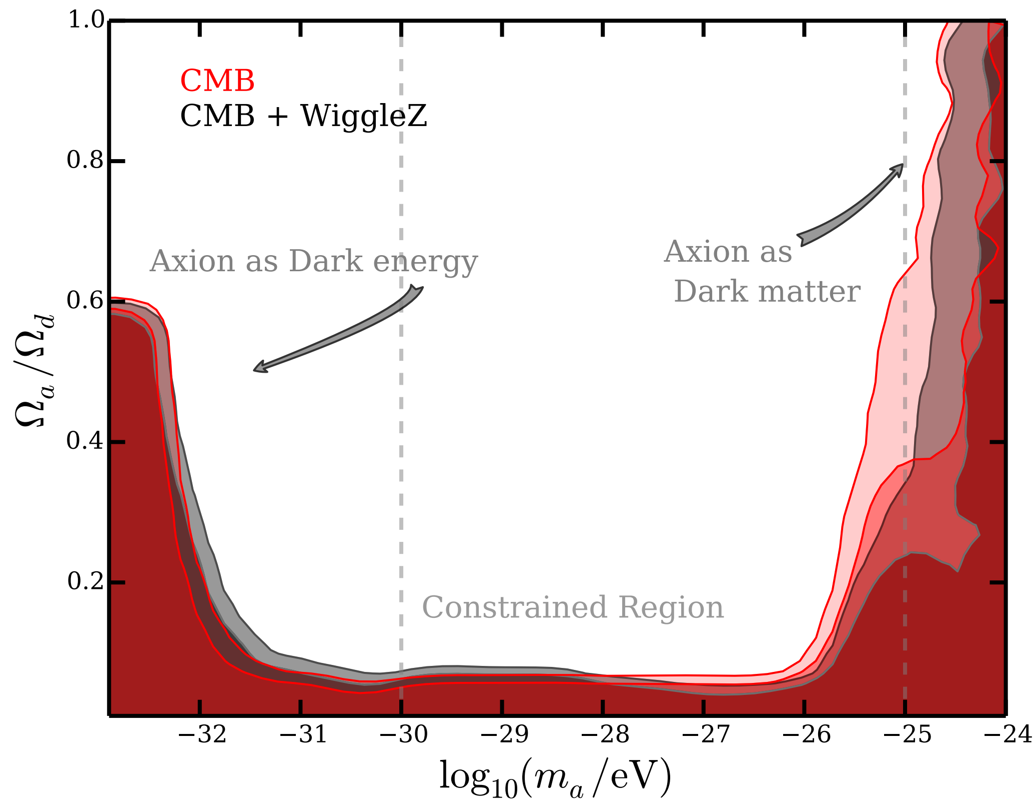
Cosmology of Ultralight Axions



David J. E. Marsh

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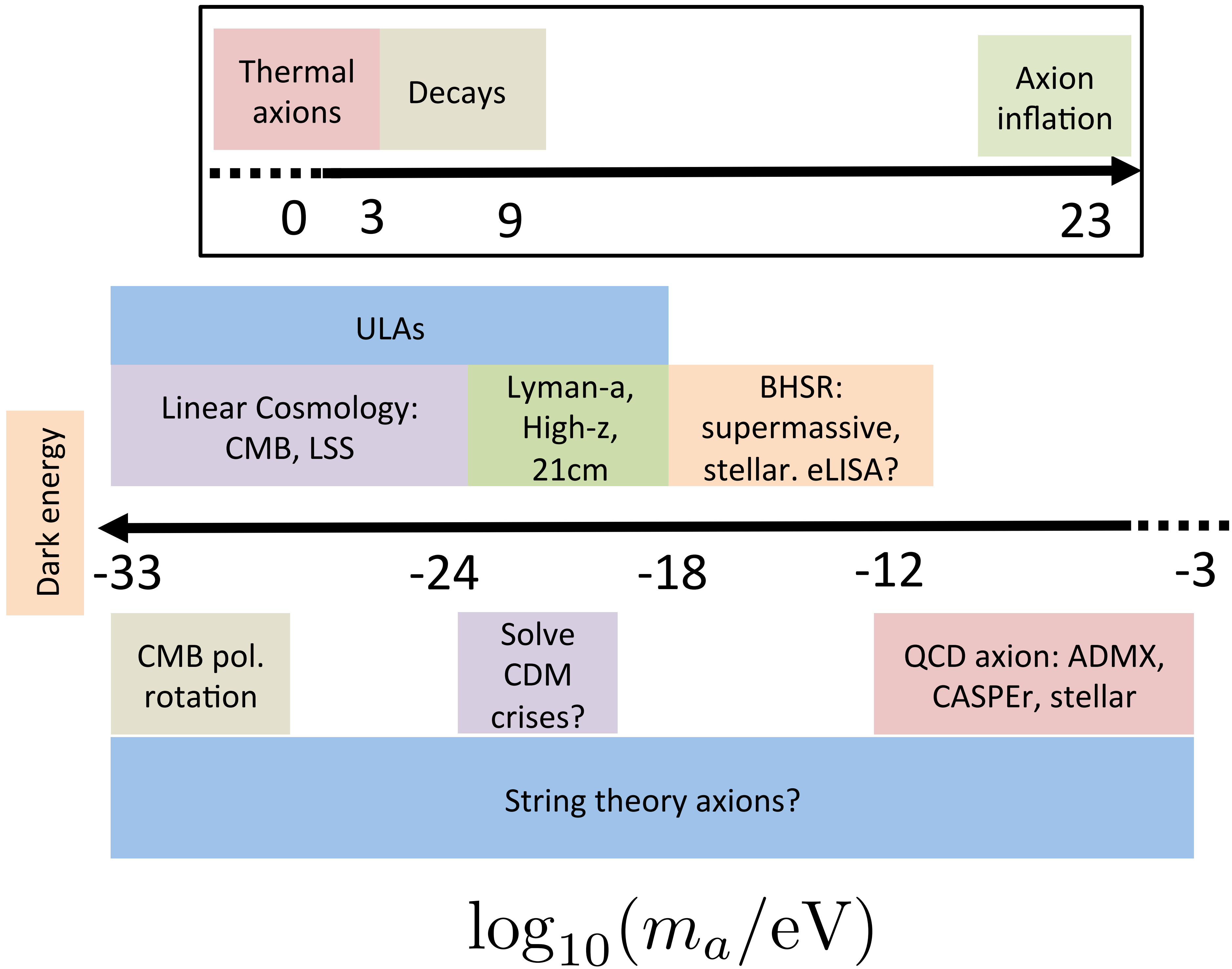
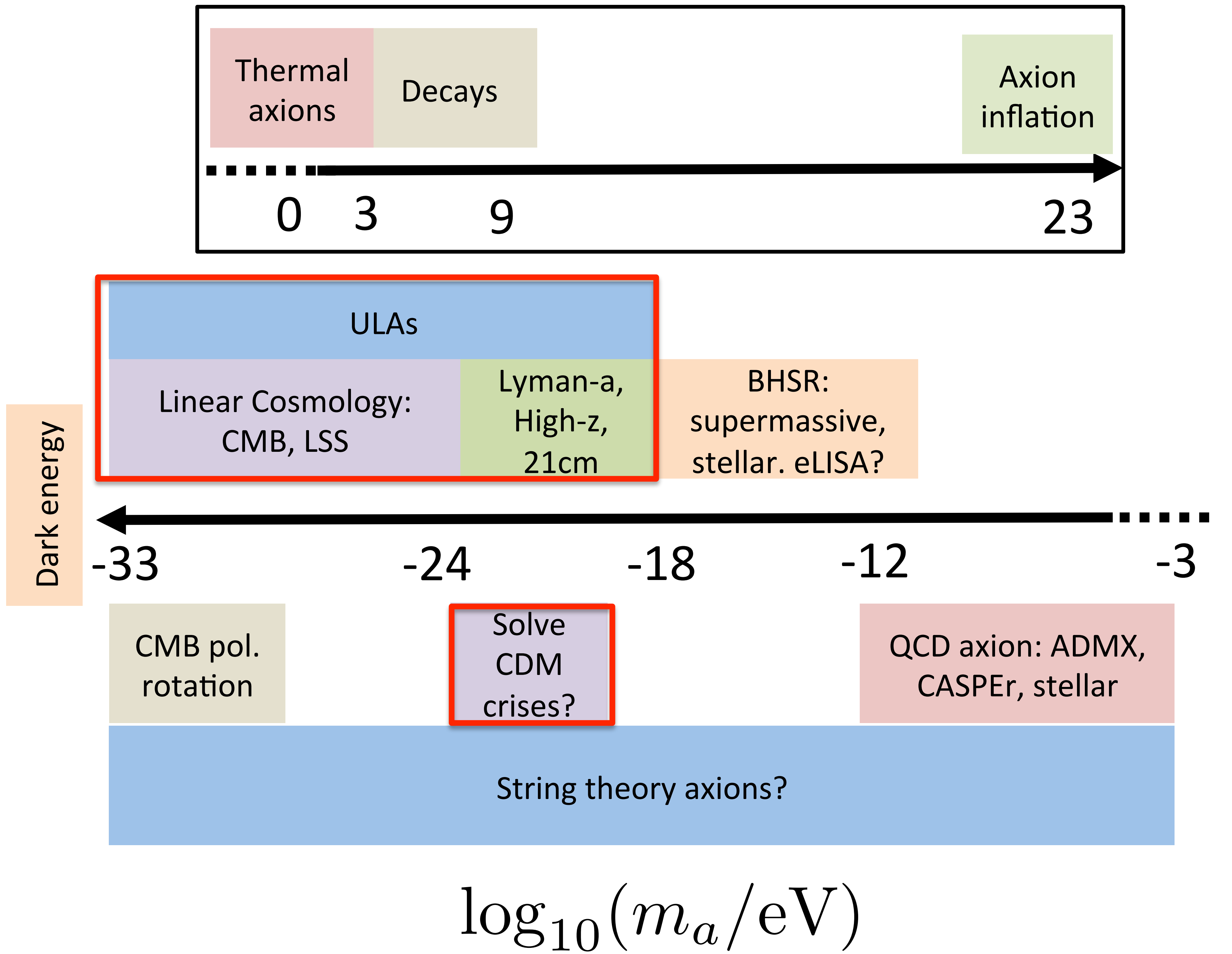


Thermal axions
Decays
Axion inflation
0
3
9
23
ULAs
Linear Cosmology: CMB, LSS
Lyman-a, High-z, 21cm
BHSR: supermassive, stellar. eLISA?
Dark energy
-33
-24
-18
-12
-3
CMB pol. rotation
Solve CDM crises?
QCD axion: ADMX, CASPEr, stellar
String theory axions?
$\log_{10}(m_a/\mathrm{eV})$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Ultralight Axions From Vacuum Realignment

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi - \nabla^2\phi = S(g_{\mu\nu})$$

coherent field from SSB

friction

potential

"pressure"

gravity

Why ultralight axions are special

Axions behave as DE for H>m and DM for H<m:

- Change background expansion rate compared to LCDM
- Affect CMB acoustic peaks, damping, and ISW
- Affect growth of structure and BAO

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In perturbations, gradient energy → pressure → Jeans scale:

- Suppress matter power spectrum (galaxies & clusters)
- LSS on linear scales ~ effect of massive neutrinos.
- CMB gravitational lensing also suppressed.
- Non-linear scales: reduce halo formation, reion, substructure.

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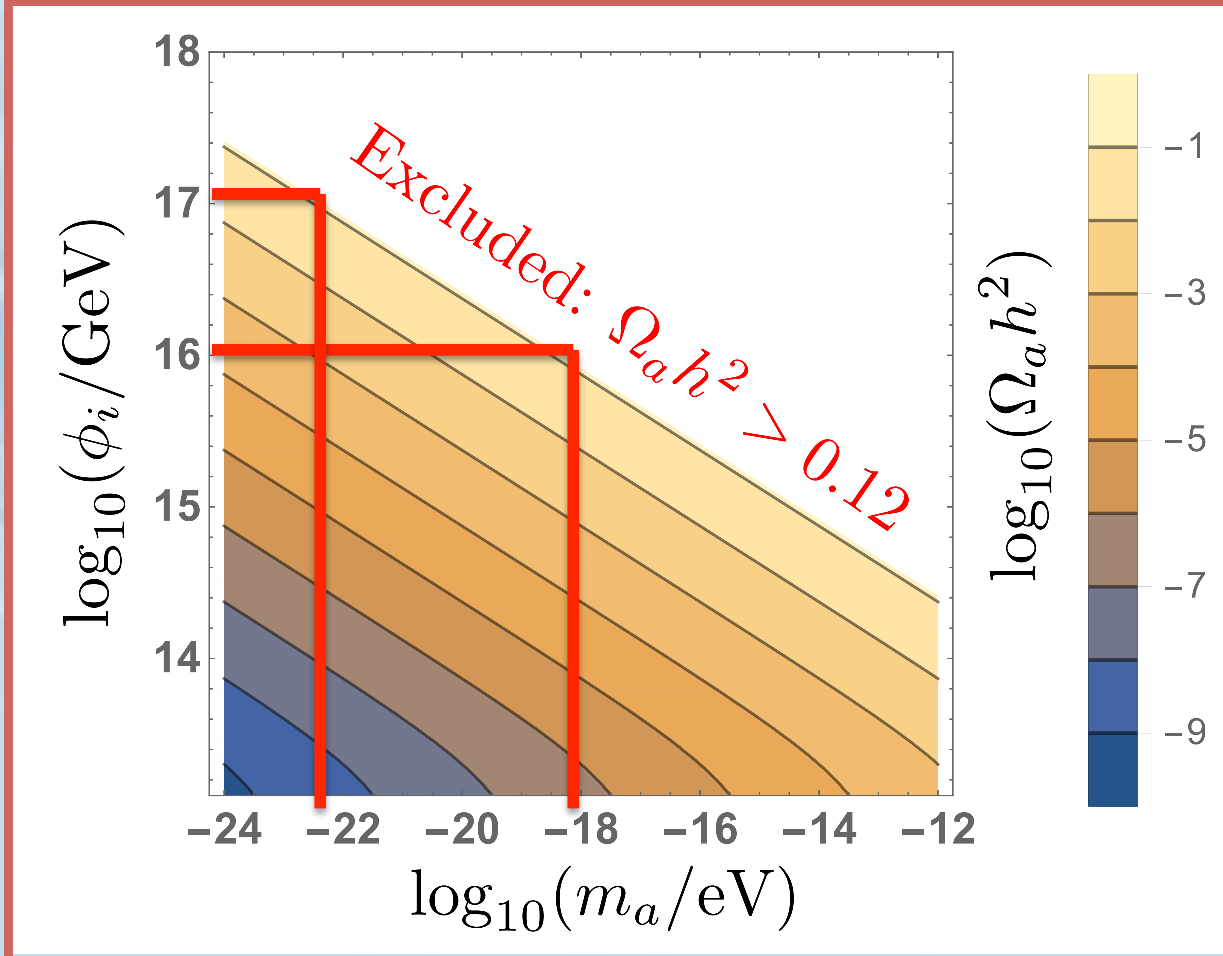
Behaviour changes drastically as mass varied in range:

$$H_0 \sim 10^{-33}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-15}\ \mathrm{eV} \sim H_{\mathrm{BBN}}$$

→ scanning full parameter space for constraints is challenging

Constraints from relic abundance

Ultralight axions, harmonic V, no T dep., in DM regime:



Large f_a necessary for any contribution

→ PQ always broken during inflation.

All DM "Natural" and observable for:

$$10^{-22} \lesssim \frac{m_a}{\mathrm{eV}} \lesssim 10^{-18}$$

$$10^{16} \lesssim \frac{f_a}{\mathrm{GeV}} \lesssim 10^{17}$$

→ from string models?

The ULA Jeans scale

Hlozek et al (2015)

Heuristically: the de Broglie wavelength with the Hubble flow.

Uncertainty on position: $$\lambda_{\rm dB} = \frac{1}{mv}$$

Recede @ Hubble: $$v_H = rH$$

Q: How far away does a particle have to be before it can be localized within that radius?

$$r > 1/\sqrt{mH}$$

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Other typical velocities and scales?

- Minimum uncertainty for v=c

→ $m>H_0$ no localization at all within our horizon

→ behave as cosmological constant for $m<10^{-33}$ eV

- Typical velocity in galaxy is v_{vir}~100 km s-1, scale ~ kpc

m~10^{-22} eV → r~kpc at virial velocity, “like CDM” if heavier

Axion DM as coherent field

The galactic DM is an oscillating condensate:

$$\phi = \phi_0(t, \vec{x}) \cos(m_a t) \,, \quad \rho_{\rm DM} = \frac{1}{2} m_a^2 \phi_0^2 \,.$$

$$\omega \approx 10^{-7}\ {\rm Hz} \left(\frac{m_a}{10^{-22}\ {\rm eV}} \right)$$

Coherent over distances ~ de Broglie wavelength.

$$\lambda_{\rm dB} = \frac{1}{m_a v_{\rm vir}} \approx 0.2\ {\rm kpc} \left(\frac{m_a}{10^{-22}\ {\rm eV}} \right)^{-1}$$

Detection of coherent effects at low frequencies.
Novelties in structure formation.

