Searching for Axions

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COSMO-18, Daejon, Korea

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Unterstützt von / Supported by
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Axion Parameter Space

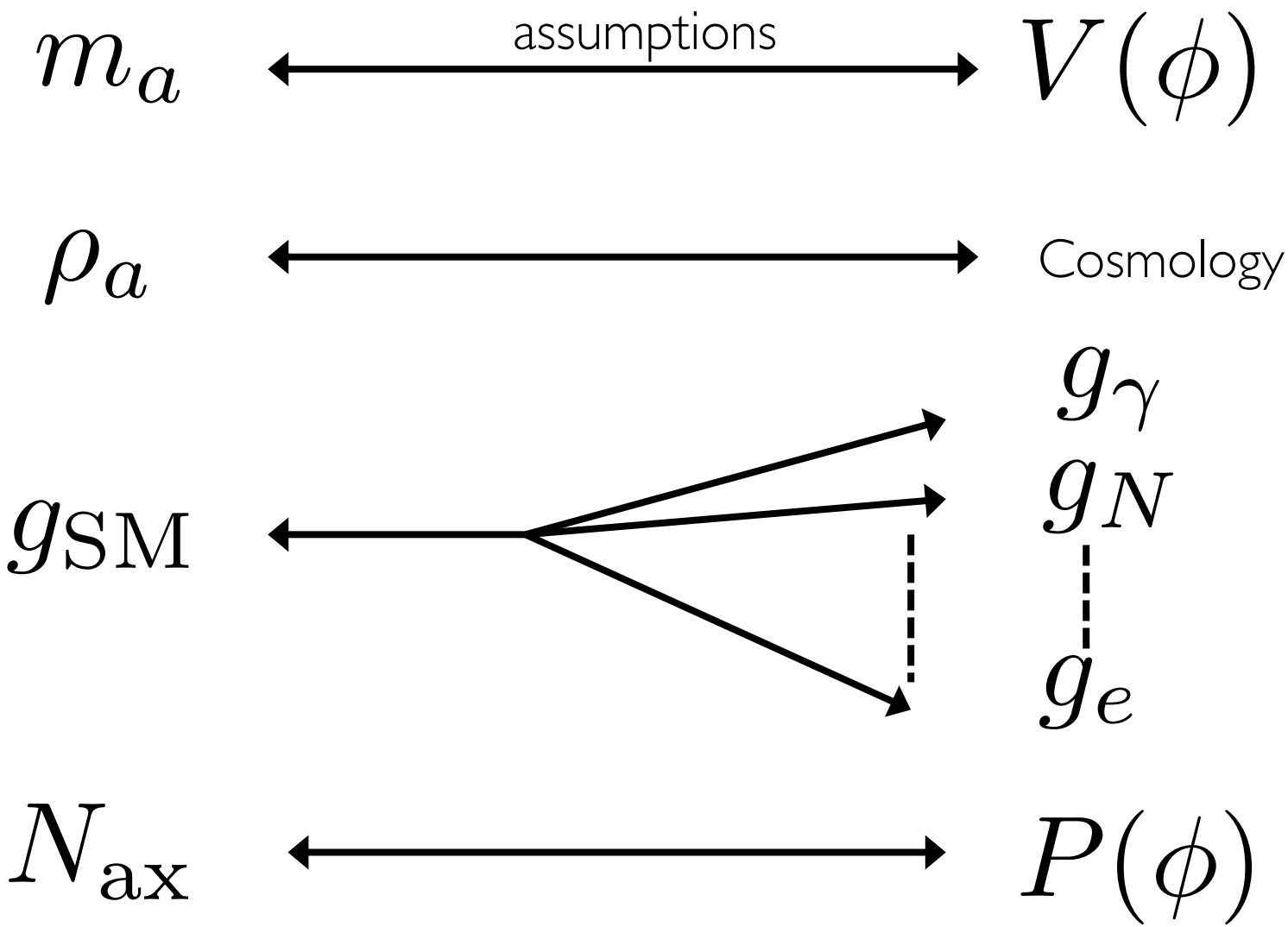
$$m_a$$

$$\rho_a$$

$$g_{\mathrm{SM}}$$

$$N_{\mathrm{ax}}$$

Axion Parameter Space



Axion Parameter Space

m_a $g_{\rm SM}$ $V(\phi)$ $N_{\rm ax}$

Cosmology

ρ_a

Dark matter (hot, cold, fuzzy…), dark radiation, dark energy, inflation …

100% Jeleran
AXION
PENGHAPUS MINYAK
Limau

(Baryogenesis via CP-violating couplings, see e.g. Servant, 2014)

BLACK HOLE SUPERRADIANCE

Arvanitaki & Dubovsky (2010), Brito et al (2015)

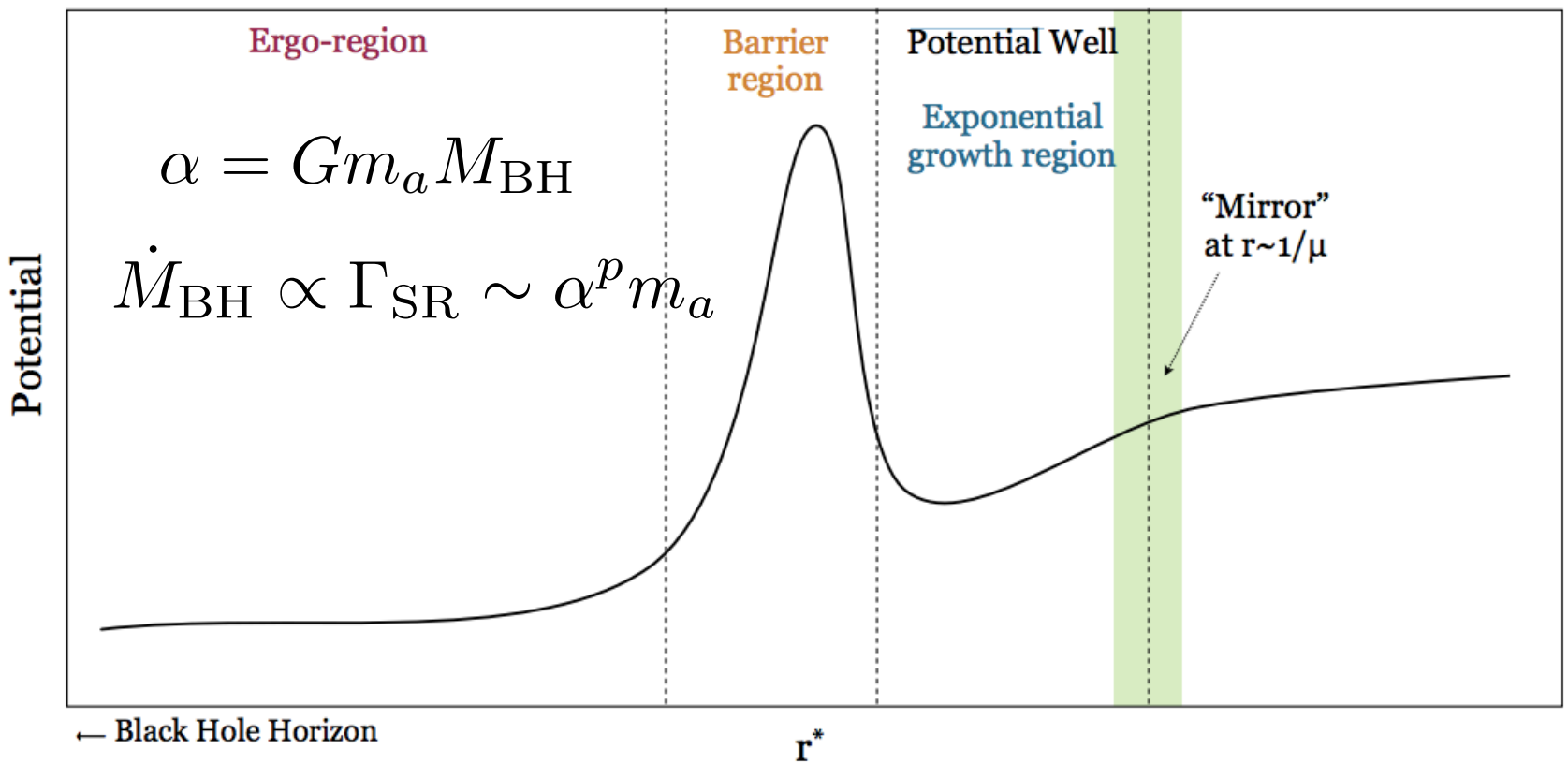
$$m_a \quad V(\phi) \; N_{\mathrm{ax}}$$

See Matt Stott's talk tomorrow!

Theory of BHSR

Arvanitaki & Dubovsky (2010)

Axion orbitals grow superradiantly by extraction of BH spin.

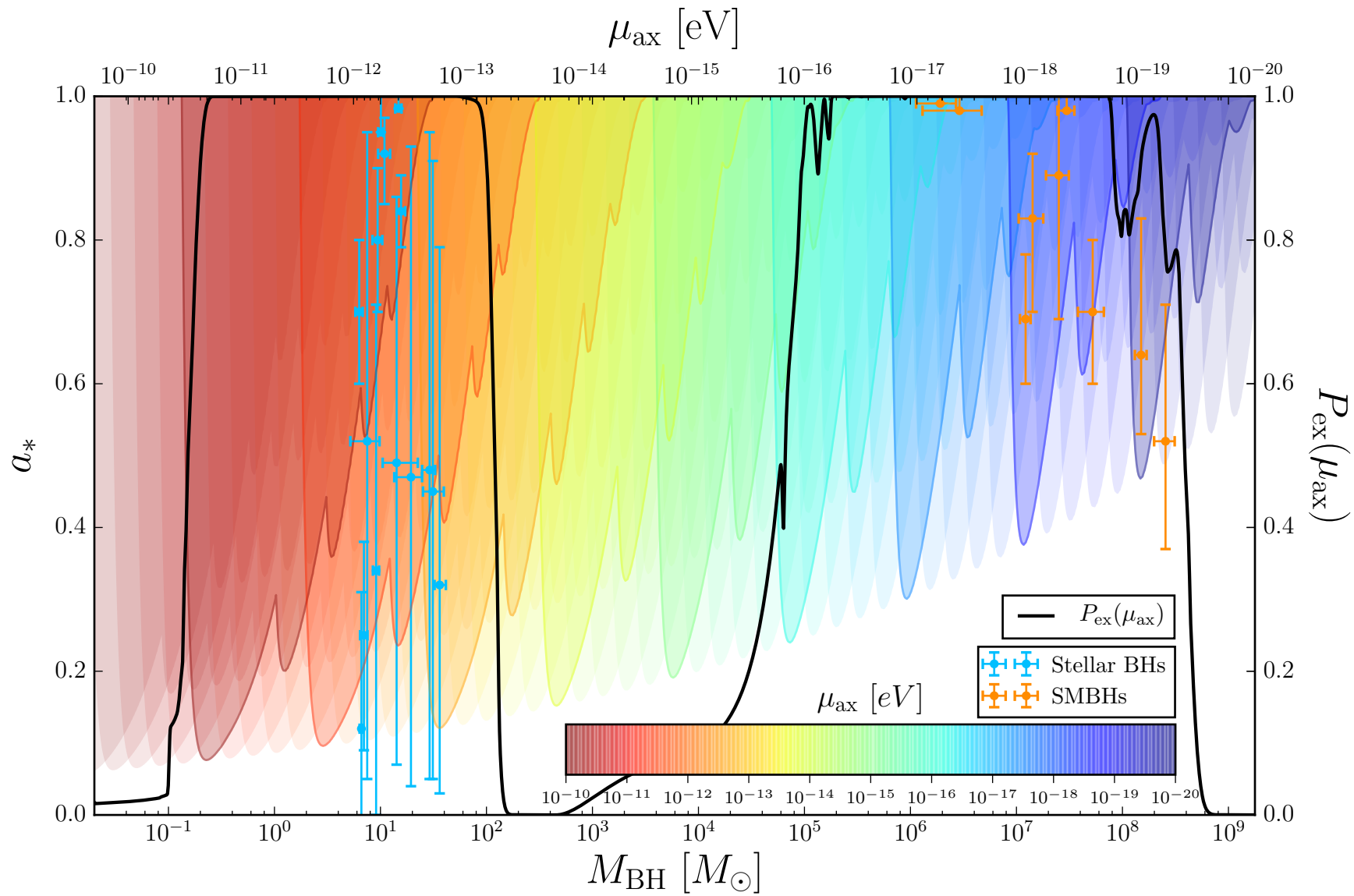


$$\alpha = G m_a M_{\rm BH}$$

$$\dot{M}_{\rm BH} \propto \Gamma_{\rm SR} \sim \alpha^p m_a$$

$\alpha \sim 1$ maximises SR which should exceed e.g. accretion timescale.

