Axion Dark Matter

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This is a huge subject, so necessarily I made idiosyncratic choices (and not complete list of citations!)

— Brief introduction to properties of DM

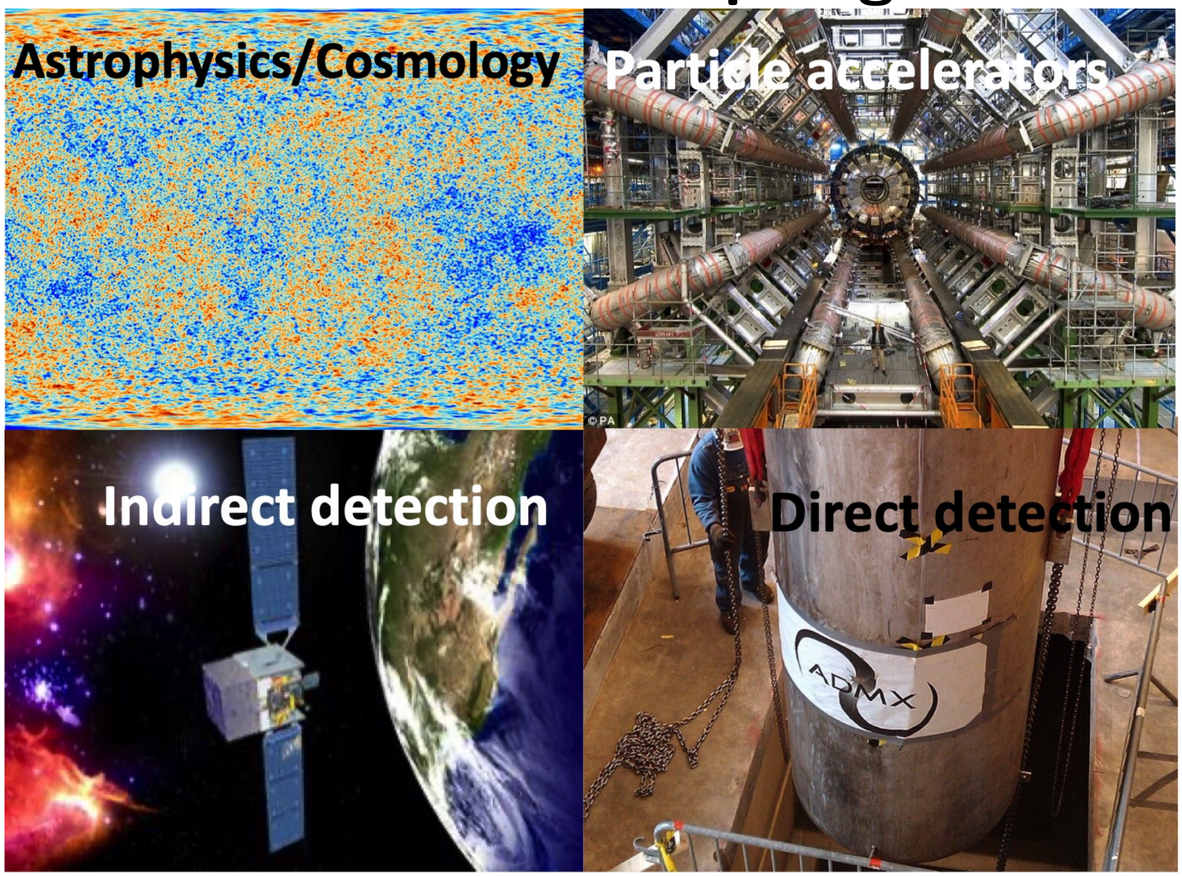
— Time evolution of DM models, since the 1980's

— Recent advances in pre- and post-inflationary ALP models ("canonical" and "non-canonical" misalignment, mini-clusters in pre-i and post-nflationary models, String Theory cosmic strings and walls?)

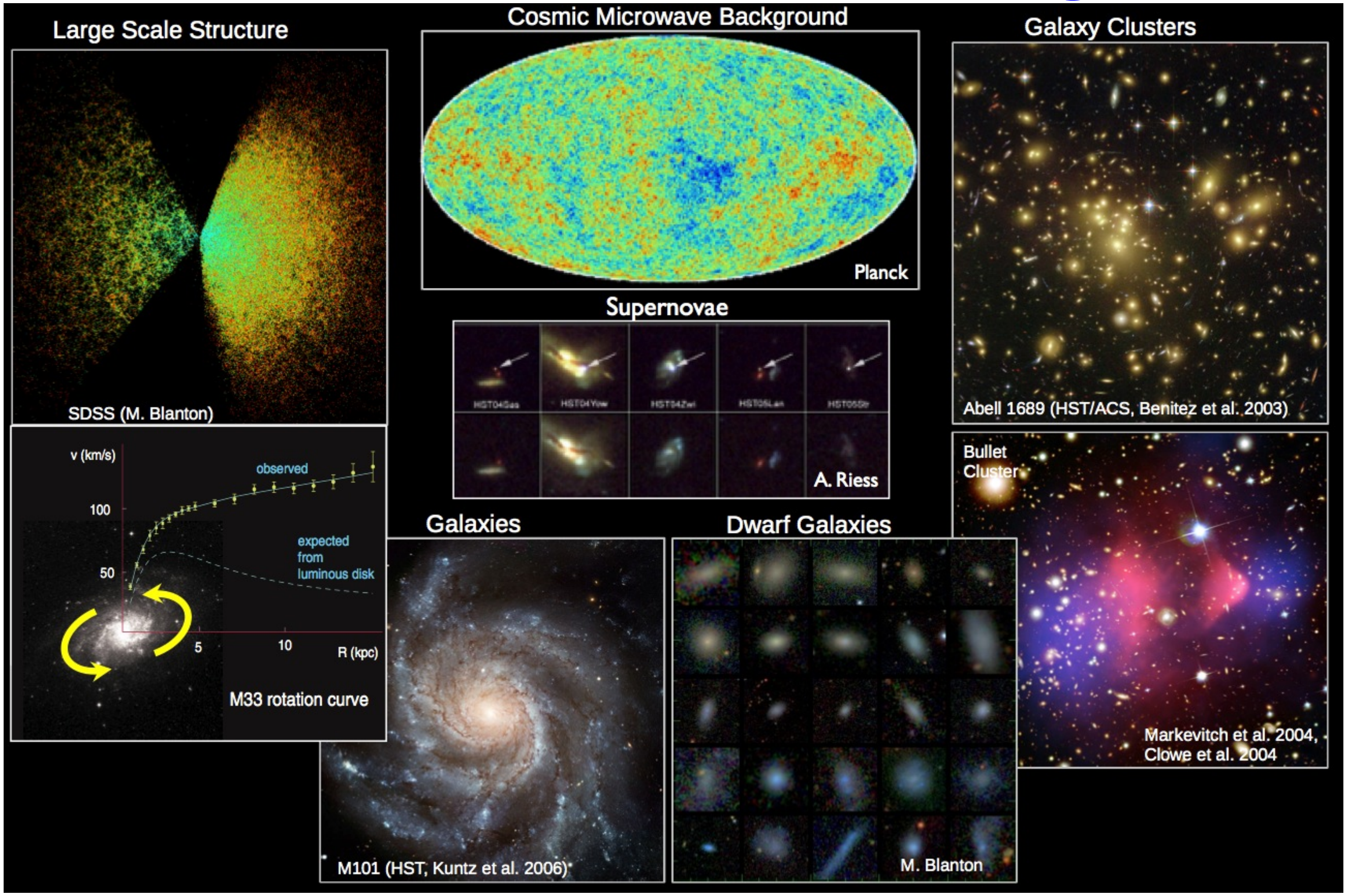
— Gravitational Wave signal of axion cosmic strings and cosmic walls

— Concluding remarks-Next steps?

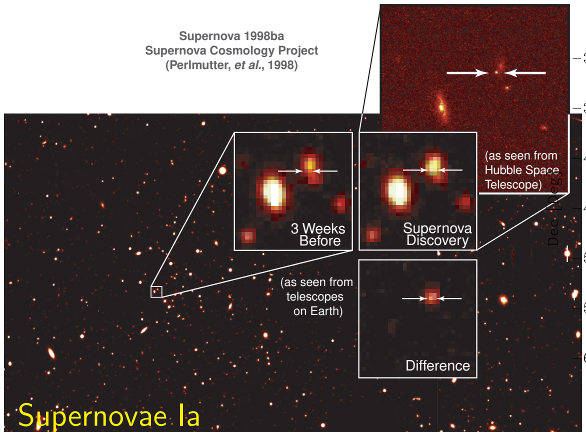
The search for Dark Matter, the most abundant form of matter in the Universe, is multi-pronged involving ...

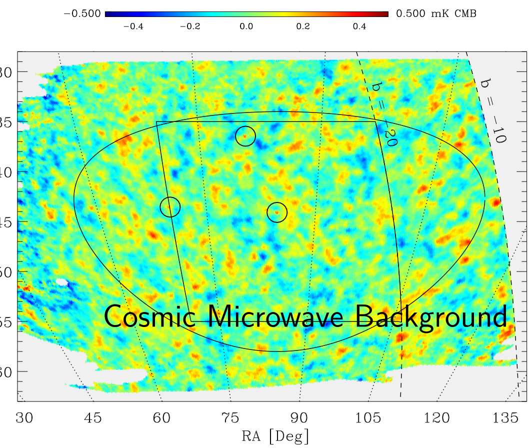


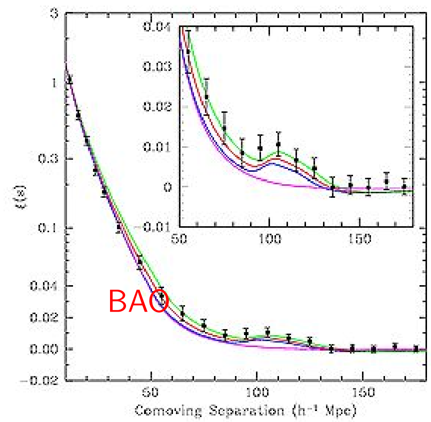
Evidence for DM at all scales, from dwarf galaxies on...

