Axions Dark Matter*

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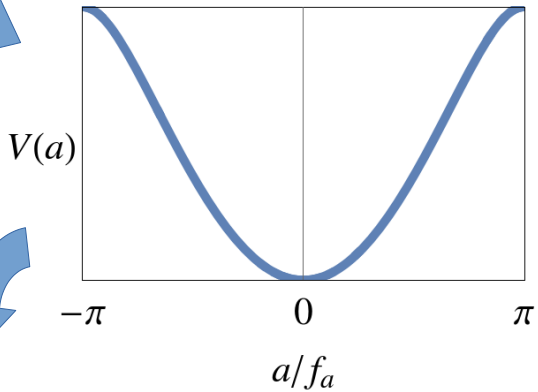
*Assuming Standard Cosmology and neglecting baroque model-building

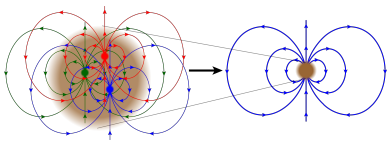
Strong CP-problem and QCD Axion

Peccei,Quinn '77
Weinberg, Wilczek '78

$$\mathcal{L} \supset \frac{\theta}{32\pi^2} G\tilde{G} \rightarrow \frac{1}{32\pi^2}\frac{a}{f_a} G\tilde{G}$$



from neutron EDM



$$\theta \lesssim 10^{-10}$$

$$f_a = v_{PQ}/N$$

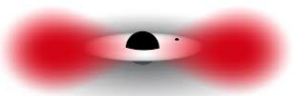
$$m_a \sim \frac{\Lambda^2_{QCD}}{f_a} \qquad m_a = 5.691(51)\,\mu\text{eV}\,\frac{10^{12}\ \text{GeV}}{f_a}$$

Gorghetto, GV '19

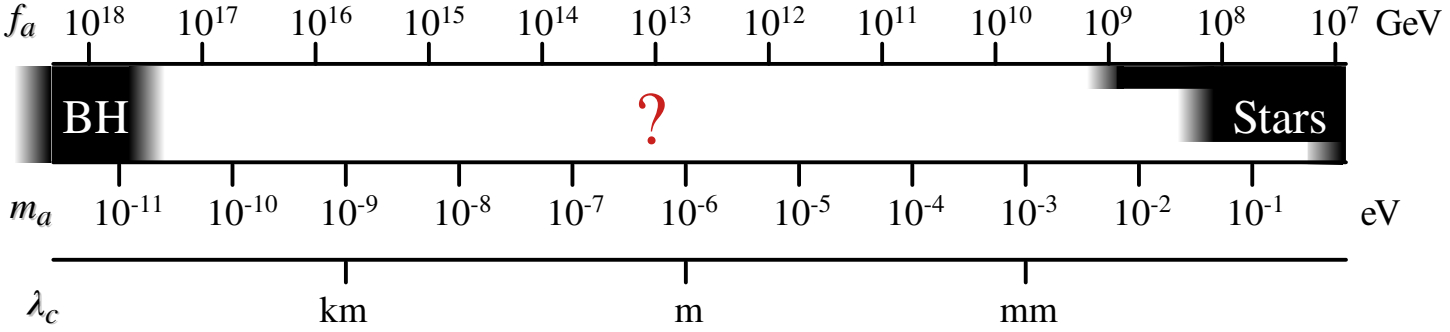
$$g_{a-SM} \propto \frac{1}{f_a} \propto m_a$$

See Ringwald's seminar

Axions Searches



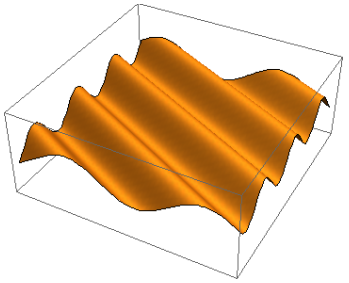
Arvanitaki et al. '09



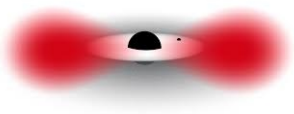
QCD Axion → DM

Abbott, Dine, Fischler, Preskill, Sikivie, Wise, Wilczek '83

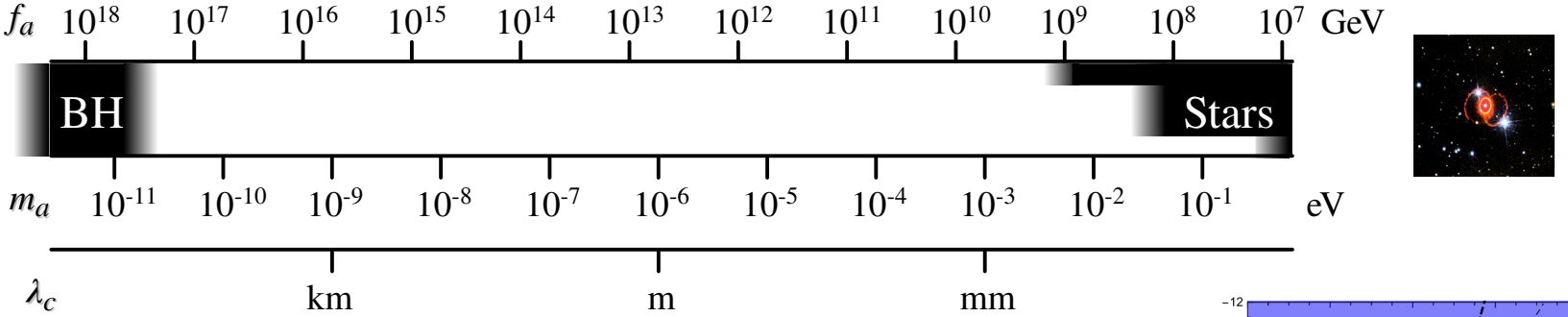
$$\rho_a = \rho_{DM} \quad + \quad m_a < 0.1 \text{ eV} \quad \Rightarrow \quad N_{occ.} \gg 1$$

