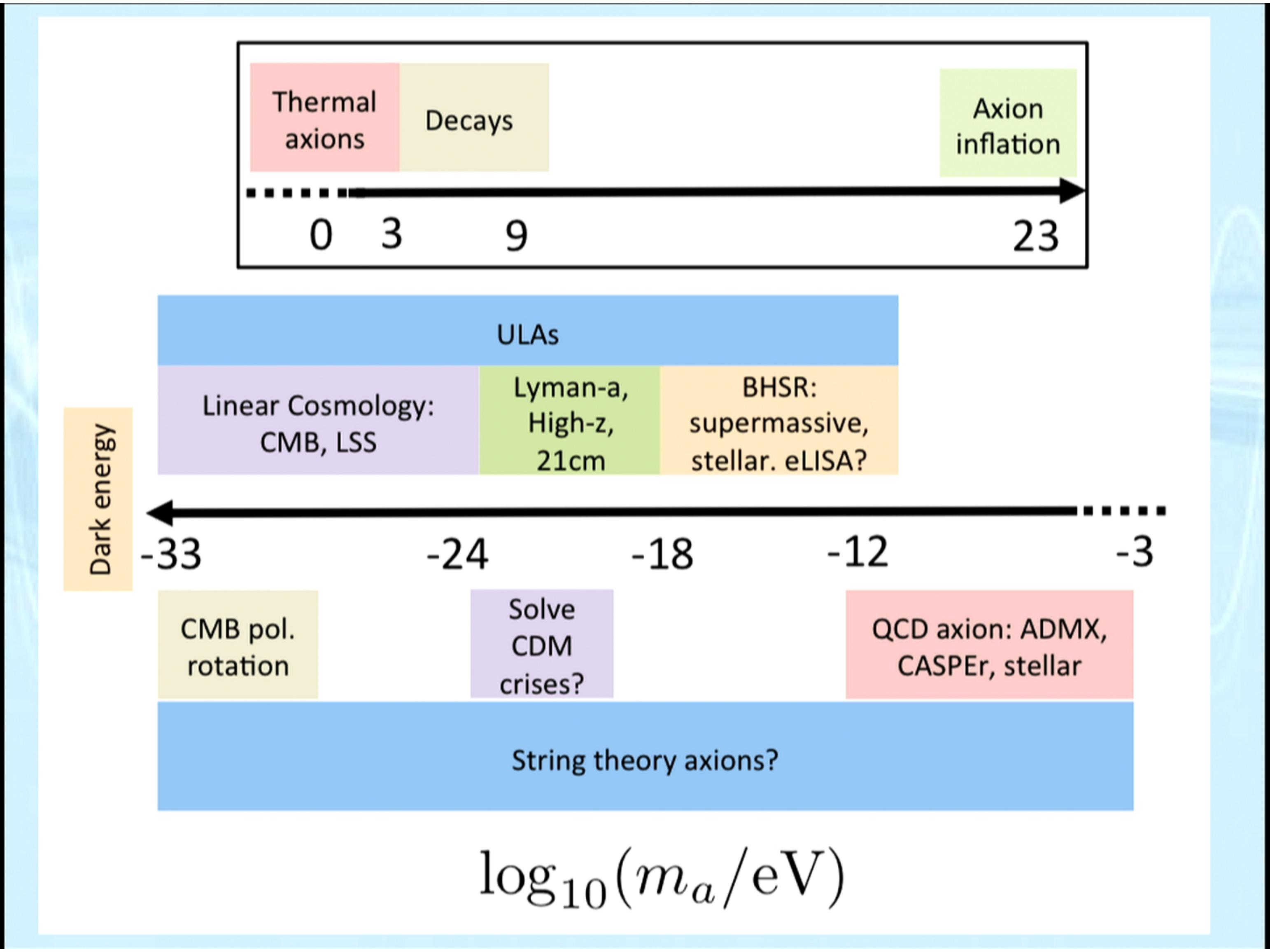
Title: Ultralight Axions

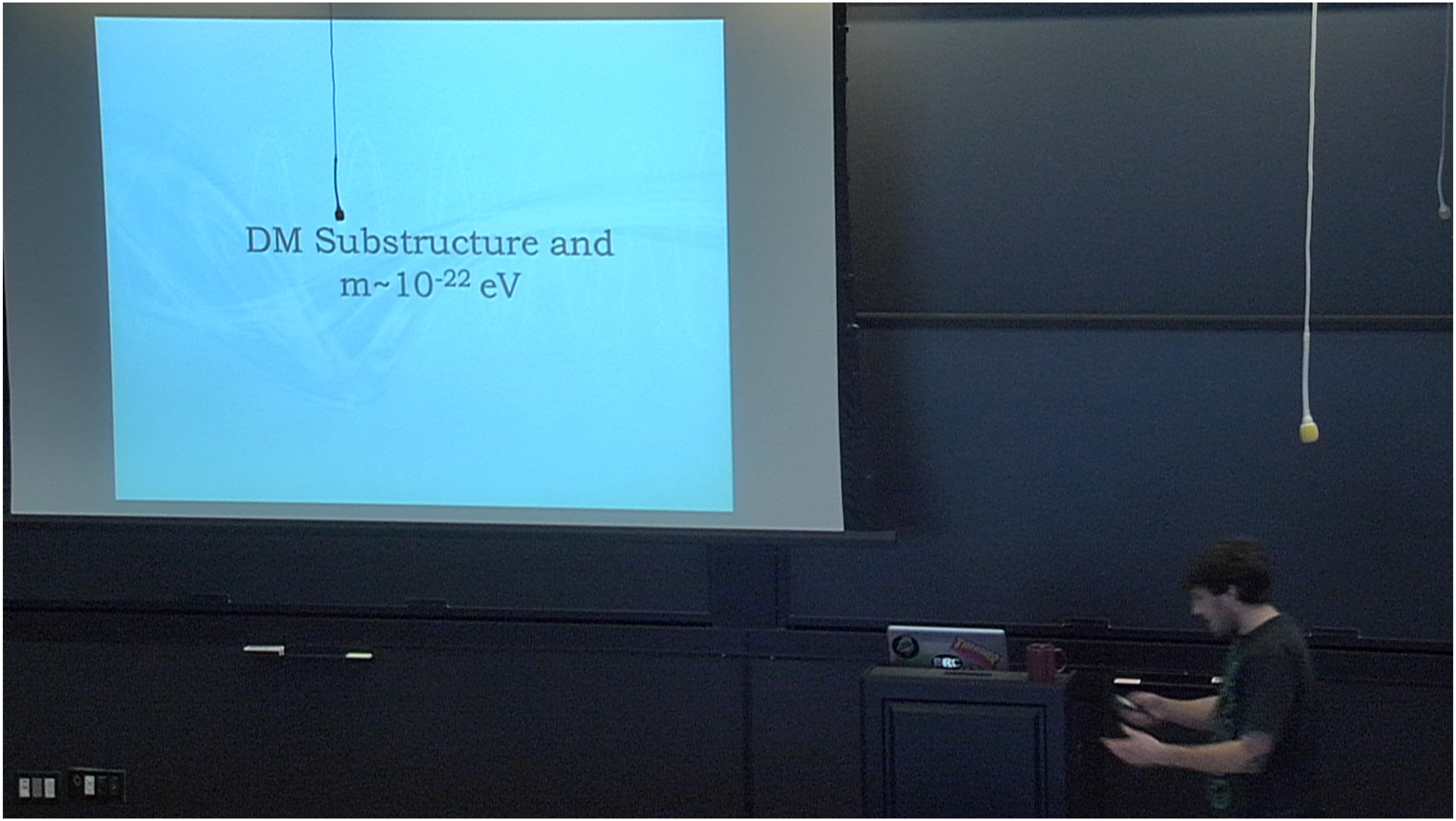
Date: Mar 01, 2016 01:00 PM

URL: http://pirsa.org/16030086

Abstract: <p>Axions, having a perturbative shift symmetry, can have masses much smaller than other types of particles in a technically natural way. Ultralight axions (ULAs) with m~10^{-22} eV are attractive dark matter candidates with novel properties that distinguish them from cold dark matter (CDM). A single ULA with a GUT scale decay constant provides the correct relic density without fine-tuning. Quantum gravitational effects are expected to break continuous global symmetries, and may spoil the axion potential. However, if the axion global symmetry is an accidental symmetry descending from an exact discrete symmetry, then the problematic higher dimensional operators can be forbidden to very high order. I will discuss the astrophysical and cosmological phenomenology of ULAs that makes them attractive, and methods to distinguish them from CDM observationally. I will also discuss a two-axion model which solves the strong CP problem and in addition possesses a ULA that may be detectable via ~month period nuclear spin precession in an experiment such as CASPEr-Wind. Given time, I may discuss other experimental searches for axion-like particles.</p>