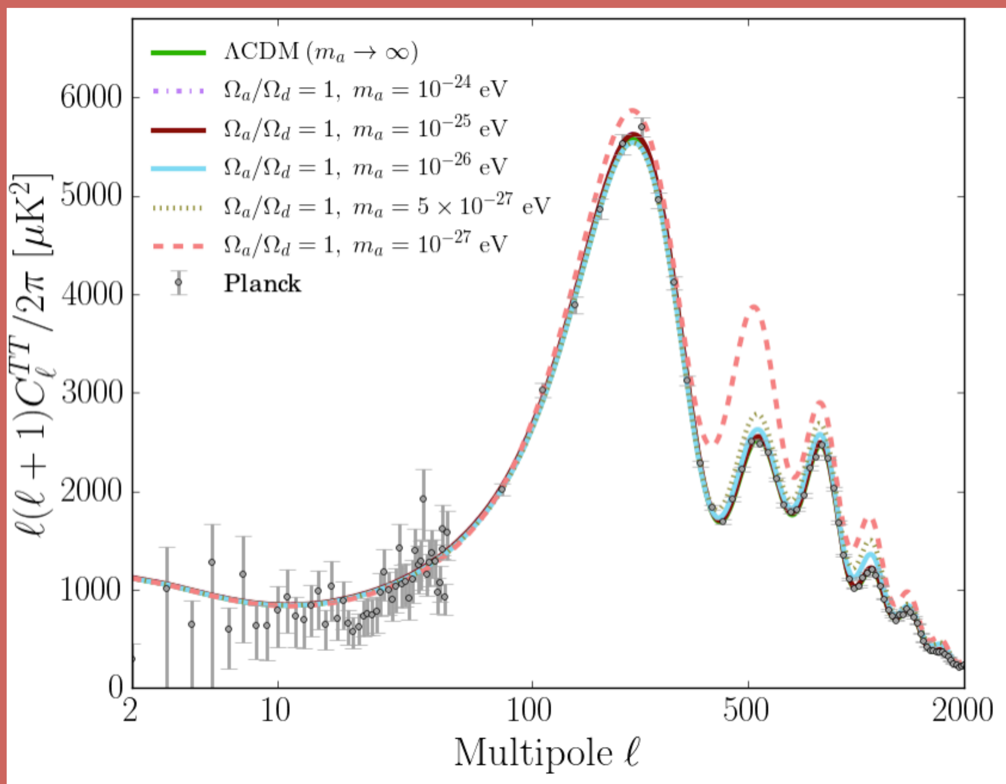
Graham & Rajendran (2013), Arvanitaki et al (2014), DJEM+ (2010+) …

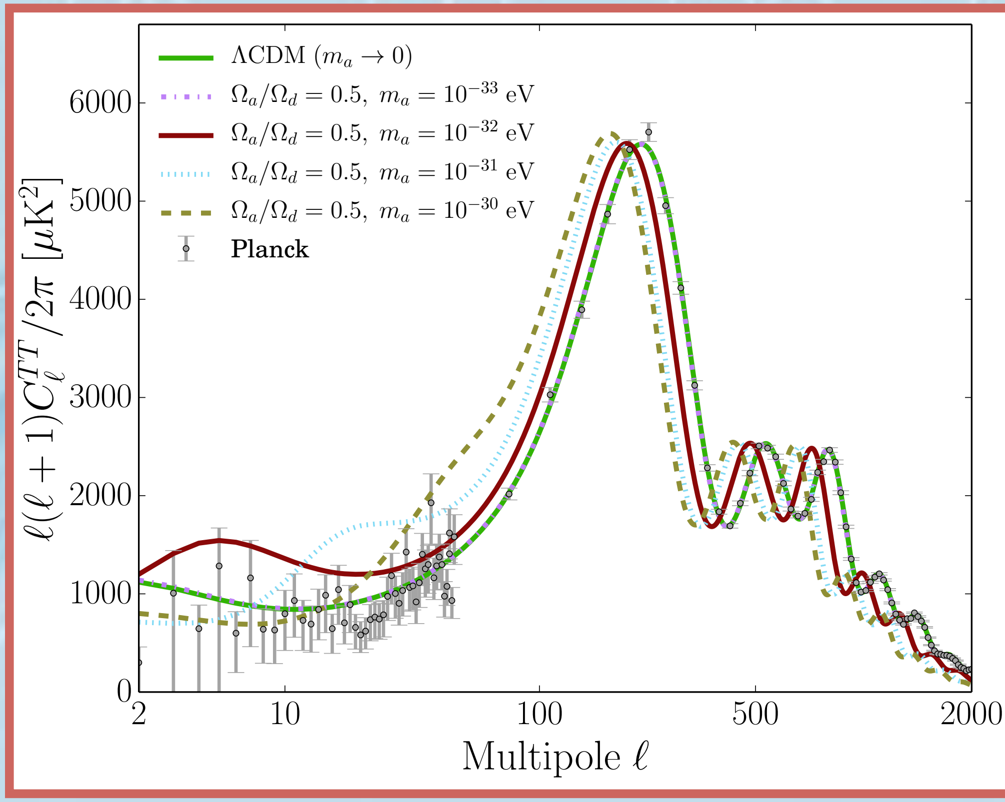
Precision Tests of One-Component CDM Paradigm

CMB temperature power

Hlozek et al (2015)
+CAMB, cosmoMC,Multinest

Data: Planck (2013) + ACT + SPT. (2015 + lensing in prep)
Code: axionCAMB(+cosmosis), public release ~ June 2016





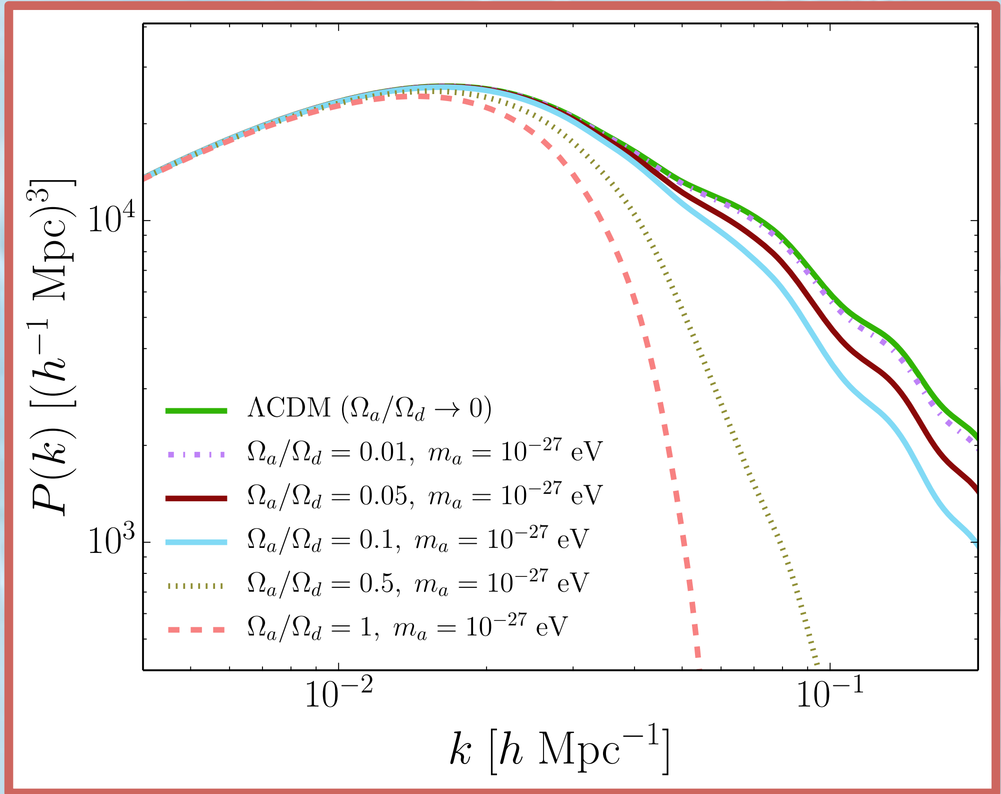
DM-like axions affect acoustic peaks by expansion rate in rad. dom. era.
Effects vanish for large m.

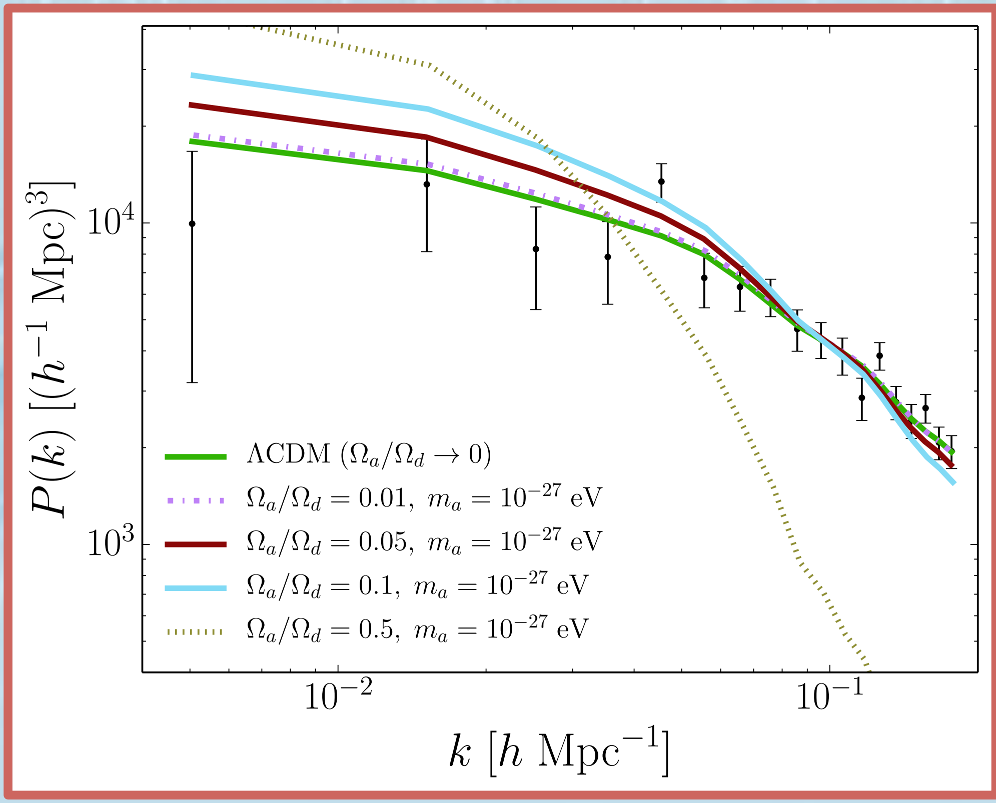
DE-like axions affect angular size + ISW by expansion rate in matter dom. era.
Effects vanish for small m.

Galaxy Power

Hlozek et al (2015)

Data: WiggleZ, code: axionCAMB.
Account for k-dep. bias by classing $k_J<k_{eq}$ as "Dark Energy".

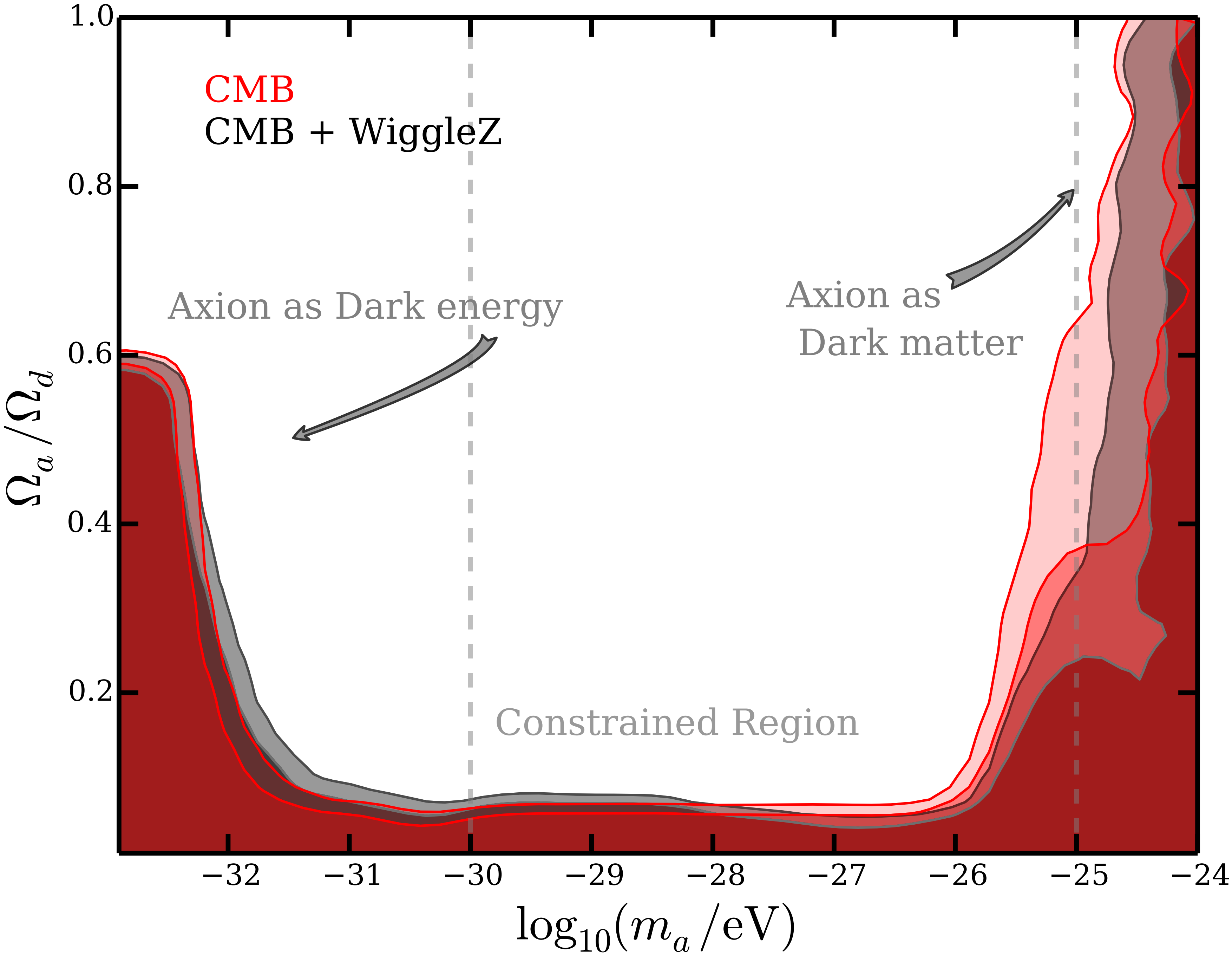




Ideal world P(k). DM-like axion, vary fraction → reduce power suppression.

Real world: convolve with survey window, marginalise over bias, linear scales.

Contours are 2 and 3σ exclusions



Robust constraints

Hlozek et al (2015)

For axions to be all DM: $m_a > 10^{-24}\ \text{eV}$

→ An absolute lower bound on DM mass!