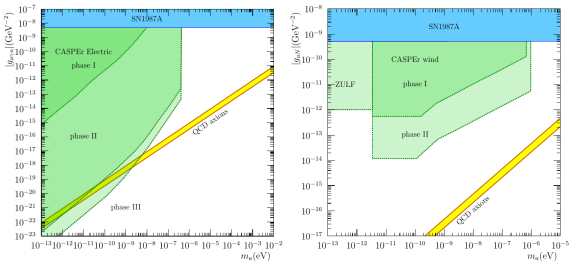


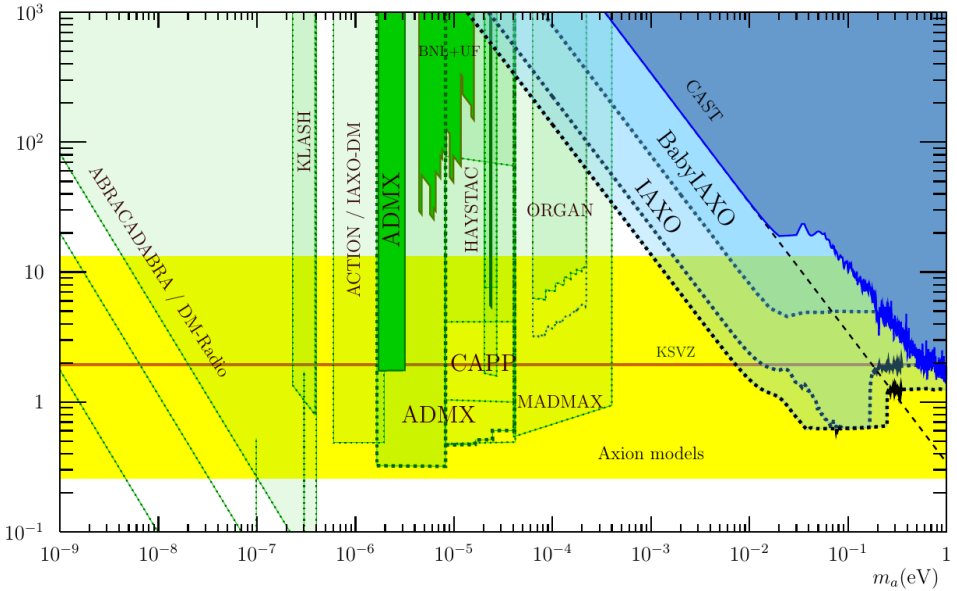
Axions Searches

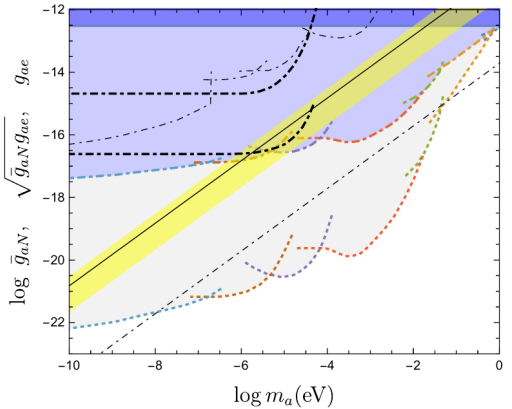


Arvanitaki et al. ‘09





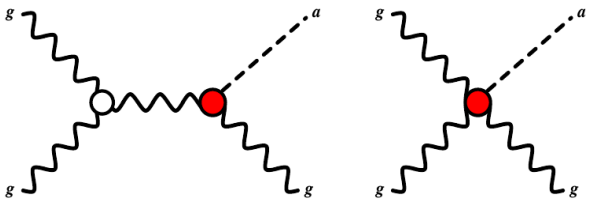




Irastorza, Redondo ‘18

Primordial Axions

Axion Thermal Production



$$\sigma \approx 10^{-5} \frac{k}{f_a^2}$$

for recent analysis see e.g.

Salvo, Strumia, Xue ‘13
Baumann, Green, Wallisch ‘16
Ferreira, Notari ‘18
Arias-Aragon, D’Eramo, Ferreira, Merlo, Notari ’20

Thermal Equilibrium

$$\xi \frac{T^2}{M_p} = H \lesssim \Gamma = \langle \sigma n v \rangle \approx 10^{-5} \frac{T^3}{f_a^2}$$

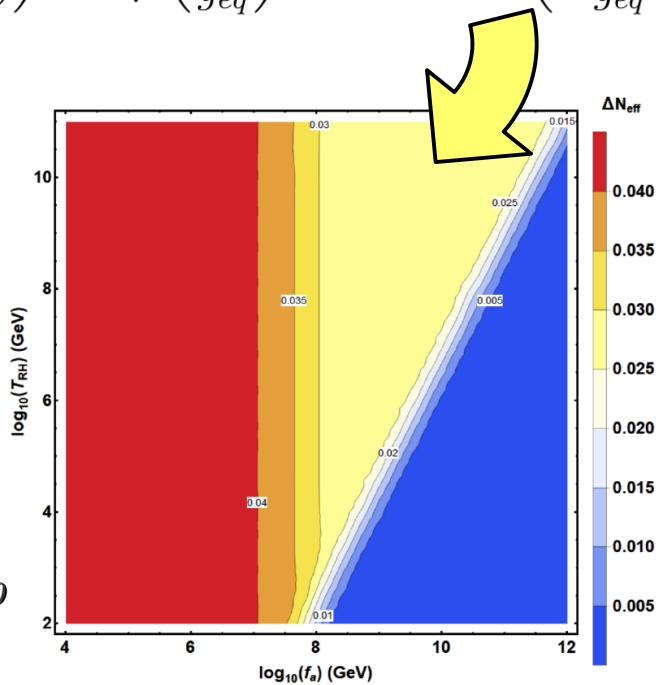
$$T \gtrsim f_a \left(\frac{f_a}{10^{13}\ \text{GeV}} \right)$$

Thermal Axion still relativistic during early Universe....

Contribution to Relativistic Species:

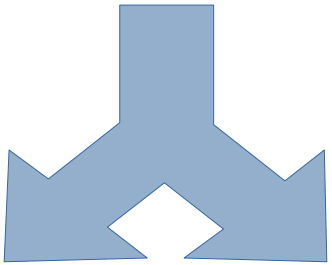
$$\Delta N_\nu = \frac{\rho_a}{\rho_\nu} = \frac{\frac{\pi^2}{30} T_a^4}{2\frac{7}{8}\frac{\pi^2}{30} T_\nu^4} = \frac{4}{7}\left(\frac{T_a}{T_\nu}\right)^4 = \frac{4}{7}\left(\frac{g_\nu}{g_{eq}}\right)^{4/3} = 0.0264\left(\frac{107.75}{g_{eq}}\right)^{4/3}$$

$\approx$ CMB S4



from:
Arias-Aragon, D'Eramo, Ferreira,Merlo,Notari '20

Non-Thermal Cold Axions



$v_{PQ} \gtrsim \max(H_I, T_{\rm max})$

pre-inflation scenario

PQ-symmetric phase
not restored after inflation

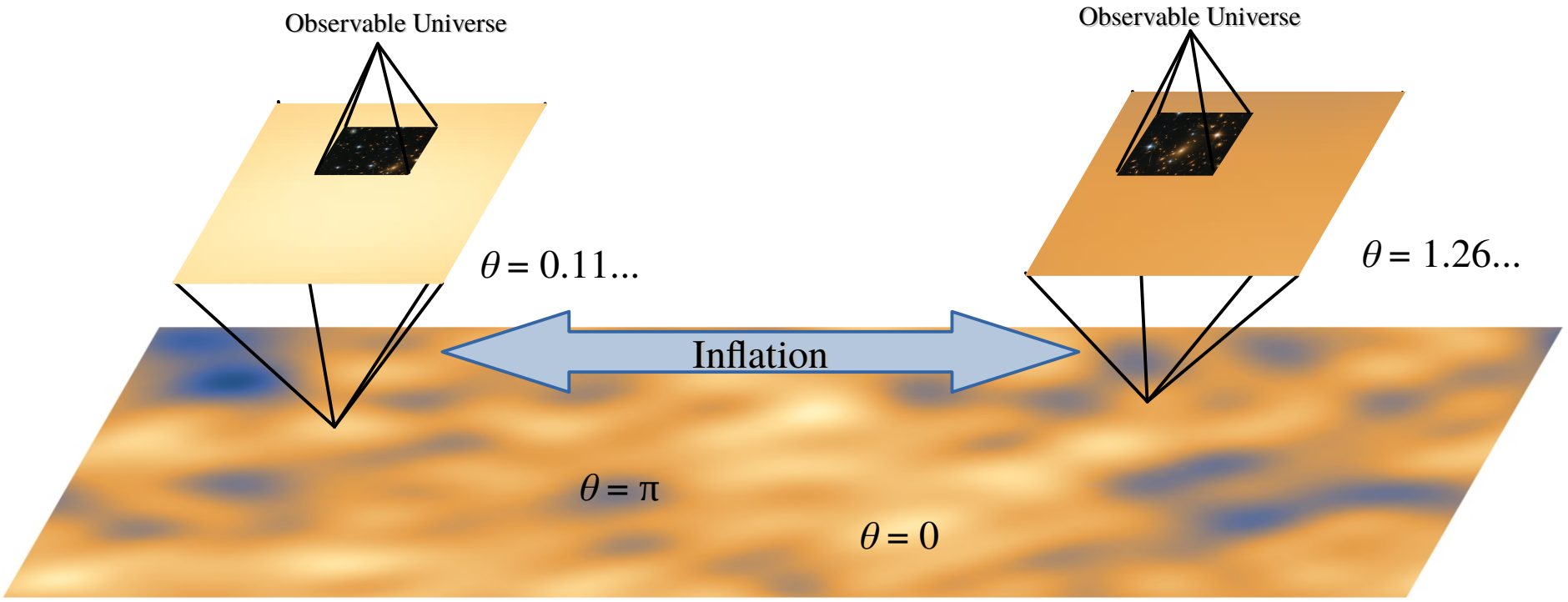
$v_{PQ} \lesssim \max(H_I, T_{\rm max})$

post-inflation scenario

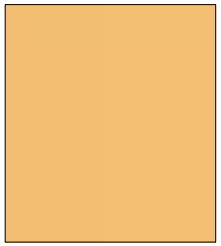
PQ-symmetric phase
restored after inflation