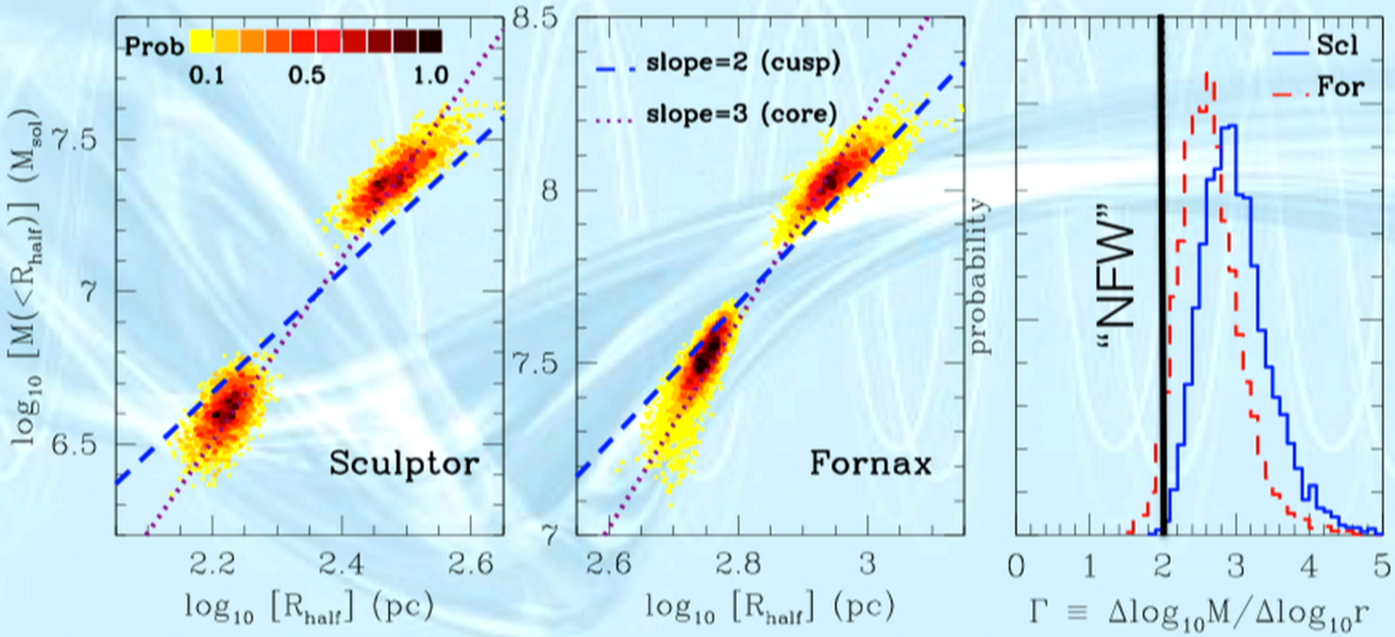
Thermal axions
Decays
Axion inflation
0
3
9
23
ULAs
Linear Cosmology: CMB, LSS
Lyman-a, High-z, 21cm
BHSR: supermassive, stellar. eLISA?
Dark energy
-33
-24
-18
-12
-3
CMB pol. rotation
Solve CDM crises?
QCD axion: ADMX, CASPEr, stellar
String theory axions?
$\log_{10}(m_a/\mathrm{eV})$


DM Substructure and
m~10-22 eV

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

Cusp-Core Problem in dSphs (?)

Example: Walker & Penarrubia (2011) measure slopes.



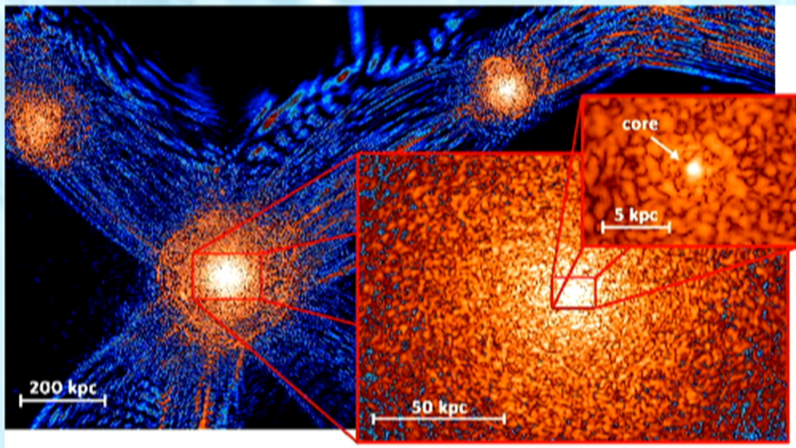
Velocity dispersion at half-light measures enclosed mass.
Two pops. in Fornax+Sculptor → constrain slope of DM halo.
Observe "cores" not "cusps:" "excludes NFW" at >99% C.L.

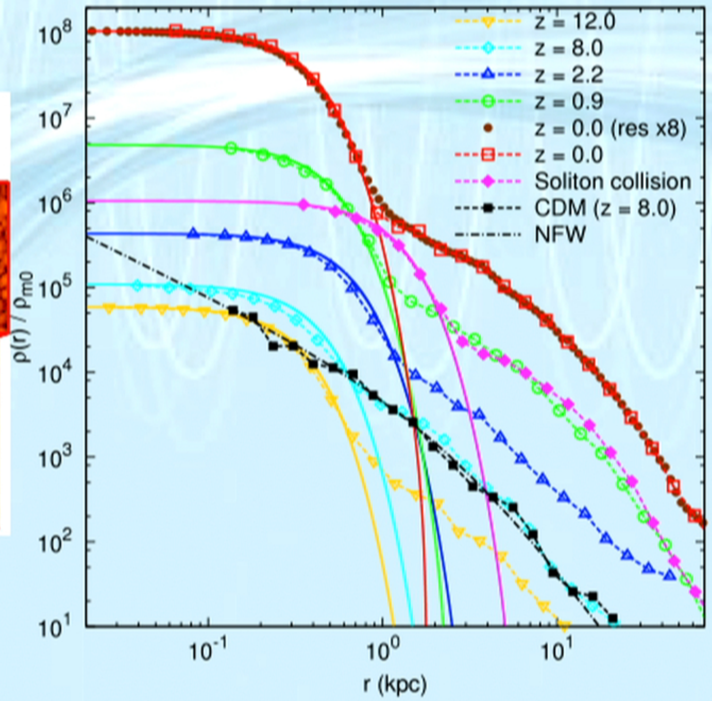
LETTERS
PUBLISHED ONLINE: 22 JUNE 2014 | DOI: 10.1038/NPHYS2996

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]





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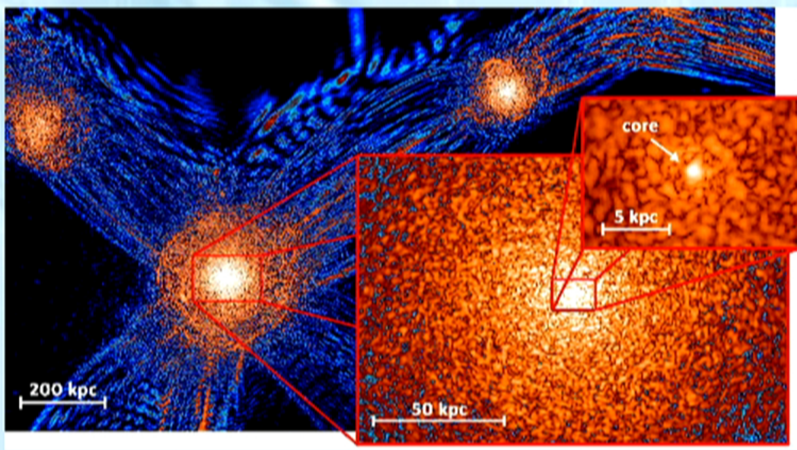
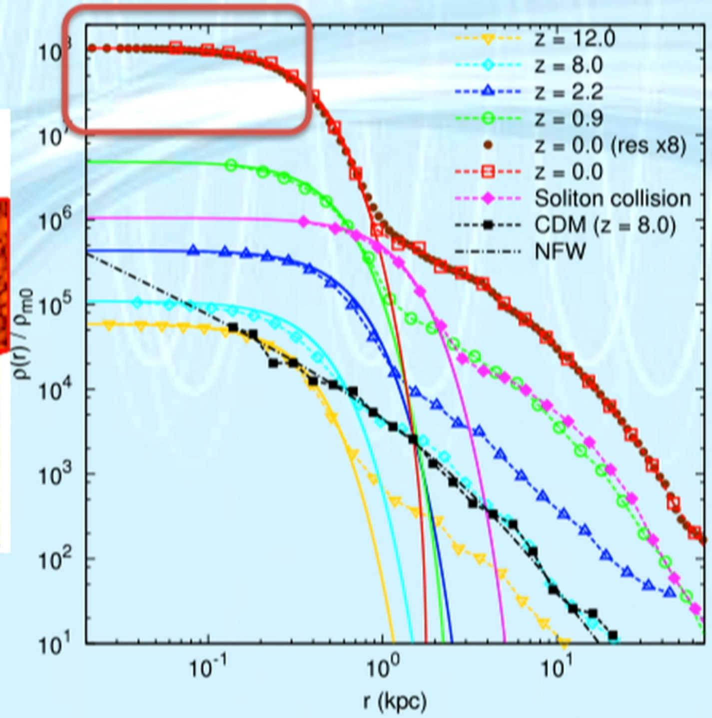


CORE



★ FIELD GRADIENT ENERGY

The Axion Condensate

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

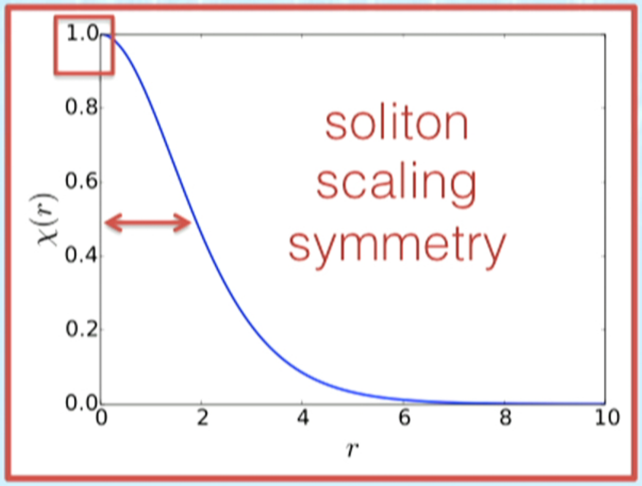
Non-relativistic: Klein-Gordon-Einstein → Schrödinger-Poisson.

$$i\partial_t \psi = -\frac{1}{2m_a}\nabla^2\psi + m_a V\psi$$
$$\nabla^2 V = 4\pi G|\psi|^2$$

- Classical field → quantum particles (large N occupation).
- ψ= osc. averaged axion field.
- EOM has stable, localized "oscillaton" solutions:

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

- Size ~ linear Jeans scale.



