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Astrophysical Constraints on Axions

David J. E. Marsh

Recent Progress in Axion Physics,

Durham, Sept. 2022

Science and Technology Facilities Council

King's College London

COSMIC STRUCTURES

Axion Cosmology

Eq. of state, w → homo. pressure. Appears in Friedmann → affects expansion.
Sound speed, c_s → pressure perts. Affects growth of structure.

	CDM	Baryons	Photons	Λ
w	0	0	1/3	-1
c_s^2	0	0 (late) 1/3 (early)	1/3	Does not cluster (-1)

Cosmology: measure n-point functions on the sky, normally in Fourier space.
Compare to theory predictions by Bayesian parameter fitting (typically MCMC).

CMB measures the expansion rate via Sachs Wolfe (late) and Silk Damping (early).
Late time observables sensitive to late time expansion + growth of structure.

CMB Constraints

Estimate

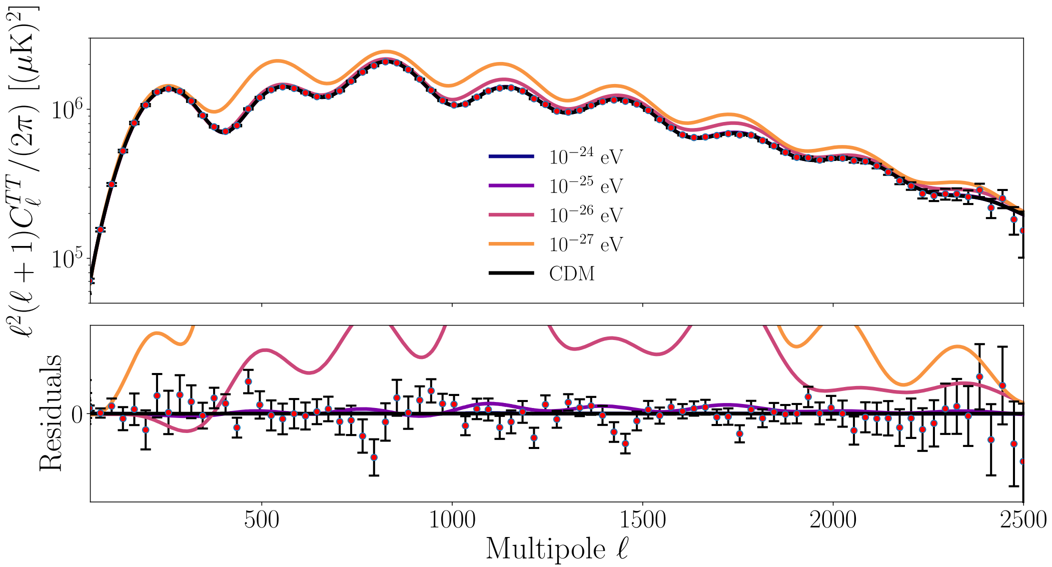
Consistent w/ ΛCDM expansion rate to $z \sim 10^5$ → DM formed before this time.

$$m > 2.6 \times 10^{-25} \text{ eV}$$

$=H(10^5)$

Precision

Solve Boltzmann equations & MCMC 8+ parameters with Planck likelihood using cosmosis+axionCAMB.



Also use polarization & lensing anisotropies + correlations. Vary UBDM and CDM density simultaneously.

CMB Constraints

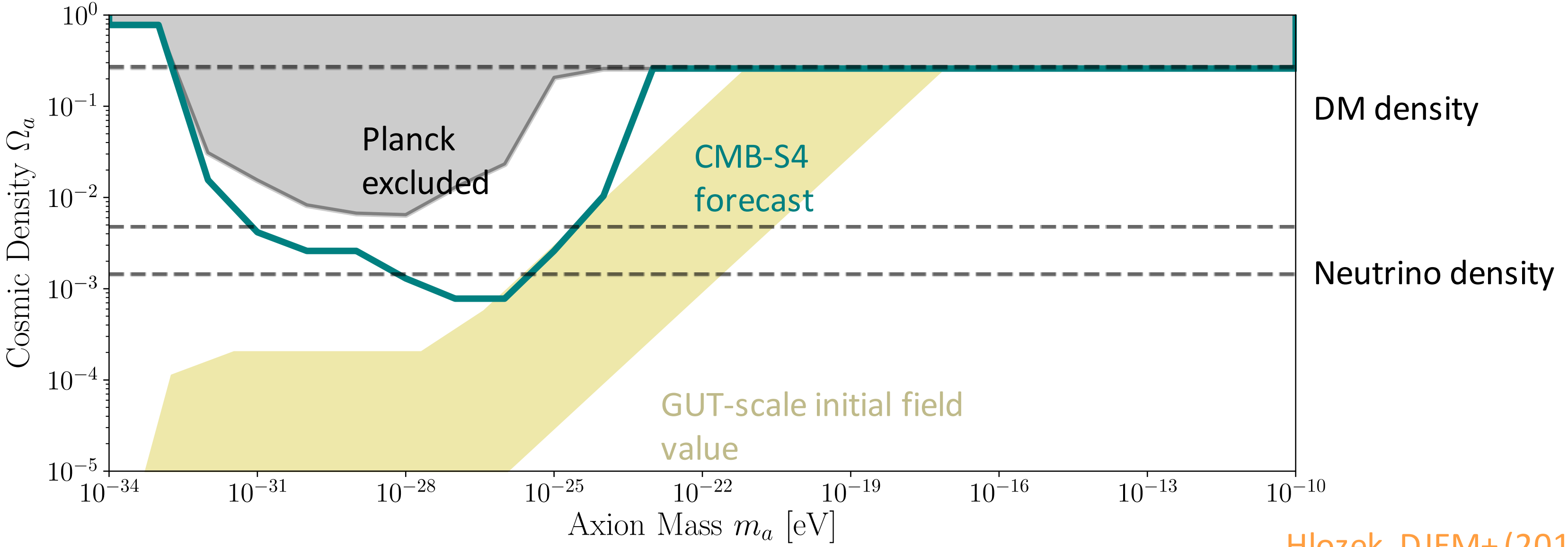
Estimate

Consistent w/ LCDM expansion rate to $z \sim 10^5$ → DM formed before this time.

$$m > 2.6 \times 10^{-25}\ \text{eV}$$

Precision

Solve Boltzmann equations & MCMC 8+ parameters with Planck likelihood using cosmosis+axionCAMB.

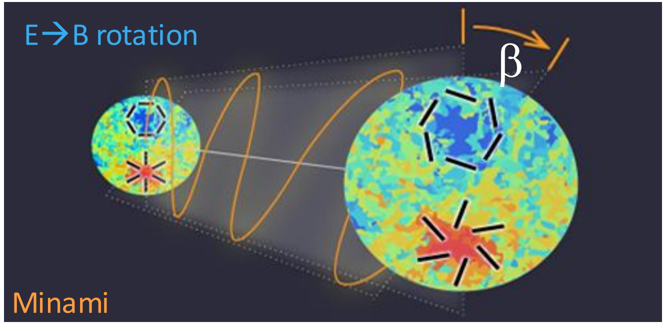


Hlozek, DJEM+ (2014+)

Birefringence

$$\beta = 0.30^{o} \pm 0.11^{o}$$

Minami & Komatsu (2020)
Planck collab. (2022)



Isotropic birefringence can be caused by an ultralight axion via:

$$\mathcal{L} = g\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \;\; \Rightarrow \beta = \int_{\eta_{\rm CMB}}^{\eta_0} g\frac{d\phi}{d\eta}d\eta$$

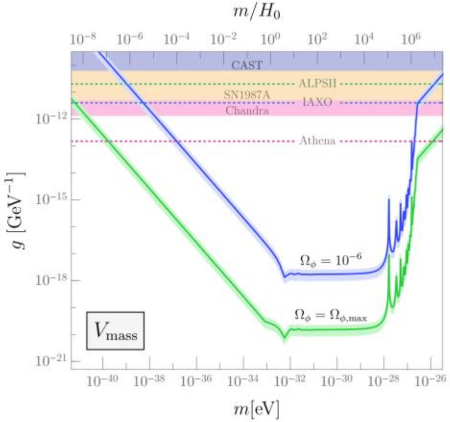
This fixes the axion mass to a range also probed by primary anisotropies and lensing:

$$10^{-33}\ \mathrm{eV} \lesssim m \lesssim 10^{-28}\ \mathrm{eV}$$

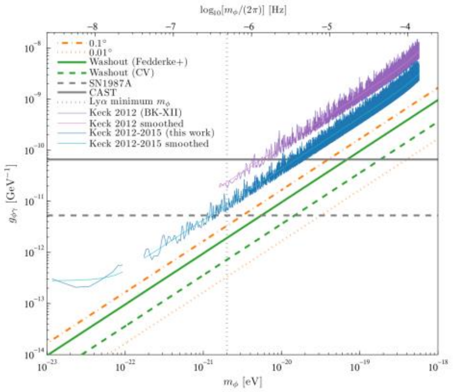
H_0 $\qquad$ H_{CMB}

Isocurvature in the ultralight axion also induces anisotropic birefringence and large angle BB with amplitude fixed by scale of inflation.

Birefringence constraints can be highly complementary/synergistic to direct searches:



Enforcing β=0.3
Fujita et al (2021)

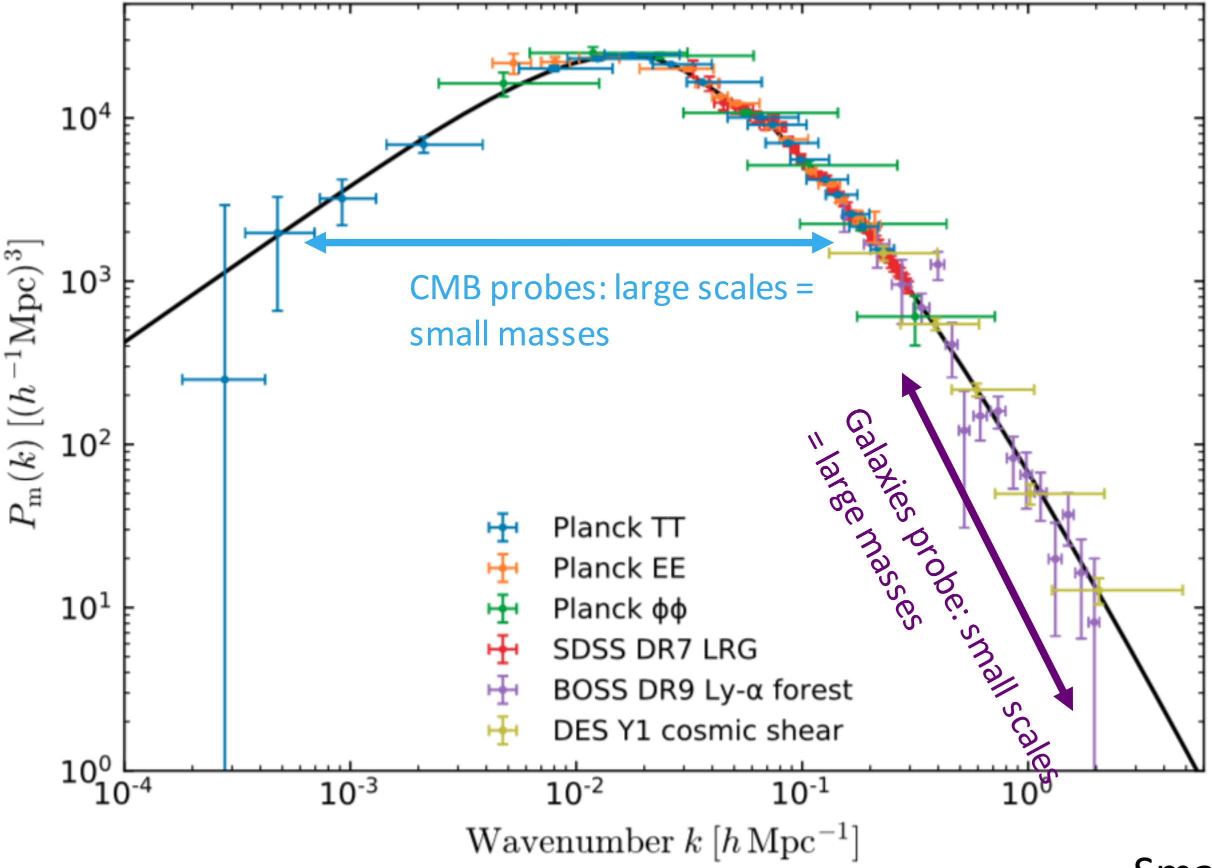


"Washout" & heavier axions
Keck (2022)

SO opportunities: foregrounds, anisotropic component, ultralight DM bounds...

Fig: Planck (2018)

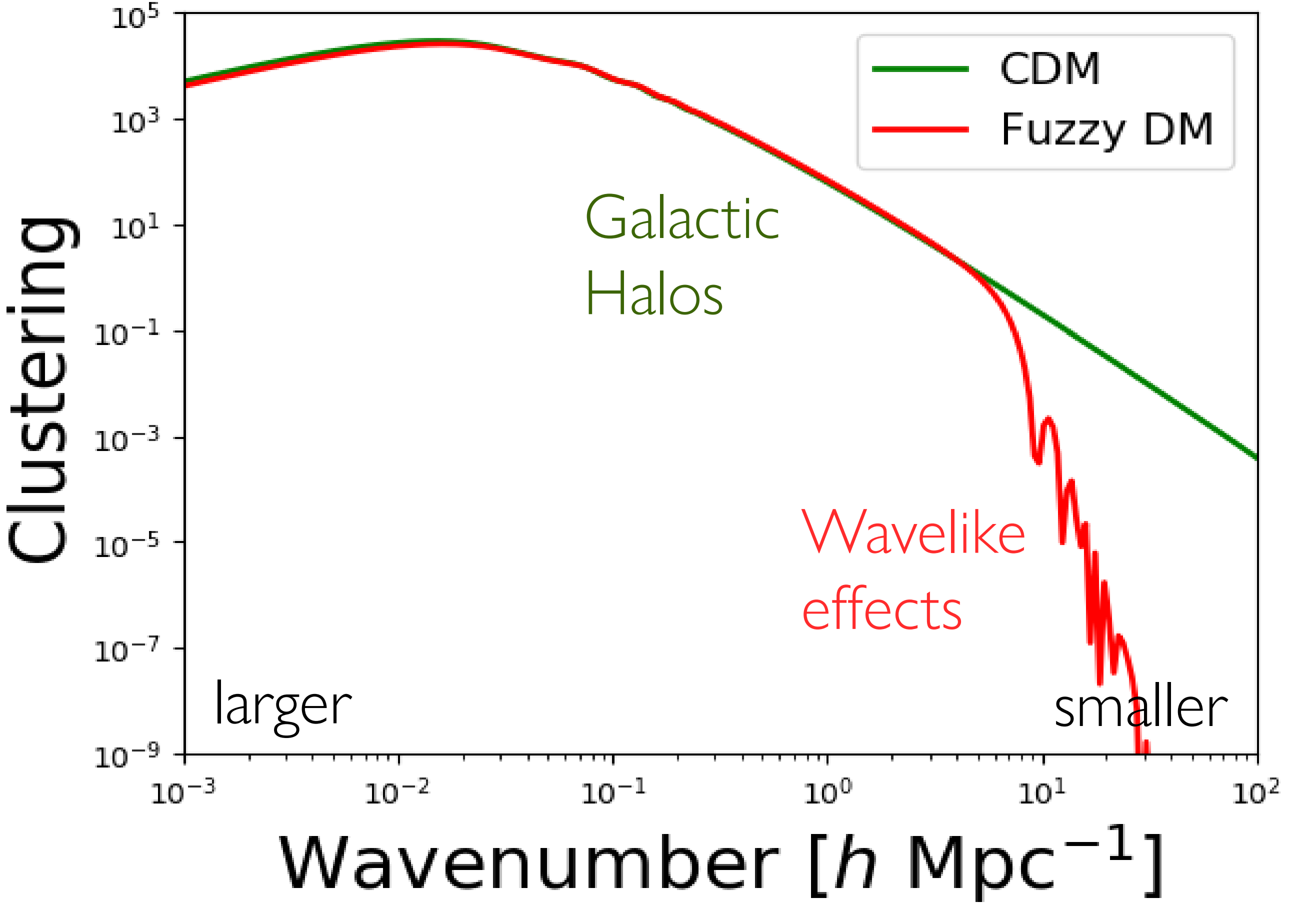
Power spectrum = F.T. of two-point correlation of density perts.