Cosmic Evolution of Axions

pre-inflationary scenario

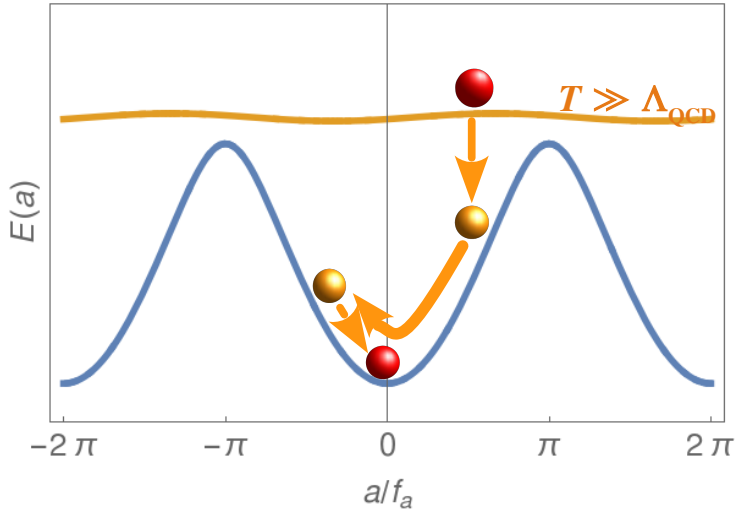


Misalignment mechanism



$a(t_0) = \text{const} \equiv \theta_0 f_a$

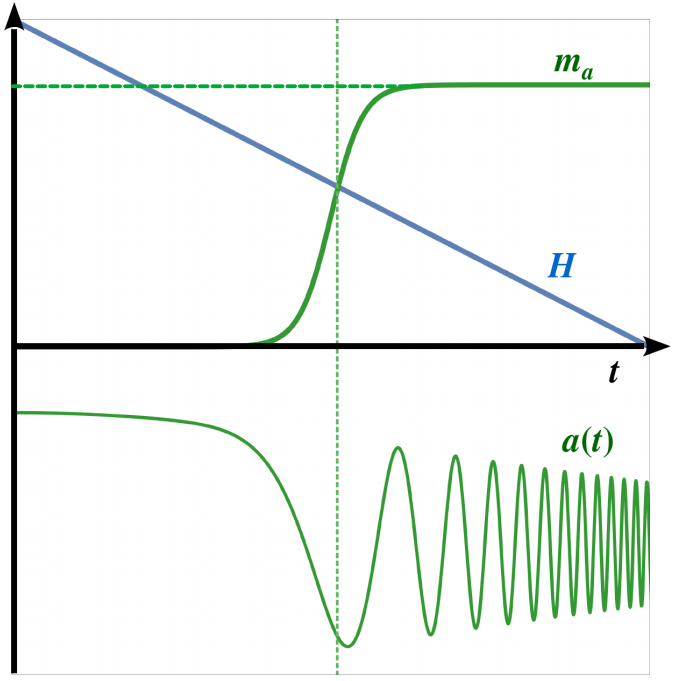
$a(\vec{x}, t) \to a(t)$ EOM: $\ddot{a} + 3H\dot{a} + V'(a) = 0$



$V(a) \sim T^{-\alpha}$

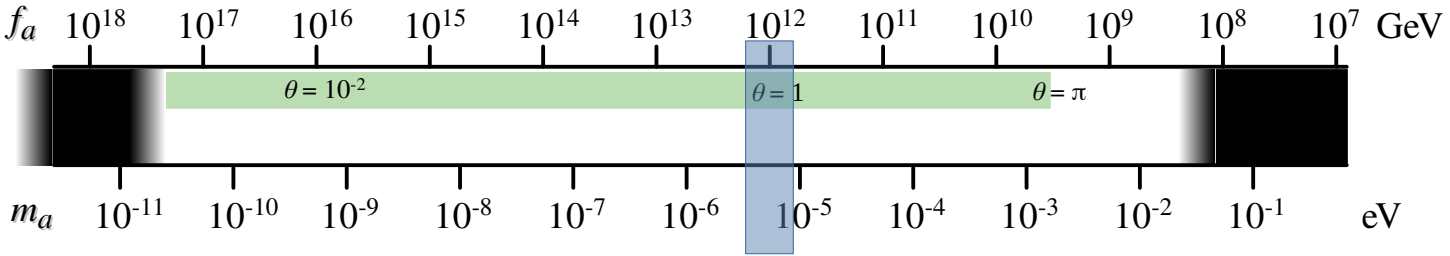
$\alpha \approx 8$

Gross, Pisarski, Yaffe ‘81
Petreczky ‘15
Bonati et al. ‘15, ‘18
Borsanyi et al. ‘16
Burger et al. ‘18

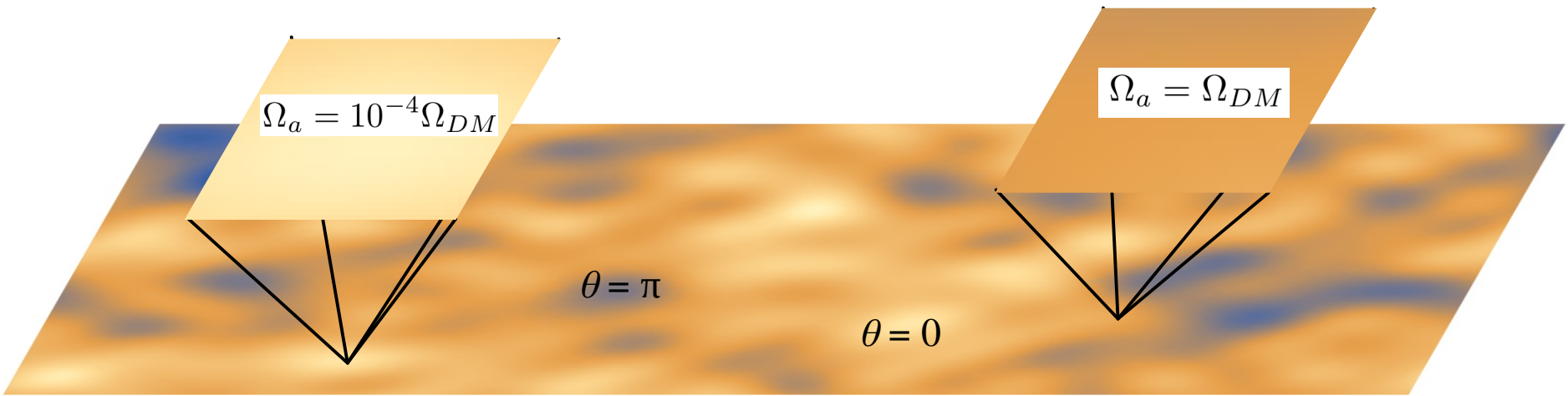


Misalignment mechanism

$$\Omega_a \simeq \Omega_{DM}\,\theta_0^2 \left[\frac{f_a}{10^{12}\ \mathrm{GeV}}\right]^{\frac{7}{6}} \qquad \theta_0 \lesssim 1$$



