Ultralight dark matter

Javier Redondo (Zaragoza U)

Dark Matter: Astrophysical probes, Laboratory tests, and Theory aspects (DARK MALT 2015)

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Javier Redondo
Ramón y Cajal fellow
Universidad de Zaragoza (Spain)

Outline

- ultralight dark matter?

1 - candidates: QCD axion, ALPs, HPs ...

2 - Non-thermal production mechanisms

3 - BEC?

4 - Detection ...

Ultralight dark matter? *

- Low mass ... stabilised by symmetry?
    - Nambu-Goldstone Bosons,
    - U(1) vector-boson
    - ...

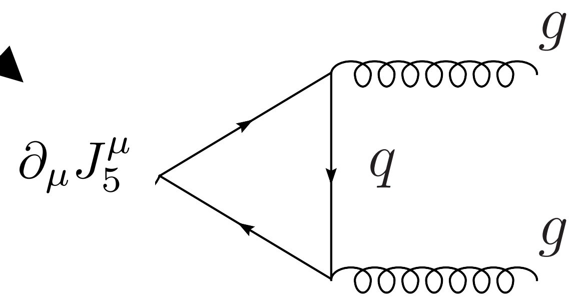
- Tremaine-Gunn, mass < eV -> Bosons

- Secluded from SM interactions... Weakly-Interacting-SLIM-Particles
    - Production mechanism?
    - Isocurvature constraints?
    - BEC?
    - Experimental Detection?

The strong CP problem

Flavor conserving CP-violation in the SM, one phase $\theta = \theta_{\rm QCD} + N_q \delta$

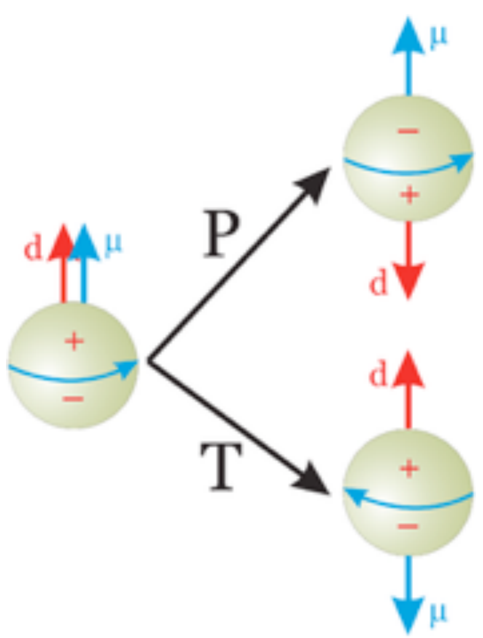
$$\mathcal{L}_{\rm SM} \in -\begin{pmatrix} \bar{u} & \bar{d} & \dots \end{pmatrix}_L \begin{pmatrix} m_u e^{i\delta} & 0 & \dots \\ 0 & m_d e^{i\delta} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\, \theta_{\rm QCD}$$

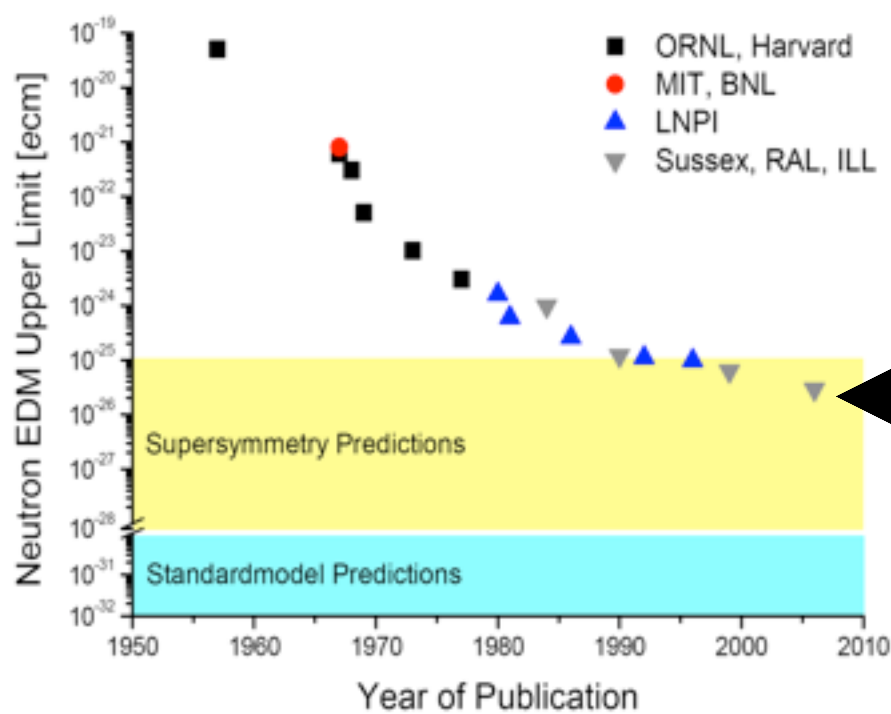


This CP violation is not observed (Neutron electric dipole moment,..)

$d_n \sim \theta \times \mathcal{O}(10^{-15})[e\,{\rm cm}]$

predictions





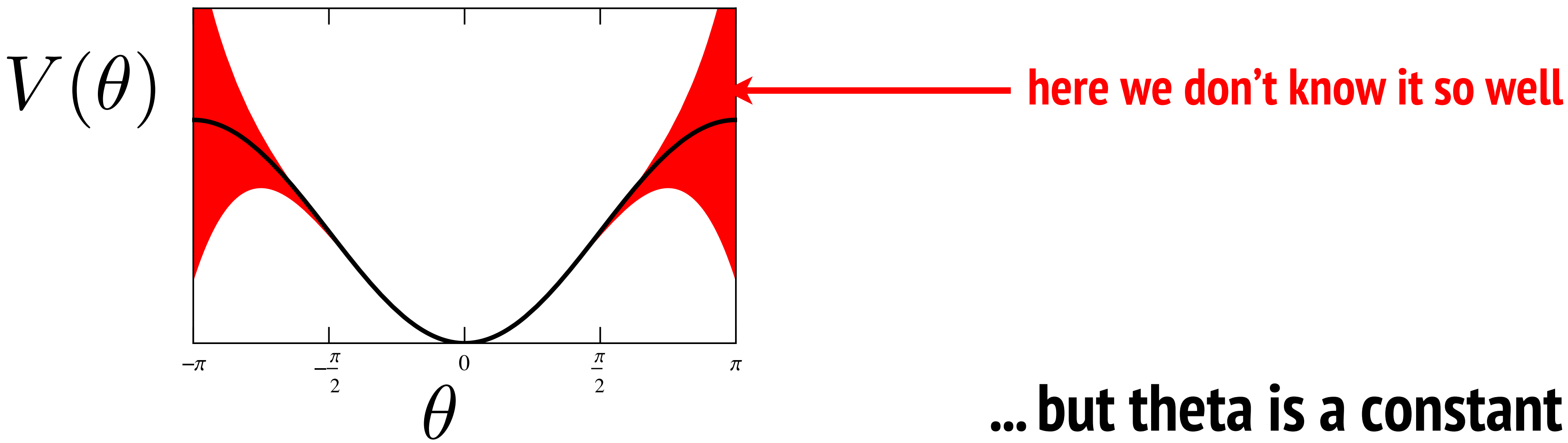
$d_n^{\rm exp} < 3 \times 10^{-26} [e\,{\rm cm}]$

$\theta < 10^{-10}$!!

The strong CP problem and axions

In pure SM the vacuum energy has a minimum at $\theta = 0$

$$\exp\left(-\int_x V(\theta)\right) = \int \mathcal{D}A^i_\mu \exp\left(-S_{\rm eff}[\phi, A^i_\mu]\right) \exp\left(-i\theta \frac{\alpha_s}{8\pi} G\widetilde{G}\right) < \exp\left(-\int_x V(0)\right)$$



... but theta is a constant of nature...

If θ **is a dynamical field (axion!), will roll down to zero, problem solved!**

$$\frac{\alpha_s}{8\pi} G\widetilde{G}\theta \to \frac{\alpha_s}{8\pi} G\widetilde{G}\theta(x) + \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta) f_a^2$$

$$\theta(x) = \frac{a(x)}{f_a}$$

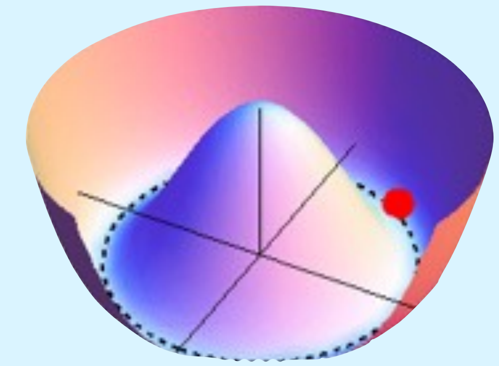
new energy scale!

Simple model KSVZ

- Peccei-Quinn symmetry, color anomalous, spontaneously broken at f_a

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{Q}DQ - (y\bar{Q}_L Q_R \Phi + {\rm h.c}) - \lambda|\Phi|^4 + \mu^2|\Phi|^2$$

$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

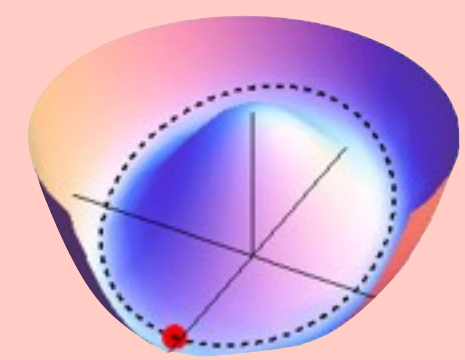


- At energies below f_a **(SSB)**

$$\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi} G\widetilde{G}\frac{a}{f_a}$$

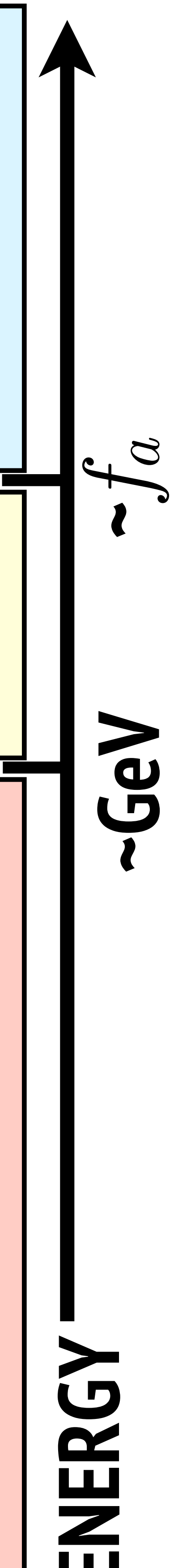
- At energies below $\Lambda_{\rm QCD}$, $a - \eta' - \pi^0 - \eta - \ldots$ **mixing**

axion mass $m_a \simeq \dfrac{m_\pi f_\pi}{f_a} \sim 6{\rm meV}\dfrac{10^9{\rm GeV}}{f_a}$

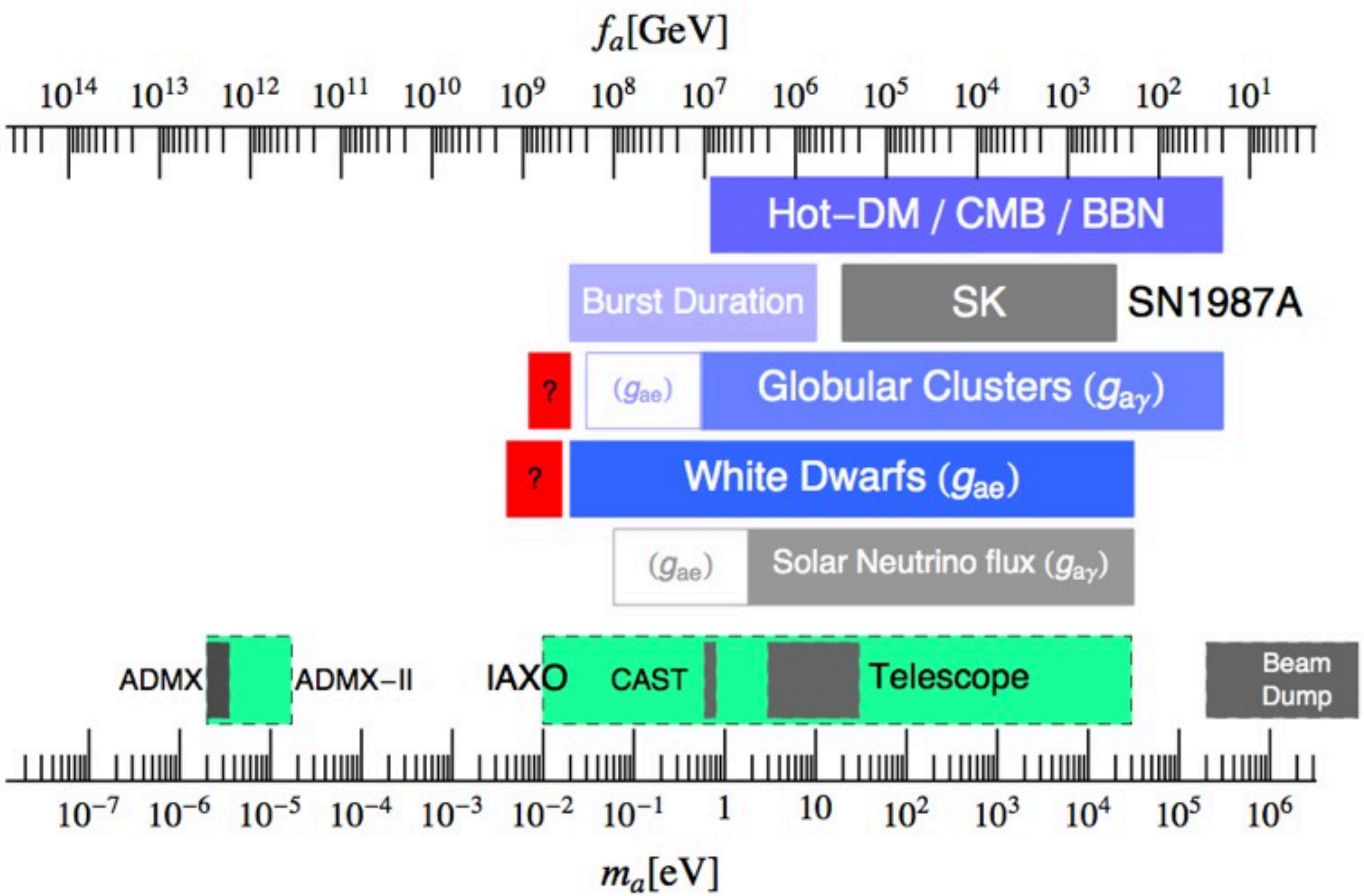


couplings $\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\dfrac{a}{f_a} + c_{a\gamma}\dfrac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\dfrac{a}{f_a} + \ldots$

nucleons ... photons ... mesons ...