For axions to be all DE: $m_a < 10^{-33}\ \text{eV}$

Strong constraints on intermediate masses:

$$10^{-32}\ \text{eV} < m_a < 10^{-25.5}\ \text{eV}$$

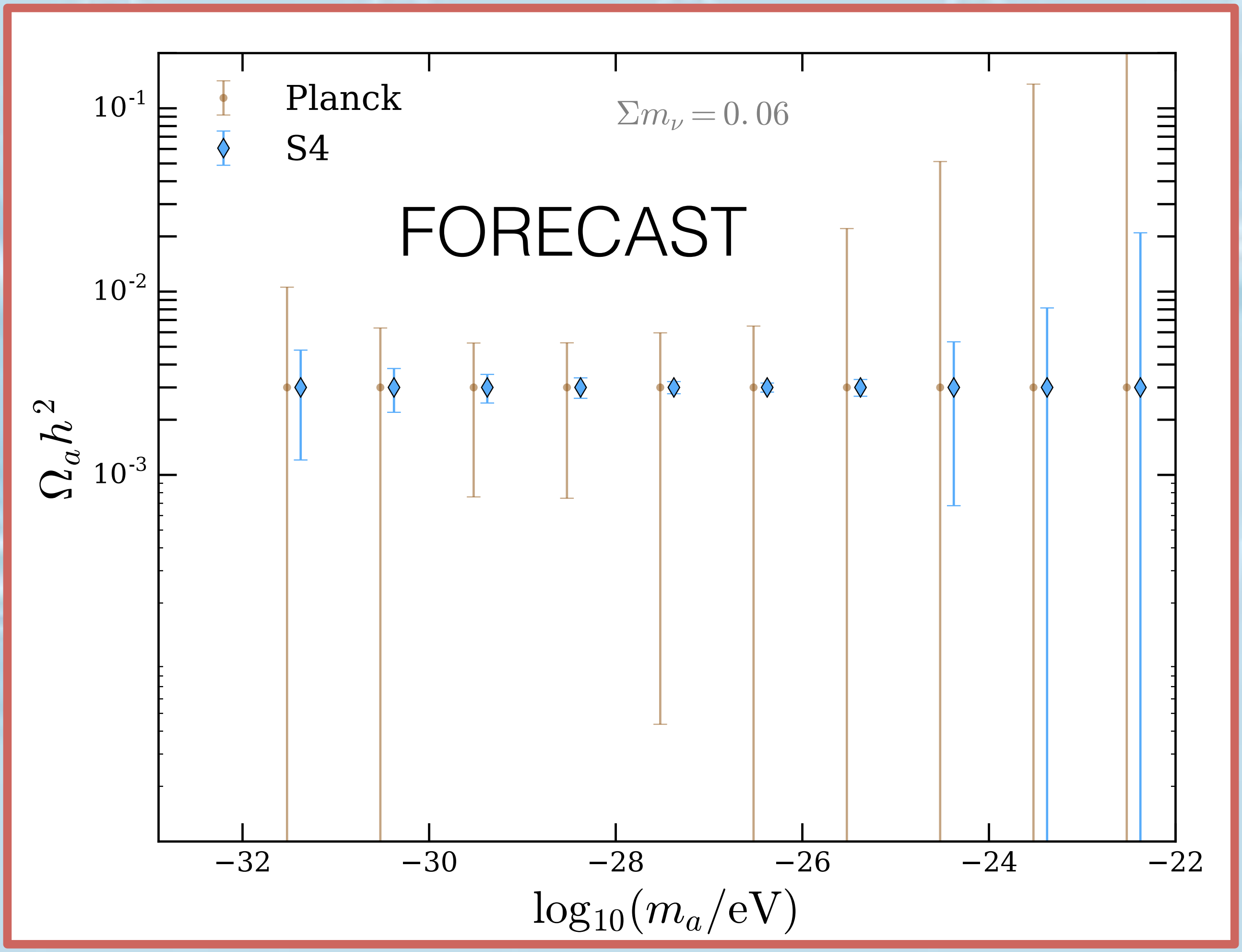
$$\Omega_a h^2 < 0.006\,(95\%\text{C.L.})$$

All from linear physics and model-independent production!

In prep w/ Hlozek, Grin +

CMB-S4: precision DM physics

Combined ground based telescopes w/ 10^5 detectors in T+P.



O(10) > Planck. >3σ detection of 1% departure from CDM over 8 orders of mag in mass.

DM Substructure and $m \sim 10^{-22}$ eV

Hu et al (2000), DJEM & Silk (2013)
+ much growing interest!

Axion DM Halos

Schive et al (2014+)
DJEM & Pop (2015)

Pseudo-Soliton solutions of EOM: "oscillotons". (Eikonal) equivalence Schrodinger-CDM above de Brolgie wavelength. Transition soliton → NFW at fraction ε of central density.

$$\rho(r) = \begin{cases} \dfrac{\rho_{\rm sol}}{\left(1+\left(\frac{r}{r_{sol}}\right)^2\right)^8} & \text{for} \quad r < r_\epsilon \\ \dfrac{\rho_{\rm NFW}}{\left(1+\frac{r}{r_s}\right)^2 \frac{r}{r_s}} & \text{for} \quad r \geq r_\epsilon \end{cases}$$

$$r_{\rm sol} = \left[\frac{\rho_{\rm sol}}{2.42\times 10^9\ {\rm M_\odot kpc^{-3}}}\left(\frac{m_a}{10^{-22}{\rm eV}}\right)^2\right]^{-0.25} {\rm kpc}\,.$$

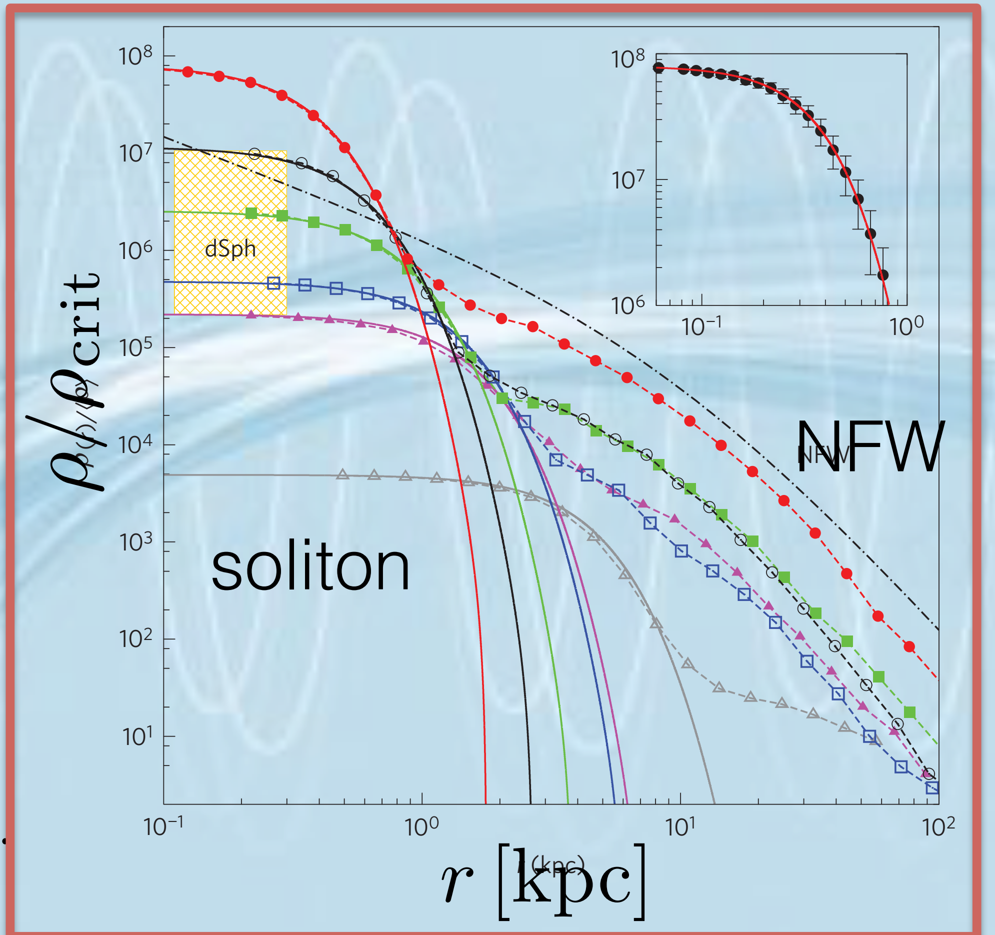
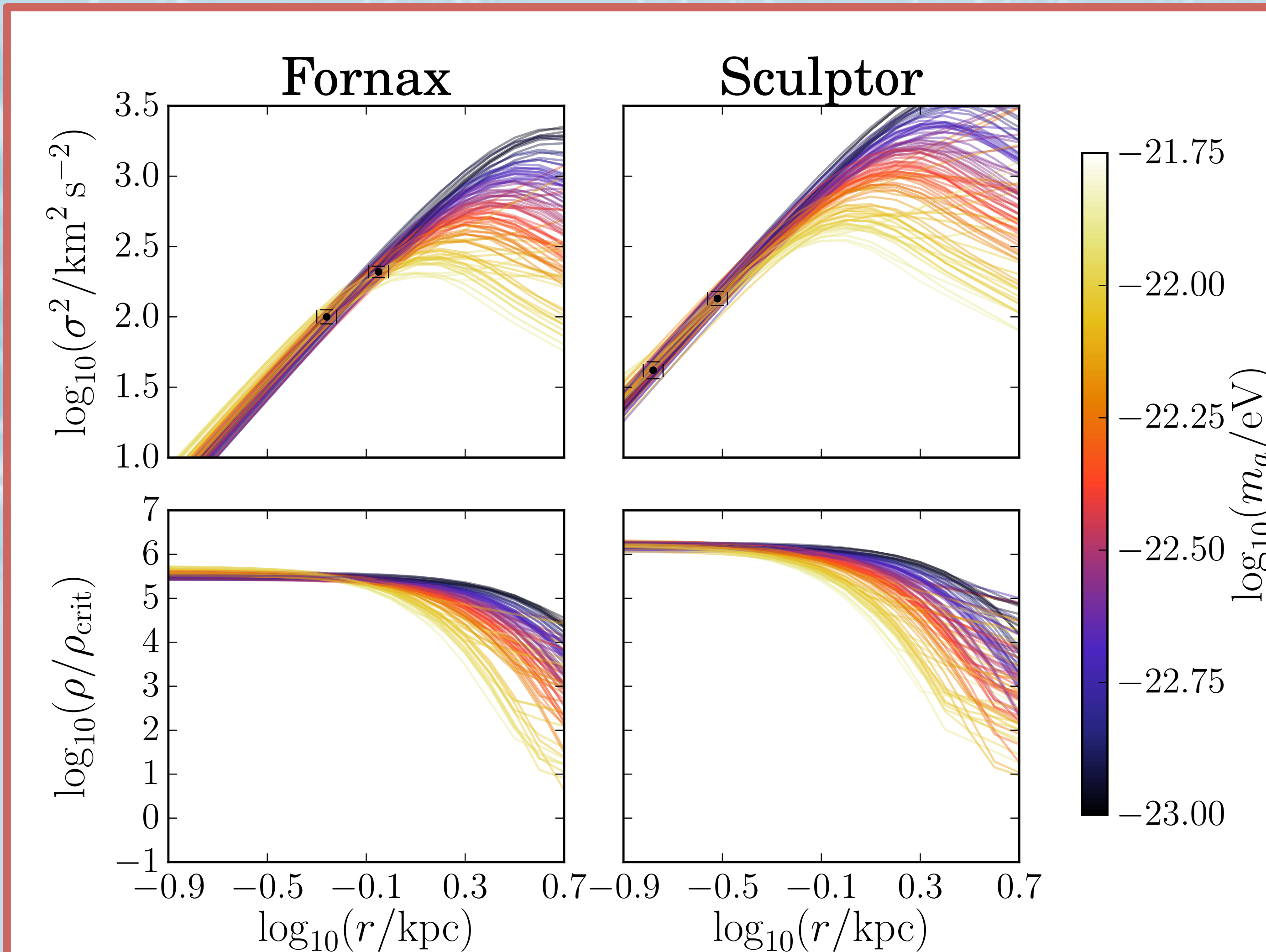


Fig: Schive et al (2014)

Cores in dSphs

Walker & Penarrubia (2011)
DJEM & Pop (2015)

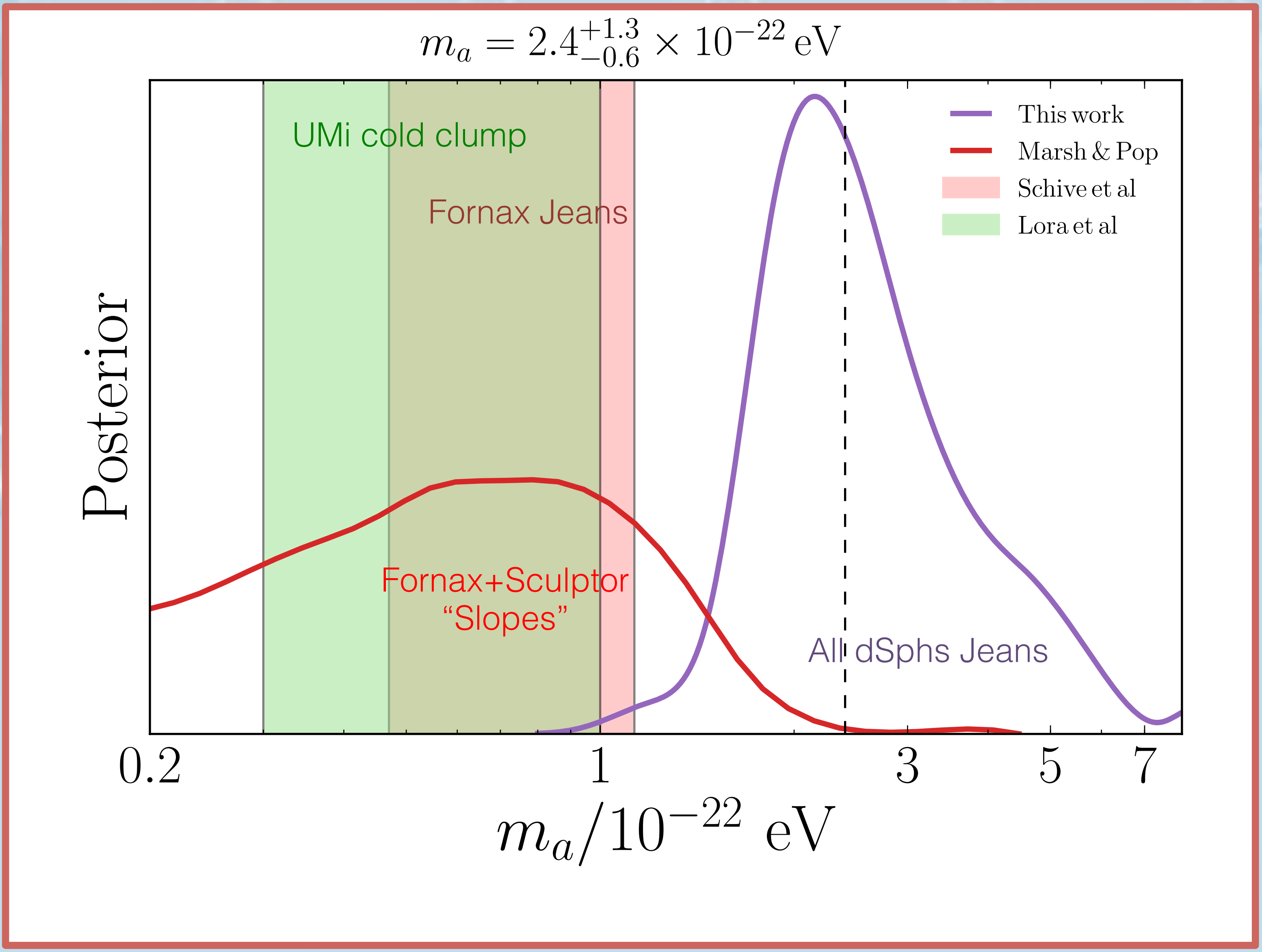
Velocity dispersion at half-light measures enclosed mass.
Two pops. in Fornax+Sculptor → constrain slope of DM halo.



Jeans analysis ++

w/ Gonzelz-Morales et al (in prep)

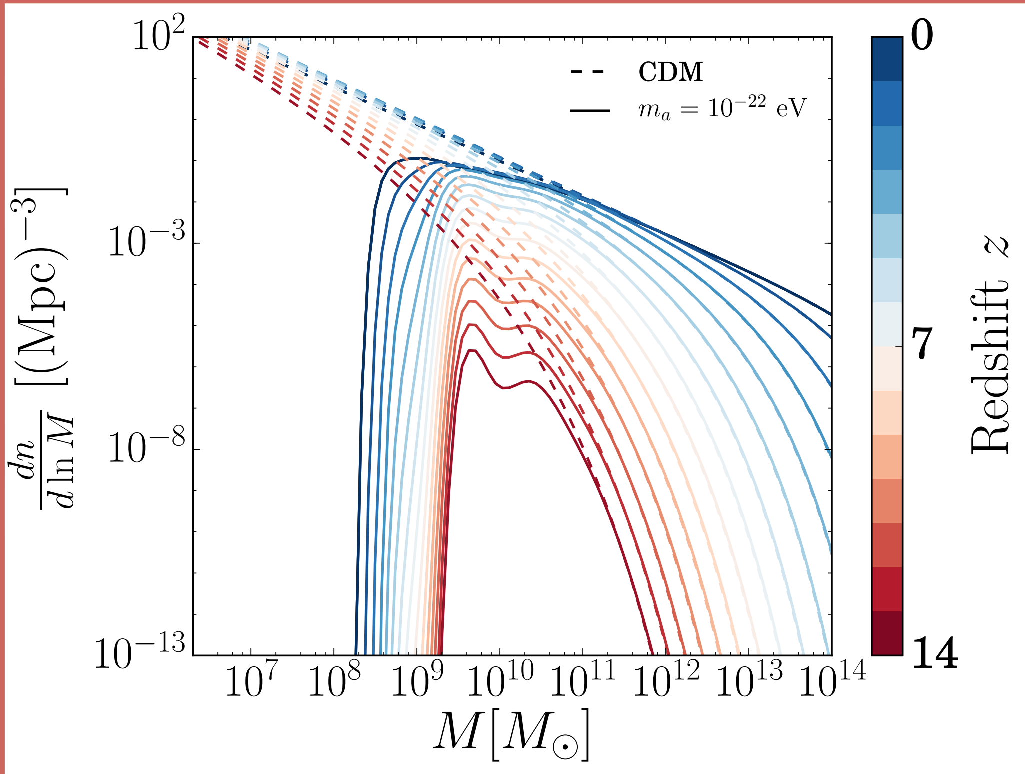
Bayesian analysis of all eight dSphs + mocks. Preliminary.

