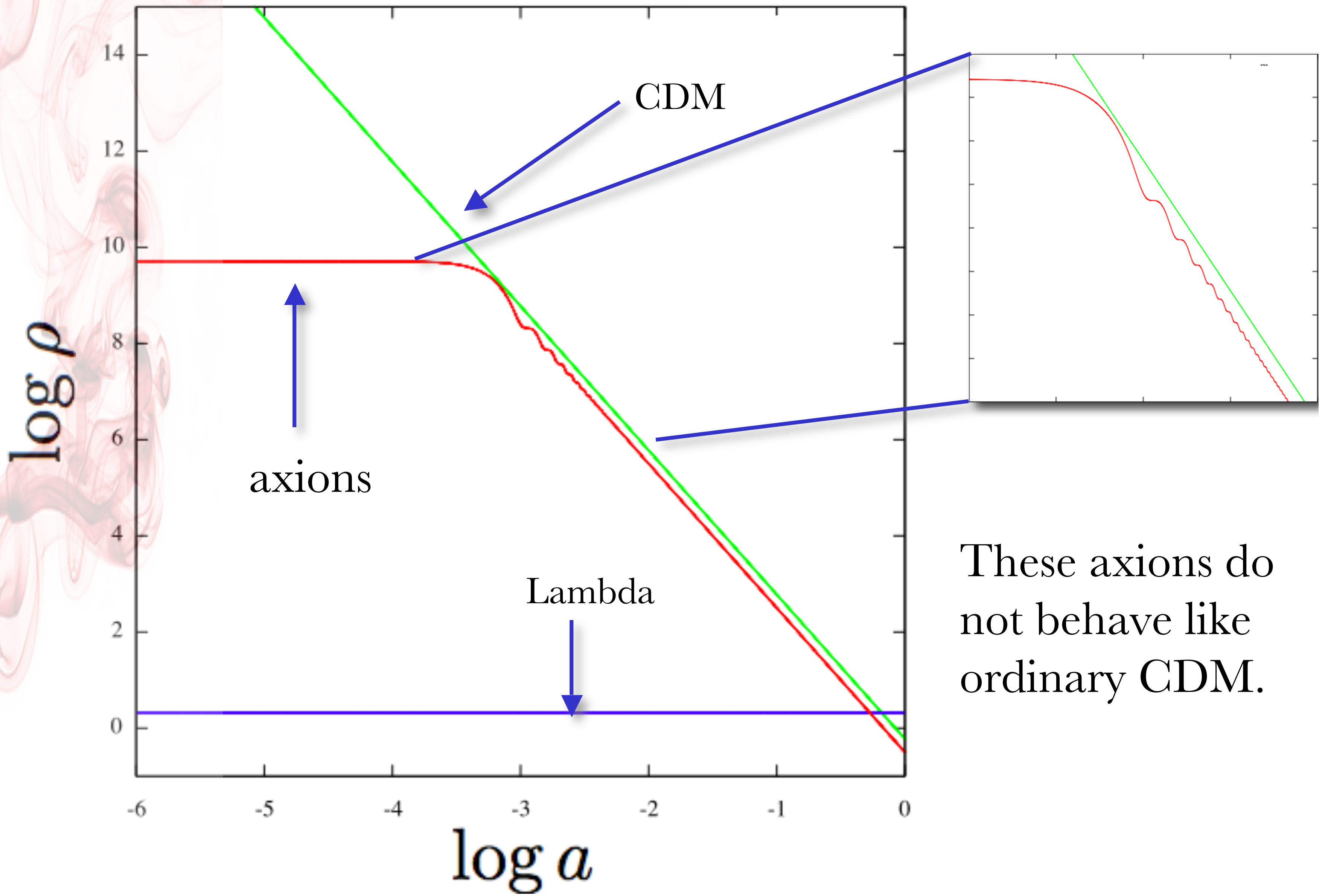
- ❖ Very light particles have large Compton wavelength manifest on astrophysical scales:

$$10^0 H_0 \lesssim m \lesssim 10^{10} H_0$$

- ❖ High occupation numbers (BEC) allow us to treat the axions as a classical field:

$$\begin{aligned} c_s^2 &= \frac{k^2}{4m^2a^2}; \quad k < 2ma \\ c_s^2 &= 1; \quad k > 2ma \end{aligned}$$