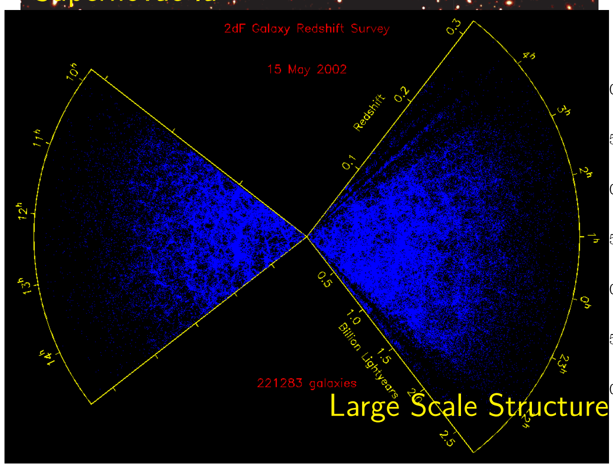


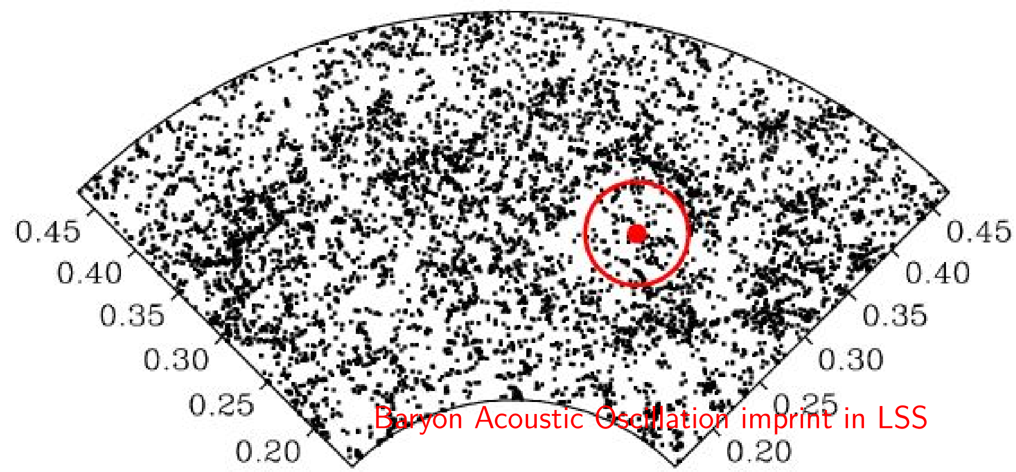
And it is data at the largest scales



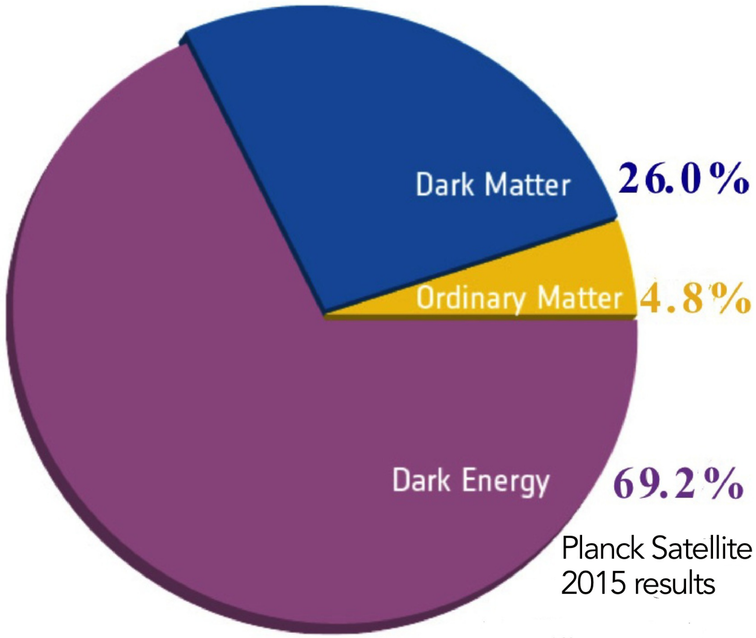


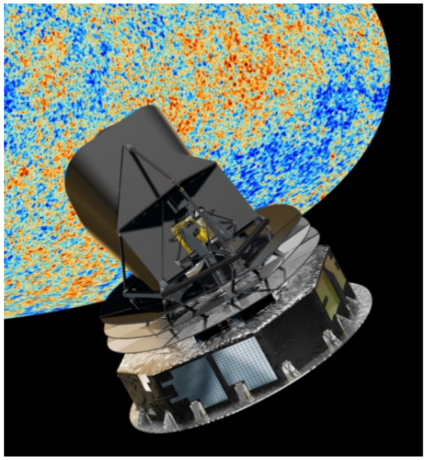






that allows us to define the “Double-Dark” model





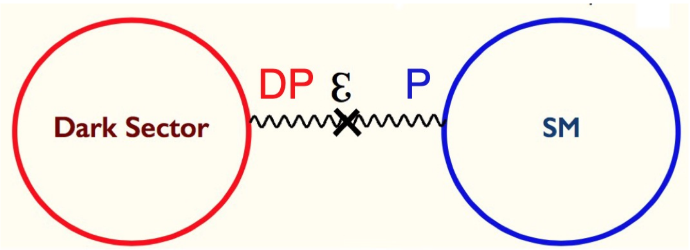
“DARK ENERGY” 69% (with repulsive gravitational interactions)
“MATTER” 31% (with usual attractive gravitational interactions- forms gravitationally bound objects) and most of it is **“DARK MATTER” 26%**

DM problem since the 1930's

After 90 years, what we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
  But idea always there,, e.g. "Aether-Scalar-Tensor- AeST"? (Skordis, Zlosnik 2021)
- **3- DM is not observed to interact with light or other SM particles**
  but could have a very small electromagnetic coupling such as:
  — "electric or magnetic dipole DM", or "anapole DM"

  —"Milli-Charged DM", interacting through a **Dark Photon** (DP) which has a small mixing ϵ with the photon (thus also couples to all charged particles with strength ϵQ) and could itself be the DM.



  or small couplings, "portals", to other SM particles

  So DM can be part of a whole Dark Sector

DM problem since the 1930's

After 90 years, what do we know about DM?

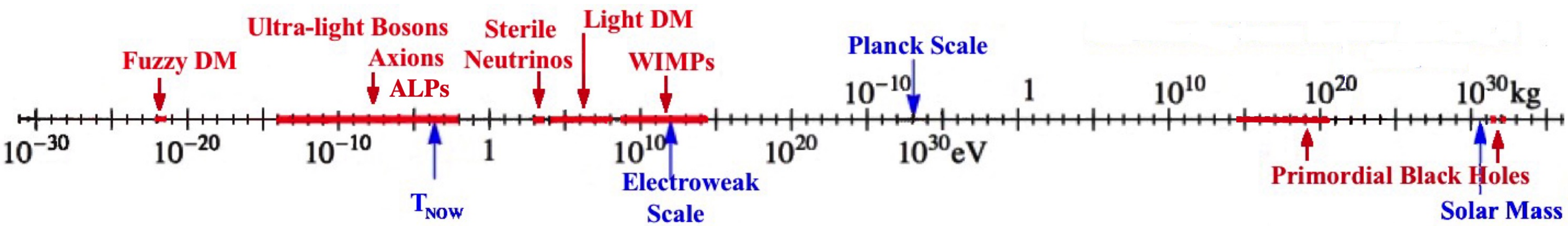
- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless but** $\leq$**few% of it could be dissipative** (looses energy into dark light particles, thus dark sector)
- **5- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**
  $\sigma_{\rm self}/{\rm m} \leq 1$ cm^2/g $=$ 2 barn/GeV $= 2\times10^{-24}$ cm^2/ GeV

- **6- The mass of the major component of the DM has only been constrained within some 70 orders of magnitude.**

10^{-22}eV $= 10^{-31}$ GeV $\leq$ **mass** $\leq 10^{-10} M_{\odot} = 10^{41}GeV= 2 \times 10^{14}$kg

Higher end: Primordial Black Holes (PBH), in the "asteroid" mass range

Lower end: "Fuzzy DM", boson with de Broglie wavelength 1 kpc (Hu, Barkana, Gruzinov, 2000)



-Axions (QCD-axions and ALPs) constitute the lightest DM candidates. How light can they actually be?

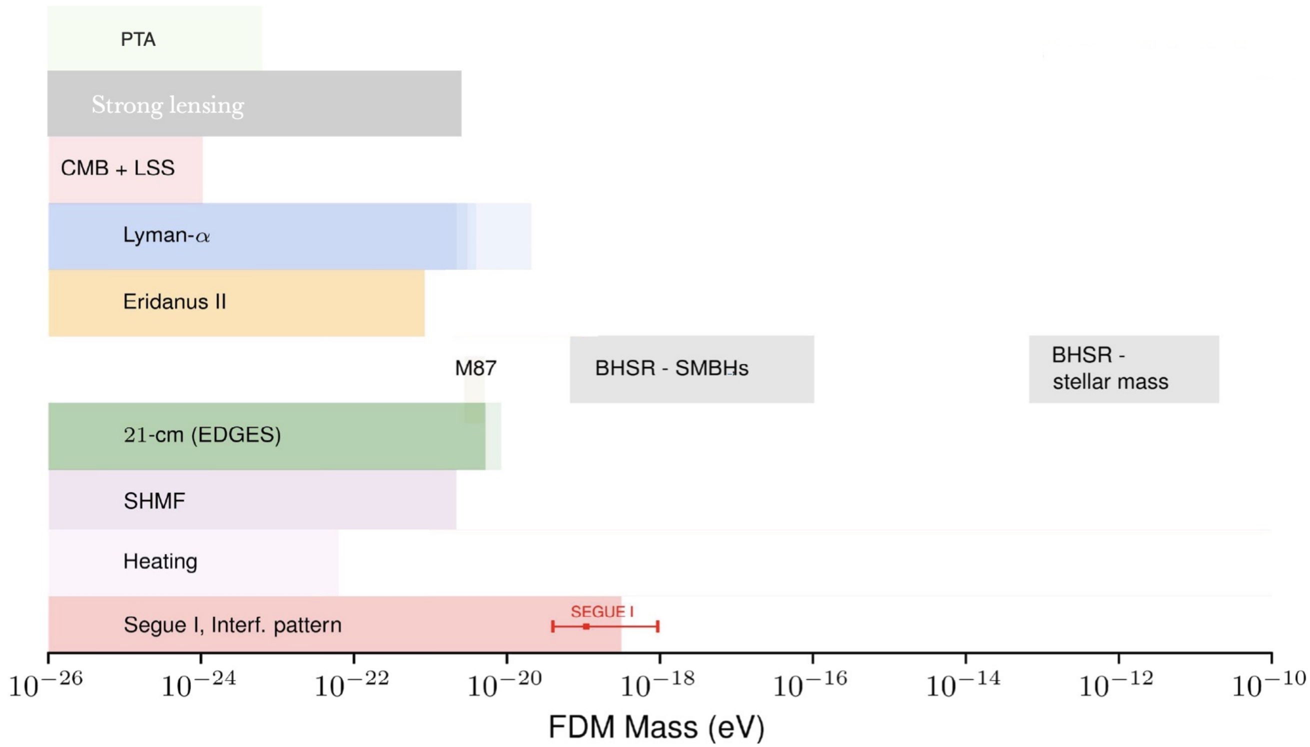
Ultra-Light Axions (ULA) or Scalar Field (SF) or Wave or Fuzzy DM

Light axions (with $m_a \ll 10$ eV in our galaxy) have a very large number density so behave like a classical field or "wave-like DM" e.g. in our galaxy, $v \simeq 10^{-3}$, $\rho \simeq 0.4$ GeV/cm^3 for $m_a = 10^{-9}$ eV, $\lambda_{\rm deBroglie} = 2\pi/mv \simeq 10^3$ km Occupation number $N = (\rho/m)\lambda^3_{dB} \simeq 10^{44}$
$N \sim 1/m^4$, so $N \simeq 1$ for $m \simeq 30$ eV, Quantum corrections $\sim \sqrt{N} \ll N$ negligible.
(WIMPs of $m = 10^2$ GeV, have $\lambda_{\rm dB} \simeq 10^{-16}$km, and $N = 10^{-36}$)

Fuzzy DM $m_a \simeq 10^{-22}$ eV, $\lambda_{\rm deBroglie} \simeq$ galactic scales. At smaller scales pressure due to the uncertainty principle (quantum pressure) has several effect, e.g. balances gravity and forms dense and stable soliton cores

(First paper to consider Scalar Field DM to form galactic halos in 1983- same year when QCD axions were proposed as DM candidates: Baldeschi, Gelmini, Ruffini PLB 122 (1983) 221-224. Concluded the bosons mass should be 10^{-24} eV $< m <$10 eV)

Limits if ALL of the DM is Fuzzy DM: $m > 10^{-16} M_\odot$ (Elena Ferreira, UCLA DM 2025)



But there are still uncertainties: systematic effects, dynamics of FDM not fully understood.

And only recently, since 2020, mixed DM models FDM and CDM studied (e.g. Schwabe etal 2007.08256, Lague etal 2310.20000)

After 90 years, what we know about DM:

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- **2- So far DM and not modified dynamics + only visible matter**
- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but** $\leq$**few% of it could be dissipative.**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit**
- **6- Mass within some 70 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** i.e. either non-relativistic of becoming so when dwarf galaxy core size structures start to form, $T \simeq$ keV
- **8**- No CDM or WDM in the SM: **particle DM requires BSM physics**

But which BSM?

The scope of DM models has changed since the 70's:

- 1980's: DM candidates were an afterthought, models proposed exclusively to solve problems in Standard Model, such as SUSY, Technicolor, "Little Higgs" models (electroweak hierarchy), Peccei-Quinn symmetry (strong CP problem), see-saw models (neutrino masses) - which also contain DM candidates: WIMPs, **QCD axions**, sterile neutrinos

- 1990's: DM candidates were mandatory in all BSM models

- Since 2000's: DM/Dark Sector models independent of solving any SM problem

Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM- but have implications for accelerators e.g. search for light mediators, displaced vertices... Led to all types of DM and interactions, to "dark sectors" seen through **"portals"**, i.e. a small coupling to one type of SM particle (could be γ's and Z's, the Higgs boson, neutrinos), classified according to possible experimental signals....