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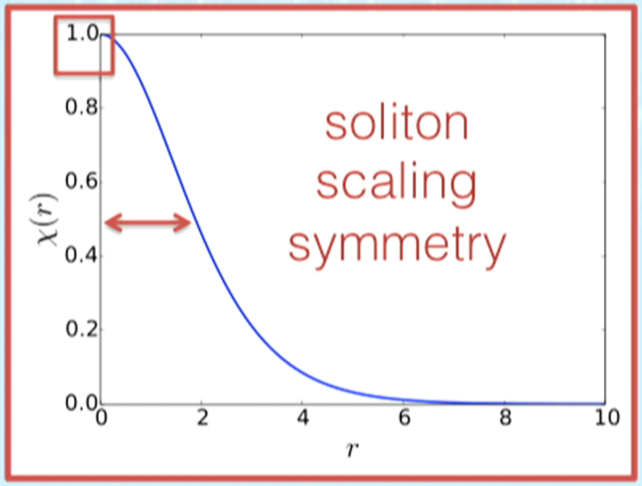

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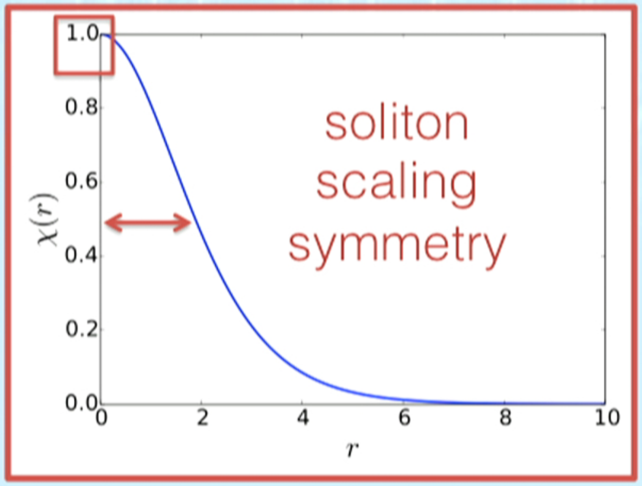

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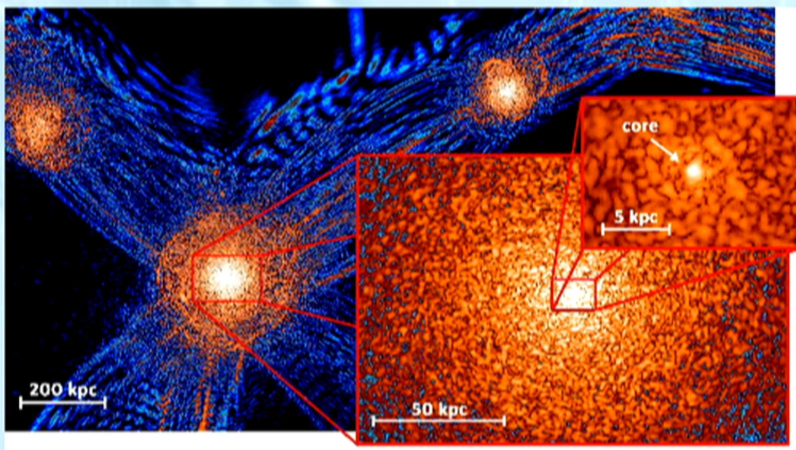

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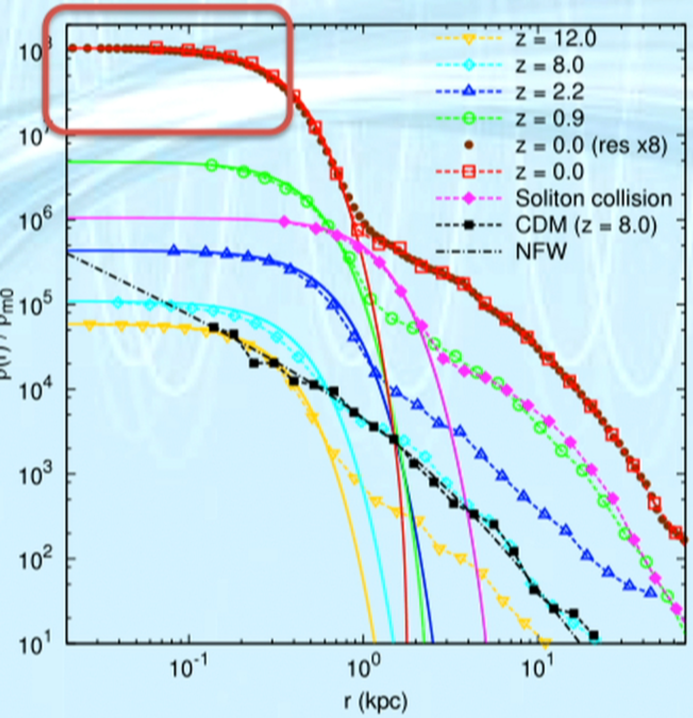

★ FIELD GRADIENT ENERGY

Axion DM Halos

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

(Eikonal) equivalence Schrodinger-CDM above Jeans mass.
Transition soliton → NFW at fraction ε of central density.

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

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

Jeans analysis

In prep w/ Gonzalez-Morales et al
Related work: Diez-Tejedor et al (2014)

Fornax, Sculptor, Draco, Leo-I, Leo-II, Sextants, Carina, Umi.

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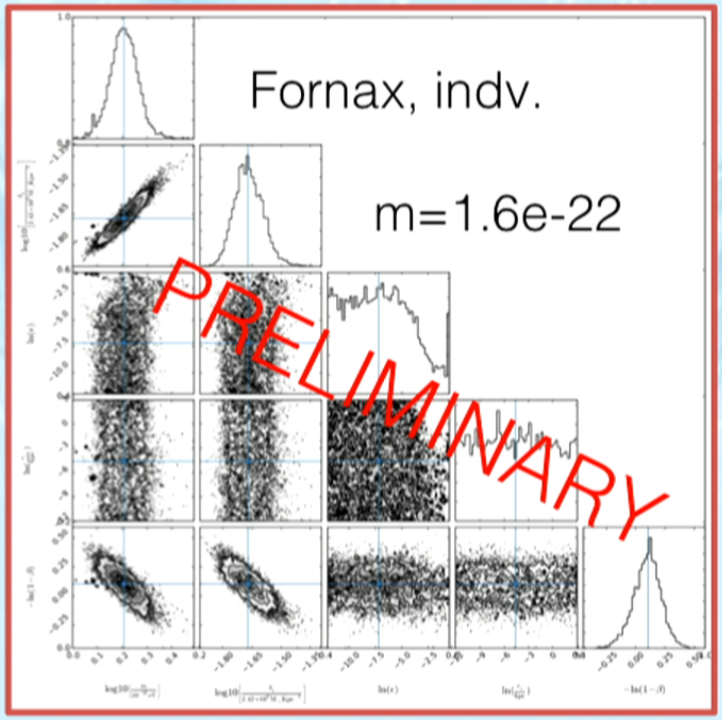
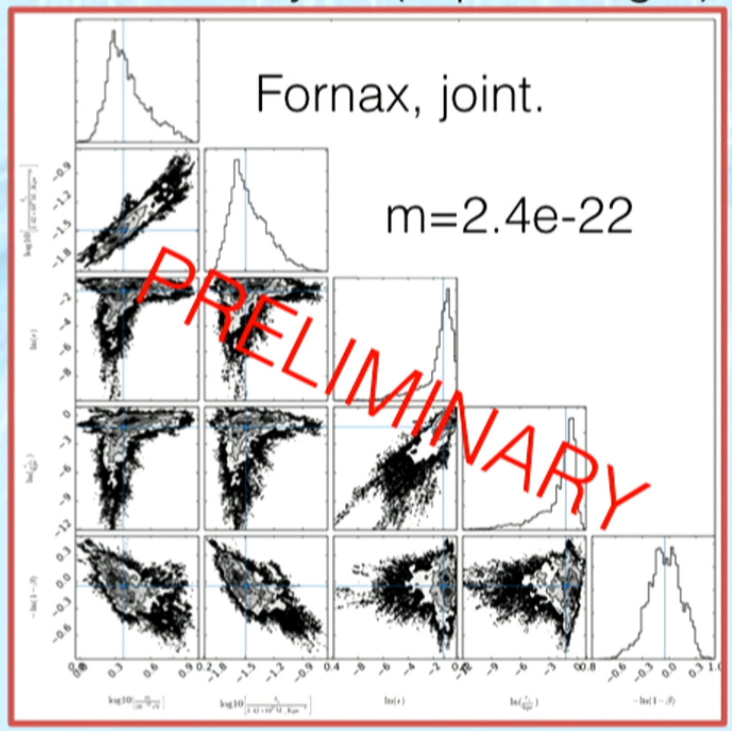
"Individual" analysis:

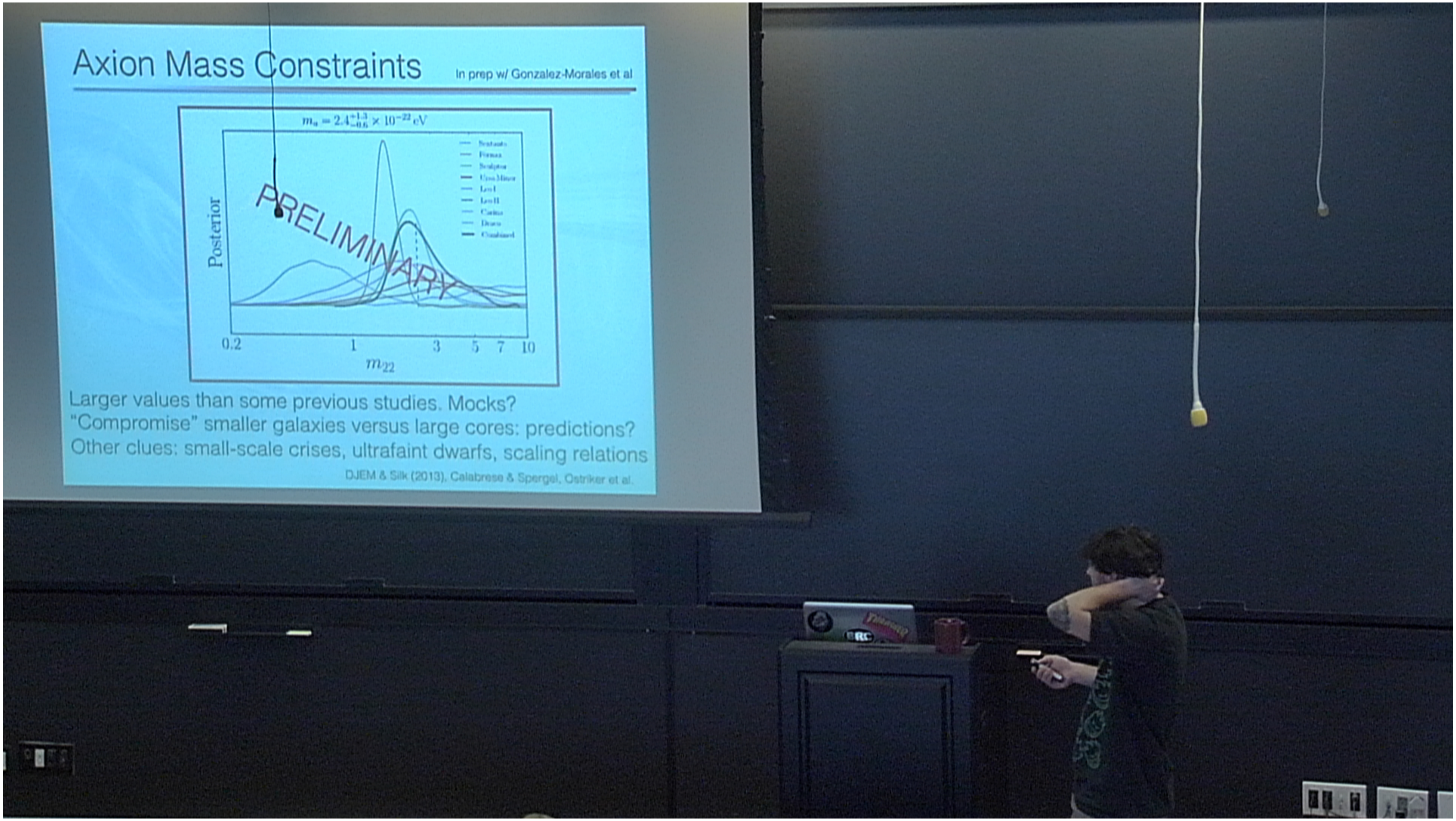


Core, no pref. for NFW params.

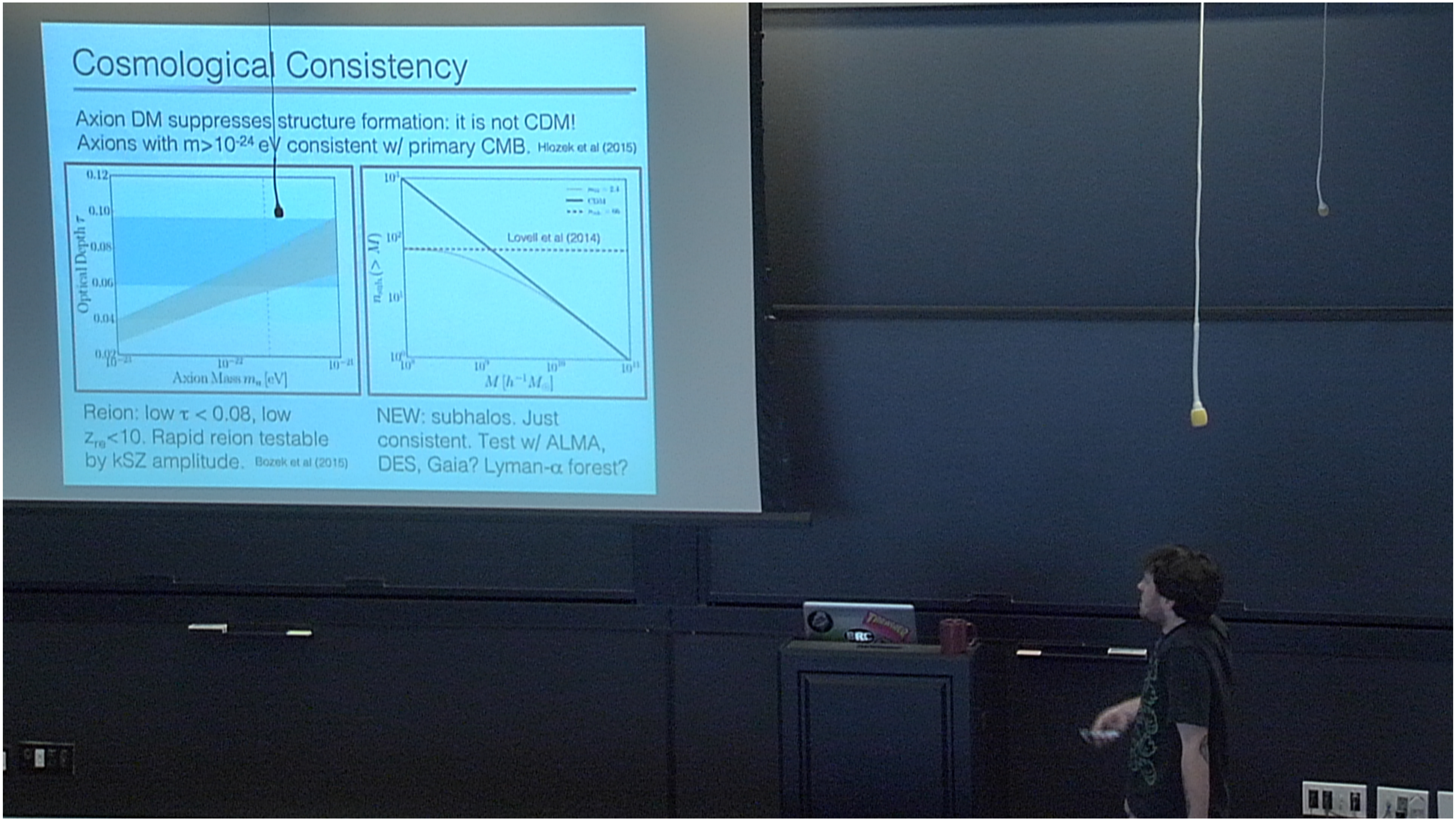
"Joint" analysis (equal weight):



Less freedom → NFW params.



Axion Mass Constraints
In prep w/ Gonzalez-Morales et al
$m_a = 2.4^{+1.3}_{-0.6} \times 10^{-22}$ eV
Posterior
PRELIMINARY
0.2
1
3
5
7
10
m_{22}
Larger values than some previous studies. Mocks?
“Compromise” smaller galaxies versus large cores: predictions?
Other clues: small-scale crises, ultrafaint dwarfs, scaling relations
DJEM & Silk (2013), Calabrese & Spergel, Ostriker et al.


Cosmological Consistency
Axion DM suppresses structure formation: it is not CDM!
Axions with m>10^-24 eV consistent w/ primary CMB. Hlozek et al (2015)
Optical Depth τ
Axion Mass m_a [eV]
Lovell et al (2014)
CDM
M [h^-1 M_⊙]
Reion: low τ < 0.08, low z_re<10. Rapid reion testable by kSZ amplitude. Bozek et al (2015)
NEW: subhalos. Just consistent. Test w/ ALMA, DES, Gaia? Lyman-α forest?

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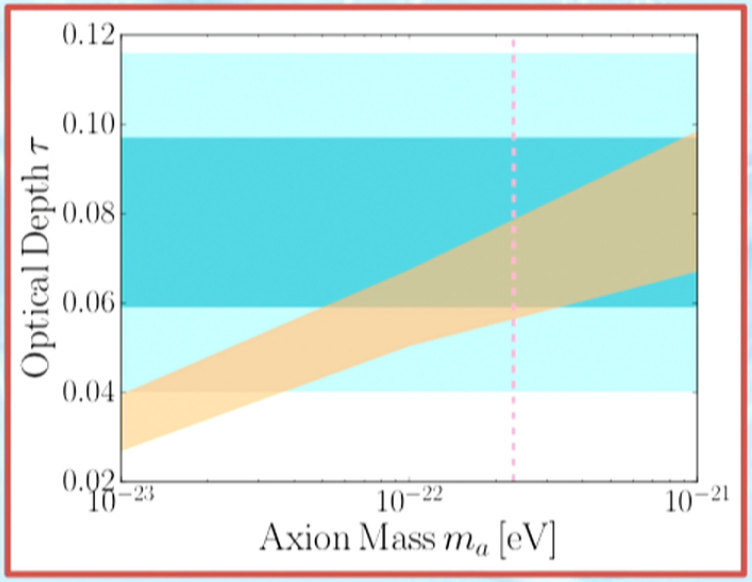

