Probing Ultra-light Axions with Galaxy Cluster Counts

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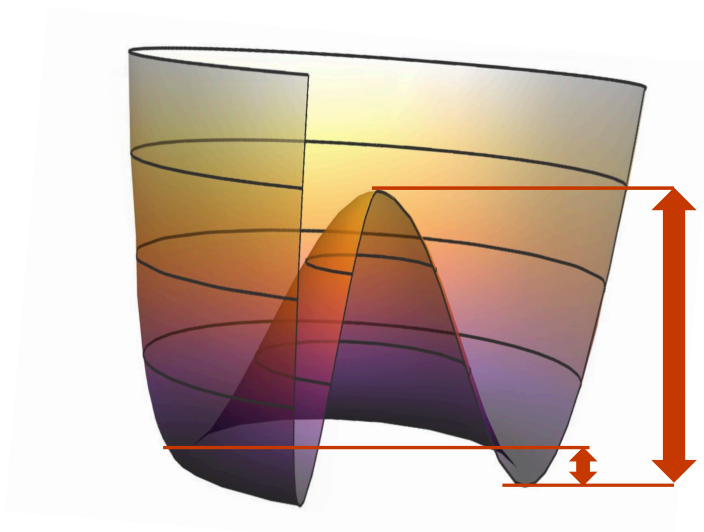
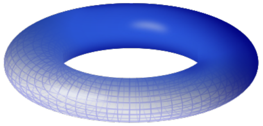
Theoretical Background

- QCD Axion:
  - Introduced to solve the CP problem of QCD
  - global chiral U(1) symmetry
  - complex scalar field w/ spont. sym. breaking potential
    $\longrightarrow$ mexican hat
  - Color anomaly $\longrightarrow$ hat tilted, $\mathrm{m_a} \sim 10^{-5}$ eV



Theoretical Background

- ULA (ultra light axion like particle):
  - Ultra light ($\mathrm{m_a} \sim 10^{-22}$ eV)
  - Zero modes of antisymmetric tensors in compact space

potential	compact manifold	#axions
A_μ		2

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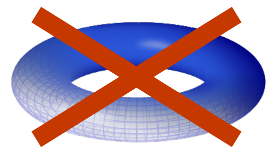
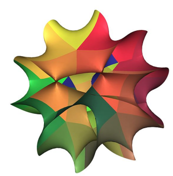
$\cancel{A_\mu}$		$\cancel{2}$
B_{MN}		~ 30

Motivation

Hui, Ostriker, Tremaine, Witten (2017) arxiv: 1610.08297

- ULAs:
  - Natural, well motivated
  - Potentially solving ΛCDM small scale problems
    - Macroscopic wavelength: $\frac{\lambda}{2\pi} = \frac{\hbar}{mv} \propto 1.92 \text{ kpc} \left(\frac{10^{-22} \text{ eV}}{m_a}\right)$
    - suppressed structure formation at small scales
    - Solves cusp-core, missing satellite, too-big-to-fail problems
- Cluster number counts:
  - Well established for > 20 years
  - Tight constraints on Ω_{dm}
  - Very robust

Cluster Number Counts

Calculate predicted cluster number counts (NCs) for given axion parameters:

Cluster NCs in z and M bins (observable)

Halo Mass Function (cosmology)

ULA parameters ($F = \Omega_a/\Omega_{dm}$)

$$N_{ij} = \Delta\Omega \int_{z_i}^{z_{i+1}} dz \frac{dV}{dz} \int_{M_j^{obs}}^{M_{j+1}^{obs}} \frac{dM^{obs}}{M^{obs}} \int_0^{\infty} \frac{dM}{M} \frac{dn\boxed{(m_a, F)}}{d(\ln M)} p(M^{obs}|M)$$

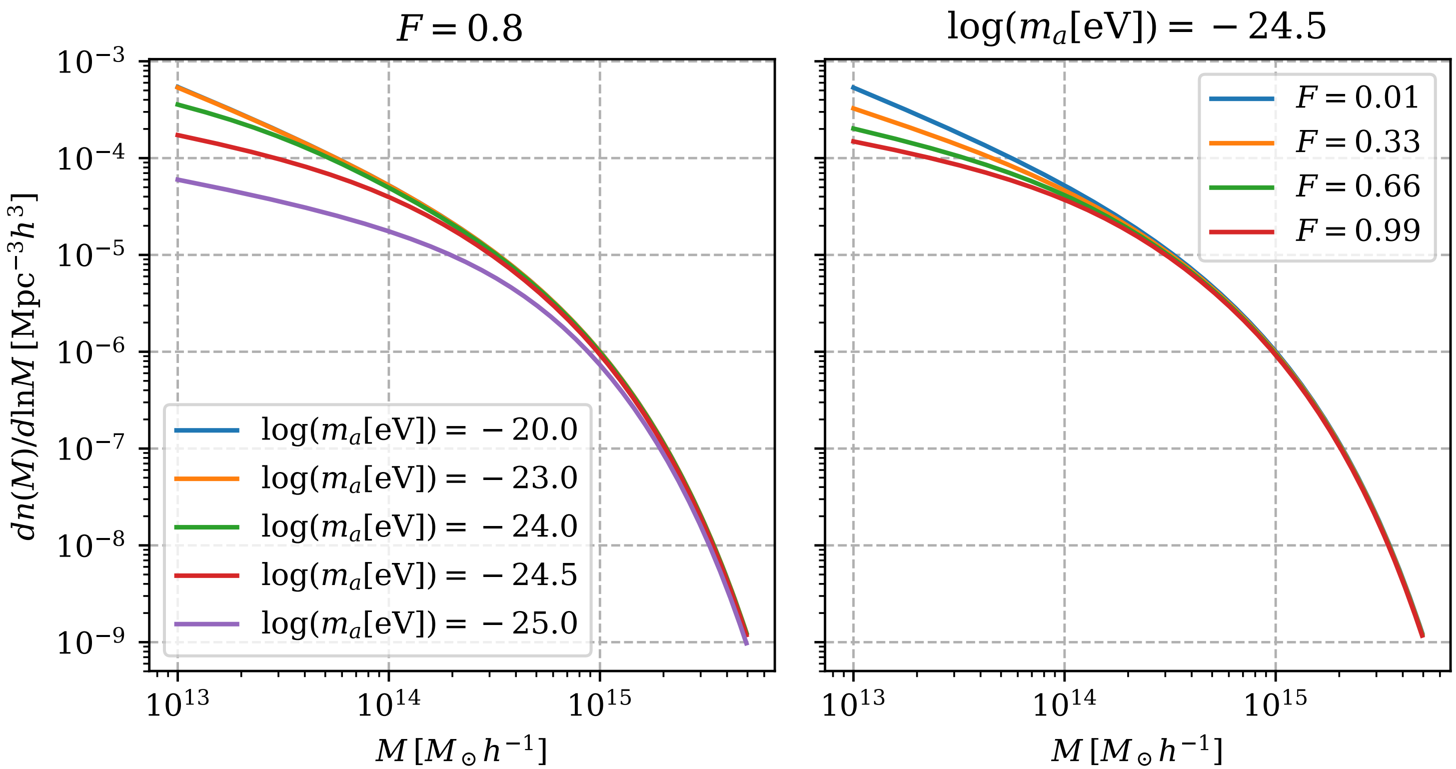
Survey volume (fixed)