$$f_a = 10^{12}\ \mathrm{GeV}$$



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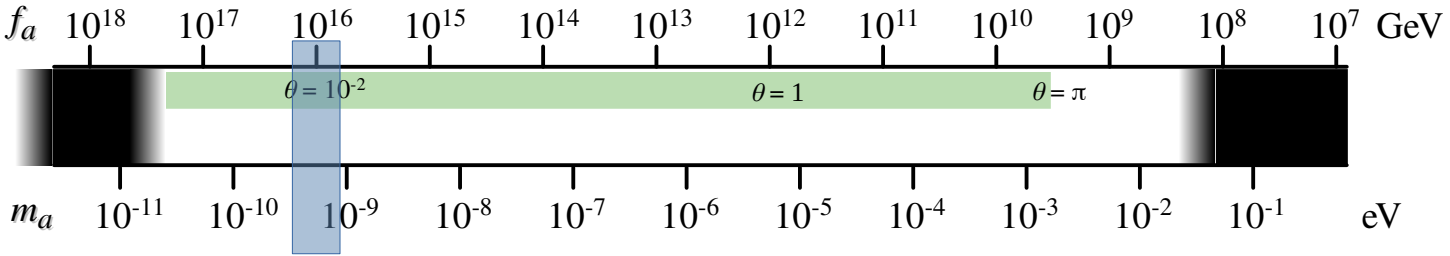
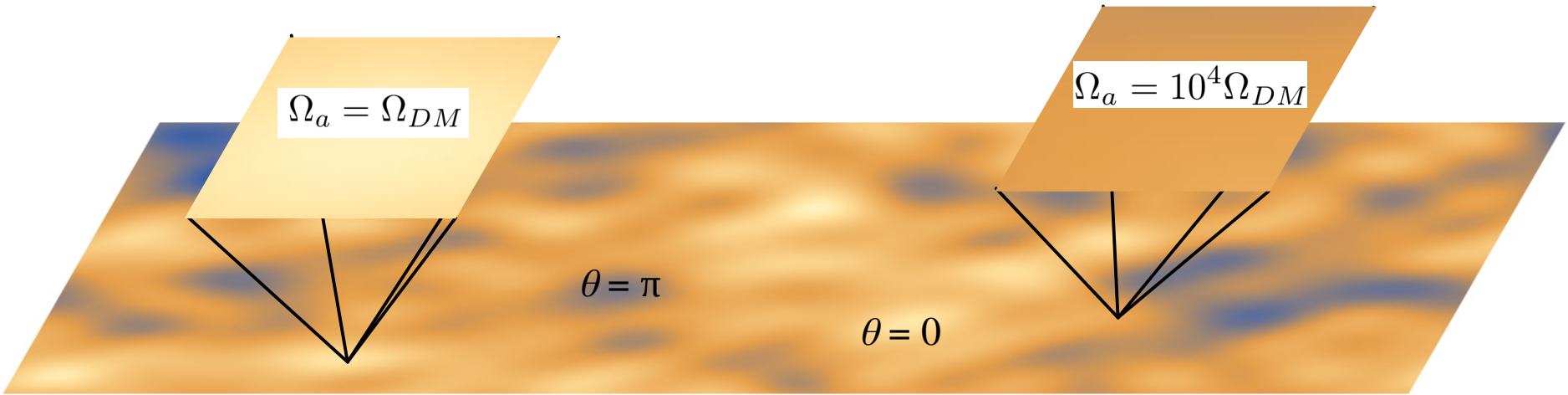


$$f_a = 10^{16}\ \mathrm{GeV}$$



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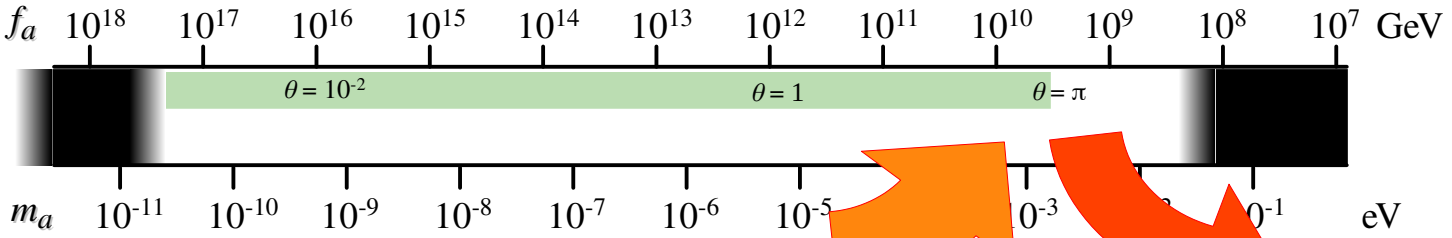


Isorcurvature Bound

$$\sigma_\phi^2 = \langle \delta\phi^2 \rangle = \frac{H_I^2}{(2\pi)^2}$$

$$\alpha_a = \frac{(\delta T/T)^2_{iso}}{(\delta T/T)^2_{tot}} < 0.02 \qquad \text{from Planck}$$

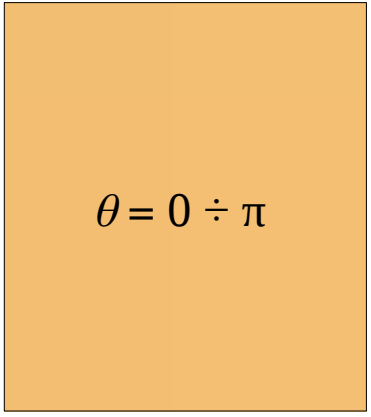
$$H_I \lesssim 10^8\ \mathrm{GeV} \left[\frac{\alpha_a}{0.02}\frac{0.24}{\Omega_a}\frac{f_a}{10^{12}\ \mathrm{GeV}}\right]^{\frac{1}{2}}$$

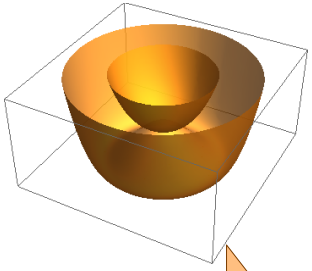
Small-structures from non-linearities

Arvanitaki et al. ‘19

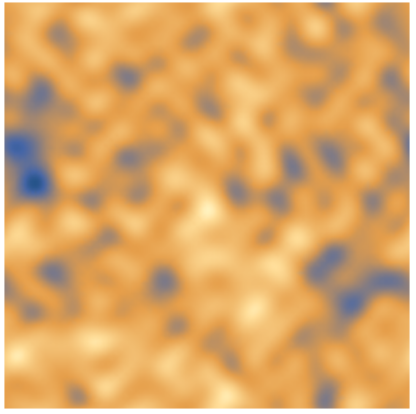
$\theta = 0$

Post-Inflationary Scenario



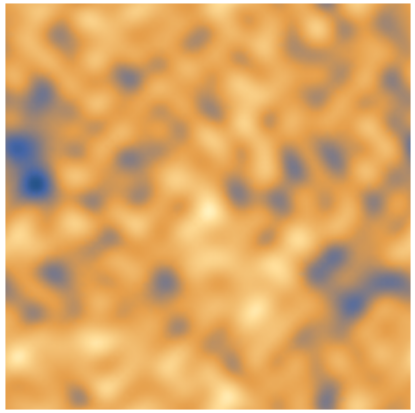


U(1) restoration



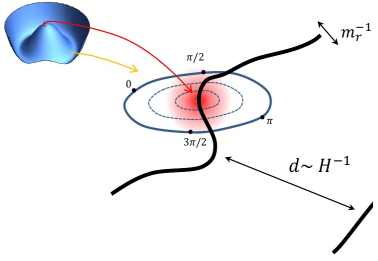
No initial θ dependence

$$\Omega_a = \Omega_{DM}$$ → Prediction for m_a !