This trend also in axion models: from UV-complete to phenomenological

Interplay between theory and detection capabilities

e.g. in direct detection Detectors are sensitive to very different energies:

- Traditional experiments (since the 1980's onwards):

  - E $>$ keV's for scattering off nuclei, $\simeq E_K \simeq 10^{-6}$m reach m$>$GeV (now multi tonne)
  - E $\simeq 10^{-6}$eV$\simeq$m for axion resonant absorption in cavities

- Last 20 years driven by impressive developments in detectors, quantum sensors

  - E$>$eV for scattering or absorption off electrons
  - E$>$meV for scattering or absorption off collective excitations

• and smaller with quantum sensors e.g. atomic clocks and magnetometers, sensitive to small perturbations of internal degrees of freedom (energy levels, spins, etc). by coherent, classical waves allowing to reach Ultralight DM, where even small exposures can break new ground

AXIONS: QCD-axions and Axion-Like Particles (ALPs):

Light pseudoscalar bosons that couple weakly to SM particles

— **Field Theory Axions:** are pseudo-Nambu-Goldstone (NG) bosons of an approximate $U(1)$ global symmetry broken spontaneously at a large scale f_a (e.g. QCD-axions, Majorons, familons)

Light because of global symmetry: if exact, NG bosons have $m_a = 0$, thus
$m_a \sim$ (small explicit breaking $/f_a$)
Small couplings because GB couplings are $\sim 1/f_a$

— **String Theory Axions:** zero-modes of gauge fields corresponding to compactified extradimensions > 4 of linear size R. Here $f_a \sim 1/R$

Light because local gauge symmetry in 10 (or 11) dim implies $m_a = 0$,
but non-local violations (instantons) may give small m_a
Small couplings turn out again to be $\sim 1/f_a$

QCD Axions Solve the strong CP problem.

The Lagrangian of QCD includes a CP violating term

$$L_{QCD} = \theta \frac{g^2}{32\pi^2} G_a^{\mu\nu} \ \ \tilde{G}_{a\mu\nu}$$

Besides, the quark mass matrix M is in general complex

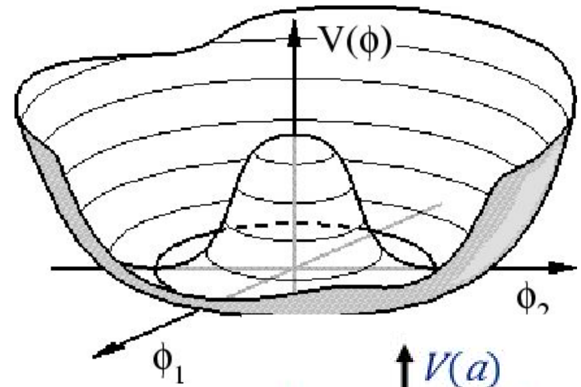
$$L_{\rm Mass} = \bar{q}_{iR} M_{ij} q_{jL} + h.c.$$

A $U(1)_A$, i.e. one that rotates right and left handed fields by opposite faces, is necessary to diagonalize it and change the θ value

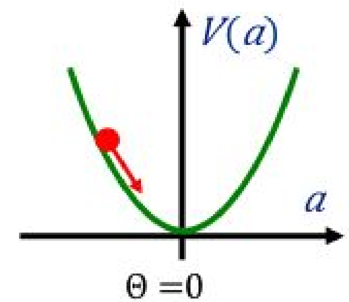
$$-\pi \leq \bar{\theta} = \theta + arg \ det(M_u M_d) \leq \pi$$

The experimental limit on the neutron electric moment $d_n \simeq e\bar{\theta} m_q / M_n^2$ implies $\bar{\theta} < 10^{-10}$! The strong CP problem is why is this $\bar{\theta}$ angle, coming from the strong and weak interactions, so small?.

QCD Axions: Viable solution of the "strong-CP" problem of QCD: augment the SM to make the Lagrangian invariant under a global chiral symmetry $U(1)_{PQ}$ (Peccei-Queen 1977) spontaneously broken at a scale f_a, whose Nambu-Goldstone boson is the AXION a (Wilczek 1978, Weinberg 1978)



The phase a/f_a sums to $\bar{\theta}$, and the explicit $U(1)_{PQ}$ violation due to QCD chiral symmetry breaking close to Λ_{QCD} (confinement scale) produces a potential for the field a, so that at its minimum $a = < a >$ there is no strong CP violation.



Original axion model (Peccei and Quinn 1977)
$f_a \simeq$ EW scale failed experimentally.

Invisible axion (now just called QCD axion) models (KSVZ: Kim 1979; Shifman, Vainshtein and Zakharov 1980-heavy quarks carry PQ charge); (ZDFS: Zhitnitsky 1980; Dine, Fischler and Srednicki 1981 - 2 Higgs fields and quarks carry PQ charge)

$f_a \gg$ EW scale. A singlet scalar VEV $<\phi> \simeq f_a \gg \Lambda_{QCD}$ breaks $U(1)_{PQ}$ spontaneously $\phi = <\phi> e^{a/f_a}$ at the orbit of minima: shift symmetry $a \rightarrow a+$ const. if no-explicit breaking.

String Theory Axions (Witten 1984; Conlon 0602233; Svrcek, Witten 0605206; Arvanitaki et al 0905.4720; Jaeckel, Ringwall 1002.0329...)

— Generically present in all string theories, zero modes of gauge boson components in compactified dimensions of size R, then $f_a \sim 1/R$, small m_a due to non-perturbative effects.

— Chern-Simons couplings (e.g. at one-loop, through triangle diagrams with three external gauge bosons) may emply CP violating couplings to gluons and photons in the low-energy EFT.

— No"PQ quality problem": Quantum Gravity violates global symmetries (e.g."BHs have no hair") so why QG does not produce large explicit PQ symmetry breaking and spoil the strong CP solution? (Georgi, Hall, Wise 1981; Dine, Seiberg 1986;..)
In string theory the PQ symmetry is secretly tied to a gauge symmetry, protected by QG

—- Generic feature is an "axiverse" with a large number of ALPs with different masses and couplings: one could play the role of "QCD" axion, the others are ALPs not coupled to gluons but yet to photons. (Arvanitaki et al 0905.4720) It motivates phenomenological...

Generic EFT ALP models (e.g. Jaeckel and Ringwald 2010...)

Ad-hoc global U(1) with explicit breaking at scale $v << f_a$, with f_a and v arbitrary.

AXIONS- mass and couplings

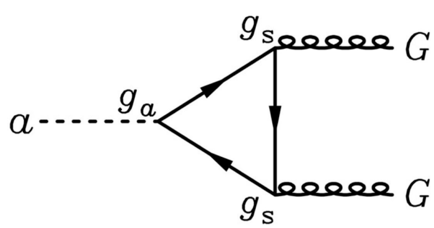
For QCD axions: m_a related to f_a and T-dependent in the Early Universe

$$m_a(T)^2 = \min\left[\frac{\alpha_a \Lambda^4}{(T/\Lambda)^n f_a^2}, m_a^2\right], \quad m_a = \frac{\sqrt{m_u m_d} m_\pi}{(m_u + m_d) f_\pi f_a} \simeq 6.3 \text{ eV} \left(\frac{10^6 \text{GeV}}{f_a}\right)$$

$\lambda \simeq 400$MeV, $n \simeq 8$ (e.g. Buschmann, Foster, Safdi 1906.00967)

Necessary coupling to gluons $\sim N$=number of PQ charged fermions

(so $f_a = <\phi> / N$)



$$L_{agg} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

Model dependent couplings to γ's and fermions,

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} C_{a\gamma\gamma} \frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad L_{aff} = \frac{C_{\text{aff}}}{2 f_a} \partial_\mu a \; \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f \partial_\mu a_{\text{phys}}.$$

For ALPs: m_a is independent of T and f_a, and each coupling may or not exist.

Axion Cold Dark Matter as pseudo-Nambu-Goldstone bosons (pNGB)

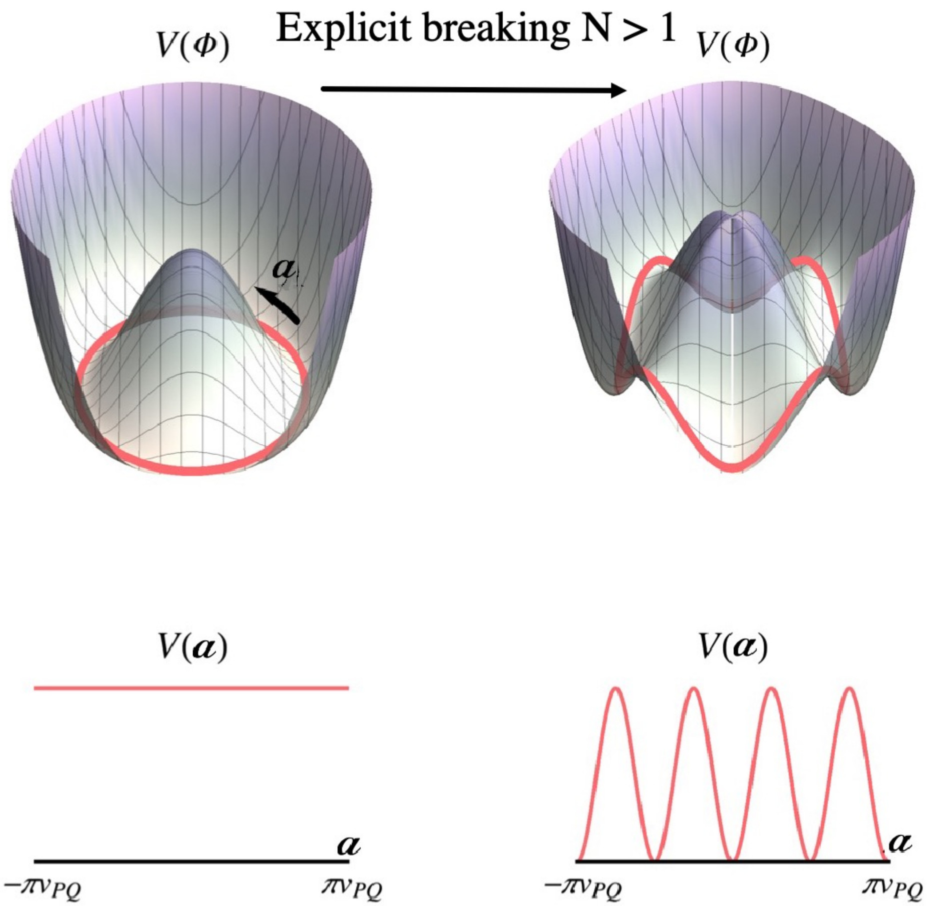
(Prekill, Wise 1983; Abott, Sikivie 1983; Dine, Fischler 1983)

WHICH m_a, f_a? Not simple answer, rich cosmology, many models..

- U(1) global symmetry spontaneously broken at scale f_a, a is field component along the orbit of degenerate minima, phase $\theta = a/f_a$.

- explicit breaking at a scale $v << f_a$- leaves one $(N = 1)$ or more $(N > 1)$ true minima (discrete symmetry Z_N) gives mass to the pseudo-NGB $m_a \simeq v^2/f_a$.

(Fig. adapted from Armengaud et al 1904.09155)



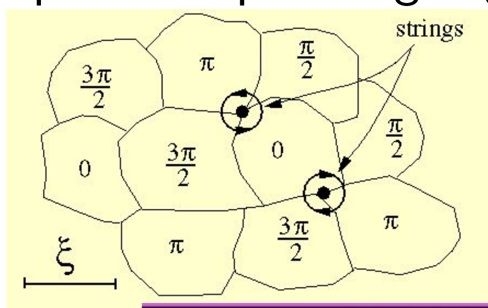
Surprisingly complex cosmology of pseudo-NG bosons

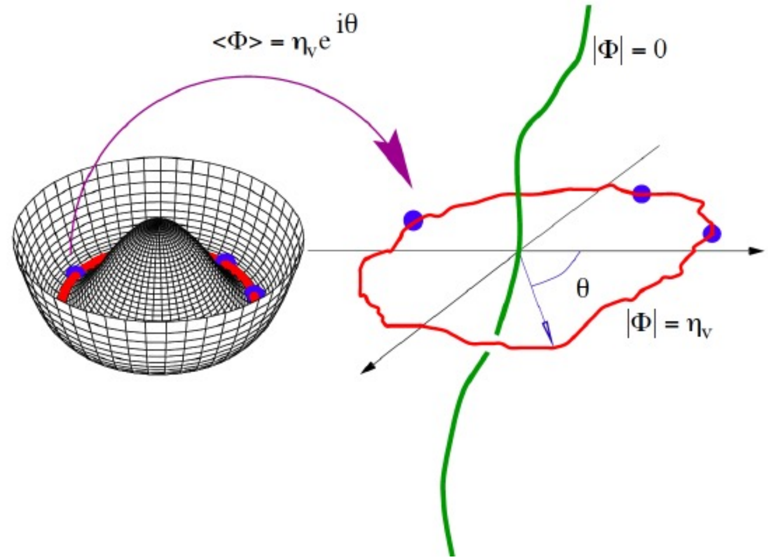
Spontaneous breaking at scale f_a: creates different θ domains of size $<$ct$\simeq H^{-1}$

-Pre-inflationary scenarios: after inflation Universe is in one domain.