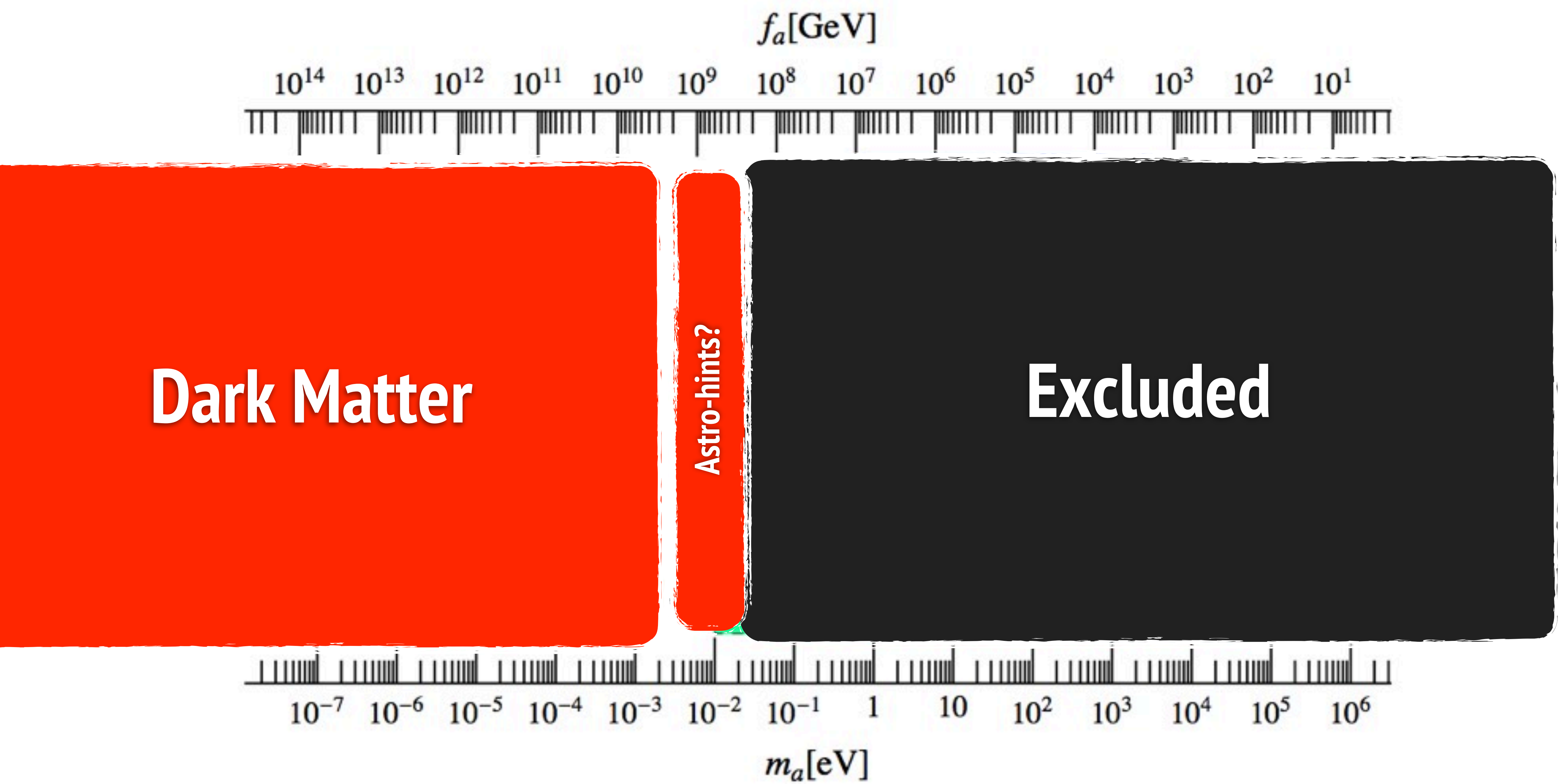


Landscape, what do we know?



If axions exist, they are very light and VERY weakly interacting!

Landscape, what do we know?

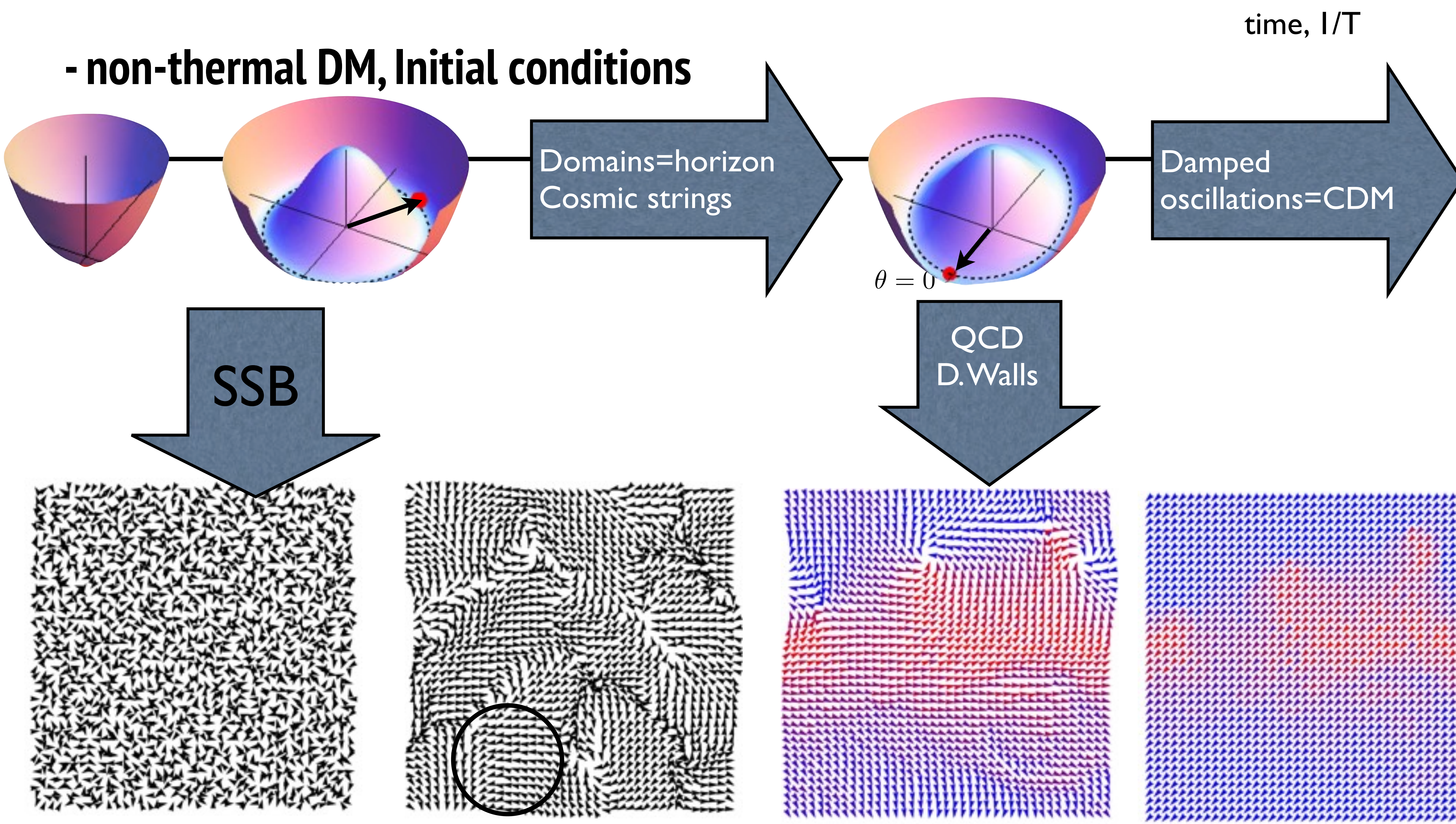


If axions exist, they are very light and VERY weakly interacting!

Vacuum realignment, strings, walls...

- Axions: small mass, small interactions, ~~thermal DM~~

- non-thermal DM, Initial conditions



Vacuum realignment, strings, walls...