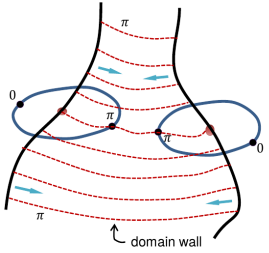


Complex non-linear evolution

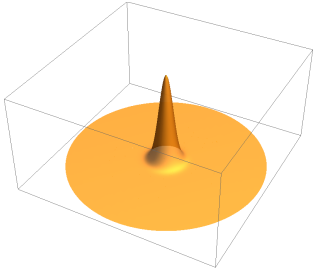
Strings



Domain Walls

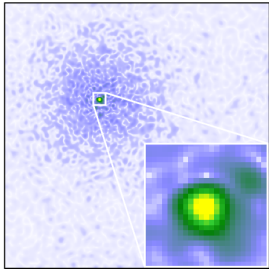


Oscillons

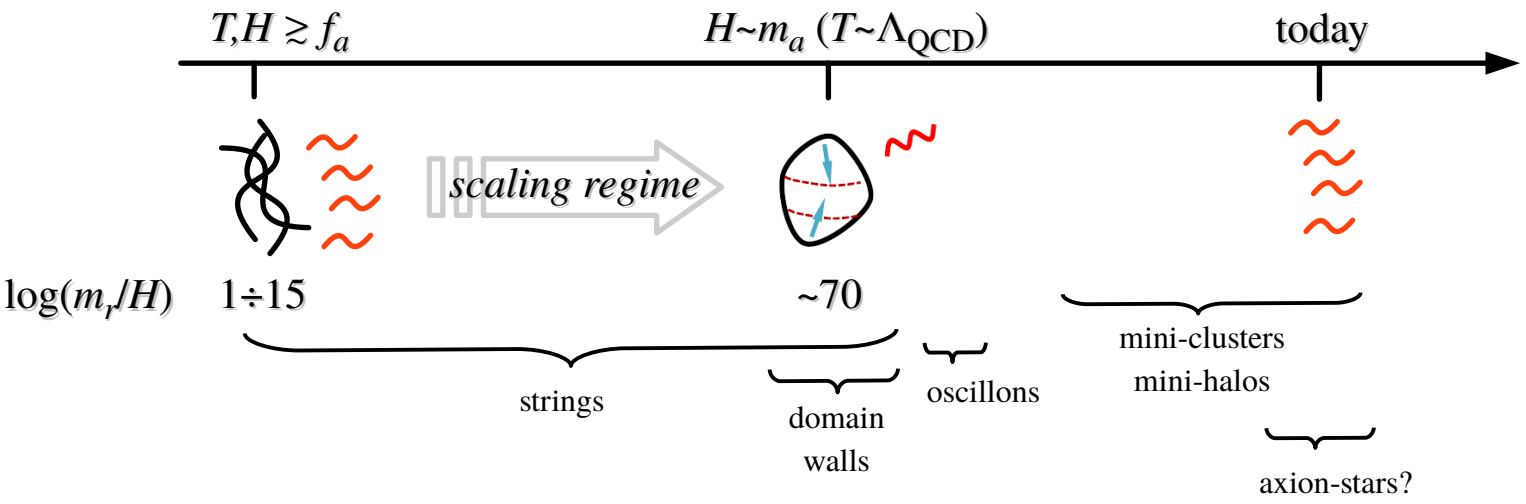


Mini-Clusters

Axion-Stars



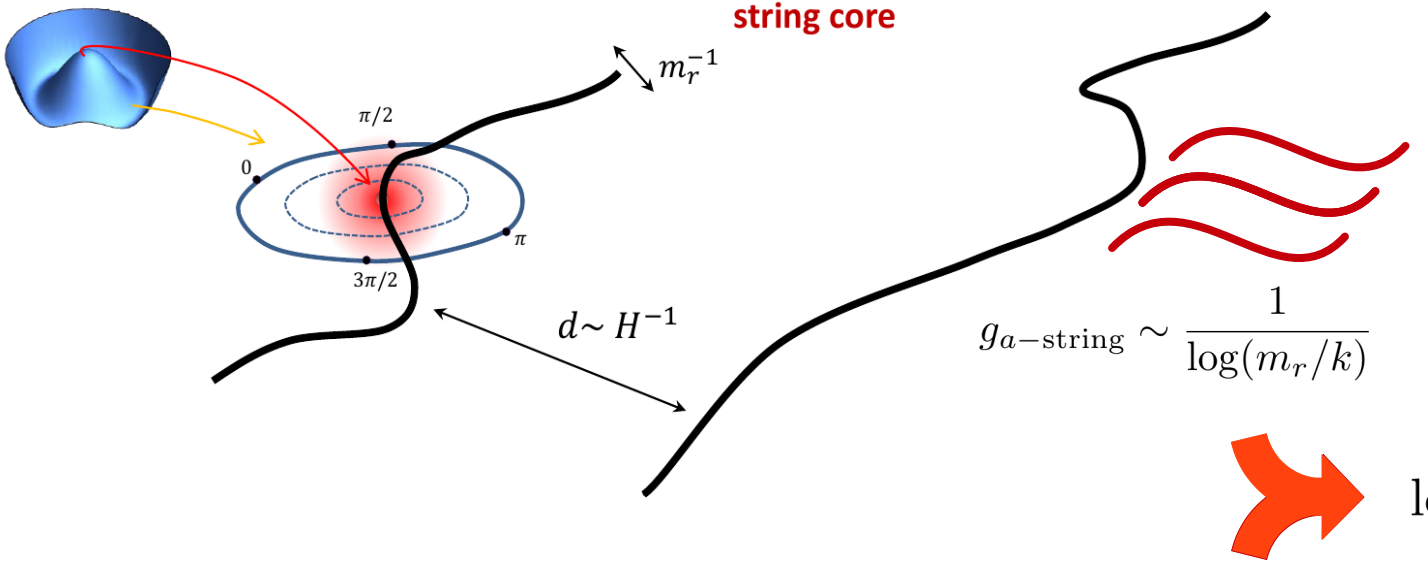
from 1804.05857



Non-Linear Evolution → Analytic

Multi-Scale Problem → Numerical

Axionic Strings

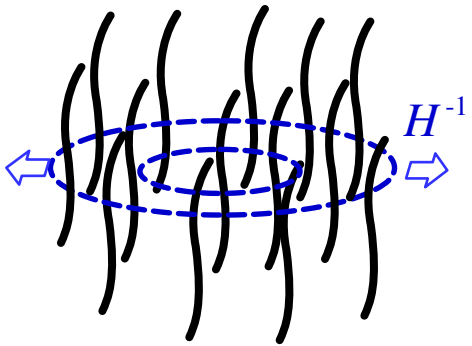


string tension $$\mu = \frac{E}{L} = \pi v_{PQ}^2 \log(m_r \ell_{IR}) \simeq \pi v_{PQ}^2 \log\left(\frac{m_r}{H}\right)$$