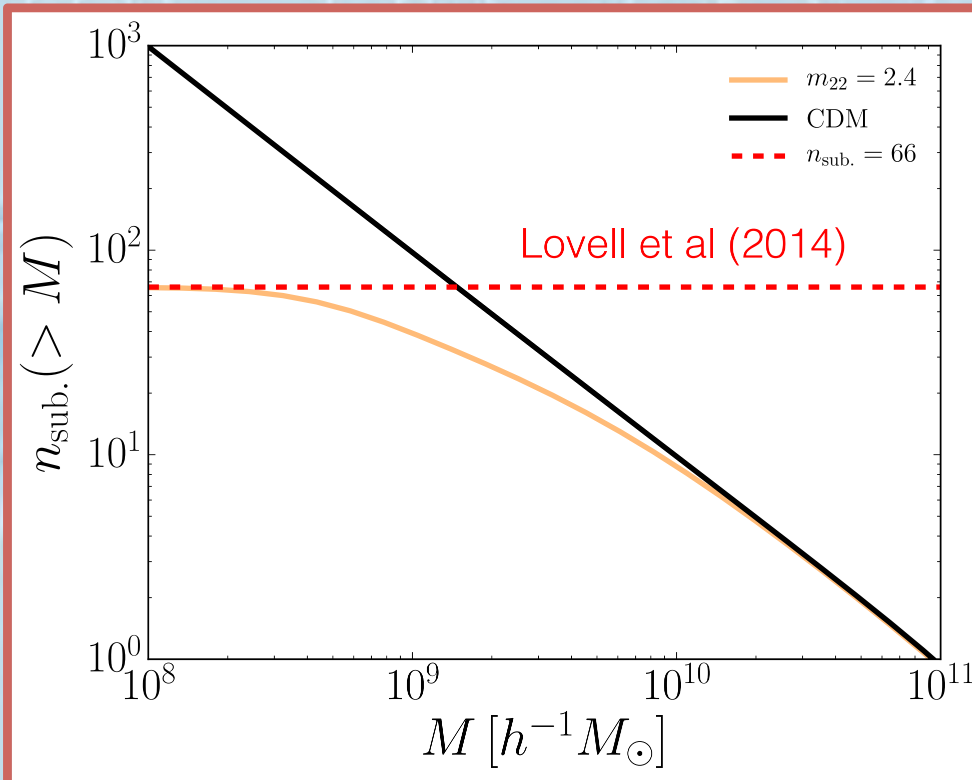


The Halo Mass Function

DJEM & Silk (2013)
Schive et al (2015)

Axion DM suppresses structure formation → halos form later and have a minimum mass $M>10^8\ M_{sol}$.





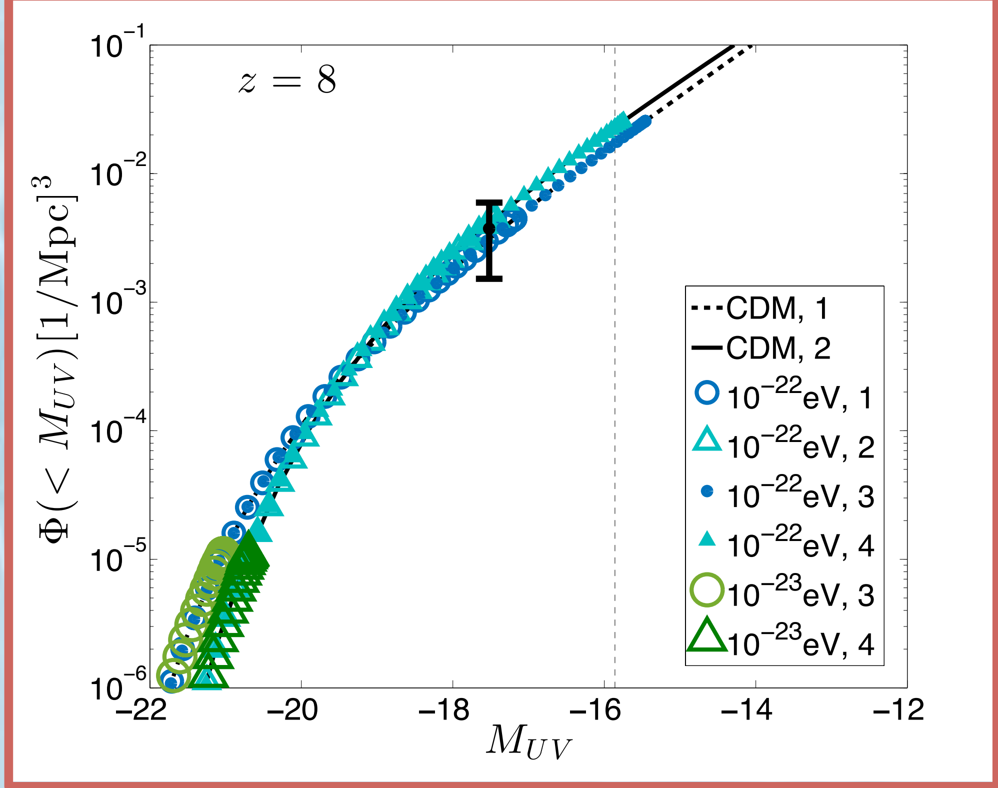
HMF cut-off → solve "missing satellites?" Test with high-z galaxies. Halo model.

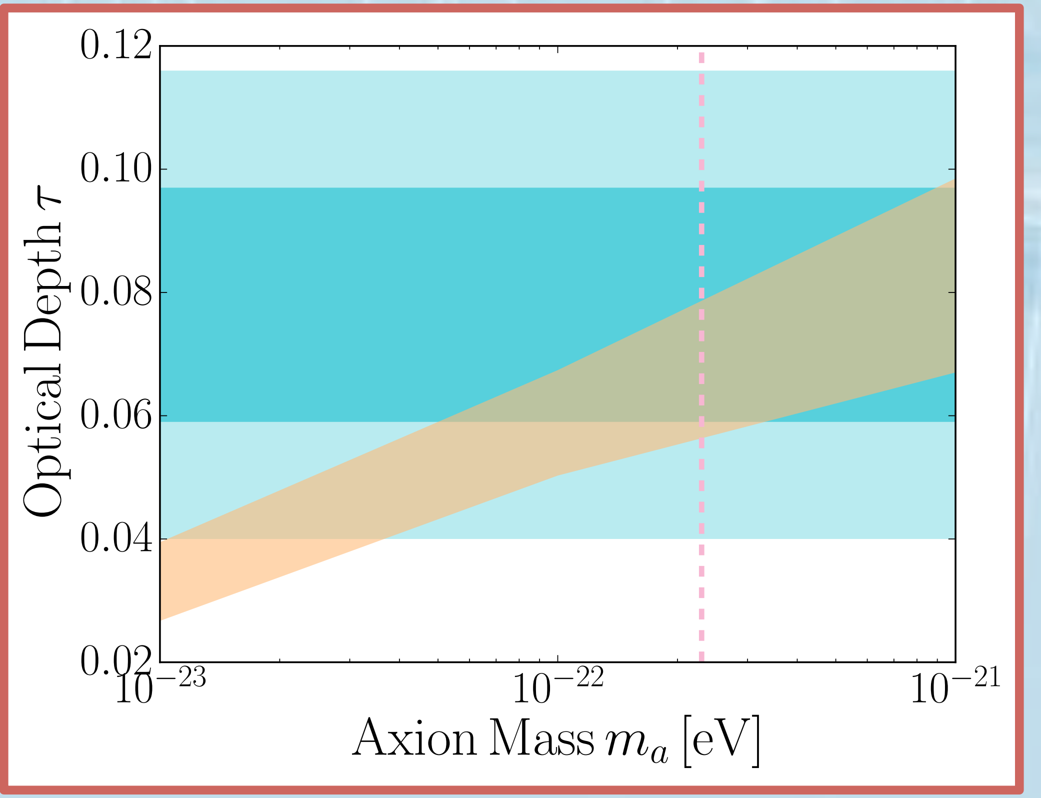
NEW: subhalos. Just consistent. Test w/ ALMA, DES, Gaia?

Reionization and High-z

Bozek, DJEM, Silk, Wyse (2015)

Delayed galaxy formation → powerful tests from high-z.
Planck τ keeps getting lower: a new small-scale problem?





No high-z gals: HUDF luminosity → m>10^{-23} eV. JWST improve by factor 10.

Reion: low τ < 0.08, low z_{re}<10. Rapid reion testable by kSZ amplitude CMB-S4.

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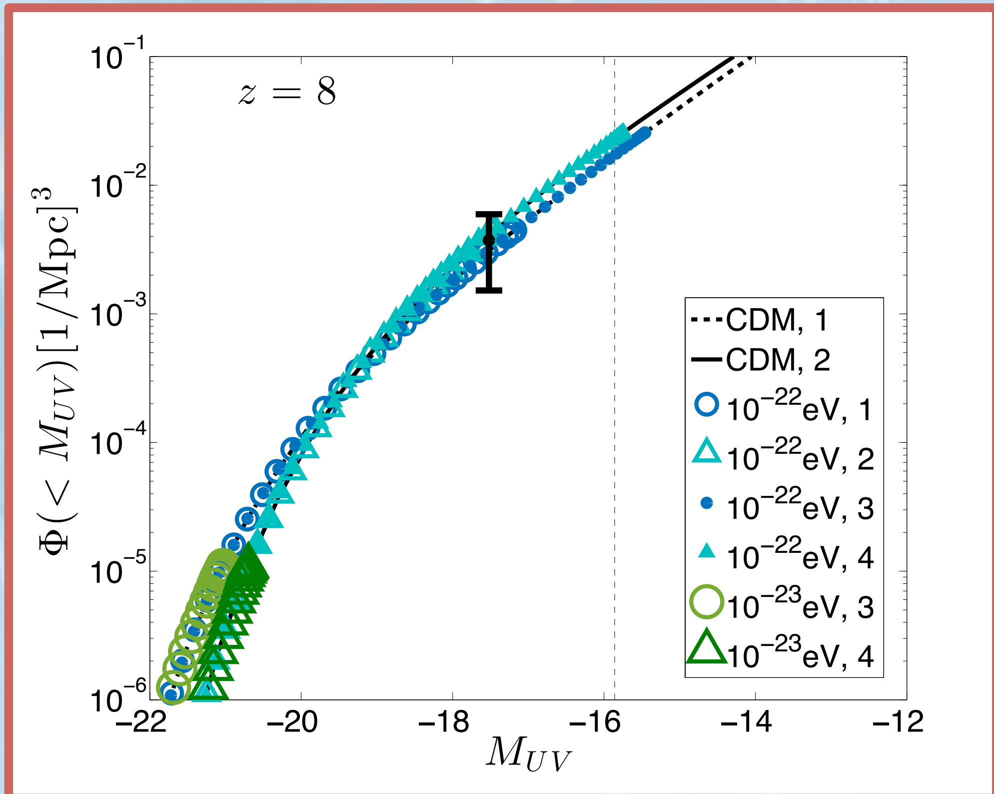

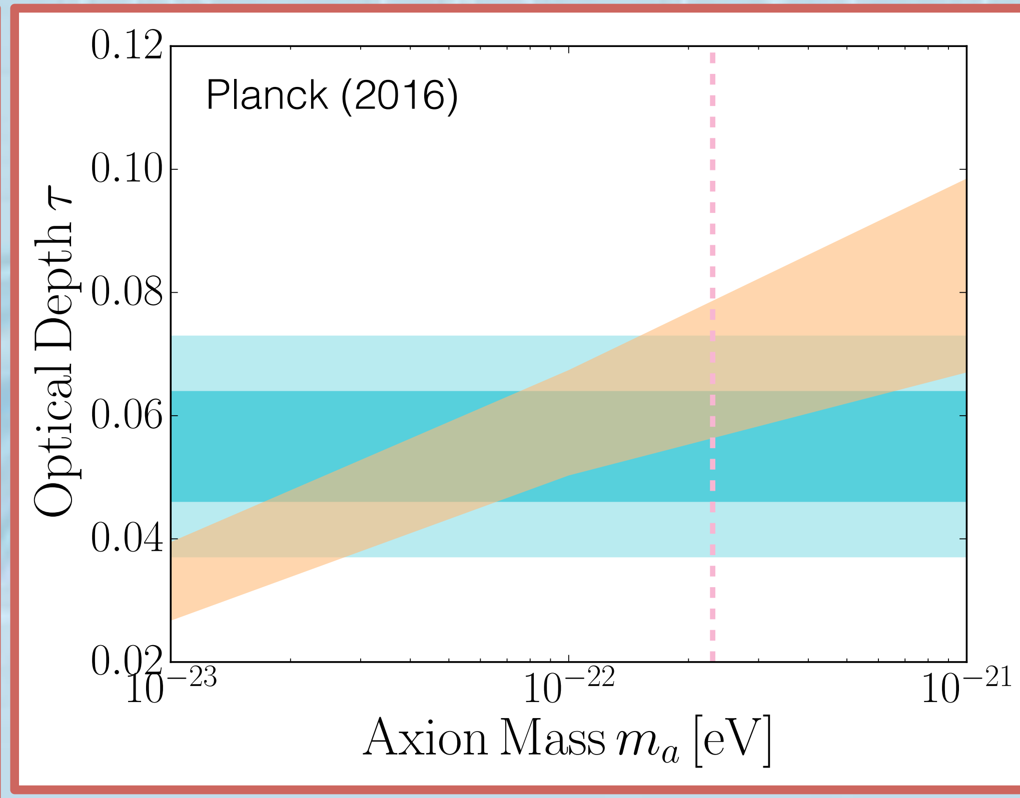

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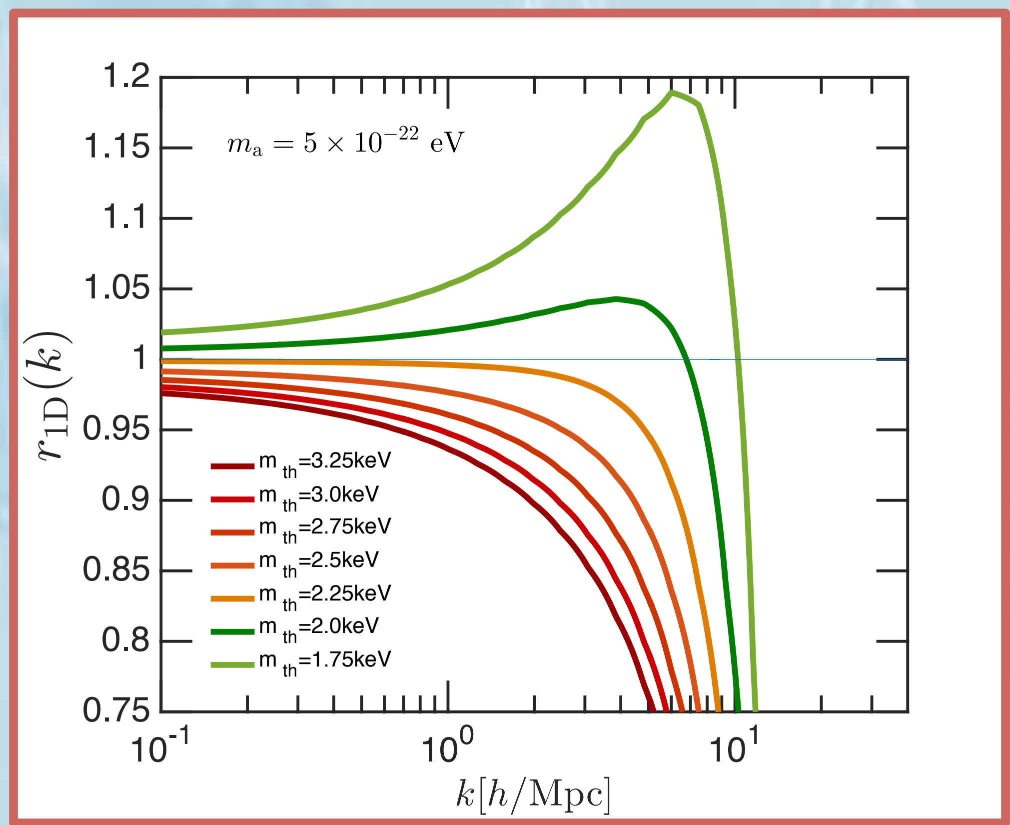
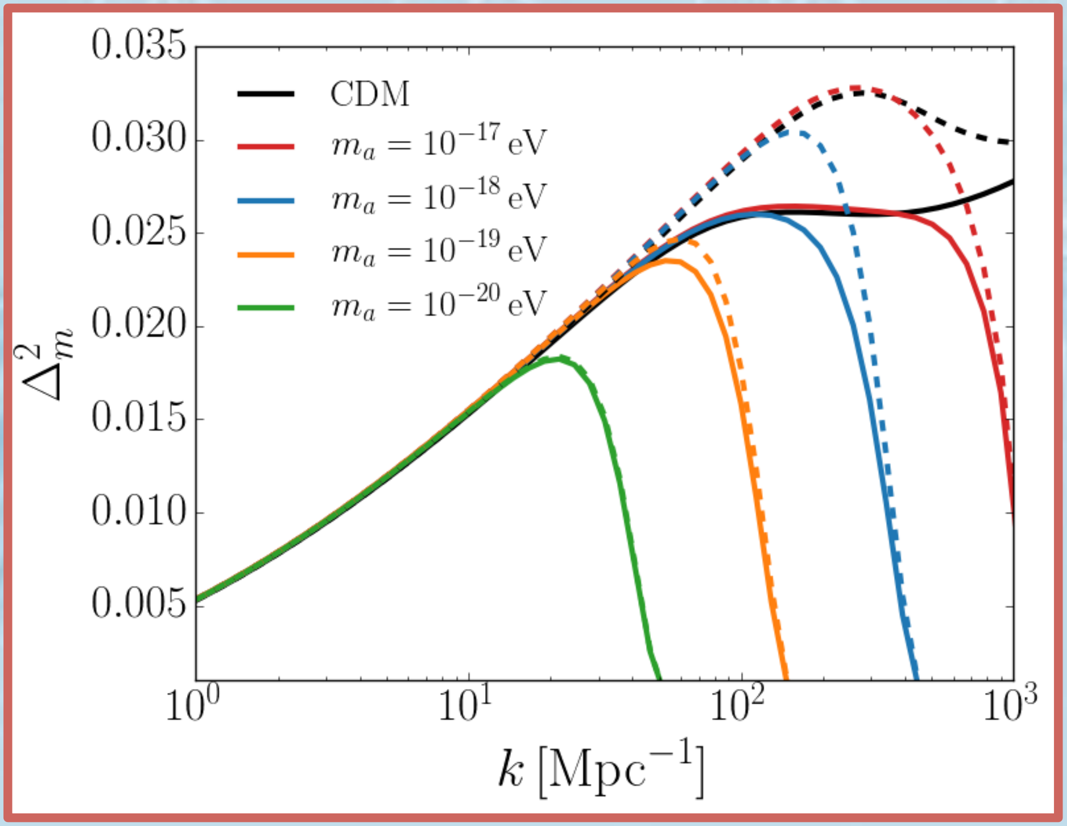
Lyman-alpha and 21cm?