- Axions: small mas

- non-thermal DM,

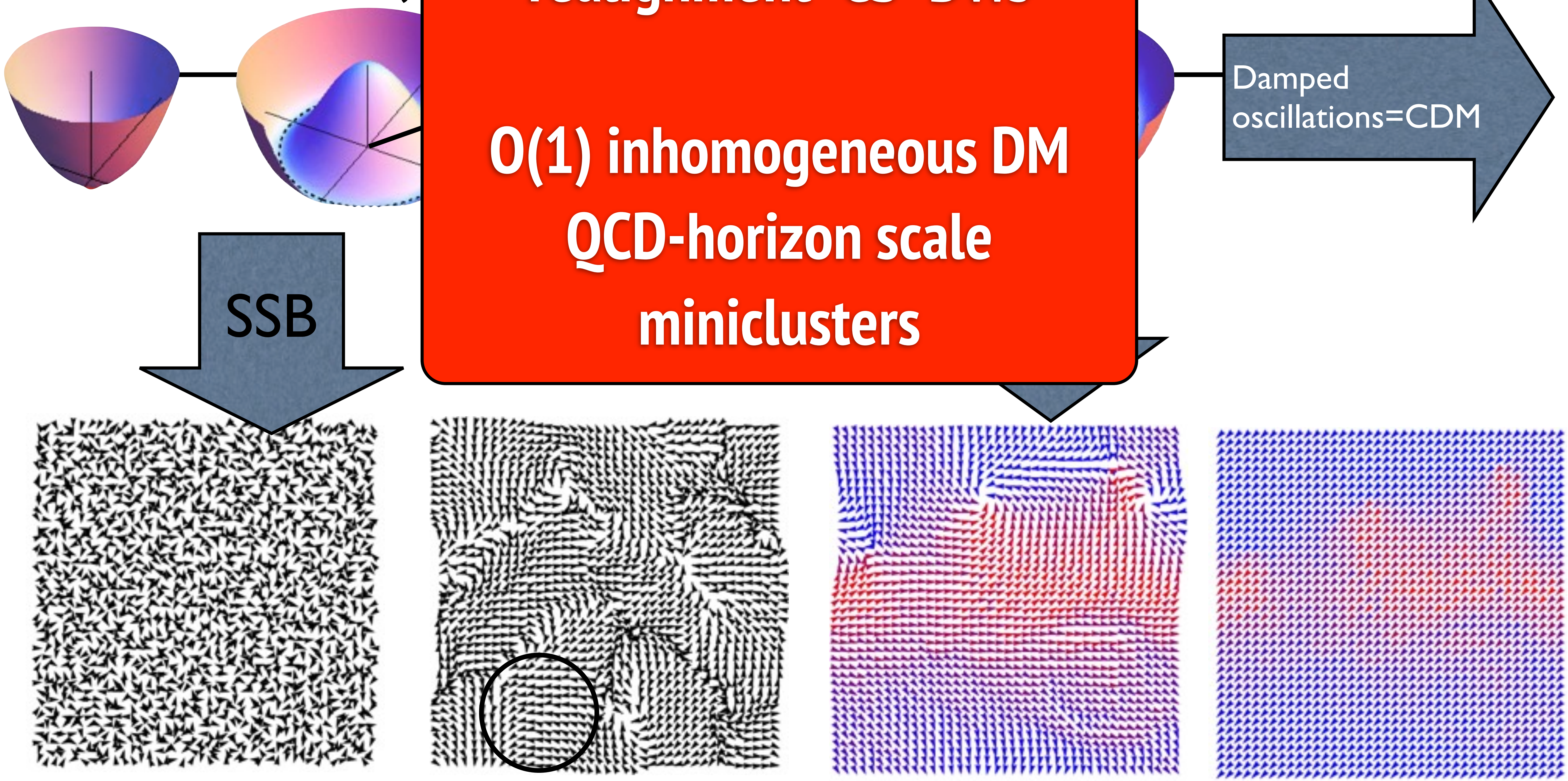
SCENARIO-I

realignment+CS+DWs

O(1) inhomogeneous DM

QCD-horizon scale

miniclusters



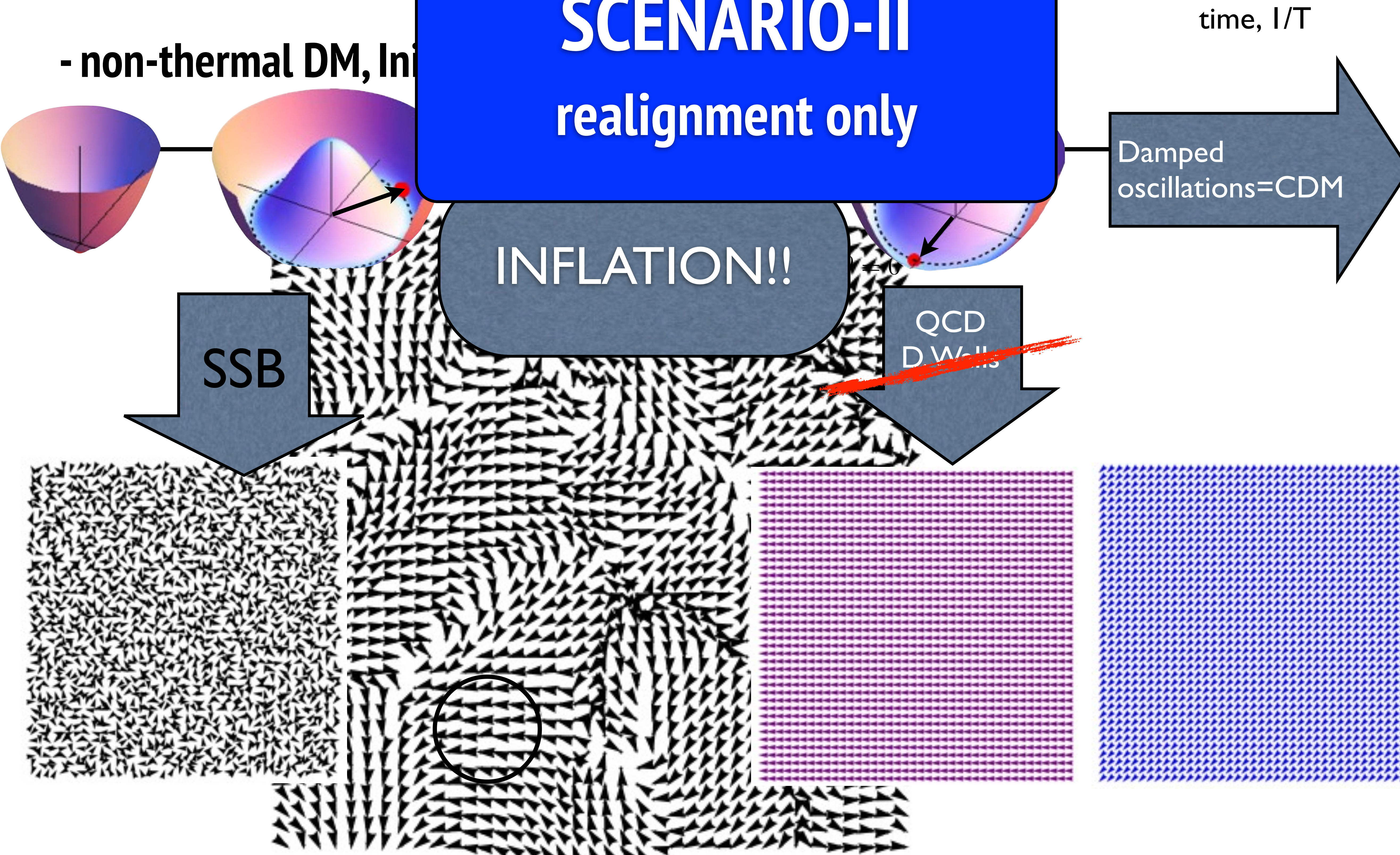
Vacuum realignment, ~~strings, walls~~...

- Axions: small mass, small interactions ... ~~thermal DM~~

- non-thermal DM, Ini

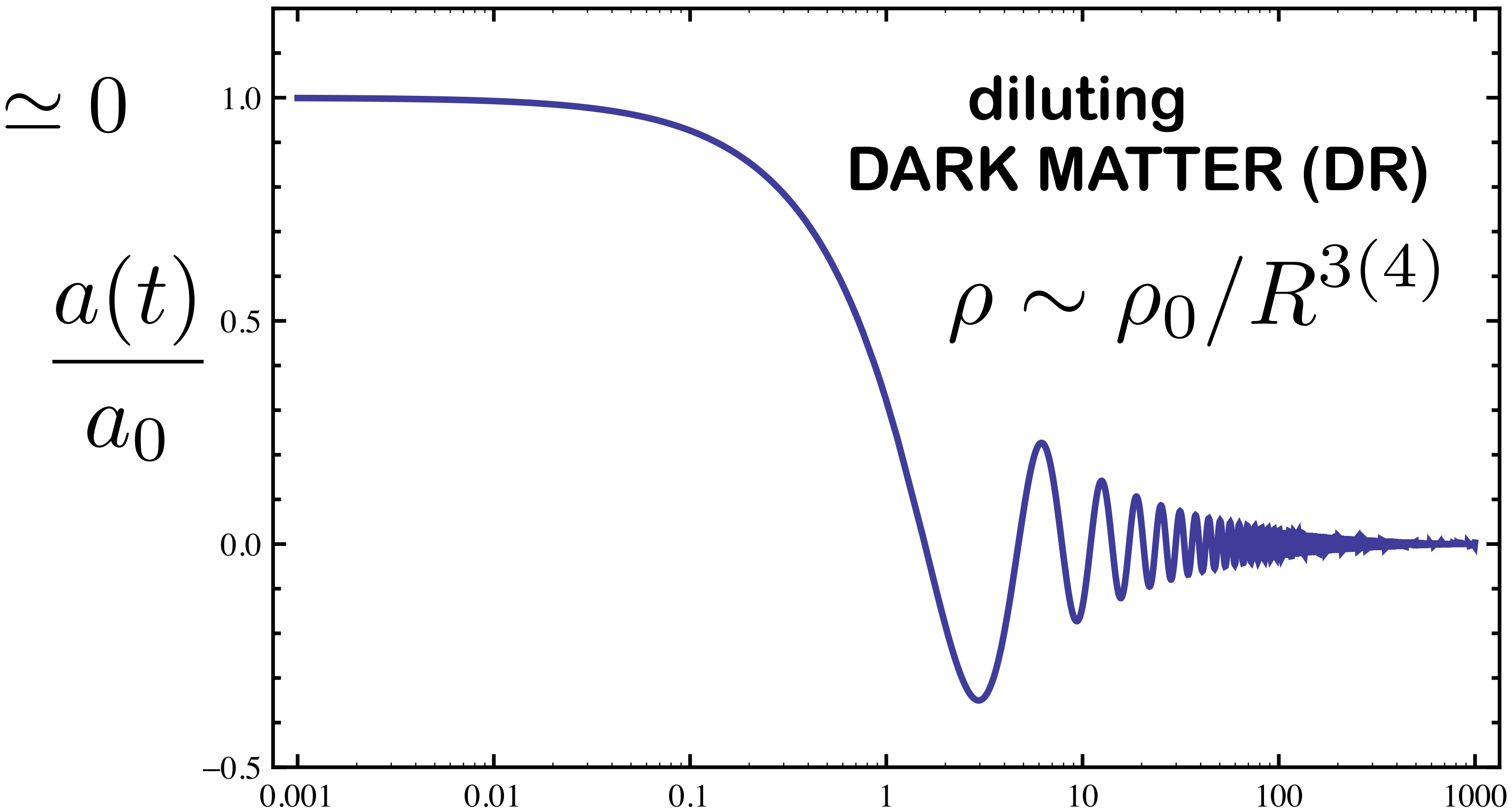
SCENARIO-II

realignment only



Axion DM, how much

$$\ddot{a}_k + 3H\dot{a}_k + (k^2 + m_a^2)a_k \simeq 0$$



this time is given by

$$t \sim \frac{1}{\sqrt{k^2 + m_a^2}} \sim \min\{\lambda, \frac{1}{m_a}\}$$

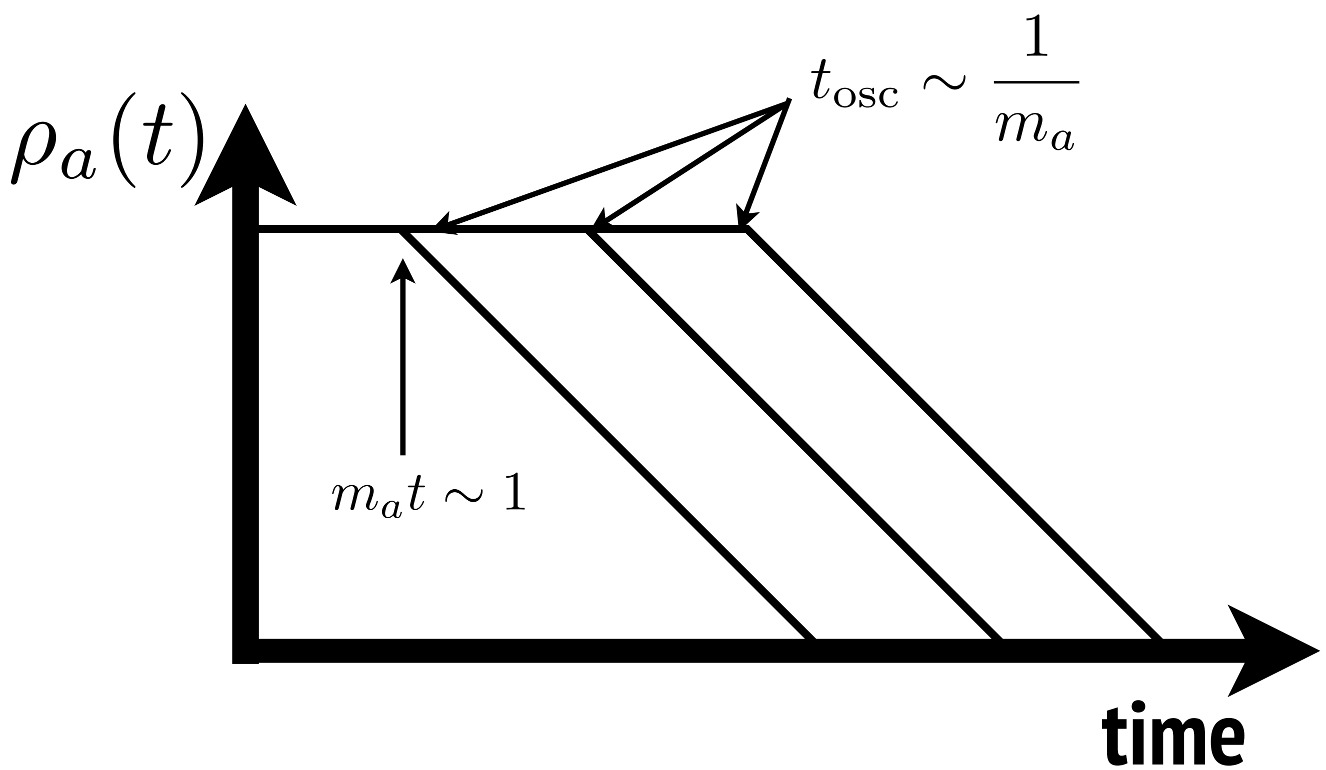
why decreases with the mass?

- Energy density redshifts as matter, from the onset of oscillations

$$\rho_a(t) \sim \theta_I^2 \Lambda_{\rm QCD}^4 \left(\frac{R_1}{R(t)}\right)^3 \propto \theta_I^2 \Lambda_{\rm QCD}^4 m_a^{-3/2}$$

dilution factor $$\left(\frac{R_1}{R_0}\right)^3 \sim \left(\frac{T_0}{T_1}\right)^3 \sim \left(\frac{T_0}{\sqrt{H_1 m_{\rm Pl}}}\right)^3 \sim \left(\frac{T_0}{\sqrt{m_a m_{\rm Pl}}}\right)^3 \propto m_a^{-3/2}$$

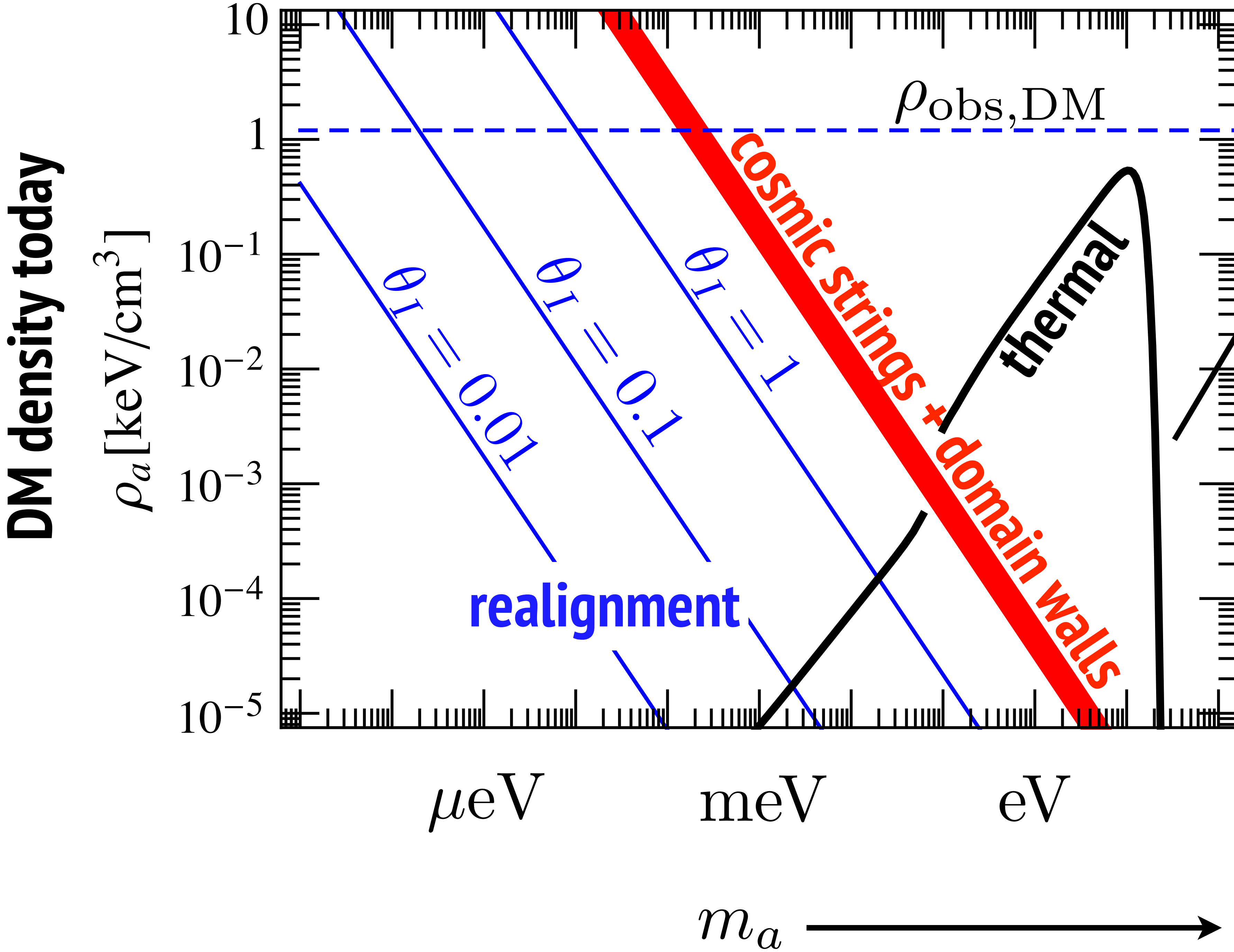
Smaller mass axions, start oscillating later, and get less diluted ...