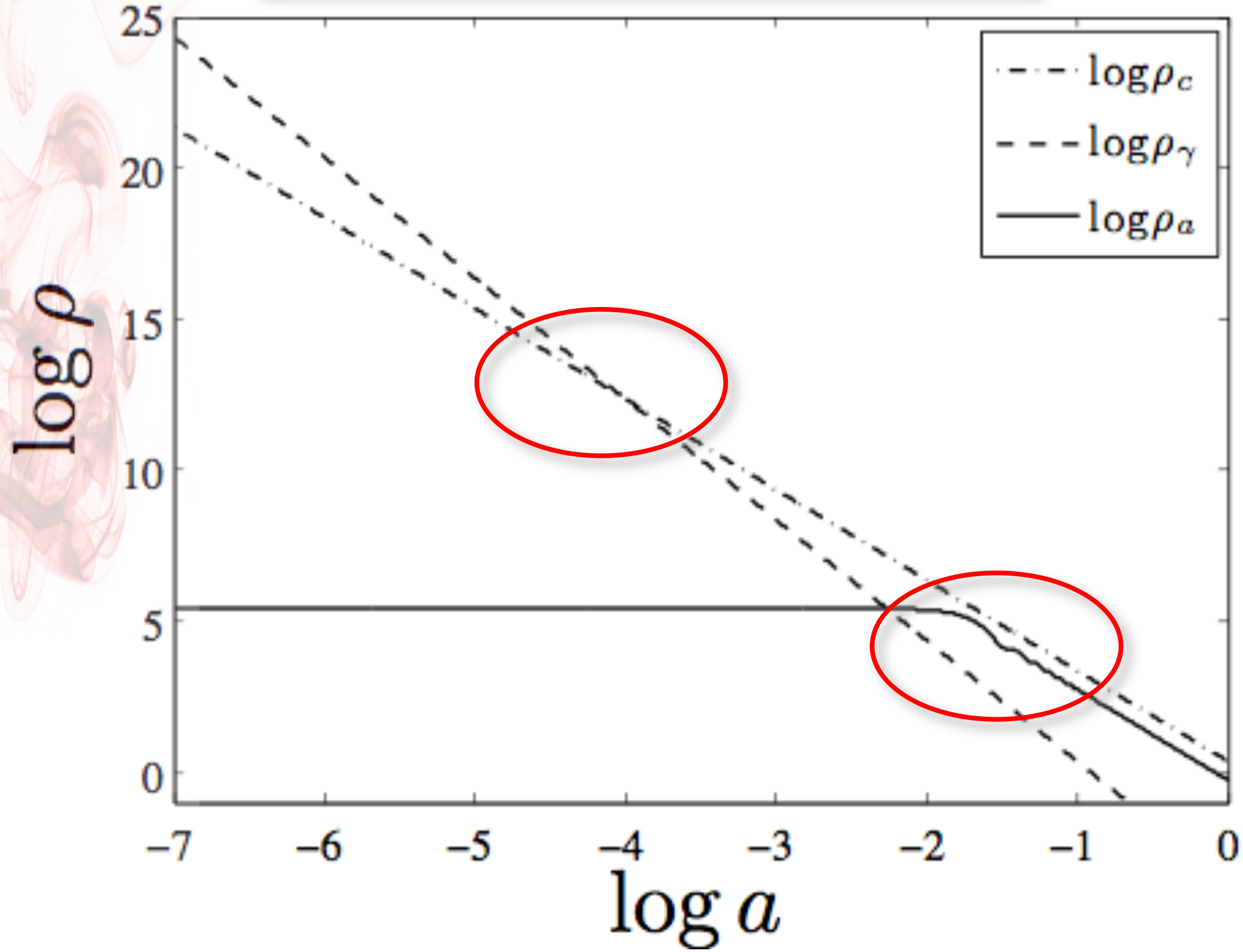
Background evolution: generalities



These axions do not behave like ordinary CDM.

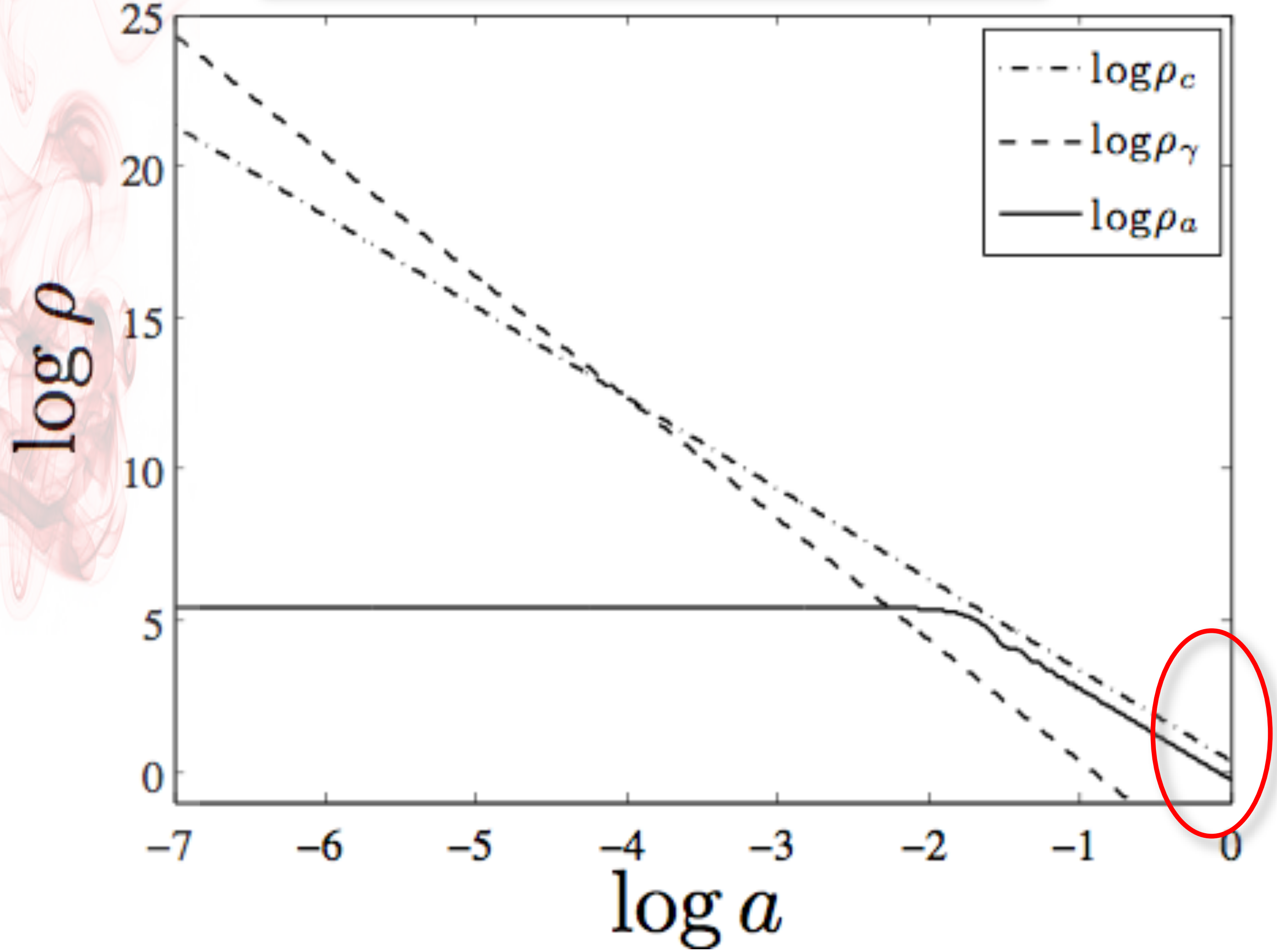
Background evolution: specifics I

$$\boxed{10^{-31}\mathrm{eV} \lesssim m \lesssim 10^{-27}\mathrm{eV}}$$



Background evolution: specifics II

$$\boxed{\rho_a(t_0) \sim \rho_c(t_0)}$$



Cosmological Perturbation Theory

Ma & Bertschinger arXiv:astro-ph/9506072v1

Flat Ω=1 universe, perturbed FRW metric, synchronous gauge:

$$ds^2 = a^2(\tau)(d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j)$$

Perturb the fluid of axions, photons and dark matter; unperturbed Λ:

$$\begin{aligned} T^0{}_0 &= -(\bar{\rho} + \delta\rho) \\ T^0{}_i &= (\bar{\rho} + \bar{P})v_i \\ T^i{}_j &= (\bar{P} + \delta P)\delta^i{}_j \end{aligned}$$

Suppression of Power

$$P(k) = \delta^2$$

$$\delta = \frac{\delta \rho_m}{\bar{\rho}_m}$$

Modes inside the horizon have:

$$k \gtrsim Ha$$

Modes become non-relativistic when:

$$k \lesssim ma$$

Suppress structure formation in modes that cross the horizon whilst still being relativistic. This is just like free streaming neutrinos (Bond et al, 1980).