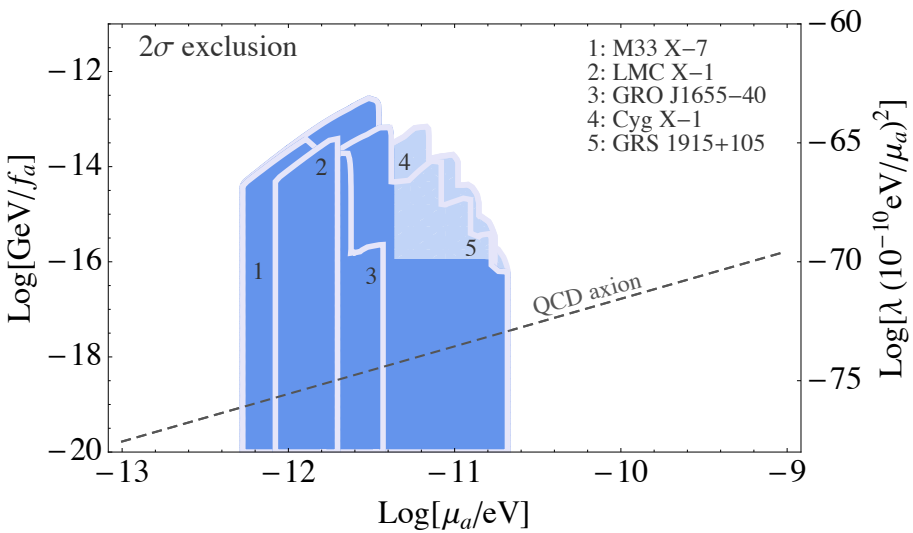
This process is independent of the axion density or SM coulings.
→ Excludes the existence of massive scalars in certain windows

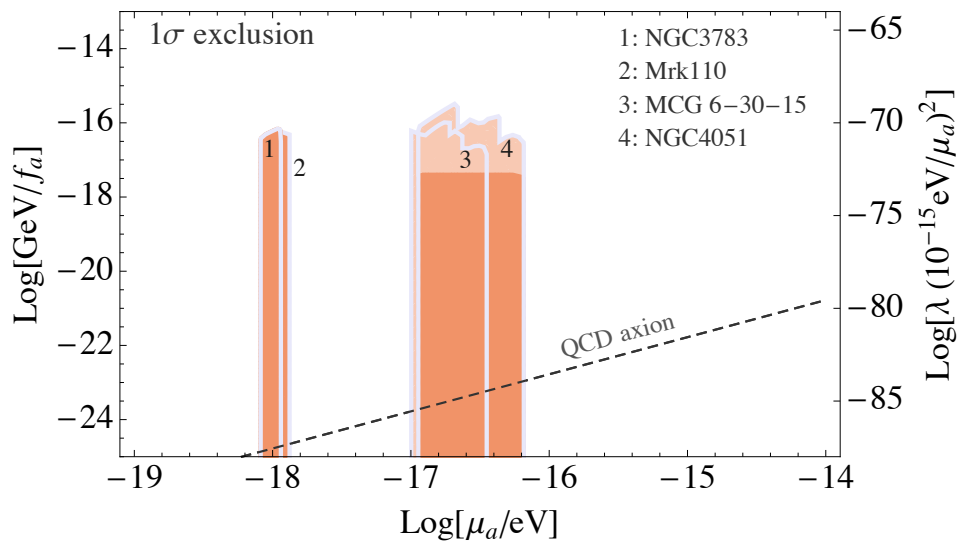


Stott & DJEM (2018)

Self interactions, i.e. V(ϕ), can shut down superradiance via "Bosenova".

$$V(\phi) = m_a^2 f_a^2 (1 - \cos\phi/f_a)$$





Stellar BHSR applies when:

$$f_a \gtrsim 10^{14}\ \mathrm{GeV}$$

Supermassive BHSR applies when:

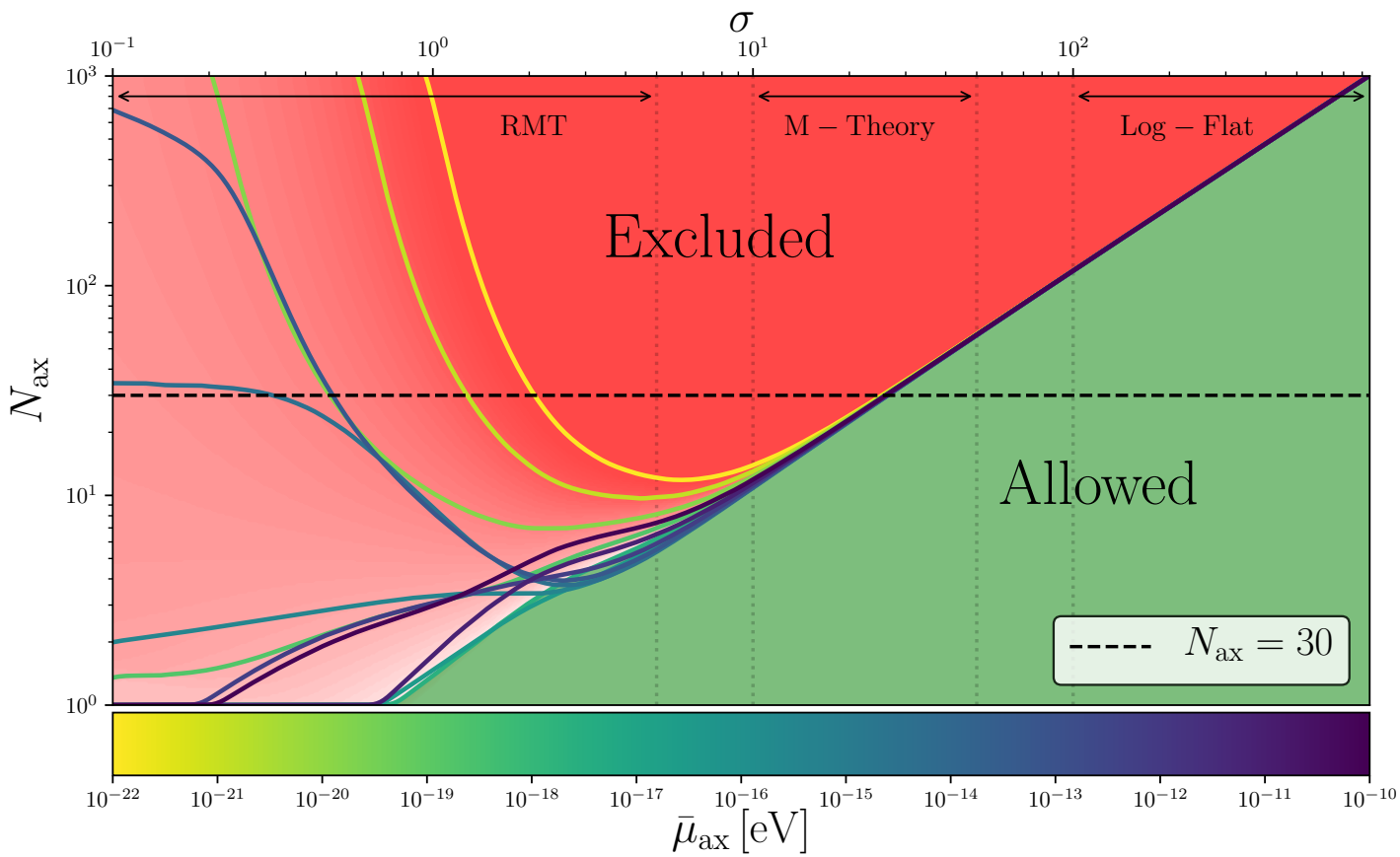
$$f_a \gtrsim 10^{16}\ \mathrm{GeV}$$

Arvanitaki et al (2015)

Constraining N_{ax}

Stott & DJEM (2018)

Axion mass distributions in string theory have log-space support.
How many axions are allowed until P(BHSR) is large due to tails?



ULTRALIGHT AXIONS

Hlozek, Grin, DJEM + et al (2014+)

$$m_a \quad \rho_a \quad V(\phi)$$

Axion Dark Matter

Review: DJEM Phys. Rep. (2016)

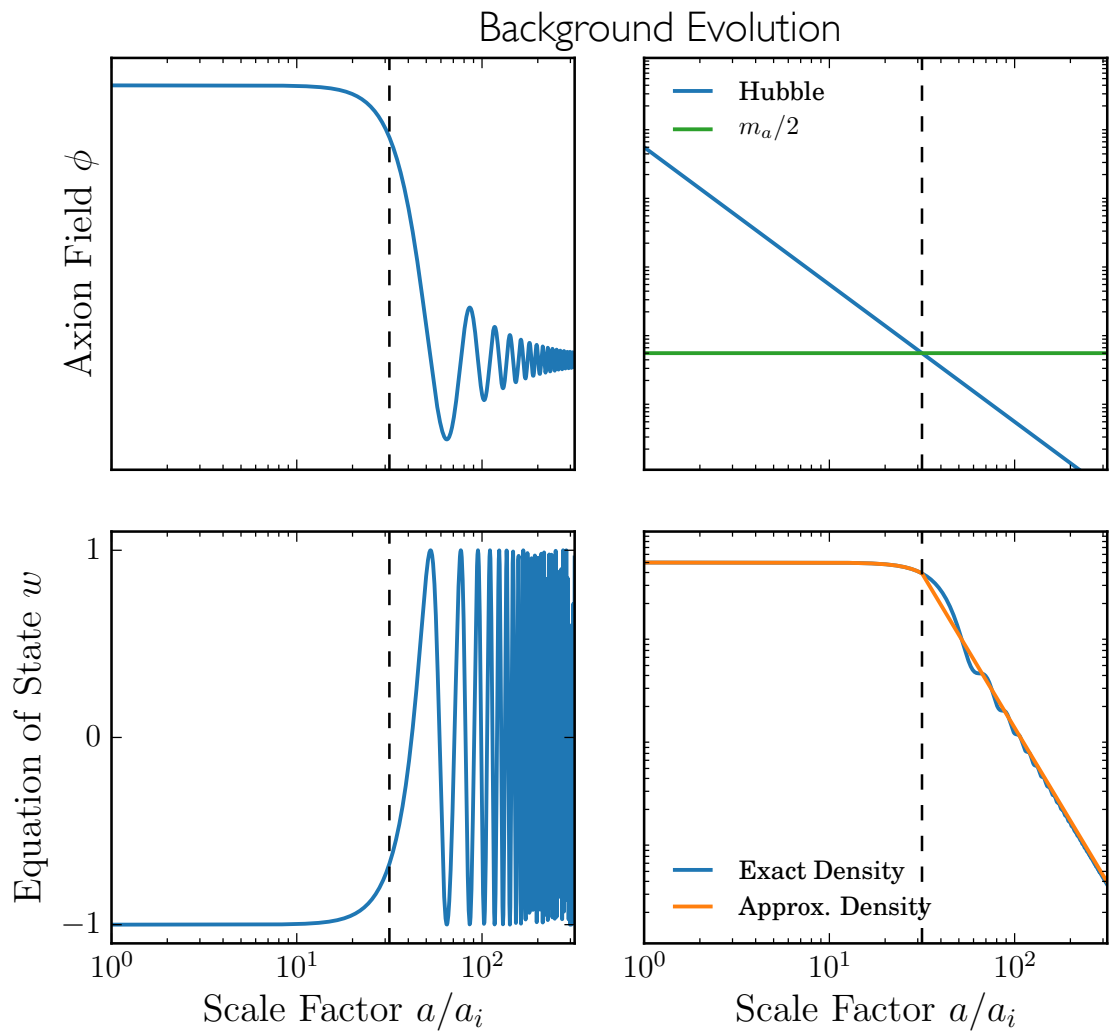
Non-thermal classical field. DM in coherent oscillations.

