Axions, Astrophysics and Dark matter

Frascati 17/12/2015
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Overview

- Strong CP problem

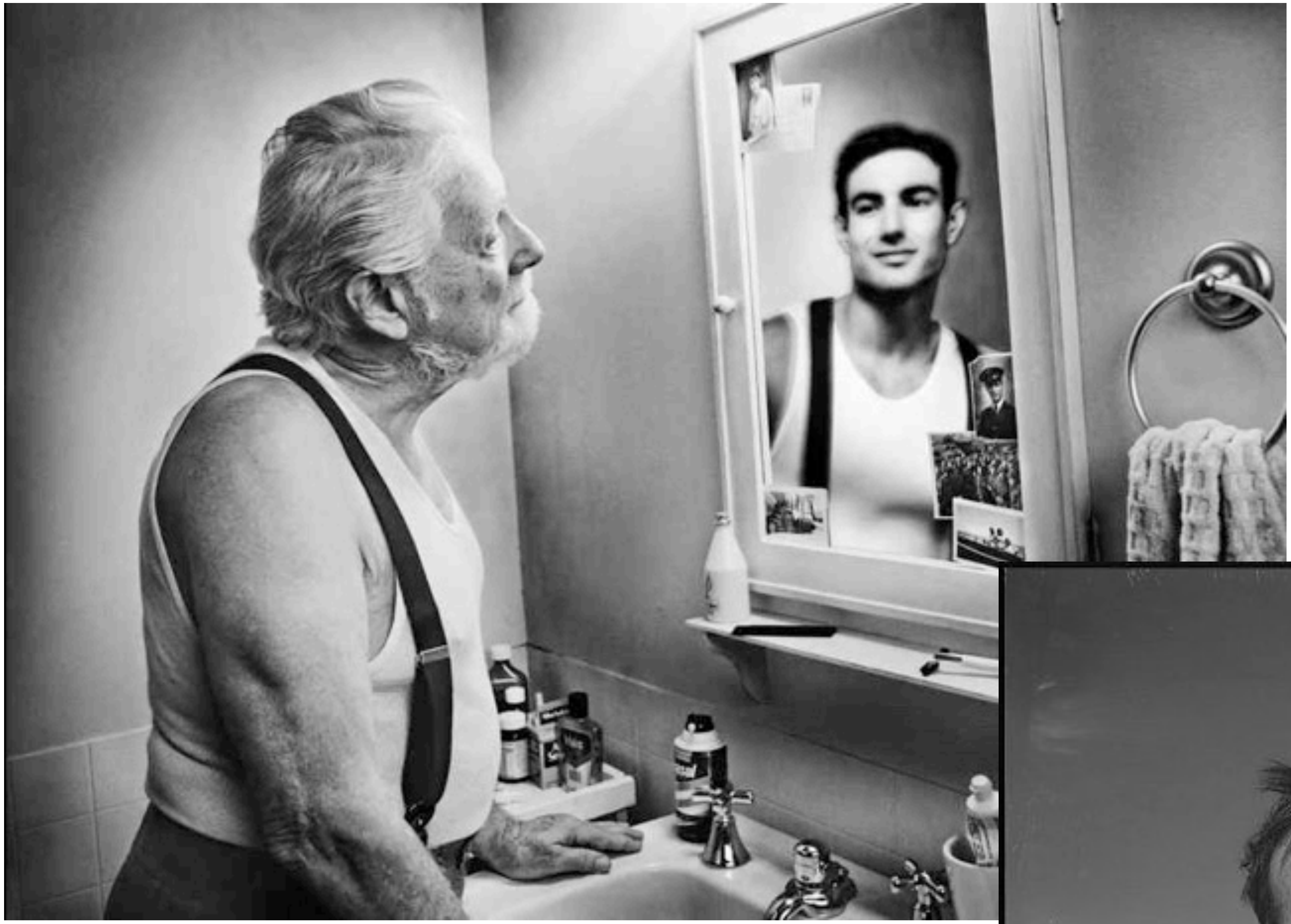
- Axions

- Axions and stars

- Axion Dark matter

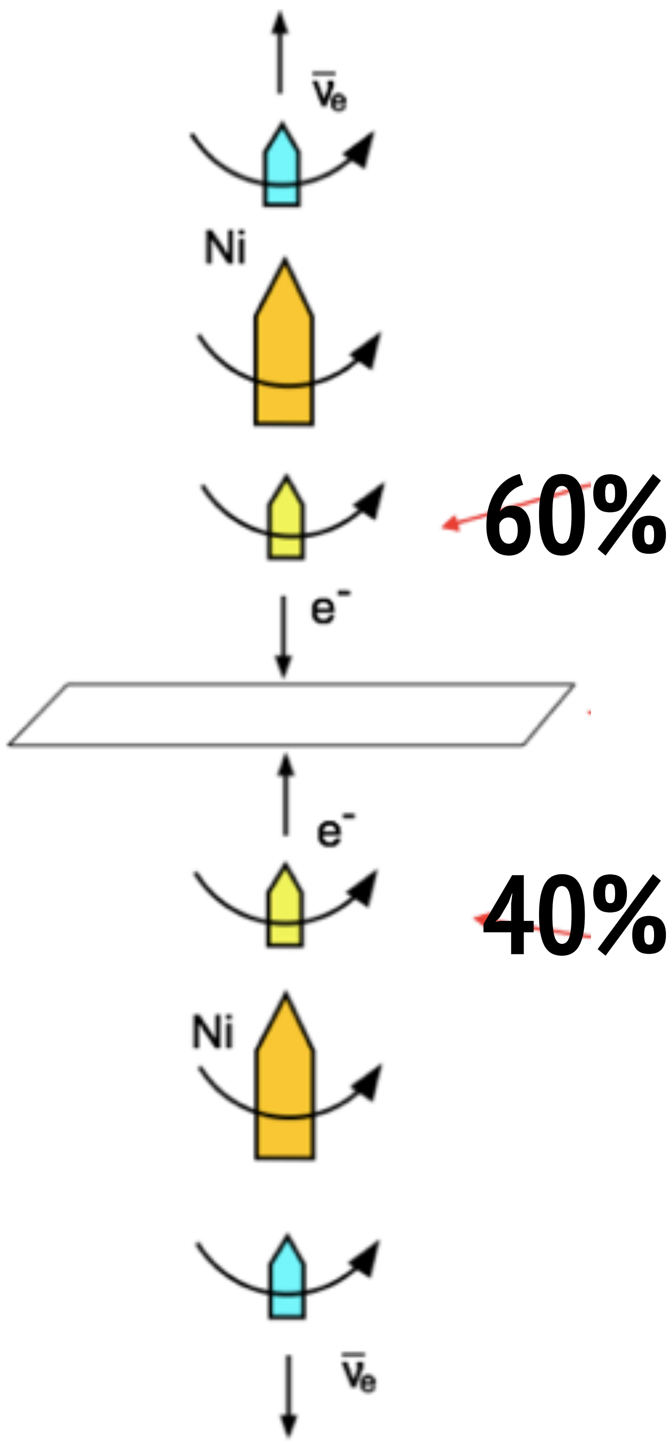
- Dark matter experiments

Parity and Time reversal



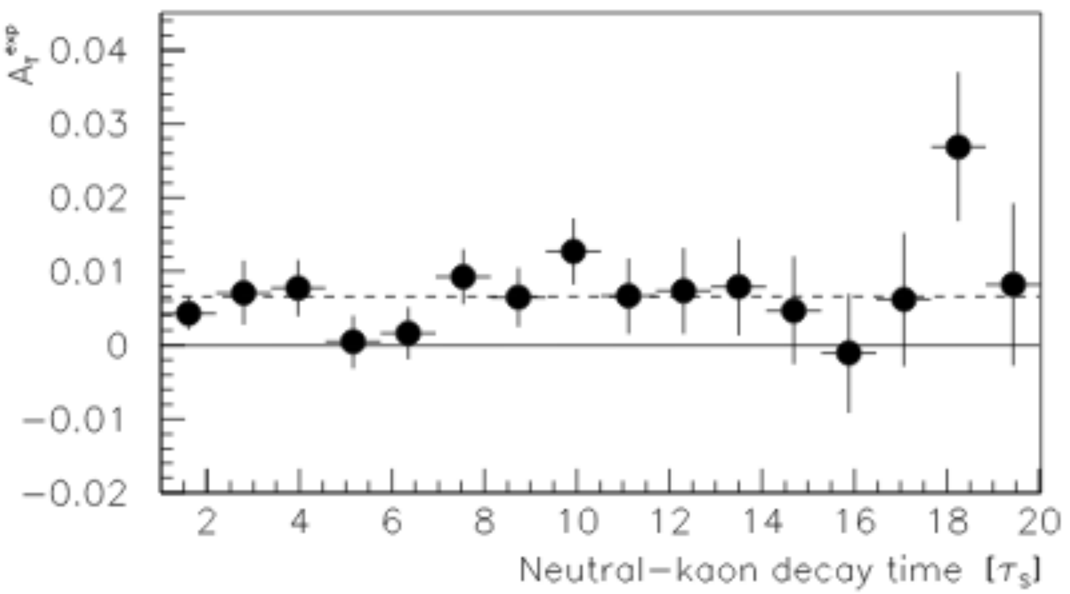
in particle physics (electroweak interactions)

P-violation (Wu 56)



T-violation (CPLEAR 90's)

$$\frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$



... but not in the strong interactions

many theories based on SU(3)c (QCD)

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q} m q + \frac{\alpha_s}{8\pi} \theta G_{\mu\nu a} \widetilde{G}_a^{\mu\nu}$$

P,T conserving — **P,T violating**

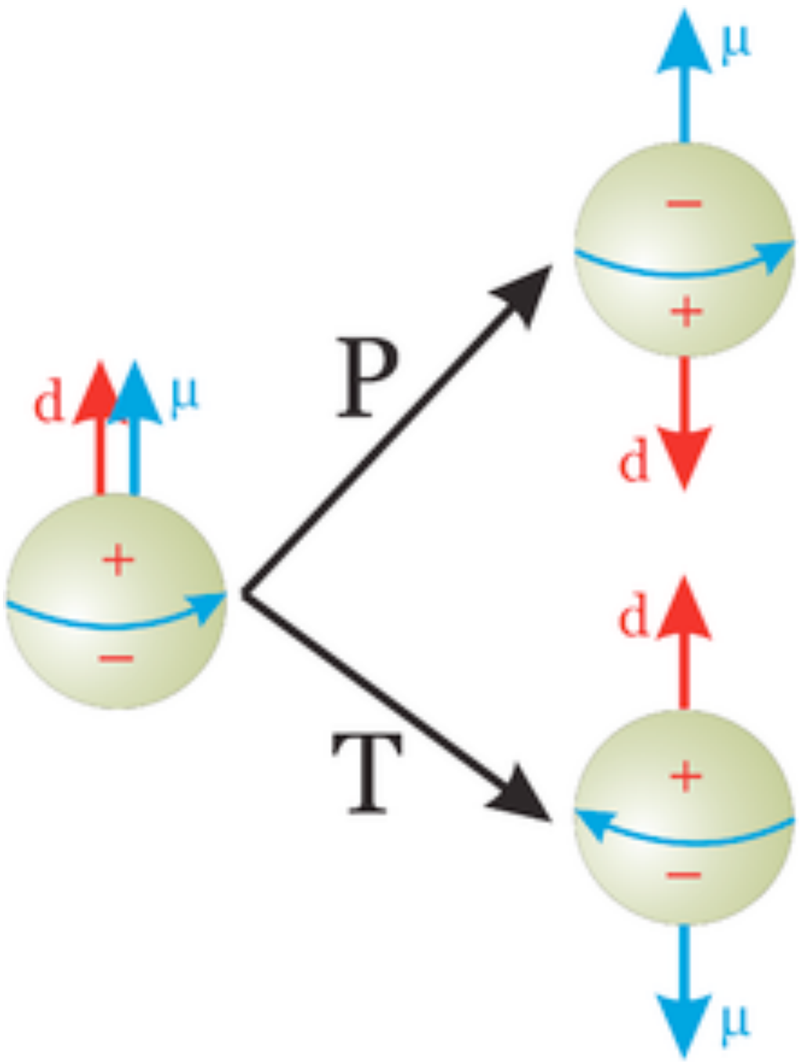
we tend to forget this

$\frac{\alpha_s}{8\pi} \theta G_{\mu\nu a} \widetilde{G}_a^{\mu\nu}$ **induces P and T (CP) violation** $\propto \theta$