Consistent with CDM on all observed scales → $c_{\rm eff}=w=0$ when these modes "entered the horizon"

Large scales

Small scales

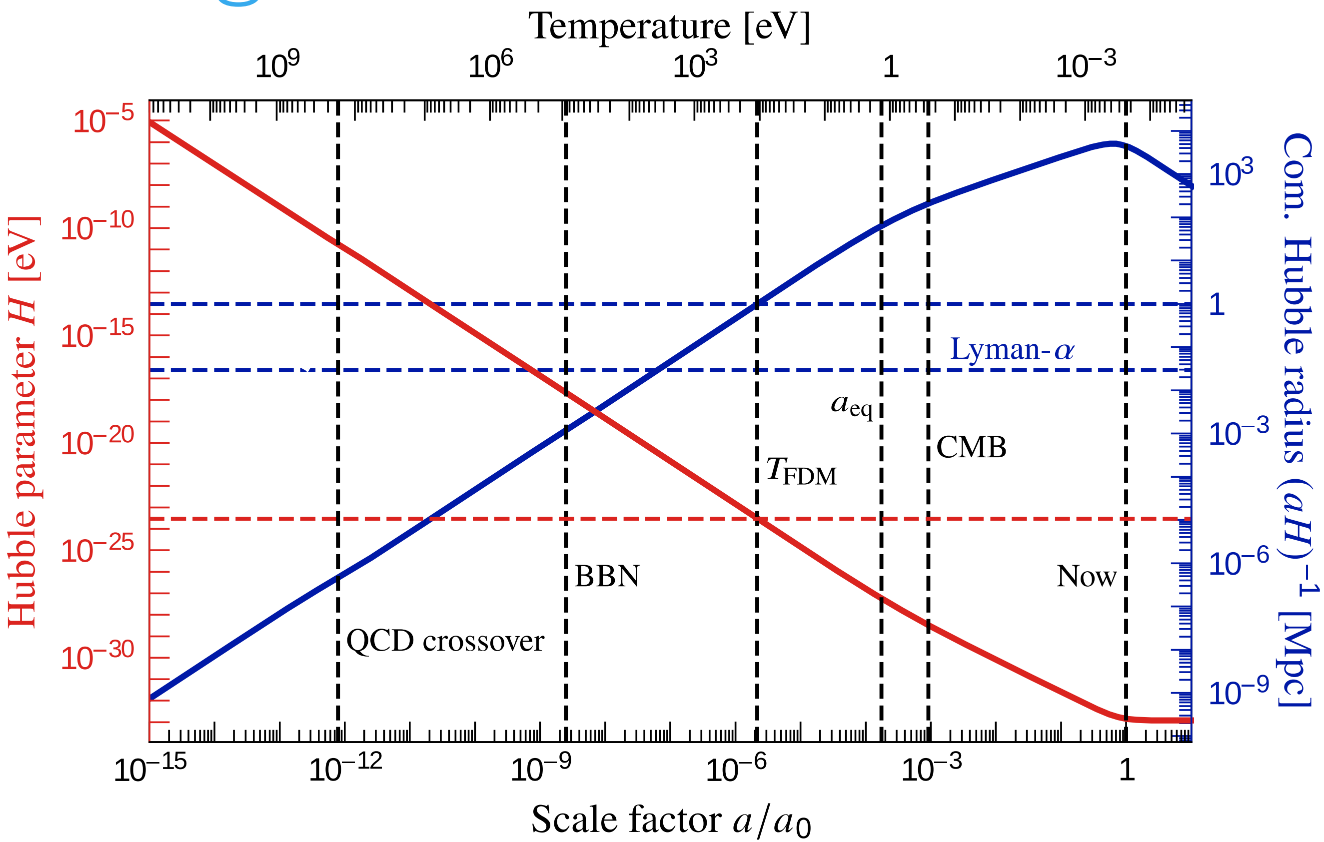


CDM
Fuzzy DM
Galactic Halos
Wavelike effects
larger
smaller
Clustering
Wavenumber [h Mpc−1]

Estimating Bounds

DJEM & Hoof (2021)

Read off particle mass constraint

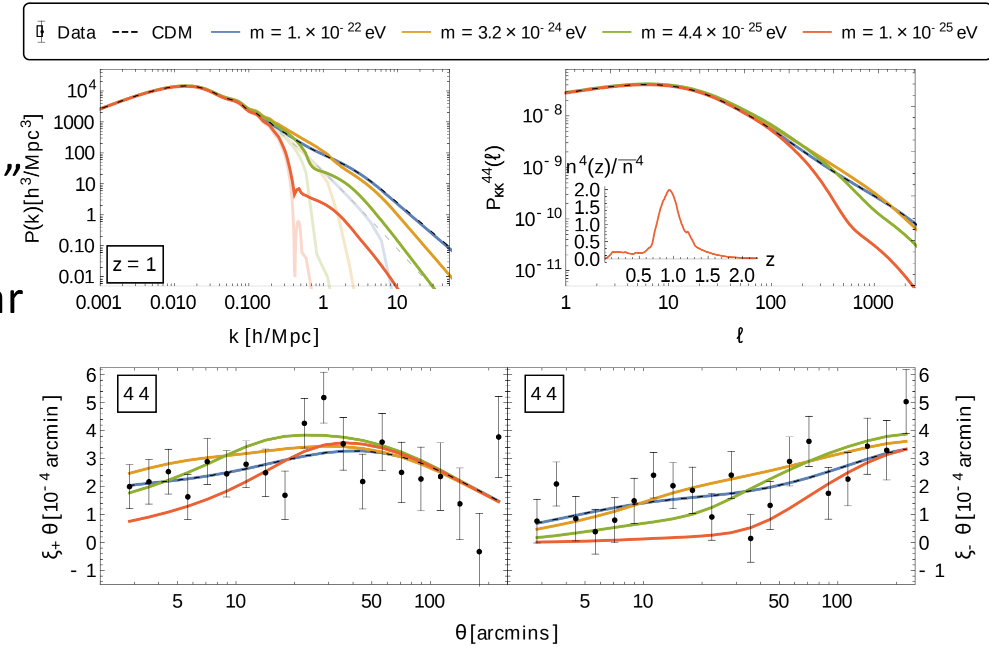


Compare to wavenumber k in P(k)

Power Spectrum Constraints

Example 1: DES lensing
(Dentler, DJEM et al, 2021)

- Measure "galaxy shear correlation function" consistent with CDM.
- Compute from P(k) using axionCAMB (linear theory) + "halo model" non-linearities.
- DES-Y1 Bayesian → m>10^{-23} eV.
- DES-Y3 forecast 10^{-22} eV, Euclid 10^{-20} eV.



Lensing advantage: directly measure DM

Example 2: BOSS Lyman-alpha forest (Rogers & Peiris, 2020). Measure flux power spectrum consistent with CDM. Non-linear and gas physics using N-body +hydro+"emulator" for parameter dependence. Limit m>2x10^{-20} eV.

INSIDE GALAXIES

Schrödinger-Poisson

Non. relativistic limit of the Klein-Gordon-Einstein equations:

$$\phi = \frac{1}{\sqrt{2m^2}}\left(\psi e^{imt} + \psi^* e^{-imt}\right)$$

Real field → Complex
Both are ”condensates”

$$\psi = \sqrt{\rho}e^{iS}\,, \vec{v} = \nabla S$$

Madelung/fluid interpretation

Brackets = spatial average

$$i\dot{\psi} - \frac{1}{2m}\nabla^2\psi + m\Phi\psi = 0\,, \quad \nabla^2\Phi = 4\pi G\left(|\psi|^2 - \langle|\psi|^2\rangle\right)$$

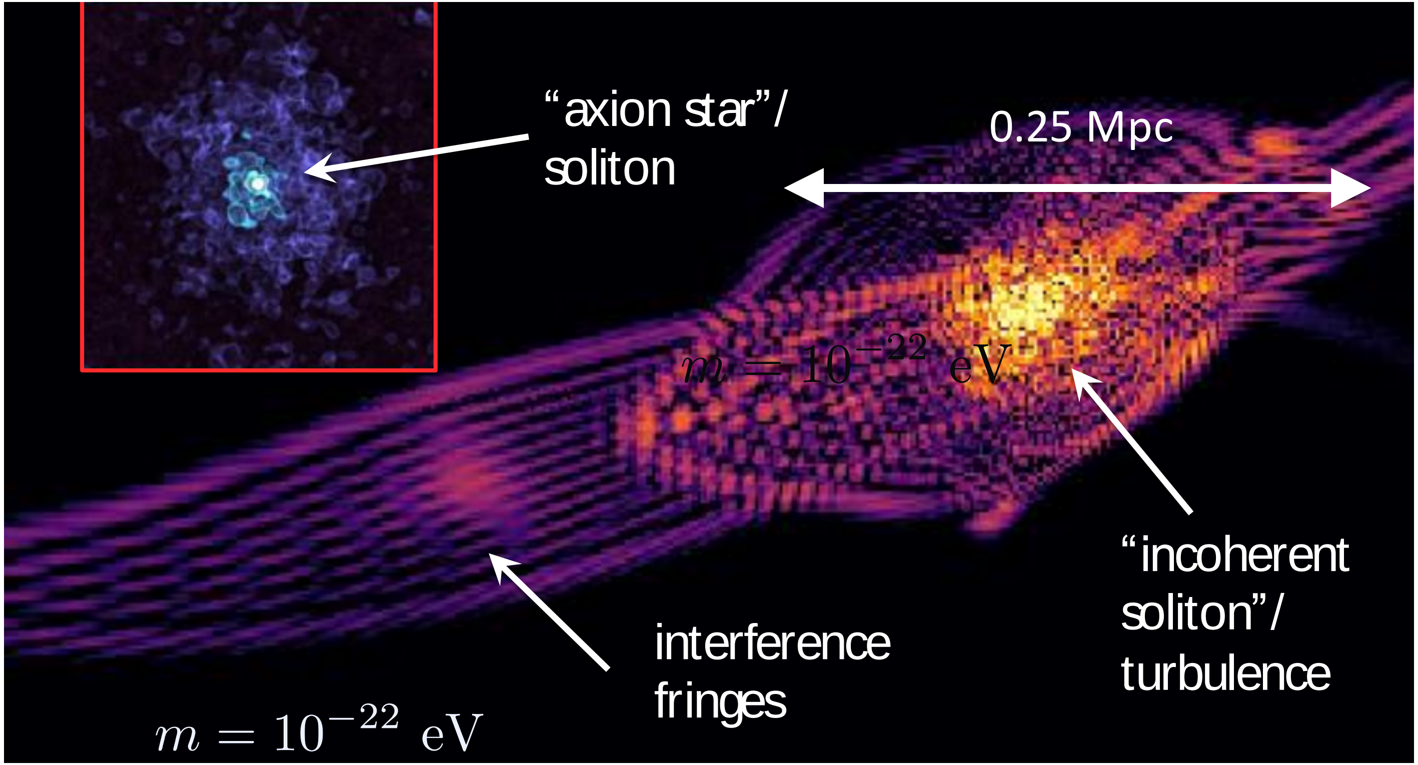
“quantum pressure” in fluid
c_{eff}^2 in perturbations
de Broglie coherence

$$\left[Gm\int\frac{|\psi(x')|^2}{|x-x'|}d^3x'\right]\psi(x)$$

non-linear and non-local

“Fuzzy DM physics” different from CDM/WDM etc on scales ~ de Broglie.
Waves → interference. Gradient pressure → stable solutions & coherence.

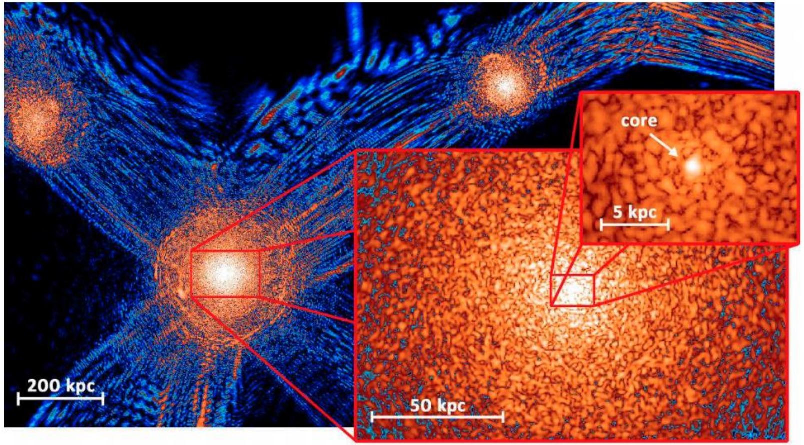
Challenge: simulate this equation over a wide range of scales.
Cosmology covers Gpc → kpc lengths, and overdensities ~ 10^5.



Soliton+ halo structure also in non-linear optics. Called "incoherent soliton"

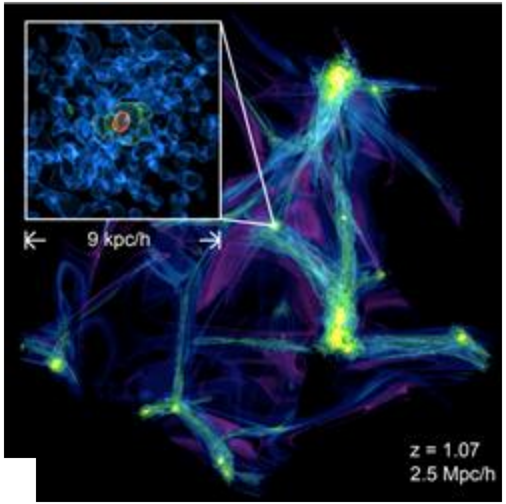
Note: this is all classical physics

Fig. Philip Mocz

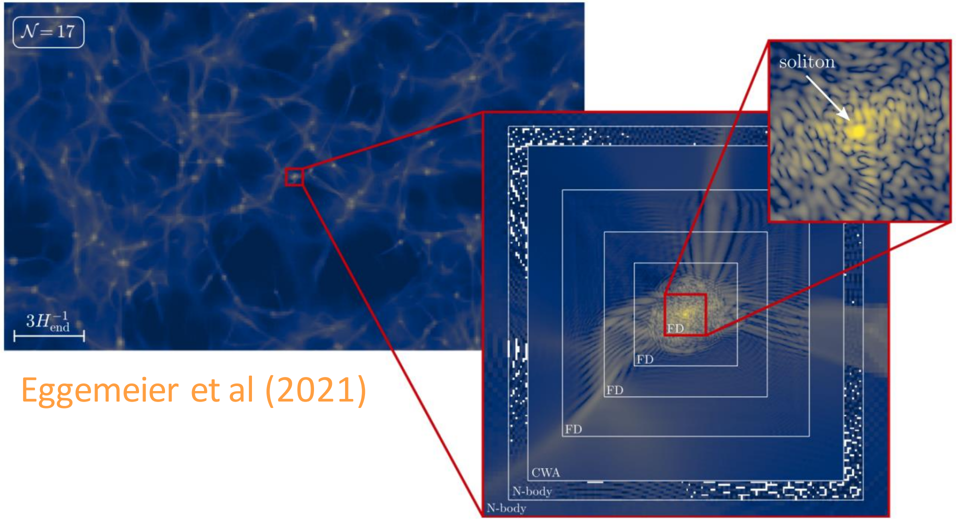


Schive et al (2014)