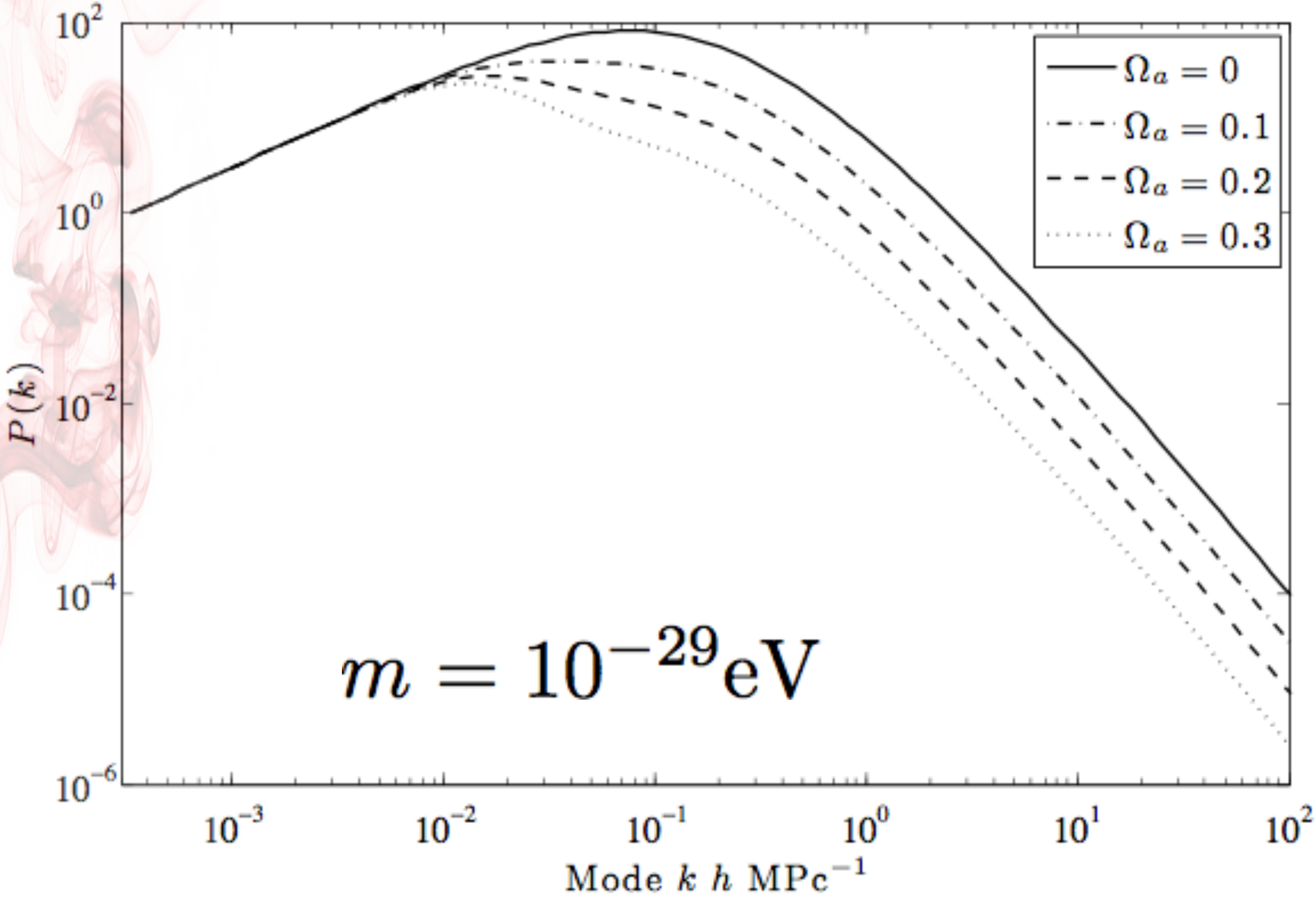
$$\delta \propto a \quad k \lesssim k_m \qquad\qquad k_m \sim m^{1/3}$$

$$\delta \propto a^q \quad k \gtrsim k_m \quad q = 1/4(-1 + \sqrt{25 - 24f})$$

Power Spectra

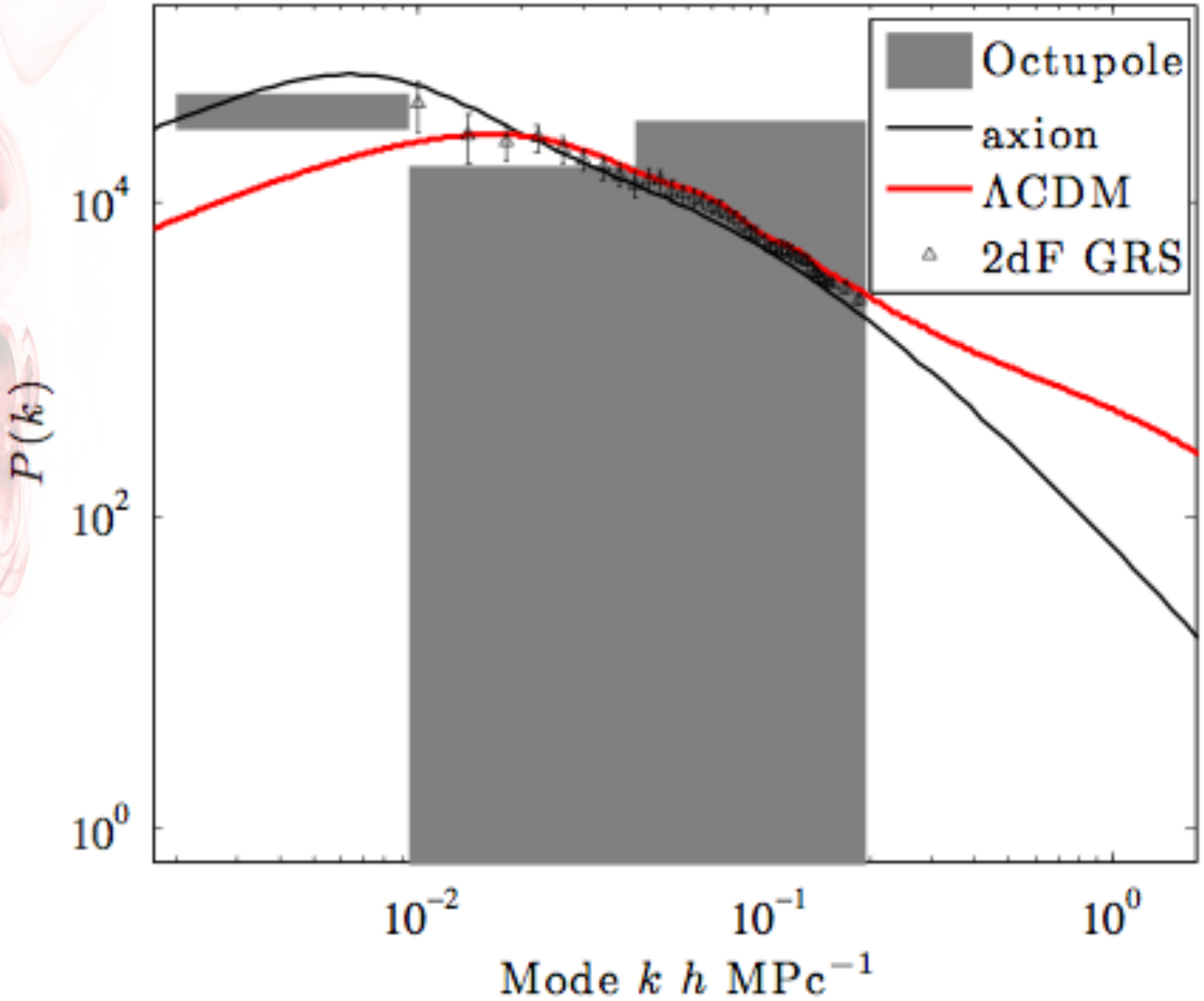
Amendola and Barbieri: arXiv:hep-ph/0509257v1