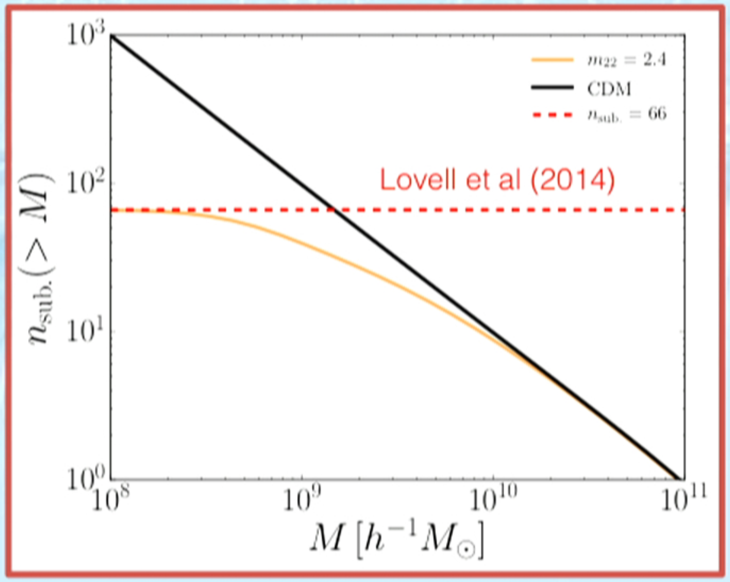

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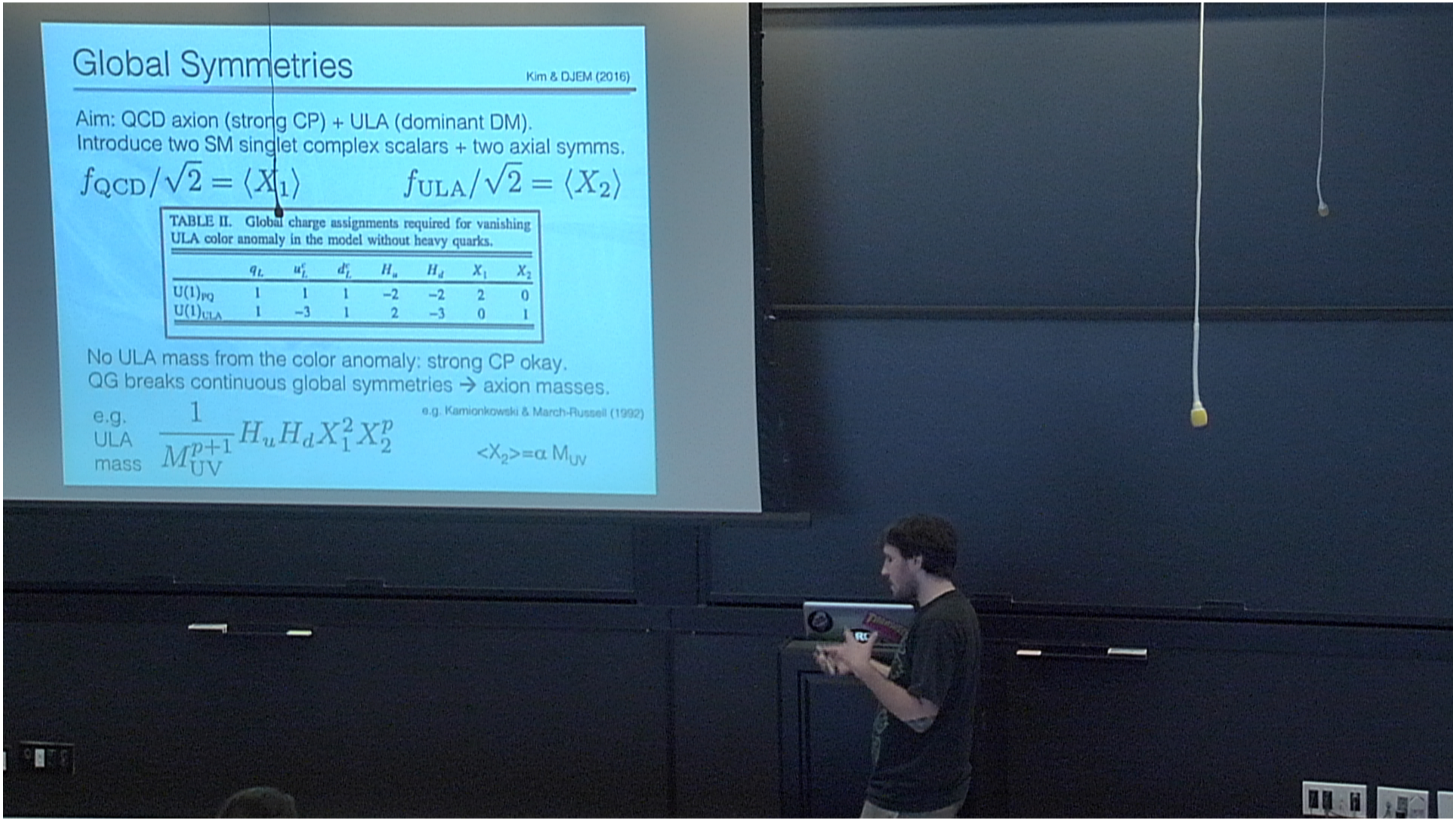
Model Building for
Ultralight DM


Global Symmetries
Kim & DJEM (2016)
Aim: QCD axion (strong CP) + ULA (dominant DM).
Introduce two SM singlet complex scalars + two axial symms.
$f_{QCD}/\sqrt{2} = \langle X_1 \rangle$
$f_{ULA}/\sqrt{2} = \langle X_2 \rangle$
TABLE II. Global charge assignments required for vanishing ULA color anomaly in the model without heavy quarks.
q_L u_L^c d_L^c H_u H_d X_1 X_2
$U(1)_{PQ}$ 1 1 1 −2 −2 2 0
$U(1)_{ULA}$ 1 −3 1 2 −3 0 1
No ULA mass from the color anomaly: strong CP okay.
QG breaks continuous global symmetries → axion masses.
e.g. Kamionkowski & March-Russell (1992)
e.g. ULA mass
$\frac{1}{M_{UV}^{p+1}} H_u H_d X_1^2 X_2^p$
$\langle X_2 \rangle = \alpha M_{UV}$

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Discrete Symmetries

Kim & DJEM (2016)

Idea: continuous symms are accidental from exact Z_N global.

TABLE V. More general $\mathbf{Z}_N$ charges.

	q_L	u_L^c	d_L^c	H_u	H_d	X_1	X_2
$\mathbf{Z}_N$	1	−3	1	2	n	0	m

Restricts operators: $2 + n + mp = 0 \mod N$

Non-trivial if p=1+N

$$V = f_{\rm ULA}^2 m_{\rm ULA}^2 = \alpha^p s_\beta c_\beta \frac{m_{3/2} v_{ew}^2 f_{\rm QCD}^2}{M_{\rm UV}} ,$$

$$\frac{m_{\rm ULA}}{10^{-22}\ {\rm eV}} \approx 10^{19.69-0.77p} \left(\frac{f_{\rm ULA}}{10^{17}\ {\rm GeV}}\right)^{p/2-1} \left(\frac{f_{\rm QCD}}{10^{11}\ {\rm GeV}}\right)$$

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Example models

Kim & DJEM (2016)

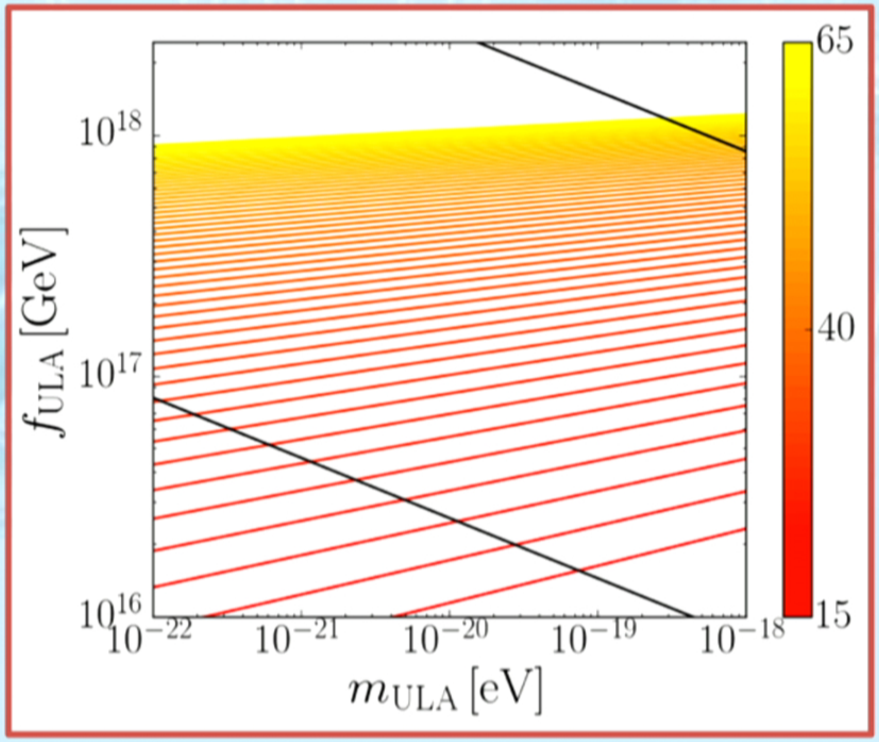
Family of solutions defined by (N,n,m), example:

$$(N = 24, m = 8, n = 14) \Rightarrow p = 25$$

$$\frac{m_{\mathrm{ULA}}}{10^{-22}\ \mathrm{eV}} = 2.8$$

$$f_{\mathrm{ULA}} = 10^{17}\ \mathrm{GeV}$$

$$f_{\mathrm{QCD}} = 10^{11}\ \mathrm{GeV}$$



Couplings to the SM

e.g. Srednicki (1985)

✧ QCD axion: DFSZ type →
EM and color anomalies, tree-level fermion couplings.

$$g_{\phi\gamma}\phi\vec{E}\cdot\vec{B} \qquad g_{\phi\gamma}\propto 1/f_{\rm QCD}$$

ADMX, stellar astrophysics, helioscopes, etc etc.

✧ ULA: anomaly free! →
no EB or EDM coupling, tree-level fermion couplings.

$$g_{\phi N}(\partial_\mu\phi)\bar{N}\gamma^\mu\gamma_5 N \qquad g_{\phi N}=C_{\phi N}/f_{\rm ULA}$$