Observable-Mass distribution (nuisance)

Halo Mass Function

Using Tinker-HMF

Tinker et al (2008) arxiv: 0803.2706



Take away:

- ULA mass determines onset of suppression, abundancy level of suppression
- Effects from axion mass and abundancy look similar
- Impossible to distinguish models with “big” axion masses

Monte Carlo Analysis

- Poisson Loglikelihood: $\sum_{i,j} N_{ij}^{obs} \ln N_{ij}^{th} - N_{ij}^{th}$
- Reference model N_{ij}^{obs} (no observational data)
- 5 bins in cluster mass, 5 bins in redshift (25 total)

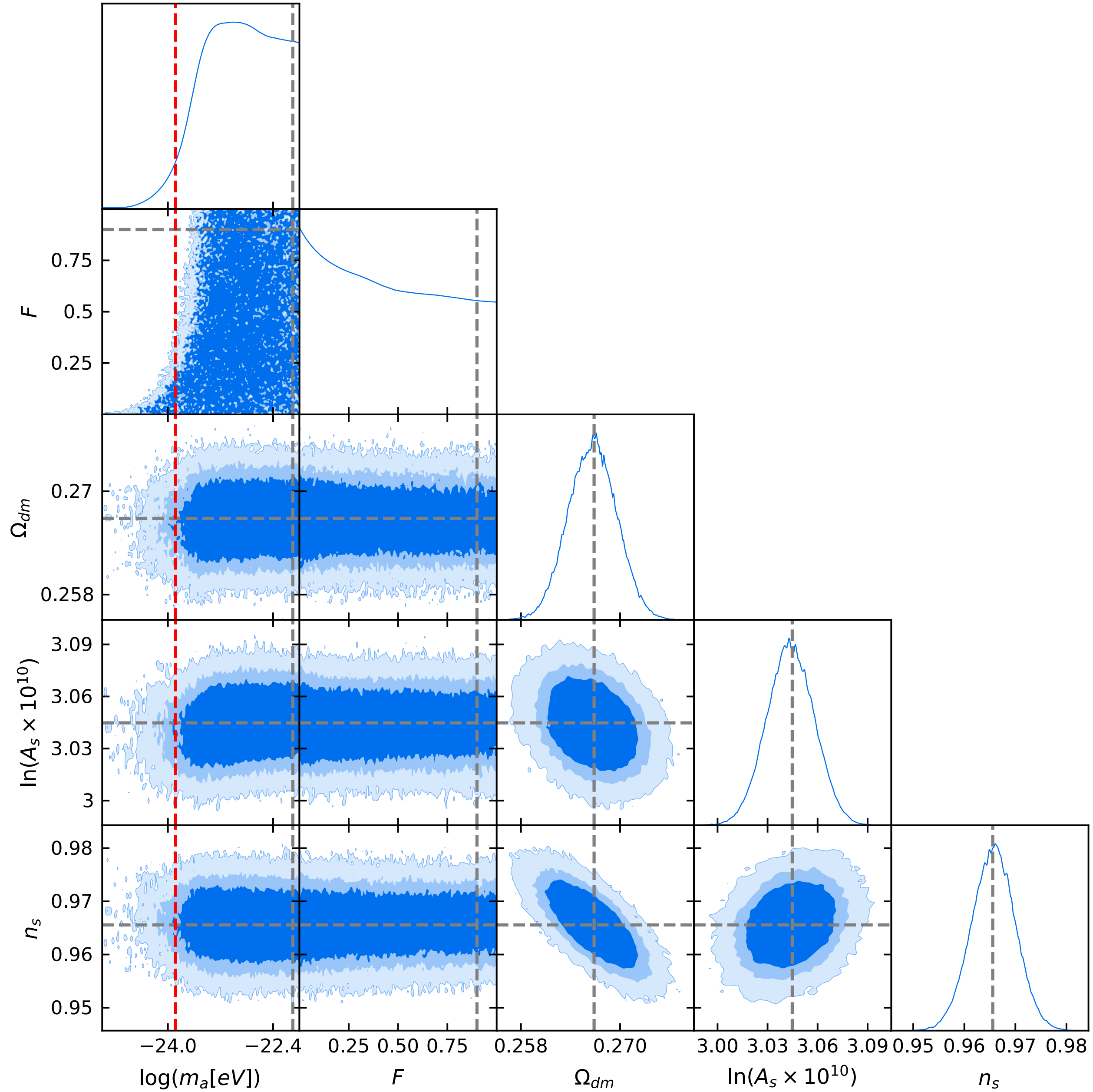
Category of parameters	ULA	Cosmology	Observable-mass distribution (Lima & Hu (2005). arxiv: astro-ph/0503363)
Names	m_a, F	Ω_{dm}, A_s, n_s	$\sigma_{lnM}, A_{bias}, n_{bias}$
Priors	uninformative	Planck	Gauss (σ_{lnM}), uninformative (rest)