DJEM (2015)
In prep w/ Bozek, Silk, Wyse

How far can we push the lower bound on axion mass?





Ly-a ratios: 3.3 keV excludes $<1.5\times10^{-21}$ eV, but 2.1 keV allows $>5\times10^{-22}$ eV.

$m<10^{-18}$ eV → no effect of baryon DM relative vel. → strong constraints from 21cm?

WarmAndFuzzy: on github

arXiv.org > astro-ph > arXiv:1605.05973

Search or Article-id (Help | Advanced search)

All papers Go!

Astrophysics > Cosmology and Nongalactic Astrophysics

WarmAndFuzzy: the halo model beyond CDM

David J. E. Marsh

(Submitted on 19 May 2016)

Cold dark matter (CDM) is a well established paradigm to describe cosmological structure formation, and works extraordinarily well on large, linear, scales. Progressing further in dark matter physics requires being able to understand structure formation in the non-linear regime, both for CDM and its alternatives. This short note describes a calculation, and accompanying code, WarmAndFuzzy, incorporating the popular models of warm and fuzzy dark matter (WDM and FDM) into the standard halo model to compute the non-linear matter power spectrum. The FDM halo model power spectrum has not been computed before. The FDM implementation models ultralight axions and other scalar fields with $m_a \approx 10^{-22}$ eV. The WDM implementation models thermal WDM with mass $m_X \approx 1$ keV. The halo model shows that differences between WDM, FDM, and CDM survive at low redshifts in the quasi-linear and fully non-linear regimes. The code uses analytic transfer functions for the linear power spectrum, modified collapse barriers in the halo mass function, and a modified concentration-mass relationship for the halo density profiles. Modified halo density profiles (for example, cores) are not included, but are under development. Cores are expected to have very minor effects on the power spectrum on observable scales. Applications of this code to the Lyman-α forest flux power spectrum and the cosmic microwave background lensing power spectrum will be discussed in companion papers. \textsc{WarmAndFuzzy} is available online at \url{this https URL}, where collaboration in development is welcomed.

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Bookmark (what is this?)

Direct Detection of ULAs

$$\mathcal{L}_{\rm int} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{\phi N}\partial_\mu\phi(\bar{N}\gamma^\mu\gamma_5 N)$$
$$+g_{\phi e}\partial_\mu\phi(\bar{e}\gamma^\mu\gamma_5 e) - \frac{i}{2}g_d\phi\bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$

$$[g_{\phi\gamma}] = [g_{\phi f}] = M^{-1};\ [g_d] = M^{-2};\ g \propto 1/f_a$$

Nucleon interactions

$$\mathcal{L}_{\text{int}} = \frac{C_G}{f_a}\frac{g_3}{32\pi^2}\phi G\tilde{G} - \sum \frac{C_i}{2f_a}\partial_\mu\phi\bar{\psi}_i\gamma^\mu\gamma_5\psi_i$$

Neutron EDM: $d_n = g_d\phi$

$$g_d^{\text{QCD}} = \frac{2.4\times 10^{-16}}{f_a} e\cdot\text{cm}$$

Crewther et al (1979)

Basis of PQ mechanism.
New constraints on ALPs?

SN1987A:

$$g_{\phi N} \lesssim 8\times 10^{-10}\ \text{GeV}^{-1}$$

e.g. Raffelt (2008)

Spin-dependent forces.

Moody & Wilczek (1984)
Arvanitaki & Geraci (2014)

“Axion wind” nuclear
spin precession.

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Accidental ULAs

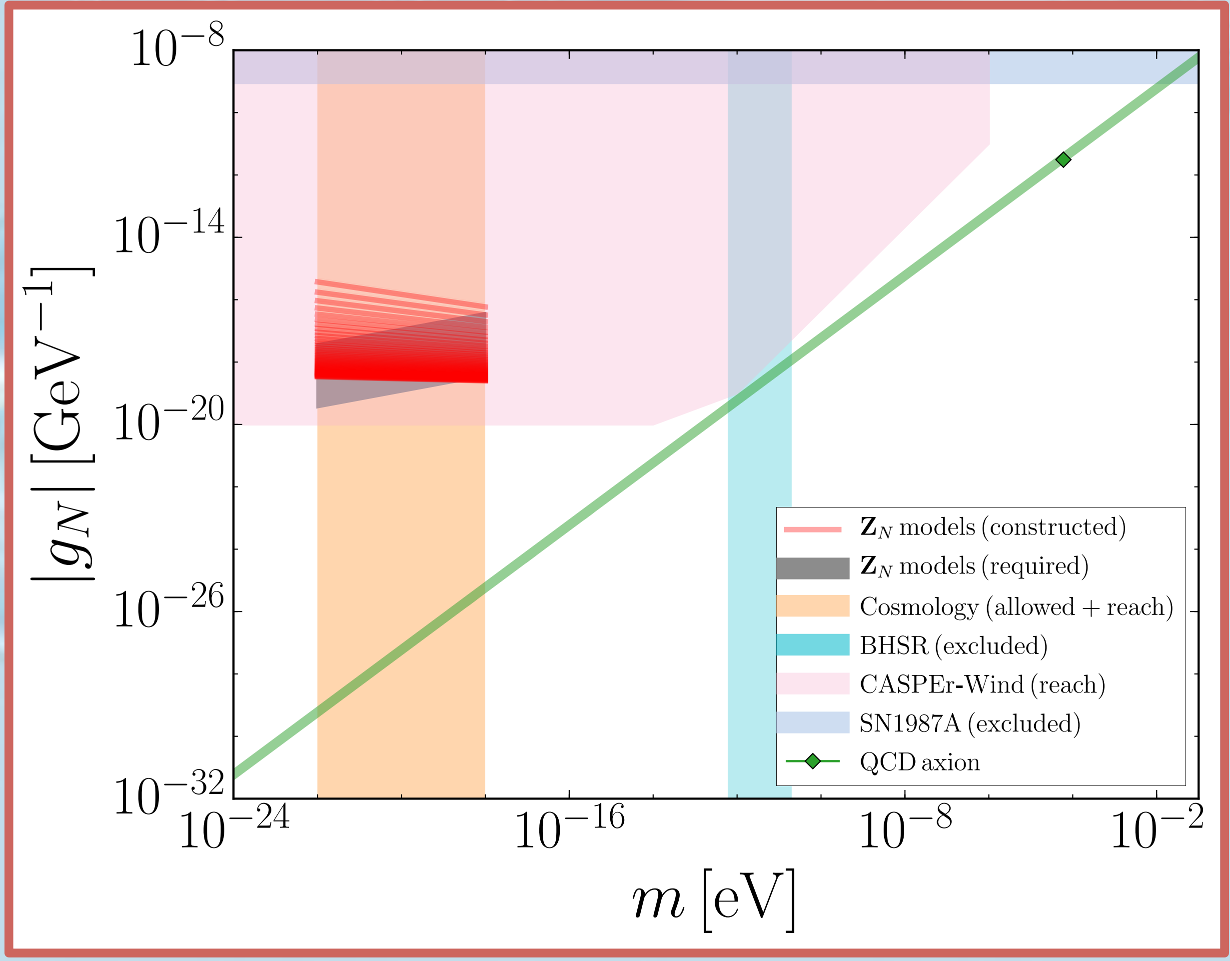
Kim & DJEM (2016)

Two axion model with two-Higgs doublet + fundamental Z_N.
Solves strong-CP, ULA-DM with $f_a \sim 10^{17}$ GeV, $m \sim 10^{-22}$ eV.

$$H_N \supset g_{\phi N} m_a a_a \cos(m_a t) \vec{v} \cdot \vec{\sigma}_N$$

Nucleon coupling:
$g_N \sim 1/f_a$

Detect via “axion-wind” effect in CASPEr?
Problem: extrapolation to ELF sensititvity.



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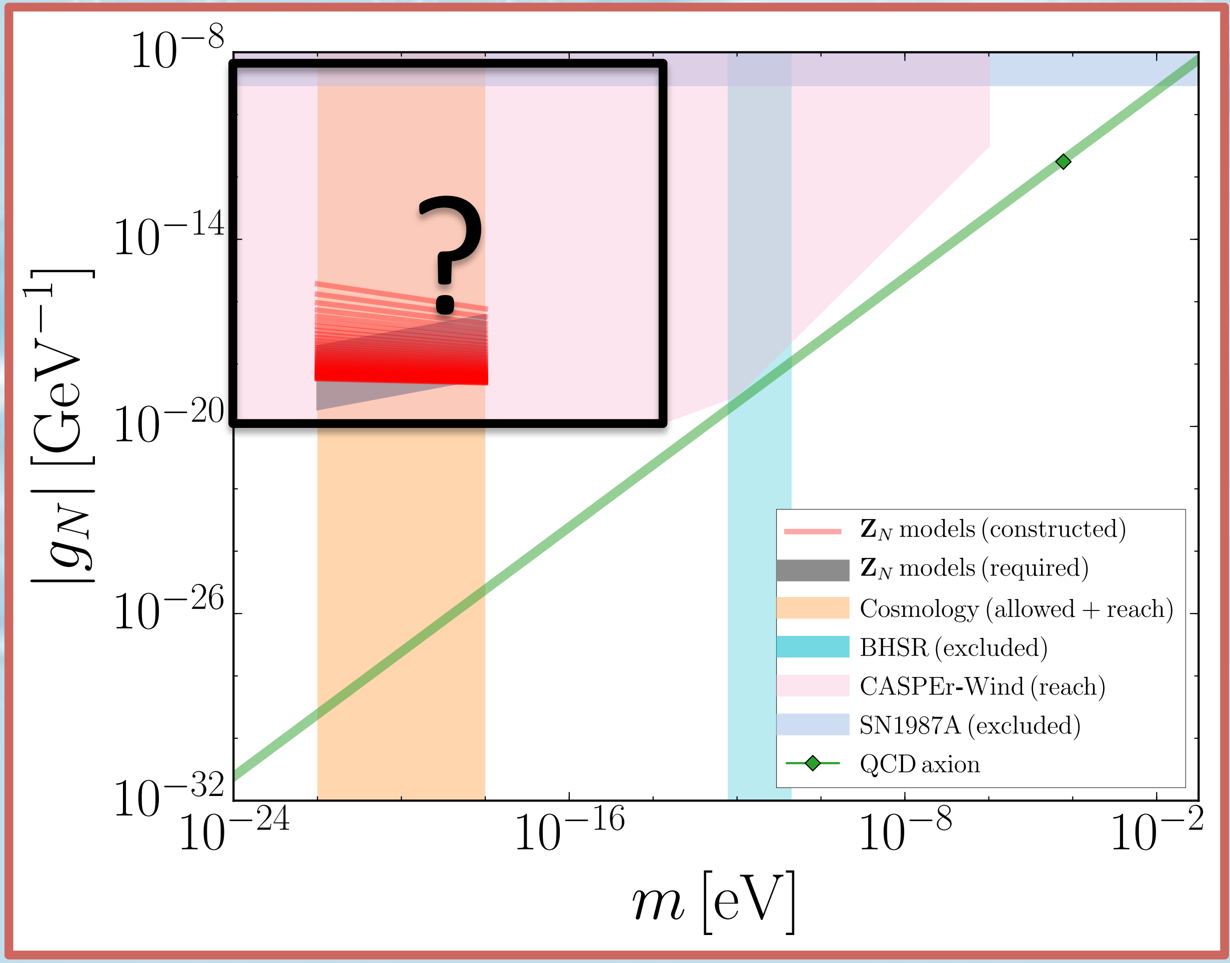


A New Search Using nEDM Experiments

In prep with:
Theory: Fairbairn, Flambaum, Stadnik
Experiment: Harris, Ayres, Rawlik et al

The Neutron EDM Experiment

Review: Harris (2007)
Baker et al (2006)
Pendlebury et al (2015)

nEDM at Sussex/RAL/ILL has current best *static* limit:

$$|d_n^{\text{static}}| \leq 3.0 \times 10^{-26}\, e \cdot \text{cm} \quad (90\%\ \text{C.L.})$$

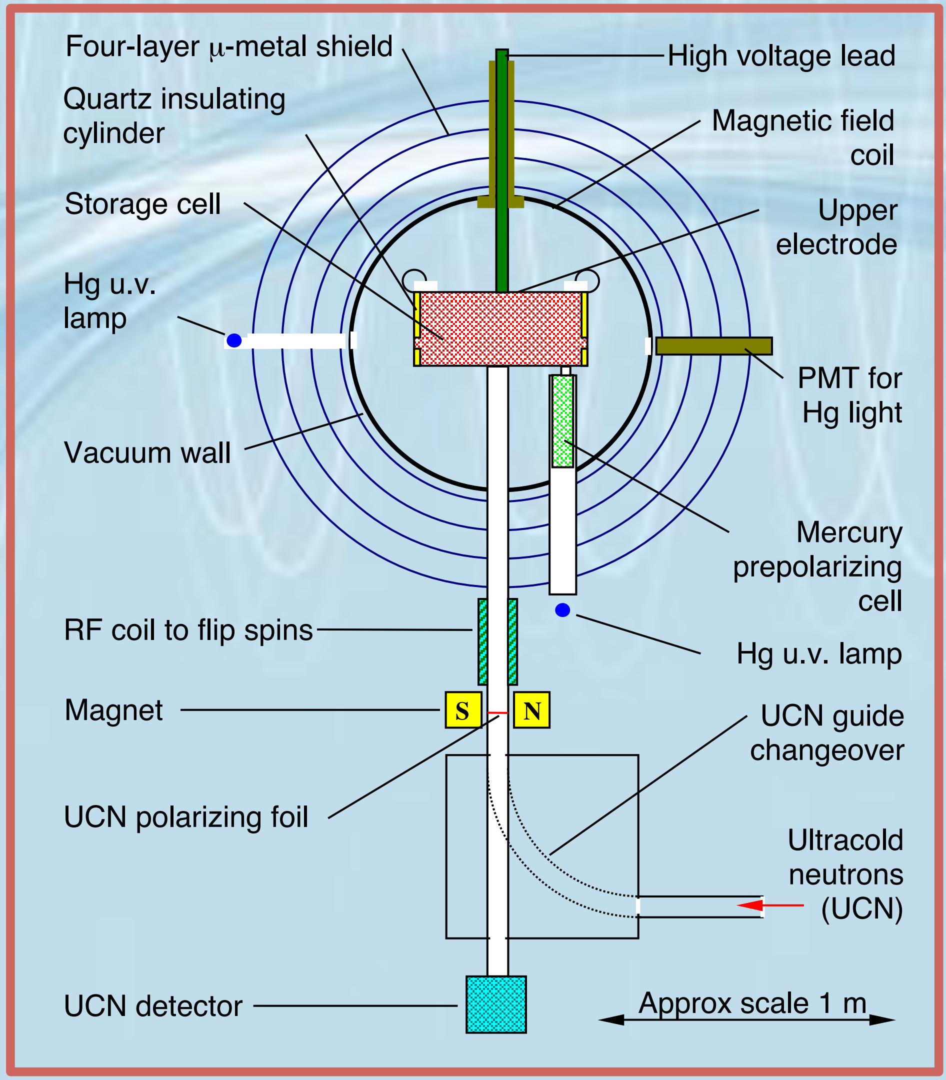
$$h\nu = 2\mu_n B + 2d_n E$$

✧ Ran for ~ 4 years until 2002.
✧ Cycles ~130s, E-flips hourly
✧ Runs ~ 1 day.

$$m_a \approx 10^{-23\to17}\ \text{eV}$$

✧ Use ratio n/Hg.
✧ E=10 kV/cm, B=μ T
✧ Sensitivity to energy shifts:

$$\Delta E \approx 10^{-21}\ \text{eV}$$



New Analysis of nEDM

Nick Ayres (Sussex): ILL data, run-by-run EDM, long time.
Michal Rawlik (PSI): PSI data, cycle-by-cycle, short time.

$$R = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right| + \Delta_{\mathrm{wind}} + \frac{(d_n + |\gamma_n/\gamma_{\mathrm{Hg}}|d_{\mathrm{Hg}})}{\nu_{\mathrm{Hg}}}E$$

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underway

g_d coupling: oscillating signal (cycles or runs)

For m^{-1} > run time, ILL run limit ~10 x worse than best limit:

$$g_d \sim 10^{-22}\ {\rm GeV}^{-2} \left(\frac{m_a}{10^{-22}{\rm eV}}\right)$$

Compete with CASPEr @ low m.
Planck coupled? Fine tuned?