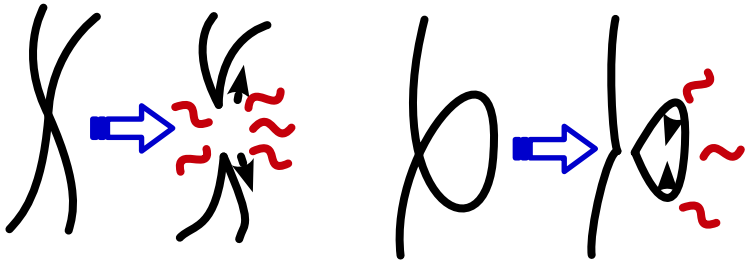
radial core

axion field

free strings



string recombination



$$\xi = \frac{\#\ \text{strings}}{\text{Hubble Volume}}$$

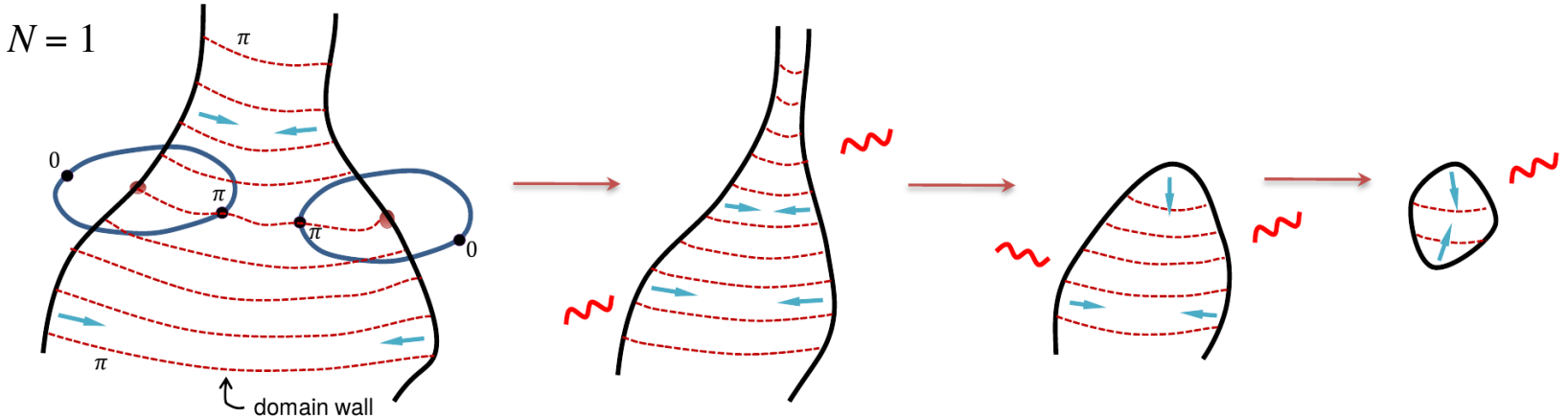
ξ

Self-Organized Criticality

Scaling Solution $\Rightarrow$ $\xi \Rightarrow \xi_{\text{scaling}}$

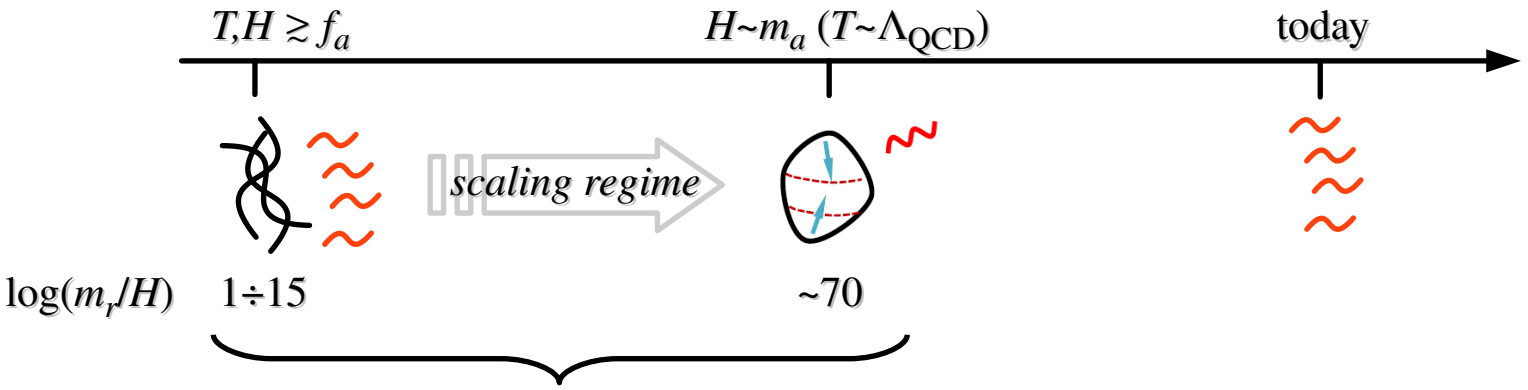
Albrecht, Allen, Battye, Bennett, Bouchet, Davis, Dabholkhar, Hagmann, Kibble, Martins, Quashnock, Shellard, Sikivie, Turok, Vilenkin, ...

@ $H \sim m_a$ ($T \sim \Lambda_{\rm QCD}$)



$\delta_{\rm DW} \sim m_a^{-1}$

Axion DM Abundance



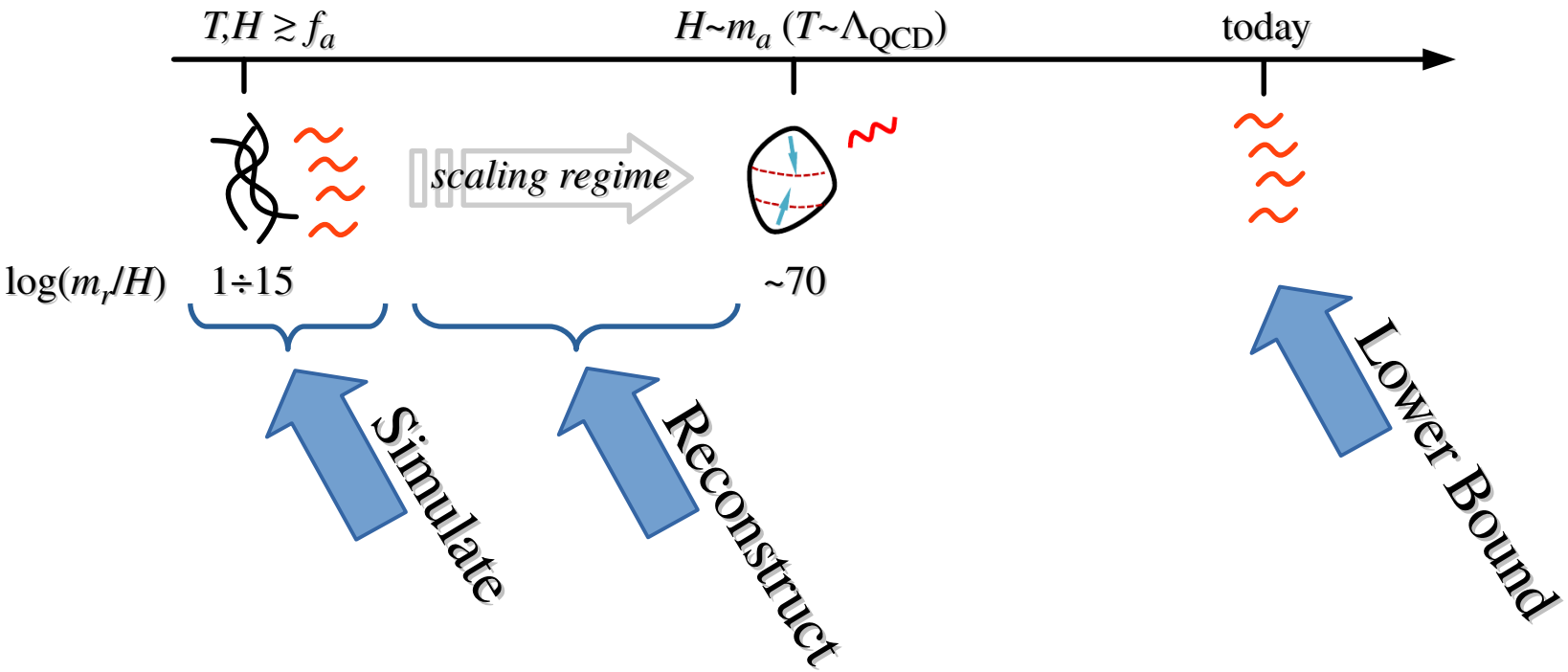
Complete (Brute Force) Simulation:

Latest by: Klaer and Moore '17 – Buschmann, Foster, Safdi '19

$$\Omega_a = \langle \Omega_a^{mis} \rangle_\theta \quad \Rightarrow \quad m_a \simeq 26\ \mu\text{eV}$$

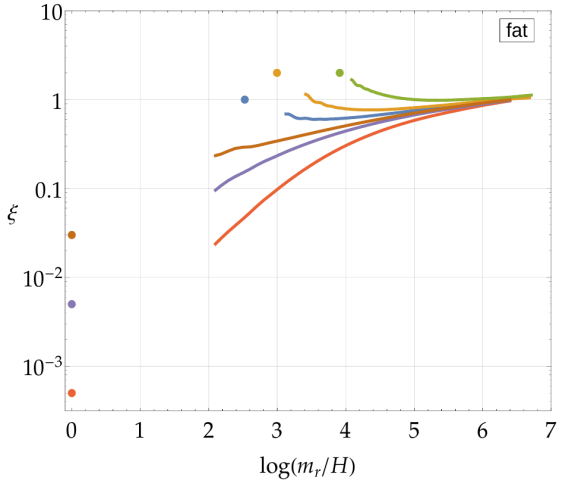
$$\frac{\delta_{DW}}{\delta_{strings}} \sim \frac{f_a}{m_a} \sim \frac{f_a}{H_\star} \sim \mathcal{O}(10^3) \ll \mathcal{O}(10^{30})$$