Results

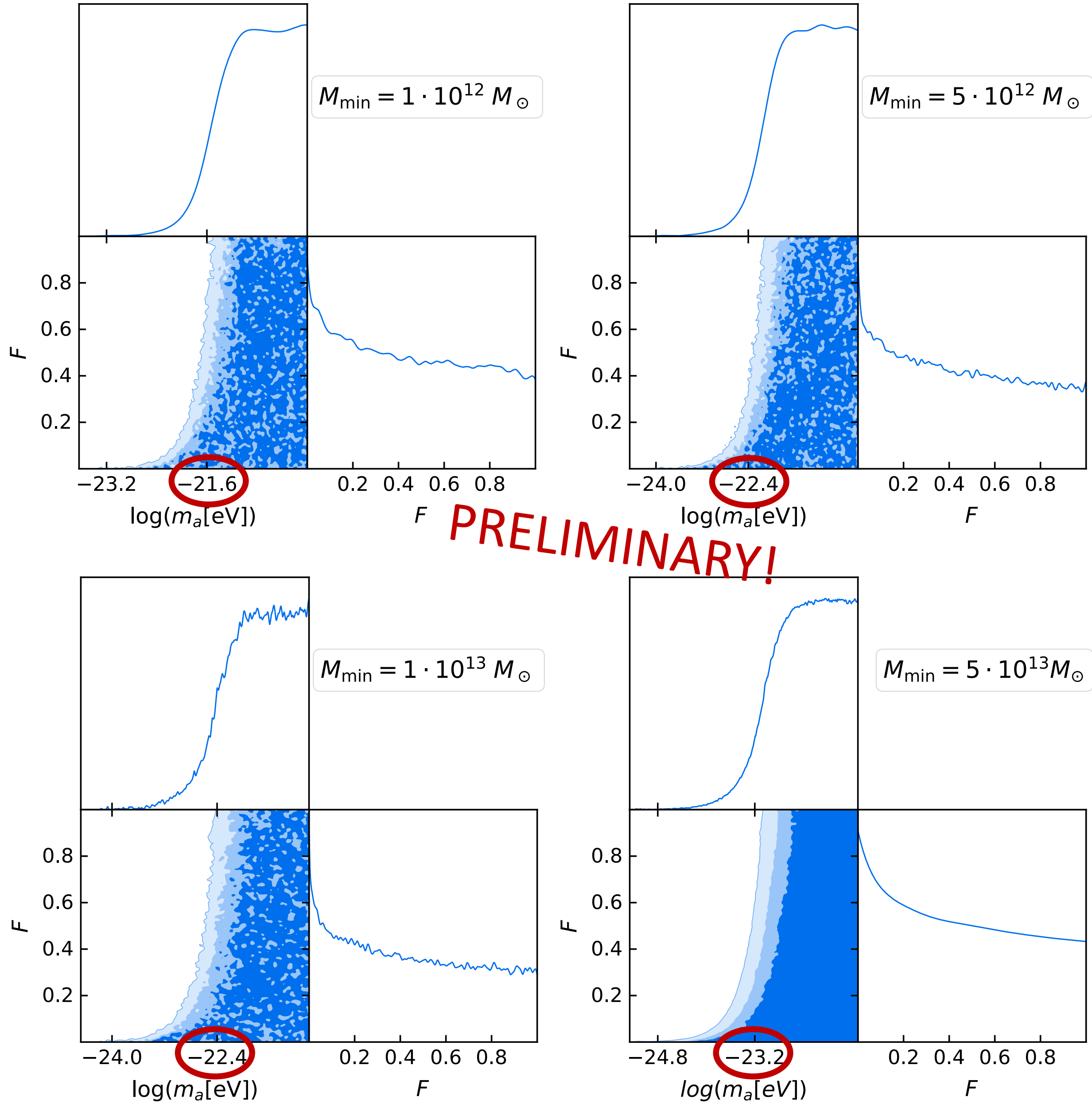
$$M_{\min} \ = 5 \cdot 10^{13} M_{\odot}$$