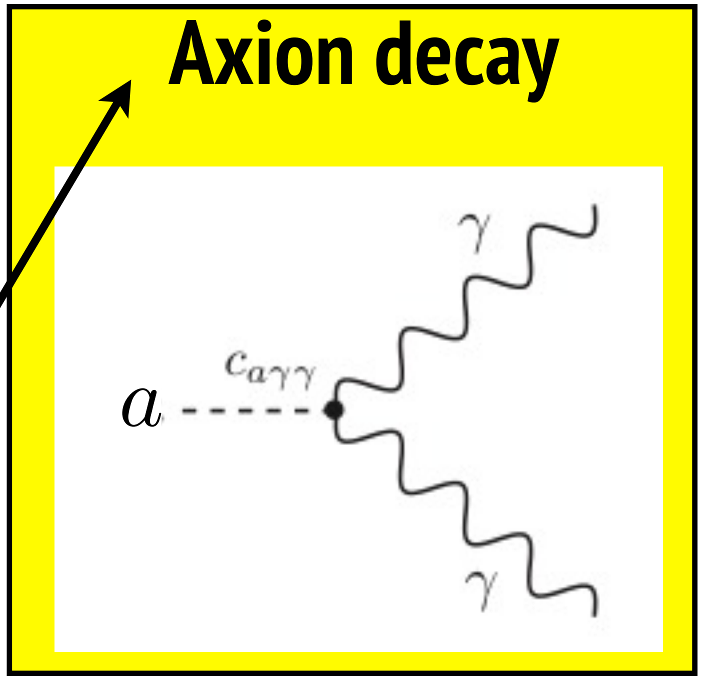


- with T-dependence

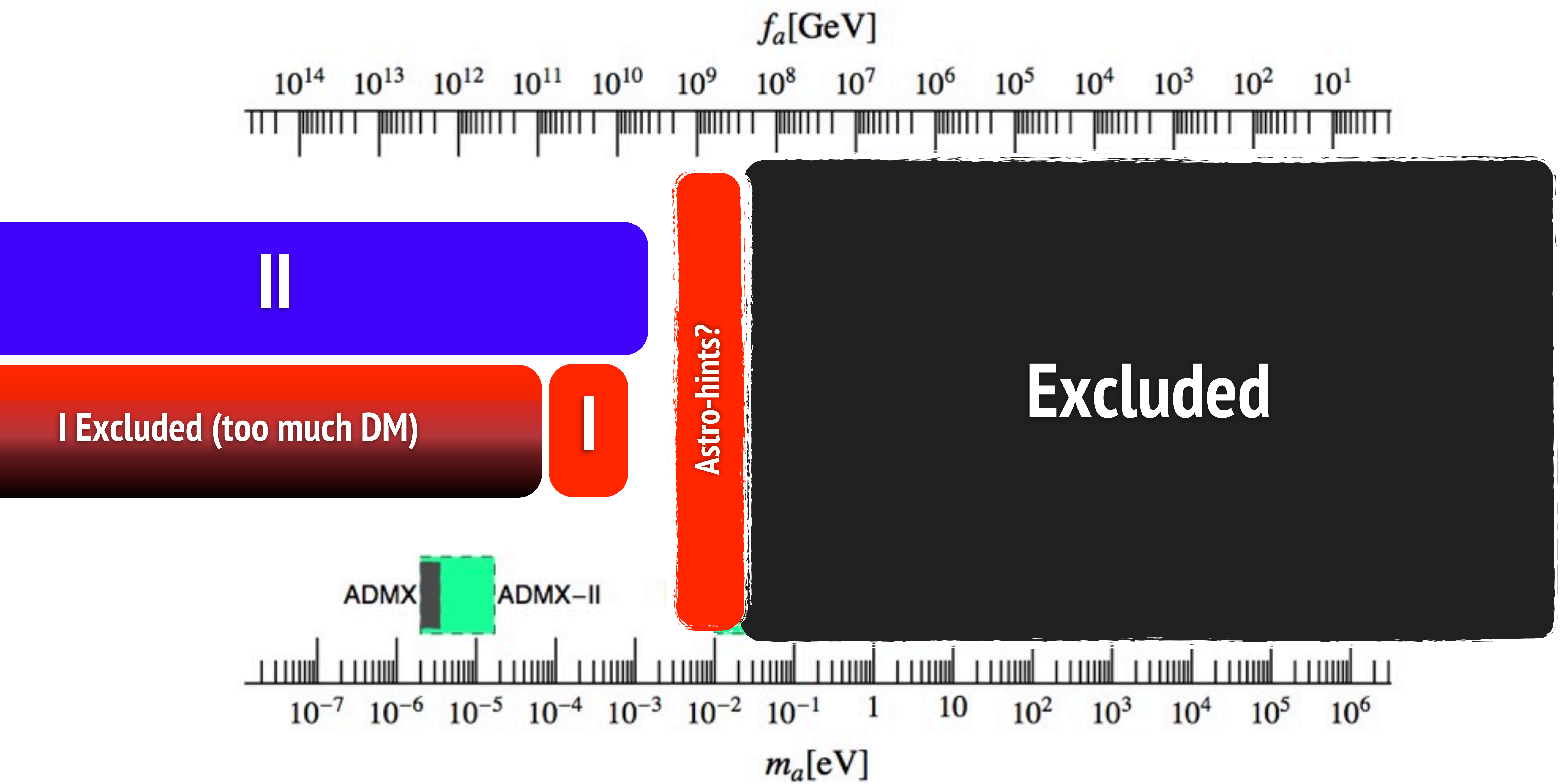
$$\rho_a(t_0) \propto \theta_I^2 m_a^{-7/6}$$

Axion DM, how much





Axion DM, how much



If axions exist, they are very light and VERY weakly interacting!

Axion DM, isocurvature issue and BICEP2-like discovery

- **Axion fluctuates during inflation** $\langle \delta a^2 \rangle \sim H_I^2/\pi^2$

$$P_{\rm iso} = \frac{d\langle n_a \rangle}{n_a} \sim \frac{d\langle a^2 \rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2} < 0.039 P_s = 0.88 \times 10^{-10}$$

insisting on axion DM $\theta_I = \theta_I(f_a)$

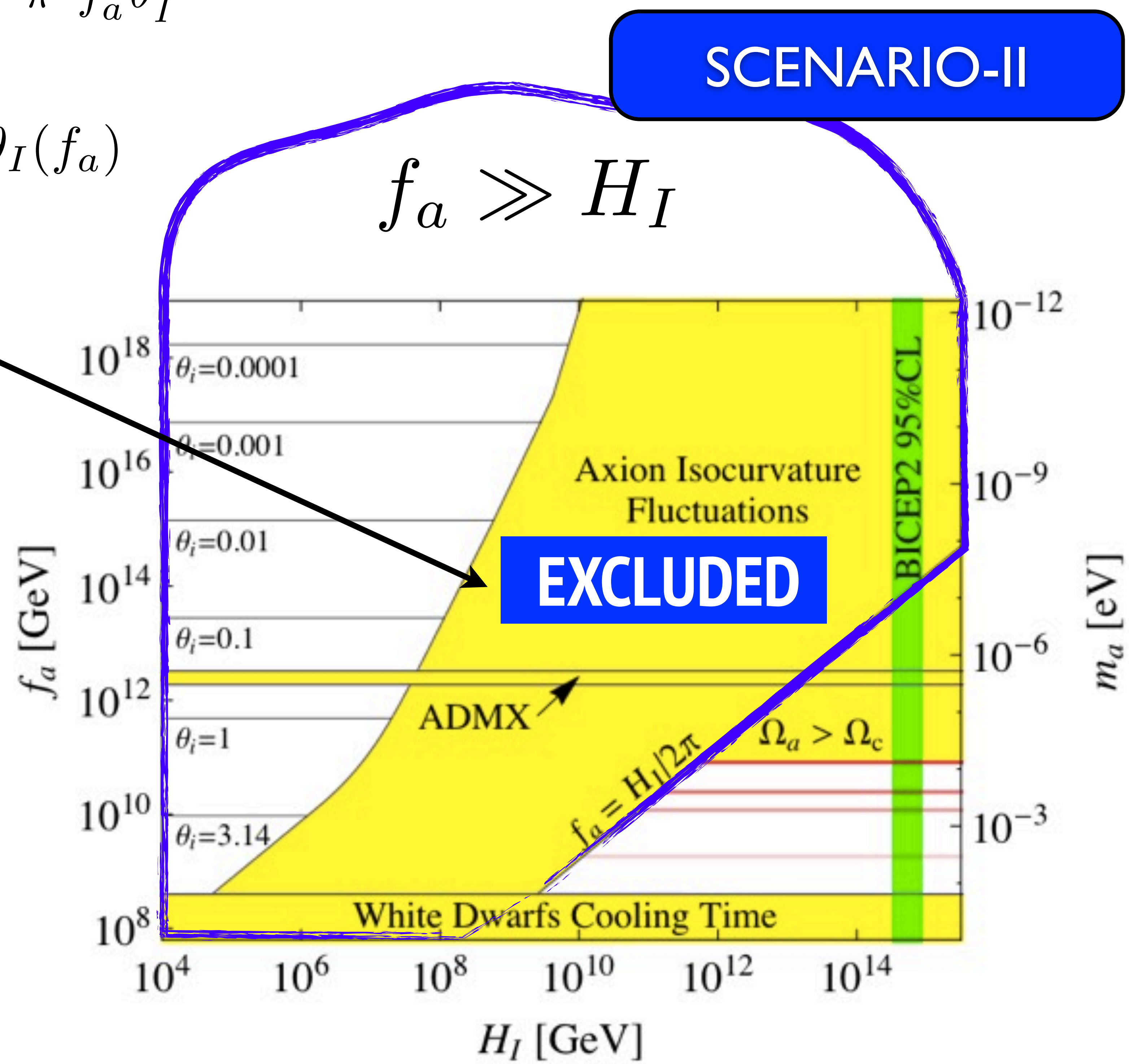
Constraint $f_a(H_I)$,

so then ...

- BICEP2 would exclude SC-II in the simplest models...

- of course, there are plenty of ways out ...

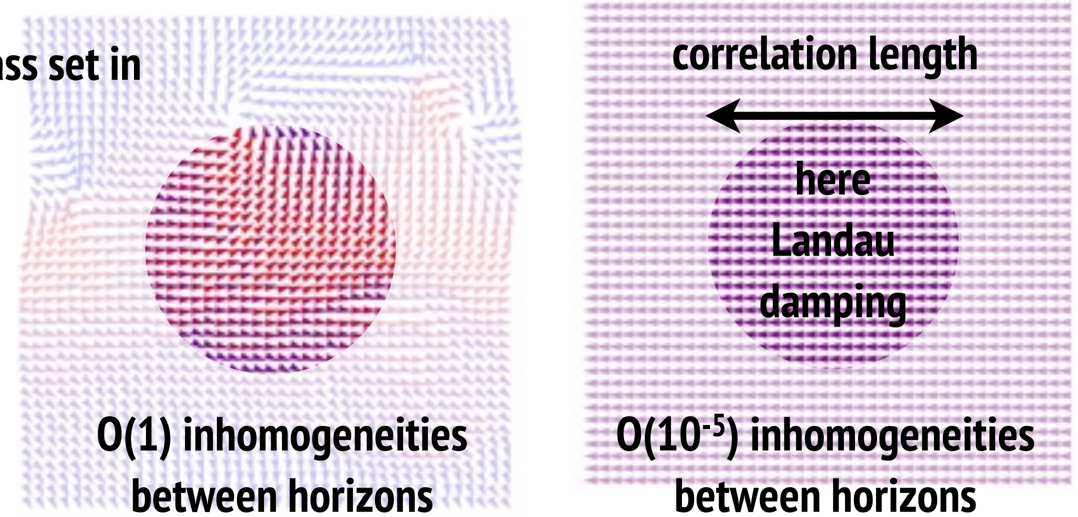
- note that inflation cannot generate the initial amplitude required for DM



ultralight DM forms a BEC?

- Condensed... they are

horizon at QCD mass set in



phase-space density $\mathcal{N} = \dfrac{\rho_{\rm DM}/m_a}{\frac{4\pi}{3}(\delta p \sim H)^3} \sim 10^{61}$

Evolution of ~ coherent state with huge number of non-relativistic quanta, subhorizon correlation scale

- thermalisation rates

Self-interactions : marginally relevant for a few H-times (axitons,...)

$$V(a) = \Lambda^4_{\rm QCD}(T)(1-\cos(a/f_a)) \simeq \frac{1}{2}\frac{\Lambda^4_{\rm QCD}}{f_a^2}a^2 - \frac{1}{24}\frac{\Lambda^4_{\rm QCD}}{f_a^4}a^4$$

$$\lambda \sim \left(\frac{m_a}{f_a}\right)^2 \sim O(10^{-40})$$

$\Gamma_\lambda \sim \dfrac{1}{4}\dfrac{\lambda n}{m^2} \propto a^3$ **(condensed regime, Sikivie 1111.1157)**

Gravity : increasingly relevant

$\Gamma_g \sim 4\pi G n m^2 l^2_{\rm corr} \propto a$ **(condensed regime, Sikivie 1111.1157)**

ultralight DM forms a BEC?