Full Simulation Not Reliable
Smaller Goal: Lower Bound on DM



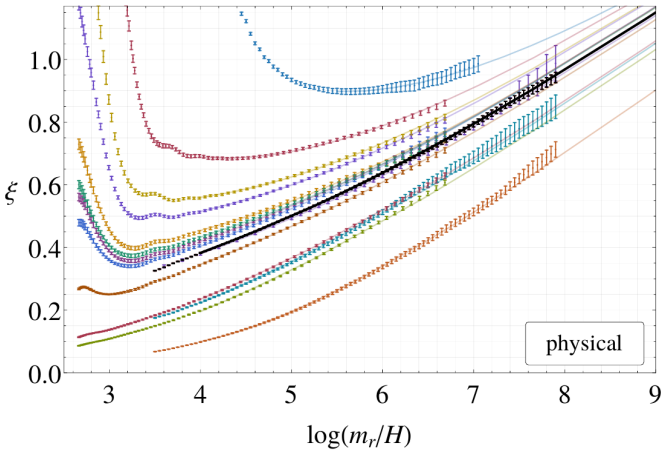
String Density Evolution

the attractor

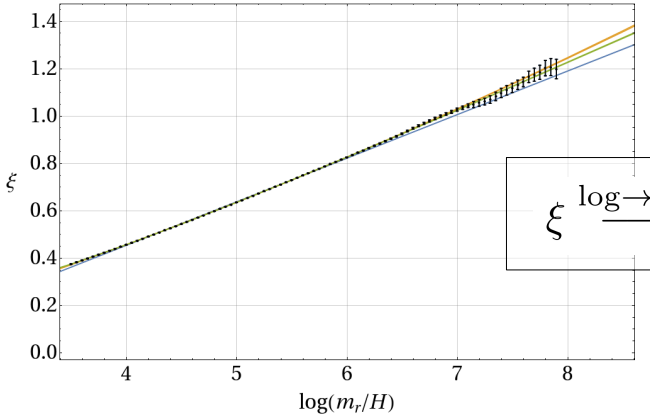


Gorghetto, Hardy, GV '18

scaling violations

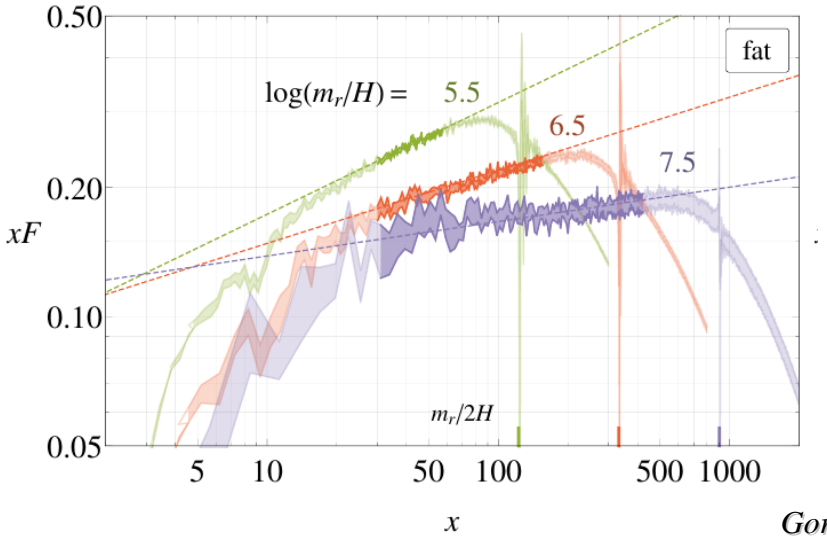


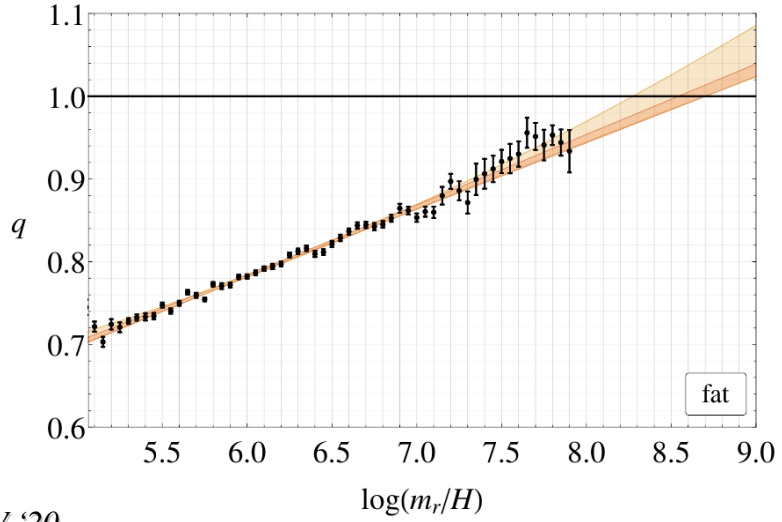
Gorghetto, Hardy, GV '20



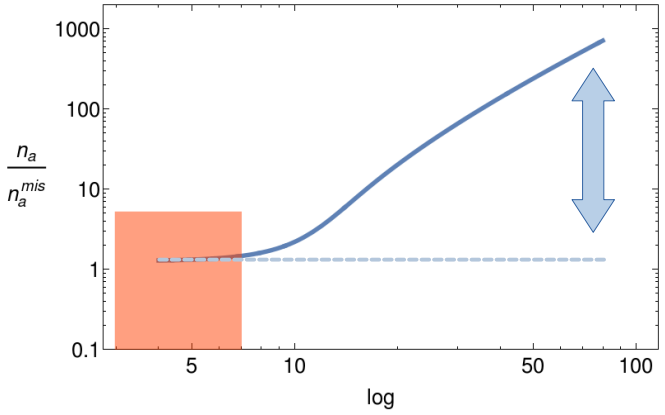
Also:
Fleury, Moore '15
Klaer Moore '17, '19
Kawasaki et al. '18
Vaquero et al. '18
Buschmann et al. '19

Axion Spectrum Evolution





Gorghetto, Hardy, GV '20



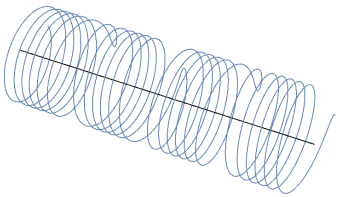
$$\rho_a \sim \frac{\xi\mu}{t^2} \sim 10^{3\div4}\left[\frac{\xi\log}{10^3}\right] H^2 f_a^2$$