Dynamics governed by Klein-Gordon.

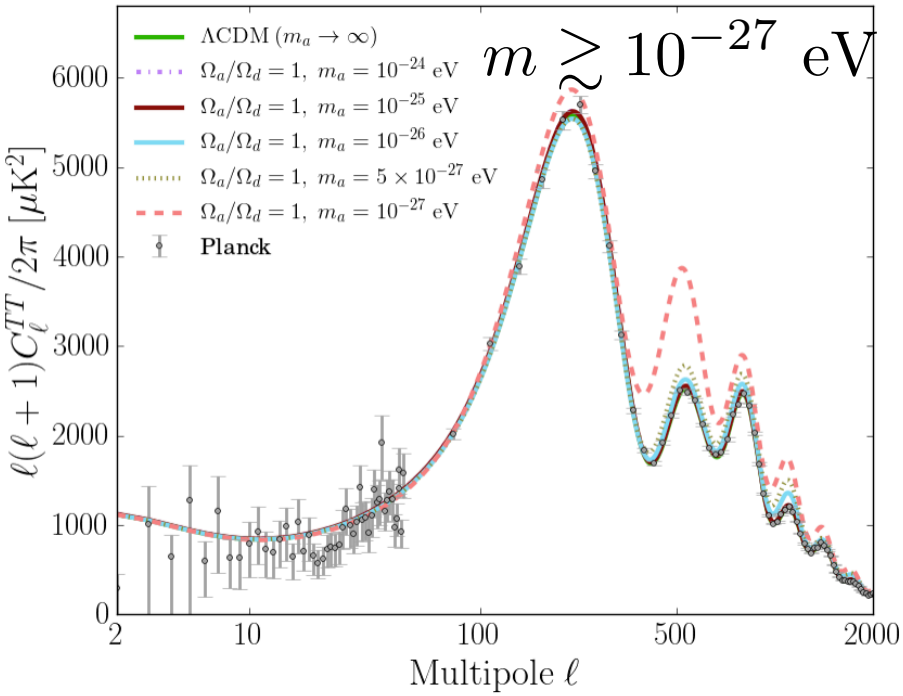
Background physics: Hubble "friction".

Perturbations physics: field gradient "pressure".

Access to limited range set by 1/m versus (k_{min},k_{max})



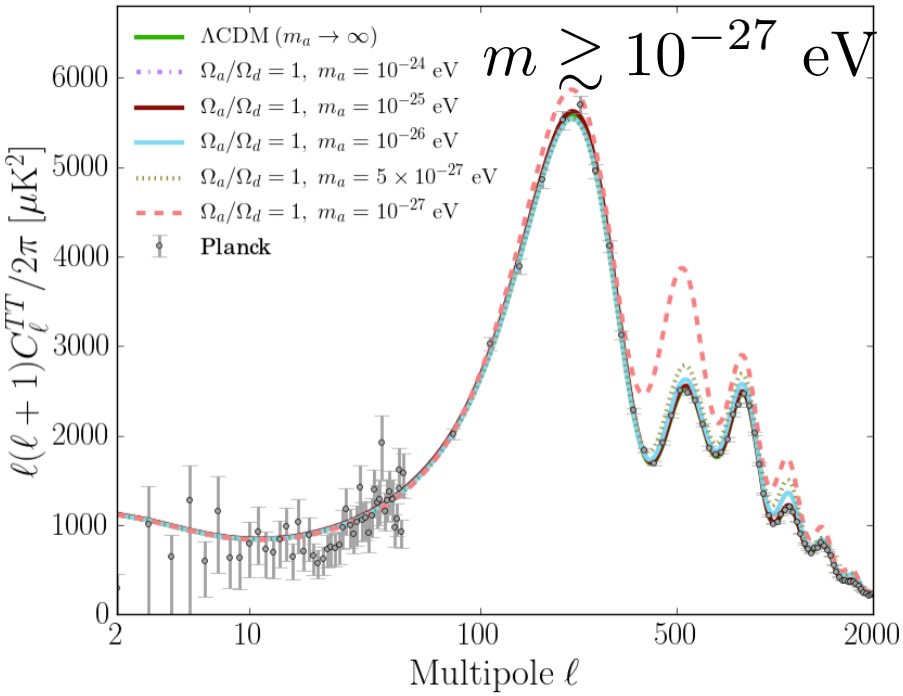
Hlozek et al (2015,2017)



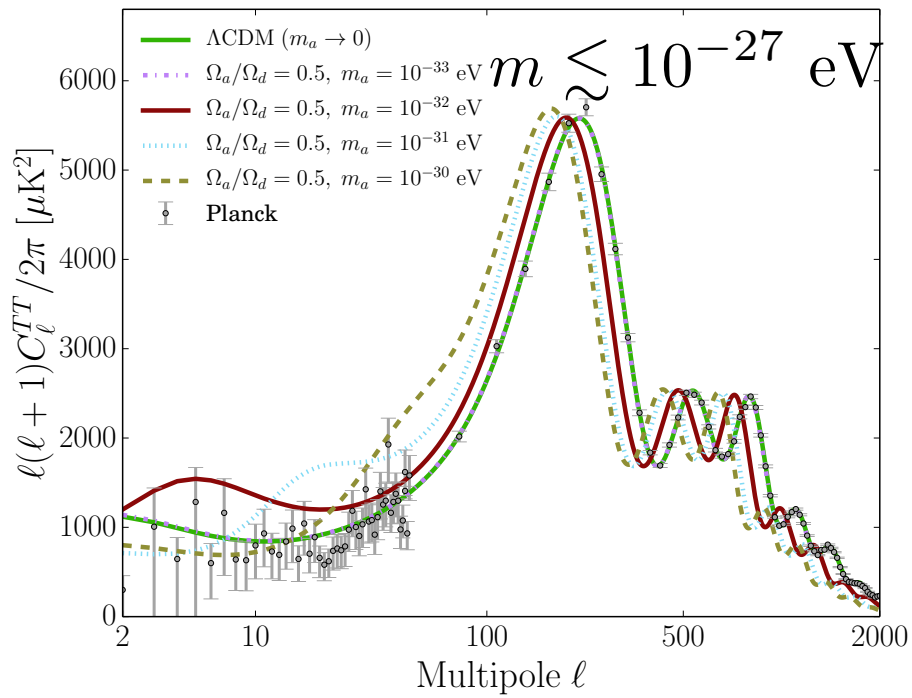
DM-like axions affect acoustic peaks by expansion rate in rad. dom. era.

Effects vanish for large m → mimic CDM.

Hlozek et al (2015,2017)



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



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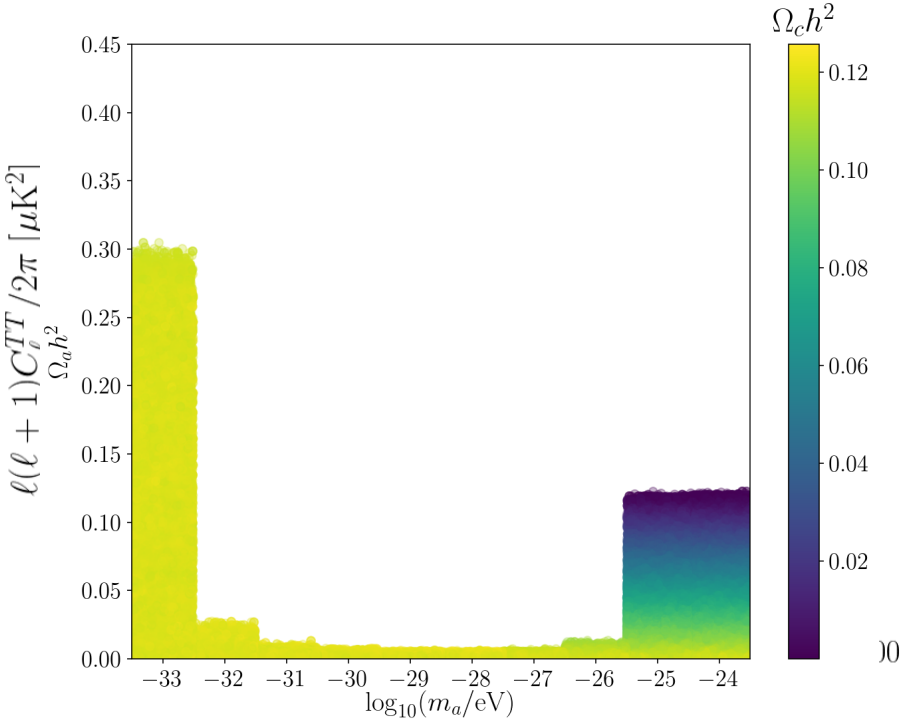

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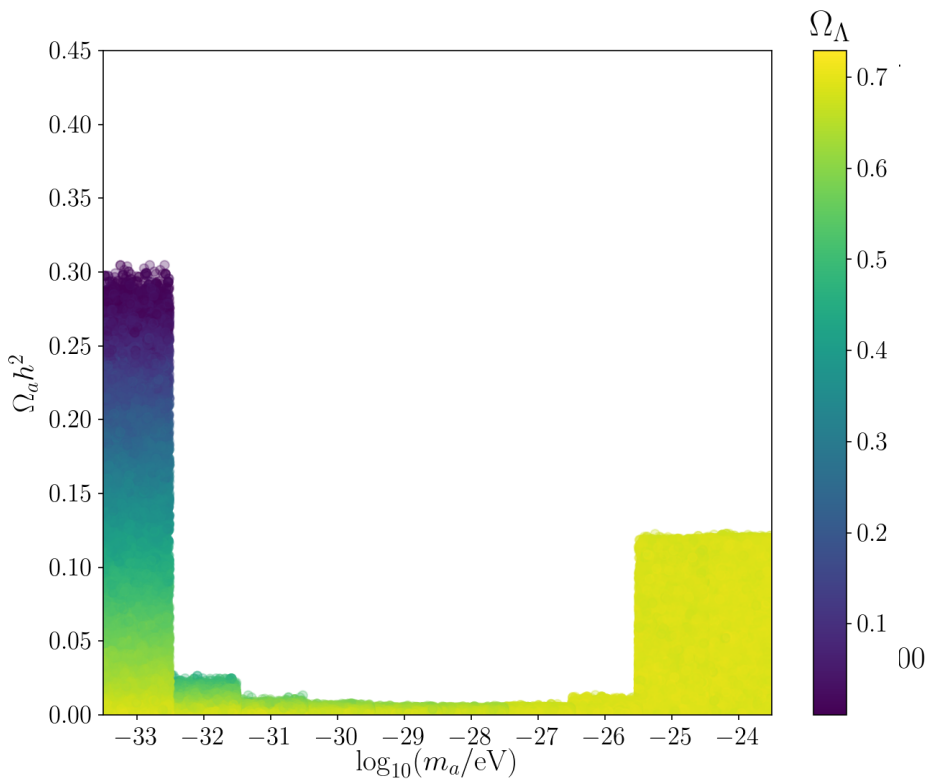