- gravitational thermalisation -> BEC ?

thermalisation, maximal entropy configuration

Intuition of BEC from atomic physics -> highly occupied k=0 state due to REPULSIVE interactions

ATTRACTIVE interactions (gravity) led to different configurations: BOSE STARS!

solutions of the Schoedinger-Newton equation $$i\,\dot{\psi} = -\frac{1}{2m}\nabla^2\psi + m\,\phi_N\psi$$

Wave-function Heisenberg-pressure Newton's potential

Jean's instability $$k < k_J = (16\pi G m^3 n_0)^{1/4}$$

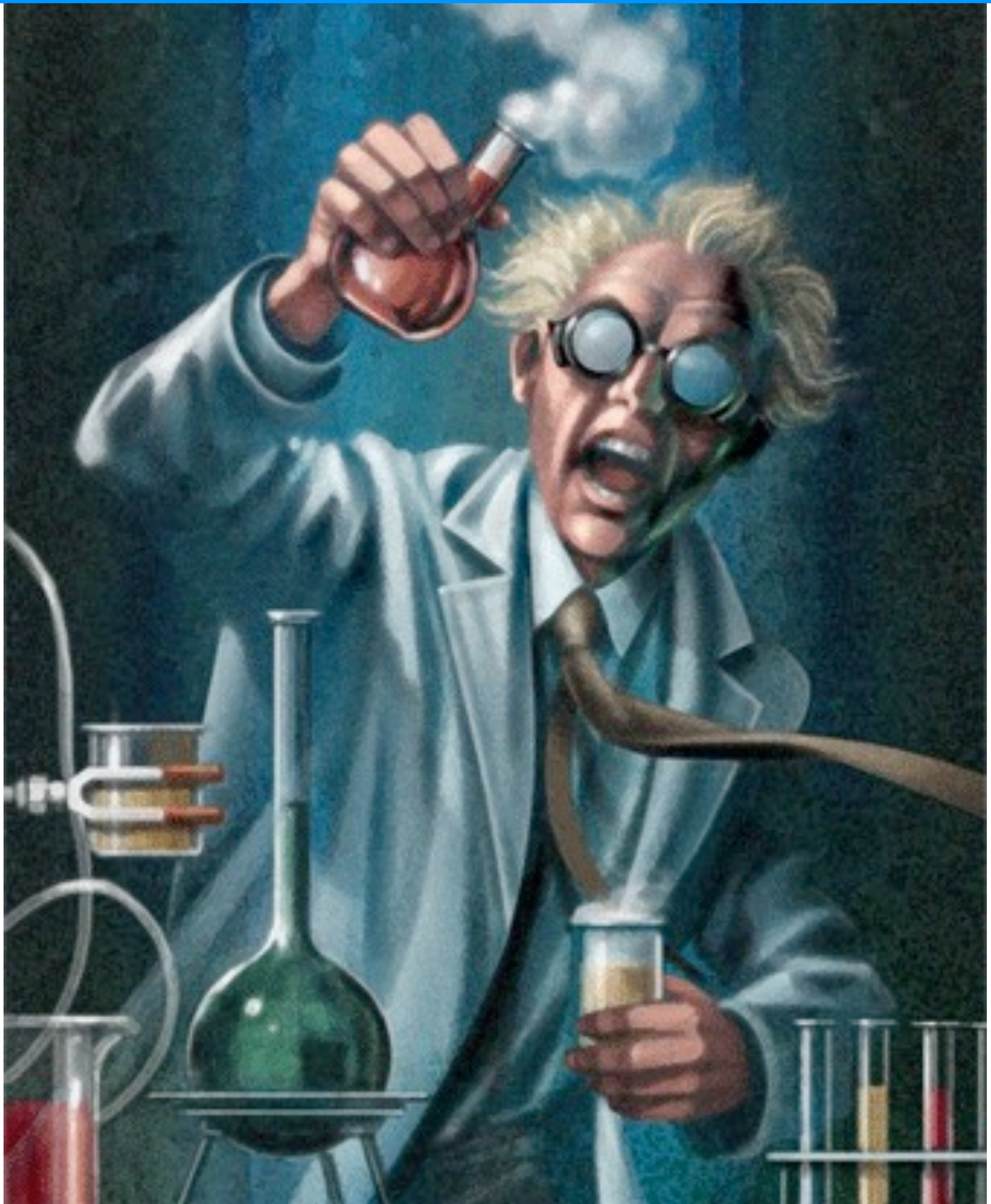
Looks like axion-modes evolve just like a q-mechanical version of density fluctuations

$$n = |\psi|^2$$ thermalisation = virialisation?

Controversy is served: Guth's bottleneck (1412.5930) vs Sikivie's big vortex (1307.3547)

Numerical simulations under way (Guth, Davidson)

Detecting Axions



Detecting Axion (Dark Matter) in the lab

$$\rho_{\mathrm{CDM}} \simeq 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3} = m_a n_a \simeq \frac{1}{2} m_a^2 f_a^2 \theta^2 \longrightarrow \theta \sim O(10^{-19})$$

velocities in the galaxy $v \lesssim 300\ \mathrm{km/s} \sim 10^{-3} c$

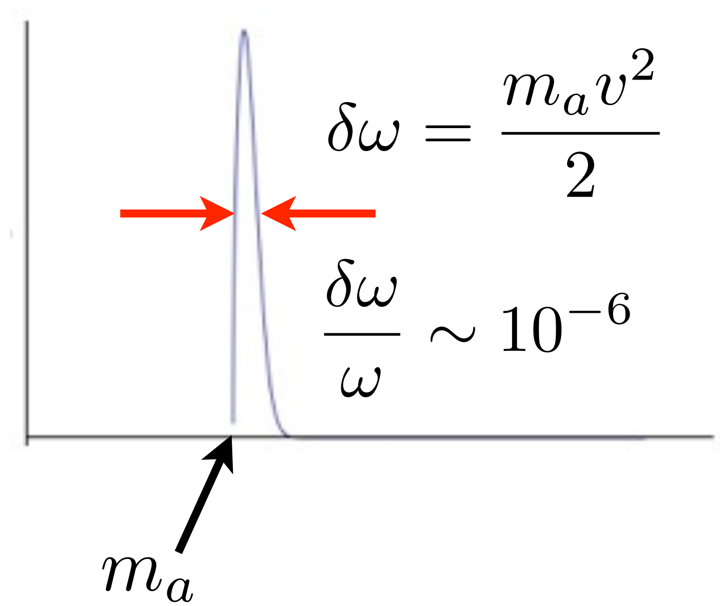
phase space density $\dfrac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29} \left(\dfrac{\mu\mathrm{eV}}{m_a}\right)^4$

occupation number is HUGE! $\longrightarrow$ **treat it like a classical coherent (NR) field**

Roughly ... $a(t) = a_0 \cos(m_a t)$

Fourier-transform $a(x)$

$$\omega \simeq m_a(1 + v^2/2 + \ldots)$$



$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

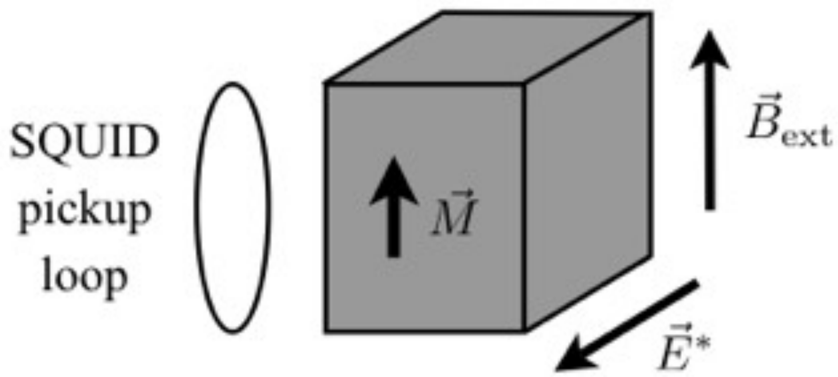
$$\boxed{\delta t \sim \frac{1}{\delta\omega} \sim 0.13\mathrm{ms}\left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)}$$

$$\boxed{\delta L \sim \frac{1}{\delta p} \sim 20\mathrm{m}\left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)}$$

Detecting Axion (Dark Matter) in the lab

mass neV μeV 0.1 meV

Spin precession



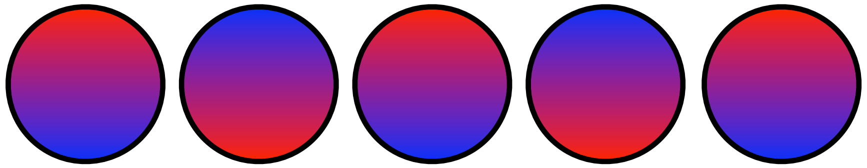
CASPER (Mainz-Berkely)

Cavity experiments

ADMX, ADMX-HF,Yale,WISPDMX
CARRACK, IAXO, RADES...

Atomic transitions?

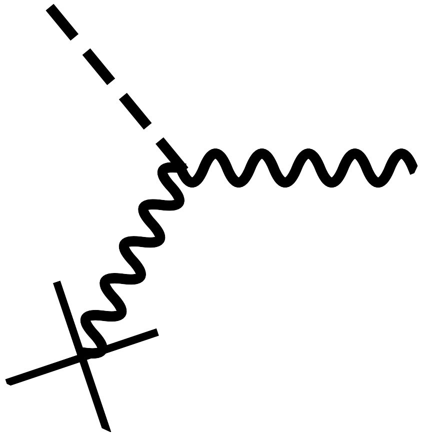
Oscillating EDM



$$d_n \sim \mathcal{O}(10^{-34})\cos(m_a t)[e\,\mathrm{cm}]$$

Graham, Rajendran 2011

Axion-photon conversion



Axion-electron absorption

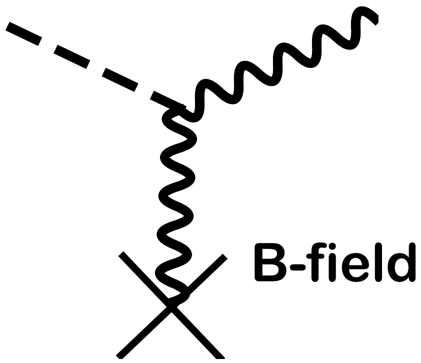
Sikivie 2014

Axion DM in a B-field

$$\mathcal{L}_I = -c_{a\gamma\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\mathbf{B}\cdot\mathbf{E}$$

- In a static magnetic field, the oscillating axion field generates EM-fields

$$\mathcal{L}_I = -c_{a\gamma\gamma}\frac{\alpha}{2\pi}\theta(t)\,\mathbf{B}_{\mathrm{ext}}\cdot\mathbf{E}$$



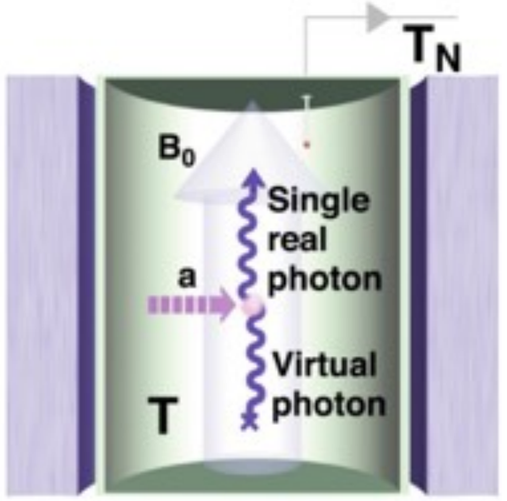
- Electric fields of order $|\mathbf{E}| \sim \mathcal{O}(10^{-12}V/m)|\mathbf{B}_{\mathrm{ext}}|\, c_{a\gamma}\ \cos(m_a t)$

- oscillating at a frequency given by the axion mass

Do not depend on mass or coupling strength!

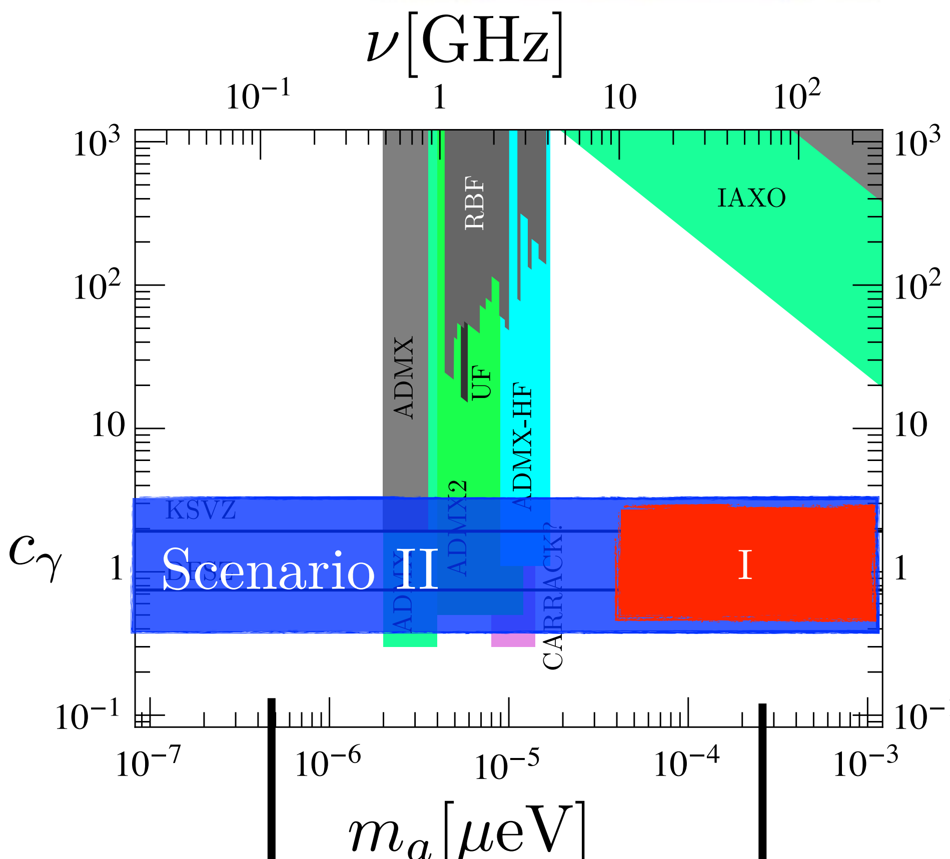
Cavity experiments

- **Haloscope (Sikivie 83)**
  "Amplify resonantly the EM field in a cavity"



$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa \qquad \text{(on resonance)}$$

- **Past experiments Florida U., RBF, ADMX, CARRACK**
- **Future endeavors: ADMX, ADMX-HF, YMCE, CAPP**
- **Parameters unexplored at low and high masses: WHY?**