$$z \in [0.1{,}0.6]$$

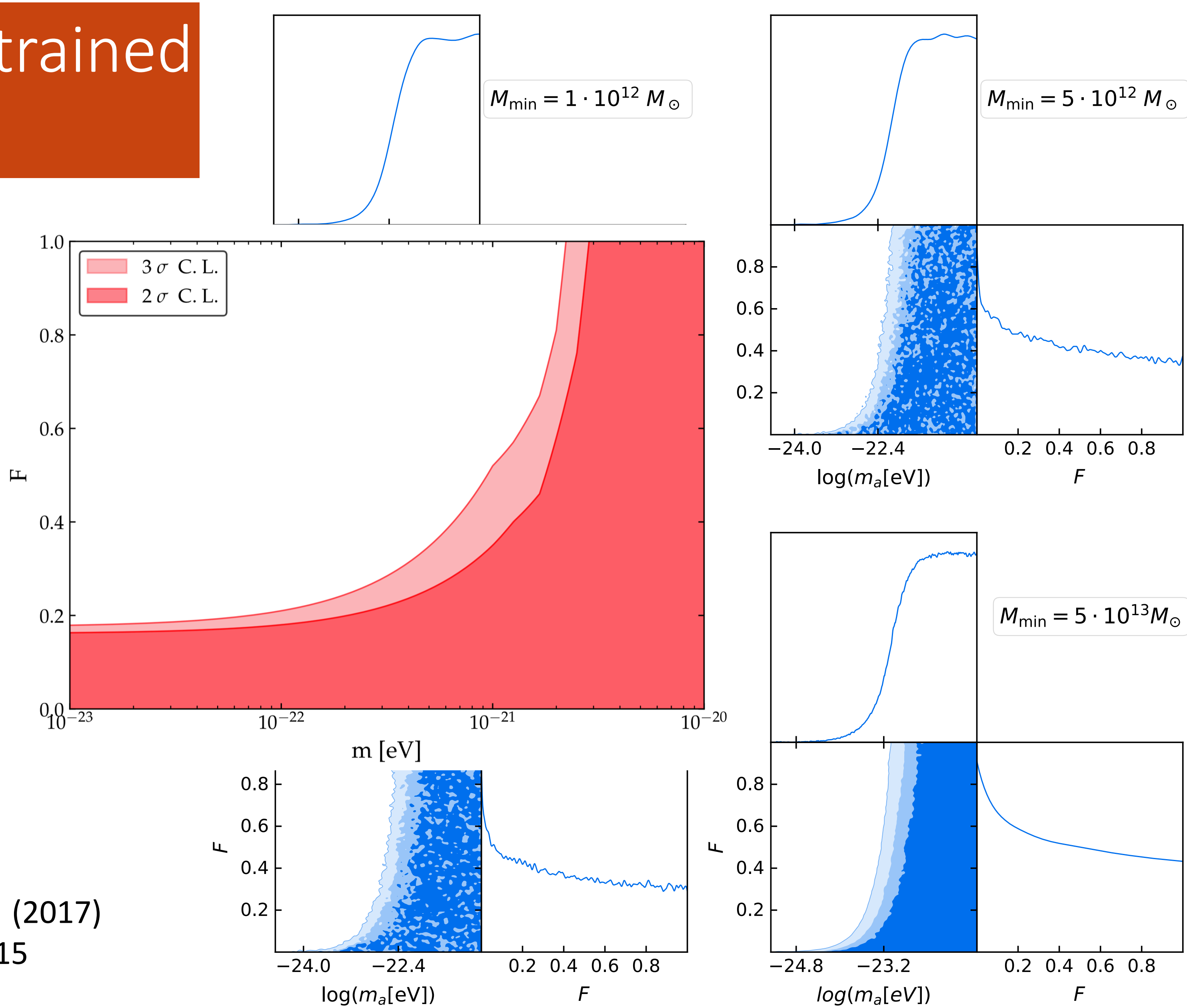
$$\Delta\Omega = 10\,000\,\mathrm{deg}^2$$



Unconstrained Regime



Unconstrained Regime



Kobayashi et al. (2017)
arxiv: 1708.00015

Summary

- General:
  - DM candidates from QCD or theories beyond the standard model
  - Tiny mass $\longrightarrow$ cosmologically relevant wavelength $\longrightarrow$ suppressed structure formation
- Probing with Galaxy Cluster Counts:
  - Two important parameters: axion mass, axion abundancy
  - Effects of mass and abundancy look similar $\longrightarrow$ anisotropic posterior
  - Constraining capability determined by smallest observable cluster masses
  - Robust probe but difficult to improve upon other constraints

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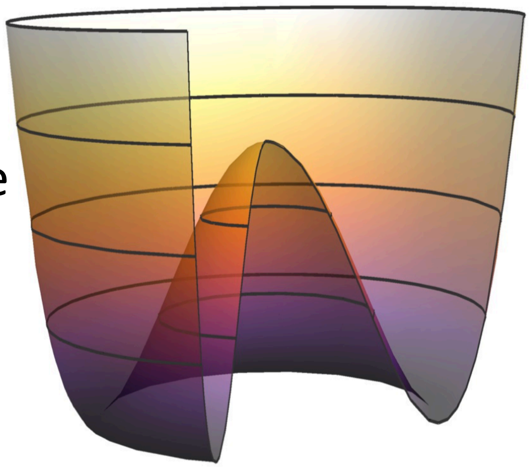
Thank you!

(+ Appendix for more in-depth information)

Some more theory: QCD Axion

- QCD Lagrangian contains the term $\mathcal{L} = \frac{\theta_{eff}}{32\pi}\,\mathrm{Tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$
  - θ_{eff} consists of two independent contributions from QCD and electroweak parameters $\longrightarrow$ fine tuning problem, upper bound $\theta_{eff} \leq 10^{-10}$
- Solution:
  - Intoduce $U(1)_{PQ}$ symmetry (chiral rotations)
  - Introduce complex scalar field $\varphi = \langle\varphi\rangle\, e^{i\phi/f_a}$
  - SSB of $U(1)_{PQ}$ $\longrightarrow$ Goldstone boson
- Color anomaly generates eff. potential of shape

$$V(\phi) = \Lambda_a^4\left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$