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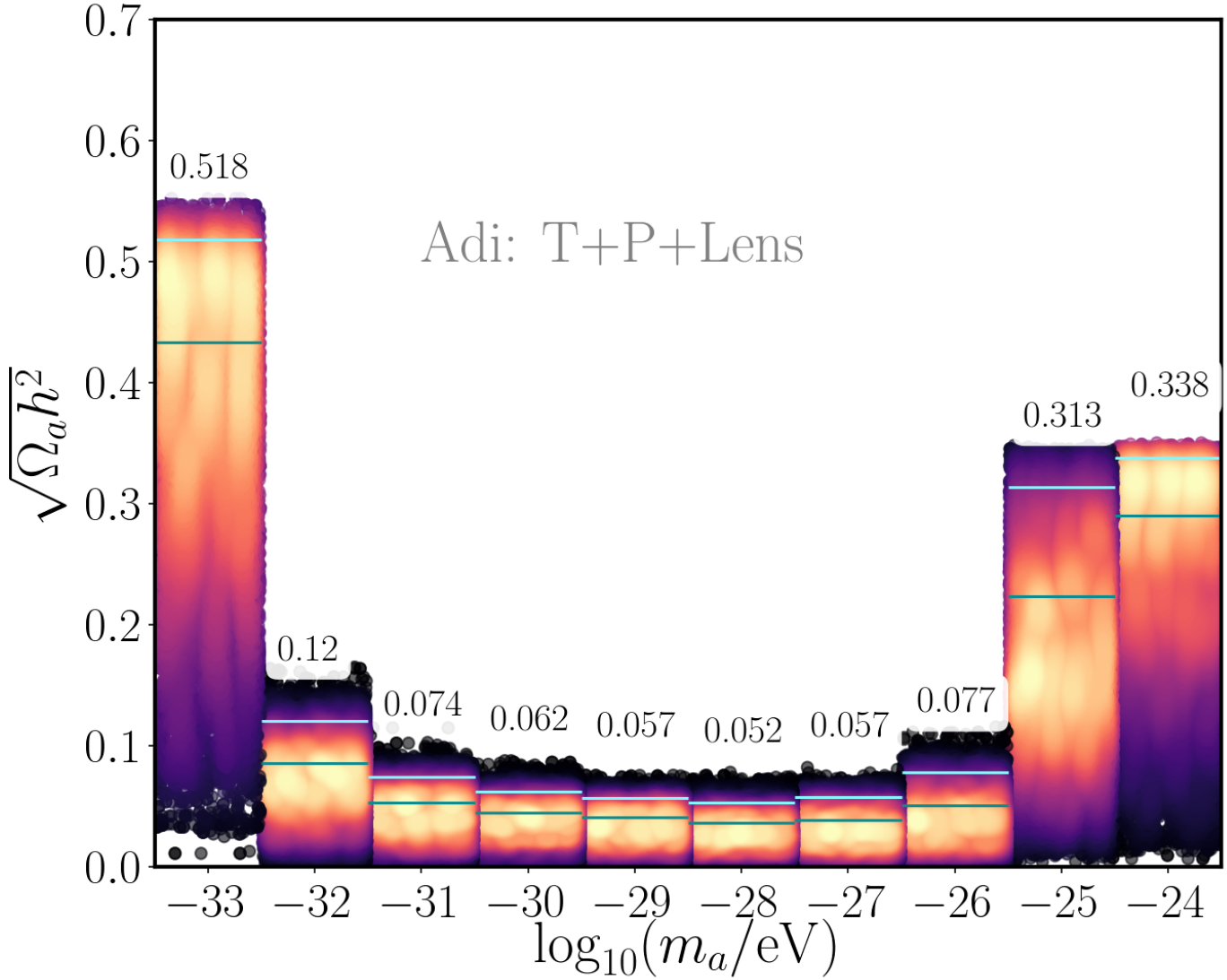
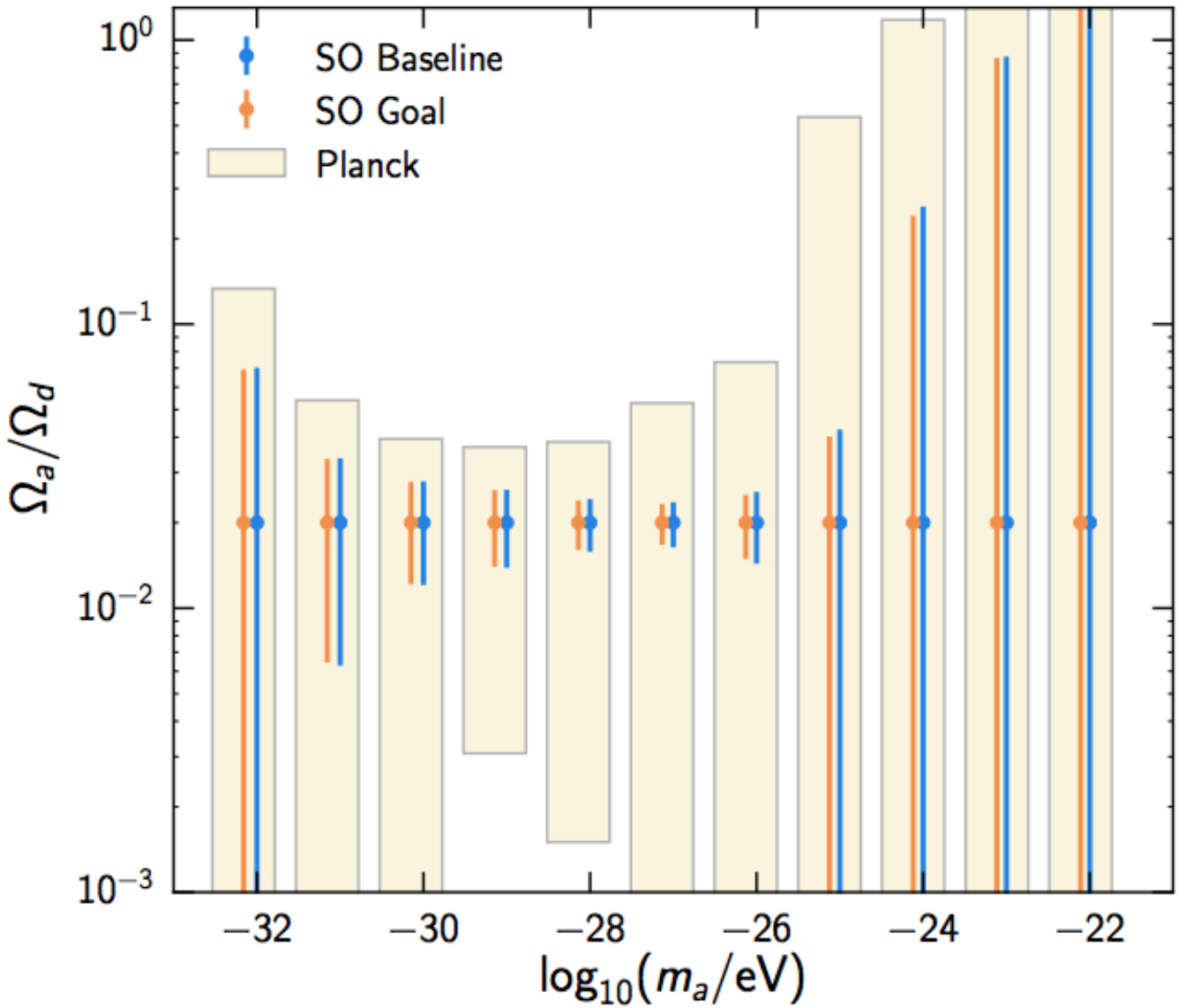


$$\Omega_a h^2 < 0.003 \Rightarrow f_{\mathrm{DM}} < 2.5\%$$ Precision test of CDM

Hlozek, DJEM, Grin (2017)



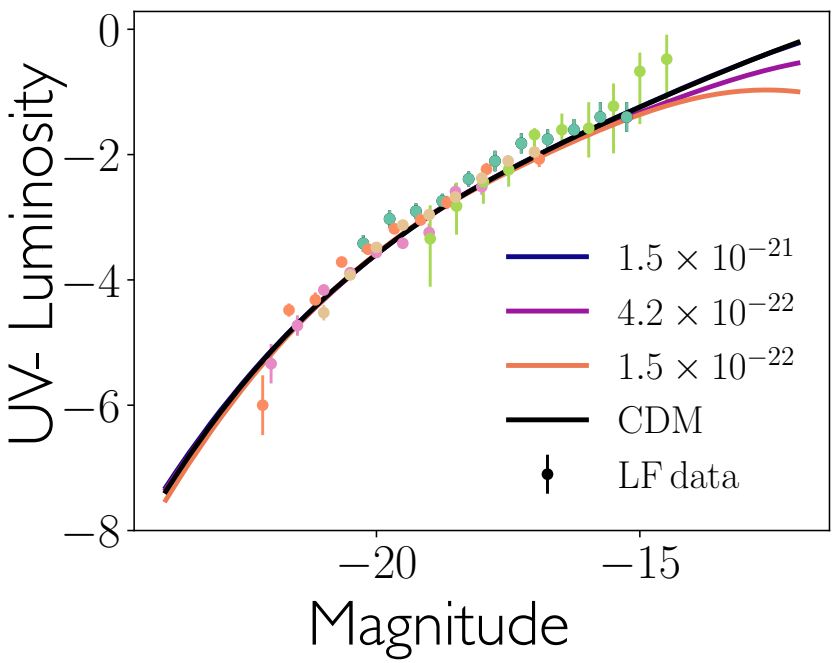
CMB-S4/SO: detect 1% at 5σ, improve max. mass limit by factor 10^2.

Hlozek, DJEM et al (2016); S4 (2016); SO (2018)

Galaxy Formation & high-k

DJEM & Silk (2014)

The axion Jeans scale suppresses low mass/high-z galaxy formation.
Use halo model/N-body sims + models of star formation.



Hubble EOR LF data require:

$$m_a \gtrsim 10^{-22}\ \mathrm{eV}$$

Corasaniti, DJEM et al (2016)

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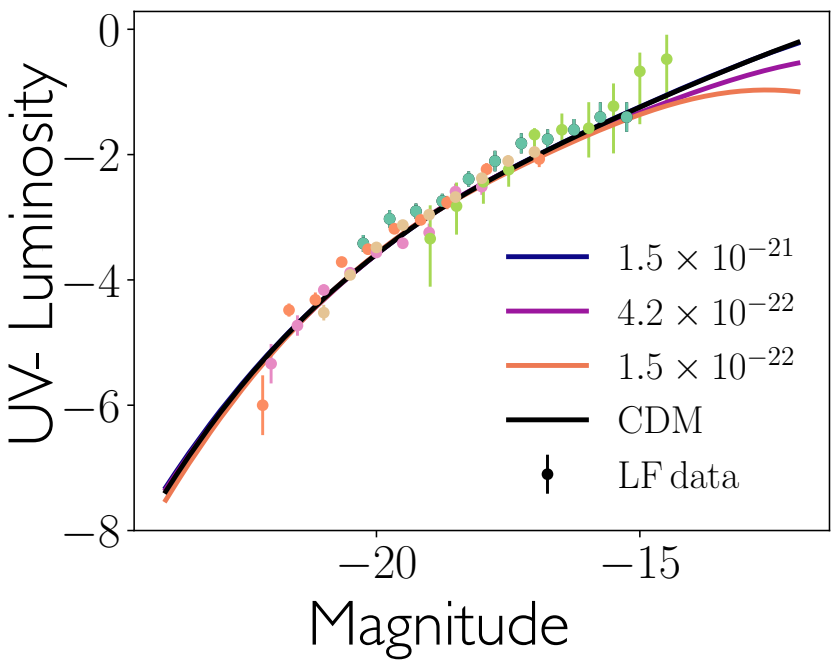
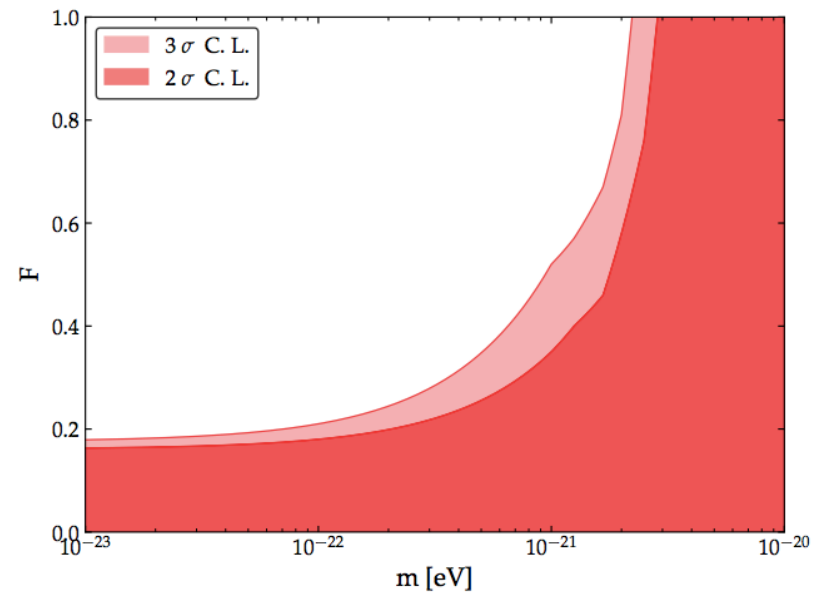