DM and P. G. Ferreira: arXiv:hep-ph/1009.3501



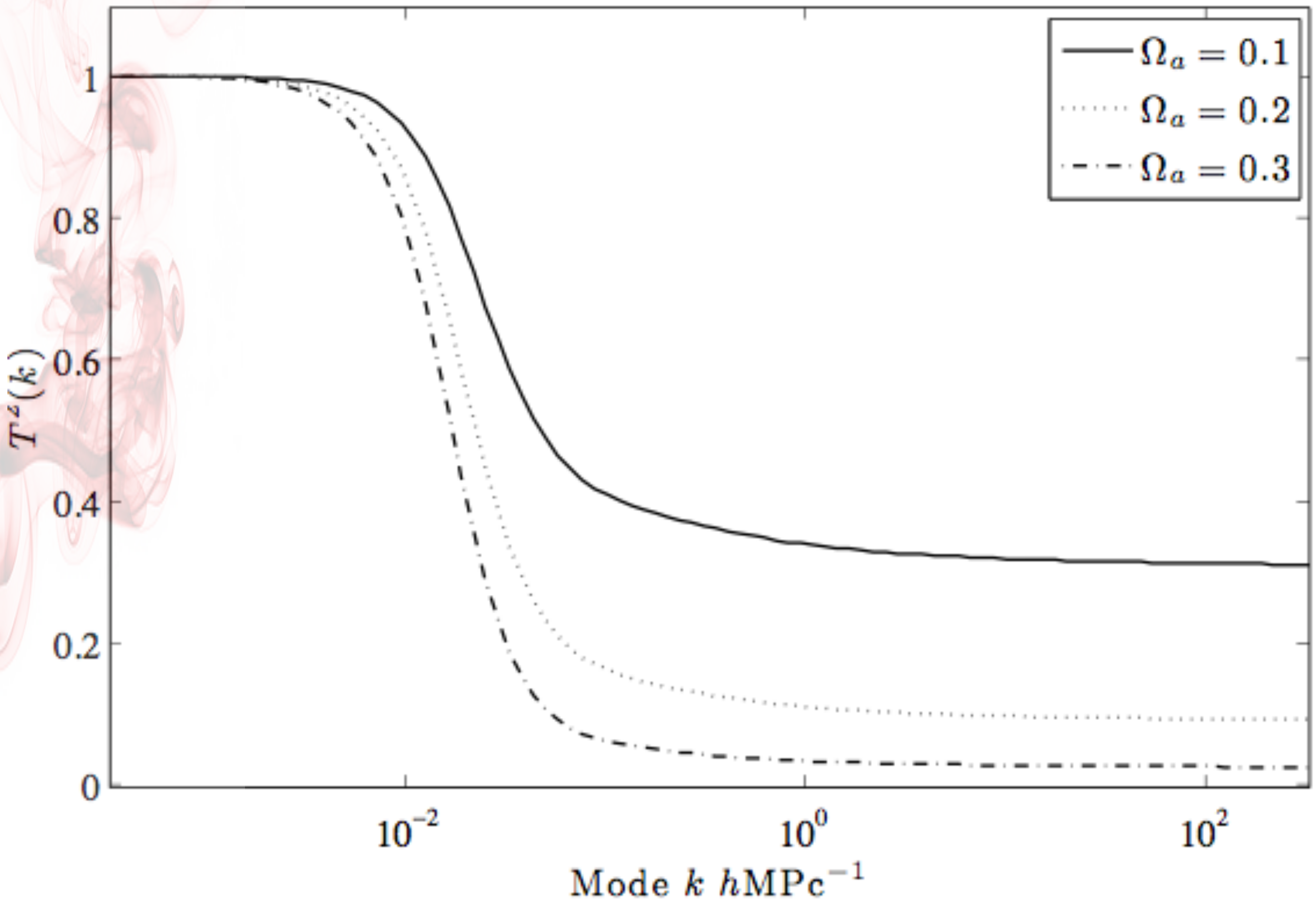
Power Spectra

Macaulay et al. arXiv:1010.2651



Power Spectra

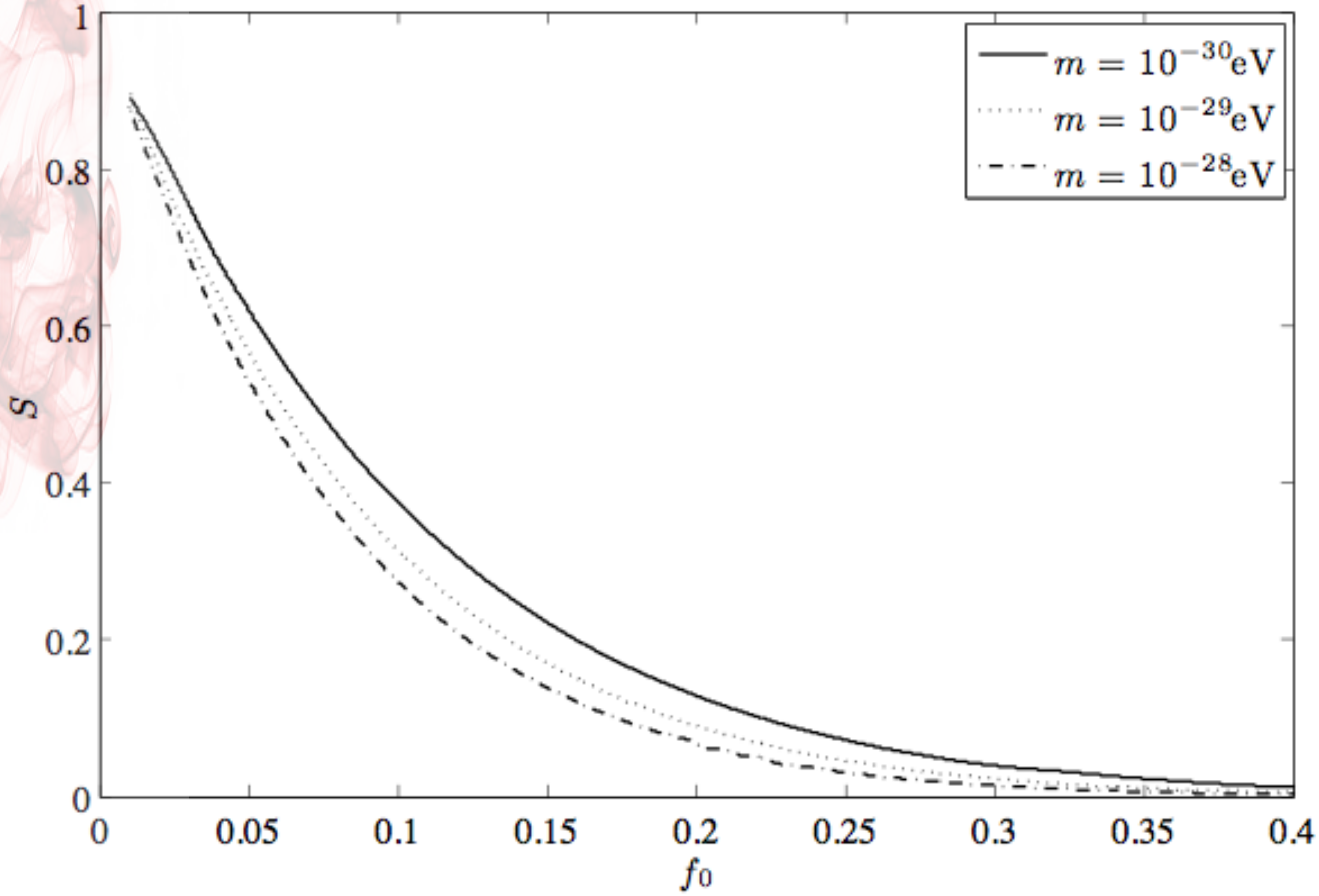