Cylindrical cavity $(h/r=b)$ **like ADMX but scaled**

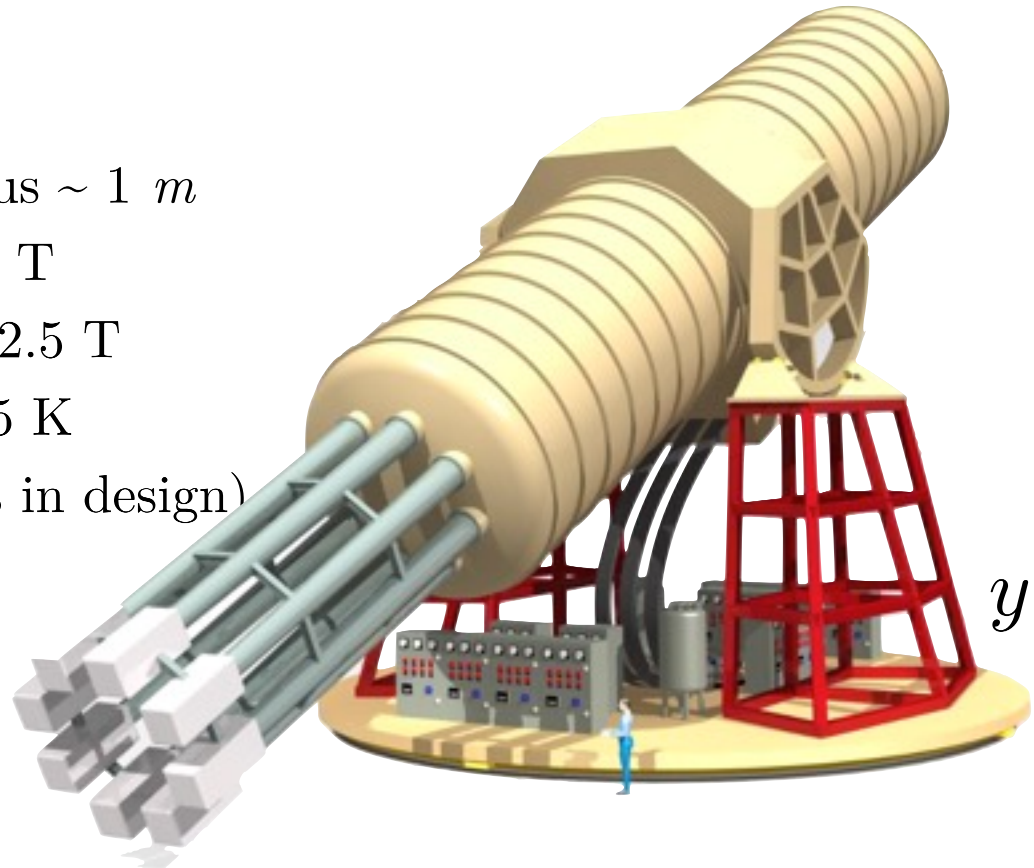
- Signal $\quad (V \propto m_a^{-3}) \quad P_{\rm out} \propto V m_a \sim \dfrac{1}{m_a^2}$
- Noise $\quad P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$
- Signal/noise in $\Delta\nu_a$ of time, t, $\quad \dfrac{S}{N} = \dfrac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$
- Scanning rate $\quad \dfrac{1}{m_a}\dfrac{d\Delta m_a}{dt} \propto \dfrac{c_\gamma^4}{m_a^9}$

Very easy, but needs large magnet volume!

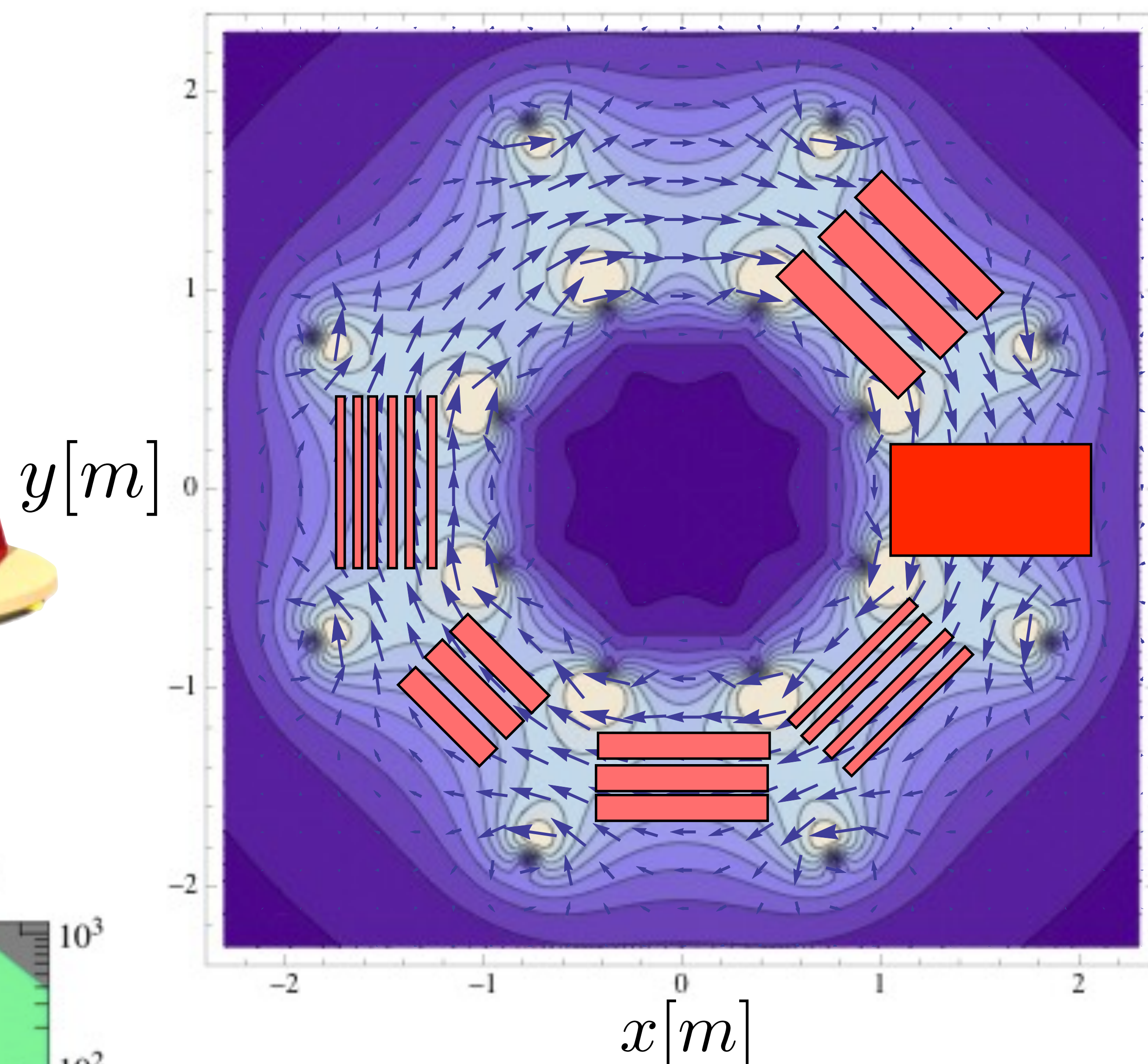
Very complicated, needs new ideas...

Axion DM searches with IAXO?

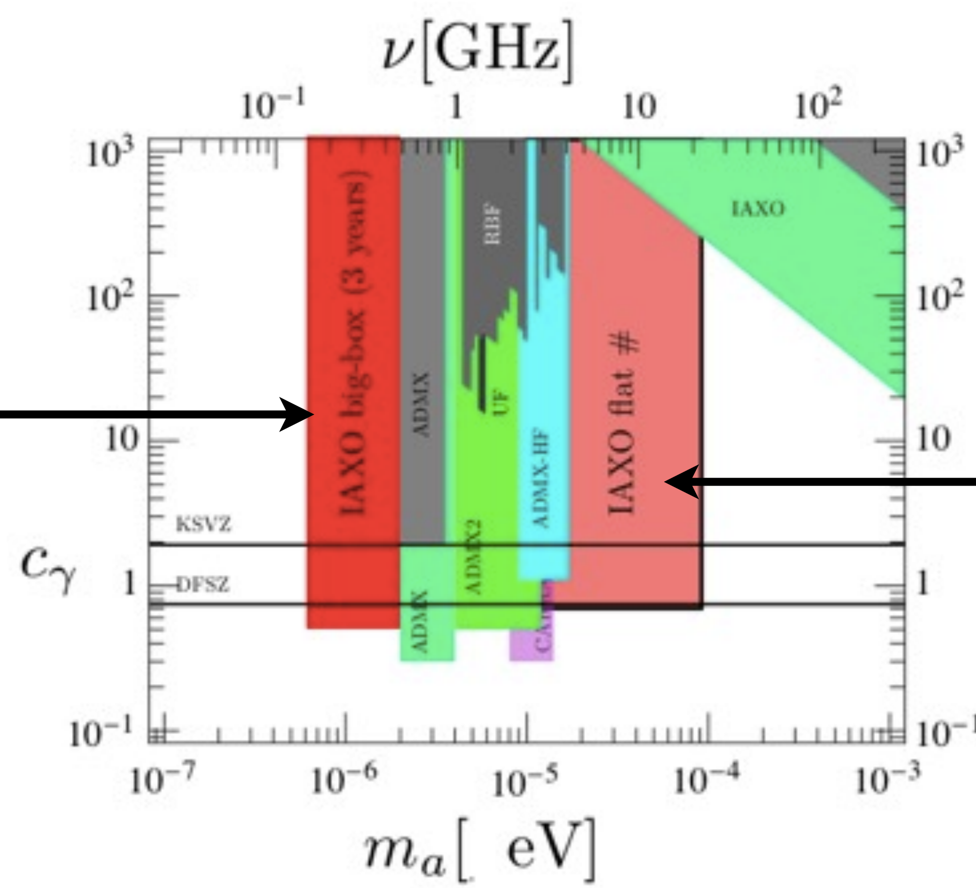
- Length $= 20\ m$
- Magnetised radius $\sim 1\ m$
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K
  (but warm bores in design)



field map of transverse cut



- Sensitivity

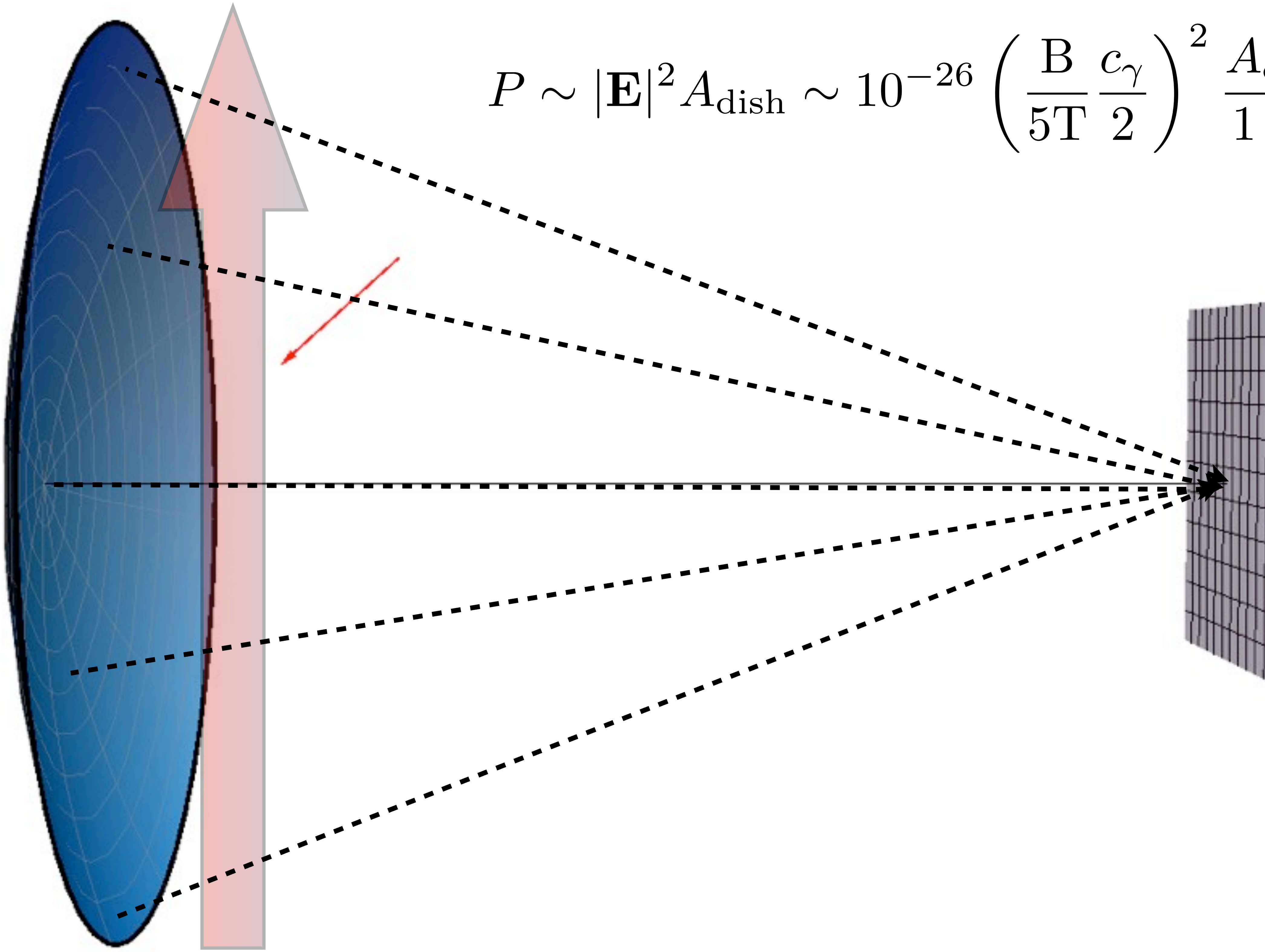


Big cavity
(realistic)

Many flat (exploit the huge volume)
(very speculative, R&D needed!)