Hubble EOR LF data require:

$$m_a \gtrsim 10^{-22}\ \mathrm{eV}$$

Corasaniti, DJEM et al (2016)

Ly-a forest constrains mass/fraction: $m_a \gtrsim 10^{-21}\ \mathrm{eV}$

Kobayashi et al (2017)

Fuzzy DM and Galaxies

Hu et al (2000)
Schive et al (2014)
Hui et al (2016)

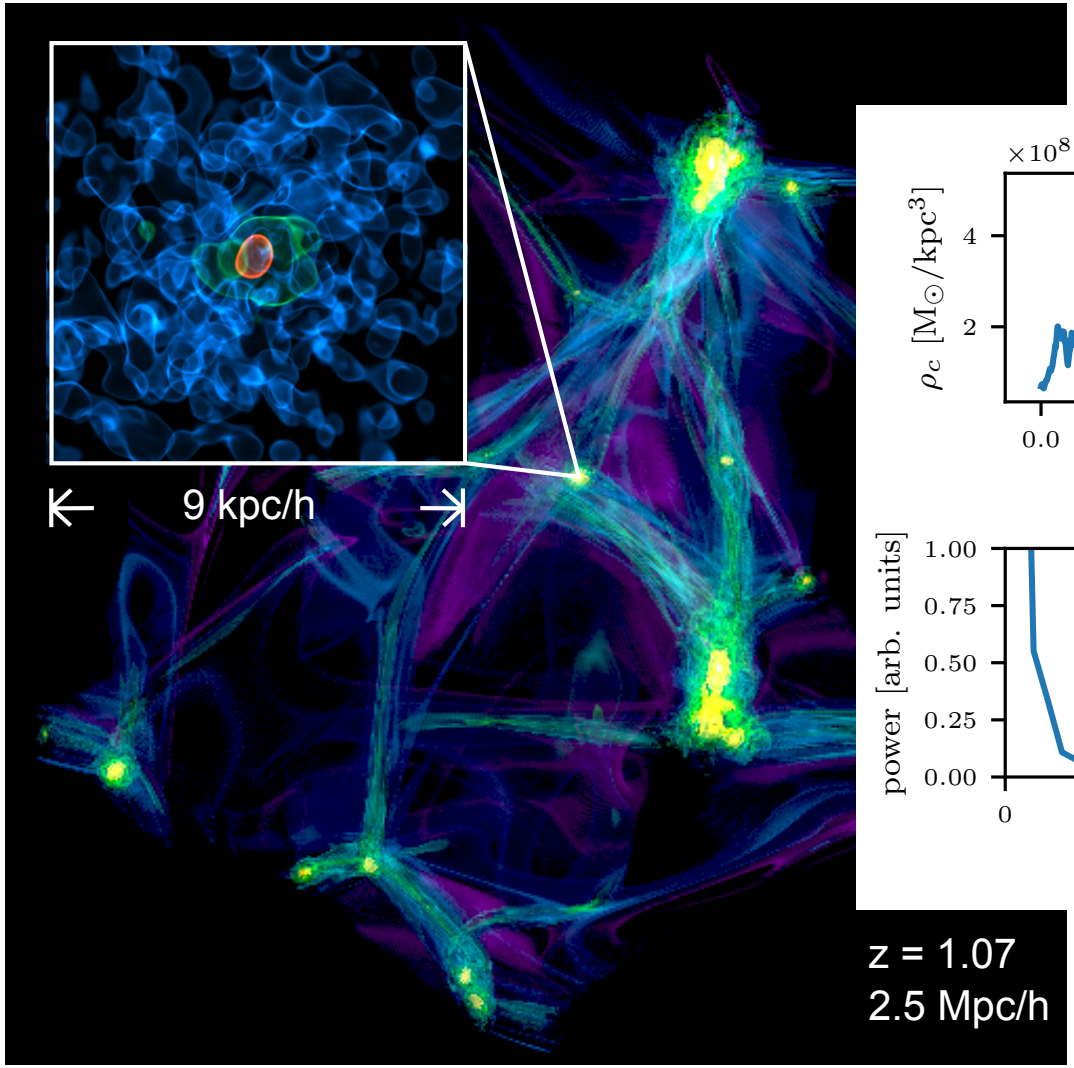
The axion de Broglie wavelength modulates ρ on kpc scales, and cores density profiles.

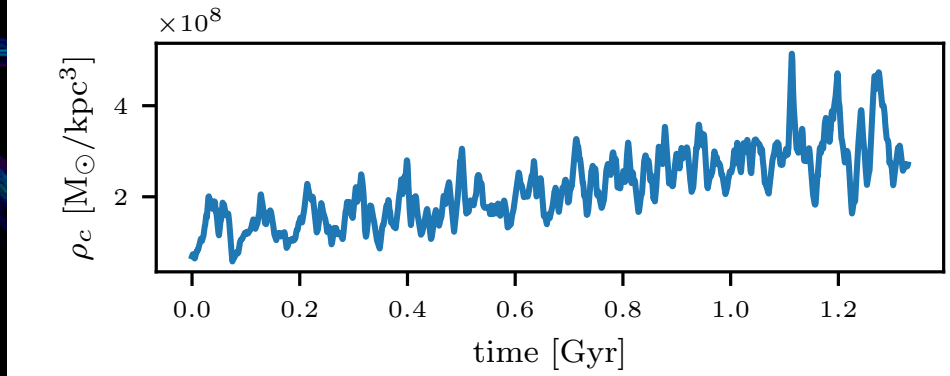
$$t_{\rm relax}(r) \sim \frac{0.4}{f_{\rm relax}} \frac{m^3 v^2 r^4}{\pi^3 \hbar^3} \sim \frac{1 \times 10^{10}\,{\rm yr}}{f_{\rm relax}} \left(\frac{v}{100\,{\rm km\ s^{-1}}}\right)^2 \left(\frac{r}{5\,{\rm kpc}}\right)^4 \left(\frac{m}{10^{-22}\,{\rm eV}}\right)^3$$

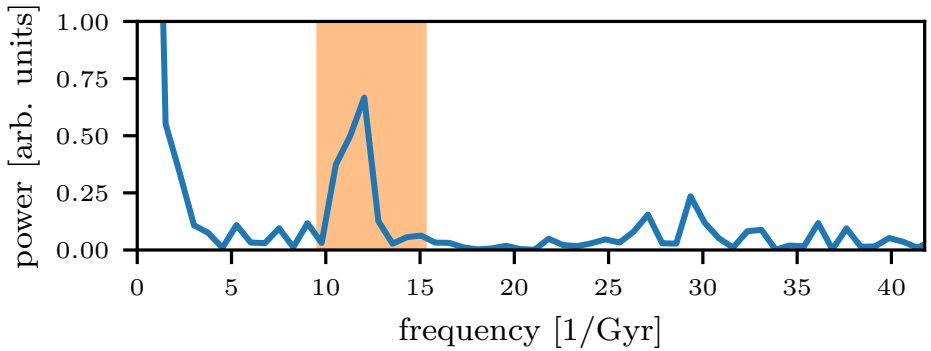
Resolving these effects require beyond N-body simulations.
Fuzzy DM is fundamentally different from CDM/WDM/SIDM etc.
Non-rel limit of Klein-Gordon-Einstein → Schrodinger-Poisson:

$$i\dot{\psi} + \frac{1}{2m_a^2}\nabla^2\psi - m_a\Phi\psi = 0;\ \ \nabla^2\Phi = 4\pi G_N|\psi|^2$$

Hybrid N-body + Schrodinger zoom method enables large boxes.
Core oscillations and evolution observed. Dynamical constraints?





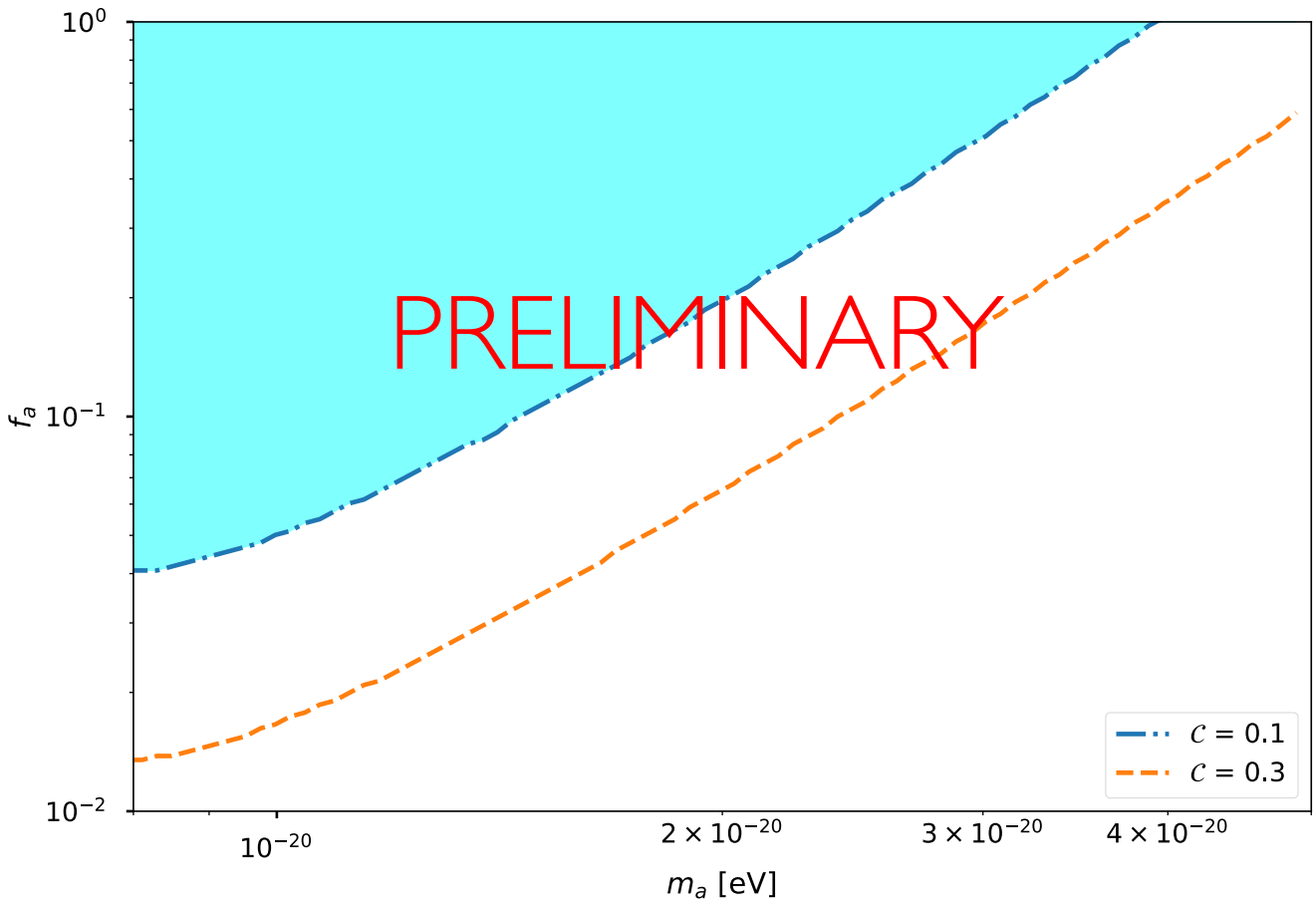


Veltmaat, Schwabe & Niemeyer (2018)

Star Cluster Stability

Brandt (2016)
DJEM & Niemeyer (in perparation)

The survival of the star cluster in Eridanus II (UFD) constrains the allowed relaxation time caused by DM fluctuations.