-Post-inflationary scenarios: cosmic strings and walls. A cosmic string appears when loop in space has phases going around the orbit of minima

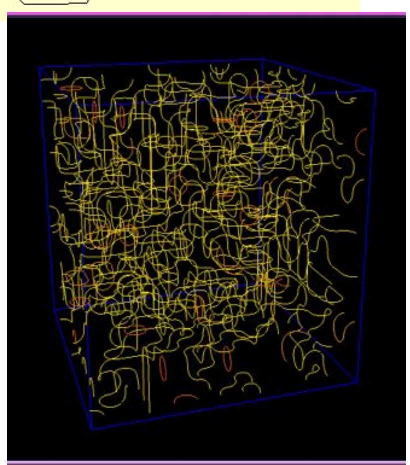
(Kibble Mechanism 1976)





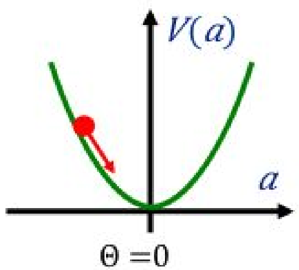
String system soon enters in a "scaling regime", with a few long strings $L \sim t$ per horizon volume

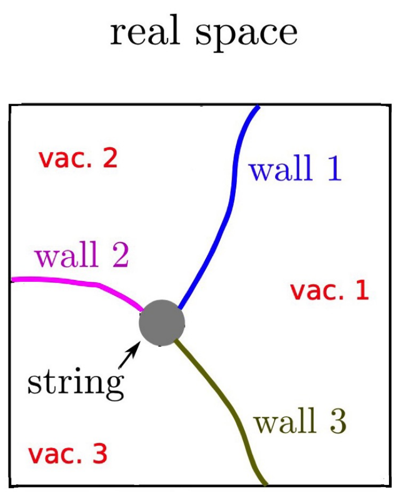
(e.g. Martins and Shellard 1996...)

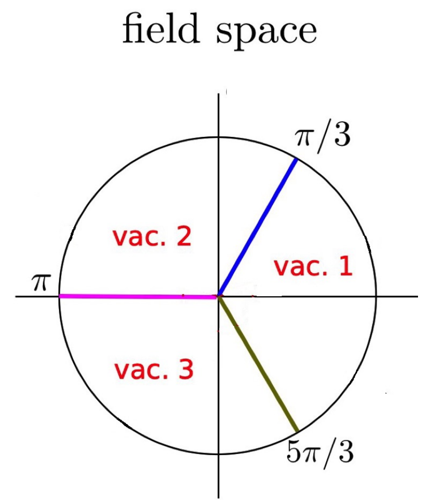


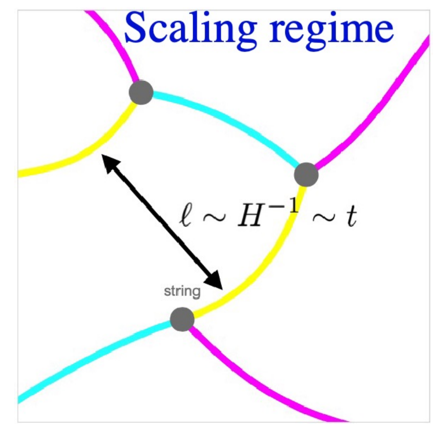
Later, when the explicit breaking becomes dynamically important

Eq. of motion $\ddot{a}+3H\dot{a}+V(a)'=0$, close to minimum $V\simeq m_a^2 a^2/2$, eq. damped oscillator. Field is driven towards closest Z_N minimum when $3H \simeq m_a \simeq v^2/V$ ($t \simeq$ oscillation period m_a^{-1}): cosmic walls appear joined to the strings. E.g. for $N=3$









- $N=1$ unstable system: "ribbons" bounded by strings shrink and annihilate fast

- $N>1$ stable string-wall system: each string attached to N walls - Soon reaches a "scaling regime" in which linear size $\simeq$ cosmic horizon t (Press, Ryden, Spergel 1989)

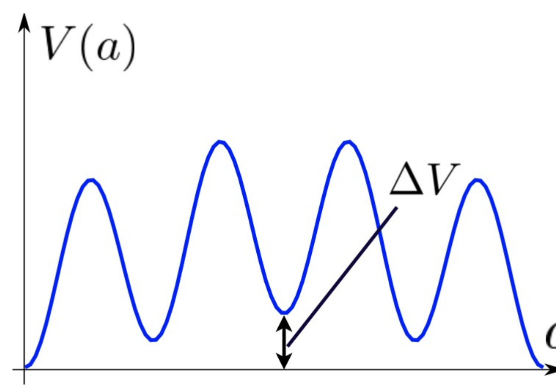
The $N > 1$ stable wall system must annihilate:

- Energy density of system $\rho_{\rm wall\ system} \simeq \sigma/t$ ($\sigma \sim v^2 f_a$: energy per unit area), while for radiation or matter domination $\rho \sim 1/t^2$ decrease faster with time. Thus stable walls would get to dominate the energy density of the Universe, leading to an unacceptable cosmology.

- Zeldovic, Kobzarev and Okun (1974) realized this problem and proposed as solution: a small breaking of the Z_N so that only one true vacuum remains.

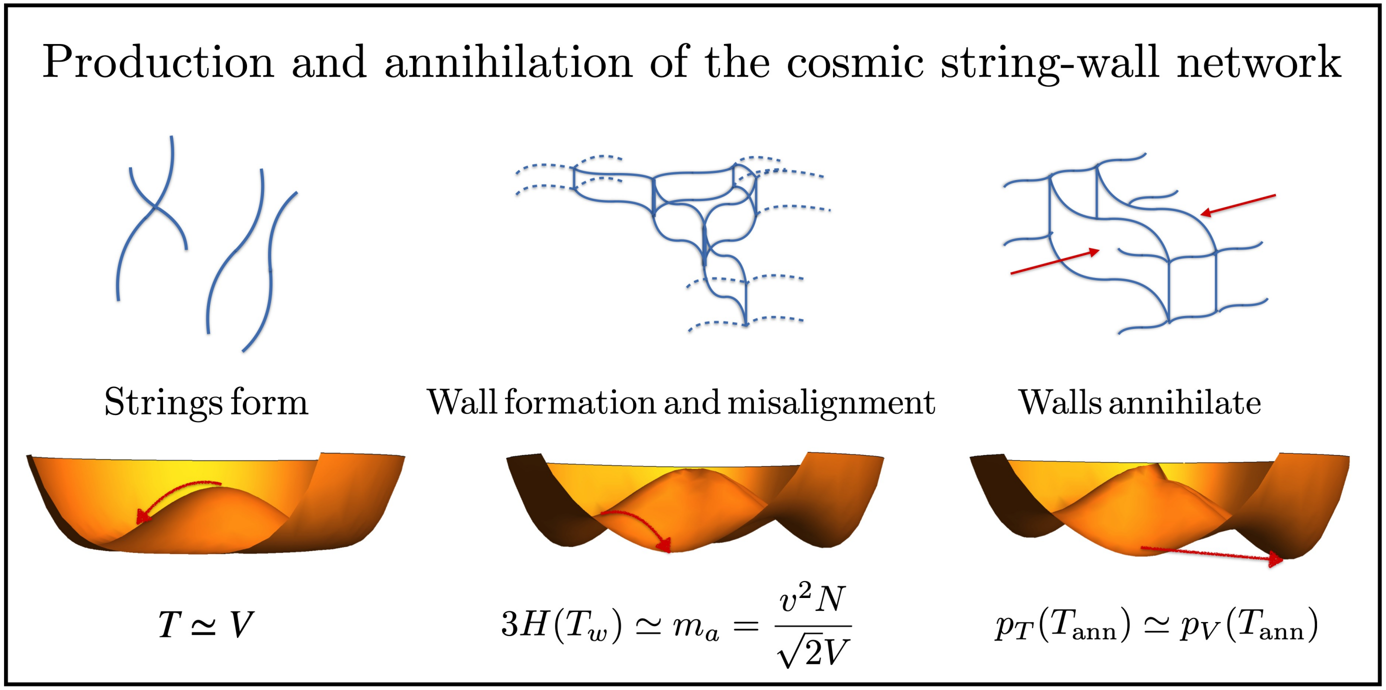
- This introduces a "bias", i.e. an energy difference or volume pressure $\Delta V = p_V \simeq V_{\rm bias}$ between the false and the true vacua.

- Initially $V_{\rm bias} \ll p_T \simeq \sigma/t$, the tension pressure.



- As p_T decreases with time, when $V_{\rm bias} \simeq \sigma/t$, walls accelerate away from the true vacuum leading to the annihilation of the string-wall system:

Complex cosmology of $N > 1$ stable wall system



(Here $V = f_a$) Axion production in pre-inflation models: misalignment.
In post-inflation models via three mechanisms:1)- misalignment, 2)- emission by strings and 3)- emission by the string-walls (only if N>1)

Axions as cold dark matter

-Pre-inflationary scenario: after inflation Universe has a unique θ_i

$\ddot{a} + 3H\dot{a} + V(a)' = 0$, close to minimum $V(a) \simeq m_a^2 a^2/2$ damped oscillator.

When $3H \simeq m_a$ ($t \simeq$ period m_a^{-1}) coherent field oscillations begin- $a(t) \sim a_0 \cos(m_a t)$ behave like cold, non-interacting DM $\rho_a \sim T^3$ on average, at scales $> m_a^{-1}$

Canonical "misalignment" coherent oscillations: initial θ_i not at its minimum.
For QCD axions, (e.g. Bae, Huh, Kim, 0806.0497; Ballesteros et al 1610.01639)

$$\Omega_a^{\rm MIS} h^2 \simeq 0.12\ \theta_i^2\ \left(\frac{f_a}{10^{12}{\rm GeV}}\right)^{1.165} \simeq 0.12\ \theta_i^2\ \left(\frac{6\mu{\rm eV}}{m_a}\right)^{1.184}$$

Larger f_a (smaller m_a) if late entropy dilution or θ_i very small ("anthropic window")

For ALPs,

$$\Omega_a^{\rm MIS} h^2 \simeq 0.12\ \theta_i^2\ \left(\frac{f_a}{10^{16}{\rm GeV}}\right)^2 \left(\frac{m_a}{5\times 10^{-19}{\rm eV}}\right)^{1/2}$$

(Prekill, WIse 1983; Abott, Sikivie 1983; Dine, Fischler 1983)

Axions as cold dark matter

-Pre-inflationary scenario: after inflation Universe has a unique θ_i

Many versions of misalignment

"Canonical 'misalignment" initial θ_i not at its minimum.

If axions account for the whole of the DM $\Omega_a h^2 = 0.12$

$$\theta_i = 0.75 \left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)^{0.592} = 1.0 \left(\frac{m_a}{10\mu eV}\right)^{0.592}$$

- $\theta_i \simeq 1$ implies $f_a \simeq 10^{12}$ GeV called "classic window"
- $\theta_i \ll 1$ implies $f_a > 10^{12}$ GeV called "anthropic window" (e.g. $f_a \simeq 10^{16}$ GeV for $\theta_i \simeq$0.003)

(Hamann, Hannestad, Raffelt, Wong 0904.0647)

- $|\pi - \theta_i| \ll 1$, called "extreme axion" or "large misalignment mechanism" (Zhang, Chiueh 1705.01439; Arvanitaki et al 1909.11665)) Onset of oscillations delayed, causes fluctuations in the axion field to grow leading to a "fragmentation" (e.g. Fonseca, Morgante, Sato, Servant 1911.08472) of the coherent field into fluctuations, larger at the scale H^{-1} when field starts oscillating, could yield minihalos ("Fempto-halos" M$=10^{-15}$M$_\odot$) DM abundance for $f_a < 2 \times 10^{10}$ GeV $(m_a > 3 \times 10^{-4})$

Axions as cold dark matter

How to detect Femto-halos? (Arvanitaki et al 1909.11665))

— Halos from the parametric-resonance are much denser than expected in ΛCDM

— The largest ones would survive tidal striping in galaxies.