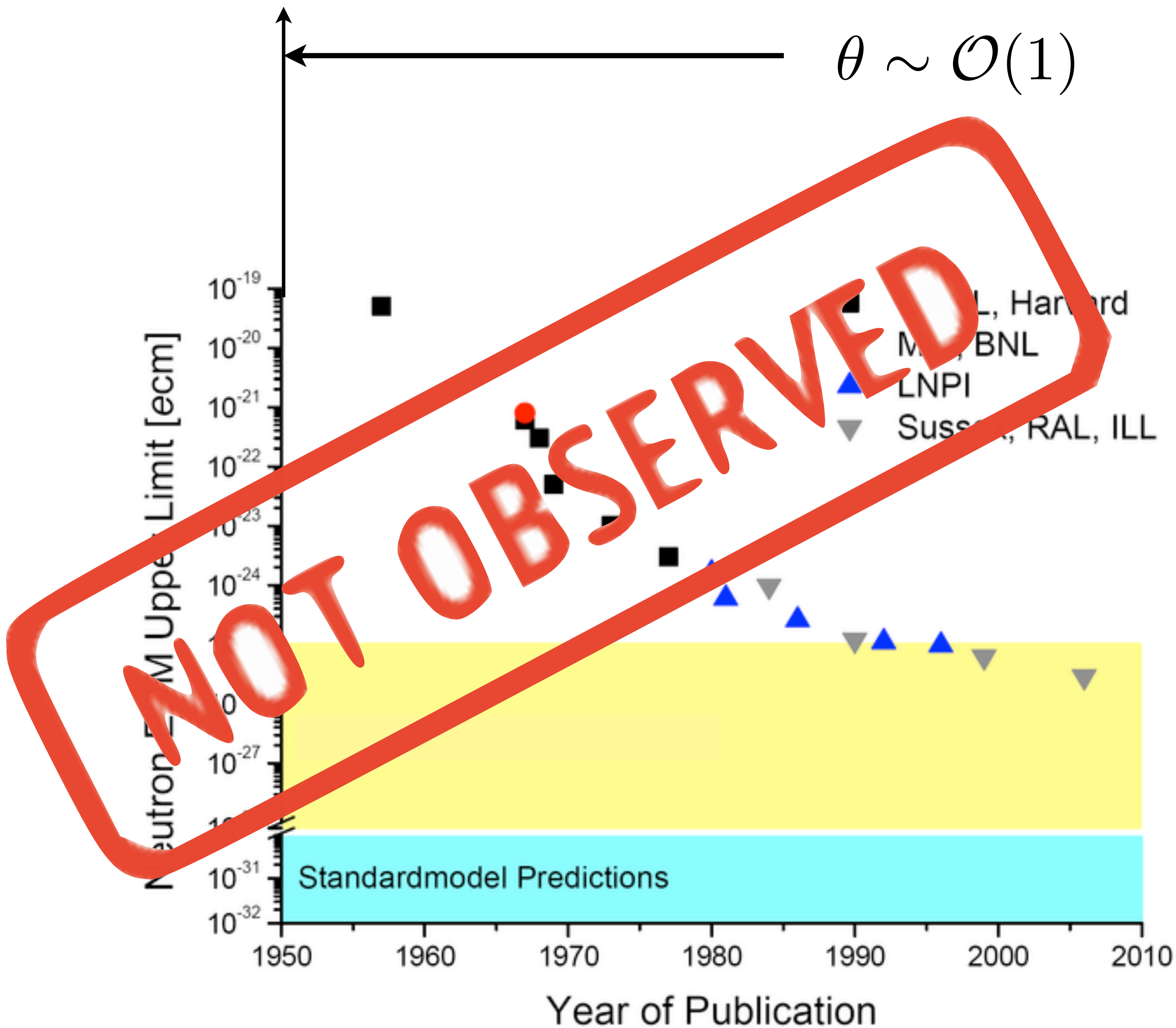
$\theta \in (-\pi, \pi)$ **infinitely versions of QCD... all are P,T violating**

Neutron EDM

Most important P, T violating observable $d_n \sim \theta \times \mathcal{O}(10^{-15})\mathrm{e\,cm}$

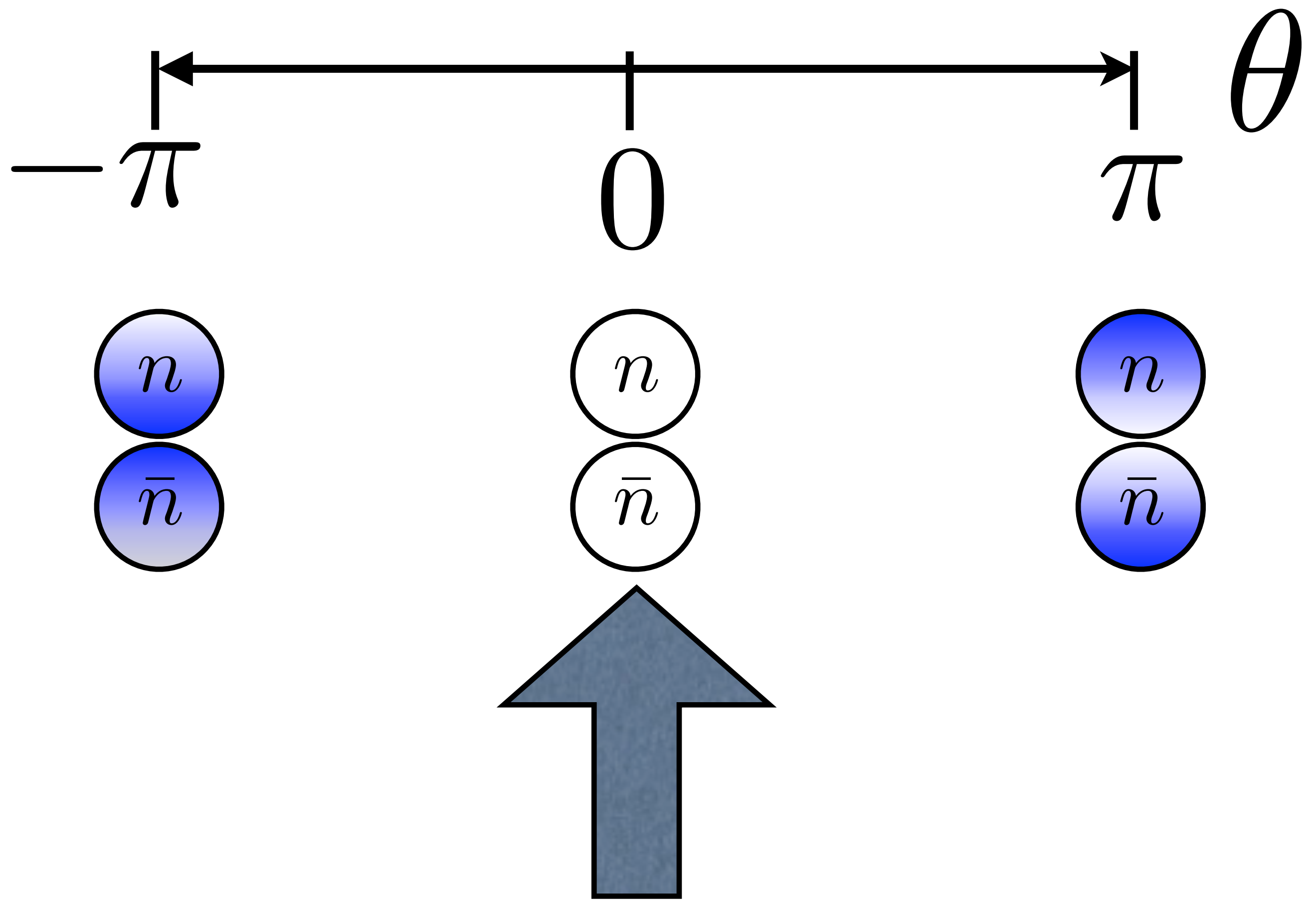


EDM violates P,T



The theta angle of the strong interactions

- The value of θ controls P,T violation in QCD



Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Roberto Peccei and Helen Quinn 77

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a

grangian.

If all fermions which couple to the non-Abelian

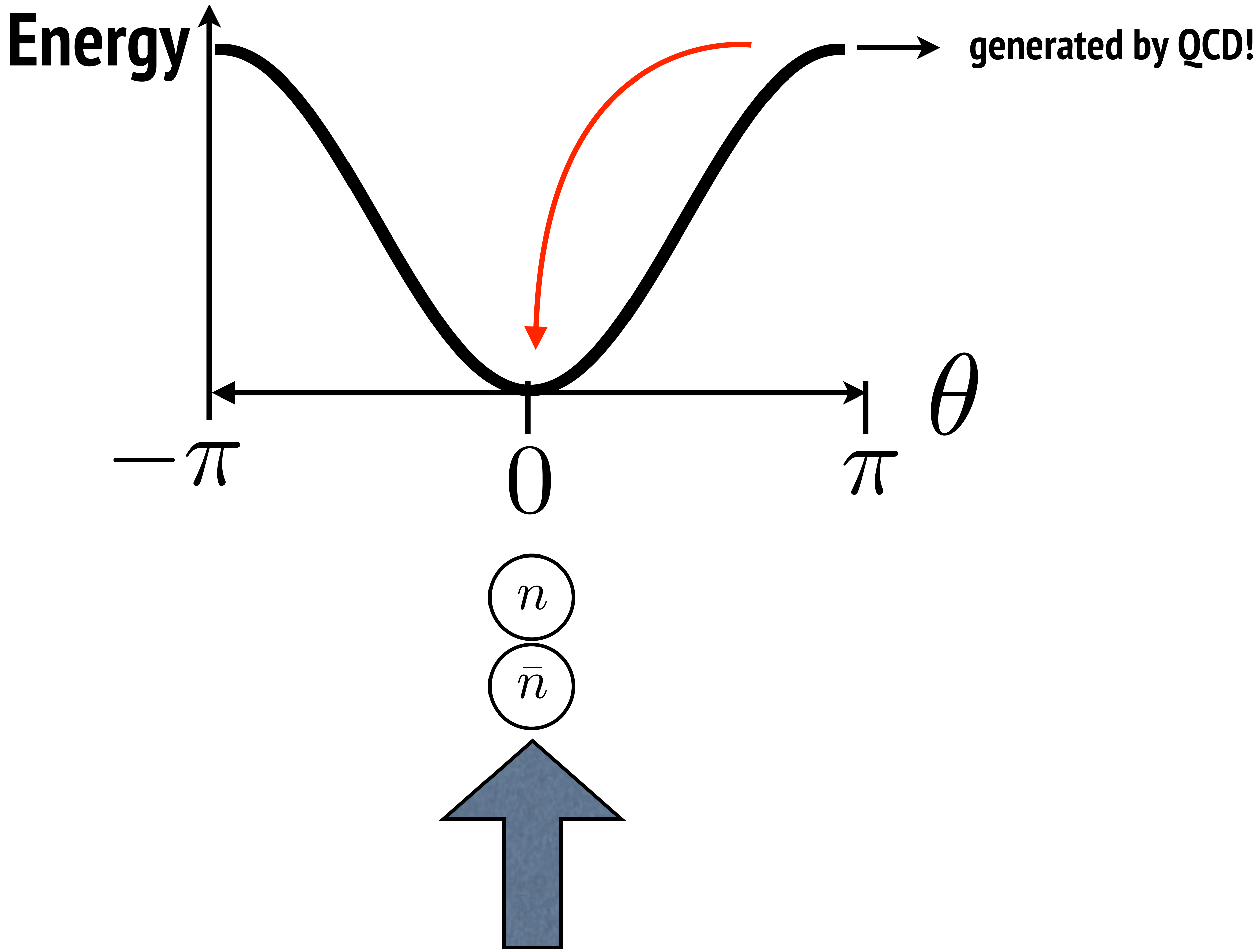
(1)