$$C_{\phi n}=0.473+0.624s_\beta^2$$

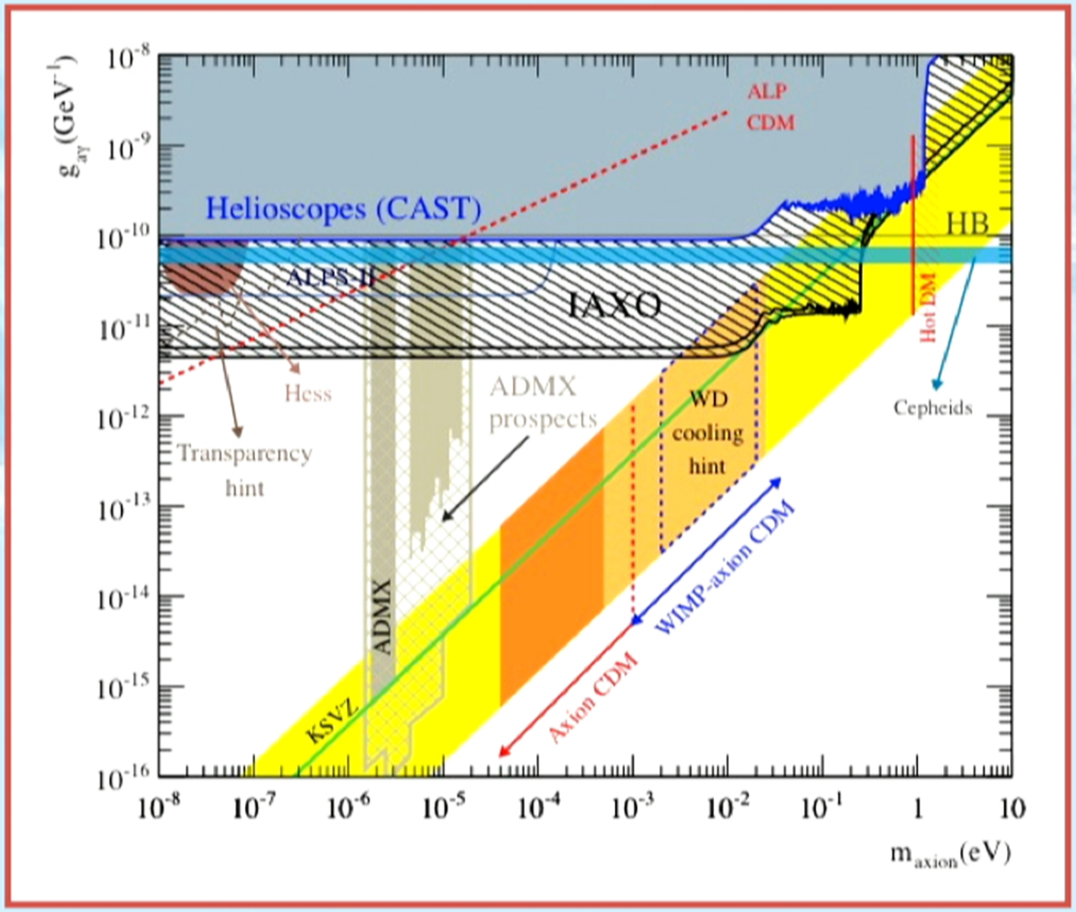
$$C_{\phi p}=-0.594-0.016s_\beta^2$$

Axion "wind", spin-dependent forces.

Constraints from Interactions

Summary of E.B constraints

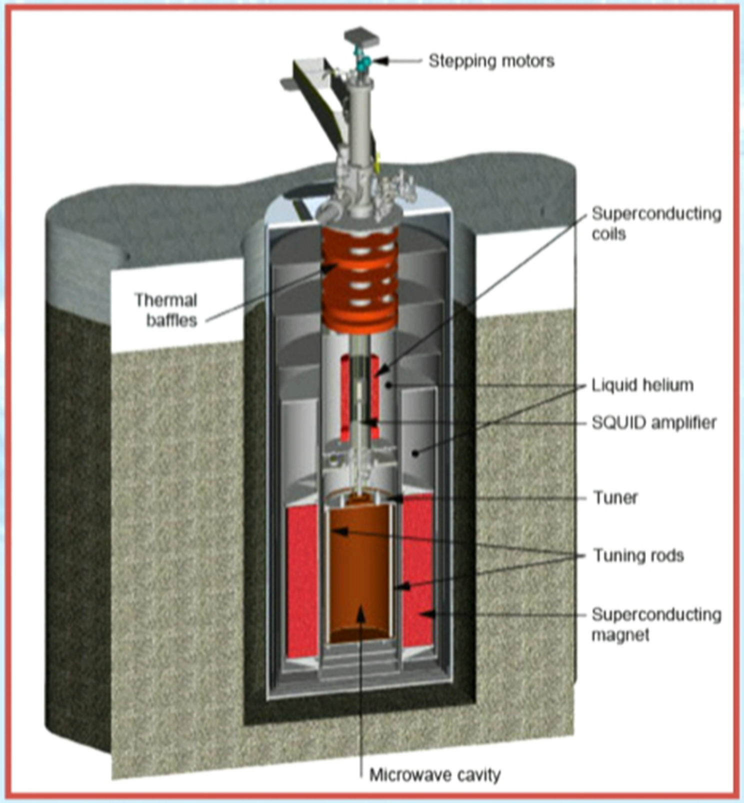
Carosi et al (2013)



Haloscopes and ADMX

Sikivie (1983)
Asztalos et al (2010)

Direct detection of axion DM using microwave cavity and B.
Very precise, but limited range because requires resonance.



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$$P = g_{\phi\gamma}^2 \frac{V B_0 \rho_a C}{m_a} \min\left(Q, Q_a\right)$$

500L

7T

Form factor

Quality ~10^5

Energy spread

In operation @ WSU. Fiducial f~10^{12} GeV → P~10^{-21} W.

Design sensitivity will cover DFSZ and KSVZ over range:

$$10^{-6}\ \text{eV} \lesssim m_a \lesssim 10^{-5}\ \text{eV}$$

"Classic window" for axion DM. Limited by physical cavity size.

Axion DM as coherent field

The galactic DM is an oscillating condensate:

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

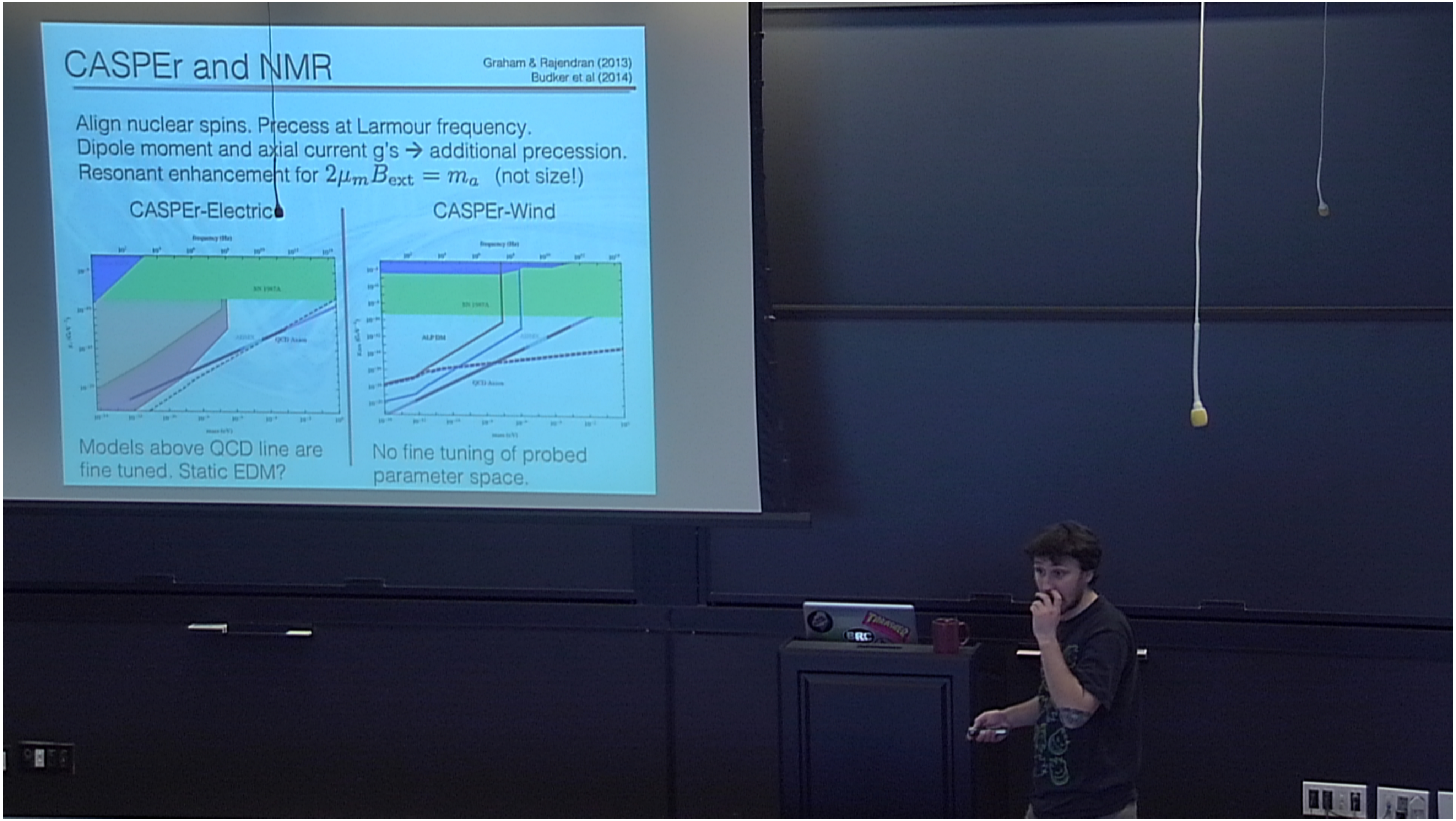
$$\omega \approx 10^{-7}\ {\rm Hz} \left(\frac{m_a}{10^{-22}\ {\rm eV}} \right)$$