DETECTING AXIONS ON EARTH

Sikivie (1983); Graham & Rajdendran (2013)

$$m_a \quad g_{\mathrm{SM}}$$

DETECTING AXIONS ON ~~EARTH~~

Sikivie (1983); Graham & Rajdendran (2013)

IN GERMANY

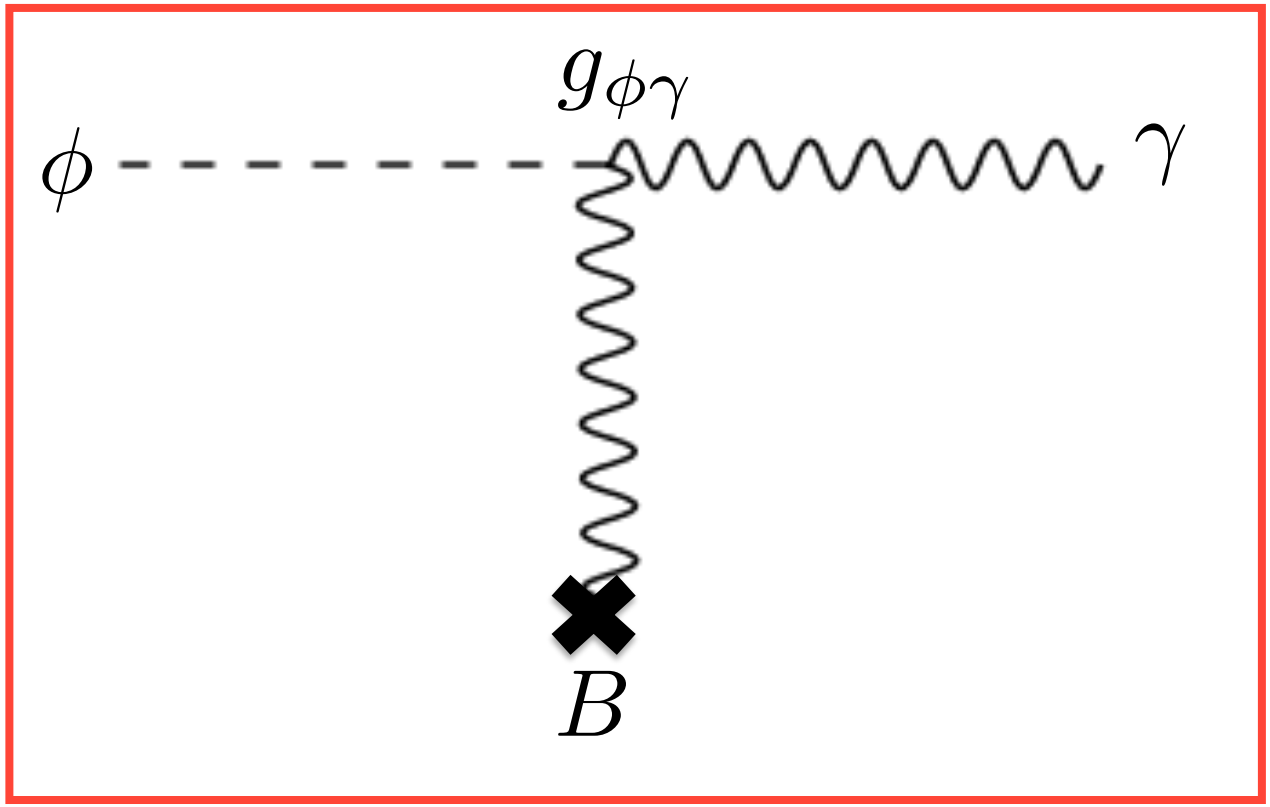
$$m_a \quad g_{\mathrm{SM}}$$

See talk by Sung Woo Youn or visit CAPP to see the equally exciting developments in South Korea!

The Classics

The Axion-EM Coupling

$$-g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}/4 = g_{\phi\gamma}\phi\vec{E}\cdot\vec{B}$$

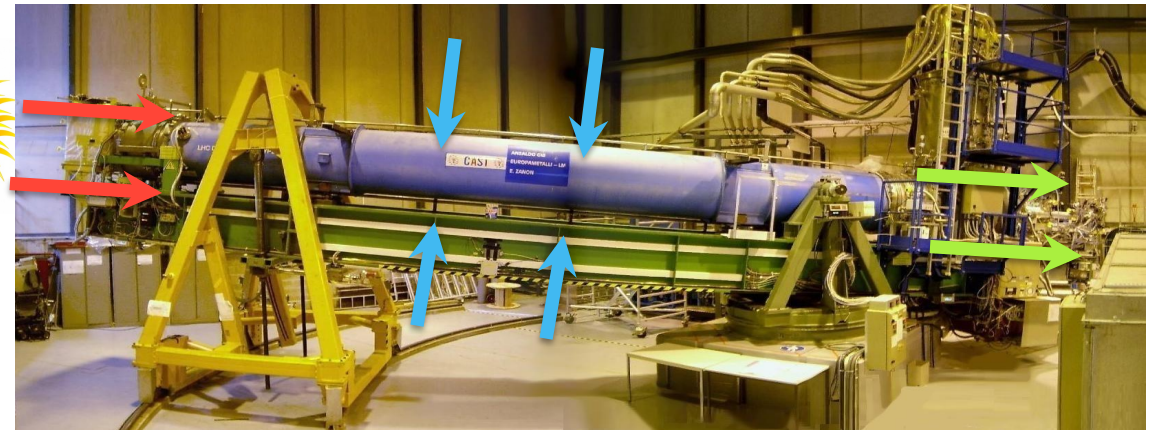


"Light shining through a wall":
Existing ALPS, OSQAR
New: ALPS-II

Van Bibber et al
(1987)

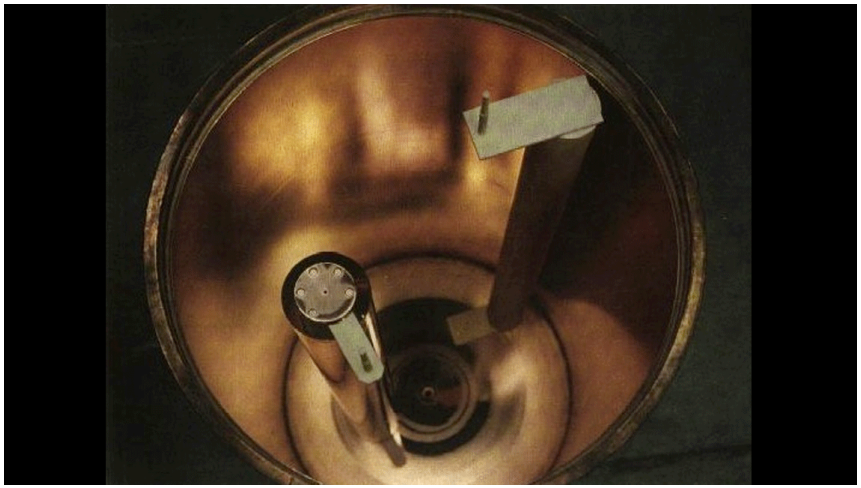
"Helioscopes":
Existing: CAST
New: IAXO

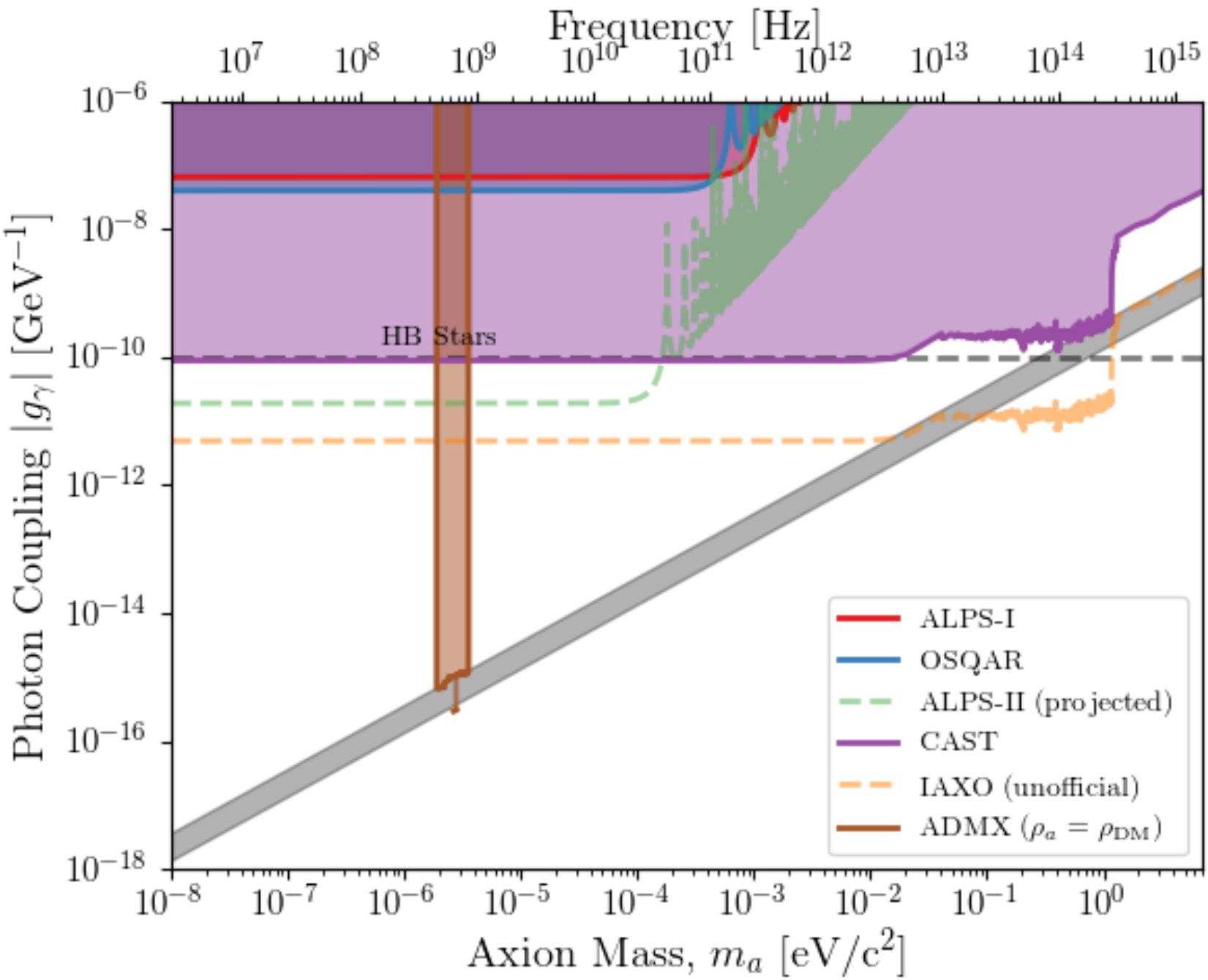
Sikivie (1983)



RF cavity "Haloscopes":
Existing: ADMX
New: ADMX-2,
CULTASK + many more

Sikivie (1983)

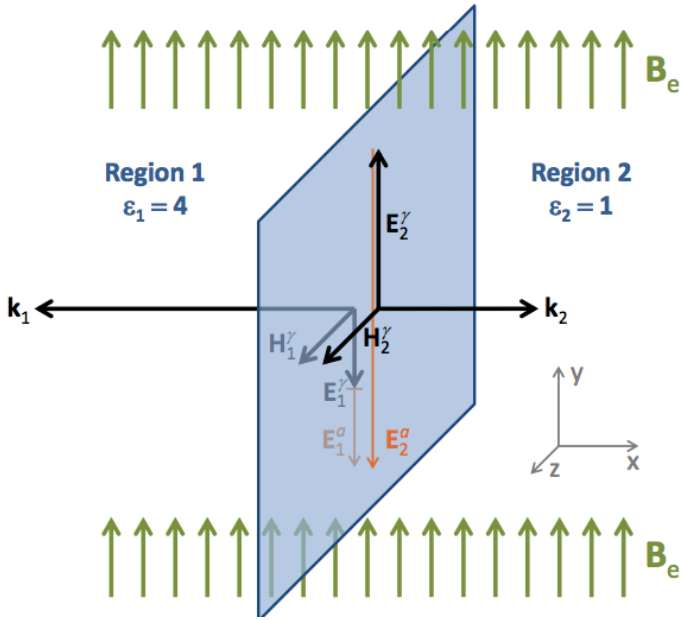


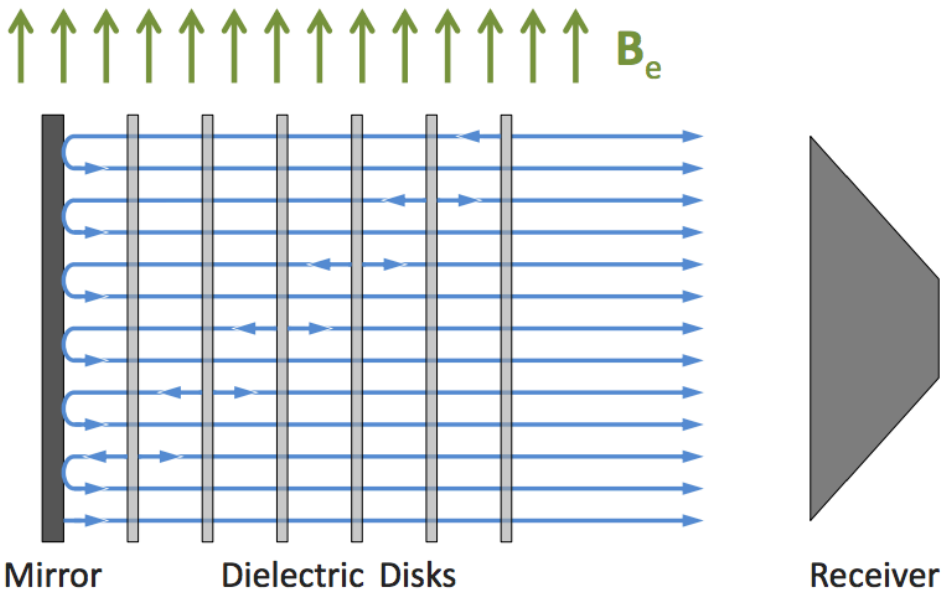

Frequency [Hz]
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Photon Coupling $|g_\gamma|$ [GeV^{-1}]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
HB Stars
ALPS-I
OSQAR
ALPS-II (projected)
CAST
IAXO (unofficial)
ADMX ($\rho_a = \rho_{\rm DM}$)
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Axion Mass, m_a [eV/c^2]

The Haloscope New Wave

MADMAX: Dielectric Haloscope

Coherent induced EM from dielectric boundary → enhancement.
Prototype built in Munich. Full experiment funded at DESY.