(2)

(3)

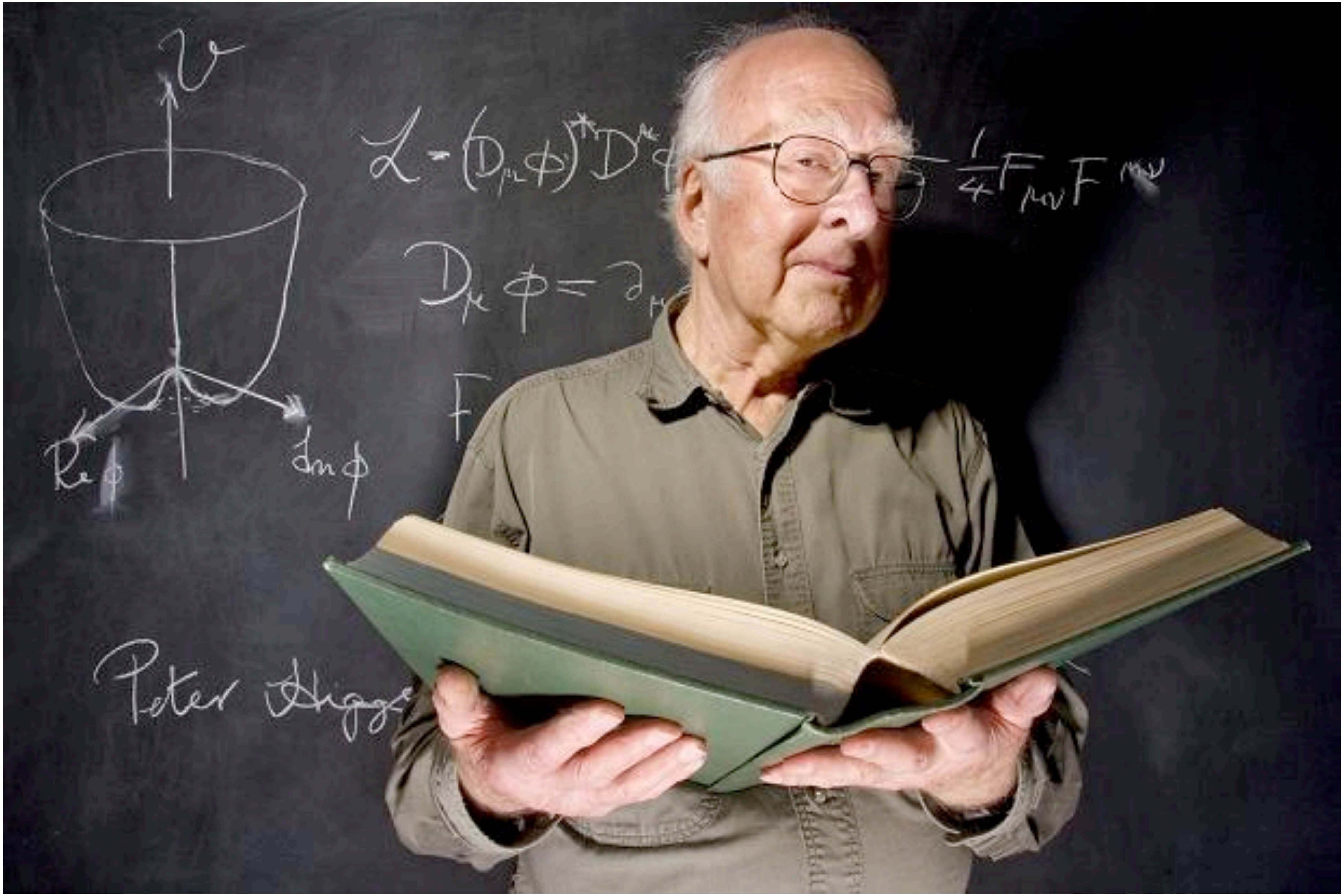
QCD vacuum energy minimised at theta = 0

- ... if $\theta(t, \mathbf{x})$ is dynamical field, relaxes to its minimum



Measured today $|\theta| < 10^{-10}$ (strong CP problem)

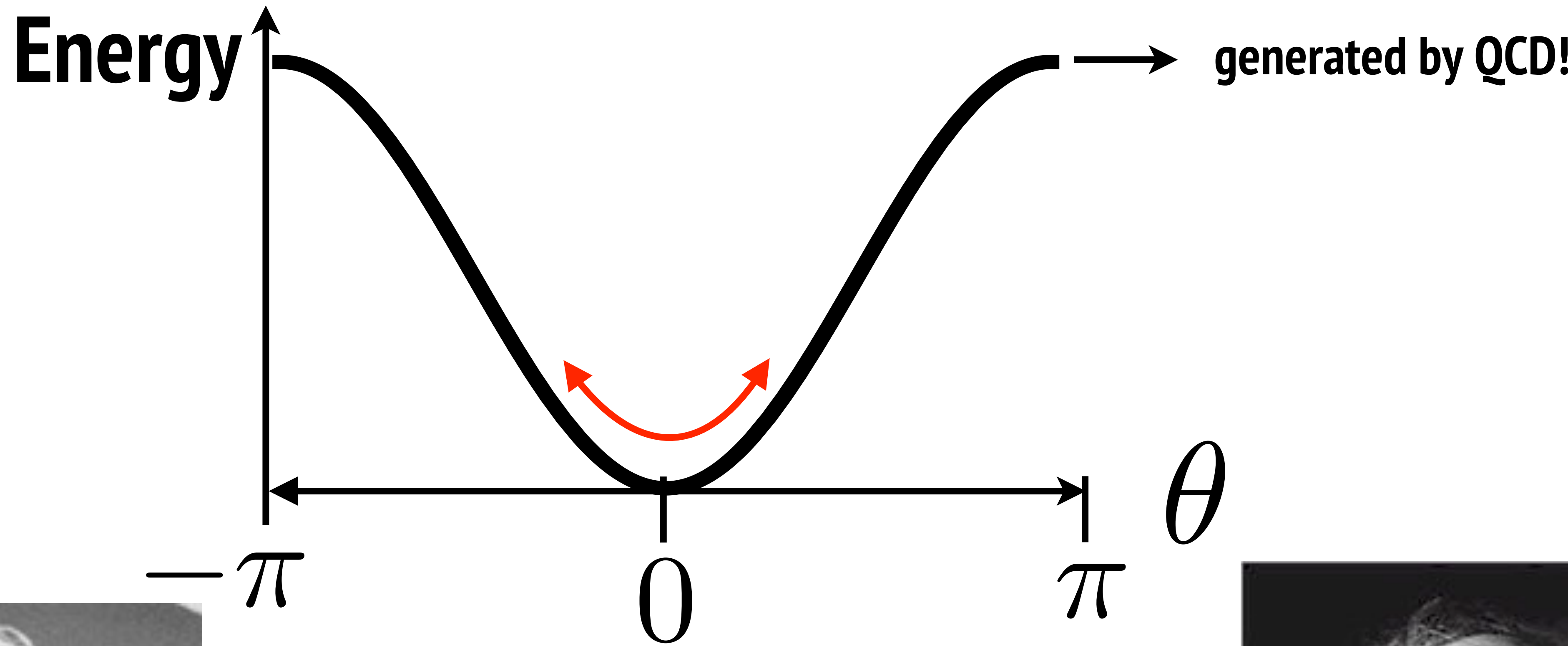
ain’t you forgetting something?



P. Higgs

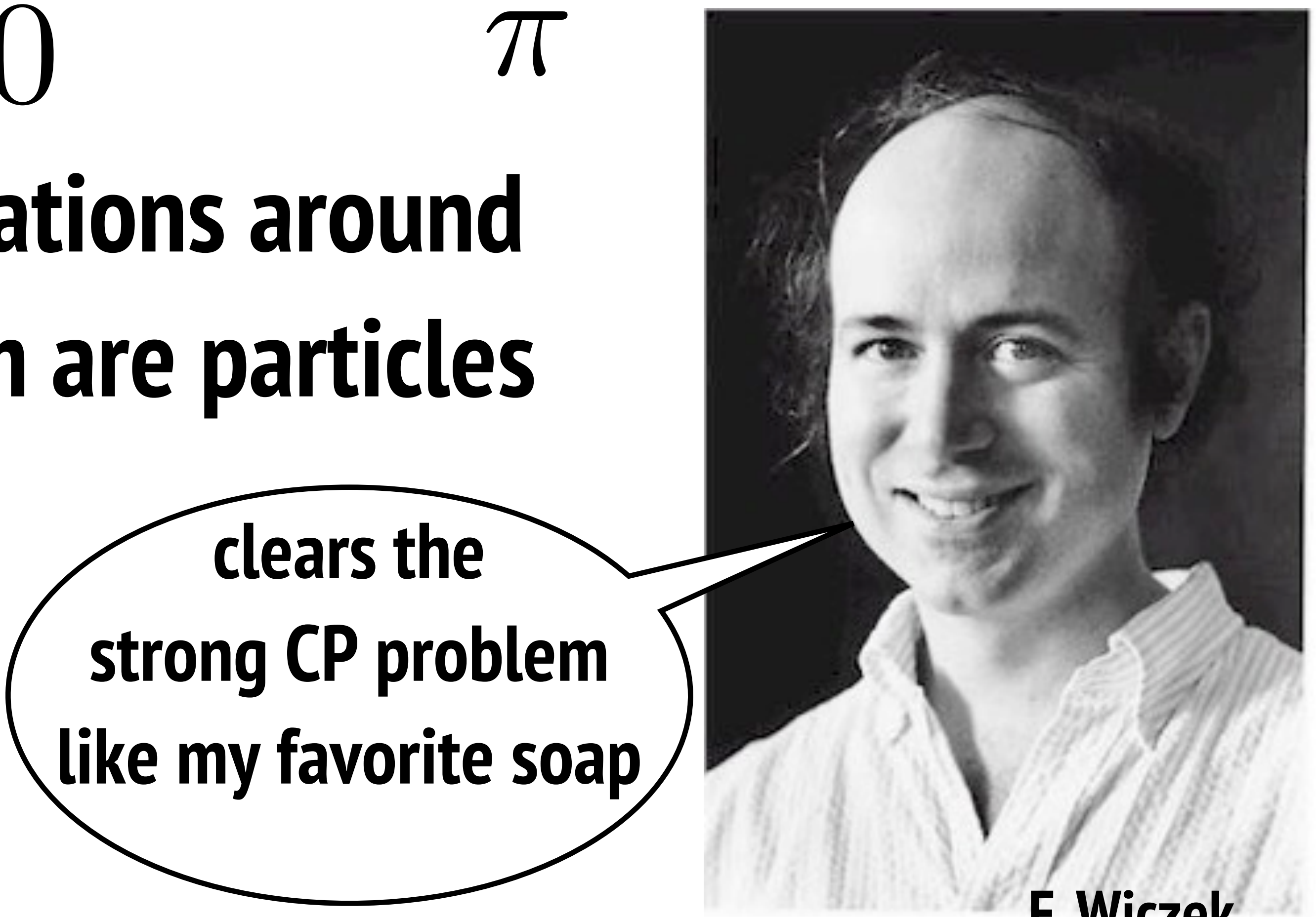
and a new particle is born ...