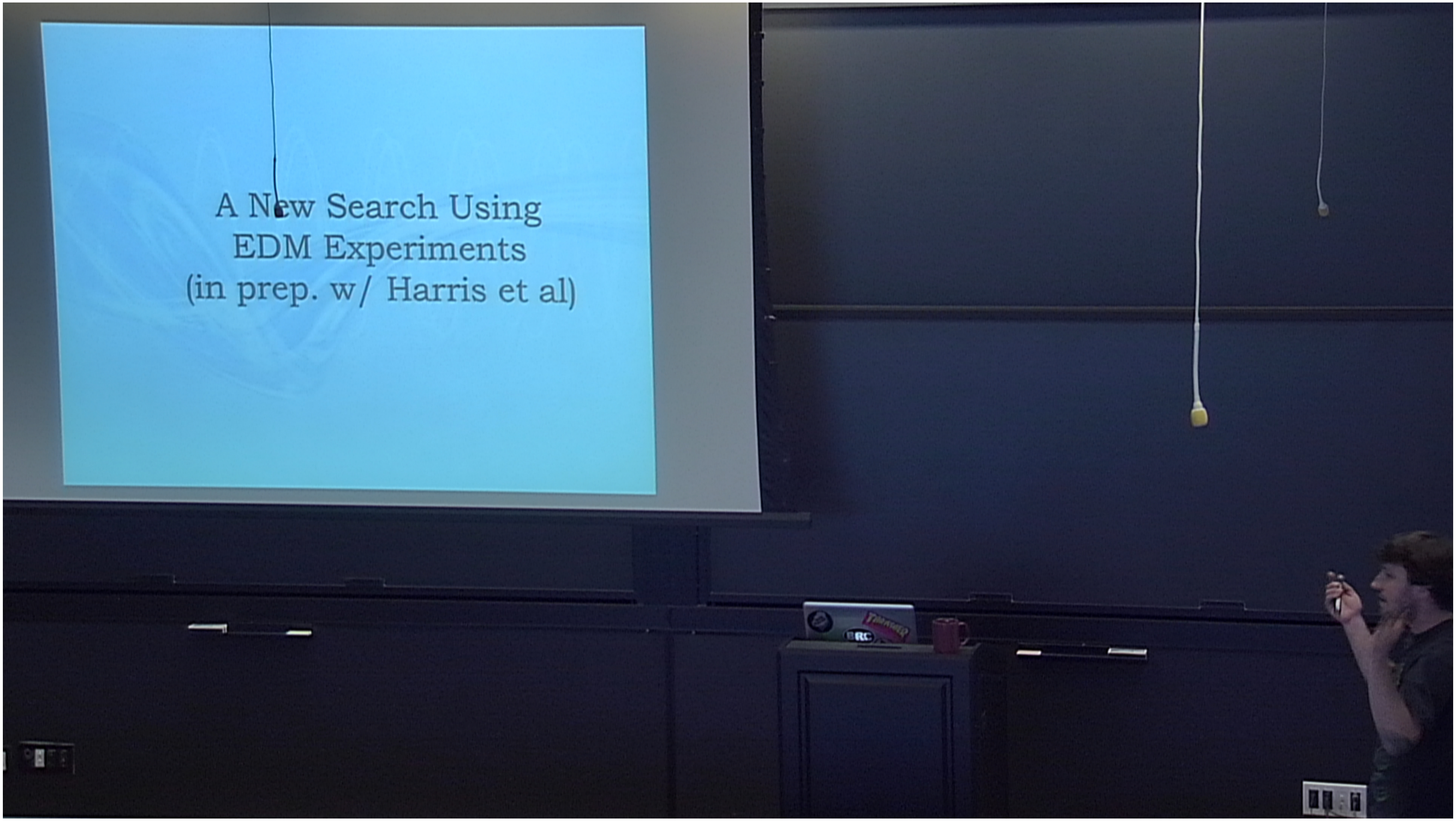
Coherent over distances ~ de Broglie wavelength.

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

Detection of coherent effects at low frequencies.

Graham & Rajendran (2013), Graham et al (2015), Arvanitaki et al (2014) …


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
CASPEr-Wind
Models above QCD line are fine tuned. Static EDM?
No fine tuning of probed parameter space.


A New Search Using
EDM Experiments
(in prep. w/ Harris et al)

New Analysis of nEDM

Work underway with nEDM collaboration (+Stadnik, Flambaum, Fairbairn)

$$\frac{\nu_n}{\nu_{\rm Hg}} = R + \frac{(d_n + R d_{\rm Hg})}{\nu_{\rm Hg}} E$$

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Axion wind: oscillating intercept (cycle by cycle).

Energy shift ~ off axis 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?

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g_d coupling: oscillating signal (cycles or runs)

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

$$g_d \sim 10^{-22}\ \mathrm{GeV}^{-2} \left(\frac{m_a}{10^{-22}\ \mathrm{eV}}\right)^{-1}$$

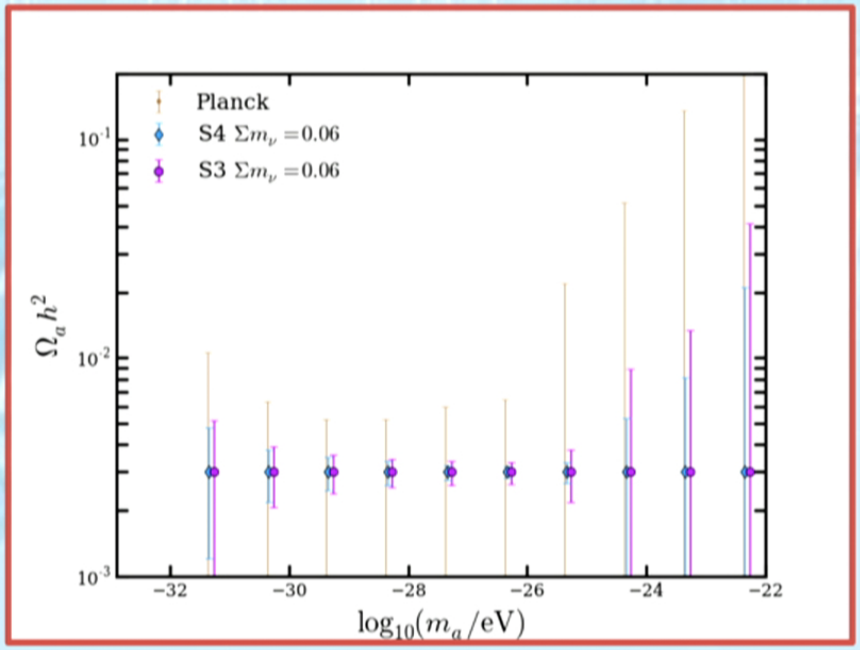
>Planck coupled C~1 (!)
Improve with PSI @ high m.

Lensing power with S4

In prep w/ Hlozek et al

S4 is a global network of ground based CMB pol. telescopes. Planned for ~2020. Upgrades to ACT, SPT etc.

- ✧ High-l >10^3 lensing measures the DM distribution.
- ✧ ULAs at m<10^{-28} eV versus <0.1 eV ν's.
- ✧ Detect m_ν=16 meV
- ✧ Improve axion density constraints by ~10.
- ✧ Improve axion mass constraints by ~10^3!



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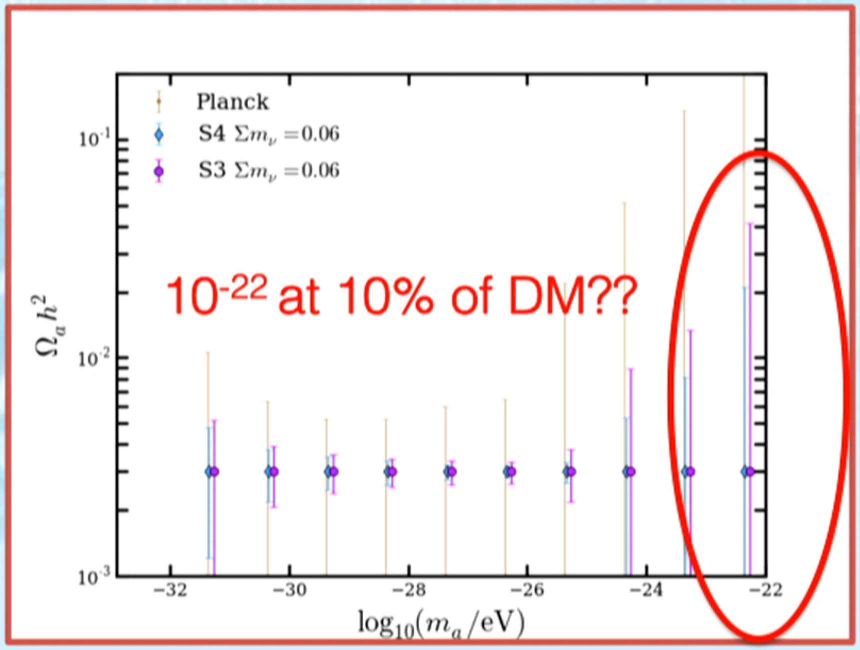


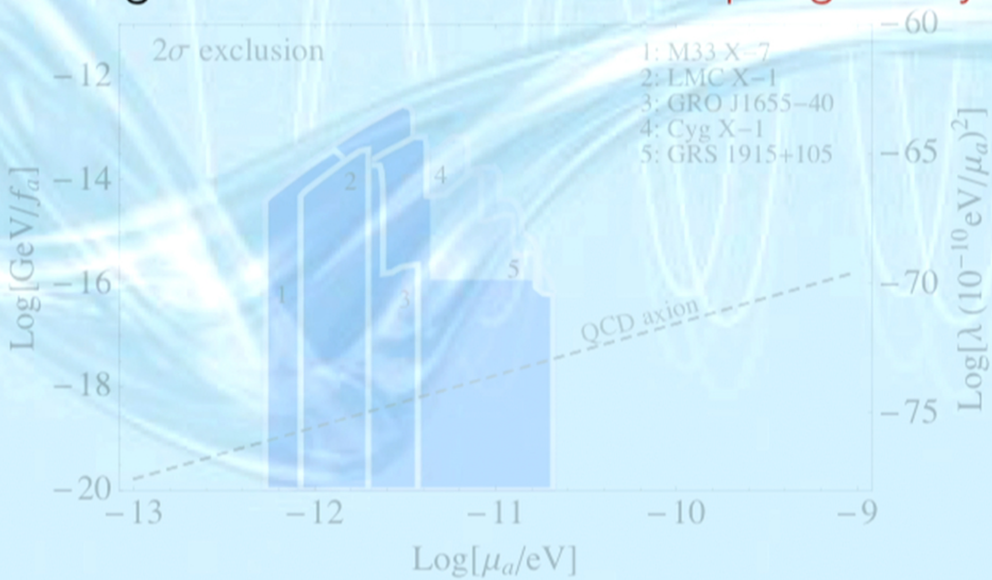
Limited by high-l non-linear clustering: need simulations!