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proposed

Axion wind: oscillating intercept (cycle by cycle).

Energy shift ~ psuedo B-field @ 0.1 x best limit.

$$g_{\phi N} \sim 10^{-8}\ \mathrm{GeV}^{-1}$$

Beats direct force by ~10^2
Improve w/ astro signature?

underway

g_d coupling: oscillating signal (cycles or runs)

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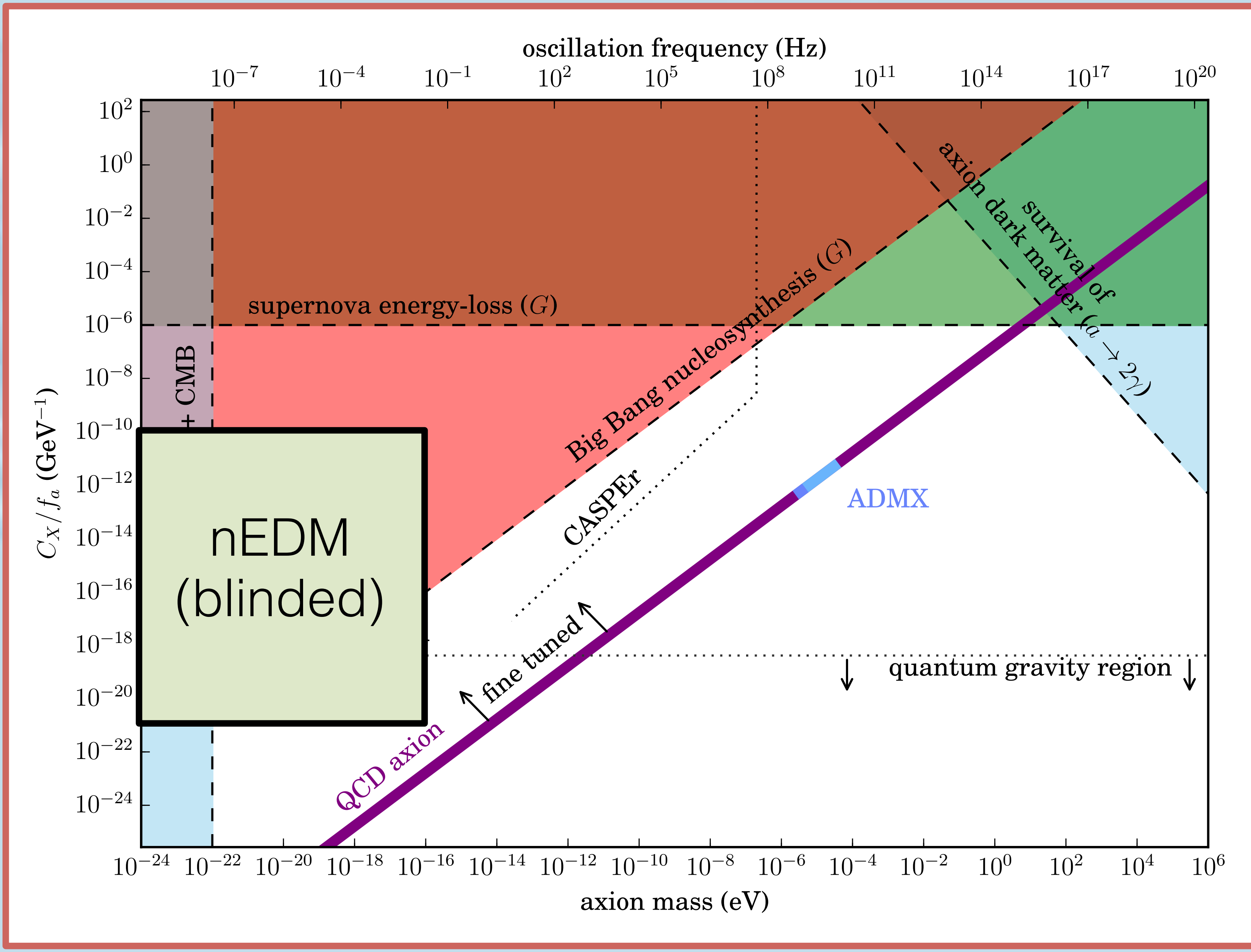
New Analysis of nEDM

Figure: Michal Rawlik for nEDM



Summary

- ✧ ULAs affect the growth of structure and CMB.
- ✧ Percent level constraints over orders of magnitude.
- ✧ CMB-S4 test one component paradigm at 3σ.
- ✧ Small scales push lower bound on DM mass.
- ✧ Direct detection through neutron interactions?

Thank You!

Questions?

Backup Slides

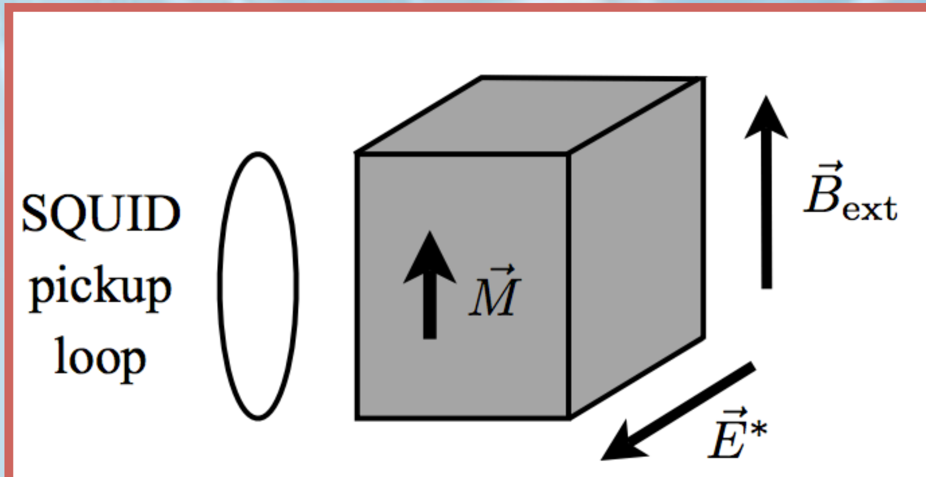
CASPEr and NMR

Graham & Rajendran (2013)
Budker et al (2014)

Align nuclear spins. Precess at Larmour frequency.
Dipole moment and axial current g's → additional precession.
Resonant enhancement for $2\mu_m B_{\text{ext}} = m_a$ (not size!)

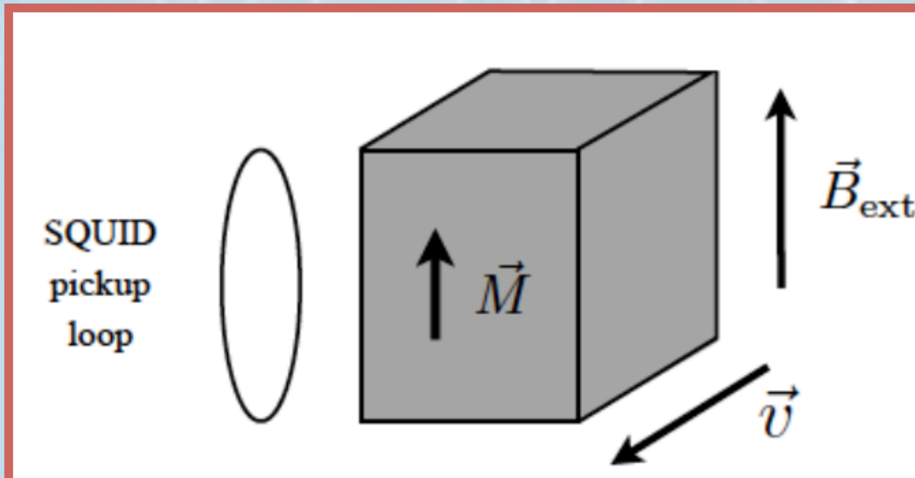
CASPEr-Electric

$$d_n = g_d(\sqrt{2\rho_a}/m_a)\cos(m_a t)$$



CASPEr-Wind

$$H_N \supset g_{\phi N} m_a a_a \cos(m_a t)\vec{v}\cdot\vec{\sigma}_N$$

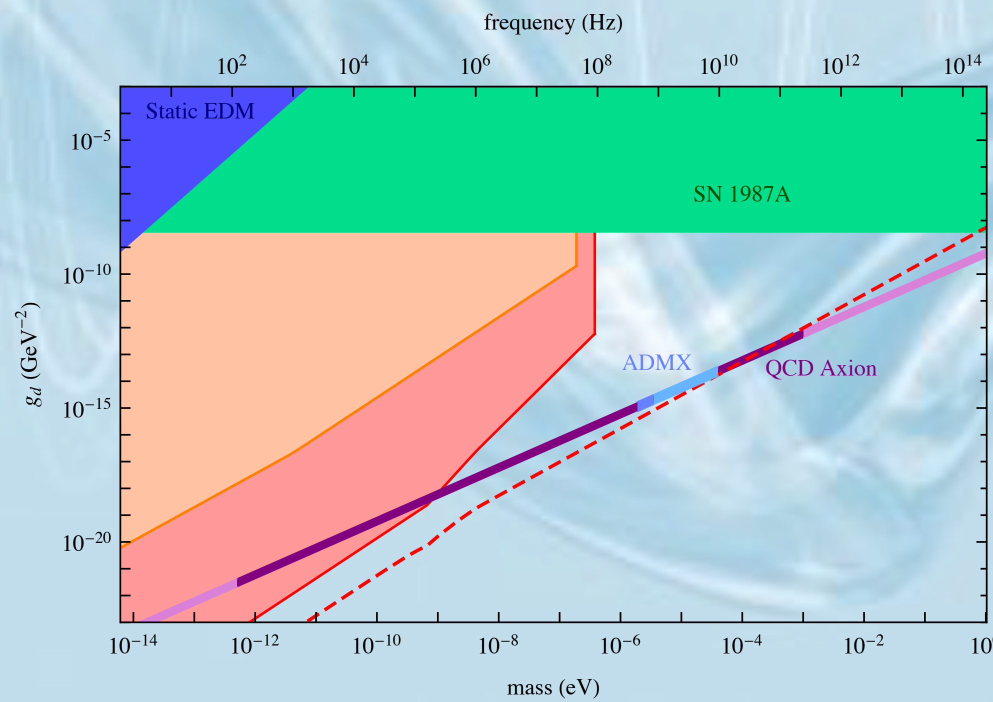


CASPEr and NMR

Graham & Rajendran (2013)
Budker et al (2014)

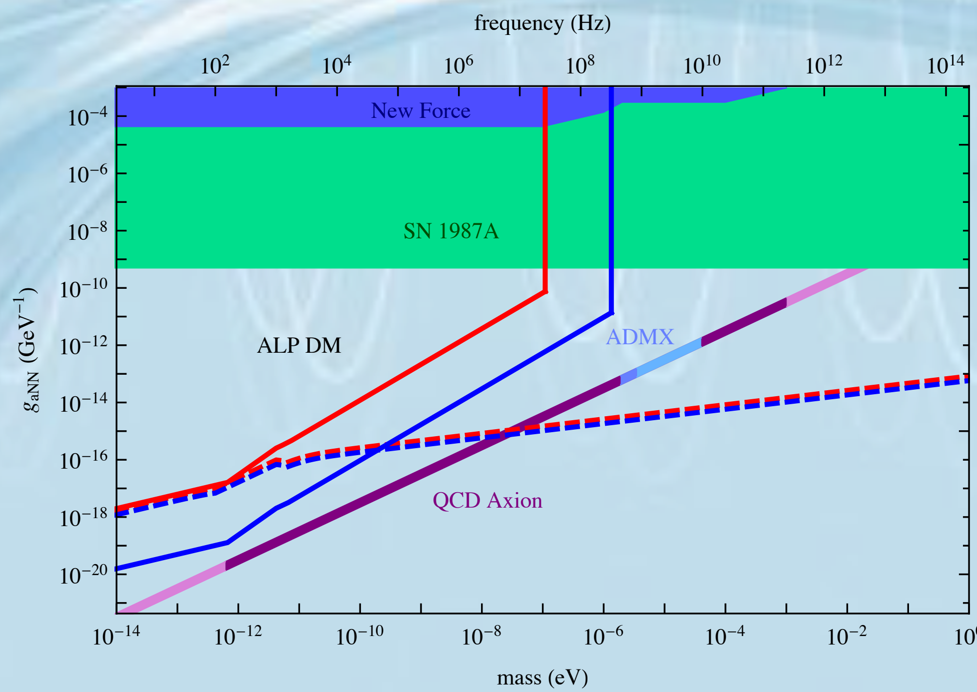
Align nuclear spins. Precess at Larmour frequency.
Dipole moment and axial current g's → additional precession.
Resonant enhancement for $2\mu_m B_{\text{ext}} = m_a$ (not size!)

CASPEr-Electric



Models above QCD line are fine tuned. Static EDM?

CASPEr-Wind



No fine tuning of probed parameter space. ELF?

ALPs in string theory

e.g. Witten (1984)
Svrcek & Witten (2006)
Arvanitaki et al (2010)

In the SUGRA approximaiton, there are p-form fields in 10d

$$S \supset -\frac{1}{2}\int F_{p+1}\wedge\star F_{p+1} = -\frac{1}{2(p+1)!}\int d^D x\sqrt{-g_D}F_{\mu_1\cdots\mu_{p+1}}F^{\mu_1\cdots\mu_{p+1}}$$

Field is p-form potential as F=dA (like in electromagnetism)
Compactify, and take homogeneous and isotropic 3+1 dims:

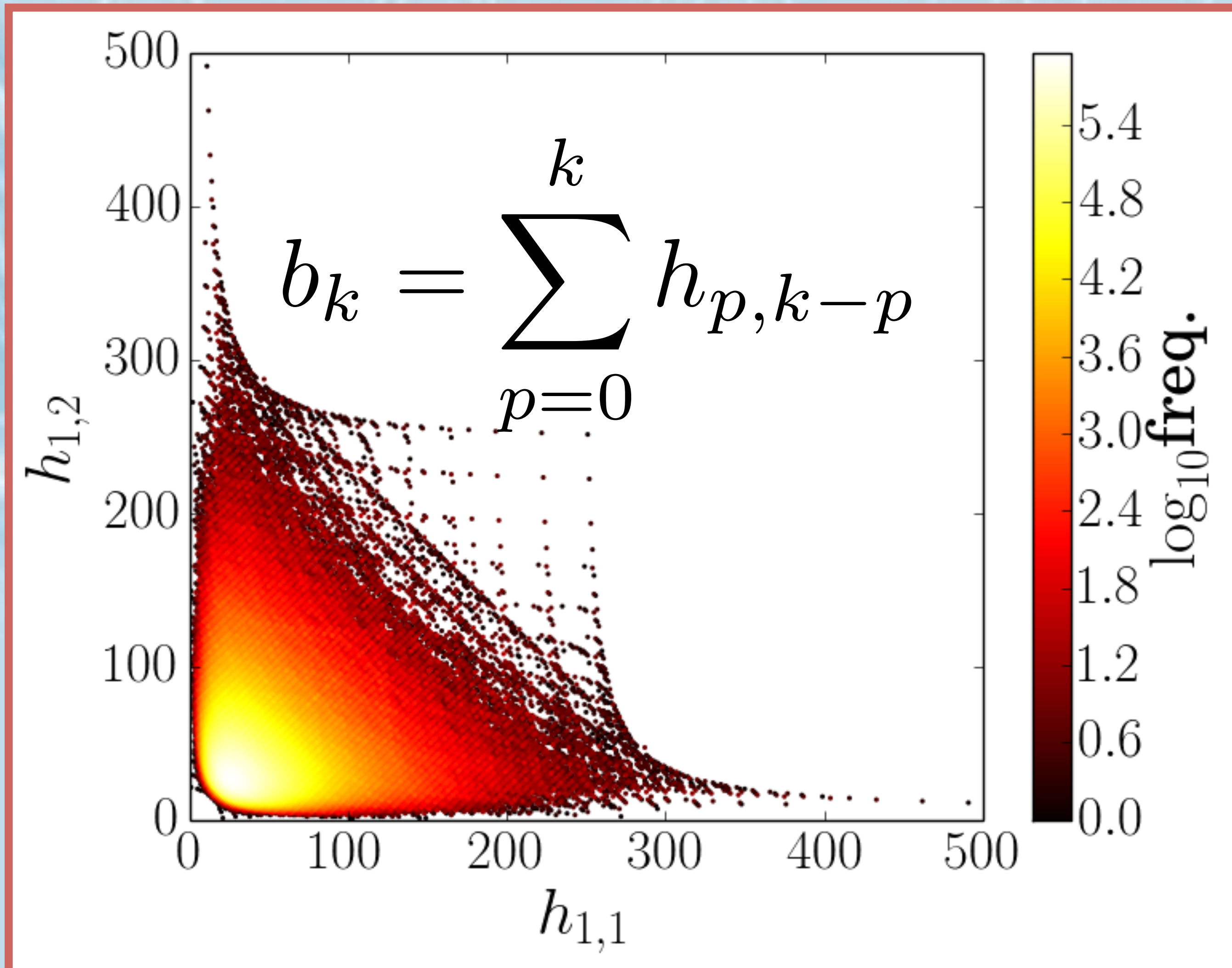
$$A_p = \frac{1}{2\pi}\sum a_i(x)\omega_{p,i}(y) \Rightarrow a_i = \int_{C_{p,i}} A_p$$

ω fields are harmonic basis of the compact space.
Gauge invariance of F → a fields have a shift symmetry.
Sum extends over all p-cycles, i.e. pth Betti # → # of axions.