Dwarf galaxies 10^8 M_{sol}, particle mass $\sim 10^{-22}$ eV

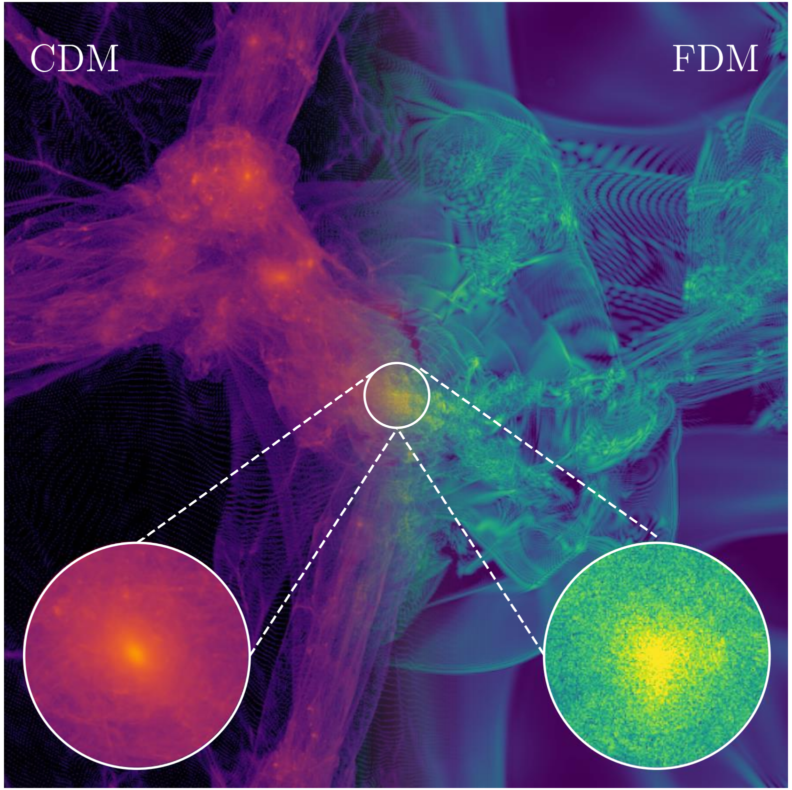


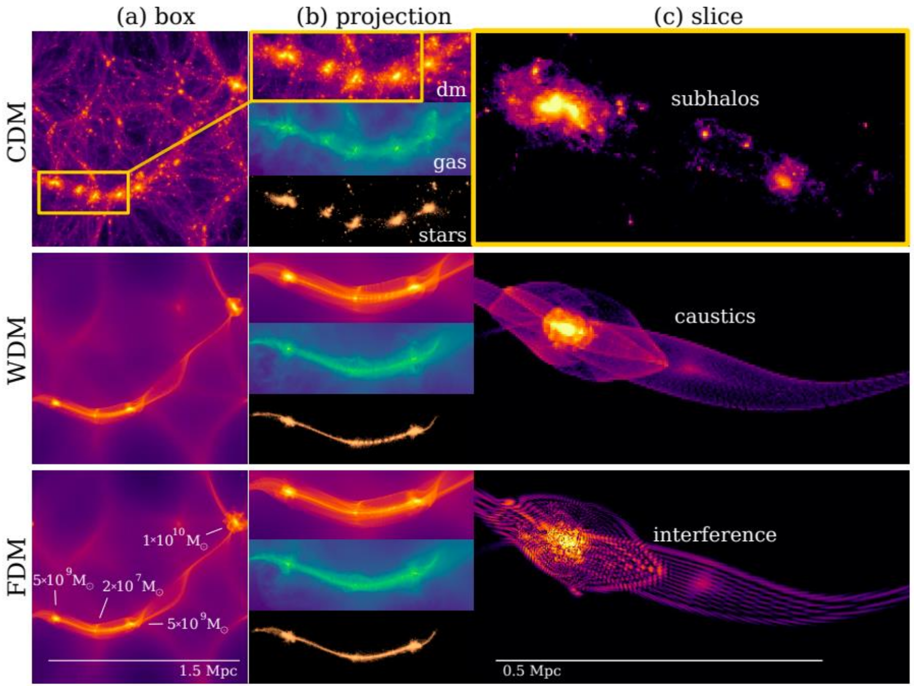
Veltmaat et al (2018)



Eggemeier et al (2021)

"Inflaton halos" ~ 100g, particle mass $\sim 10^{14}$ GeV





Mixed CDM+gas

Mocz et al (2019)

Mixed CDM+ FDM

Lague et al (forthcoming)

Opportunity/challenge: physics consequences of interference fringes.

Note: this is all classical physics

Inside a Halo: Dynamics

Velocity field obeys Maxwell-Boltzmann.
Coherence length and time:

$$L = \frac{2\pi}{m\langle v \rangle} \qquad \tau = \frac{2\pi}{m\langle v \rangle^2}$$

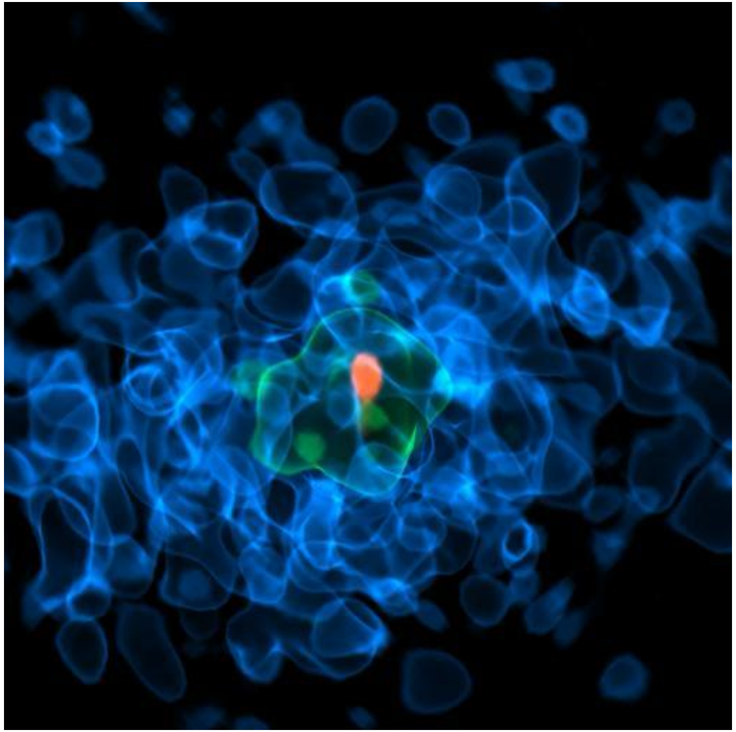
Coherent patches ~ quasi-particles →
gravitationally scatter and heat/cool.

$$t_{\rm relax} \sim 10^{10} m_{22}^3 v_{100}^2 R_5^4 \ {\rm yr}$$

Survival of old star cluster in Eridanus-II →
exclude too much heating
→ Lower bound m>10^{-19} eV

DJEM & Niemeyer (2019)

Avoid with mixed DM models, and
v low masses.



Movies made with data from Veltmaat et al (2018)

INTENSITY MAPPING

The future of cosmology…

Bauer, DJEM et al (2020); Hotinli, DJEM & Kamionkowski (2021)

Neutral Hydrogen: z=1100 to 0

Line intensity of neutral hydrogen gas → possibility to map Universe in 3d.

CMB modes ~ L^2

IM tomography modes ~ k^3

→ huge increase in available information

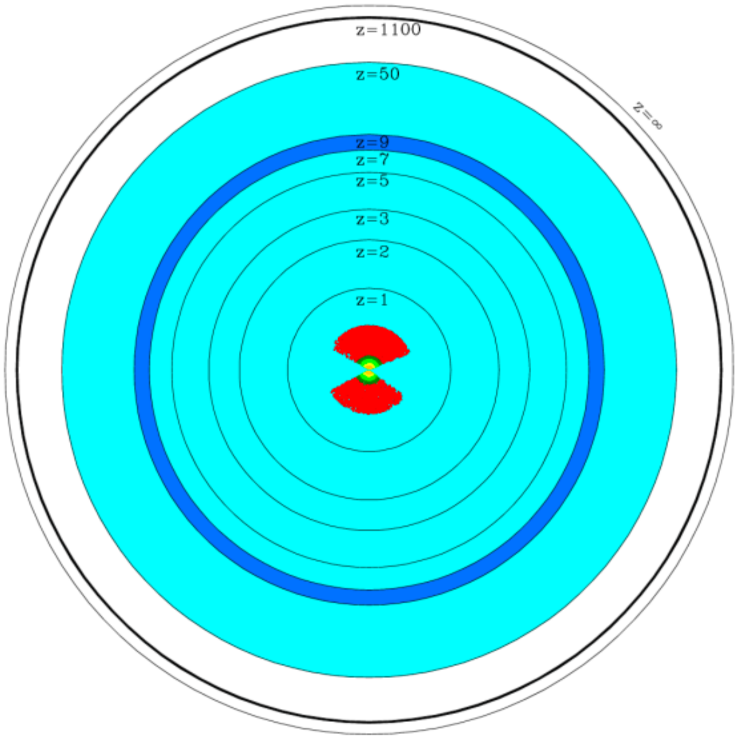
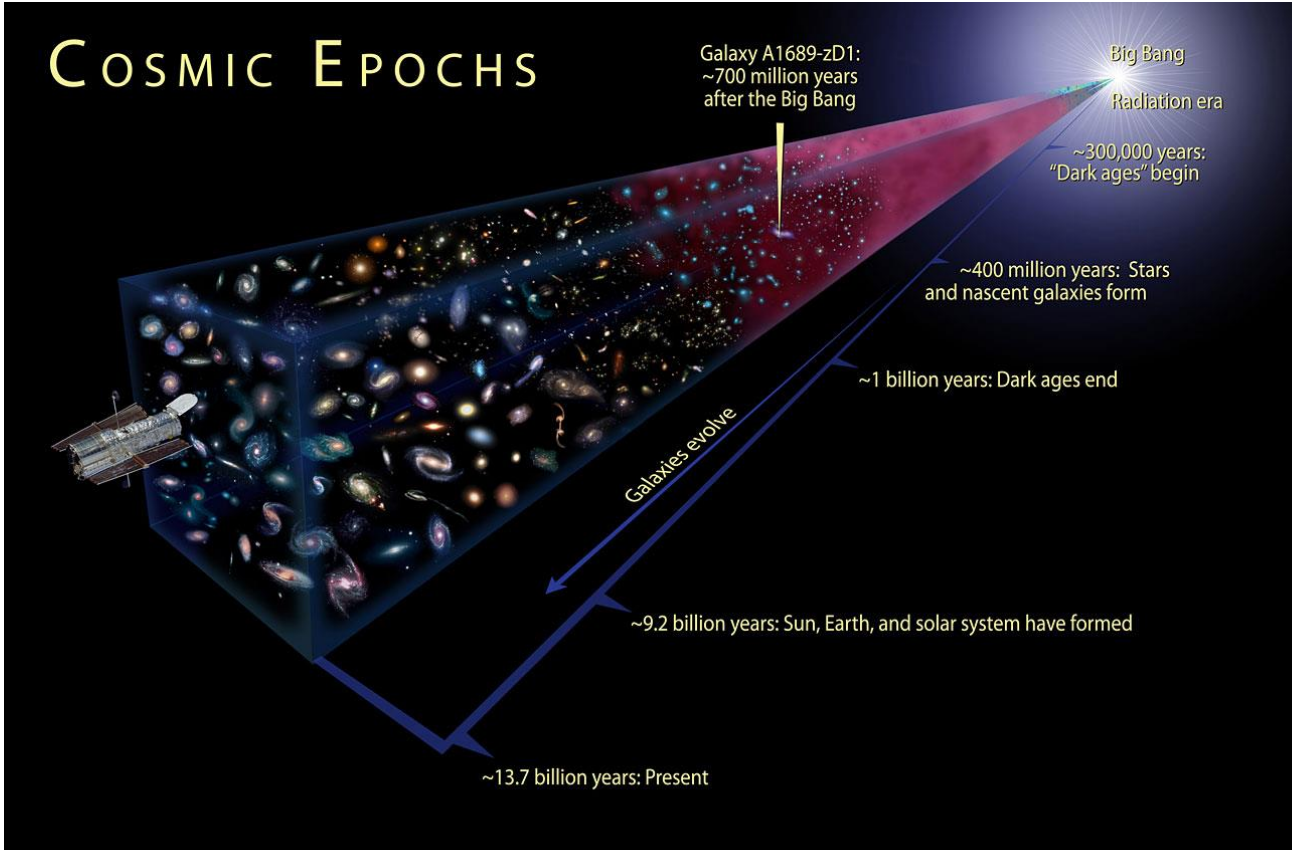


Fig: Mao et al (2008)

Neutral Hydrogen: z=1100 to 0

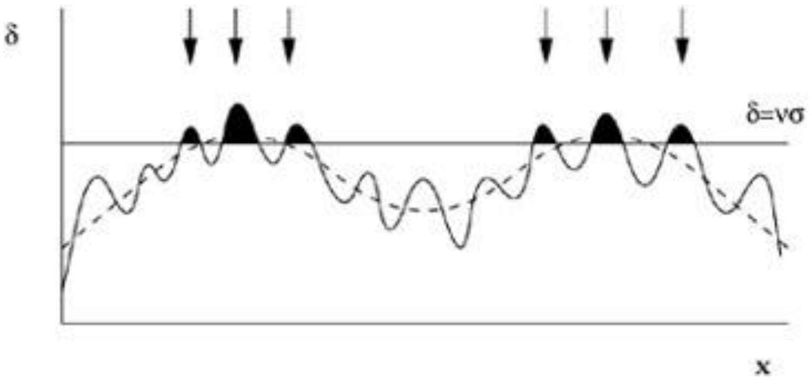
1100<z<10
"dark ages": neutral hydrogen everywhere, nearly linear.

10<z<0
"post-reionization": neutral hydrogen inside dark matter halos



Post-Reion.: Peaks and Halos

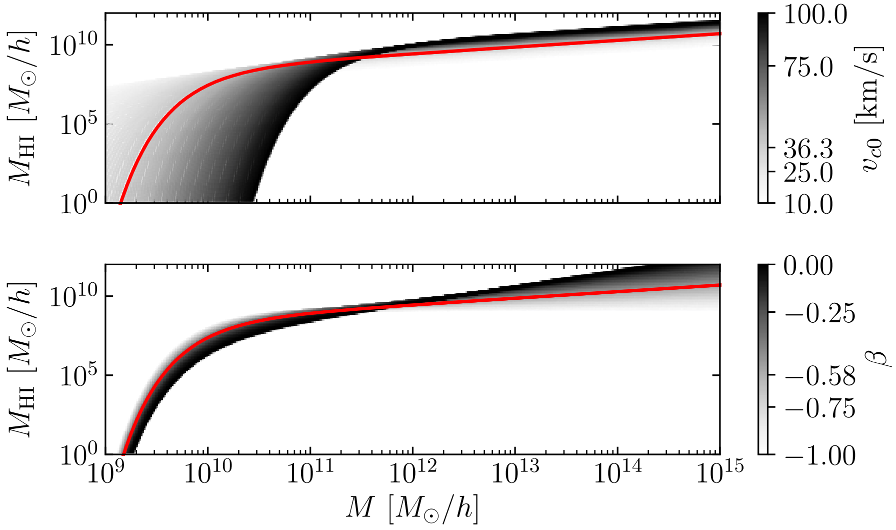
"Halo model"→dark matter distribution and statistics from "peak theory".



$$P(k) = P_{1\mathrm{h}} + P_{2\mathrm{h}}$$

Two-point stats: correlations between halos versus within. Standard calculation.

"HI halo model": assert a relation between halo mass and hydrogen + density profile.



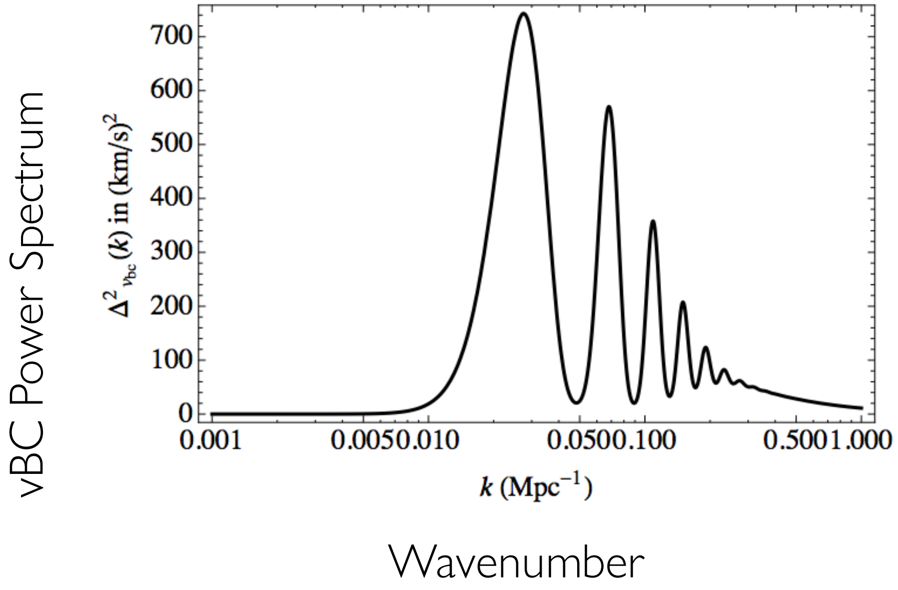
$$P_{\mathrm{H\,I}}(k,z) = P_{1\mathrm{h},\ \mathrm{H\,I}} + P_{2\mathrm{h},\ \mathrm{H\,I}}$$

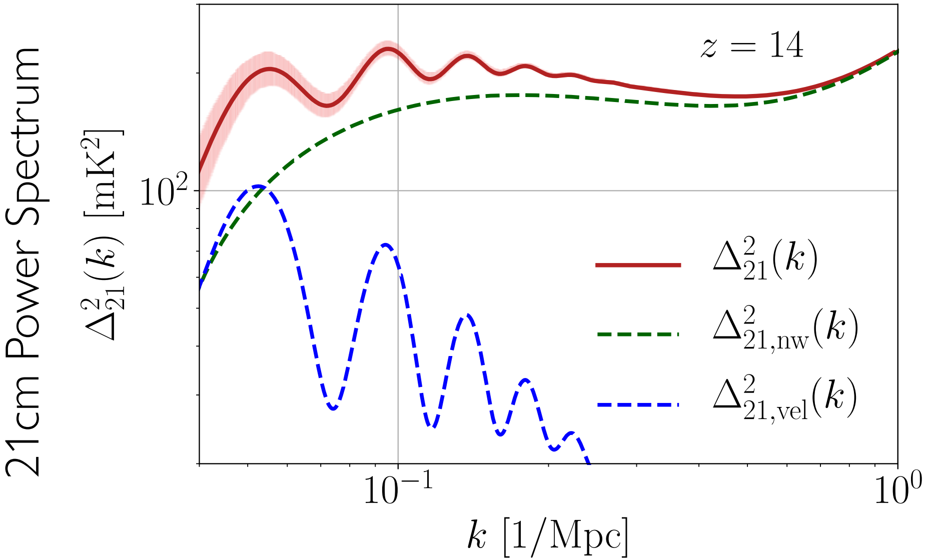
Dark Ages: "VAOs"

Theory: Tseliakhovitch & Hirata (2014)
Simulation: 21cmvFAST, Munoz (2019)

DM-baryon relative velocity (vBC): coherent on MPc scales + baryon acoustic oscillations.