$$\gg \rho_a^{mis} \sim \theta_0^2 m_a^2 f_a^2 \qquad @\ m_a = H$$

Non-linearities of Axion Spectrum

$$\rho \sim (\nabla a)^2 + \cancel{m^2 f_a^2 \cos(a/f_a)} \qquad @\ m_a = H$$

$$10^3 H^2 f_a^2 \quad \Rightarrow \quad a \sim \mathcal{O}(10)\pi f_a$$



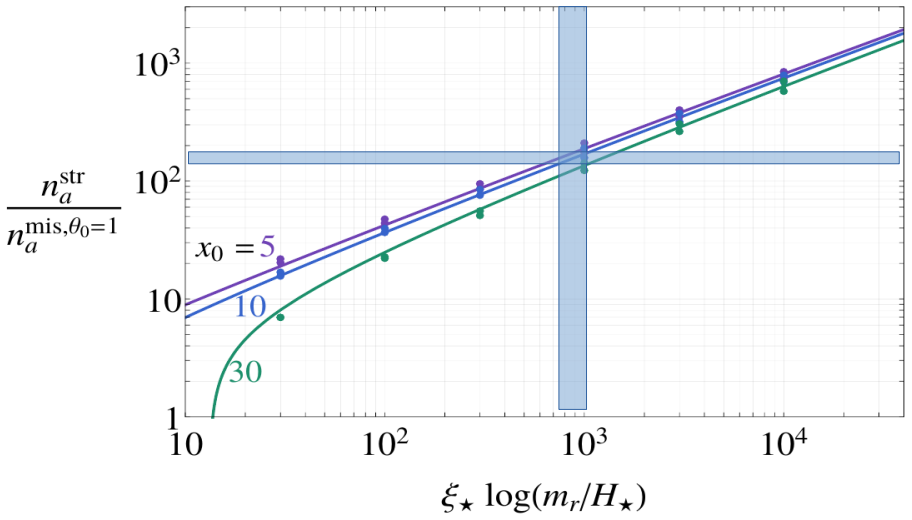
after m_a ↑ H ↓

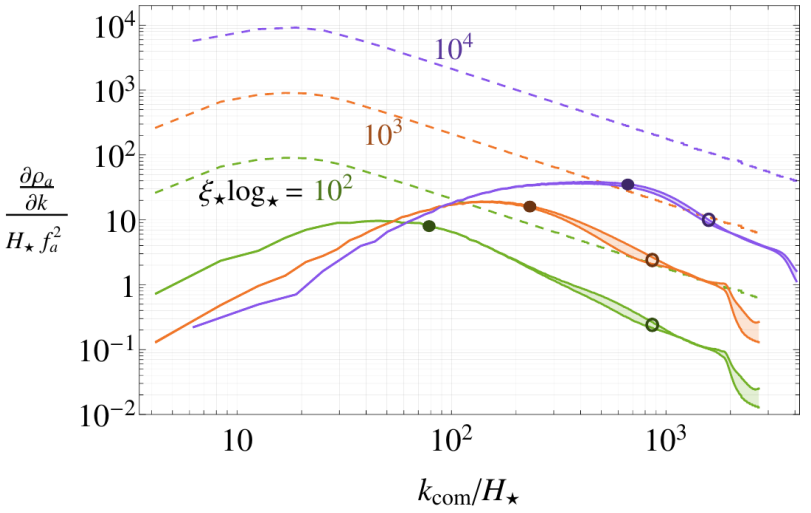
until $(\nabla a)^2 \sim m_a^2 f_a^2 \quad \Rightarrow \quad m_a \propto \sqrt{\xi \log}$

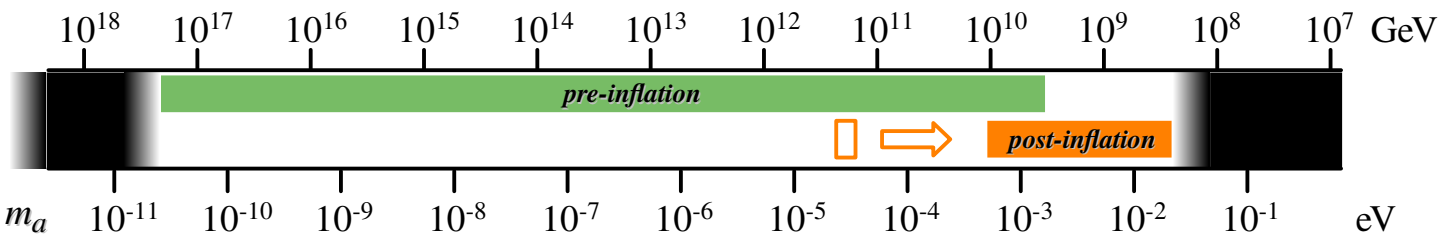
$$\Rightarrow \quad n_a \sim \frac{\rho}{m_a} \propto \sqrt{\xi \log}\, n_a^{mis}$$

A lower bound to the Axion Abundance

Gorghetto, Hardy, GV '20

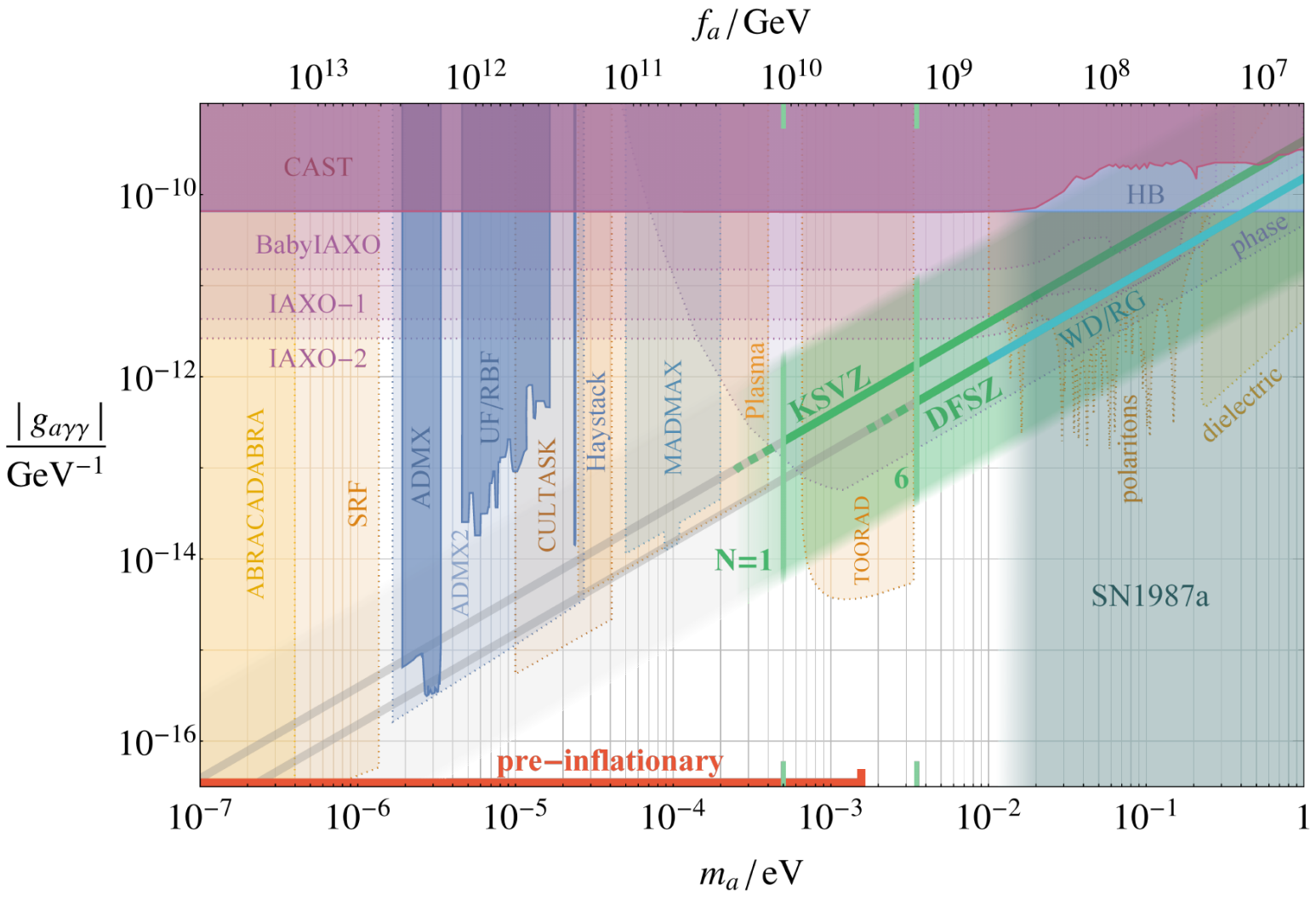






$m_a \gtrsim 0.5$ meV $\quad (N = 1)$

$m_a \gtrsim 3.5$ meV $\quad (N = 6)$


f_a / GeV
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
CAST
HB
BabyIAXO
IAXO−1
IAXO−2
ABRACADABRA
SRF
ADMX
ADMX2
UF/RBF
CULTASK
Haystack
MADMAX
Plasma
KSVZ
DFSZ
WD/RG
phase
polaritons
dielectric
6
TOORAD
N=1
SN1987a
pre−inflationary
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\frac{|g_{a\gamma\gamma}|}{\mathrm{GeV}^{-1}}$
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
m_a / eV

Conclusions

– QCD Axion is compelling candidate for DM

– Recent Efforts:

- Deeper understanding of the evolution of axion field in early universe
- Towards a more reliable estimate of axion abundance

– Still A Lot to Do:

- Extrapolations need more confirmations
  (maybe next generation simulations)
- Effects of DW? N>1? Superconducting strings?
- Right Initial conditions for future evolution (mini-clusters, etc.)