$$T^2(k) = \frac{P(k)_{\text{ALPs +CDM}}}{P(k)_{\text{CDM}}}$$



Fits and Results

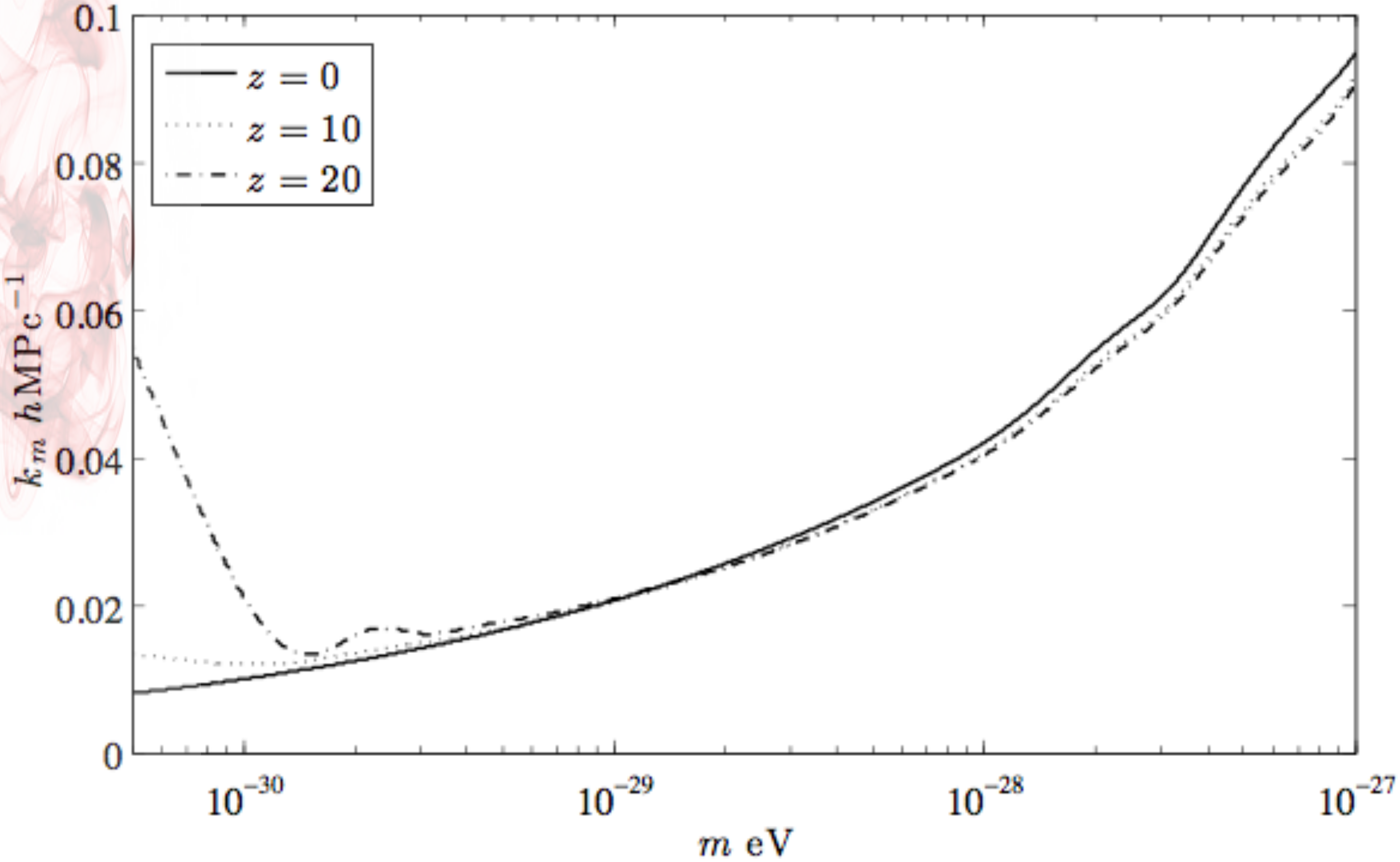
$$S(z) = \left(\frac{(1+z)^{1+\beta_1}}{(1+z_{osc})^{1+\beta_2}} \right)^{2(1-q)}$$