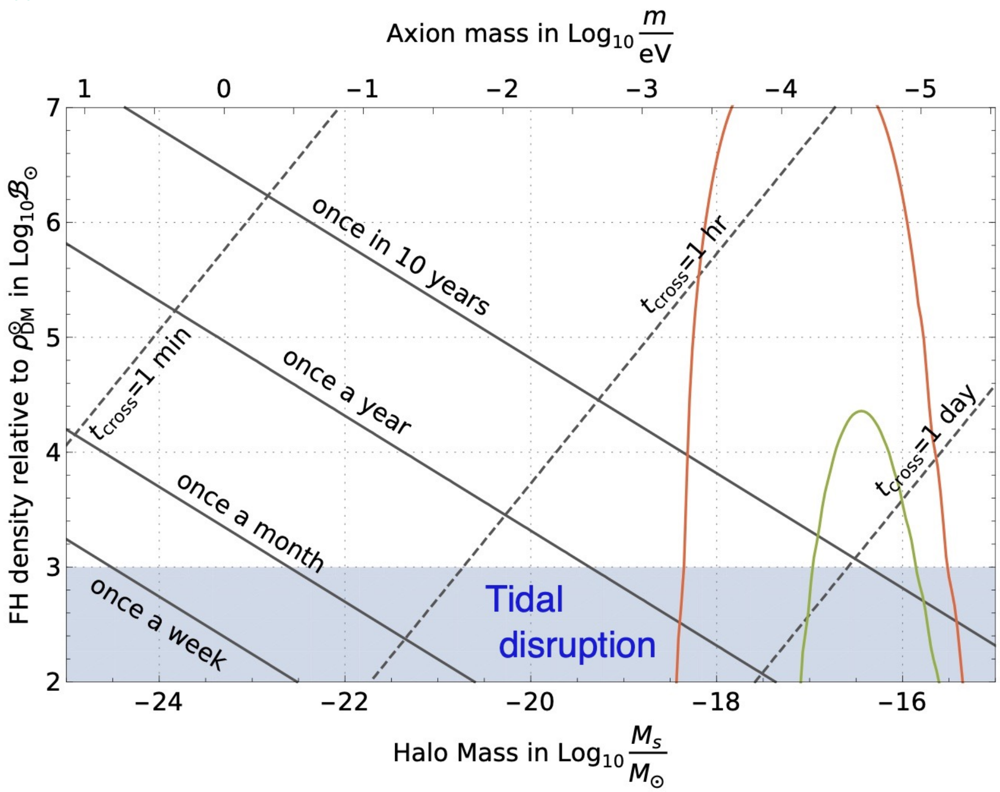
— Through gravitational interactions: perturbations in stellar phase space distributions, gravitational lensing signatures, and dynamical friction effects, gravitational effects on baryonic structures (e.g. Lyman- forests)

— Through direct detection with ad-hoc strategies: effect would be huge while Earth passes though one ($> 10^6$ in coherence), but encounters are rare, so look for off-resonance signals? record data for long periods of time over large bandwidth?

Axions as cold dark matter

Femto-halo effects in direct detection for QCD-axions $\mathcal{B}_\odot = \rho/\rho_{\rm DM}$ overdensity inside the halo

(Arvanitaki et al 1909.11665))



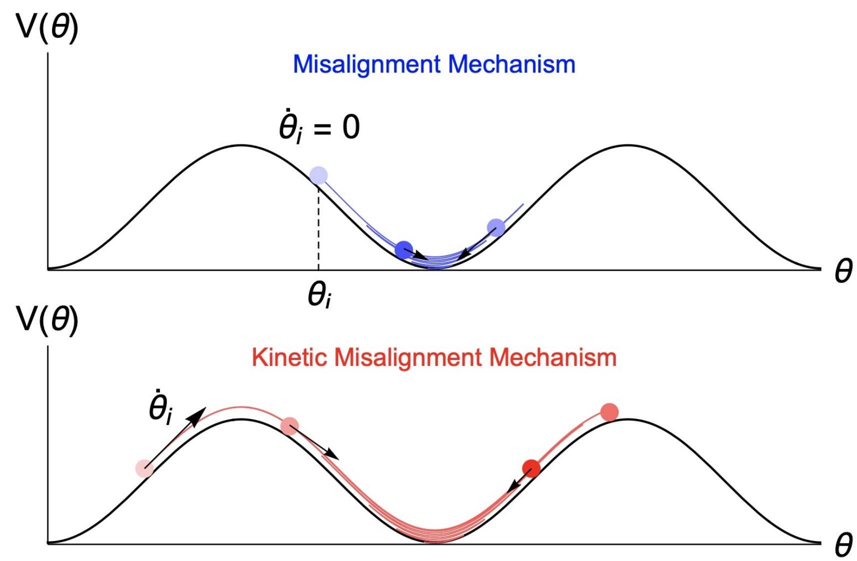
Spectrum for QCD-axions with $f_a = 10^{10}$GeV and $f_a = 2 \times 10^{10}$GeV

Axions as cold dark matter

-Pre-inflationary scenario: after inflation Universe has a unique θ_i

"Kinetic misalignment": initial axion field velocity $\dot{\theta} > m_a$ when $H \simeq m_a$. Onset of oscillations is delayed. For QCD-axions DM all $f_a < 10^{12}$ GeV ($m_a > 6\mu$eV) allowed (Co, Hall, Harigaya 1910.14152, 2006.04809; Chang, Cui 1911.11885; Barman etal 2111.03677...)

Many different variations (e.g. "cogenesis" of DM and Baryon Number). Could be sourced in various ways including by

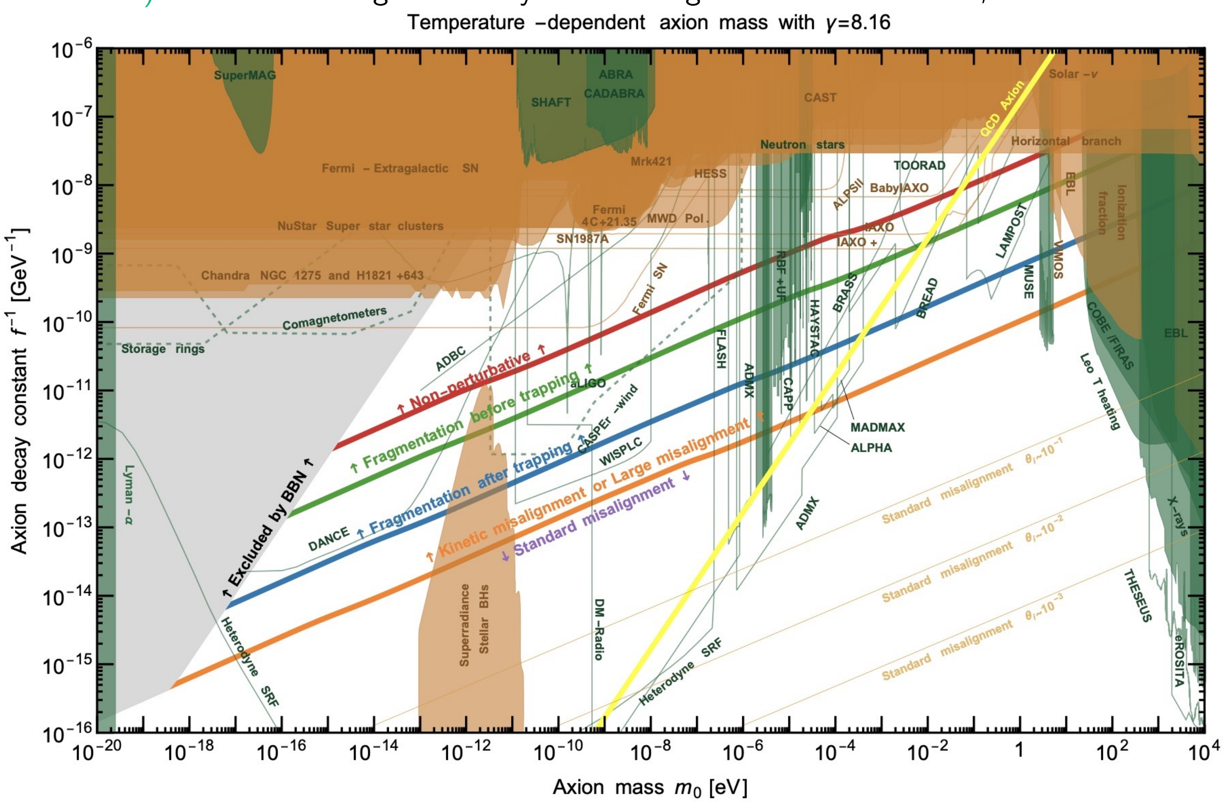


"Trapped misalignment": potential with non-trivial T dependence, produces two stages of oscillations: first about a wrong minimum, delays onset of true oscillations about $\theta = 0$. For QCD-axions DM all m_a from canonical range to Fuzzy DM allowed (Di Luzio, Gavela, Quilez, Ringwald 2102.00012 and 2102.01082)

Axions as cold dark matter

-Pre-inflationary scenario: after inflation Universe has a unique θ_i

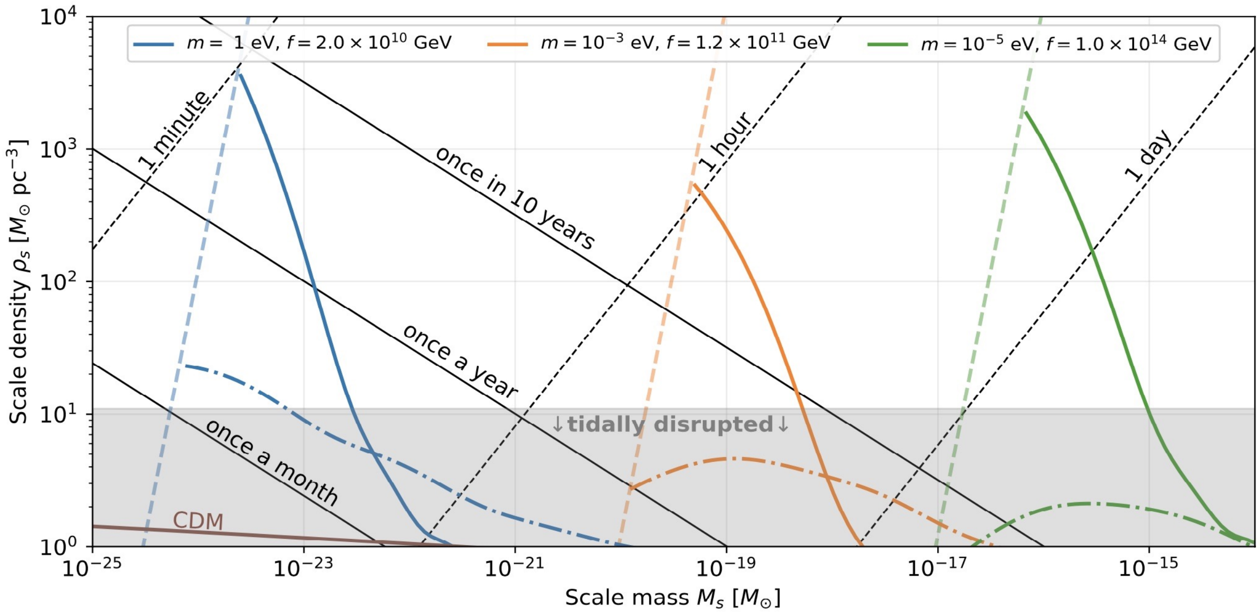
Parameter space for ALP DM produced by fragmentation in kinetic misalignment (Eroncel, Sato, Servant, Sorensen 2206.14259) Standard misalignment only below orange line. Above red line, calculations not trusted



Axions as cold dark matter

-Pre-inflationary scenario: after inflation Universe has a unique θ_i

In kinetic misalignment, while field is rolling around over the potential barriers in the orbit of minima, fluctuations can grow exponentially via parametric resonance: fragmentation- Produces miniclusters(Eroncel, Servant 2207.10111)



Pre-inflationary scenarios produce minihaloes- not only post-inflationary ones!