- if $\theta(t, \mathbf{x})$ is dynamical field



Field Excitations around the vacuum are particles

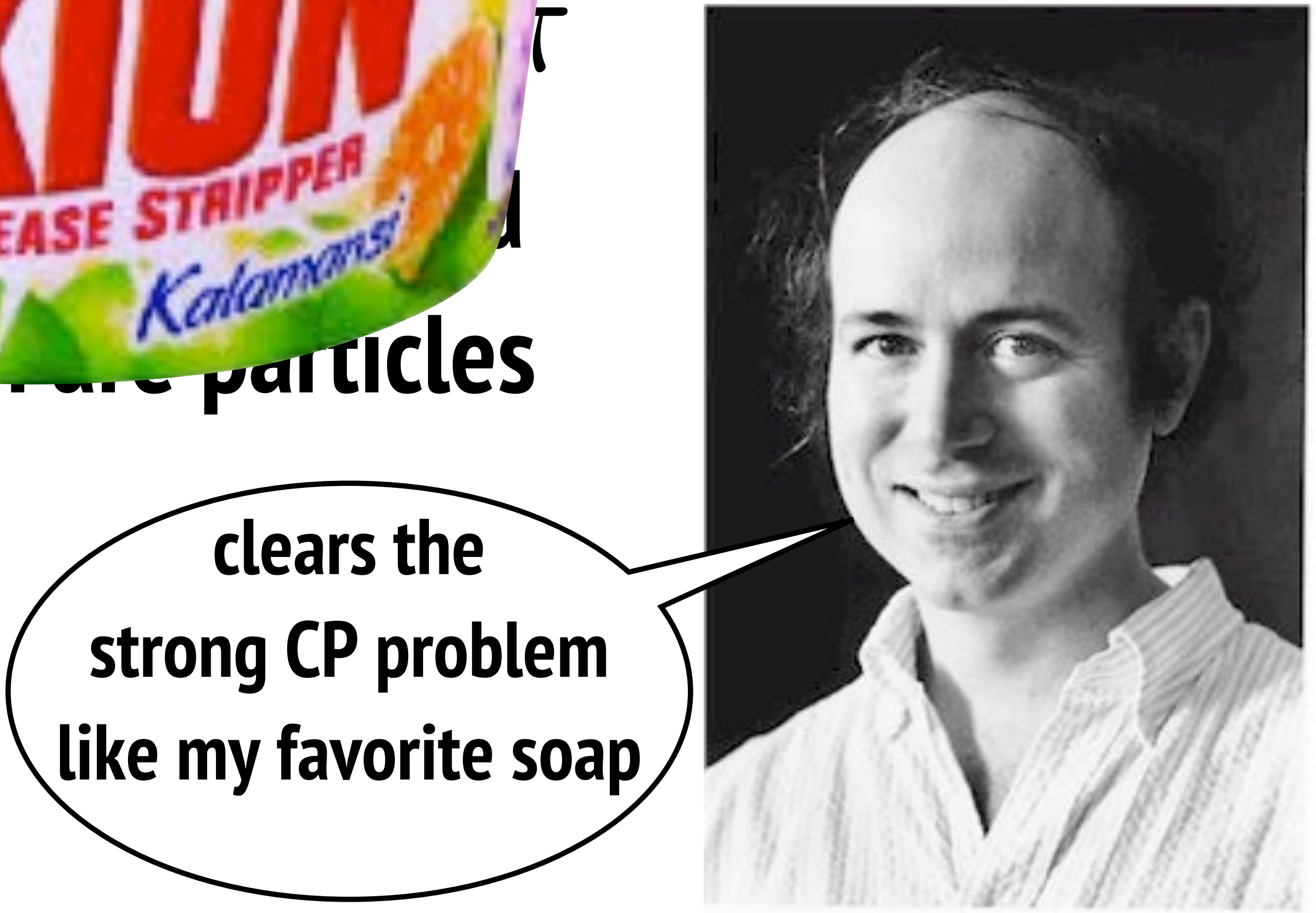
S. Weinberg



F. Wiczek

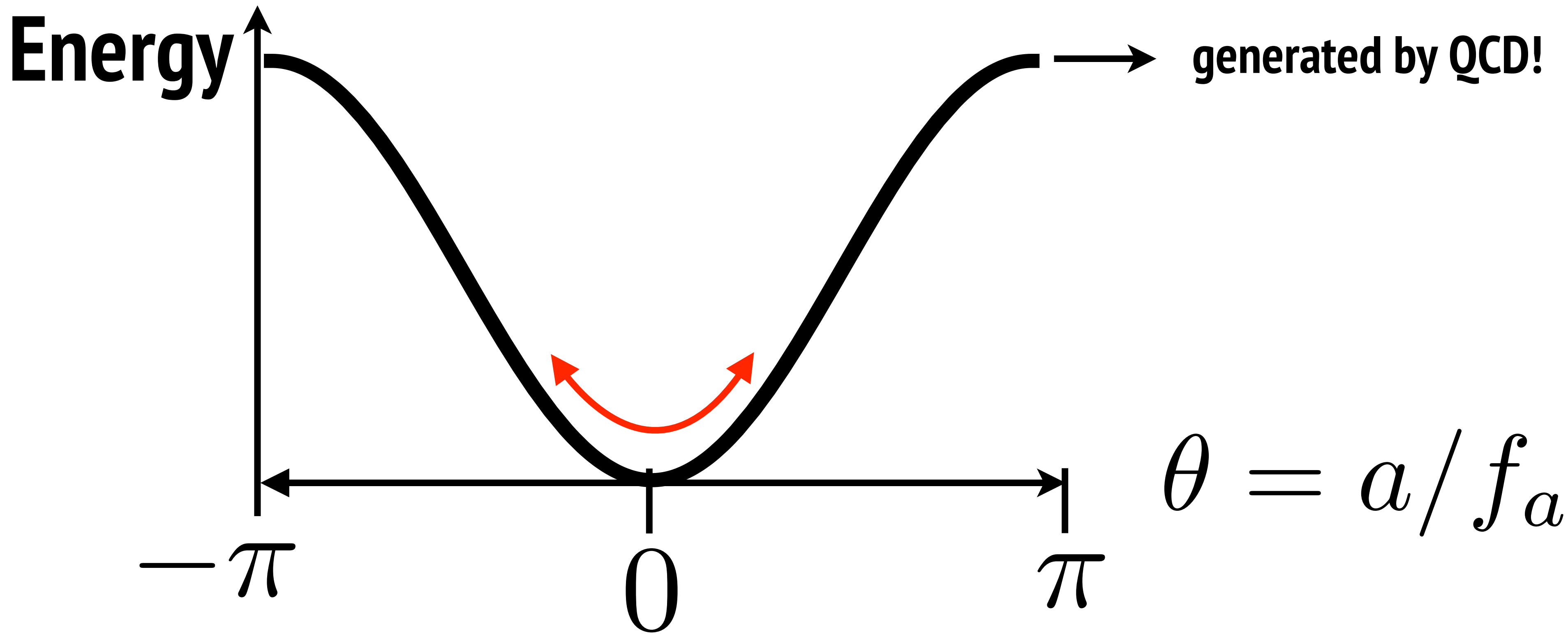
and a new particle is born ... the axion

- if $\theta(t, \mathbf{x})$ is dynamical field



and a new scale sets the game, fa

- kinetic term for θ requires a new scale



$$\theta = a/f_a$$

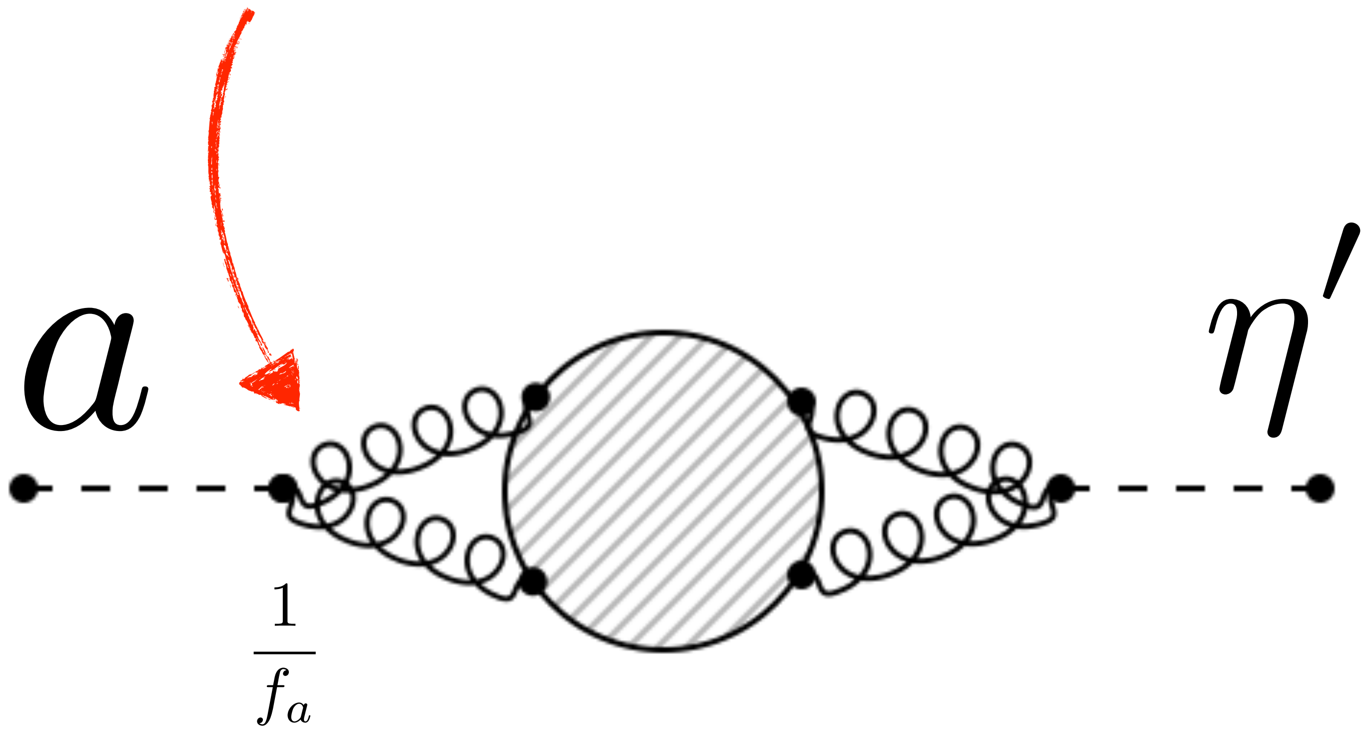
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}^{\mu\nu}_a \theta + \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f_a^2$$