$$\beta_1 = 0$$
$$\beta_2 = 0.6$$



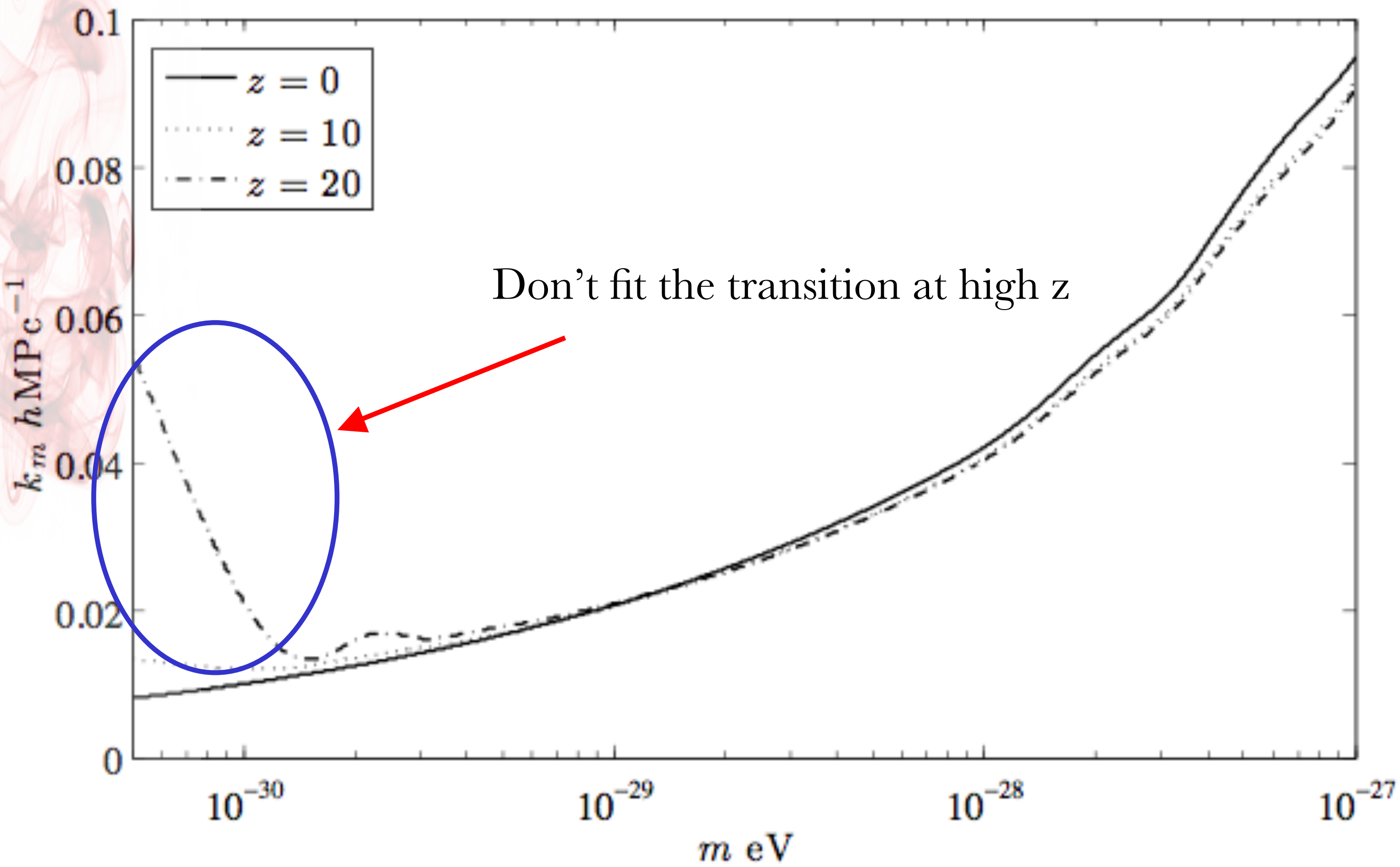
Fits and Results

$$k_m = A f_0^{\alpha_1} (1+z)^{\alpha_2} m^{1/3}$$ $$\alpha_1 = -0.5$$ $$\alpha_2 = 0$$



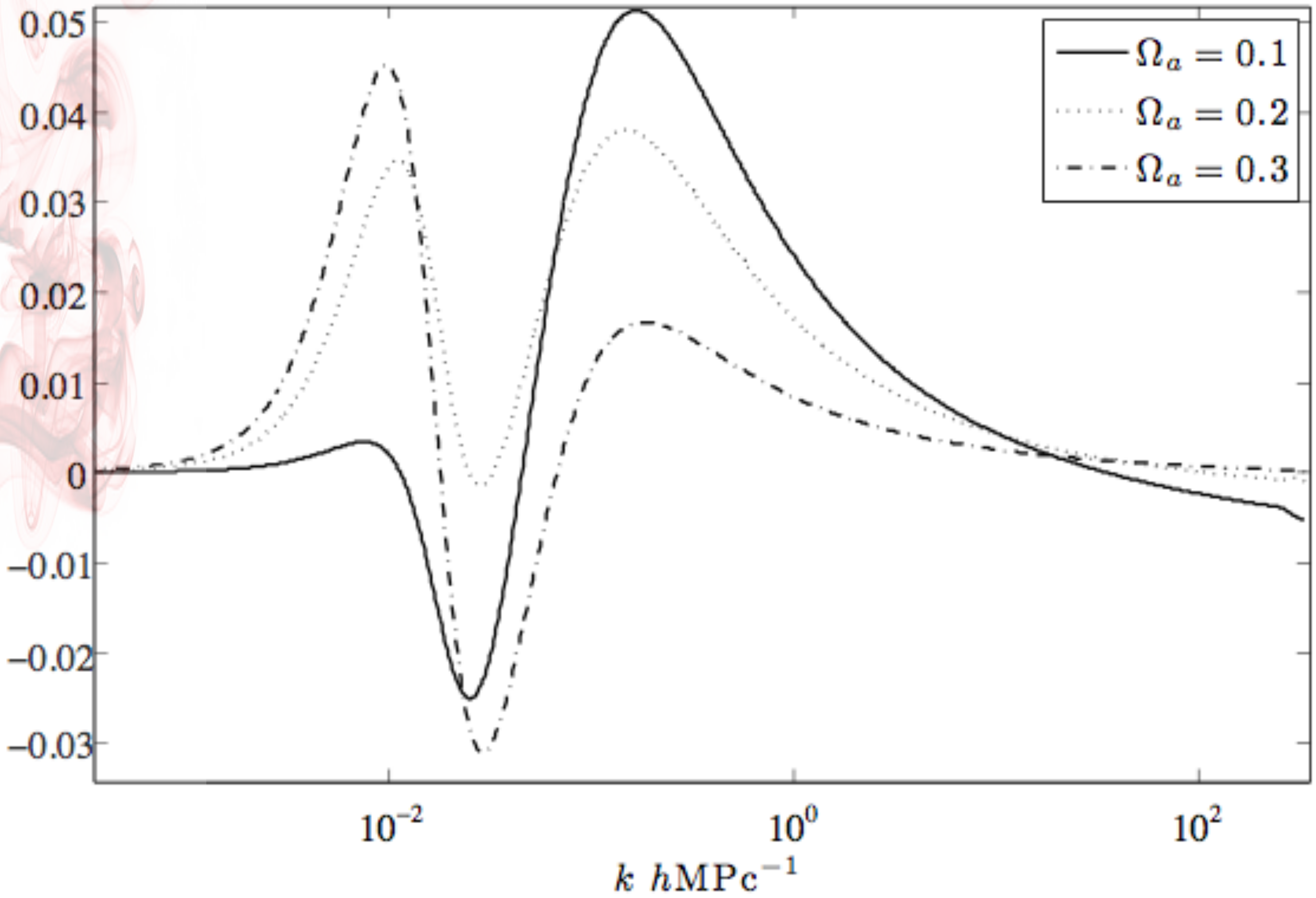
Fits and Results

$$k_m = A f_0^{\alpha_1} (1+z)^{\alpha_2} m^{1/3} \quad \begin{array}{l} \alpha_1 = -0.5 \\ \alpha_2 = 0 \end{array}$$