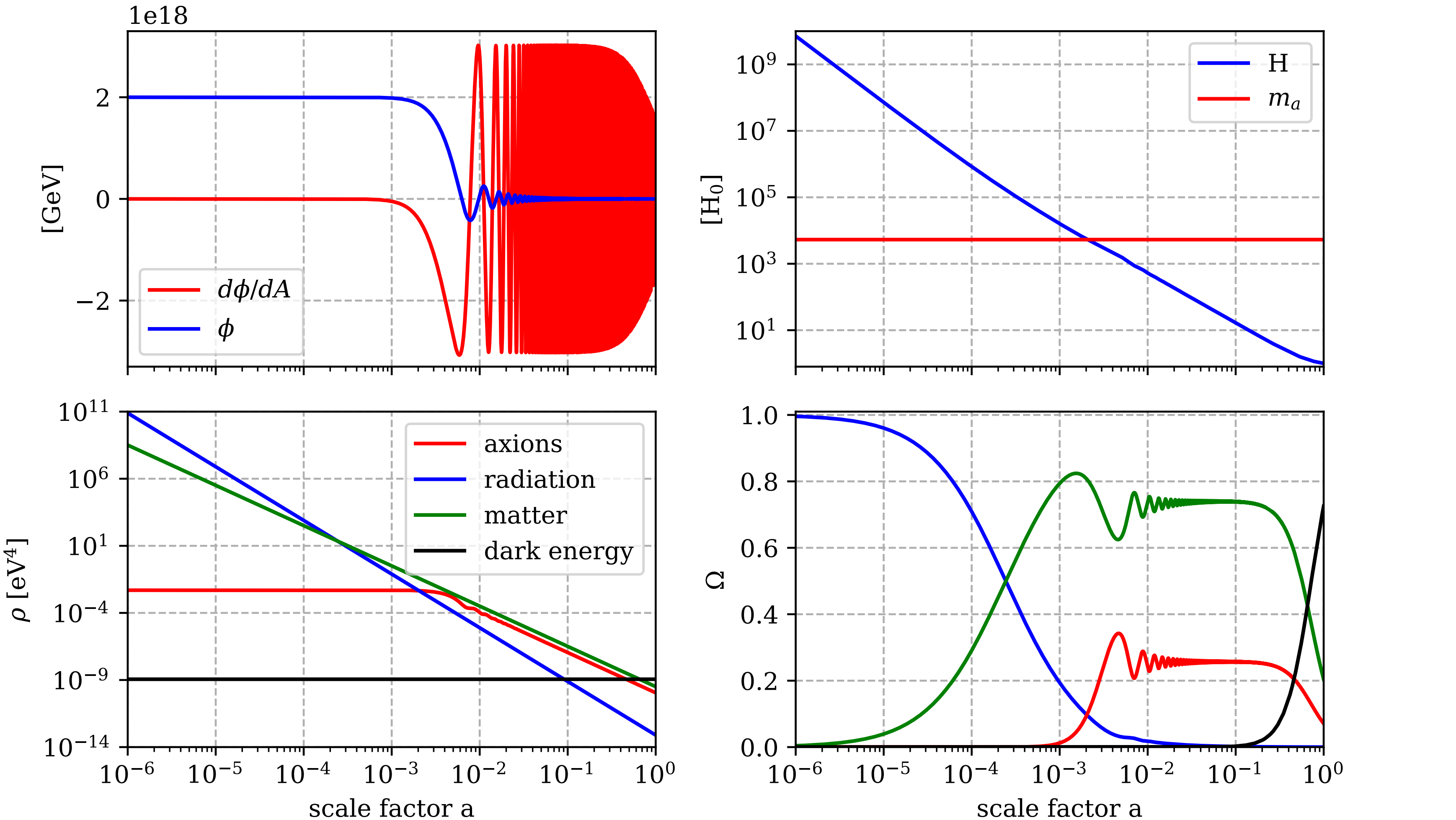
- Small angle approximation:

$V(\phi) = \frac{1}{2}\,m_a^2\,\phi^2$ with $m_a = \Lambda_a^2/f_a$

Background evolution

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

Example universe:
$m_a = 5 \times 10^{-29}\text{eV}$
$\Omega_{a,0} = 0.071$



Perturbation Theory

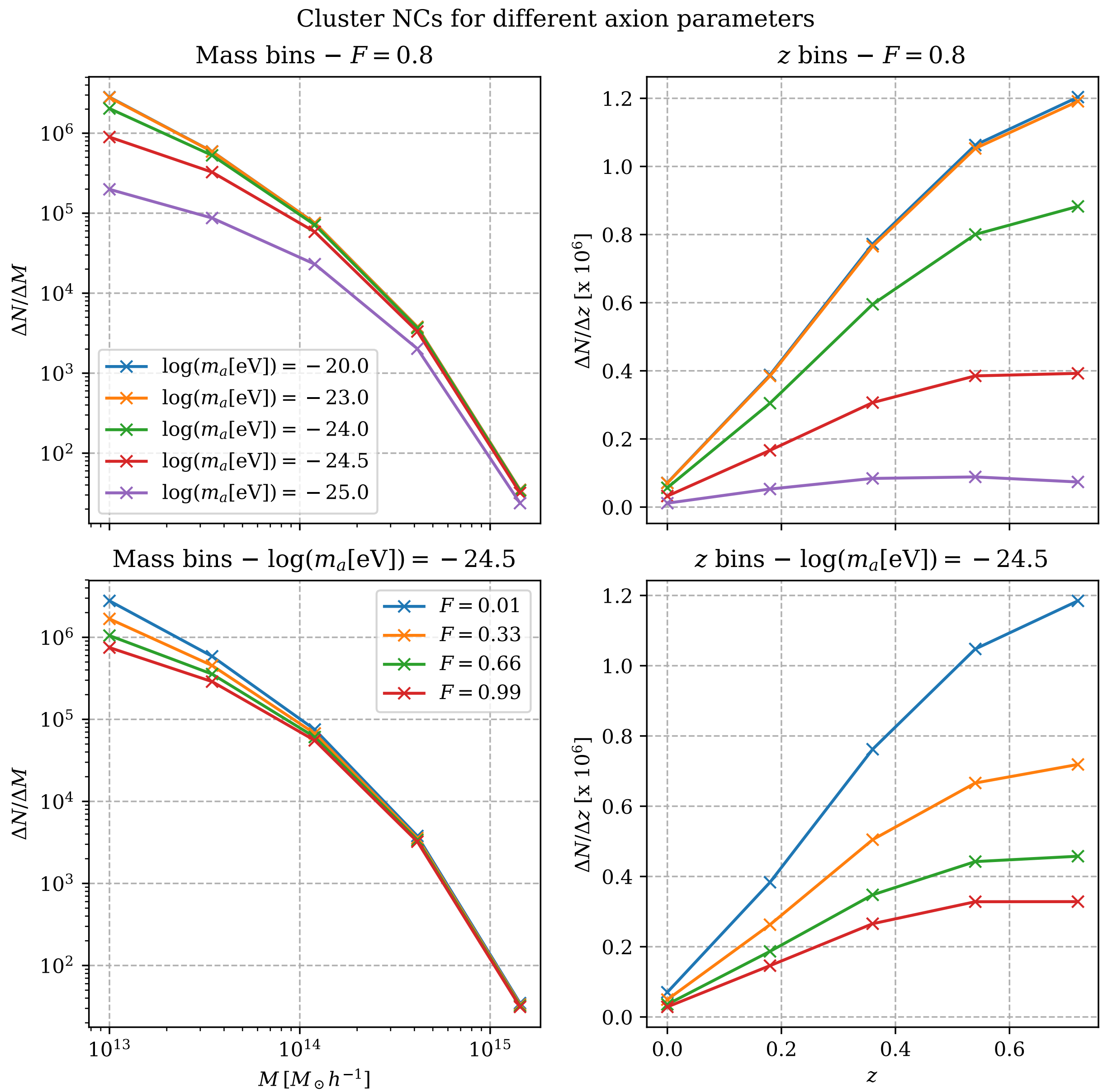
e.g. Marsh (2016) arxiv: 1510.07633

- EOM for axion overdensity:

$$\ddot{\delta}_a + 2H\dot{\delta}_a + \left(\frac{k^2 c_{s,eff}^2}{a^2} - 4\,\pi G\,\rho_a\right)\delta_a = 0$$

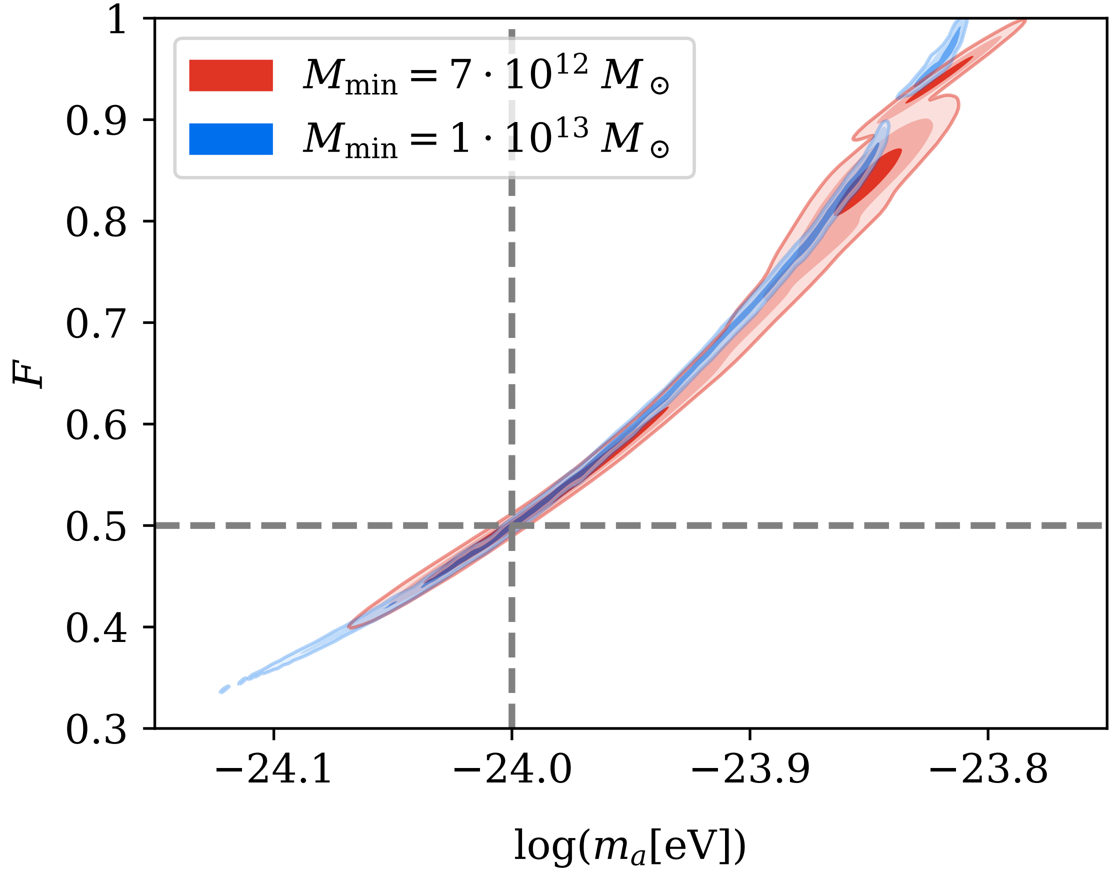
- DM: $c_{s,eff} = 0$
- AxionDM: $c_{s,eff} = c_{s,eff}(k)$

Cluster NCs



Cluster NCs for different axion parameters
Mass bins $- F = 0.8$
z bins $- F = 0.8$
Mass bins $- \log(m_a[\mathrm{eV}]) = -24.5$
z bins $- \log(m_a[\mathrm{eV}]) = -24.5$
$\Delta N/\Delta M$
$\Delta N/\Delta z$ [x 10^6]
$\log(m_a[\mathrm{eV}]) = -20.0$
$\log(m_a[\mathrm{eV}]) = -23.0$
$\log(m_a[\mathrm{eV}]) = -24.0$
$\log(m_a[\mathrm{eV}]) = -24.5$
$\log(m_a[\mathrm{eV}]) = -25.0$
$F = 0.01$
$F = 0.33$
$F = 0.66$
$F = 0.99$
$M\,[M_\odot h^{-1}]$
z