First stars collapsing HI at Jeans scale ~ kpc. Star formation different in vBC coherence patches → couple small-large scales → "VAO".



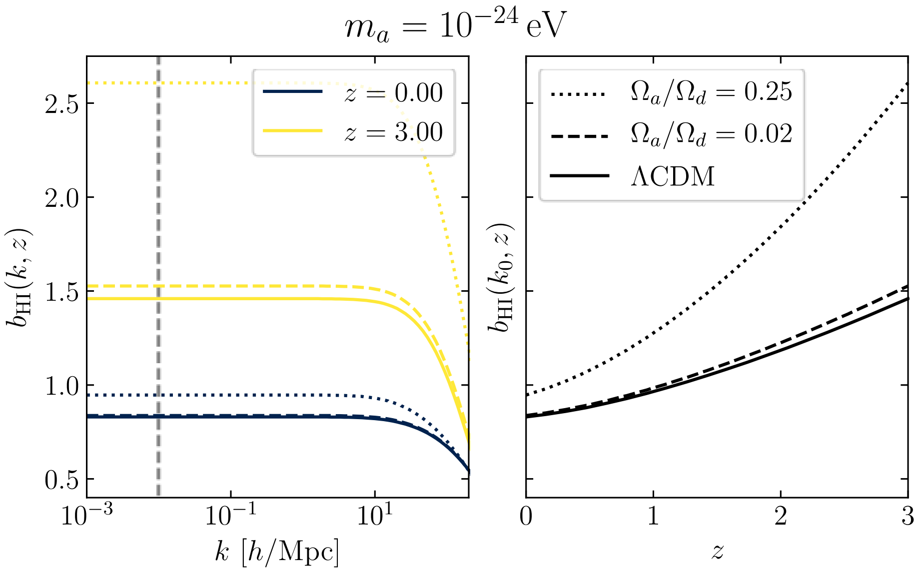


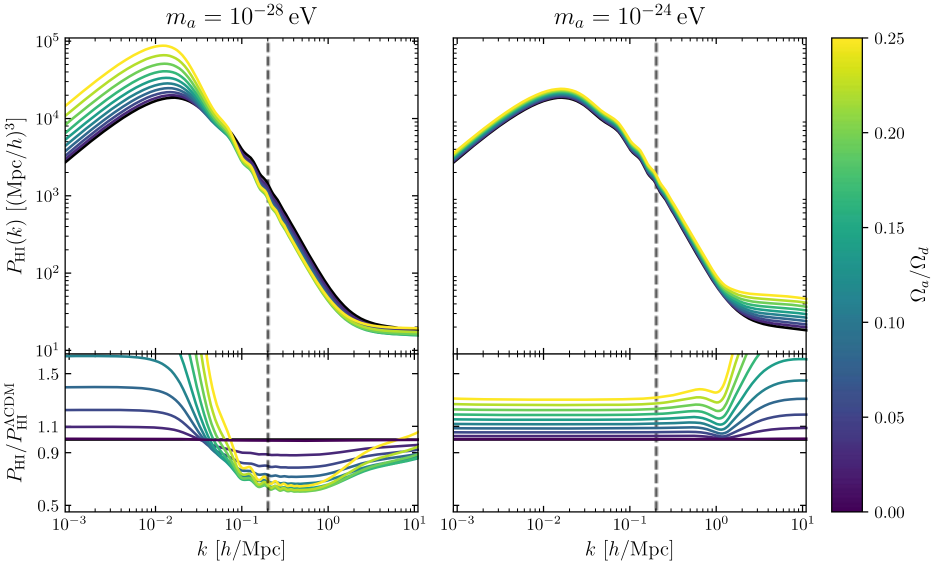
FEATURES = INFORMATION!

Bias of Mixed Dark Matter

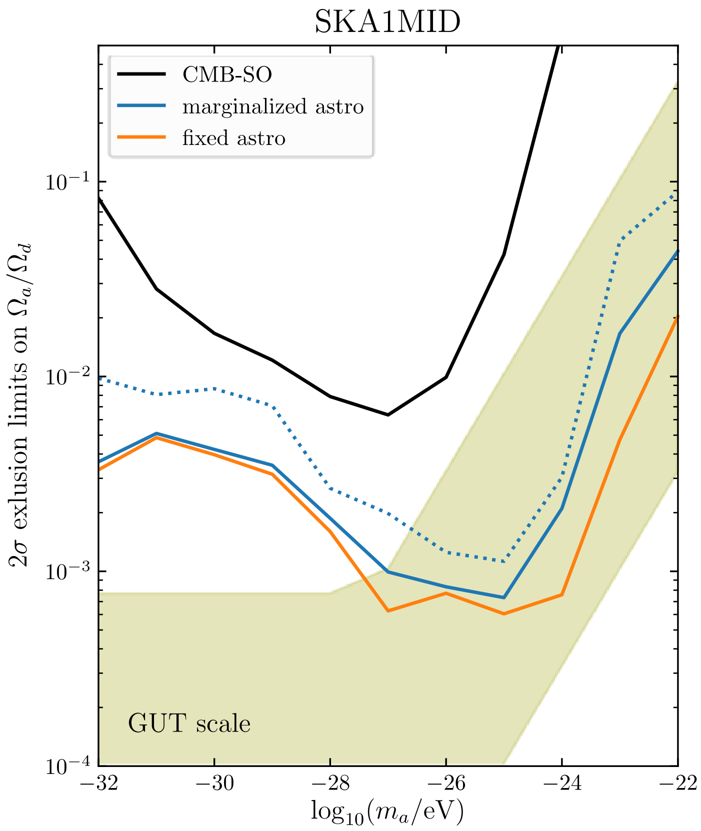
Suppressed clustering → fewer halos.
But, fixed total amount of hydrogen → increase the bias.

Consequence: increase the HI power spectrum on large scales. Consistent with N-body simulations.





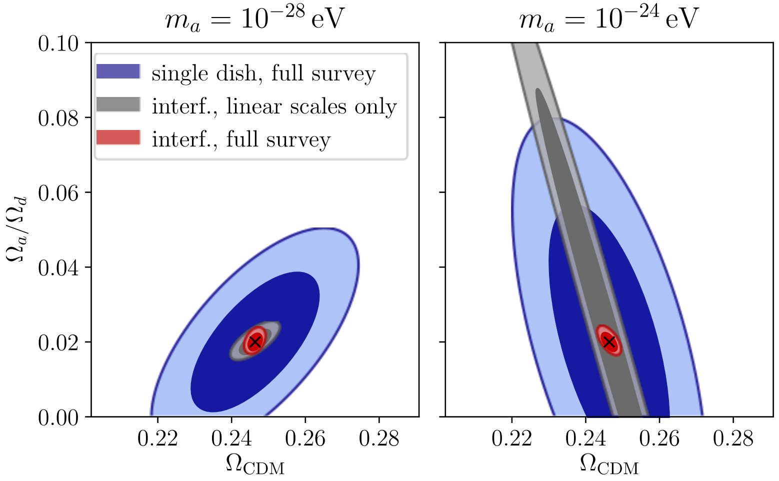
Forecasts: SKA+CMB



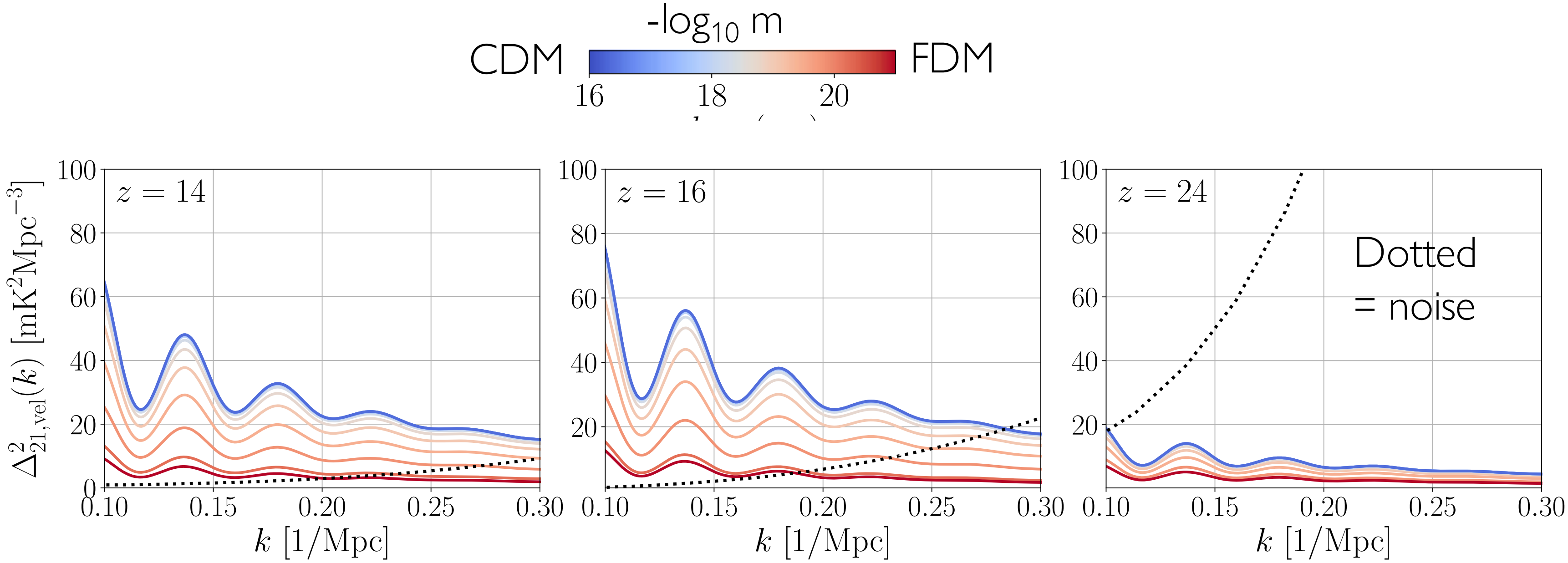
Fisher matrix = inverse covariance

$$F_{ij} = \sum_\ell \frac{1}{(\Delta C_\ell)^2} \frac{\partial C_\ell}{\partial p_i} \frac{\partial C_\ell}{\partial p_j},$$

$$(\Delta C_\ell)^2 = \frac{2}{(2\ell+1) f_{\rm sky}} (C_\ell + N_\ell)^2,$$



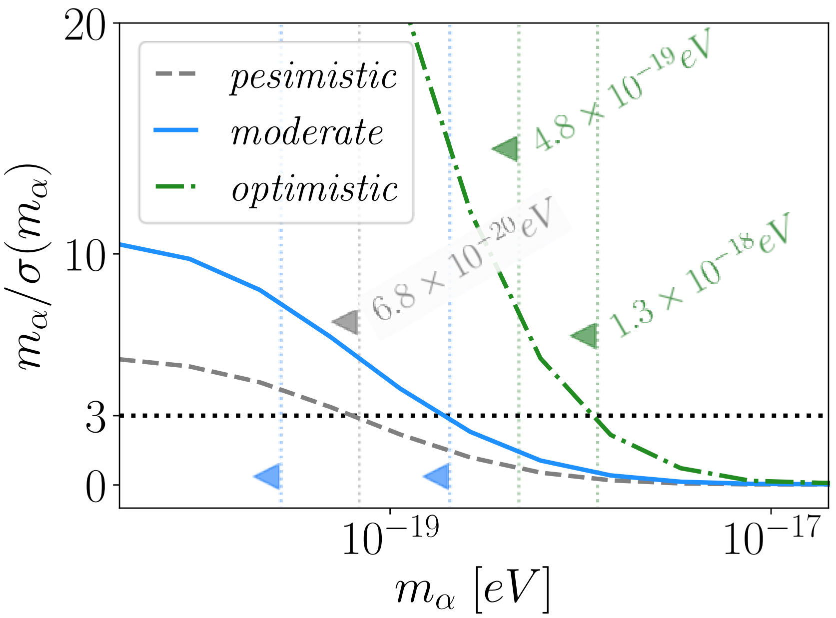
VAO Signature & Bias



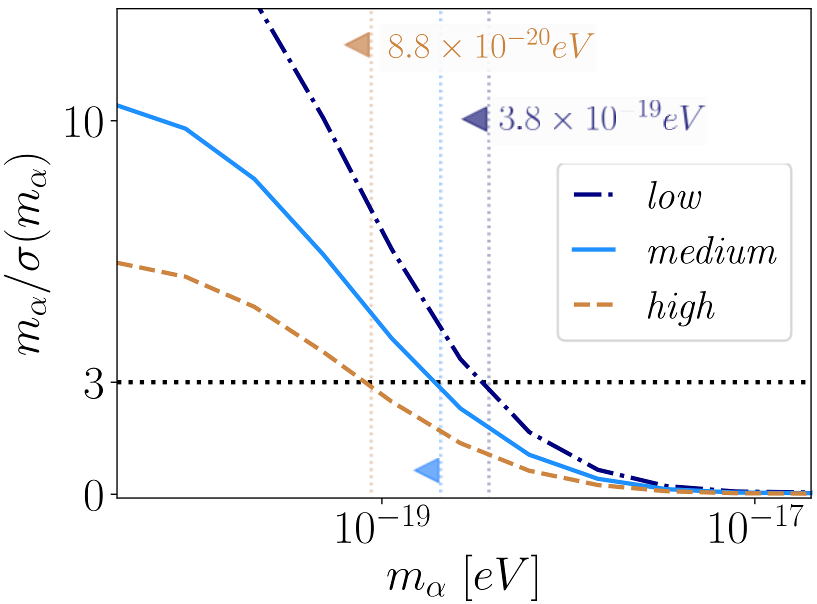
P(k) cut-off with k<kJ→ remove first stars → drastically suppress VAO amplitude for m<10^{-18} eV.

HERA Forecasts

Detect VAO signature at ~20σ with CDM, thus very sensitive to P(k) cut-off with axions.