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}^{\mu\nu}_a \frac{a}{f_a} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a)$$

Axion couplings at low energy

- From θ-term, axion mixes with eta' and the rest of mesons

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a}\widetilde{G}^{\mu\nu}_a \frac{a}{f_a} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a)$$

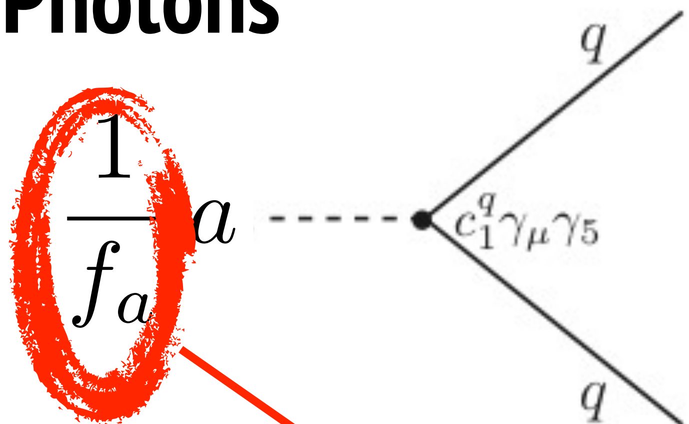


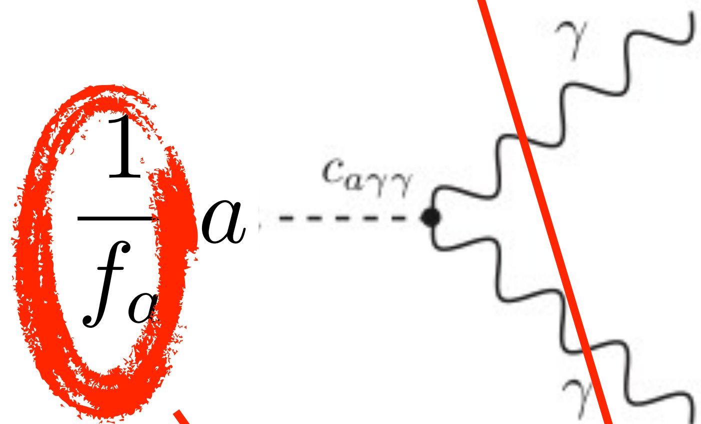
Axion couplings at low energy

Mass

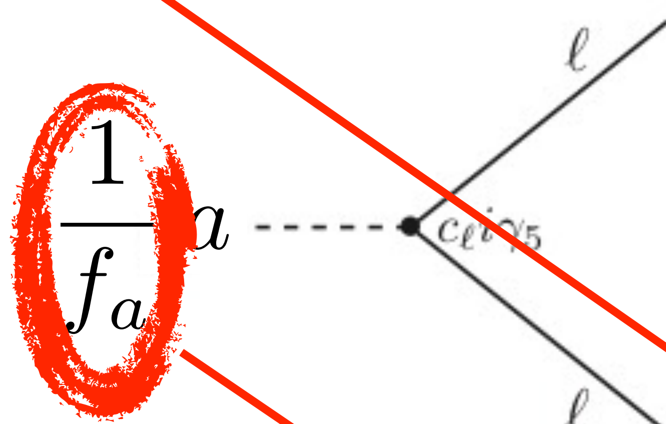
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6\ \mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a}$$

hadrons, Photons



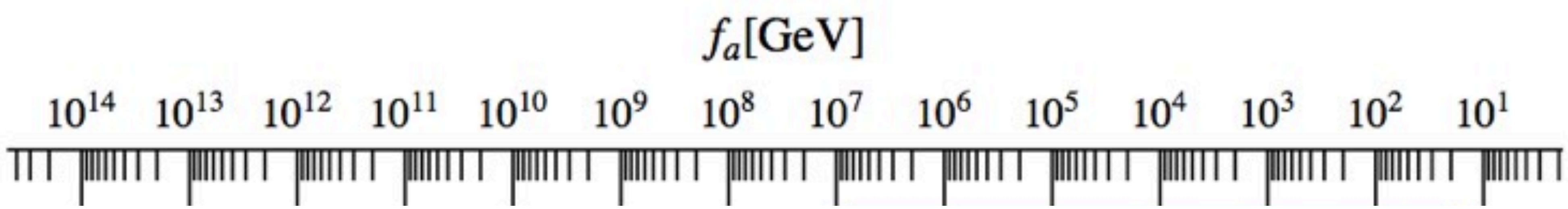


Leptons (in some models)



The lighter the more weakly interacting

Axion Landscape

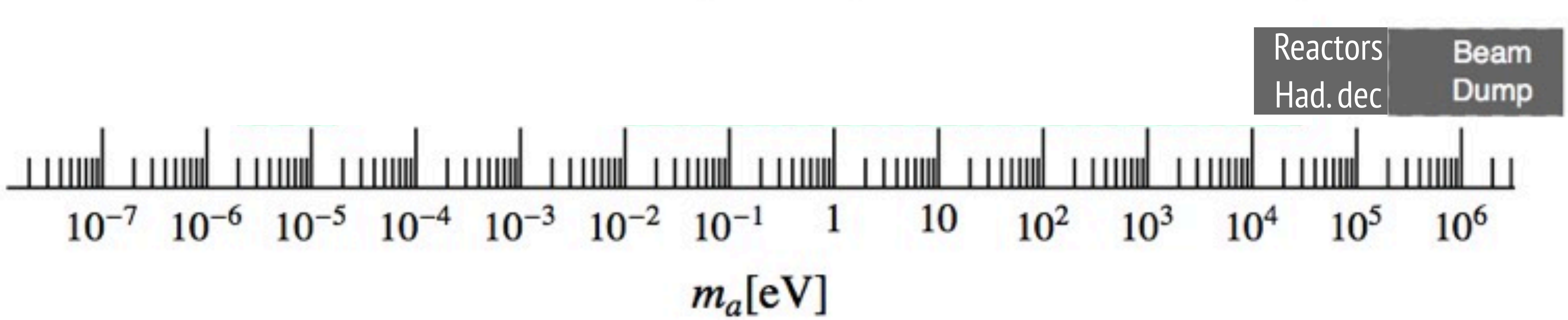


$$f_a \gg v_{\rm EW}$$

Invisible models

$$f_a \sim v_{\rm EW}$$

PQWW models

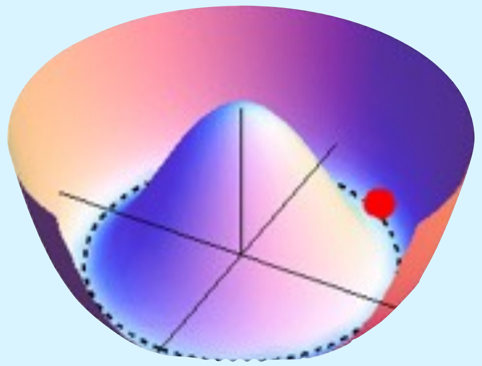


Simple model KSVZ

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

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

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

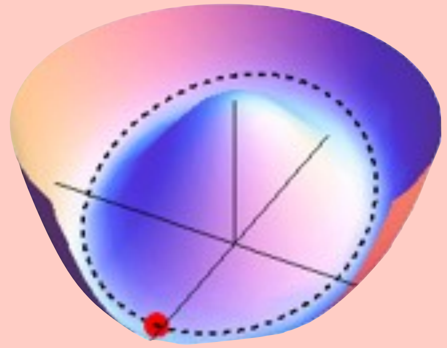


- At energies below f_a **(SSB)**

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

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

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



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

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

~f_a

~GeV

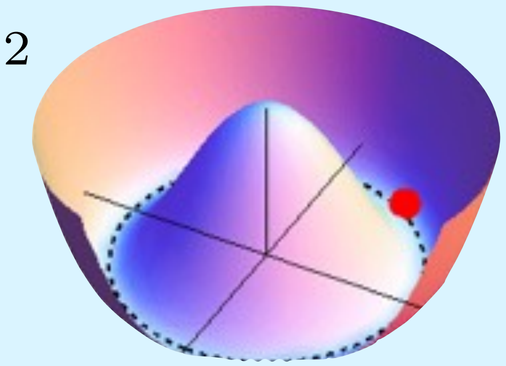
ENERGY

DFSZ

- Two Higgs, one new scalar

f_a

$$\mathcal{L} \in D\bar{q}_L H_d q_R + U\bar{q}_L \tilde{H}_u u_R + \ldots - \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2 + \lambda H_d^\dagger H_u \Phi^2$$



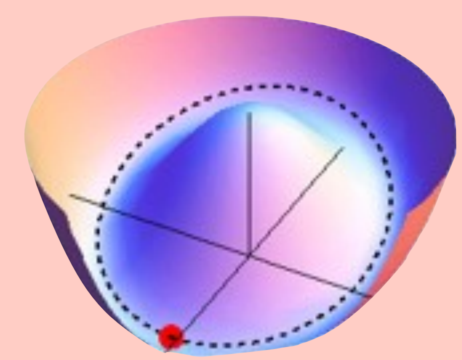
axion $\theta \sim \theta_\Phi + \cos^2\beta\theta_d + \sin^2\beta\theta_u$

- Below f_a

$$\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi} G\widetilde{G}\frac{a}{f_a}N_g + \sum_f C_f \bar{f}\gamma^\mu\gamma_5 f \frac{\partial_\mu a}{f_a}$$

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

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

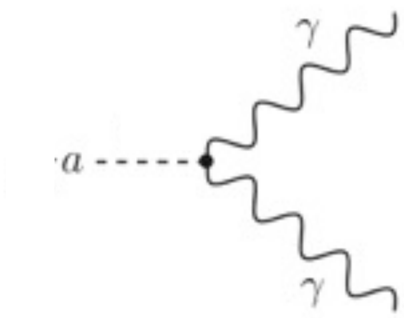
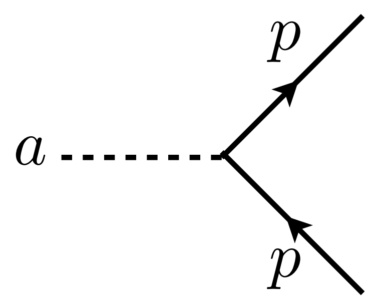
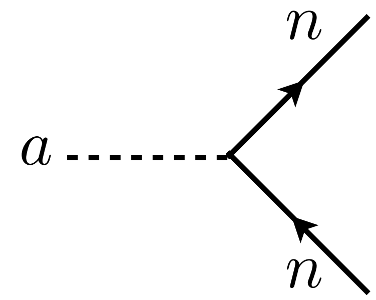
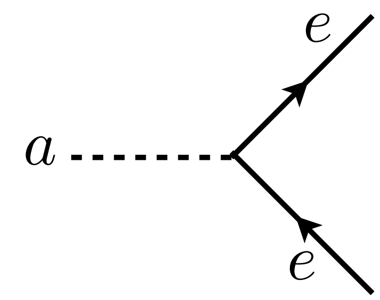


couplings $\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \ldots$

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

ENERGY ~GeV $\sim f_a$

Axion Couplings and some models

	2 photon	proton	neutron	electron
$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu}\widetilde{G}^{\mu\nu} + \text{m.d.} \rightarrow$	$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ +	$C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
				