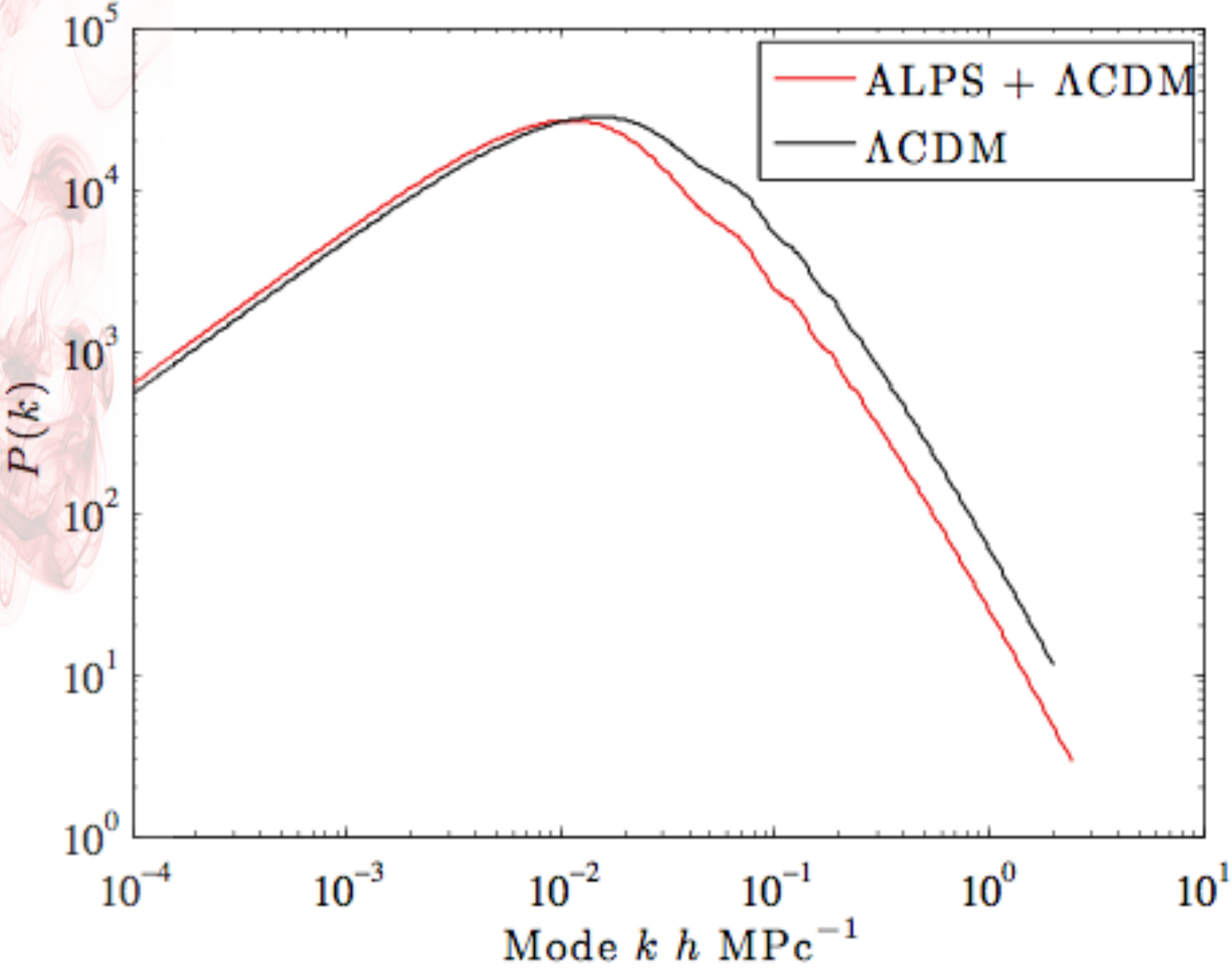


Fits and Results

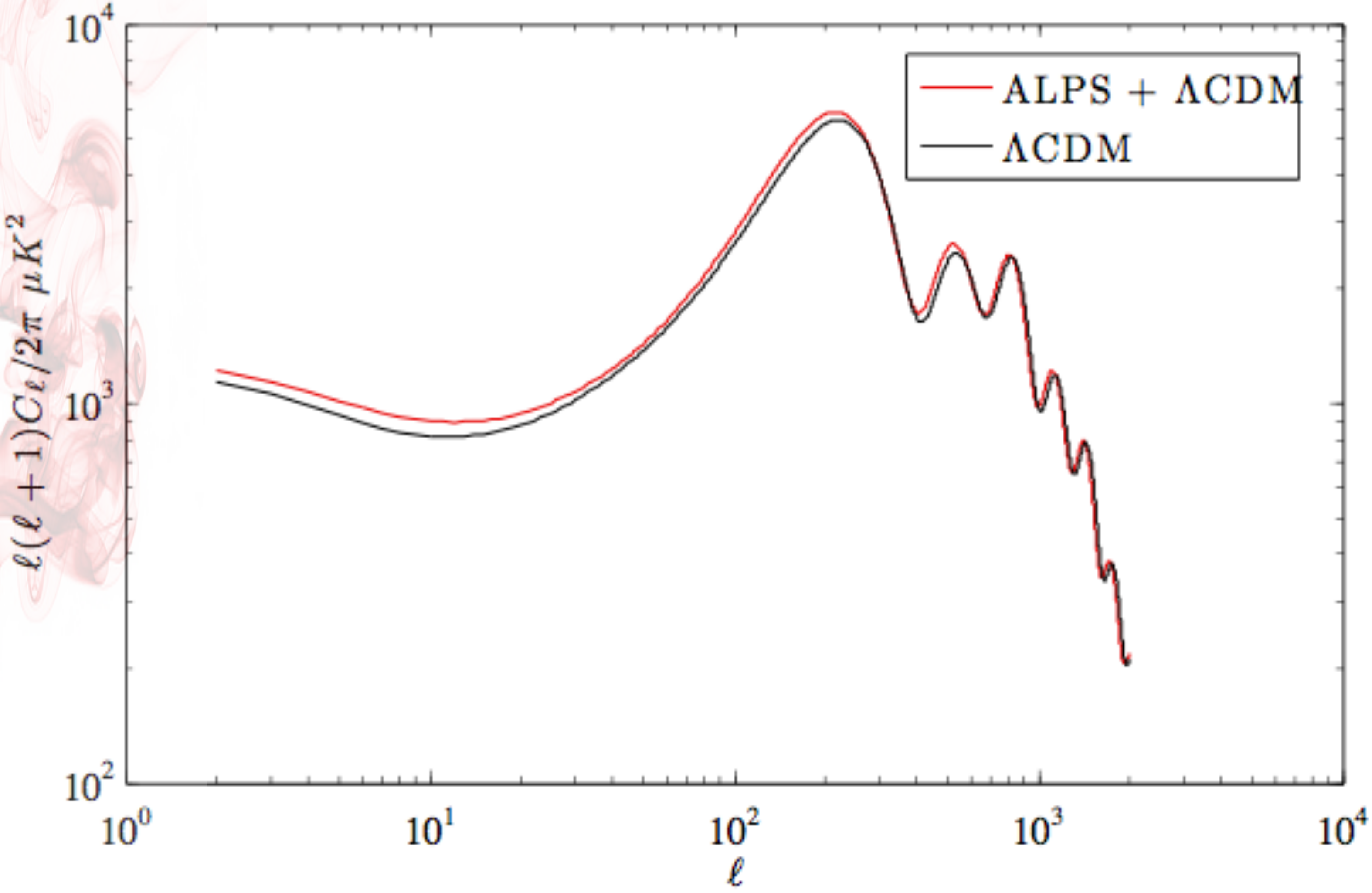
$$T^2(k) = \frac{1 + S(k/k_m)^\gamma}{1 + (k/k_m)^\gamma} \qquad \gamma = 2$$



Recent Work $m = 10^{-29}\text{eV} \quad f = 0.1$



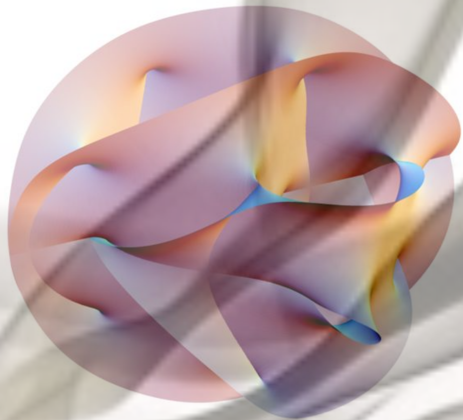
Recent Work $m = 10^{-29}\text{eV} \quad f = 0.1$

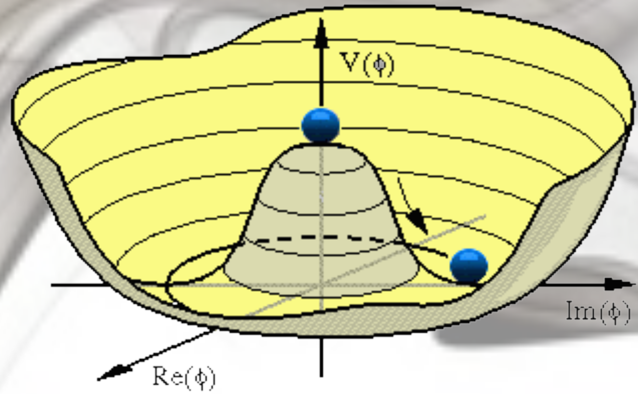


Outlook