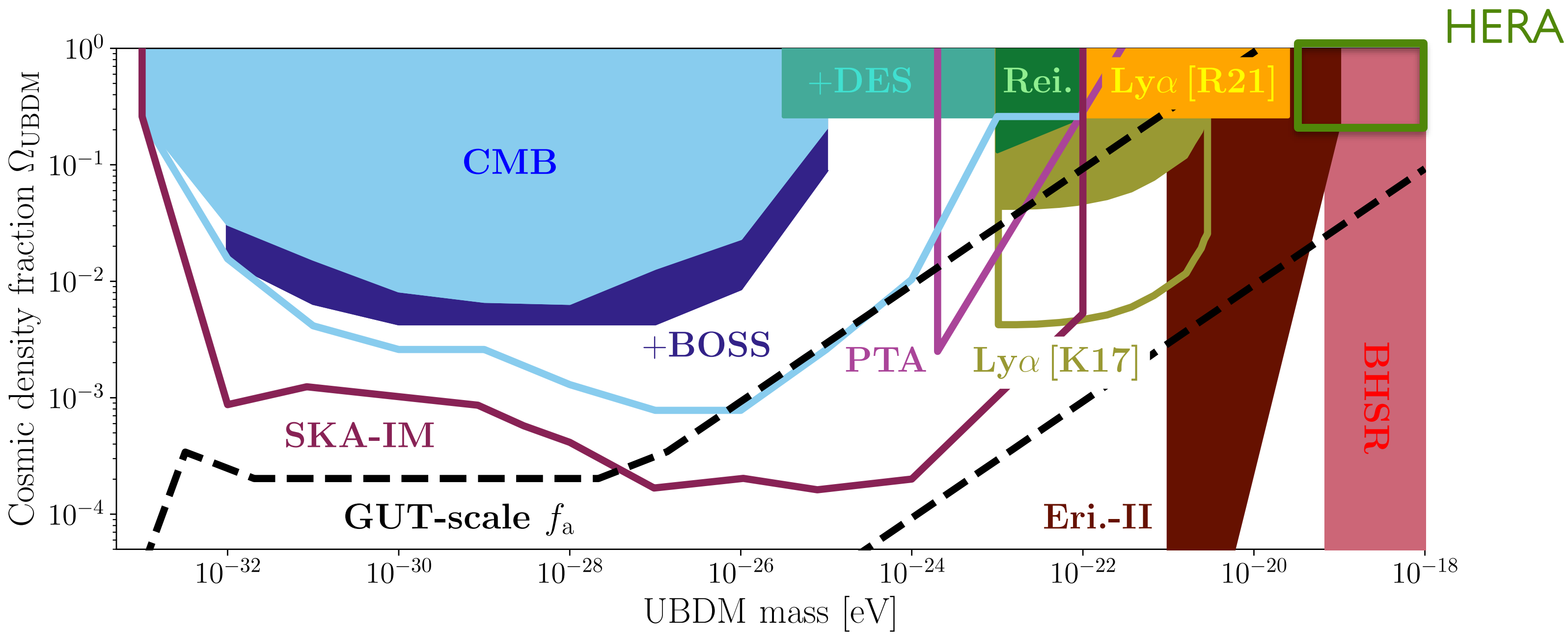


Foreground modeling.

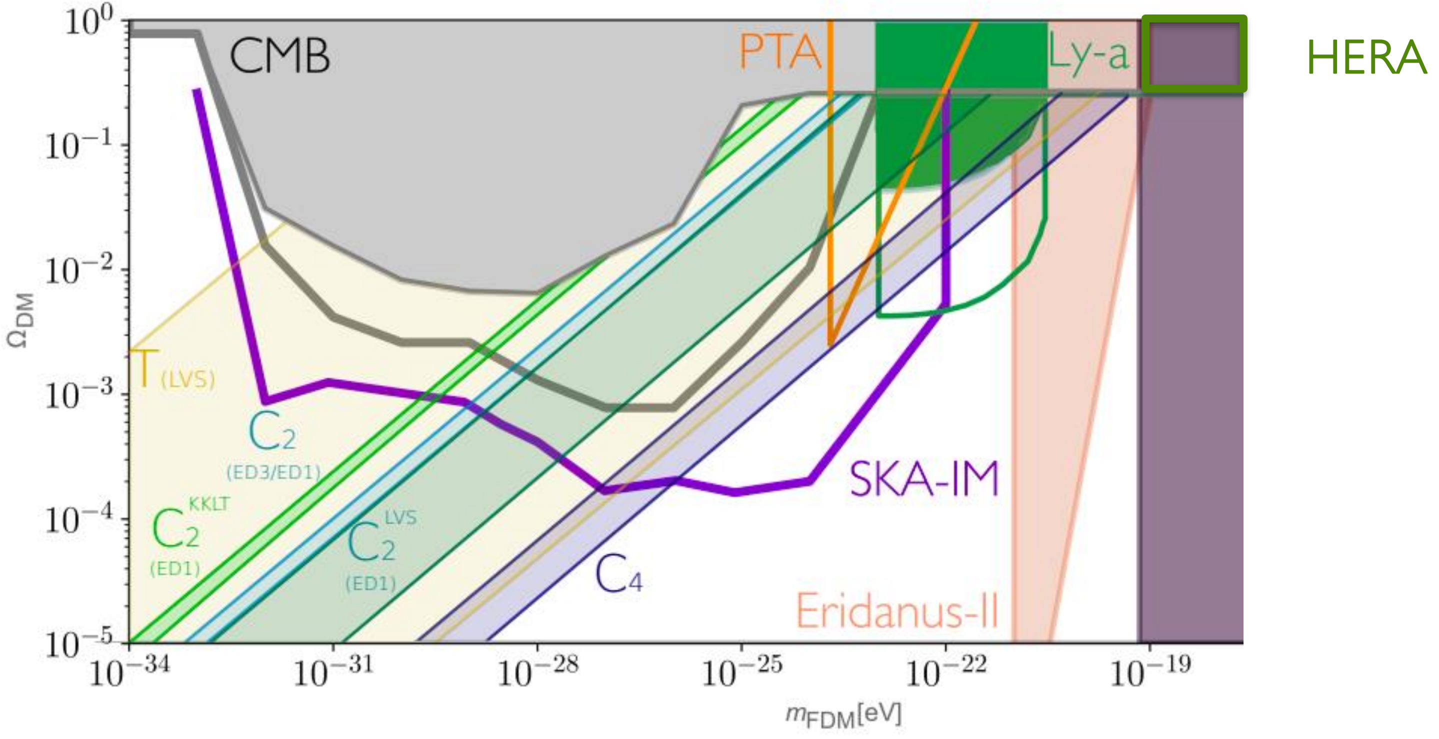


Baryonic feedback modeling.

Summary



Post-reionization → orders of magnitude improvement over CMB. Test GUT scale predictions.
Dark ages → increase lower limit on (fuzzy)DM particle mass → close gaps astro – black holes.



Test string theory predictions of Cicoli et al (2021)? Let's go further…

AXION STARS/SOLITONS

Solitons from Schrödinger

DJEM & Pop (2015)

Ground state solutions of the SP equations → one parameter family.

Ansatz

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

$$\chi'' + \frac{2\chi'}{r} = 2(V-\gamma)\chi$$

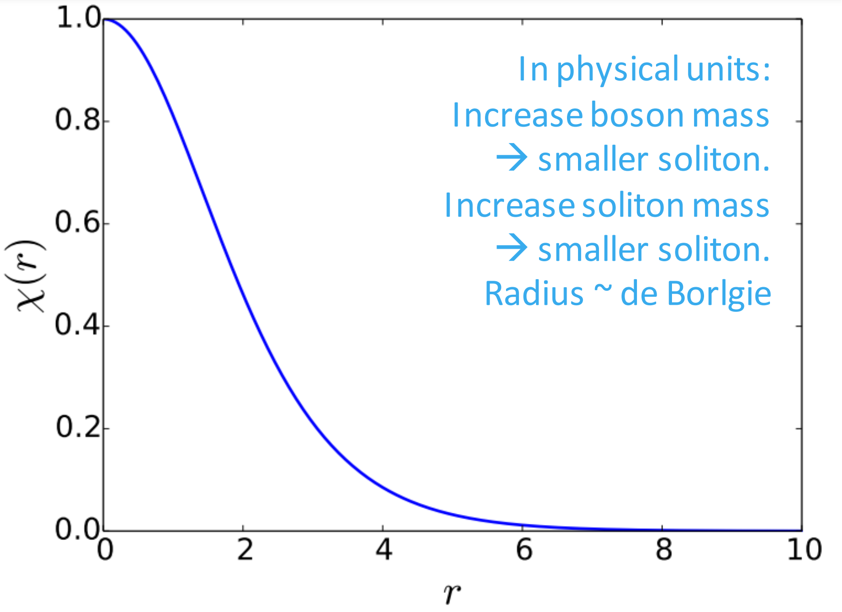
Dimensionless variables with $\chi(0)=1$.

$$V'' + \frac{2V'}{r} = \chi^2$$

→ Boundary value problem with eigenvalue γ. Solved for:

$$\gamma = -0.69\,, V_0 = -1.34$$

Zero oscillation, lowest energy solution.



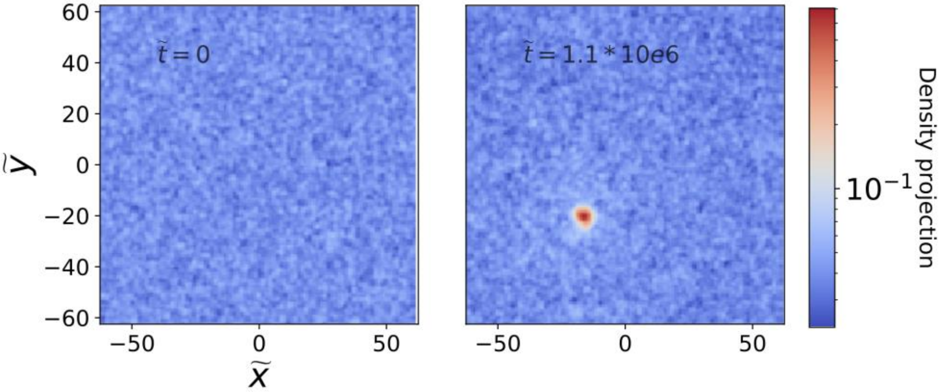
$$\rho(r) \approx \frac{\rho_0}{[1+0.091(r/r_c)^2]^8}$$

$$\rho_0 \propto m^{-2} r_c^{-4}$$

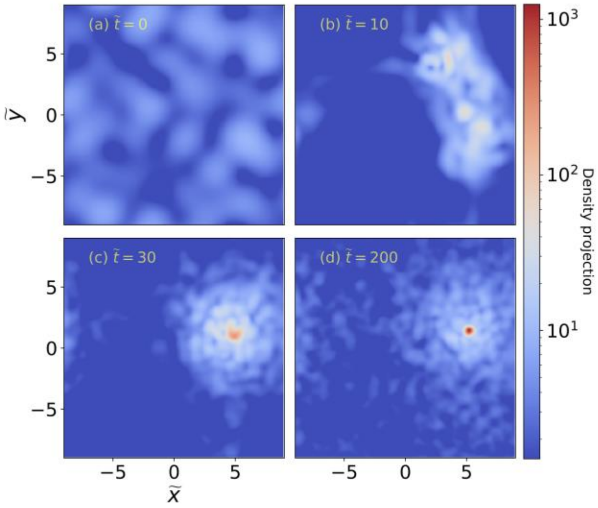
Soliton Formation

Schive et al (2014); Levkov et al (2018); Chen, DJEM et al (2020)

Solitons cores of DM halos form during "violent relaxation" from initial coherence.
Second formation mechanism: gravitational BEC in "kinetic regime".



Gravitationally stable simulation box. Condensation and growth time predictable from scattering theory.



Gravitationally unstable: form a DM halo around the nucleated axion star. Virial equilibrium → core size+growth quench.

Soliton Distribution

Soliton dists+merger rates: Du, DJEM et al (in prep)

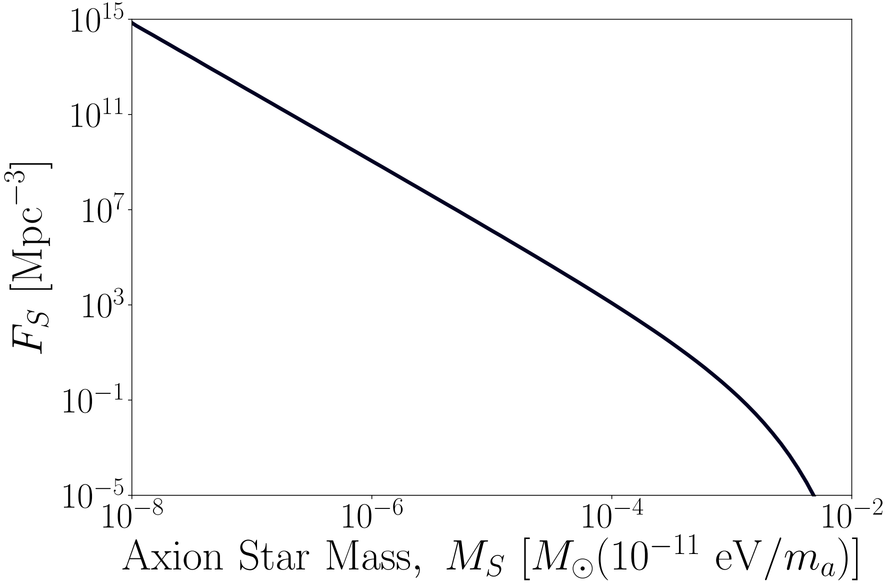
Equilibrium between core+halo → relation between host mass and soliton:

$$M_{\rm sol} \propto M_h^{1/3}$$

Compute "halo mass function" → predict soliton mass function.

$$F_S := \frac{dn_{\rm sol}}{d\ln M}$$

number density



Theory and simulation work around the initial formation in relatively low mass halos → we can do cosmology, merger rates, etc.

Challenge: what is the distribution in e.g. the Milky Way?

Boson Stars: Full GR

Seidel & Suen (1992)
Helfer, DJEM et al (2016)

Spin-0 bosons → oscillating metric on time scale m^{-1} → "oscillatons".
Simulate in full 3D, with axion interaction potential using GRChombo.

No interactions: BH formation at "Kaup mass":

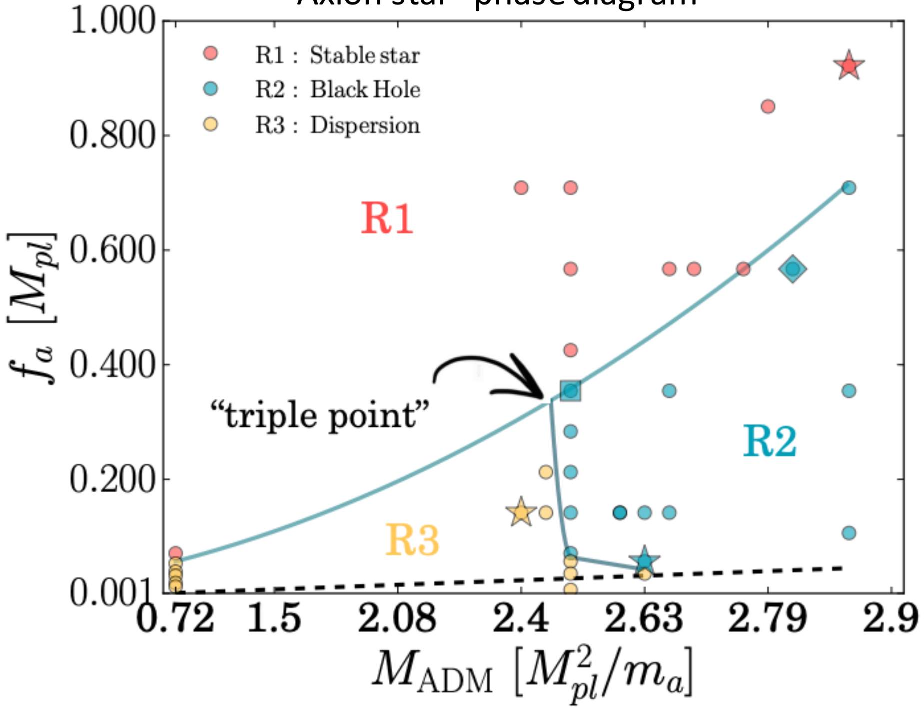
$$M_{\rm Kaup} \approx \frac{M_{pl}^2}{m} \Rightarrow \phi_0 \sim M_{pl}$$

Finite interactions given by f → explosion in "axion Nova":

$$M_{\rm Nova} \approx \frac{M_{pl} f_a}{m} \Rightarrow \phi_0 \sim f_a$$

Interactions → more instabilities e.g. radio emission by F*F (in prep.).

Axion star "phase diagram"



MINICLUSTERS

Aesthetic advantage over pre-inflation SSB: no free parameter of initial field value.
Disadvantage: very hard computational problem. Little consensus on the relic density. QCD axion axion mass in meV range + miniclusters.