$$C_{a\gamma} \simeq \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}$$

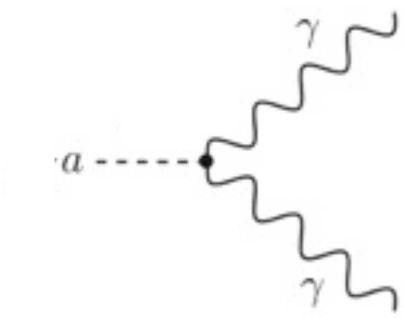
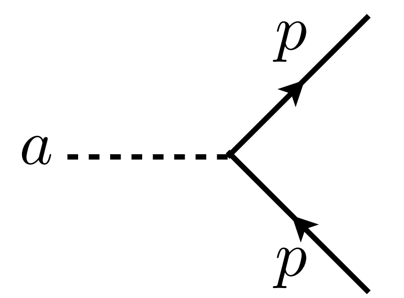
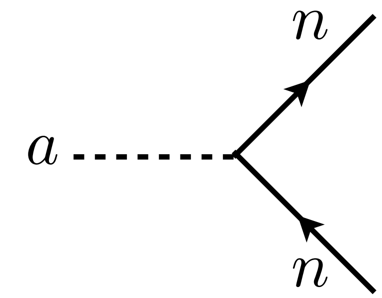
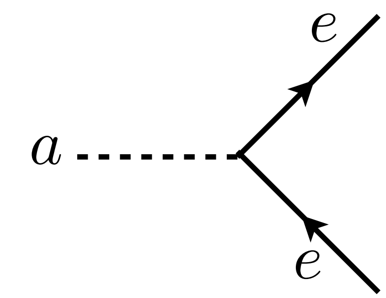
$$C_{ap} \simeq [C_{au} - \frac{m_d}{m_u + m_d}]\Delta u + [C_{ad} - \frac{m_u}{m_u + m_d}]\Delta d$$

$$C_{an} \simeq [C_{au} - \frac{m_d}{m_u + m_d}]\Delta d + [C_{ad} - \frac{m_u}{m_u + m_d}]\Delta u$$

Model	Couplings	2 photon	proton	neutron	electron
KSVZ	$C_{a(u,d,e)} = 0$	$C_{a\gamma} \simeq -1.92$	(-0.5;-0.38)	(0.1;-0.04)	~ 0
DFSZ1	$C_{au} = \frac{1}{3}\sin^2\beta$ $C_{a(d,e)} = \frac{1}{3}\cos^2\beta$	$C_{a\gamma} \simeq \frac{8}{3} - 1.92$	...	...	...
DFSZ2	$C_{a(u,e)} = \frac{1}{3}\sin^2\beta$ $C_{ad} = \frac{1}{3}\cos^2\beta$	$C_{a\gamma} \simeq \frac{2}{3} - 1.92$	...	...	...

Axion Couplings and some models

$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu}\widetilde{G}^{\mu\nu} + \text{m.d.} \rightarrow$

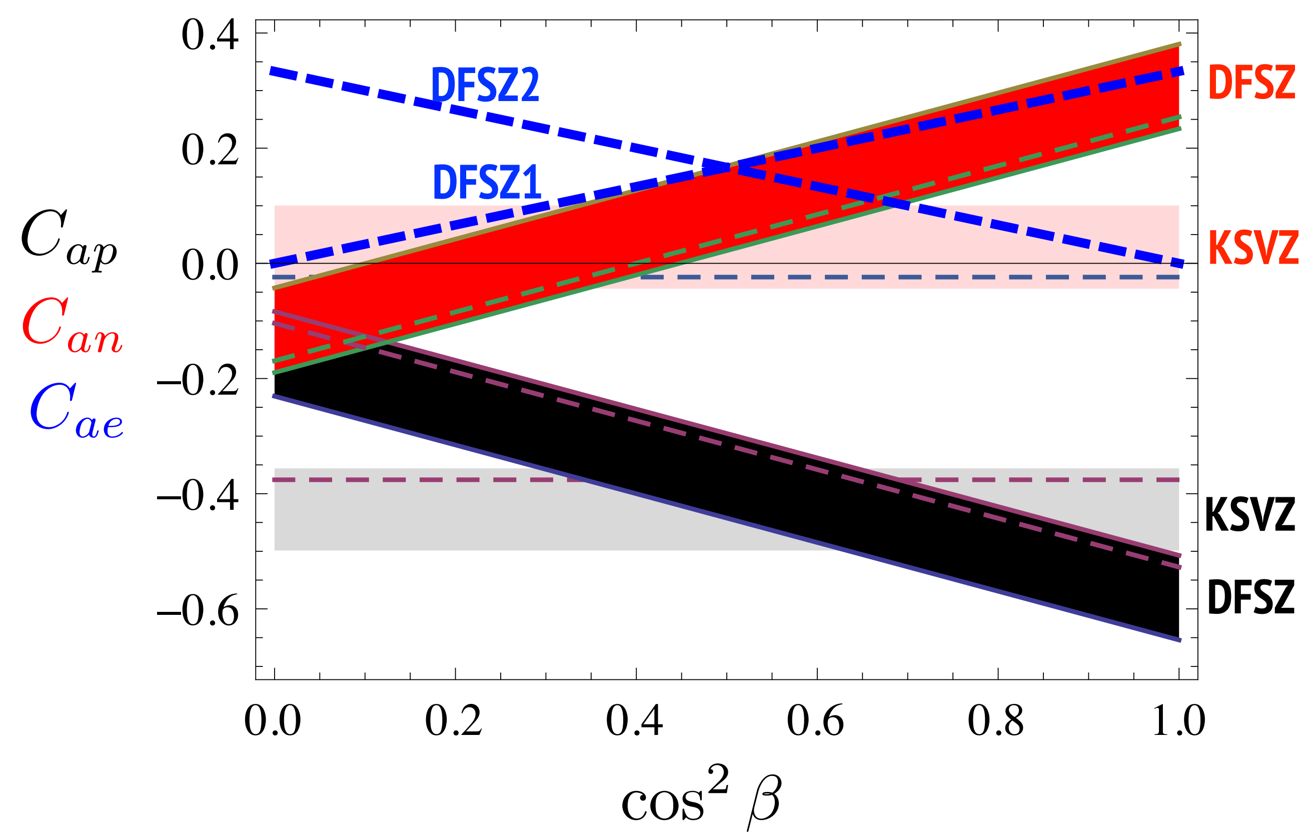
2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ +	$C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p]$ +	$C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$ +	$C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e]$ +
			

$$C_{a\gamma} \simeq \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}$$

$C_{ap} \simeq [C_{au} - \frac{\ldots}{m_{\ldots}}$ …

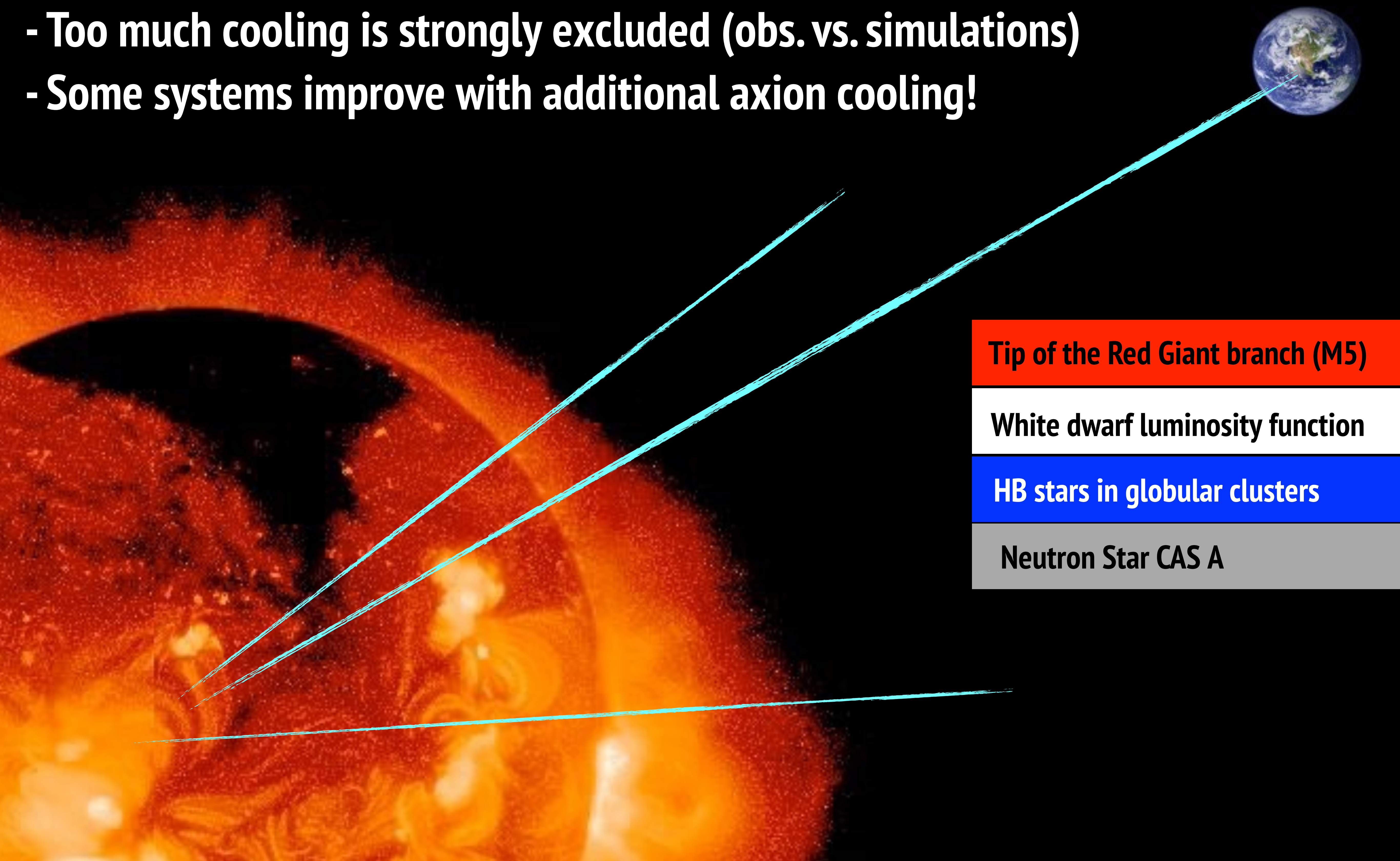
$C_{an} \simeq [C_{au} - \frac{\ldots}{m_{\ldots}}$ …

KSVZ	$C_{a(u,d,e)} = 0$	$C_{a\gamma} \simeq -1.92$
DFSZ1	$C_{au} = \frac{1}{3}\sin^2\beta$ $C_{a(d,e)} = \frac{1}{3}\cos^2\beta$	$C_{a\gamma} \simeq \frac{8}{3} - 1.92$
DFSZ2	$C_{a(u,e)} = \frac{1}{3}\sin^2\beta$ $C_{ad} = \frac{1}{3}\cos^2\beta$	$C_{a\gamma} \simeq \frac{2}{3} - 1.92$



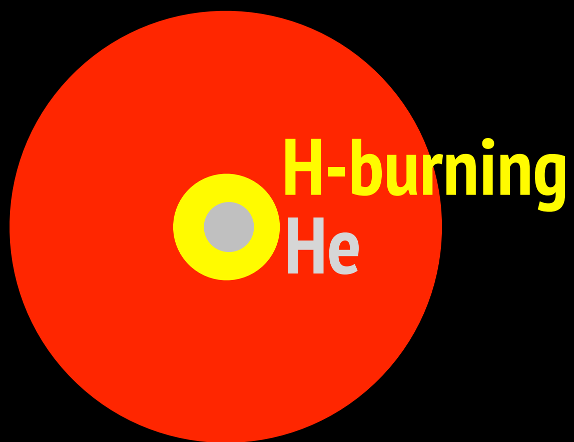
Bounds and hints from astrophysics

- Axions emitted from stellar cores accelerate stellar evolution
- Too much cooling is strongly excluded (obs. vs. simulations)
- Some systems improve with additional axion cooling!