Calabi-Yau manifolds

Candelas et al (1985)
Data: Kreuzer & Skarke (2002)
Review: Y-H. He (2013)

Betti numbers, and hence number of axions, determined by topology. Calabi-Yau → just two Hodge numbers.



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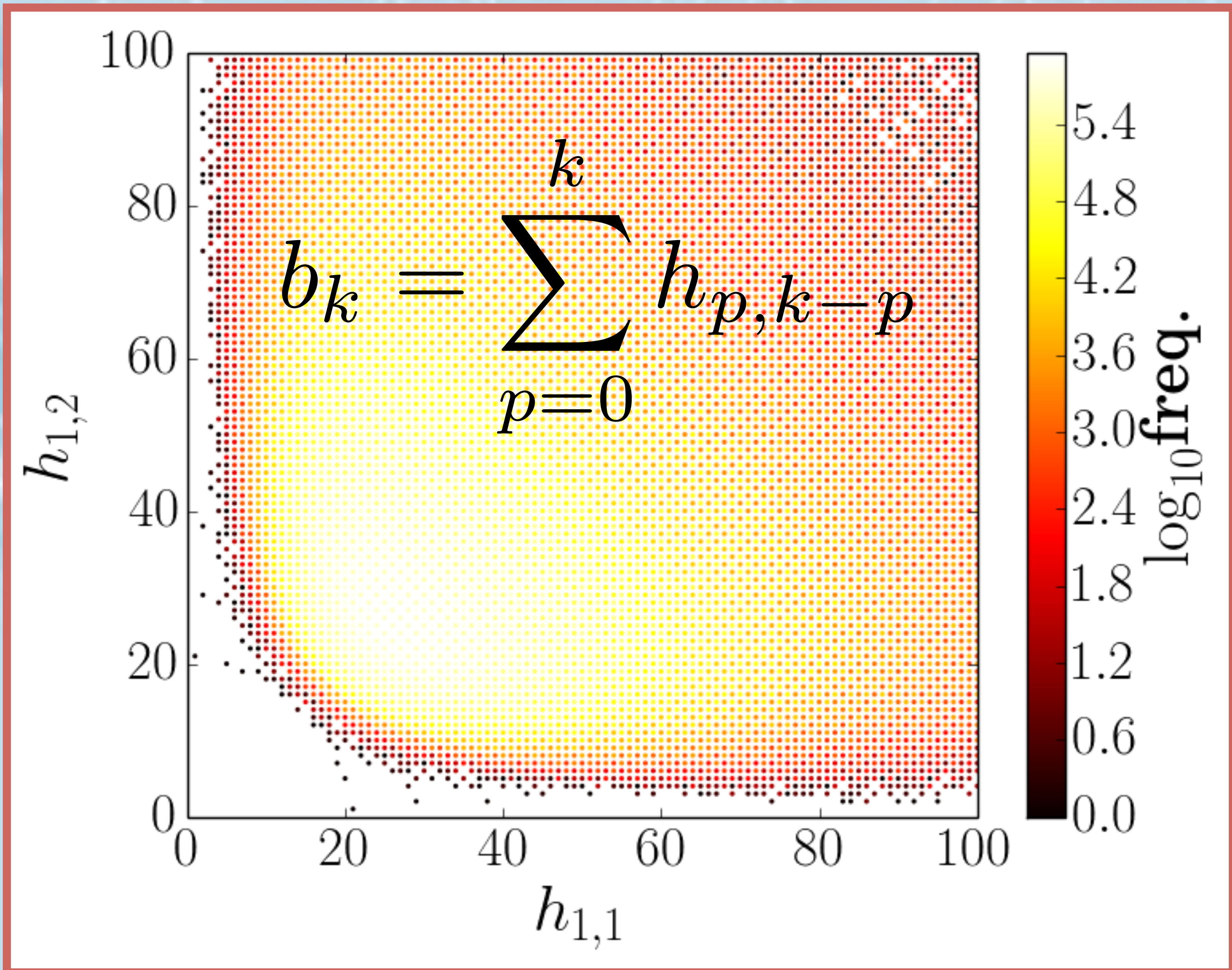

Type-IIB example

Basics e.g. Ringwald (2012)
Explicit model, e.g. Cicoli et al (2012)
M-theory: Acharya et al (2010)

Take C_4 form on 4-cycles. $b_4 = h_{1,1} \sim 30$

$$S \supset -\frac{1}{8}\int \mathrm{d}a_i \mathcal{K}_{ij} \wedge \star \mathrm{d}a_j$$

Decay constants?

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Canonically normalise: $\mathcal{L}_{\mathrm{kin.}} = -f_{a,i}^2 (\partial a_i)^2 / 2$

$$\mathcal{K}_{ij} = \frac{\partial^2 K}{\partial \sigma_i \partial \sigma_j} \Rightarrow f_a \sim \frac{M_{pl}}{\sigma_i}$$

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Masses?

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Potential from D7 branes gauge group wrapping cycle:

$$\Lambda_a \propto e^{-S_{\mathrm{inst.}}} \sim e^{-1/g^2};\ g^2 \propto \frac{1}{\sigma_i} \Rightarrow m_{a,i} \sim \frac{e^{-\#\sigma_i}}{f_a}$$

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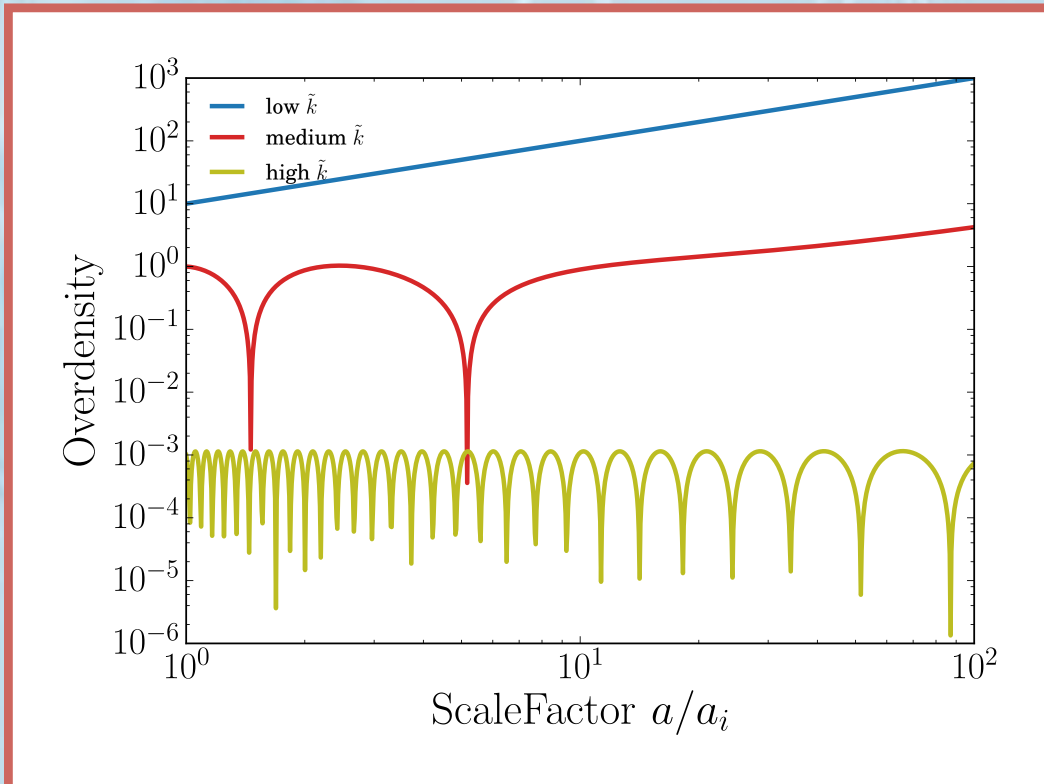
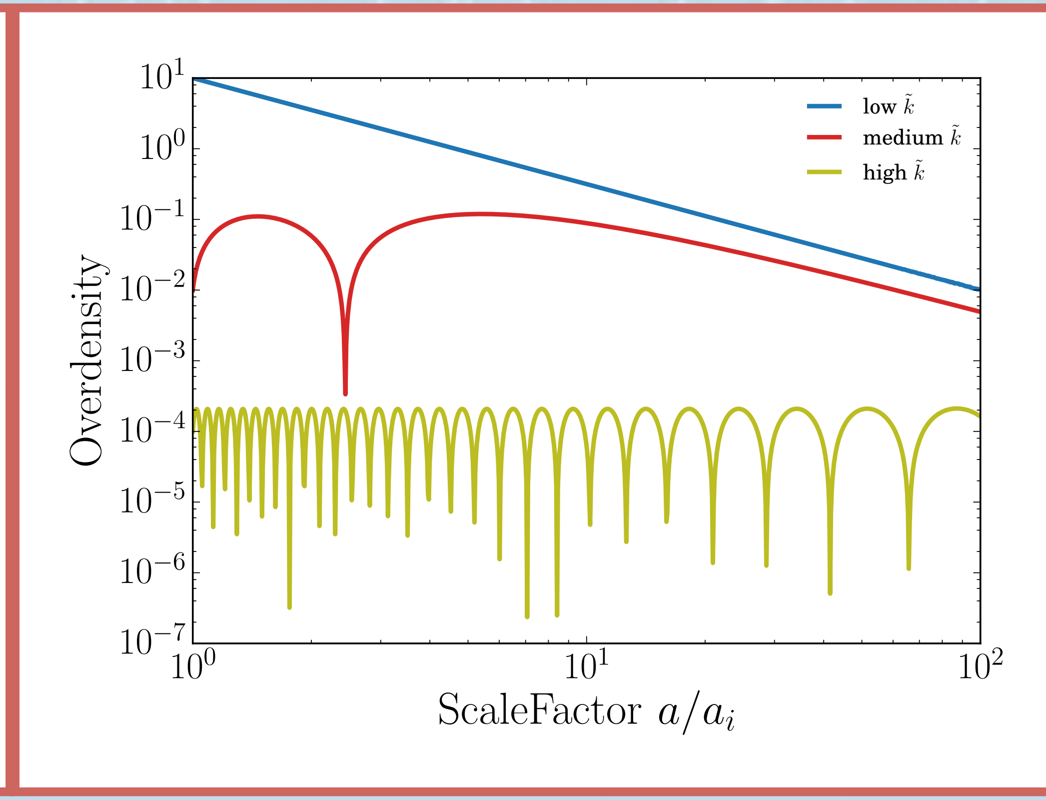
The ULA Jeans scale

DJEM (2015)

Exact solution from sound speed and Jeans eqn.:





Growing mode
$k<k_J$ → $D \sim a$

Decaying mode
$k<k_J$ → $D \sim a^{-3/2}$

→ ULAs suppress structure formation on small scales.

ULAs Outperform Warm DM

DJEM & Silk (2013)
DJEM & Pop (2015)

WDM is a classic solution to small-scale crises. e.g. Bode et al (2001)

Cut-off from thermal velocities, cores from Pauli exclusion.

Tremaine & Gunn (1979)

ULAs Outperform Warm DM

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Successful resolution to missing-satellites and TBTF:

$$1.5 \text{ keV} \lesssim m_W \lesssim 2.3 \text{ keV}$$

Lovell et al (2014)

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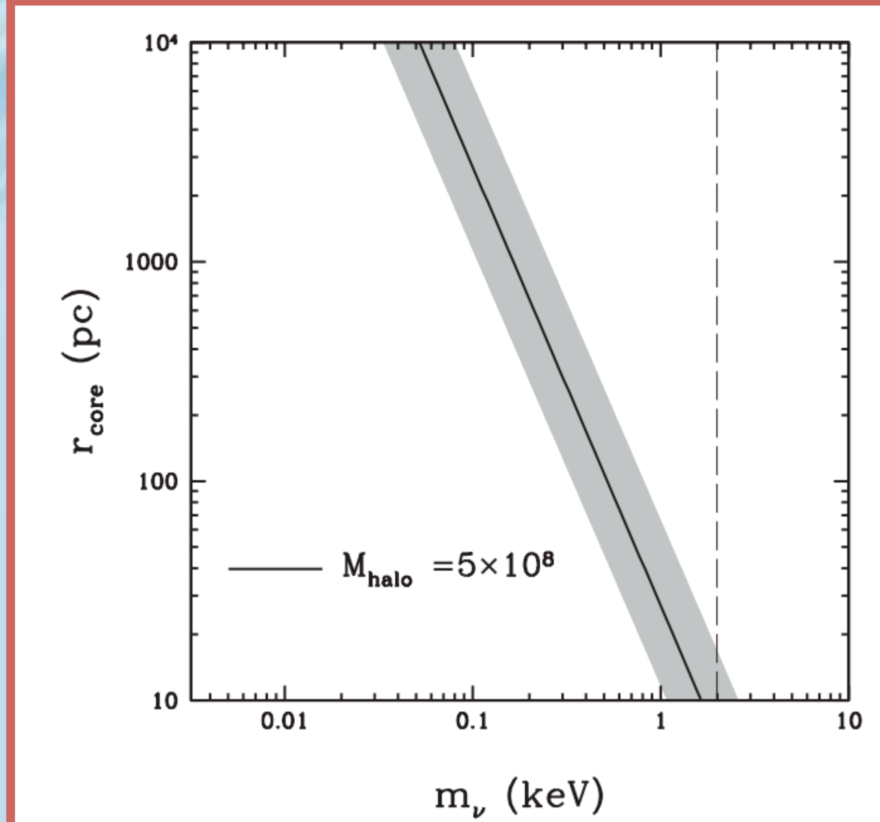
Lovell et al (2014)

Roughly consistent with LSS, but provides only tiny cores:

WDM suffers from a “Catch 22” and cannot solve all small-scale crises. Maccio et al (2012)

ULAs appear to avoid this due to diff core-size/cut-off relationship.
… *but more work needed!*