Stats: see Riess, DJEM & Hoof (2021)

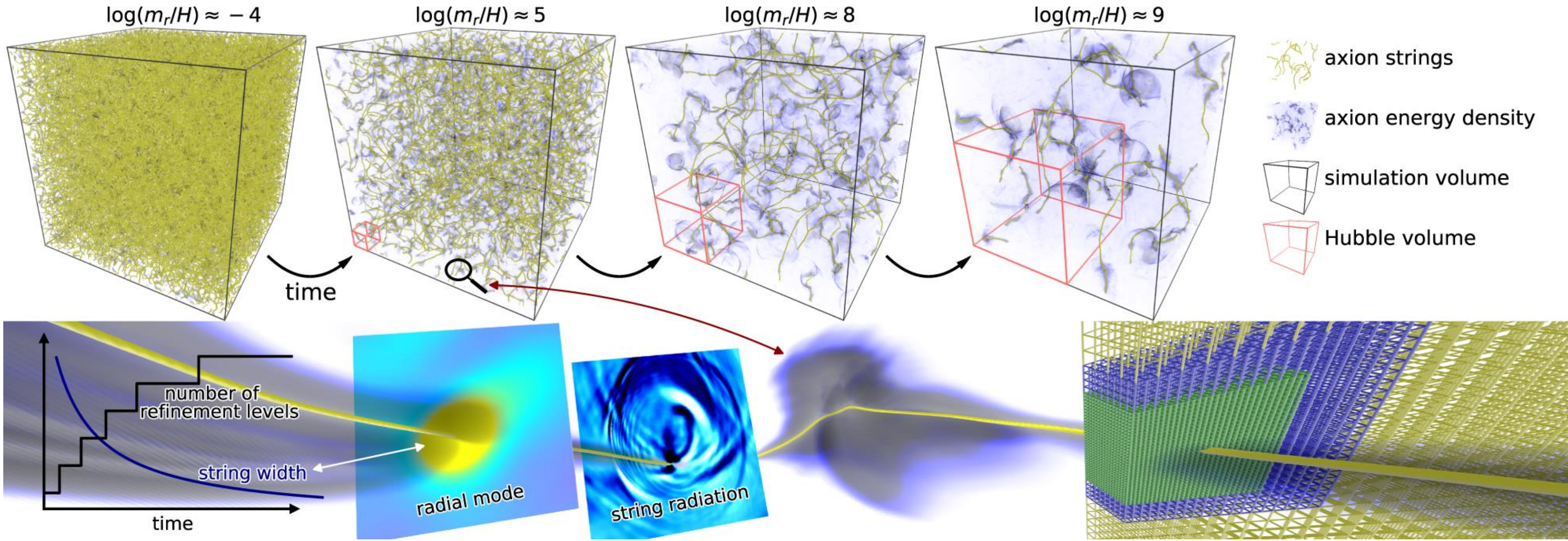


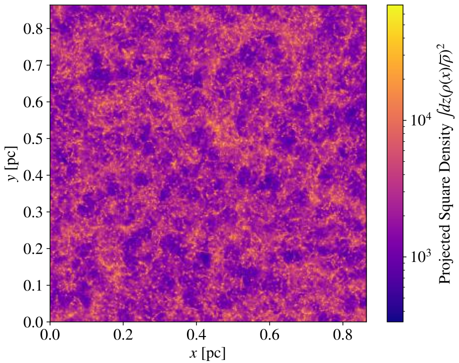
Fig: Buschmann et al (2022)

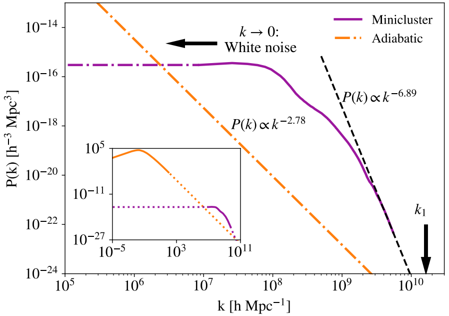
Largely unknown: role of domain walls.

Miniclusters

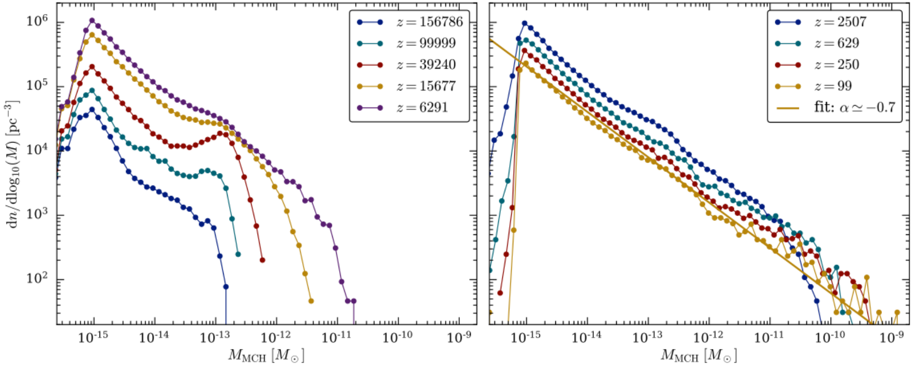
Very similar situation occurs for dark photon DM from isocurvature.

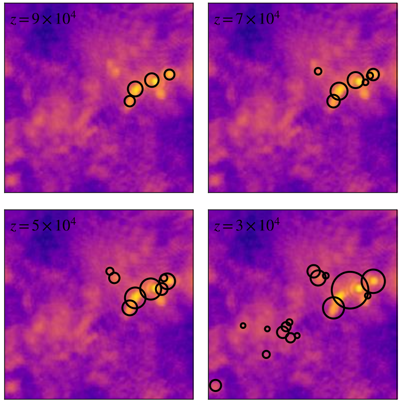
String network → enhanced fluctuations:



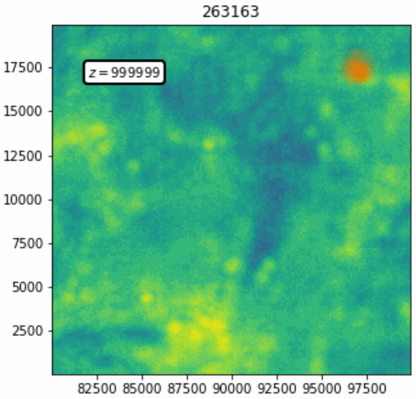


Eggemeier+ (2018+)

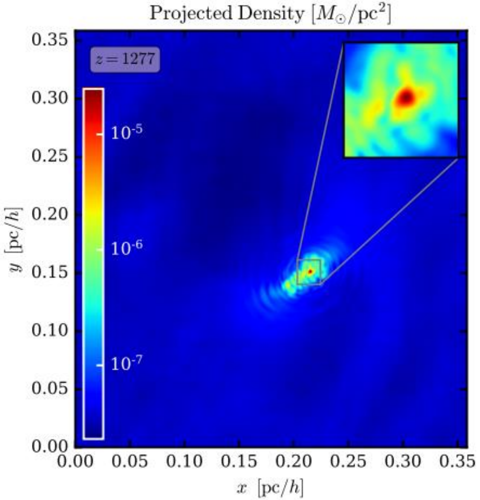




Ellis, DJEM et al (2020+);



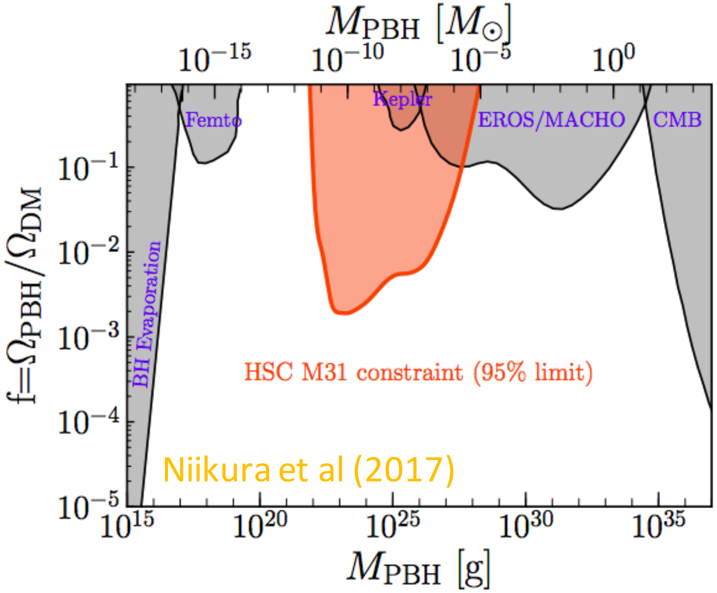
Population of dense, low mass halos. Miniclusters are not axion stars! They contain axion stars (solitons)

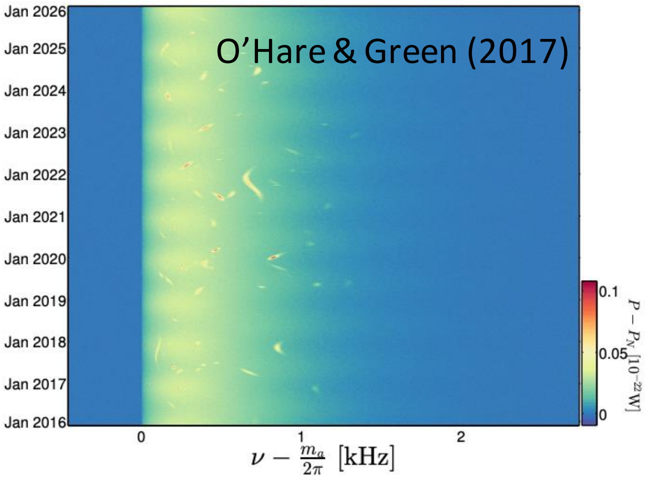


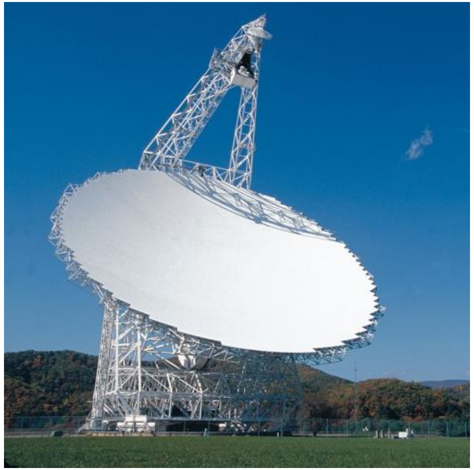
Minicluster Pheno

Possible pheno: microlensing, appearance in haloscopes, collision w/ neutron stars.

Vital questions: distribution, density profiles, survival. End-to-end sims impossible.







MCs must be dense and heavy. m~1 meV window?

Earth encounters rare, tidal streams possible → astronomy.

M31: NS pops → only low m possible.

SUPERRADIANCE!

Black Hole Superradiance

Review: Brito et al (2015)

Solve for instabilities of KG equation on Kerr: $\Box\phi - \partial_\phi V(\phi) = 0$

Non-relativistic limit in "tortoise coords", find instability (ω<0):

$$\frac{d^2\psi_{lm}}{dr^{*2}} = \left[\omega^2 - V(r,\omega)\right]\psi_{lm}\,.$$

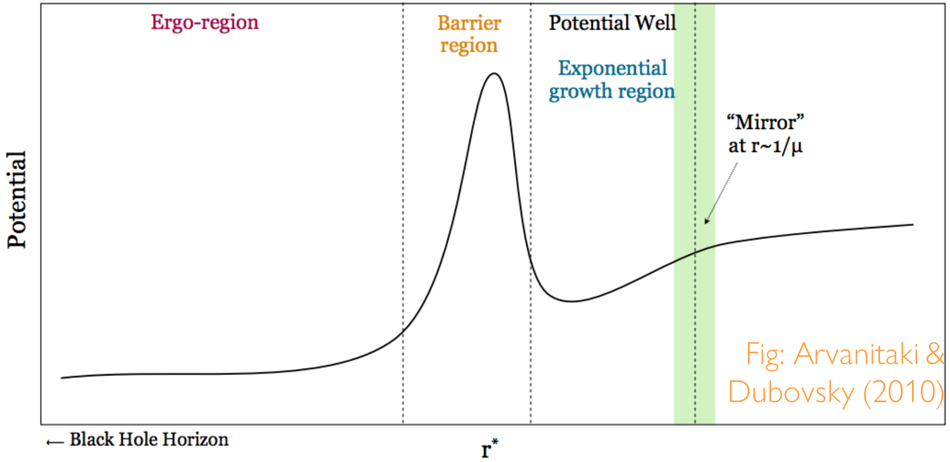
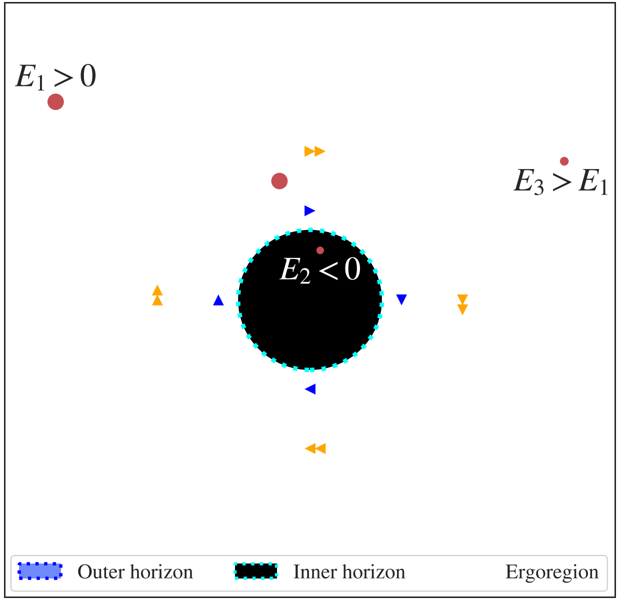


Fig: Arvanitaki & Dubovsky (2010)

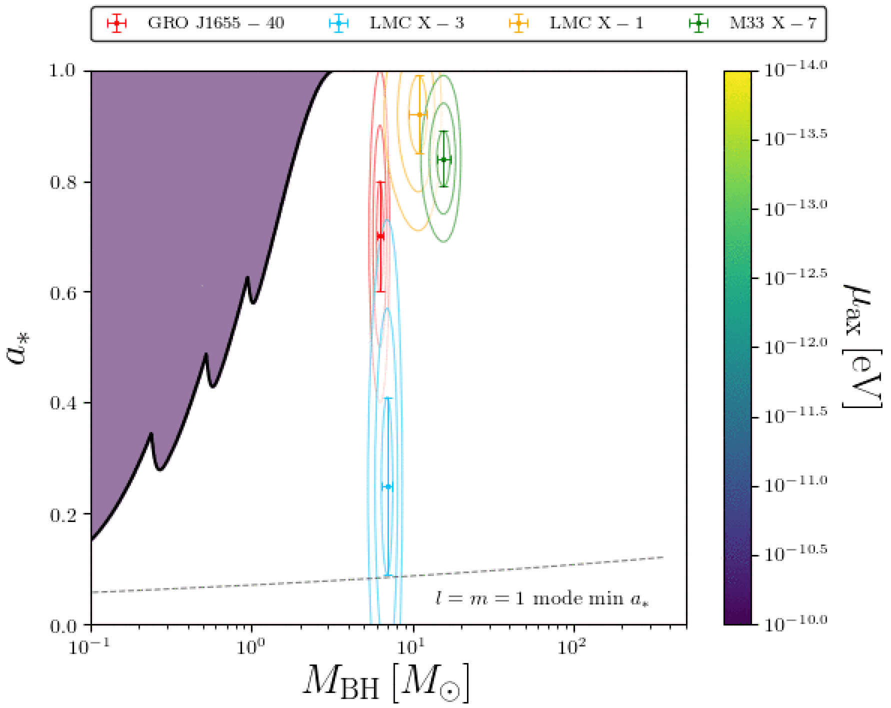
Physical picture: "Penrose process/ black hole bomb"

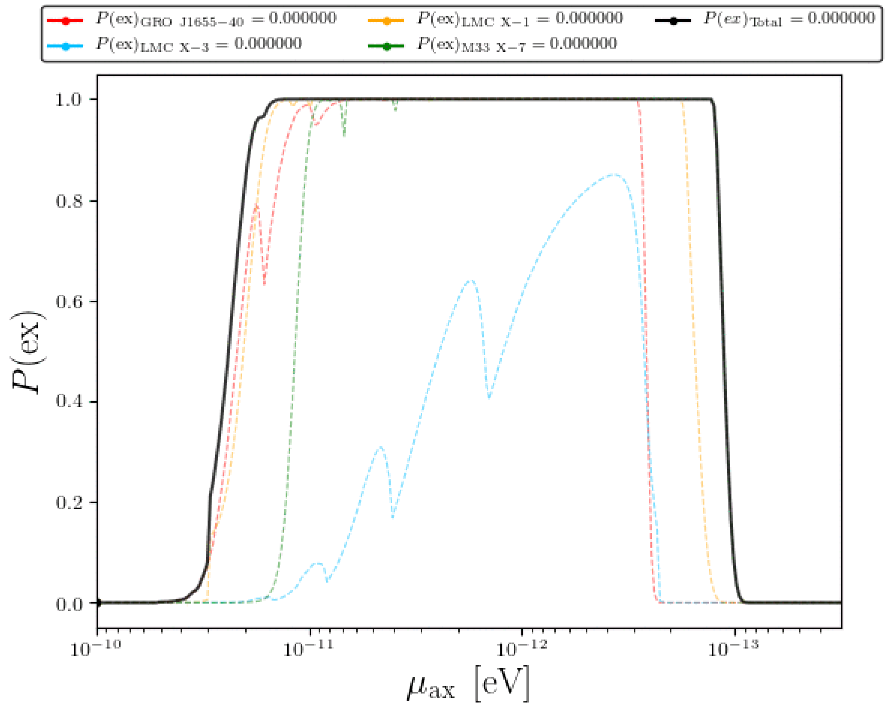


Resonant bosons extract spin from astrophysical BHs, if $\Gamma_{SR} > \Gamma_{others}$