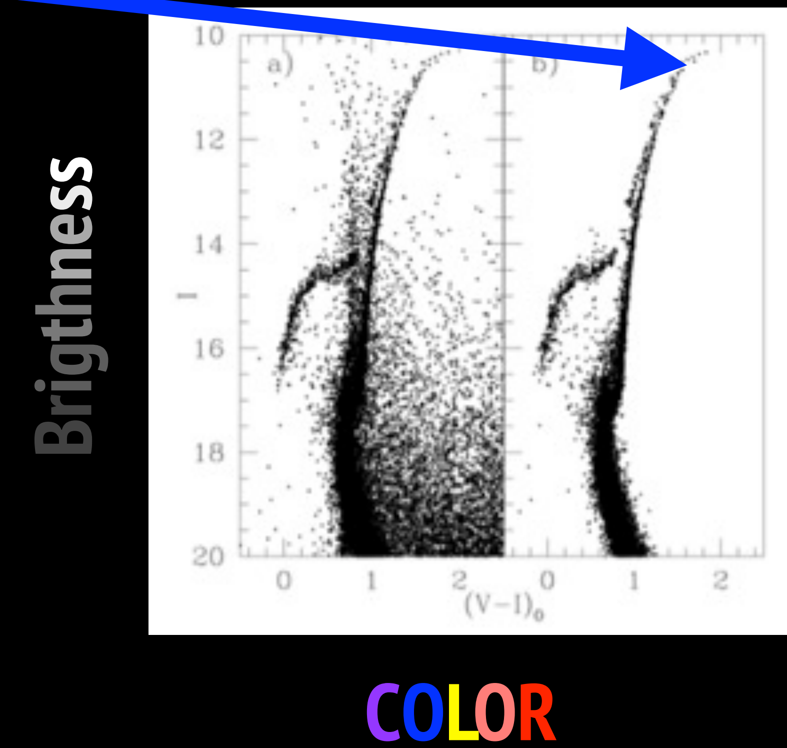


Tip of the Red Giant branch (M5)

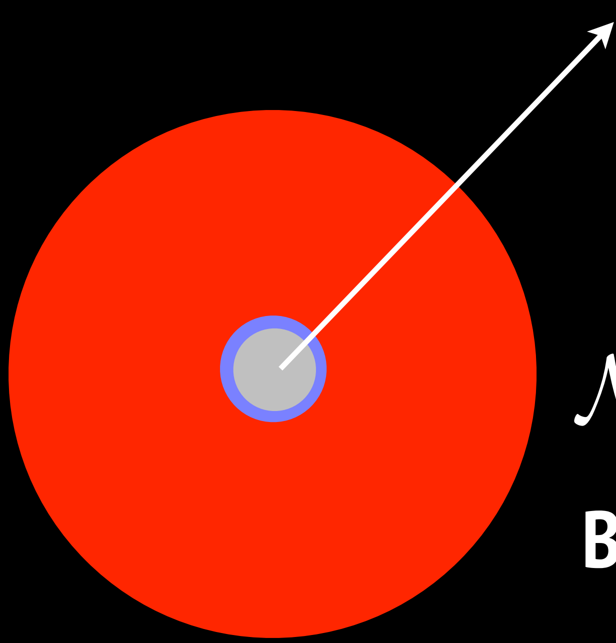
Increase He core until 3alpha ignition (T~8.6 KeV)

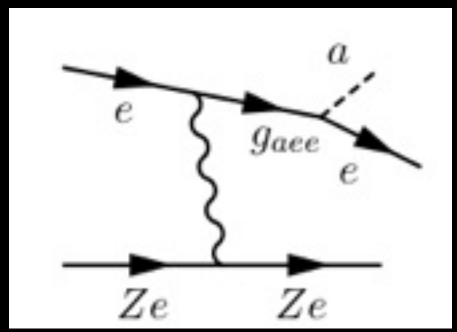


Globular ClusterM5



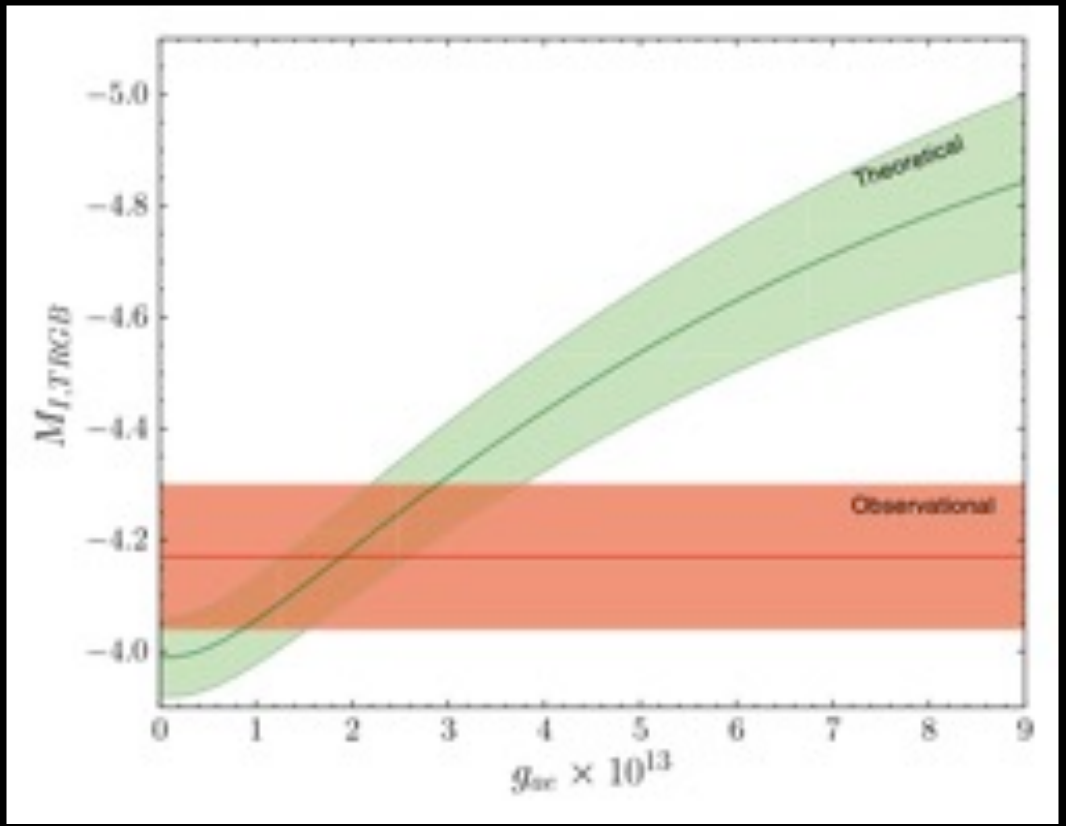
Axion emission cools down core, delays ignition





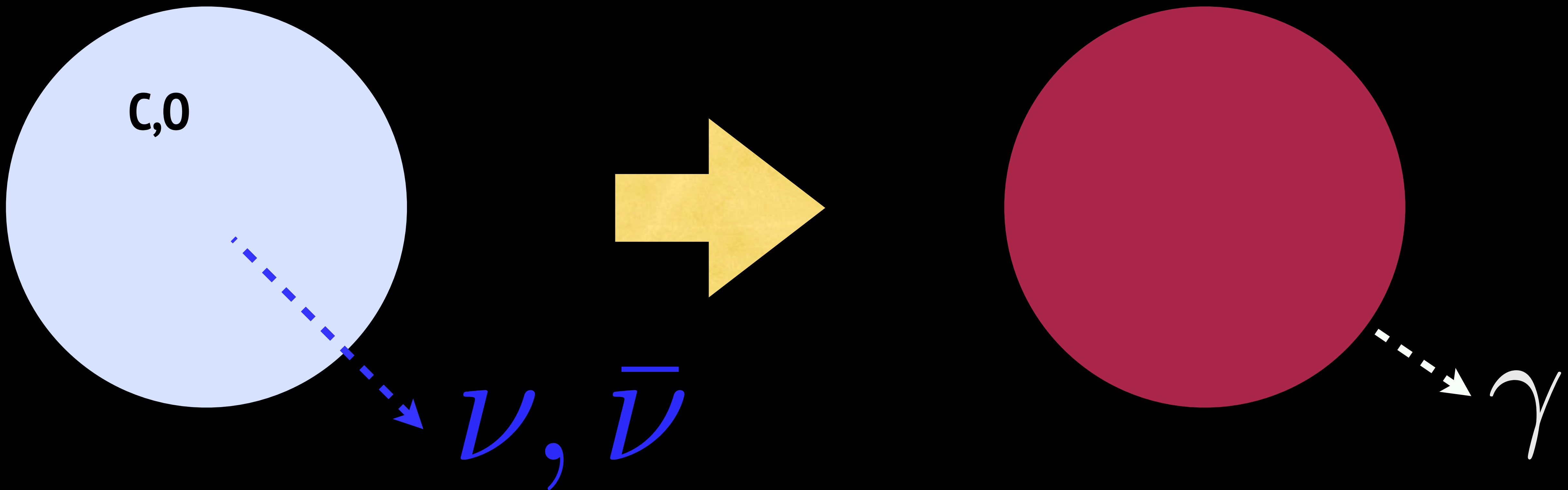
$$\mathcal{M}_{\rm core}\uparrow, T_{\rm H}\uparrow, \mathcal{L}\uparrow$$

Brighter Helium flash!



Strong constraint, small hint!