Axions as cold dark matter

-Post-inflationary scenarios: string/wall emission require simulations

very challenging because string size $\sim f_a^{-1} << H^{-1} \sim$ string length

Strings Dominant source of axion DM in $N = 1$ models, but large uncertainties in the evaluations (e.g. Kawasaki, Saikawa, Sekiguchi, 1412.0789; Gorghetto, Hardy, Villadoro 2007.04990; Buschmann et al 2108.05368; O'Hare 2112.05117, Saikawa etal 2401.17253; Kim, Park, Son 2402.00741)

QCD axion all DM: $95\mu\mathrm{eV} < m_a < 450\mu\mathrm{eV}$. For ALPs ($\xi \simeq 25$ Gorghetto etal 2007.04990)

$$\Omega_a^{\mathrm{St}} h^2 \simeq 0.1\ \xi\ \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{m_a}{\mathrm{eV}}\right)^{1/2} \ln\left(\frac{3 f_a}{\sqrt{2\xi}\ m_a}\right)$$

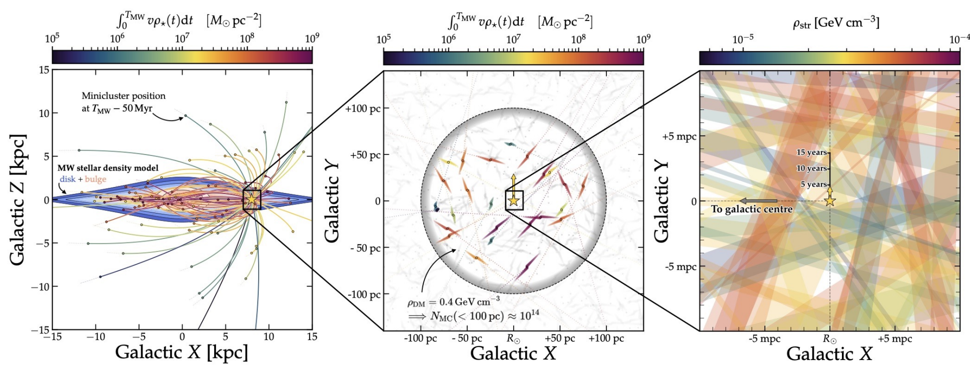
Walls in N$>$ 1 models Could be dominant source of axions if annihilate late, V_{bias} small. Simulations are more difficult than for N=1. Large uncertainties. (e.g.Chang etal 9807374; Hiramatsu etal 1202.5851.1207.3166; Saikawa 1703.02576; Chang, Cui 2309.15920;Yang Li etal 2311.02011)

$$\Omega_a^{\mathrm{walls}} h^2 \simeq 0.1 \frac{(17\mathrm{GeV})^2}{V_{\mathrm{bias}}^{1/2}} \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^3 \left(\frac{m_a}{\mathrm{eV}}\right)^{3/2}$$

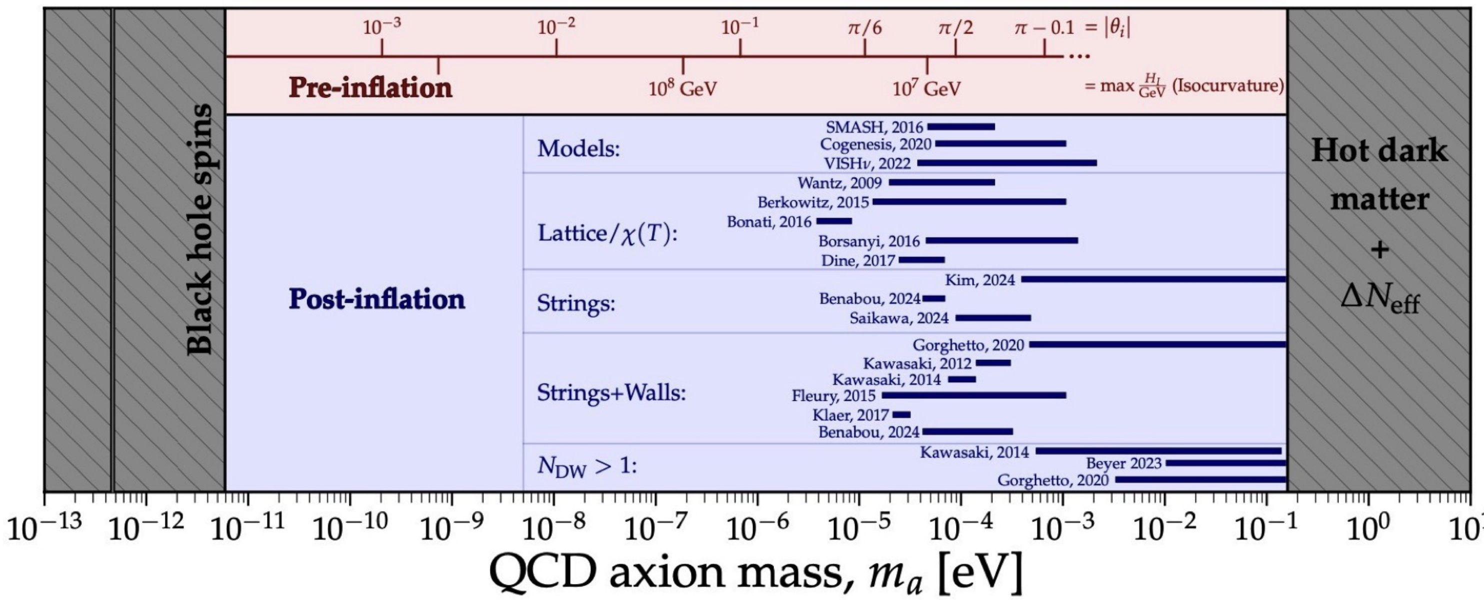
Axions as cold dark matter

-Post-inflationary scenarios: Large small-scale perturbations lead to "axion miniclusters" For QCD axions 10^{-15} -10^{-12} $M_\odot$ Hogan, Rees 1988; Kolb, Tkachev, 1993, 94, 95; Zurek, Hogan, Quinn, 2006...Buschmann, Foster, Safdi 1906.00967; Hindmarsh et al 1908.03522 and 2102.07723, Pierobon et al 2307.09941

Direct Detection? About 20% of axions remain unbounded and could be detected. Even more promising, miniclusters could be tidally stripped by stars. Recent simulation found ∼80% of local DM density in solar neighborhood, consists of O(10^2–10^3) overlapping streams which could be detected with enough frequency resolution in haloscopes O'Hare, Pierobon, Redondo 2311.17367



Summary QCD axion dark matter mass (From C. O'Hare at cajohare.github.io)



Low mass limit: BH superradiance

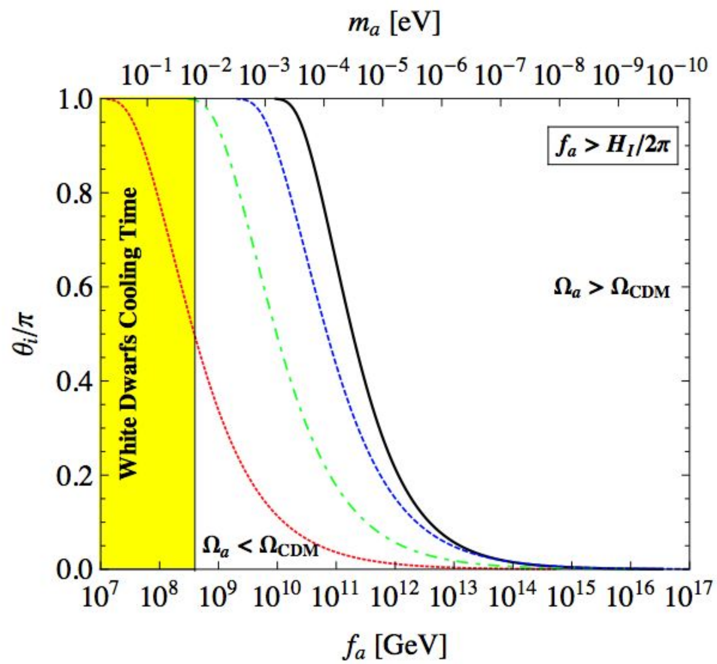
High mass limit: large axion coupling $\sim 1/f_a$, axions produced thermally, are Hot DM rejected by limits on the effective number of neutrino species

But non-canonical misalignment could extend to Fuzzy-DM mass- And so far made standard assumptions about Pre-BBN cosmology. Prediction change in non-standard cosmologies

Axions in non-Standard Pre-BBN Cosmologies?

allow for different combination of parameters. E.g.: the initial misalignment angle θ_i as function of the Peccei-Quinn scale f_a for QCD-axions to be 100% of the CDM in standard cosmology (black solid line), kination cosmology with transition to standard at 4MeV (red dotted line), 300MeV (green dot-dashed line) or 700MeV (blue dashed line).

from Visinelli and Gondolo 0912.0015



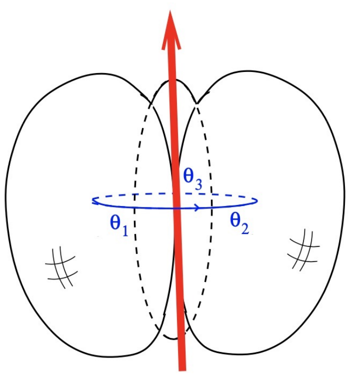
Axions as cold dark matter in extra-dimensions and string theory

Both pre and post-inflationary models exist in String Theory.

Pre-inflationary better studied generally closed string with inflation scale$<$compactification scale (e.g. M. Reece 2406.08543) Axion detection can probe extra dimensions and the string theory landscape. (e.g. Gendler, Marsh 2407.07143)

Post-inflationary, problematic, less studied open string sector with SM realized by D3 branes at singularities. (e.g. M Cicoli et al 1206.5237, 1304.0022, 2106.11964) "String-Theory axion strings" are not formed via the Kibble-mechanism, but fundamental objects (rather than solitons), with larger tension.

Benabou etal 2312.08425: overproduce QCD axions (except in some axiverse models). Cline, Litos and Xue 2412.12260 warp extra-dim. counter-example "Kibble-like" mechanism with bubbles of 1st order phase transition.
More work needed ...



Walls with N$>$1 axiverse models also very uncertain Das, Ferrer 2502.12153

Cosmology/Astrophysics probe due to only gravity

-Gravitational waves (GW) emitted in post-inflationary ALP models

by cosmic strings in $N = 1$ ALP models (e.g. Chang and Cui 1910.04781; Gouttenoire, Servant and Simakachorn 1912.02569; Gorghetto, Hardy and Nicolaescu 2101.11007)

Strings emit GW of frequency $f \simeq H$ continuously from the time they are formed (when the symmetry is spontaneously broken) until walls appear (when $H \simeq m_a$).

by cosmic walls in $N > 1$ ALP models (e.g. GG, Simpson and Vitagliano 2103.07625 and 2207.07126; GG, Hyman, Simpson and Vitagliano 2207-07126; Gorghetto and Hardy 2212.13263, Kitajima et al 2306.17146, GG and Hyman 2307.07665)

Most of the emission from walls is when they annihilate. all the l system energy goes mostly into ALPs, but some into gravitational waves (GW) and possibly Primordial Black Holes (PBH). In 2207.07126 we dubbed this "CATASTROGENESIS" from the Greek for "annihilation"

καταστροφή

Characteristic peaked spectrum. Not observable for QCD-axions (Hiramatsu, Kawasaki, Saikawa, Sekiguchi 1207.3166)

Gravitational Waves from Catastrogenesis

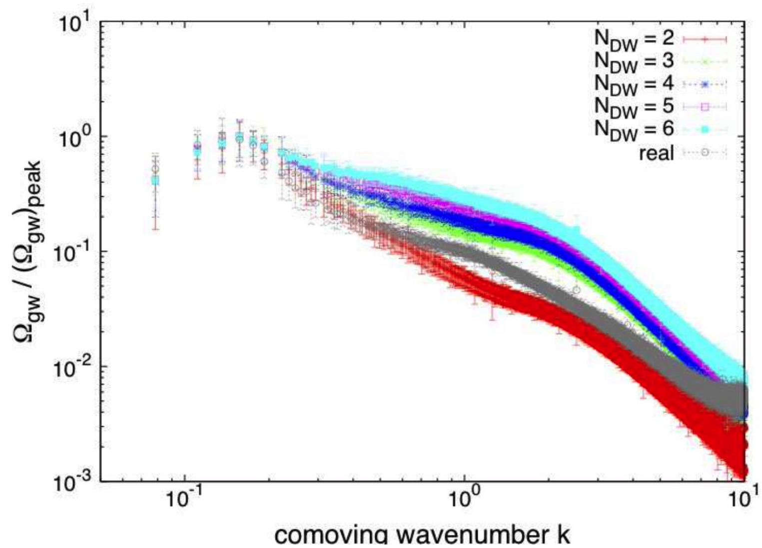
Amplitude:

- Quadrupole formula for the power emitted in GWs $P \simeq G\dddot{Q}_{ij}\dddot{Q}_{ij}$, where $Q_{ij} \simeq E_w t^2$ and $E_w \simeq \sigma t^2$. Thus $\dddot{Q}_{ij} \simeq \sigma t$, and $P \simeq G\sigma^2 t^2$.
- The energy density emitted per Hubble time is $\Delta\rho_{\rm GW} = Pt/t^3 = G\sigma^2$ independently of the emission time t, and is redshifted to the present, thus
- the peak GW amplitude, corresponds to the latest emission time $t = t_{\rm ann}$, $\rho_{\rm GW}|_{\rm peak} \simeq G\sigma^2 \left(a(t_{\rm ann})/a_0\right)^4$.