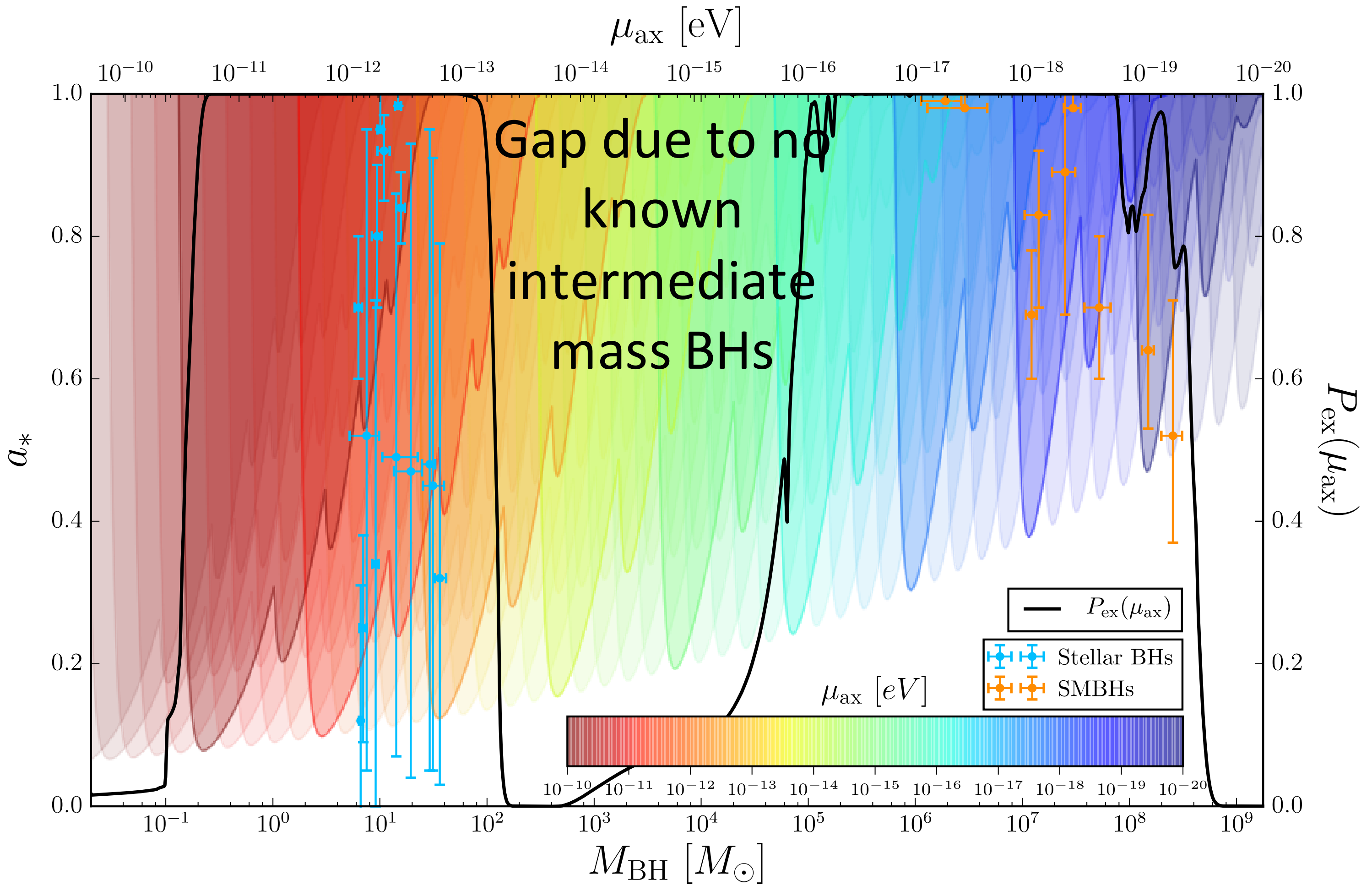
Spin-0 Fields, No ϕ^4 Term

GIF by Matthew J. Stott





"Exclusion probability" is marginal likelihood. Statistically robust constraints.



Stott & DJEM (2018)

ϕ^4 Instability: "Bosenova"

Yoshino & Kodama (2012); Arvanitaki+(2014); Stott (2018)

Bose enhanced 2-2 scattering in superradiant cloud can have a rate $\Gamma_4 > \Gamma_{SR}$.
Shuts off SR by cloud collapse above critical value of $\lambda\phi^4$ coupling, $\lambda = m^2/f^2_{pert}$.

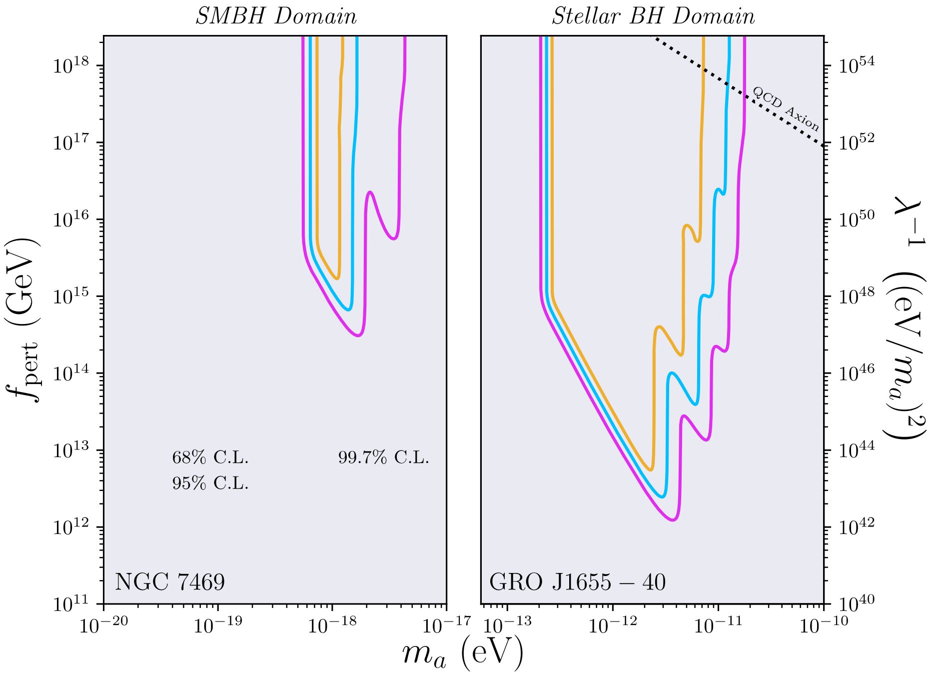
Approximate excluded regions:

Stellar BHs:

$$m_a \in [1 \times 10^{-13}\ \text{eV}, 2 \times 10^{-11}\ \text{eV}]$$
$$f_{\text{pert}} \gtrsim 10^{14}\ \text{GeV}$$

Supermassive (SM) BHs:

$$m_a \in [8 \times 10^{-20}\ \text{eV}, 1 \times 10^{-16}\ \text{eV}]$$
$$f_{\text{pert}} \gtrsim 10^{16}\ \text{GeV}$$



Implemented with a simple cut-off. See Baryakhtar+ for advanced rate calcs. Quantitatively similar.

STRING AXIVERSE

Arvanitaki et al (2009); Mehta, DJEM et al (2021)

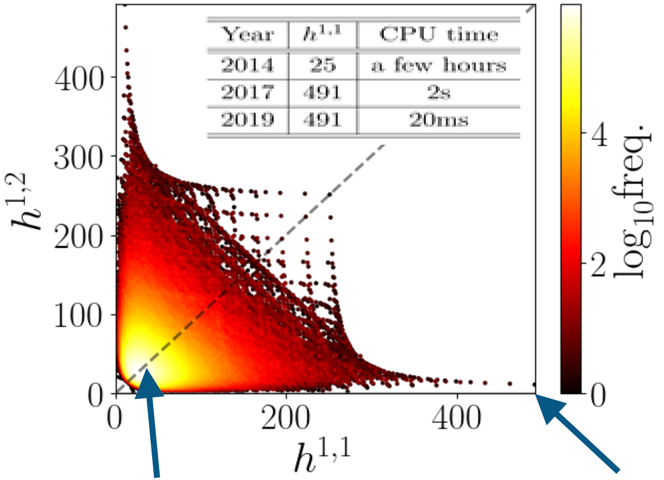
The KS Axiverse

Demirtas et al (1808.01282)

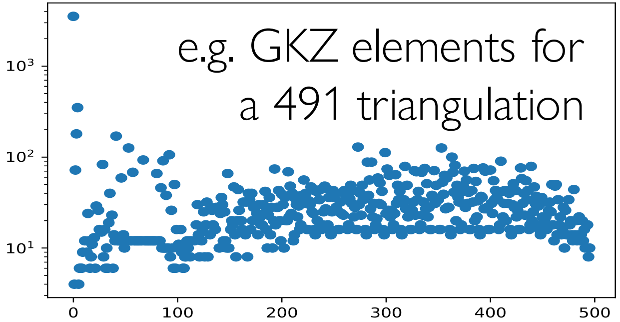
Triangulate (FRST) KS polytopes → CY_3.
1000's of CYs at large h^{11} in laptop-time!
Pick point in Kähler cone (no stabilization).
Kähler metric and axion potential computed:

$$\mathcal{L} = -\frac{M_{\rm pl}^2}{8\pi^2} K_{ij} g^{\mu\nu} \partial_\mu \theta^i \partial_\nu \theta^j - \sum_{a=1}^{\infty} \Lambda_a^4 \left\{ 1 - \cos\left(\mathcal{Q}^a{}_i \theta^i + \delta^a \right) \right\}$$

For an astrophysicist: databases of K, Λ, Q sampling KS, triangulations, and Kähler cone.
Aim: rigorously exclude CY's based only on vacuum properties of the axions.



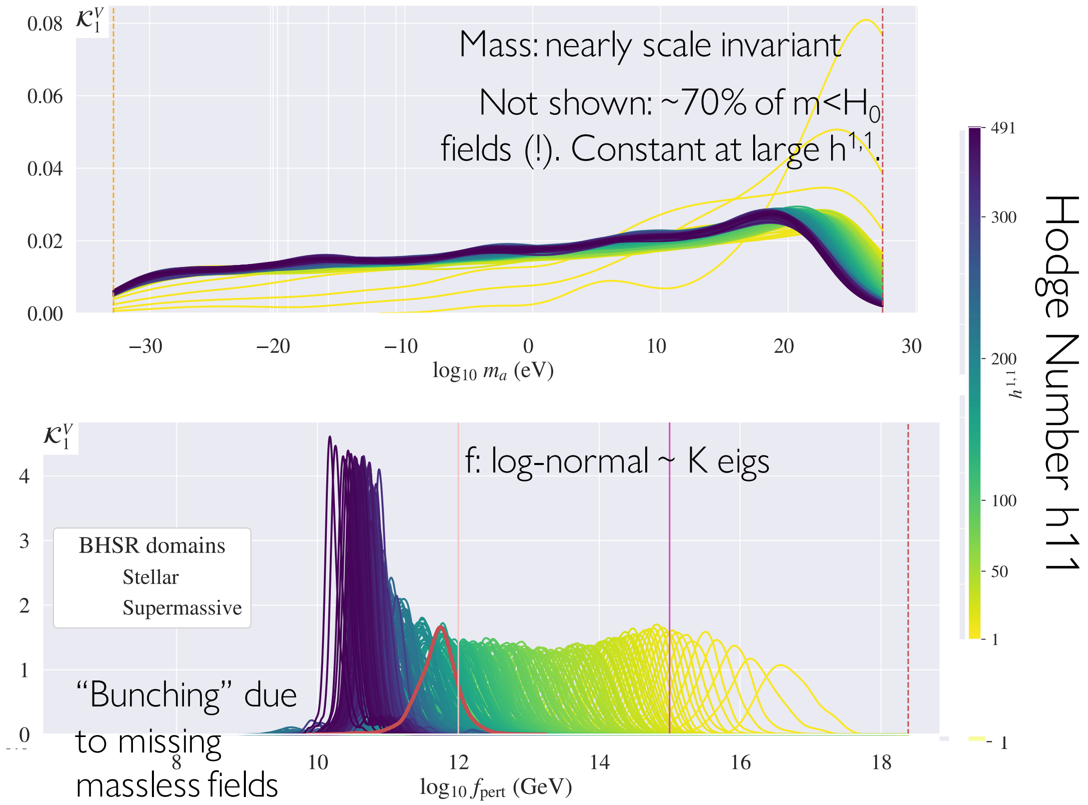
h11=27: most polytopes
h11=491: most CYs



Axion Spectra

Find vacua of V(f) in fundamental domain. Expand to quartic order → masses +quartics (“fpert”).

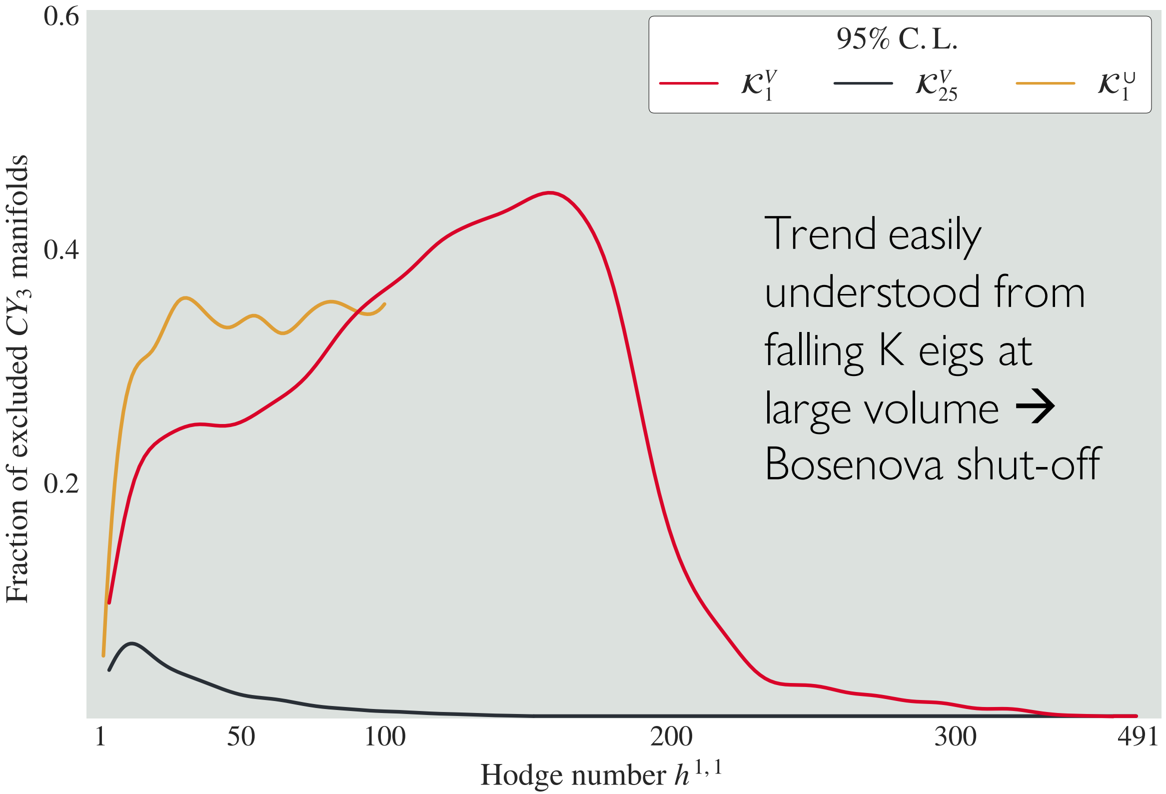
Trends: Kähler cones become very narrow at large h11 → cycles in the CY have large volumes → (ultra)light axions and smaller decay constants.