Dish antenna experiment?

$$P \sim |\mathbf{E}|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{c_\gamma}{2}\right)^2 \frac{A_{\rm dish}}{1\,{\rm m}^2}{\rm Watt}$$



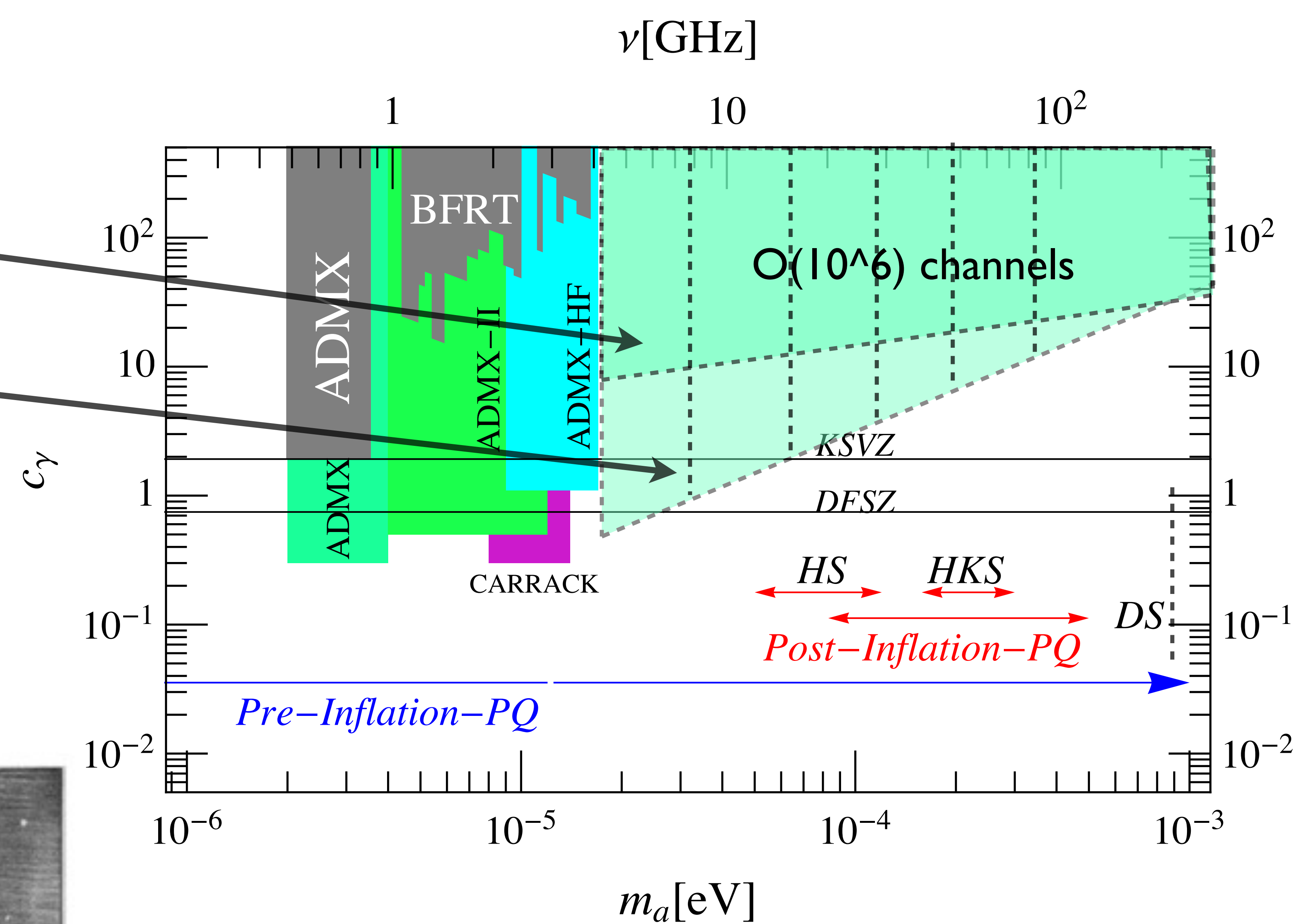
spherical reflecting dish

Dish antenna experiment?

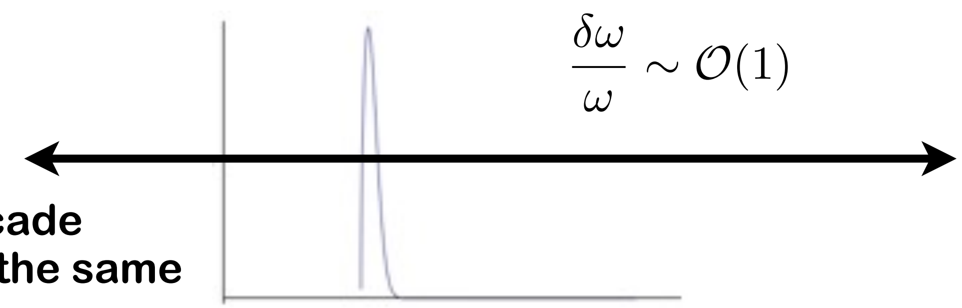
A=10m2,T=5K, B=5T, t=1year,

A=10m2, T=QL, B=10T, t=1year,

$$\rho_{\rm CDM} \sim \frac{0.3\rm GeV}{\rm cm^3}$$



broadband!

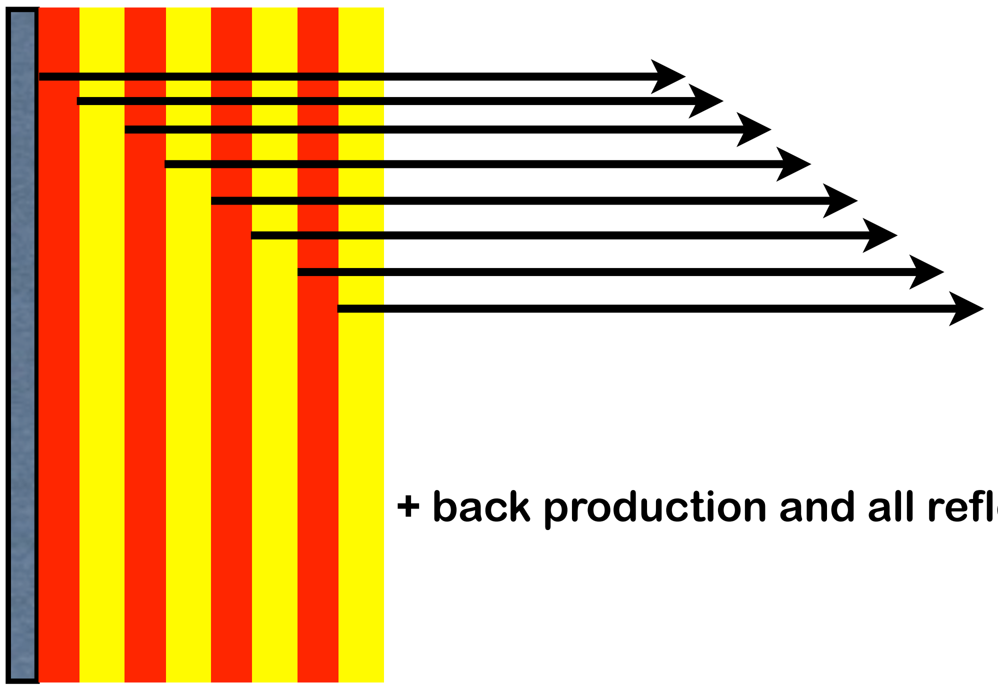


$$\frac{\delta\omega}{\omega} \sim \mathcal{O}(1)$$

measure 1/octave of a decade with the same detector at the same time

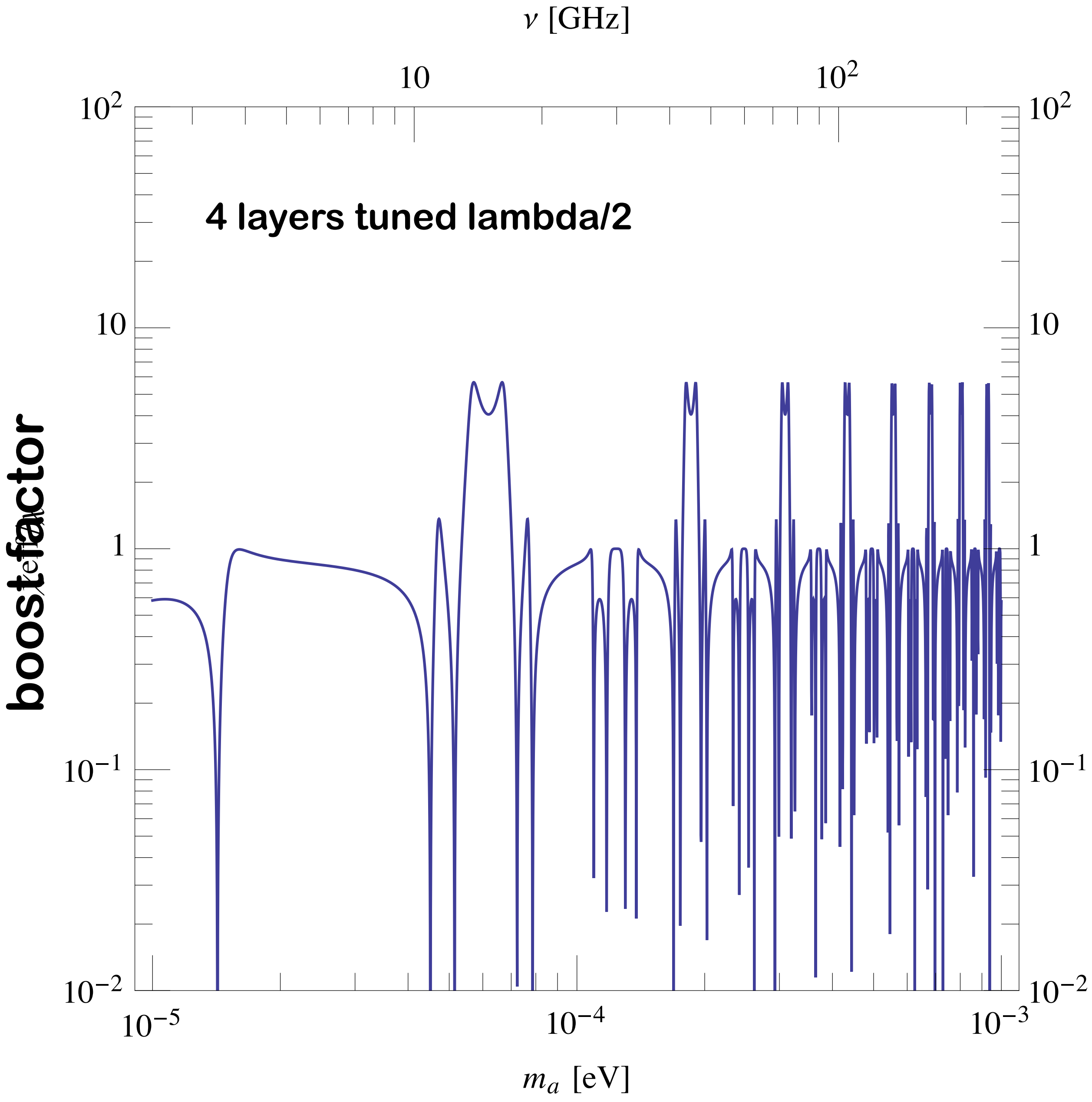
possible boost

Enhance the emissivity by multilayers of dielectric



+ back production and all reflexions ...

$$|\mathbf{E}_a| \to |\mathbf{E}_a| \times N$$



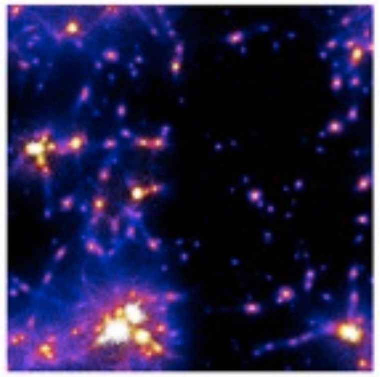
Increases sensitivity but losses bandwidth

Dish antenna and miniclusters

- Typical Dish antenna experiments fall a bit short, if the DM density is just $\rho_{\rm CDM} = 0.3{\rm GeV/cm^3}$

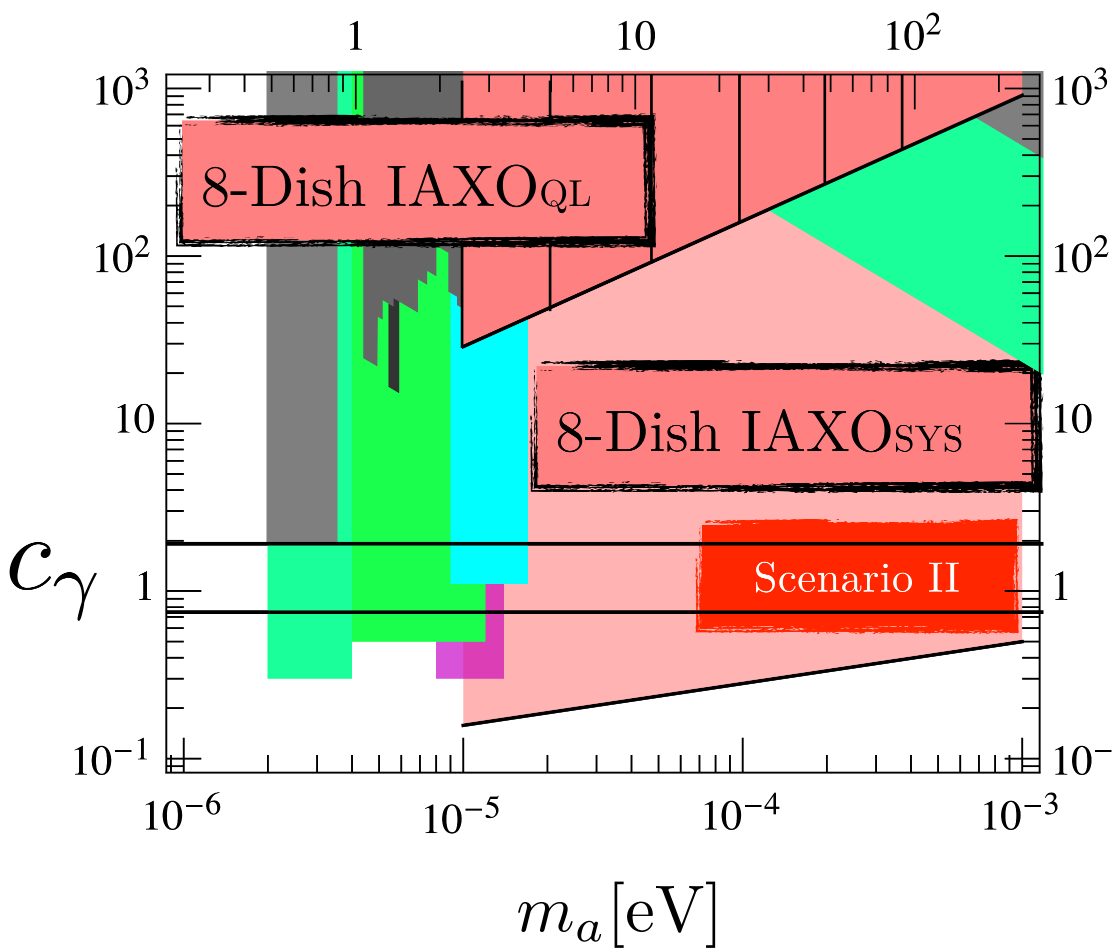
- 0.1-1 meV range is most interesting in **Scenario-II**