Spectrum:

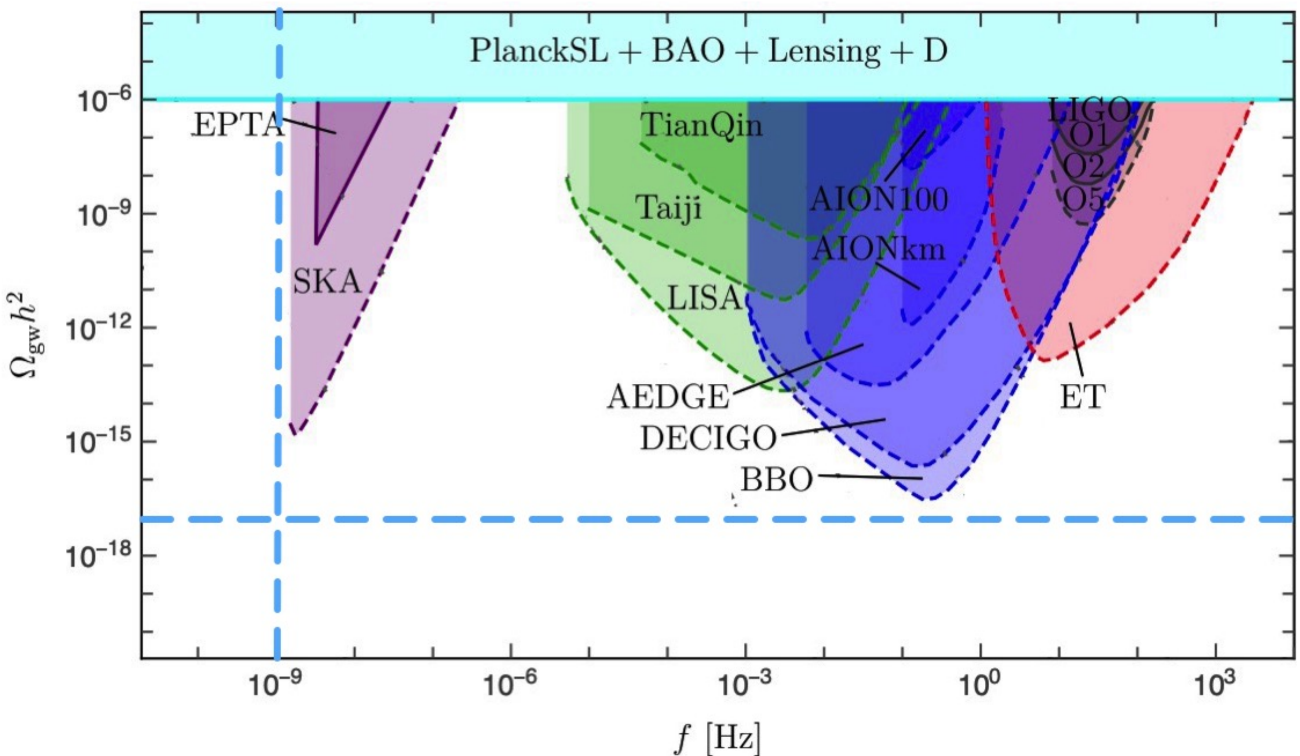
- Peaked at inverse of the horizon size at annihilation: $f_{\rm peak} \simeq H(t_{\rm ann})a(t_{\rm ann})$
- $f < f_{\rm peak}$: f^3 (white noise) super-horizon wavelengths, absence of causal correlations (Caprini et al 0901.1661])
- $f > f_{\rm peak}$: f^{-1} from simulations (plot)

(Hiramatsu, Kawasaki, Saikawa, Sikeguchi [1207.3166]



Gravitational Waves from Catastrogenesis for Stable ALPs

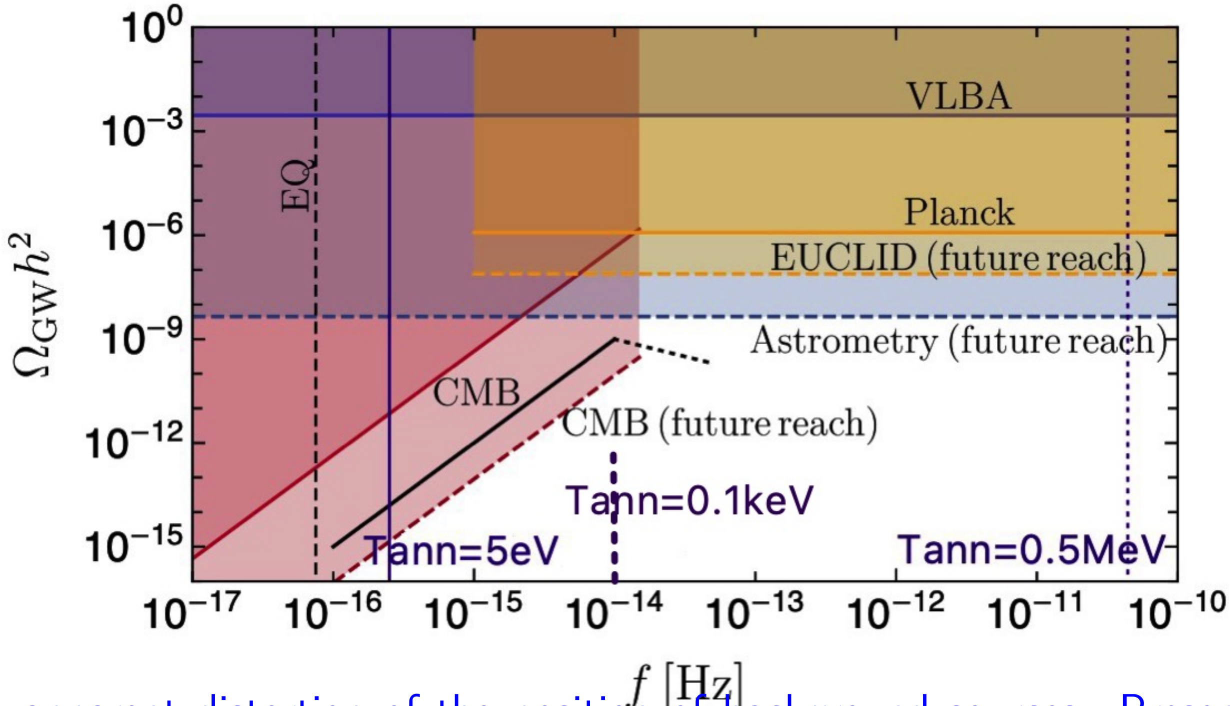
Our allowed observable window is at frequencies below the range of direct GW detection $\Omega_a h^2|_{\rm catastrogenesis} < \Omega_{\rm DM} h^2 \simeq 0.12$ implies $\dfrac{\Omega_{\rm GW} h^2|_{\rm peak}}{10^{-17}} \left(\dfrac{f_{\rm peak}}{10^{-9}{\rm Hz}}\right)^2 < 10^{-2}$



E.g for future astrometry reach $\Omega_{\rm GW} h^2 \simeq 10^{-9} \implies f_{\rm peak} < 10^{-14}$ Hz ($T_{\rm ann} < 10^2$ eV)

Gravitational Waves from Catastrogenesis for Stable ALPs

Could be detected by future CMB and astrometry measurements for $m_a \supset 10^{-16}$eV -1 MeV



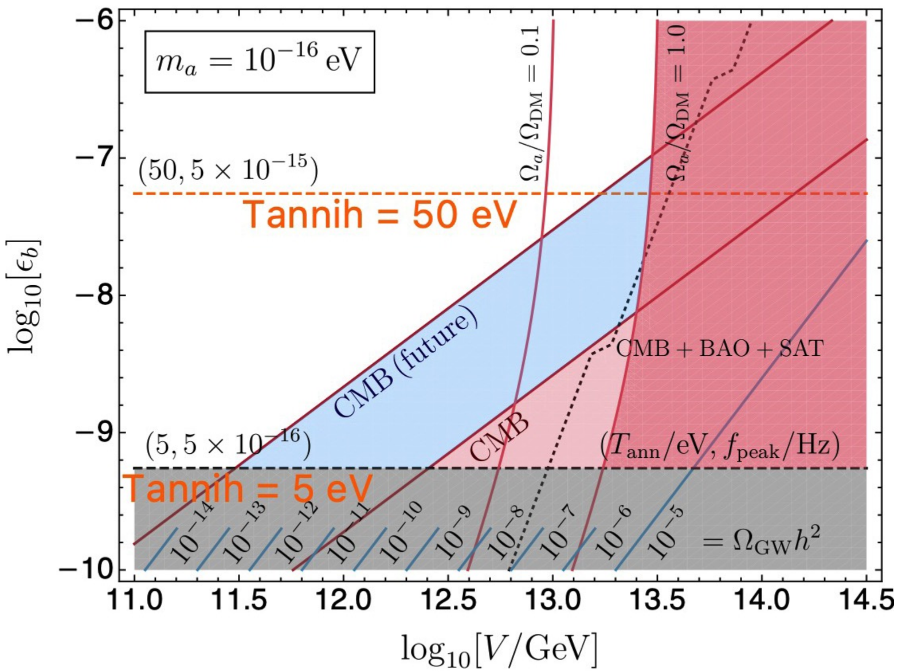
- Astrometry: apparent distortion of the position of background sources. Present: Very Long Baseline Array (VLBA) catalog. Future: optical satellites or SKA.

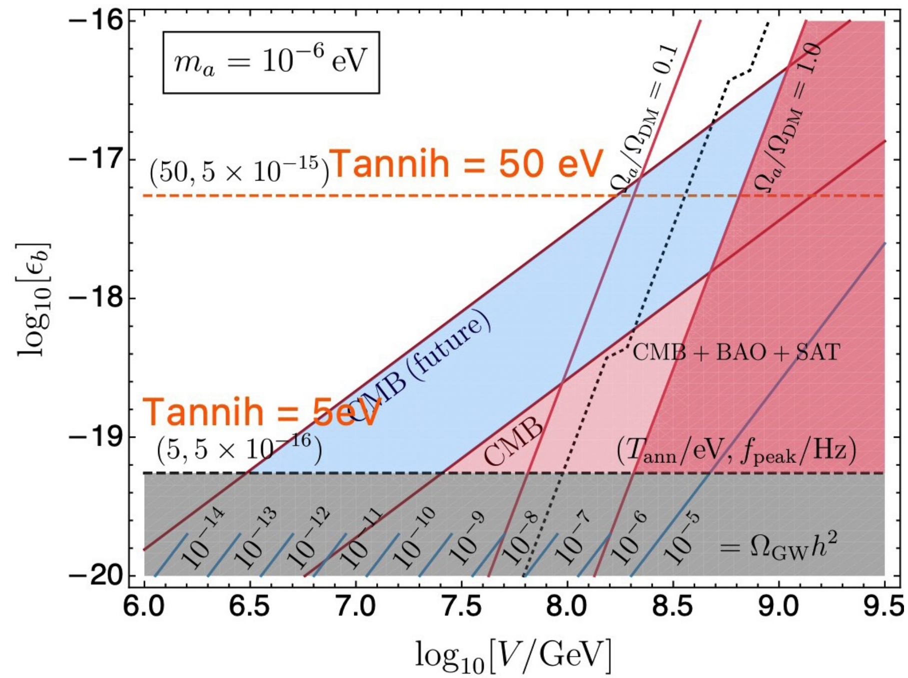
- N_{eff} at CMB emission. Present: Planck. Future: EUCLID

- CMB polarization. Present Planck, BICEP/Keck Array. Future: LiteBIRD, PICO, CORE.