Constraints on IIB CY Vacua

Ensemble of O(10^5) CYs. All up to h11=5. 100 per h11 up to 176. Up to 100 per h11 to 491.

The first rigorous use of the "axiverse" idea to test string theory.



Beyond Superradiance

- Why superrradiance? Vacuum process, no cosmological assumptions. Only need the axion potential.
- Why go further? Large h11, and moduli space away from Kahler cone tip → larger volume → lower decay constants → superradiance shuts off.
- What observables will be best? Ideally vacuum processes, cosmology independent, exploit massless fields.
- What is a bad observable? Unfortunately, axion DM from realignment: too many cosmological assumptions.

Visible Sector Couplings

Demirtas et al (2021)

- Choose divisor for QCD. Dilate V until divisor volume → α_{QCD}. Demand geometric.
- Axion masses and f's by using hierarchy of instanton scales + Kähler metric.
- Strong-CP: $\Sigma_i \theta_i$ in front of CS must be small.
- Assuming a GUT you can find $g_{a\gamma}$:

$$\mathcal{L}_{\mathrm{EM,CS}} = \sum_i c_i \frac{\alpha_{\mathrm{EM}}}{2\pi f_i} \theta_i F\tilde{F} \equiv \sum_i g_i \theta_i F\tilde{F}$$

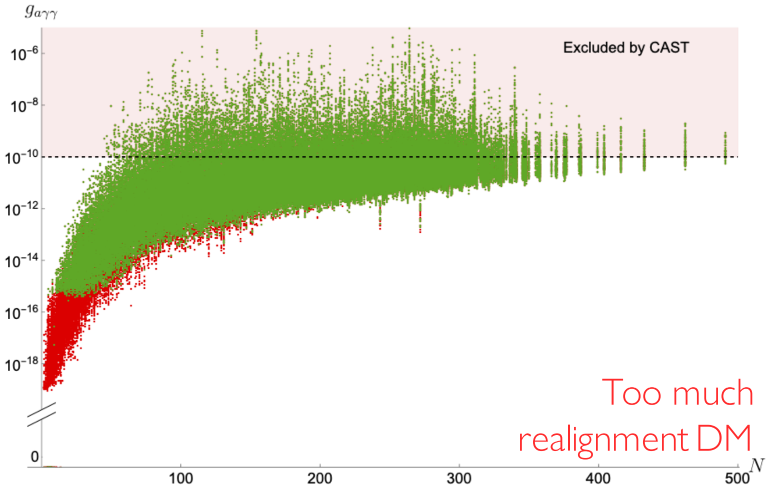
(ci's known)

Effective axion-photon coupling for massless linear combination

$$g_{\mathrm{eff}} = \sqrt{\sum_{i\in\{m=0\}} g_i^2}$$

3e4 random CYs

Computationally limited at large h11



Hodge Number $h^{1,1}$

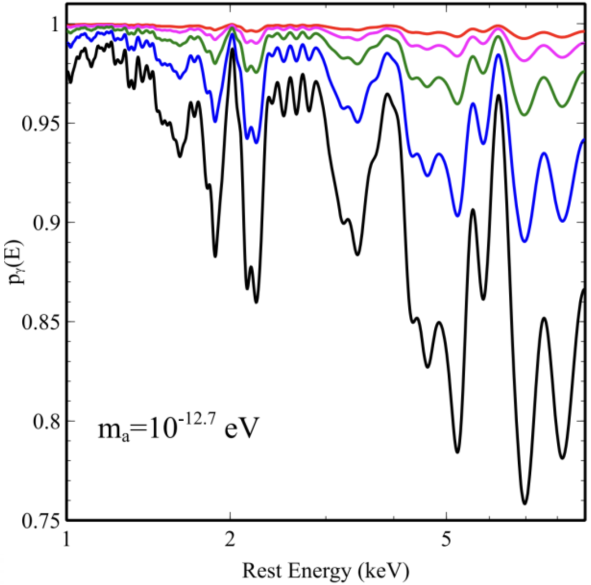
CY Tools

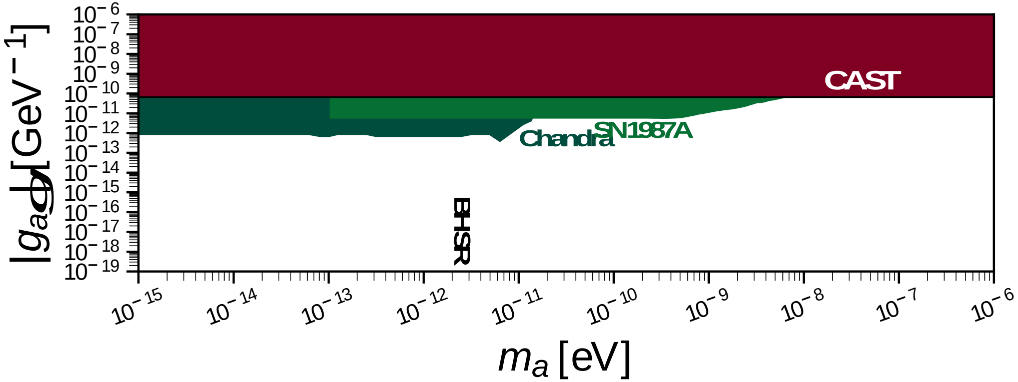
See Julia Sisk-Reynes and James Matthews talks

X-ray Spectrum Oscillations

e.g. Matthews et al (2022); Reynolds et al (2020) "other David Marsh"

Photon-axion conversion in cluster B-fields → spectrum oscillations. Vanishing if $m_a > \omega_p$.
Need to marginalize random magnetic field models. Fit Chandra satellite data.





Best limits on g at low mass. Complementary to BHSR.

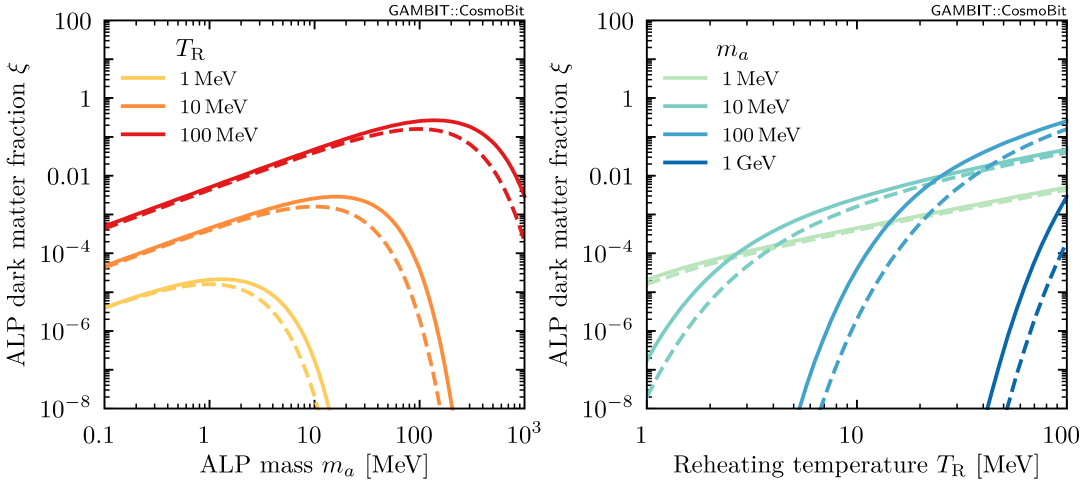
ALPRO
Axion-Like PROpagation

Xspec

Freeze-in DM & Decays

GAMBIT collab., inc. DJEM, 2205.13549

Axion production via Primakoff process off SM charged particles from vacuum initial state.
Irreducible contribution to DM, all fields with m<reheat temperature. Must not "overclose".



Perturbative decay → photodissociation of elements, cosmic reionization etc. even for $\xi \sim 10^{-10}$.

$$\Gamma_a = \frac{g_{a\gamma}^2 m_a^3}{64\pi} = \frac{1}{1.32 \times 10^8\ \mathrm{s}} \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}} \right)^2 \left(\frac{m_a}{10\ \mathrm{MeV}} \right)^3 .$$

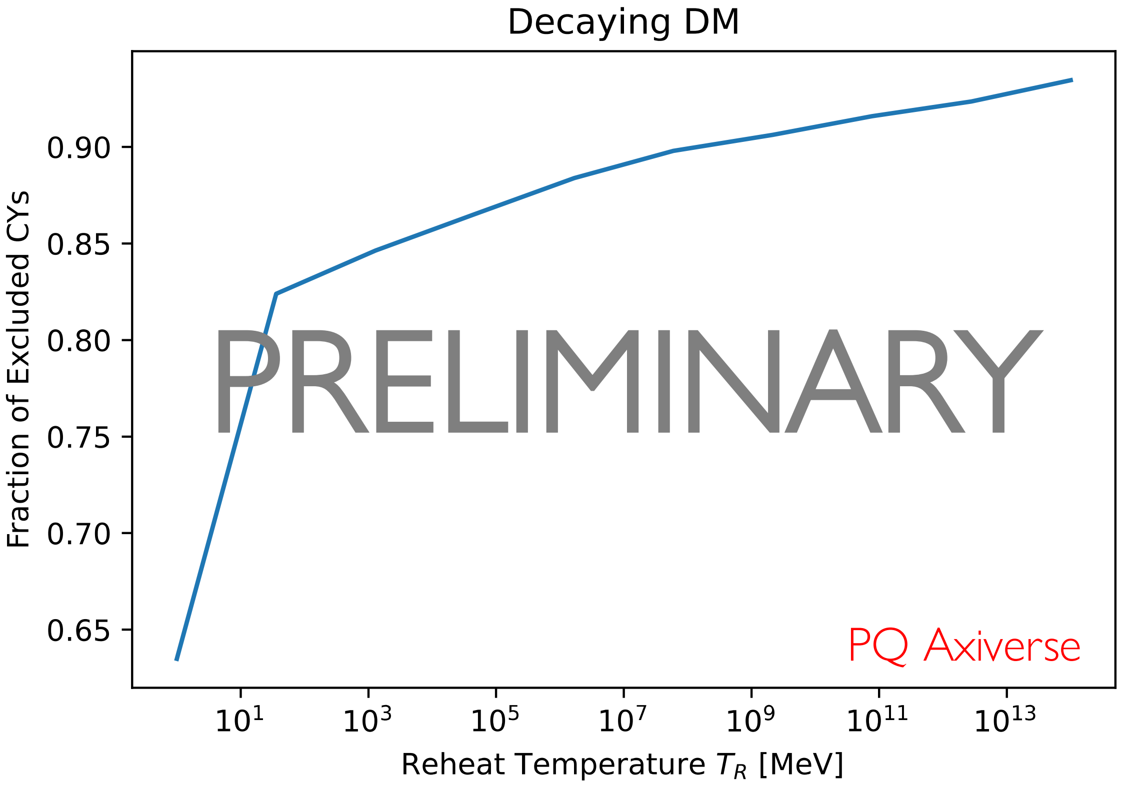
(very) Preliminary Results

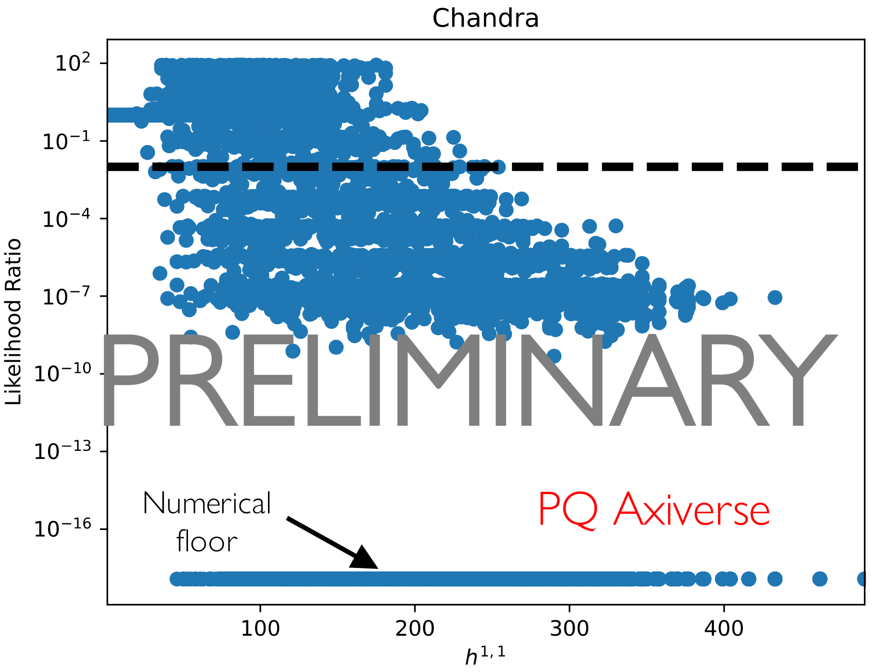
String Datasets:

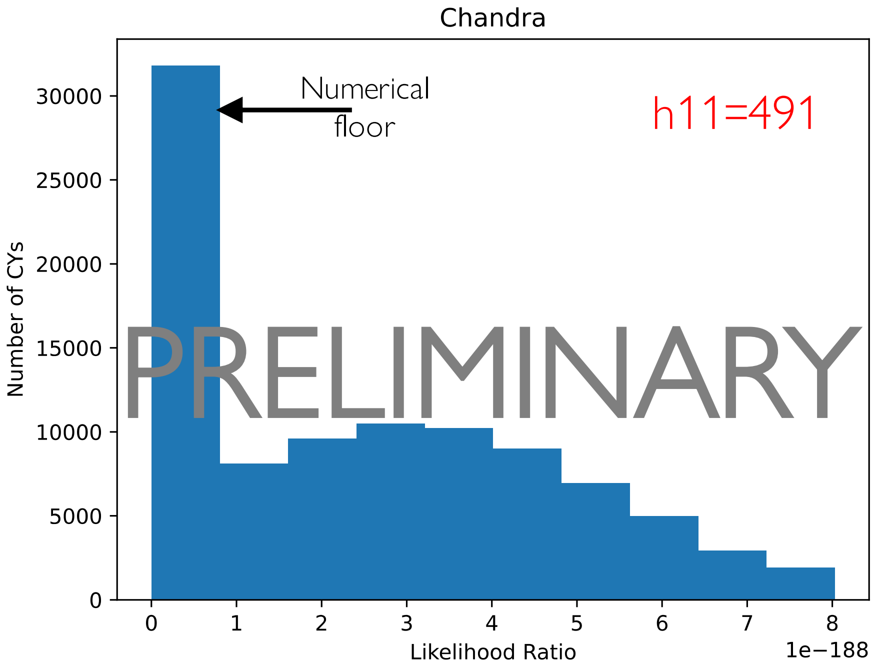
- PQAxiverse: conditioned on correct QCD coupling and strong-CP. Masses and visible sector couplings estimated. O(10) CYs at h11=491.
- h11=491: exploratory dataset, $O(10^5)$ CYs. Zeroth order assumption: massless axions, estimate couplings from Kähler eigs only. Tip of Kähler cone → smaller couplings than the bulk → limits conservative.

Astrophysical Datasets:

- Chandra: X-rays effective likelihood for single massless axion. Ignore CYs with any resonant axions. Future: modify ALPro for one axion in resonant region + massless.
- Freeze-in DM: crude cuts on overclosure and decaying DM (PQAxiverse only). Future: build cosmological likelihoods using micrOMEGAS and GAMBIT.


Decaying DM
0.90
0.85
0.80
0.75
0.70
0.65
Fraction of Excluded CYs
PRELIMINARY
PQ Axiverse
10^1
10^3
10^5
10^7
10^9
10^{11}
10^{13}
Reheat Temperature T_R [MeV]





20% favoured if h^{11}<200. Spectrum overfitting.
Zero allowed manifolds h^{11}>250.

All randomly sampled CYs at 491 are strongly excluded (saturate likelihood). Recall: tip of SKC → limits are likely conservative over moduli space (!)

Speculations and Hopes

- Triangulations (CYs) of 491 polytope obeying constraints are VERY rare. Probably true of most of moduli space. Astrophysics prefers "boundaries" of KS axiverse.
- Can we use ML techniques to find allowed models at 491?
- Is there a symmetry underlying this? Can we use to ML to find it?
- If there is a symmetry → restrict combinatorics that count the CYs at 491 → make a brute force exploration of remaining 491 landscape possible?

LEVERHULME TRUST

Topology from cosmology: axions, astrophysics, and machine learning

Seeking two postdocs. Two year positions in London (KCL and LIMS).
Extended visits to Cornell and Northeastern. Please enquire/tell your colleagues!