Degeneracy Regime



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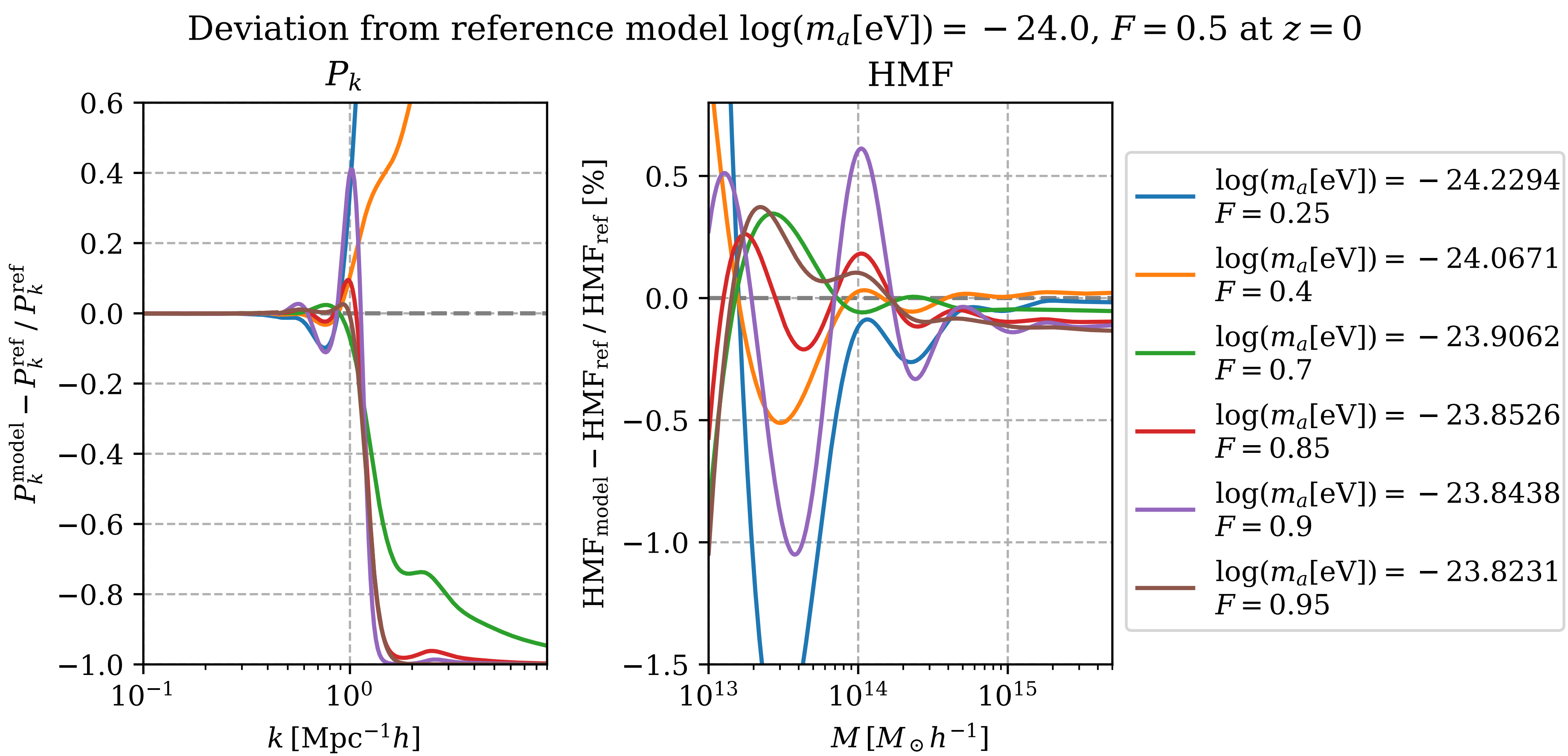