- S-II predicts miniclusters of axion CDM



$$M_{\rm mc} \sim 10^{-12} M_\odot$$
$$\Omega_{mc}/\Omega_{a{\rm CDM}} \sim O(1)$$

Zurek et al 07, See also Kolb & Tkachev 94



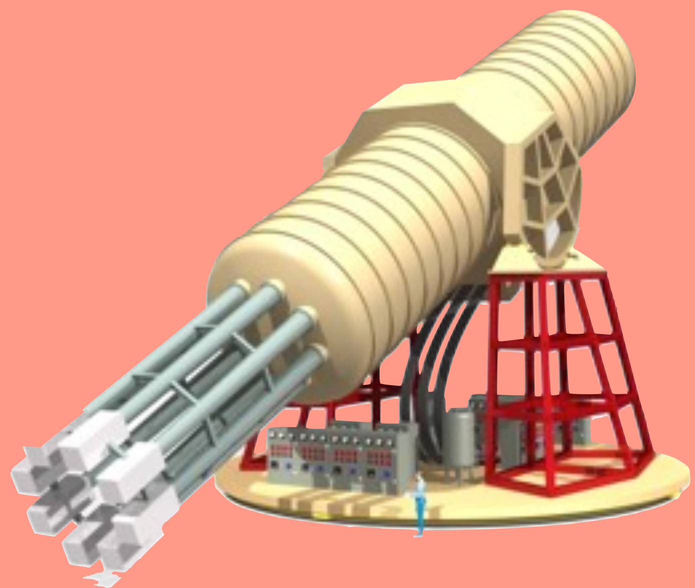
- Encounter with the Earth (every 10^4 years)

$$\rho_{\rm CDM} \times 10^6, Q_a \sim 10^9, t \sim 3{\rm days}$$

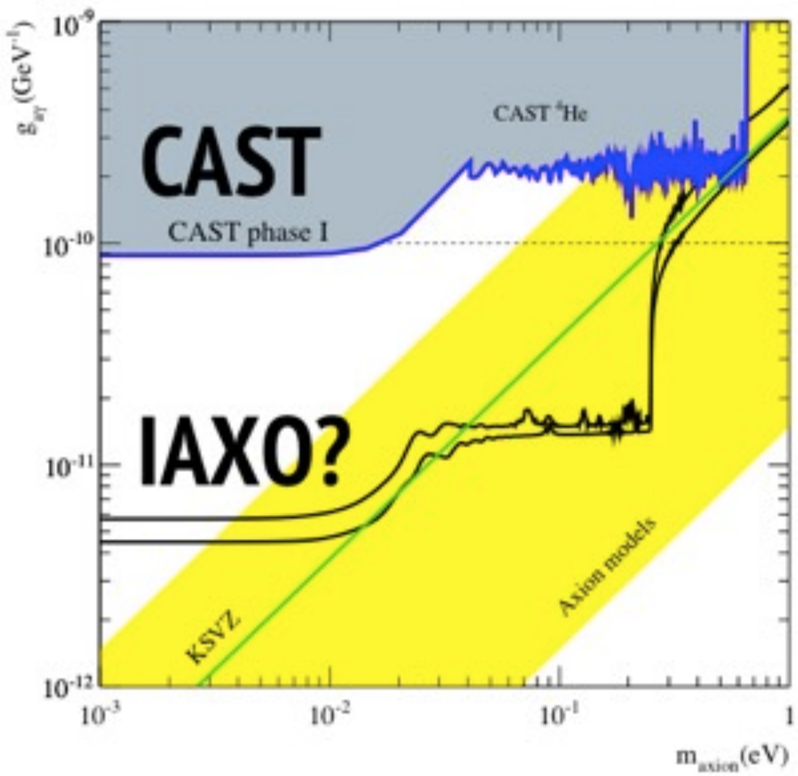
- Even with a modest realistic experiment one can get a huge signal ! (if lucky...)

Detecting Axions

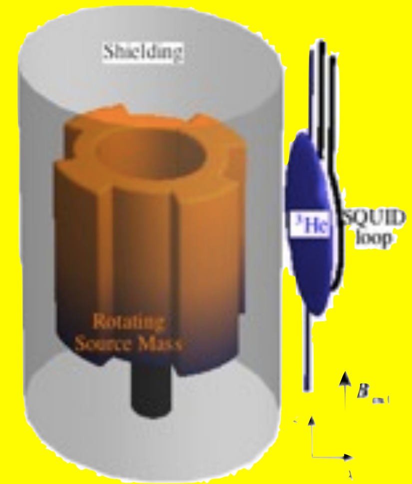
Solar Axions



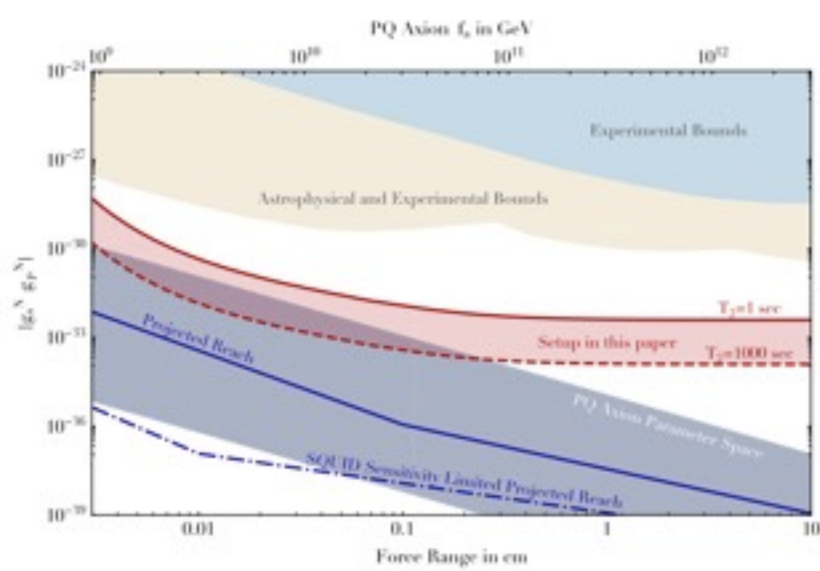
IAXO CDR 2014



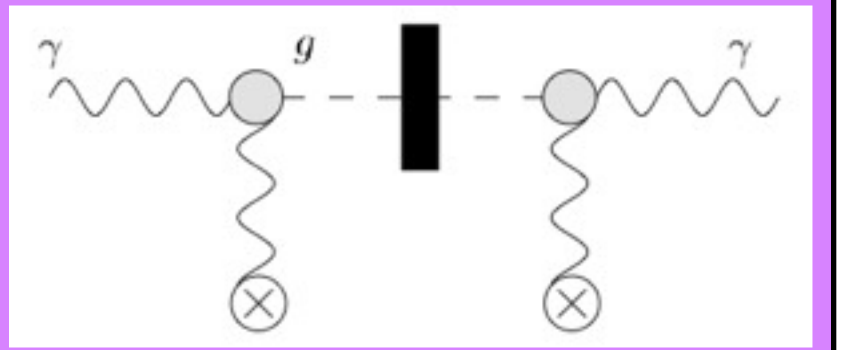
5th forces



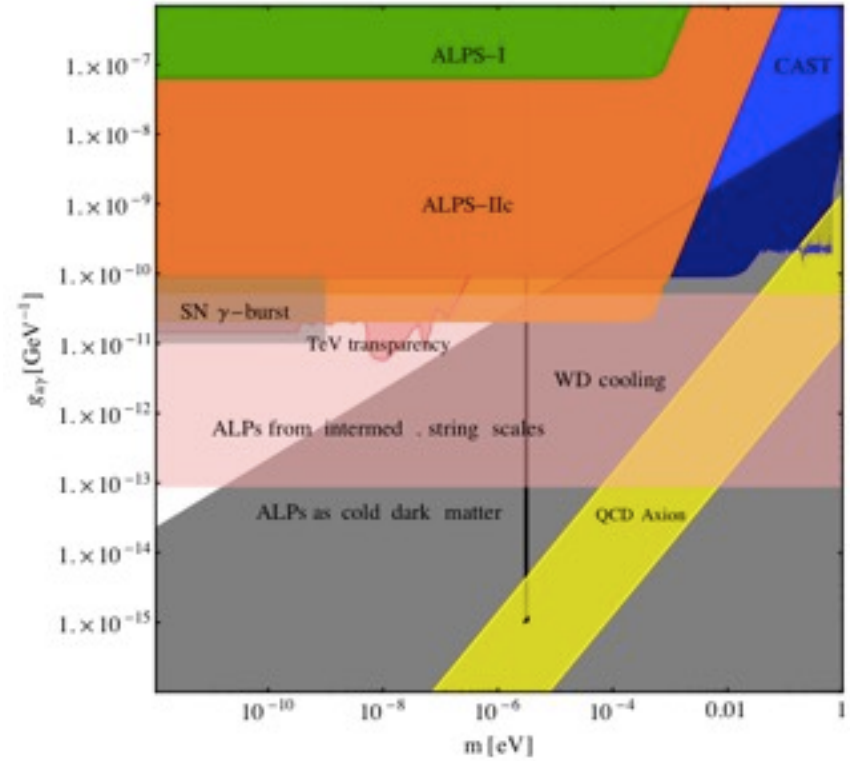
Arvanitaki Geraci PRL 2014



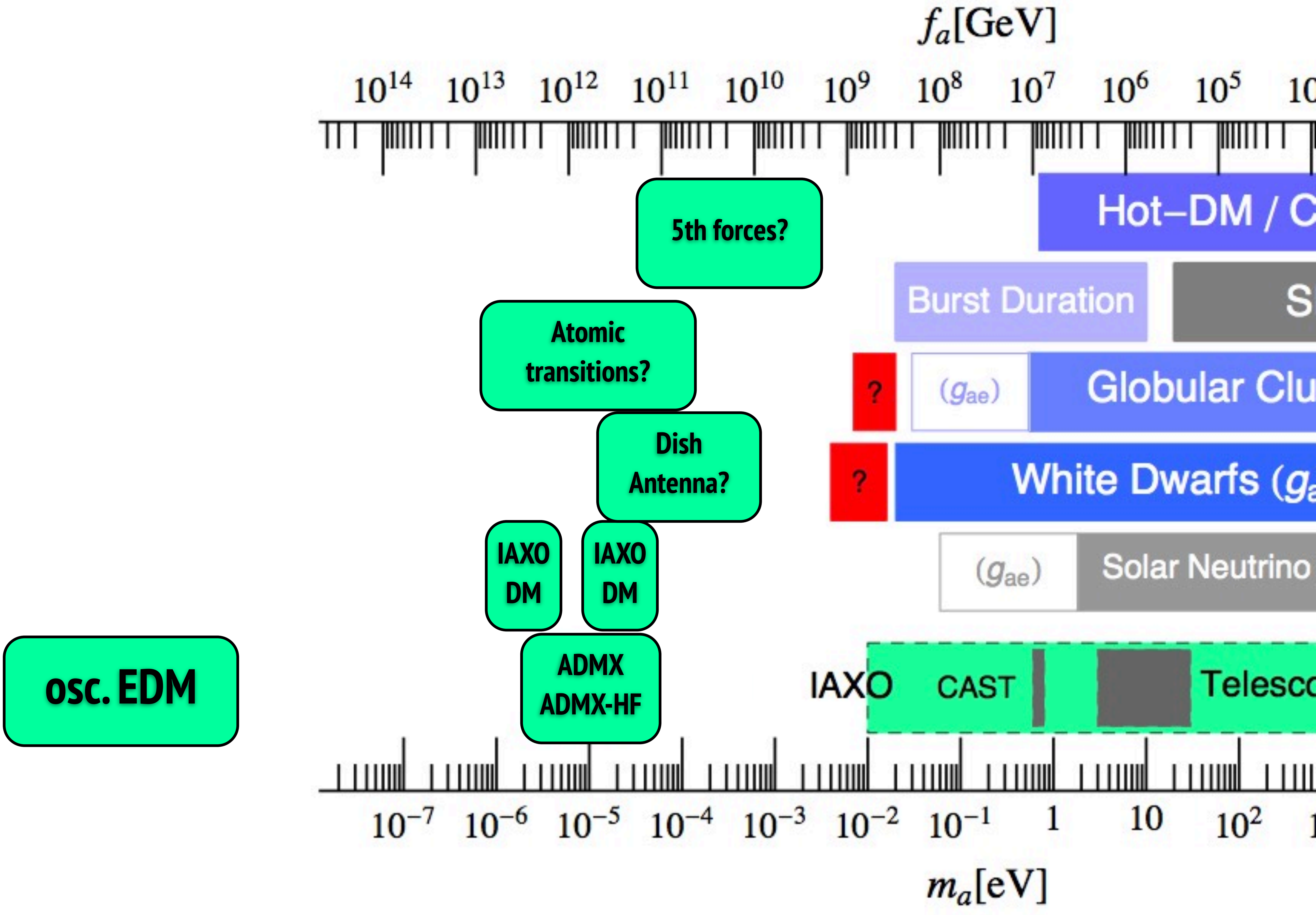
Photon regeneration



ALPS-II TDR 2013



A developing picture



Conclusions

- Axion DM - well motivated and testable
  - but underrepresented
  - key targets still not covered
  - plenty of new ideas

- Cavity experiments on the run
  - micro-eV range by ADMX, ADMX-HF, CAPP?
  - lower masses, IAXO?
  - Dish antenna?

- Millions of things not covered here
  - Axions in BSM physics
  - Axion DM astrophysics (BEC?, miniclusters?, BHs?)
  - other ultralight DM candidates...

Thank you!!!

want more? ... come to Zaragoza!

http://axion-wimp2015.desy.de/