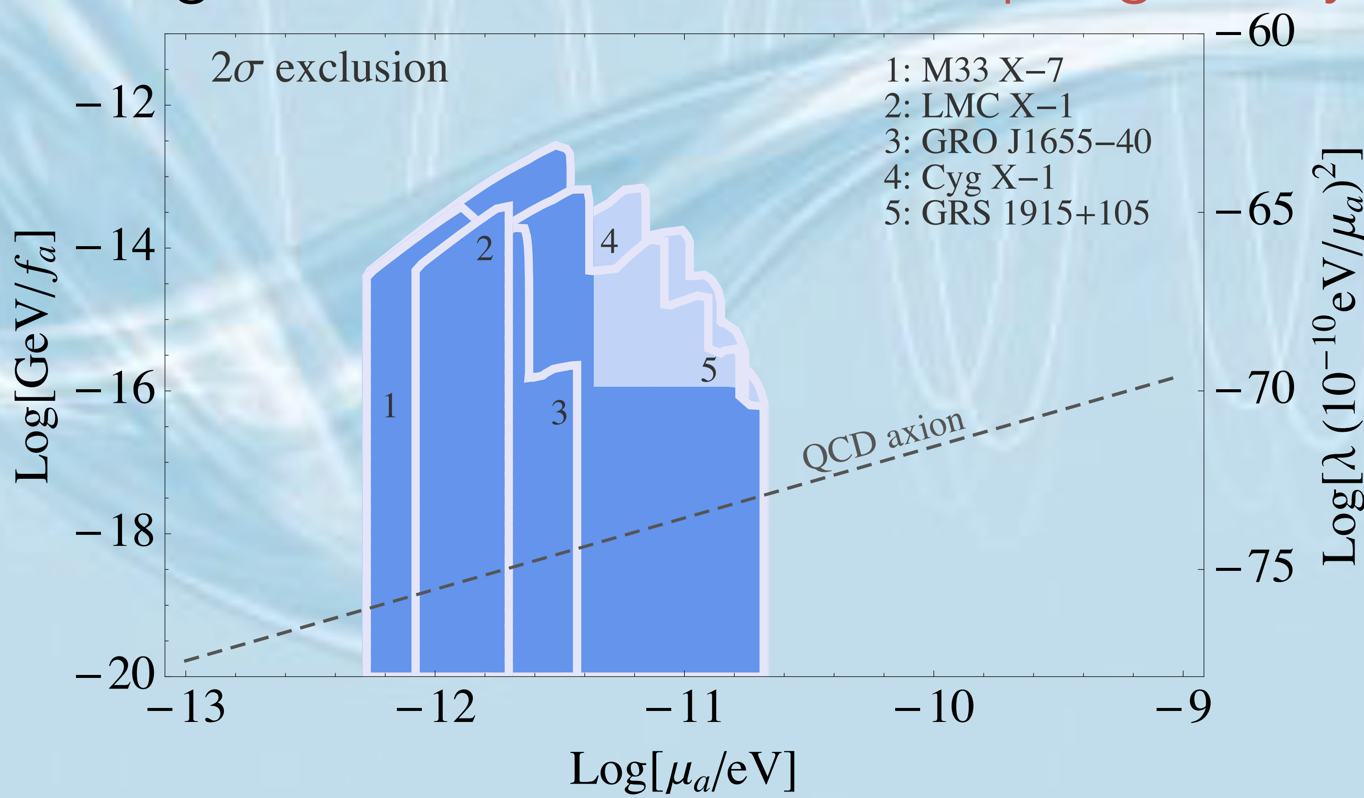


Black Hole Superradiance

e.g. Brito et al (2015)
Results: Arvanitaki et al (2015)

"Gravitational atom" with coupling $\alpha_G = G_N M m_a$
Spins down BHs by Penrose process. Emit GWs (eLISA?)
"cloud" size λ_{dB} → lighter axions spin down massive BHs.
Major advantage: no need for DM or couplings! Any boson!

Solar mass



$$3 \times 10^{17}\ \text{GeV} < f_{\text{QCD}} < 1 \times 10^{19}\ \text{GeV}$$

Black Hole Superradiance

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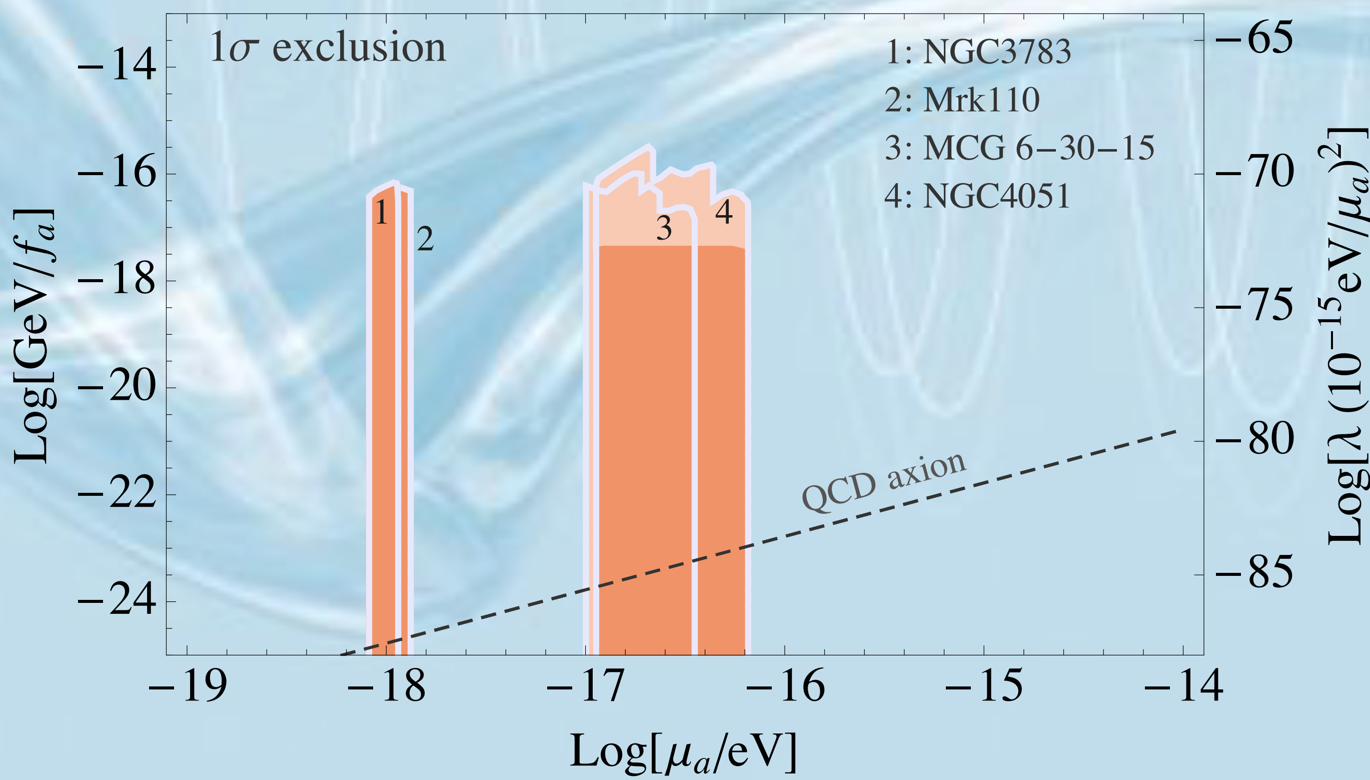
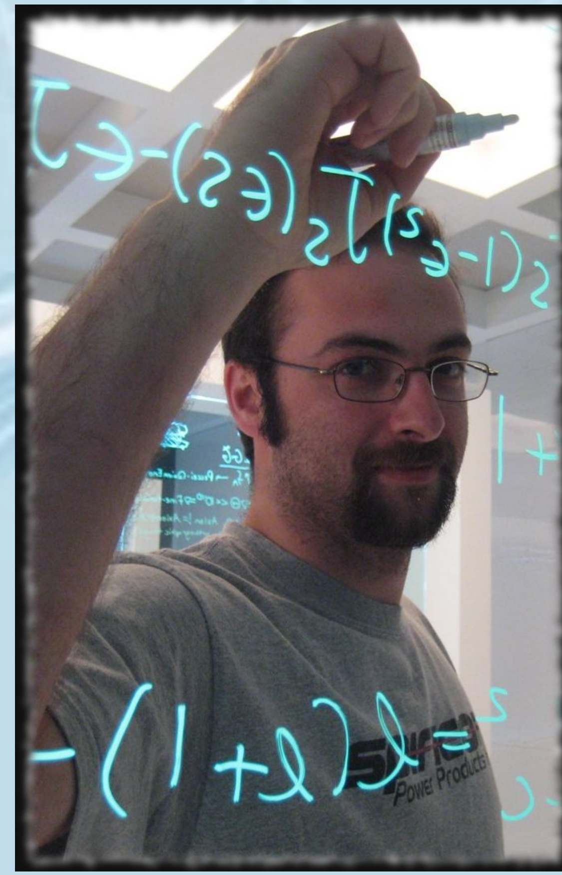
SMBH



Make contact to possible reach of 21cm and reionization.

axionCAMB

Hlozek et al (2015)



axionCAMB

Hlozek et al (2015)

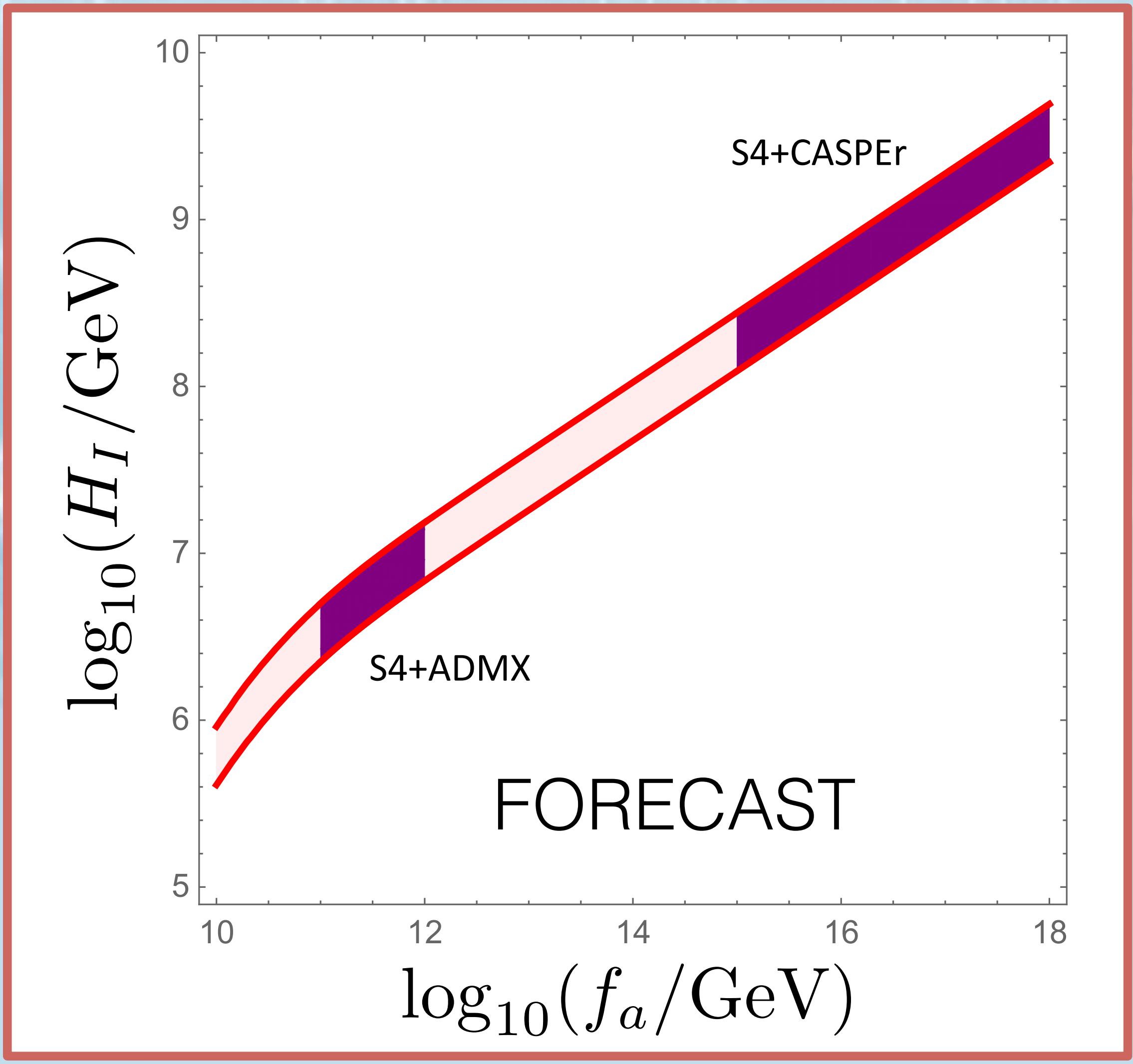
- Builds on standard CAMB architecture. Lewis et al (2000)
- Background and perturbed KG equations implemented.
- WKB approximation for H>m allows for wide dynamic range.
- Relic density found by shooting method on realignment.
- Adiabatic and isocurvature initial conditions possible.
- Axions can replace CDM, DE, or be partial contribution.
- Computes all standard cosmological observables.
- NEW: curvature and neutrino degeneracies explored.
- NEW: lensing analysis underway.
- NEW: isocurvature and B-modes analysis underway.
- NEW: fully implemented as CosmoSIS module for release.

Zuntz et al (2014)

In prep w/ Hlozek, Grin +

Isocurvature and inflation

Isocurvature with CMB-S4 + direct detection → measure low scale inflation w/ QCD axion.



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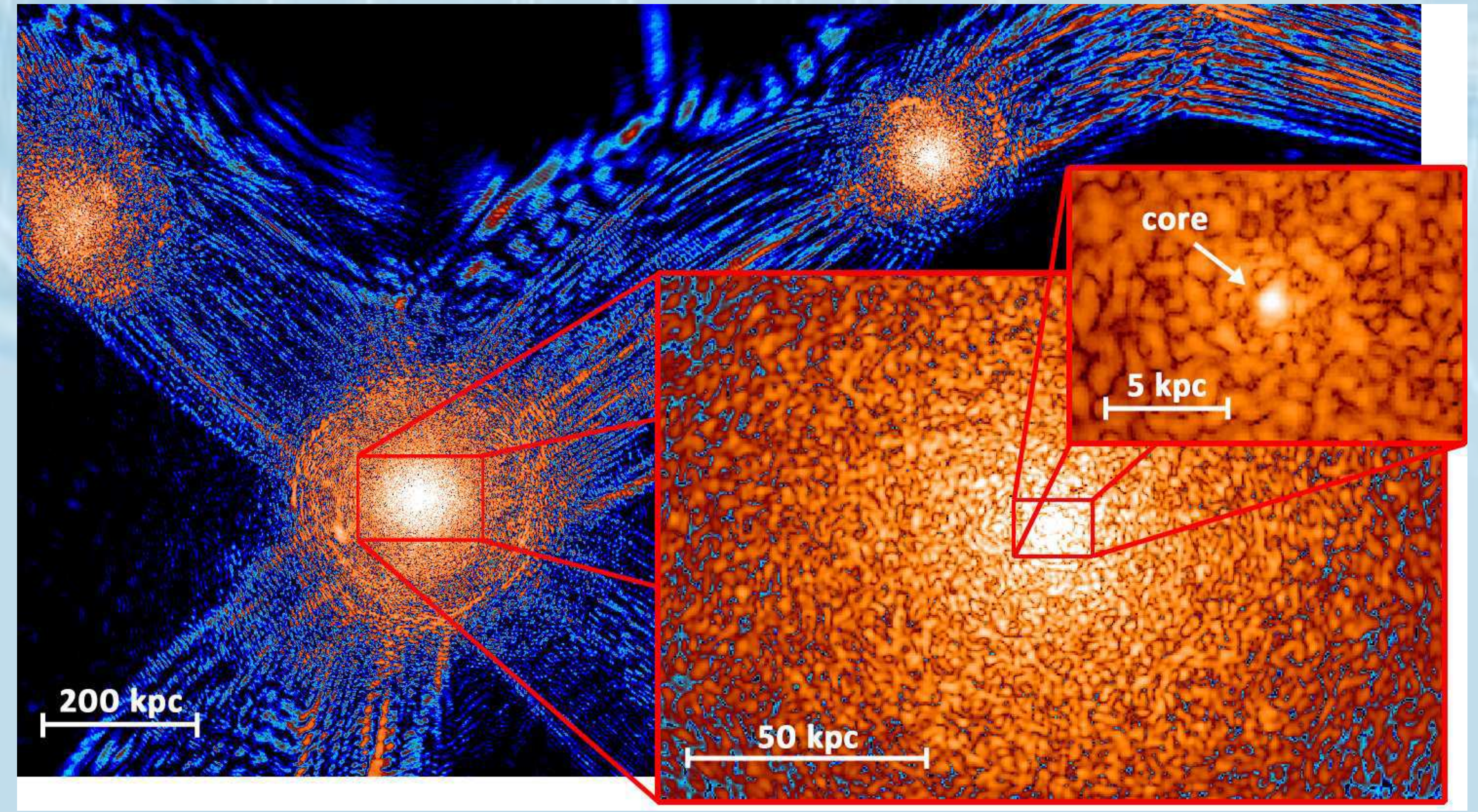
nature physics

Cosmic structure as the quantum interference of a coherent dark wave

Hsi-Yu Schive[1], Tzihong Chiueh[1,2]* and Tom Broadhurst[3,4]



The Axion Condensate

e.g. Ruffini & Bonnazola (1969)
Widrow & Kaiser (1993)
Davidson (2013), Guth et al (2014)

Non-relativistic: Klein-Gordon-Einstein → Schrödinger-Poisson.

$$i\partial_t \psi = -\frac{1}{2m_a}\nabla^2\psi + m_a V\psi$$

$$\nabla^2 V = 4\pi G|\psi|^2$$

- ψ= osc. averaged axion field.
- EOM has stable, localized "oscillaton" solutions:

$$\psi(t,r) = \chi(r)e^{-i\gamma t}$$