MADMAX interest group (2017)
Horns et al (2013)

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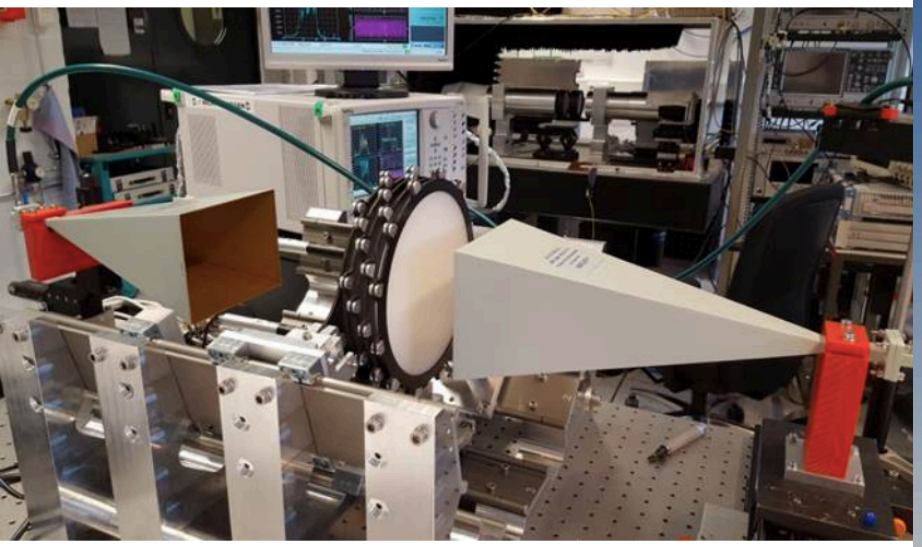
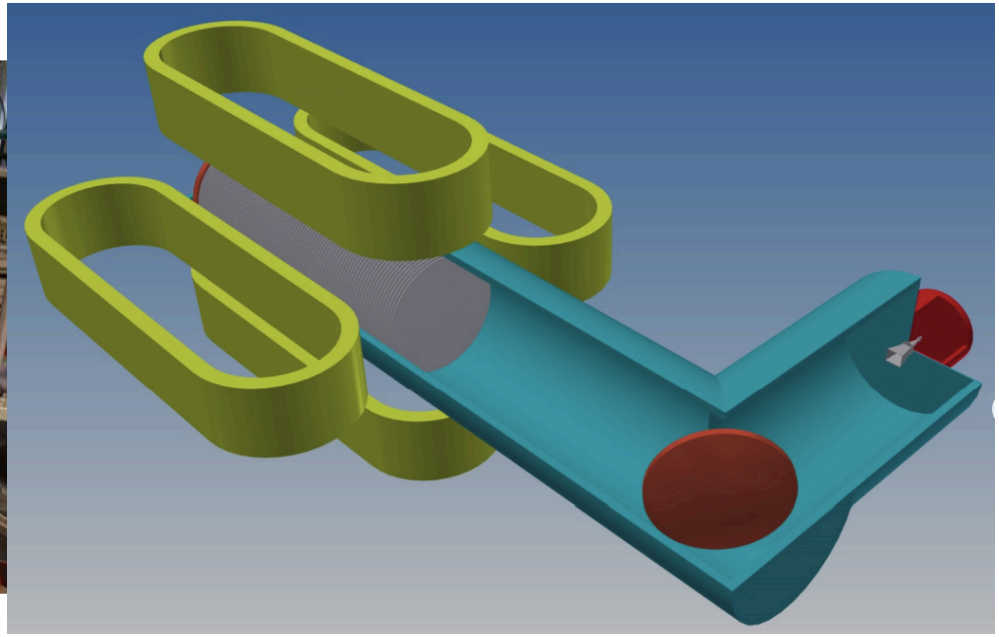
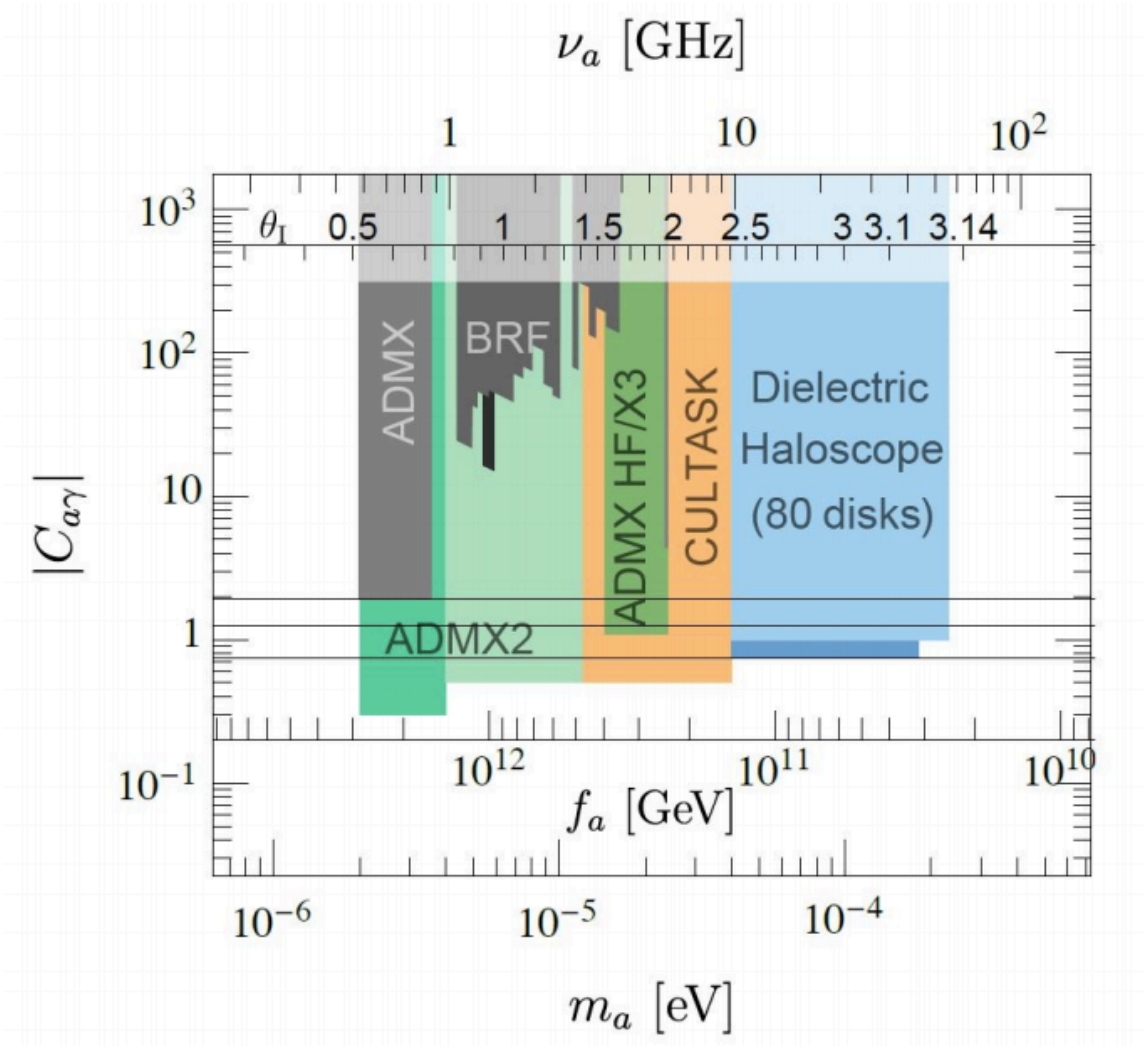




MADMAX interest group (2017)
Horns et al (2013)

MADMAX: Dielectric Haloscope

Projected sensitivity to heavier axions than RF cavities:



Millar et al (2016)

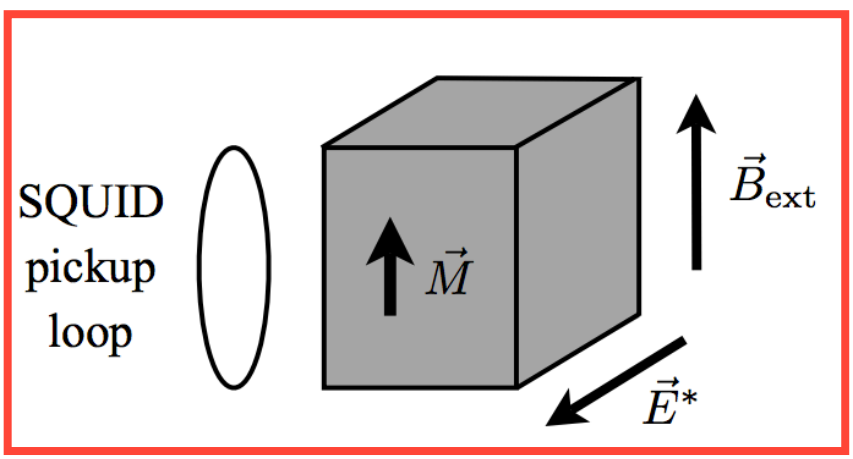
CASPEr: NMR Haloscope

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

Align nuclear spins. Precess at Larmour frequency in B_{ext}.
Dipole moment and axial current coupling → additional precession.
Resonant enhancement for $2\mu_m B_{\rm ext} = m_a$