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



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

Black Hole Superradiance

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

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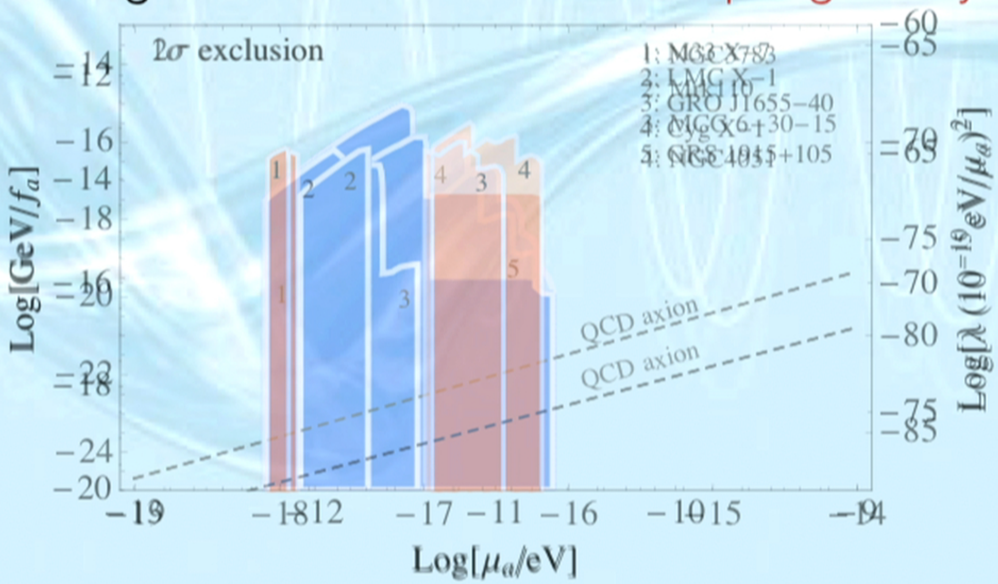
Solar mass
SMBH



Make contact to possible reach of 21cm and reionization

$3\times10^{17}\ \mathrm{GeV} < f_{\mathrm{QCD}} < 1\times10^{19}\ \mathrm{GeV}$

Back-of-the-envelope summary

JWST luminosity function sensitive to 10^{-21} eV. Bozek et al (2015)

10^6 M_{sol} cubstructure, DES, ALMA, tidal streams: 10^{-22} eV.

e.g. Hezaveh et al (2014), Bovy and Erkdal (2015)

Patchy kSZ power in CMB: reionization with 10^{-21} eV.

Calabrese et al (2014), Bozek et al (2015)

Lyman-alpha and WDM constraints: (few)x 10^{-22} eV.

Viel et al (2013), DJEM et al (in prep)

Axion-baryon streaming velocity in large scale 21cm: 10^{-18} eV.

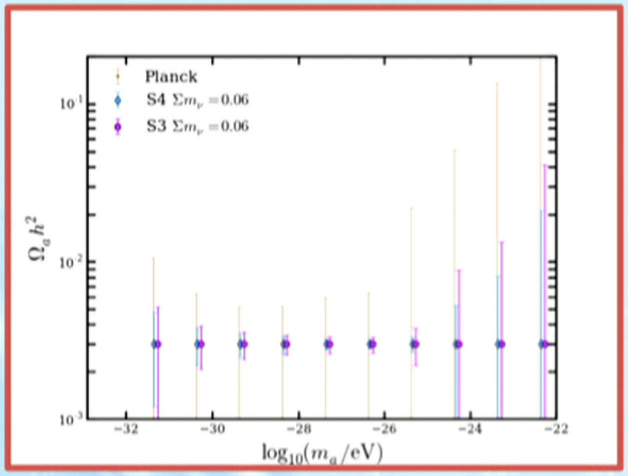
Visbal et al (2012), DJEM (2015)

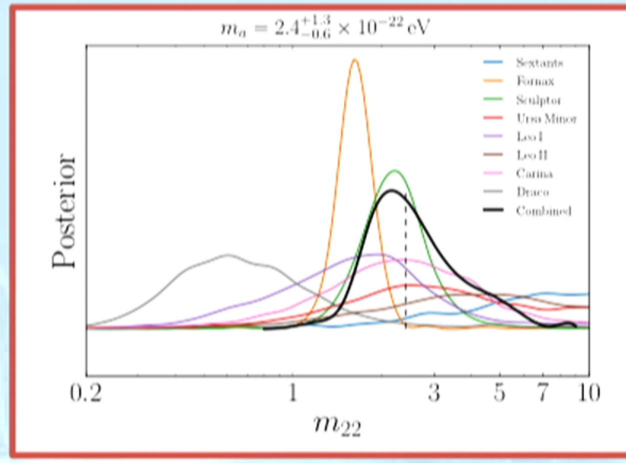
BHSR and GWs: 10^{-18} eV to 10^{-12} eV Arvanitaki et al (2014)

Pulsar timing arrays and SKA: 1% constraints @ 10^{-23} eV.

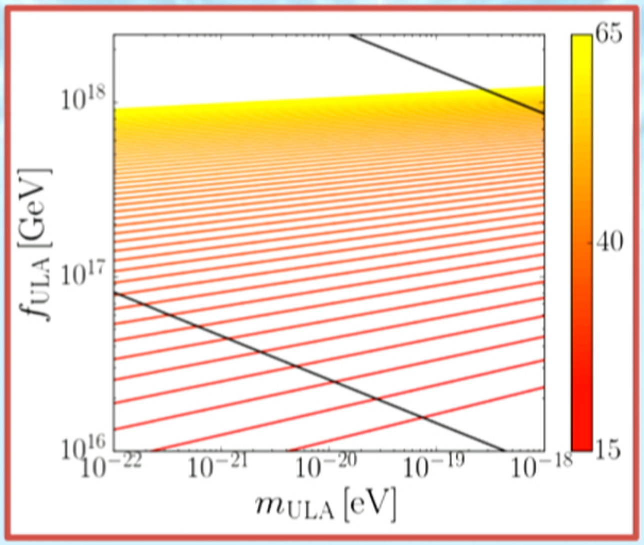
Khlemenitsky & Rubakov (2013)

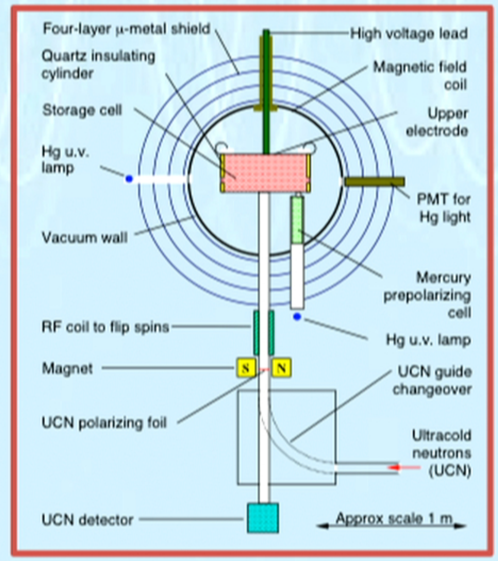
DM oscillation time scale from years to seconds!

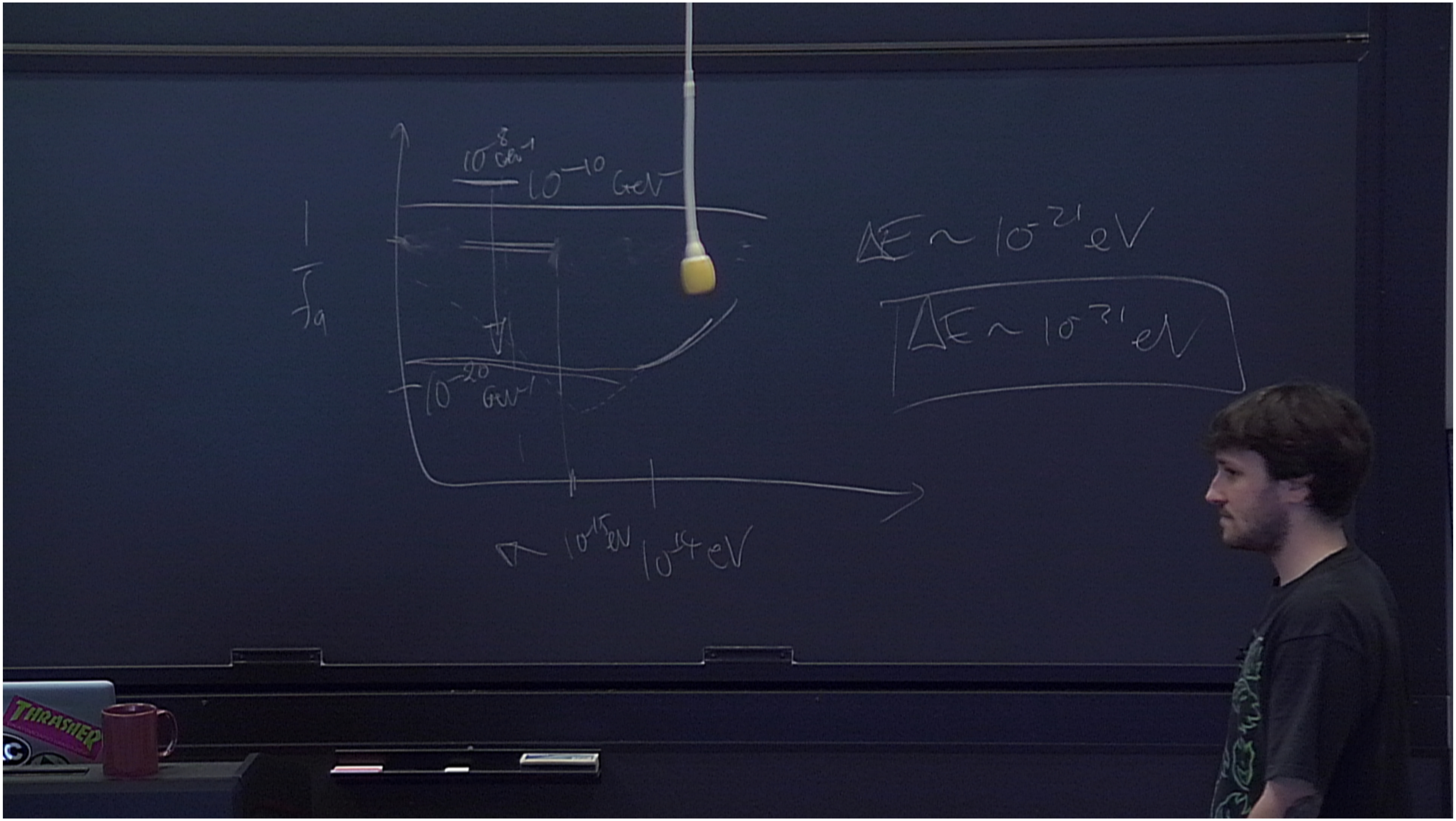




Thank You! Questions?







1/f_a
10^-8 GeV^-1
10^-10 GeV^-1
10^-20 GeV^-1
10^-15 eV
10^-14 eV
ΔE ~ 10^-21 eV
ΔE ~ 10^-31 eV