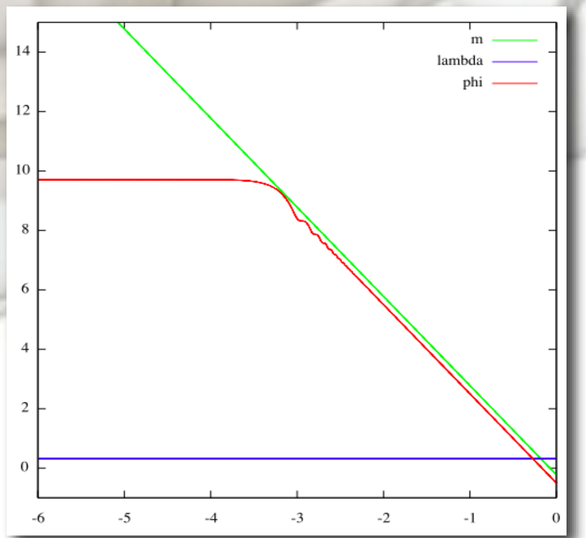
- ❖ Forecasts and parameter estimation.
- ❖ Anharmonic potentials and coupled quintessence.
- ❖ Multiple fields, multiple steps.
- ❖ String moduli.
- ❖ Isocurvature perturbations.
- ❖ …

Summary

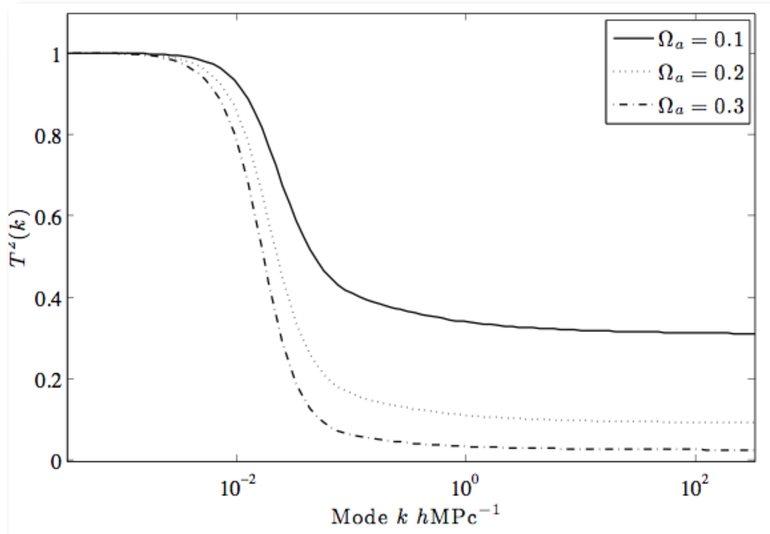




V(ϕ)
Im(ϕ)
Re(ϕ)



m
lambda
phi



$\Omega_a = 0.1$
$\Omega_a = 0.2$
$\Omega_a = 0.3$
$T^2(k)$
Mode k hMPc^{-1}