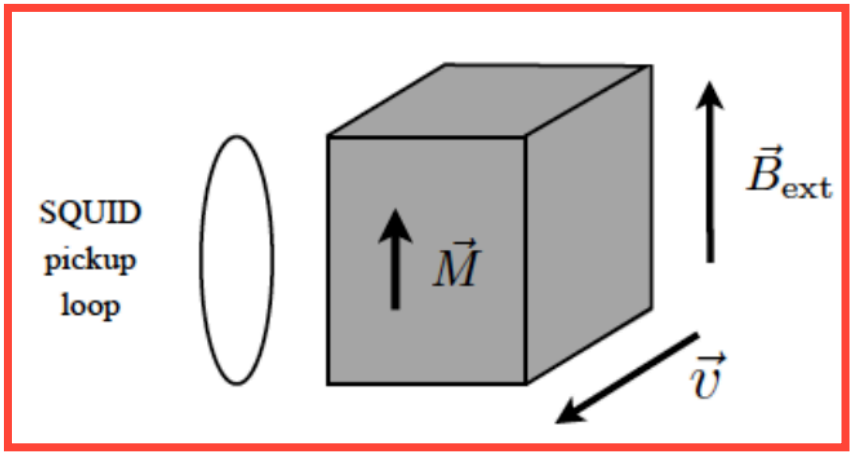
CASPEr-Electric

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



CASPEr-Wind

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

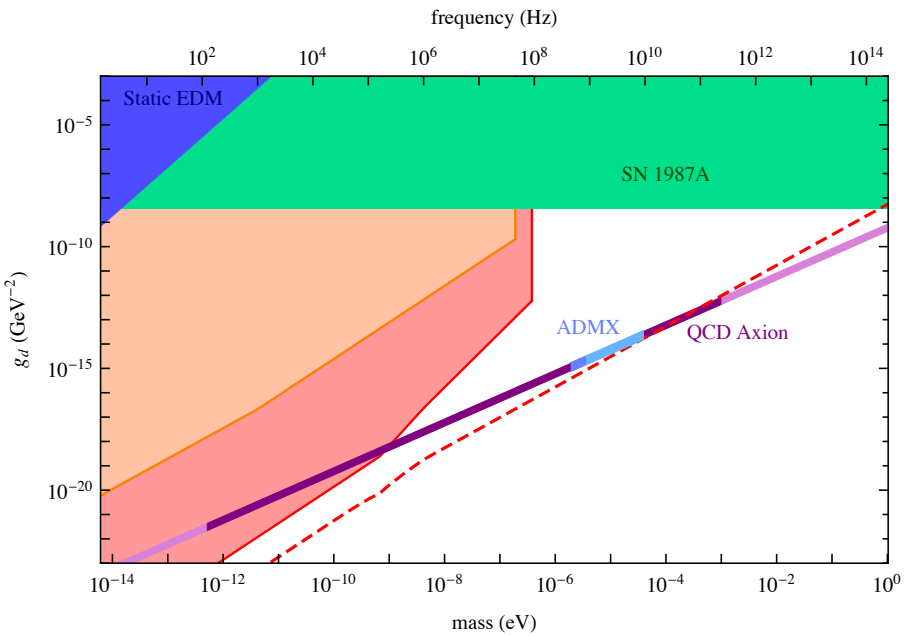


CASPEr: NMR Haloscope

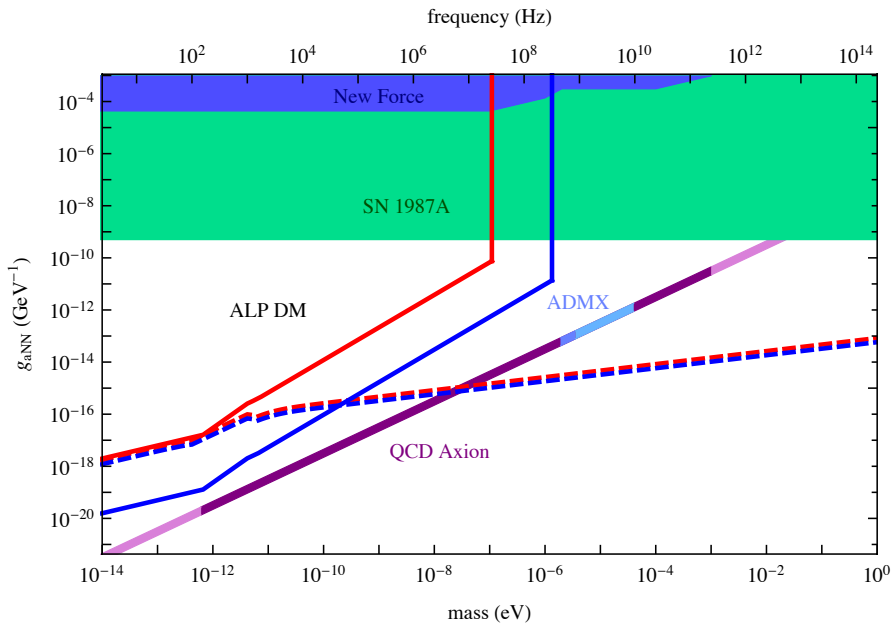
Graham & Rajendran (2013)
Budker et al (2014)

CASPEr-Now: prototype in Mainz.
Projected sensitivity to lighter axions than RF cavities.

CASPEr-Electric



CASPEr-Wind

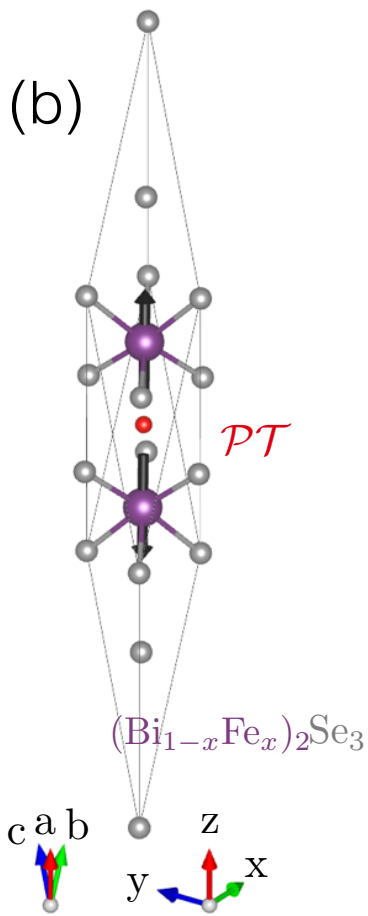


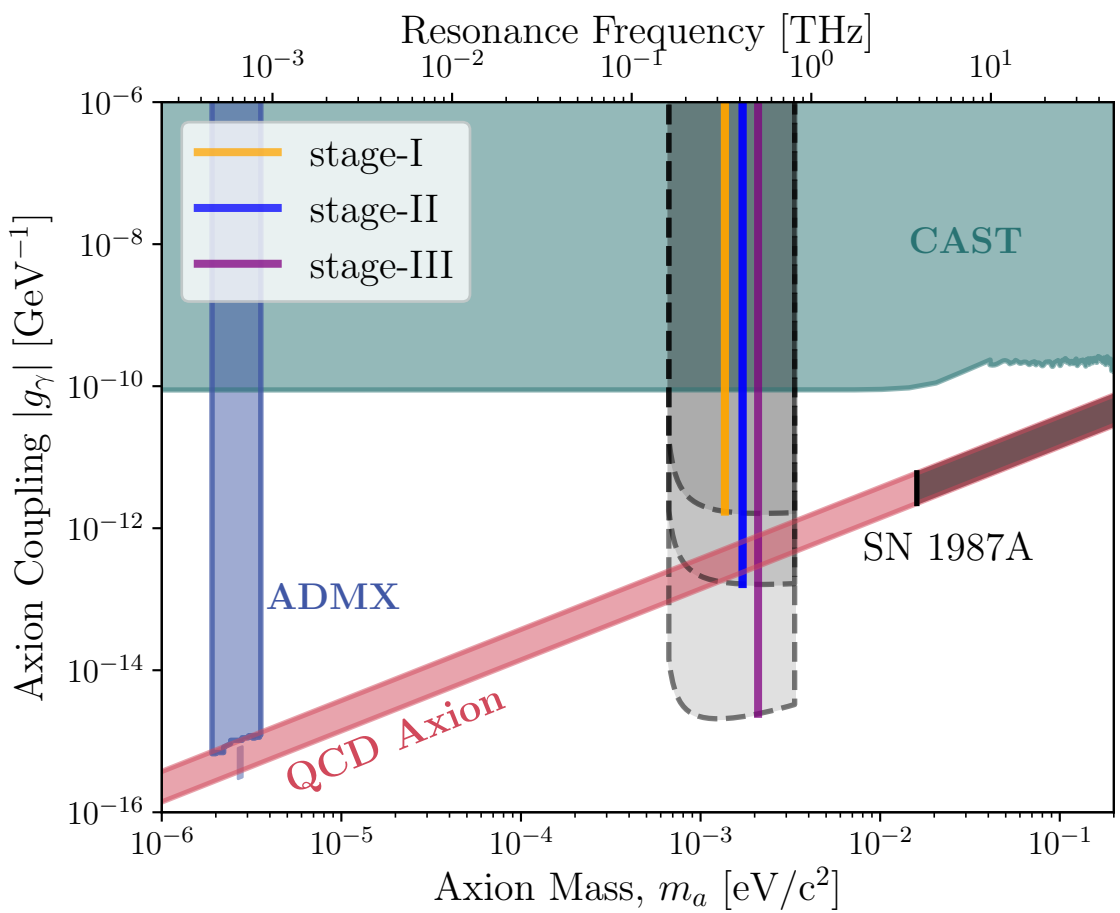
TOORAD: Axionic Materials

DJEM et al (2018)

Antiferromagnetism → pseudoscalar ~ B-tunable meV spin waves.

Dirac materials → chiral anomaly → resonantly driven by axion DM.





Thank You!

Comment on DE & Inflation

Axions → accelerated expansion via hilltop cosine with $f \sim M_{pl}$.

Axion Inflation

- Disfavoured by Planck (2018) + BICEP ns and rT

Axion Dark Energy

- Favoured by "swampland conjecture" on dS vacua?

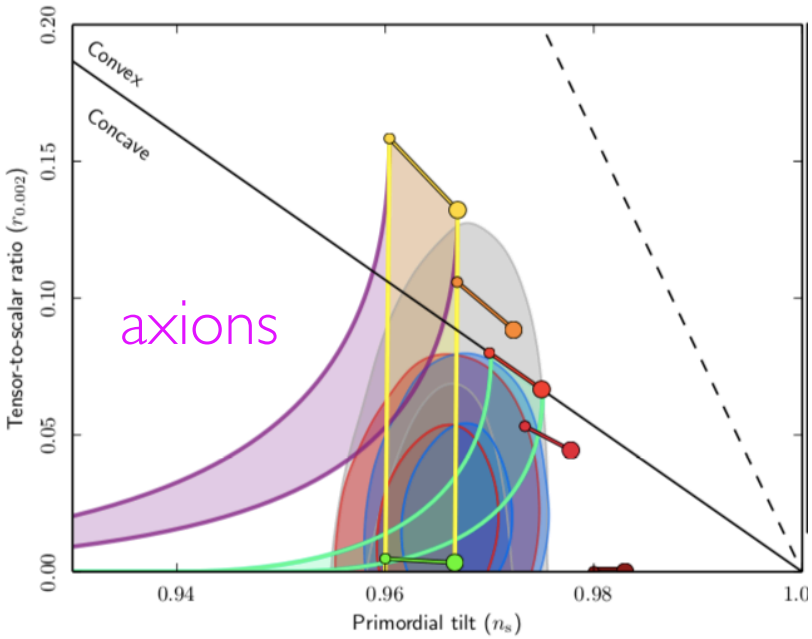


Fig. Planck (2018)

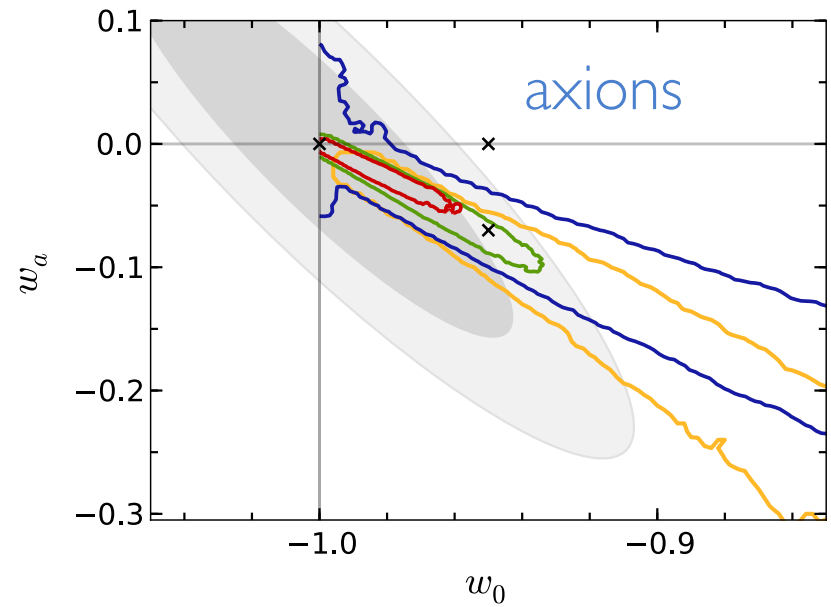


Fig. DJEM et al (2014)