Gravitational Waves from Catastrogenesis for Stable ALPs

Observable window translates in parameter space for 10^{-16} eV$<m_a<$1 MeV GW mostly from walls, and avoid Black Hole superradiance limits at low end; self consistency $v < 0.01V$ at high end





Structure formation limits not well understood may restrict $\Omega_a/\Omega_{DM} < 1$ in observable window (Gorghetto and Hardy 2212.13263 find observation of GW in $N > 1$ models in tension with the limits they derive from isocurvature perturbation upper bounds)

Gravitational Waves spectrum from cosmic strings

Entirely different from catastrogenesis.

- Quadrupole formula for the power emitted in GWs $P \simeq G\dddot{Q}_{ij}\dddot{Q}_{ij}$, where $Q_{ij} \simeq \; E_s t^2$ and $E_s \simeq \mu t$. Thus $\dddot{Q}_{ij} \simeq \mu$, and $P \simeq G\mu^2$.

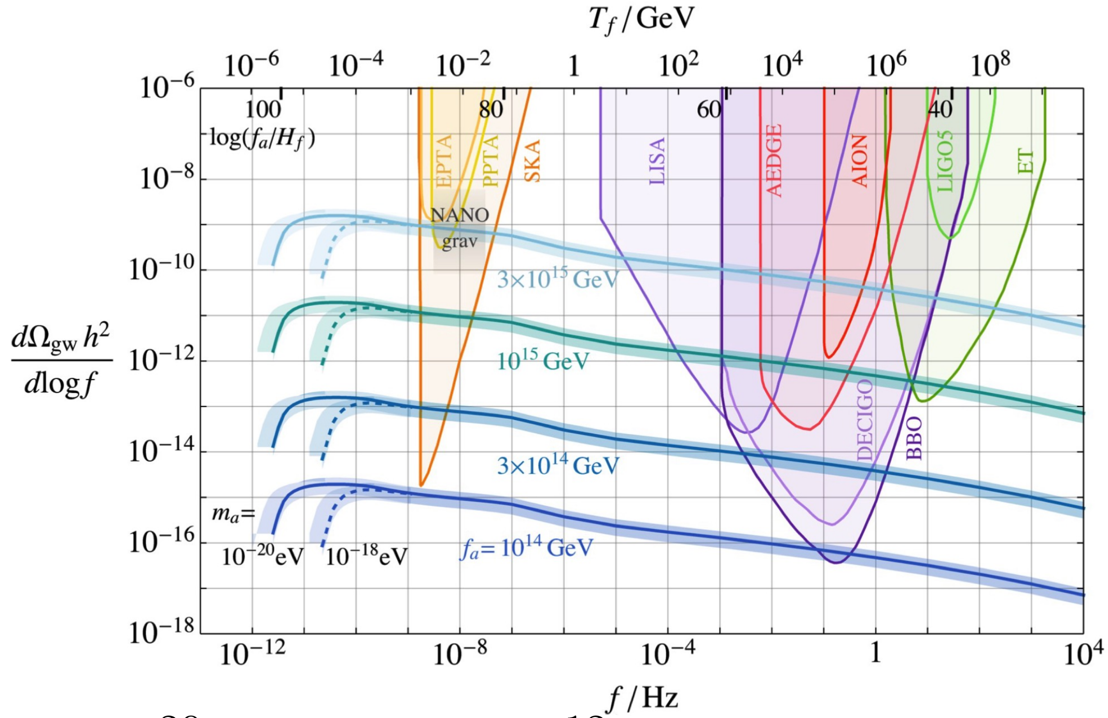
- The energy density emitted per Hubble time is $\Delta\rho_{\rm GW}(t) = Pt/t^3 = G\mu^2/t^2$ at the emission time t, which redshifted to the present by $[a(t)/a_0]^4 \simeq t^2/t_0^2$ makes an almost constant contribution

- thus the spectrum is almost flat in frequency at present except for a logarithmic correction coming from a log dependence in μ

(recall that the frequency depends on the inverse of emission time $f \sim 1/t$)

Gravitational Waves spectrum from cosmic strings

Emission ends when walls appear $H \simeq m_a \simeq f_{\rm cutoff}$ (Gorghetto, Hardy and Nicolaescu 2101.11007) GW observable for $f_a > 10^{14}$ GeV



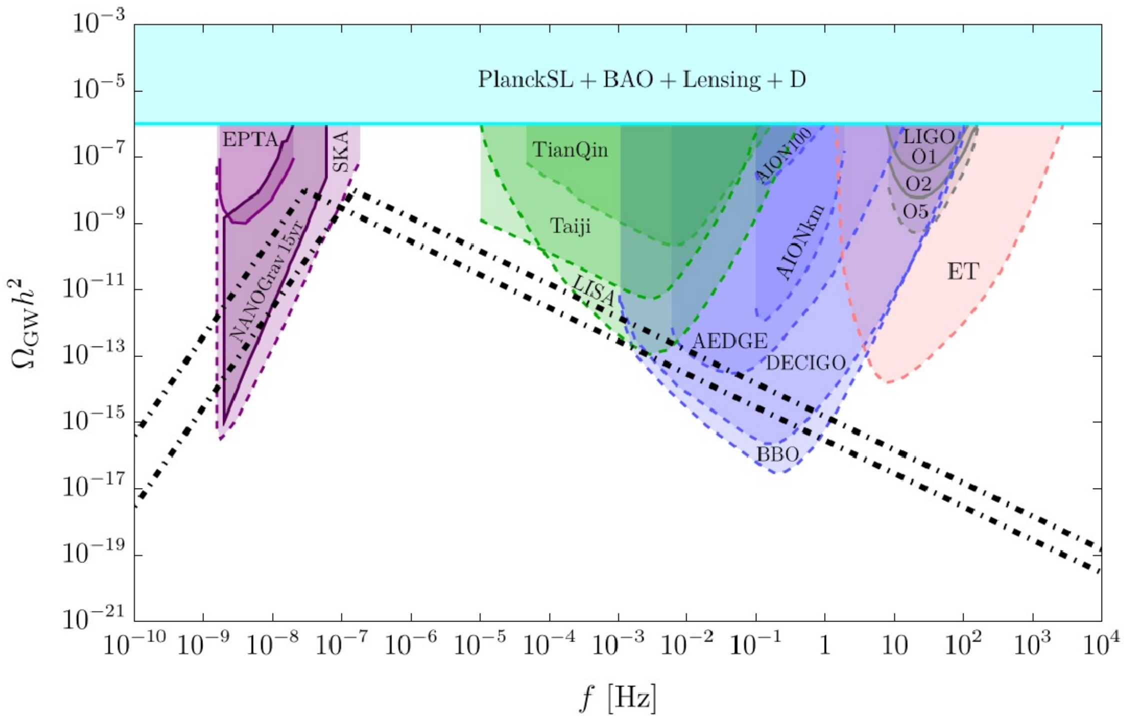
Ly-α: $m_a > 2 \times 10^{-20}$ eV and $f > 10^{-12}$ Hz. GWs from QCD-axion strings are not observable because $f_a < 10^{-10}$ to avoid DM overproduction. (Gorghetto,Hardy, Villadoro 1806.04677)

NANOGrav GW signal (Gelmini and Hyman, 2307.07665)

Catastrogenesis can explain it with $a \to \gamma\gamma$- decays before BBN,

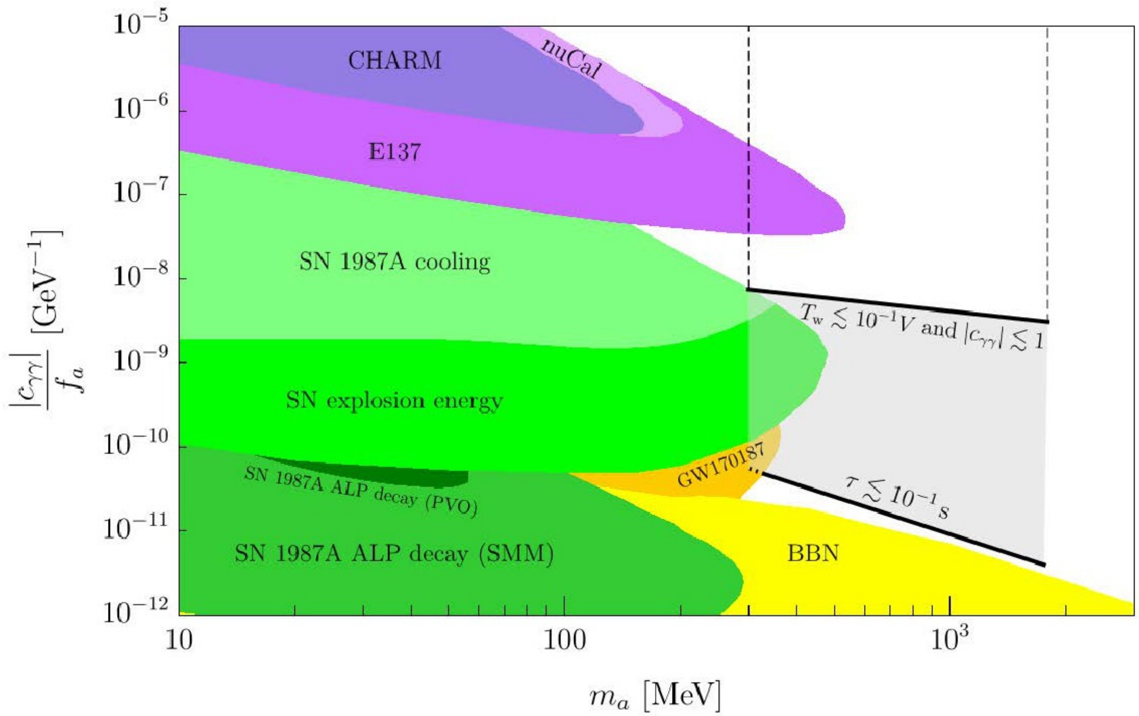
NANOGrav DW-SM fit: $T_{\rm ann} \lesssim$1GeV $\Rightarrow m_a \lesssim$1.8GeV-

ALPs limits: $m_a \gtrsim$300MeV $\Rightarrow T_{\rm ann} \gtrsim 0.2$GeV. Thus 2.9×10^{-8}Hz$< f_{\rm peak} < 1.5 \times 10^{-7}$Hz



NANOGrav 15 yrGW signal Catastrogenesis can explain it with ALPs decaying into photons before BBN, if PBH do NOT form (gray region)

Requires $|c_{\gamma\gamma}| >$ in simplest QCD models (which is $\simeq \alpha_{\rm EM}/8\pi \simeq 2.9 \times 10^{-4}$) (Gelmini and Hyman, 2307.07665)



Concluding remarks

The field of axion DM is enormously vibrant with clear advances to be made for decades to come, mostly driven by precision cosmological/astrophysical observations and progress in detection technology but also in theory:

Better simulations are needed to understand the ALP emission by strings and walls

Better simulations are needed to understand the formation and evolution of axion miniclusters. E.g. can miniclusters from non-conventional misalignment be distinguished observationaly from post-inflationary miniclusters? How do miniclusters affect ALP direct detection (are they totally tidally disrupted in the solar vecinity?)

Do String Theory ALPs reproduce all the properties of field theory ALPs? Post-inflationary models in String Theory?

Having to ensure that a detected signal actually comes from Axion DM would be a very nice problem to have, and I hope we are so lucky as to have it in the near future.