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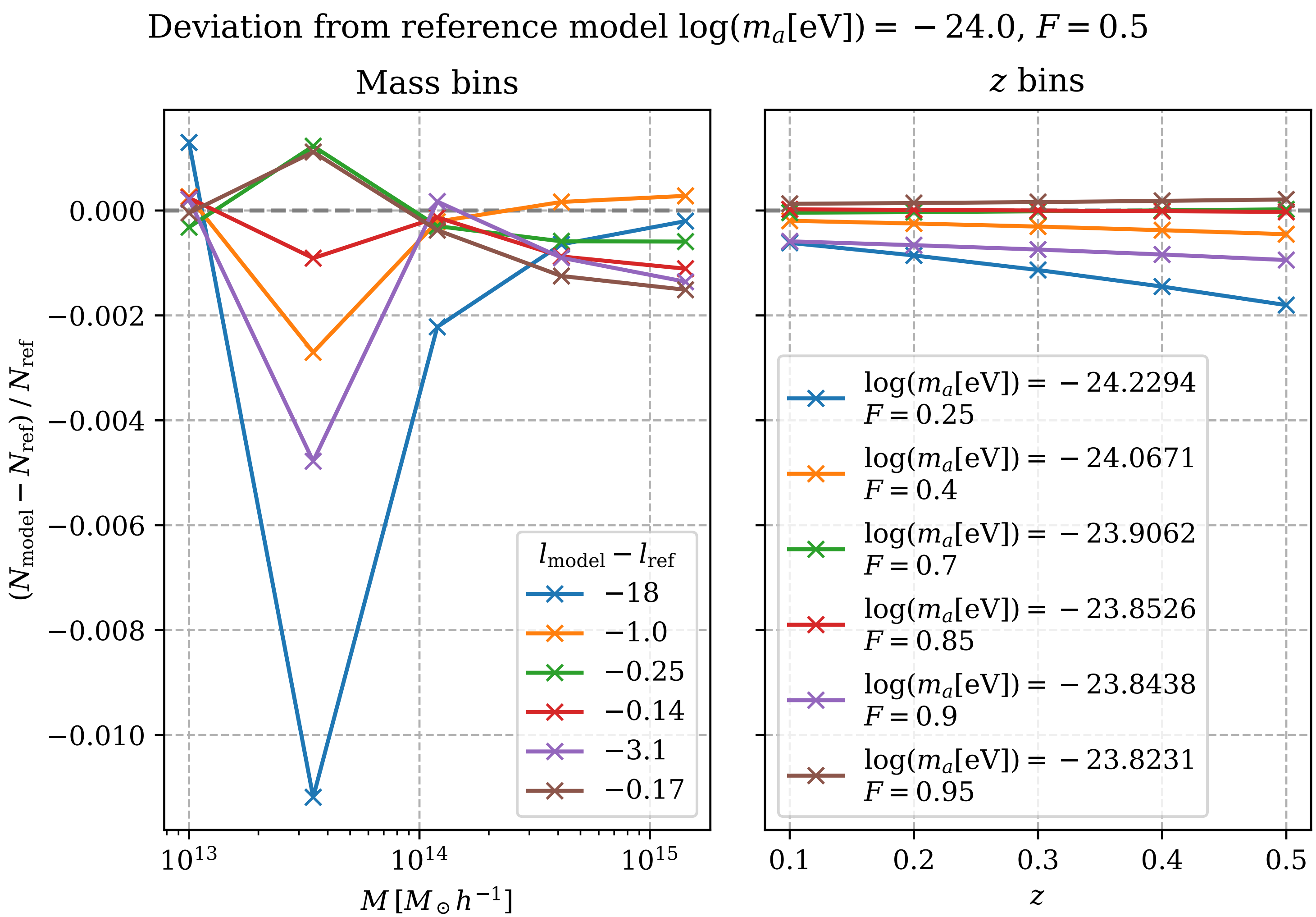
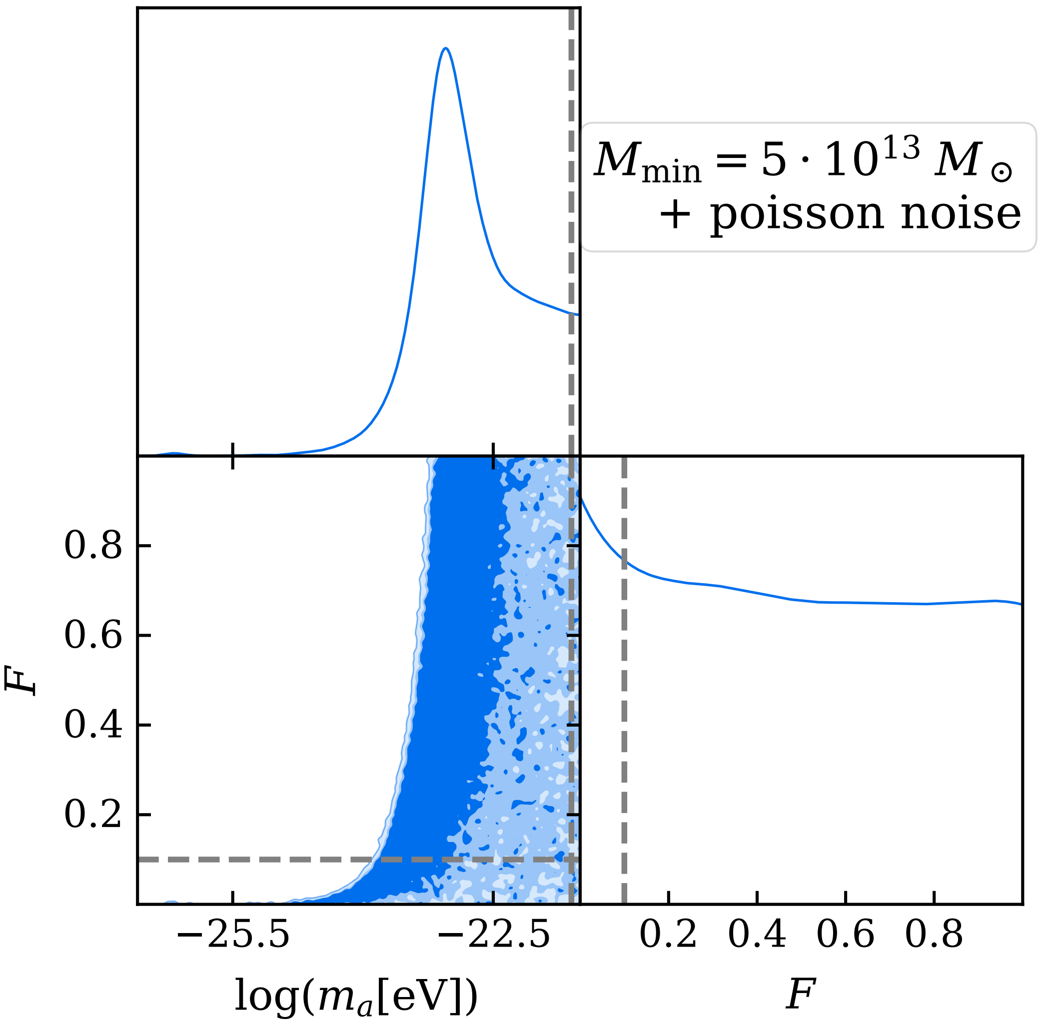


Unconstrained
+ poisson noise



Suggested reading

- David Marsh: Axion Cosmology (review)
  arxiv: 1510.07633
- Pierre Sikivie: The Pooltable Analogy to Axion Physics (fun)
  arxiv: hep-ph/9506229