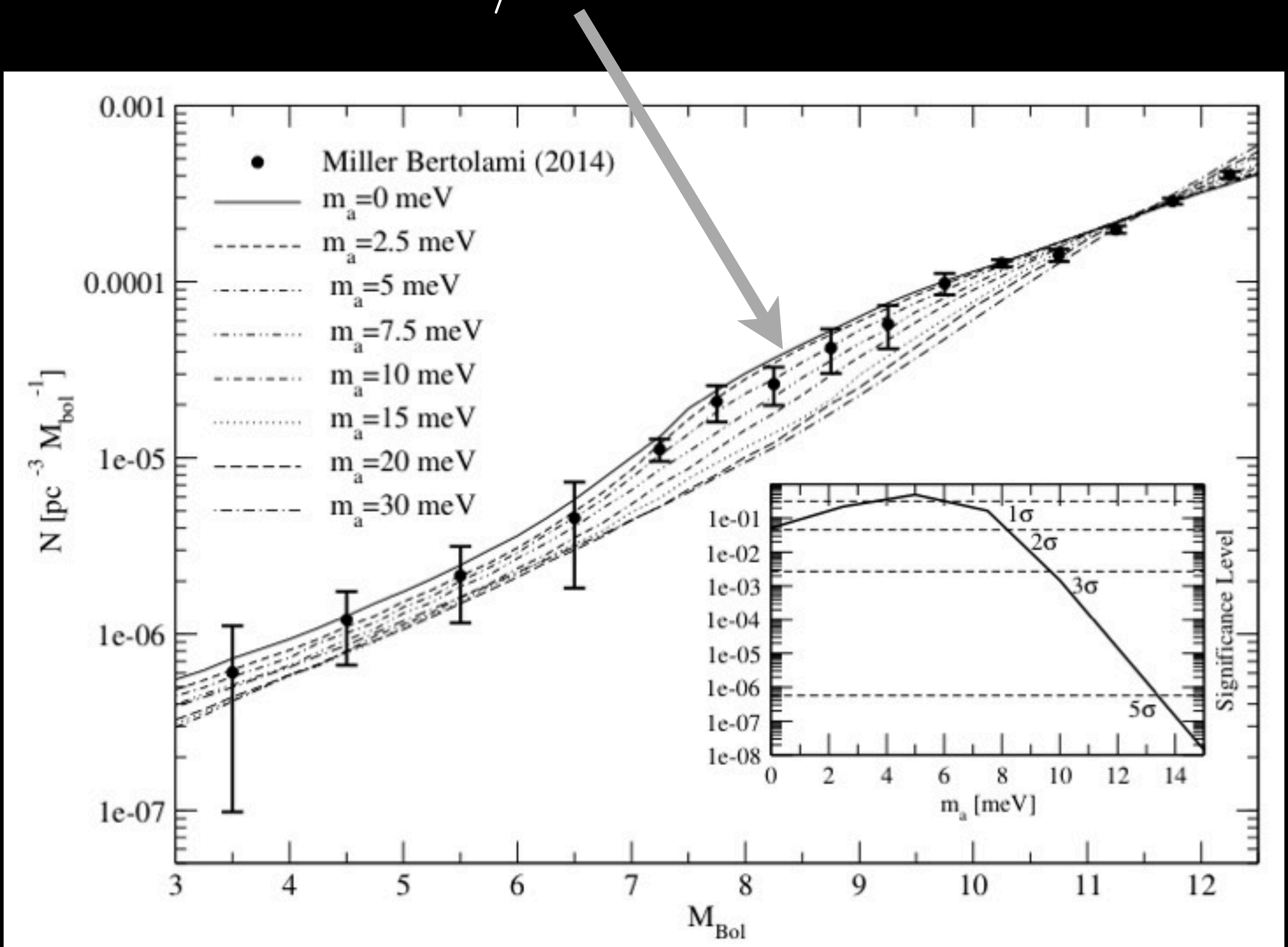
White dwarf luminosity function



- White dwarfs are death stars (sustain no fusion)
- final phase of intermediate mass stars which cannot fuse C and O (Sun...)
- Cool by 1) neutrino emission and 2) by photon surface emission

White dwarf luminosity function

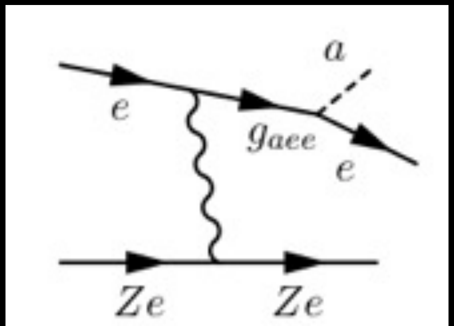
$$\frac{d\,N_{\mathrm{WD}}}{\mathrm{Vol}\,d\mathcal{L}} = \frac{k}{d\mathcal{L}/dt}$$

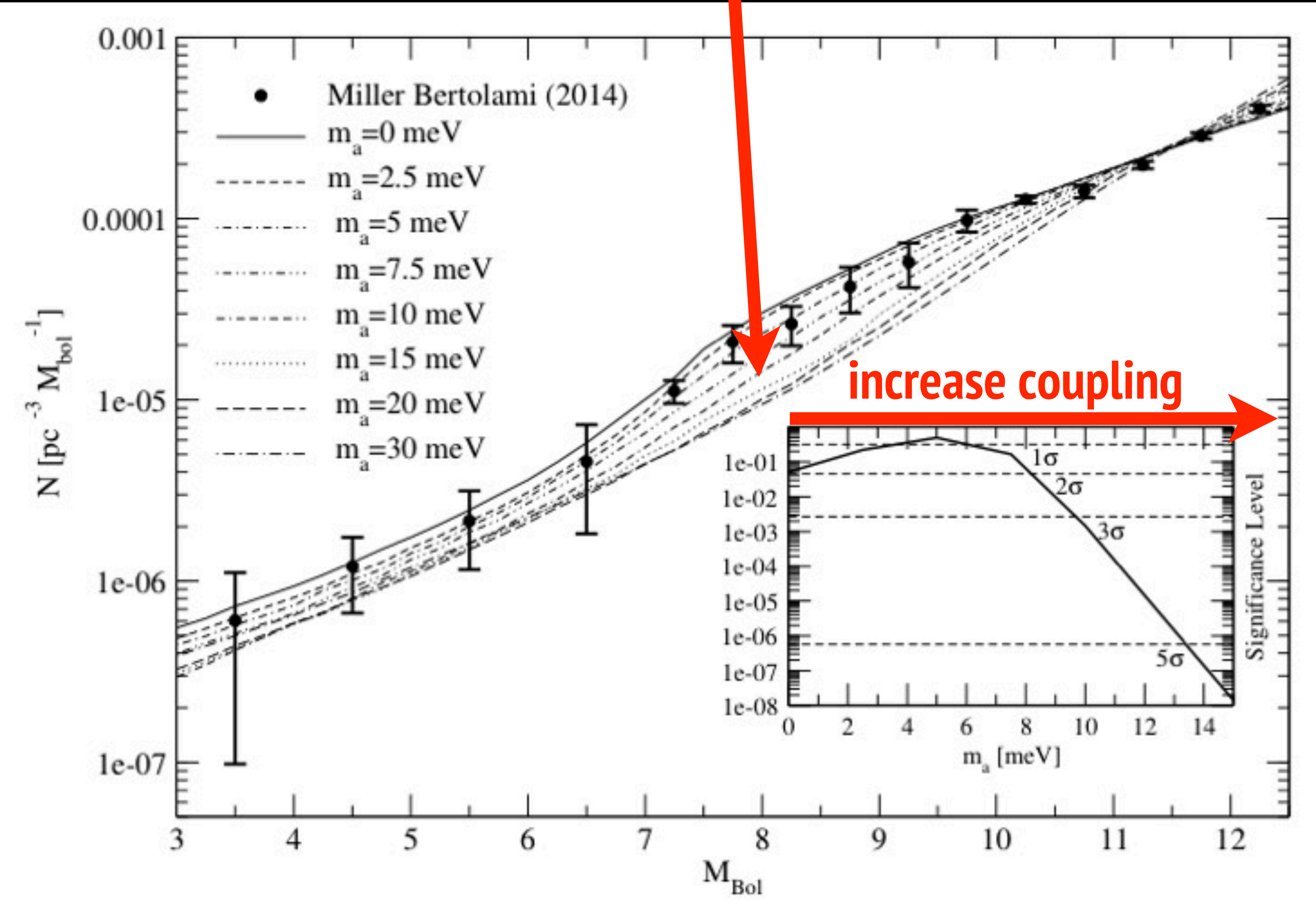


White dwarf luminosity function

$$\frac{d\,N_{\rm WD}}{{\rm Vol}\,d\mathcal{L}} = \frac{k}{d\mathcal{L}/dt + d\mathcal{L}_a/dt}$$

with axion-electron bremsstrahlung





Strong constraint, small hint!

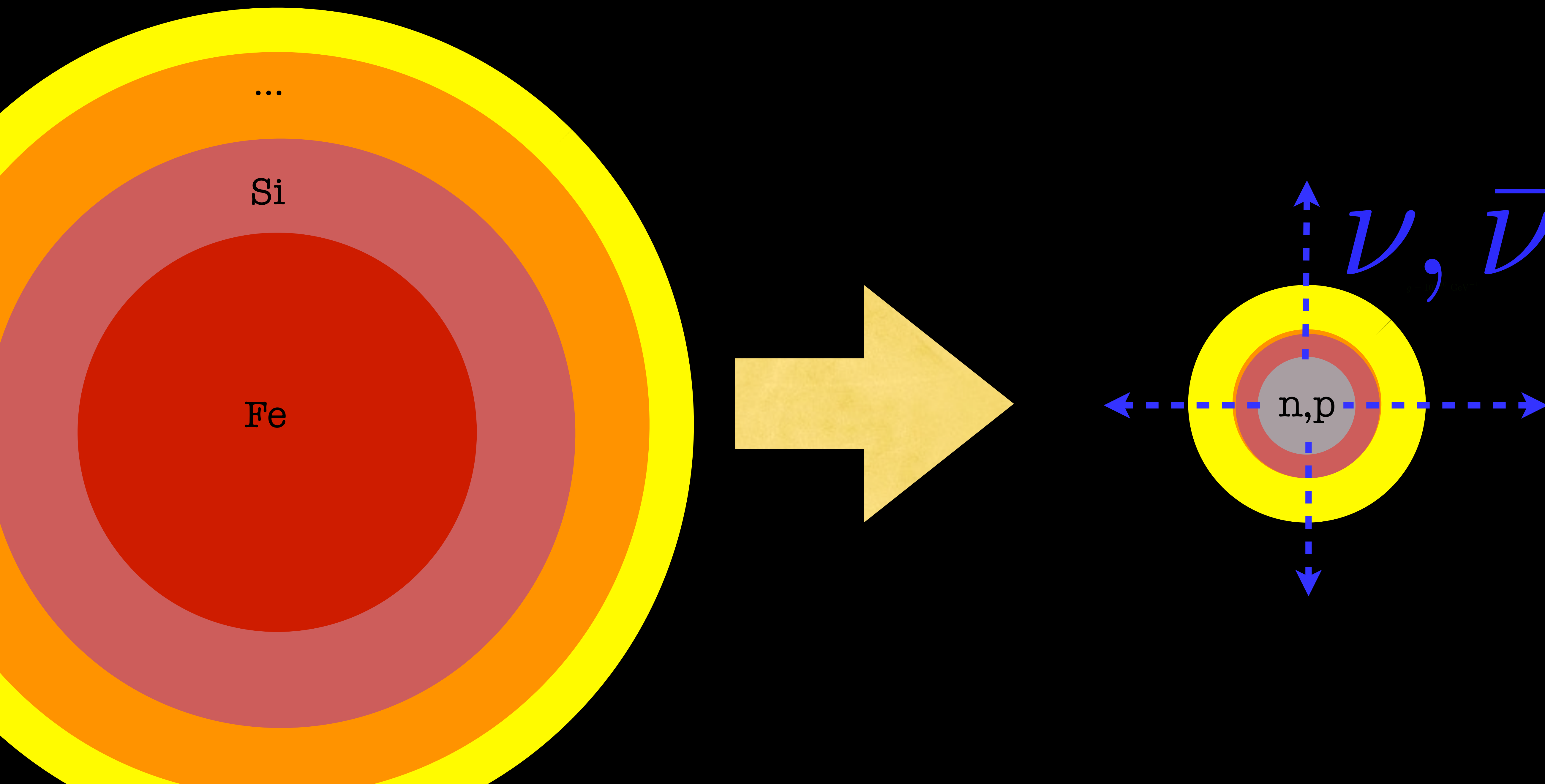
Core collapse SN

Iron Core collapse when electron degeneracy pressure cannot support its grav. pull

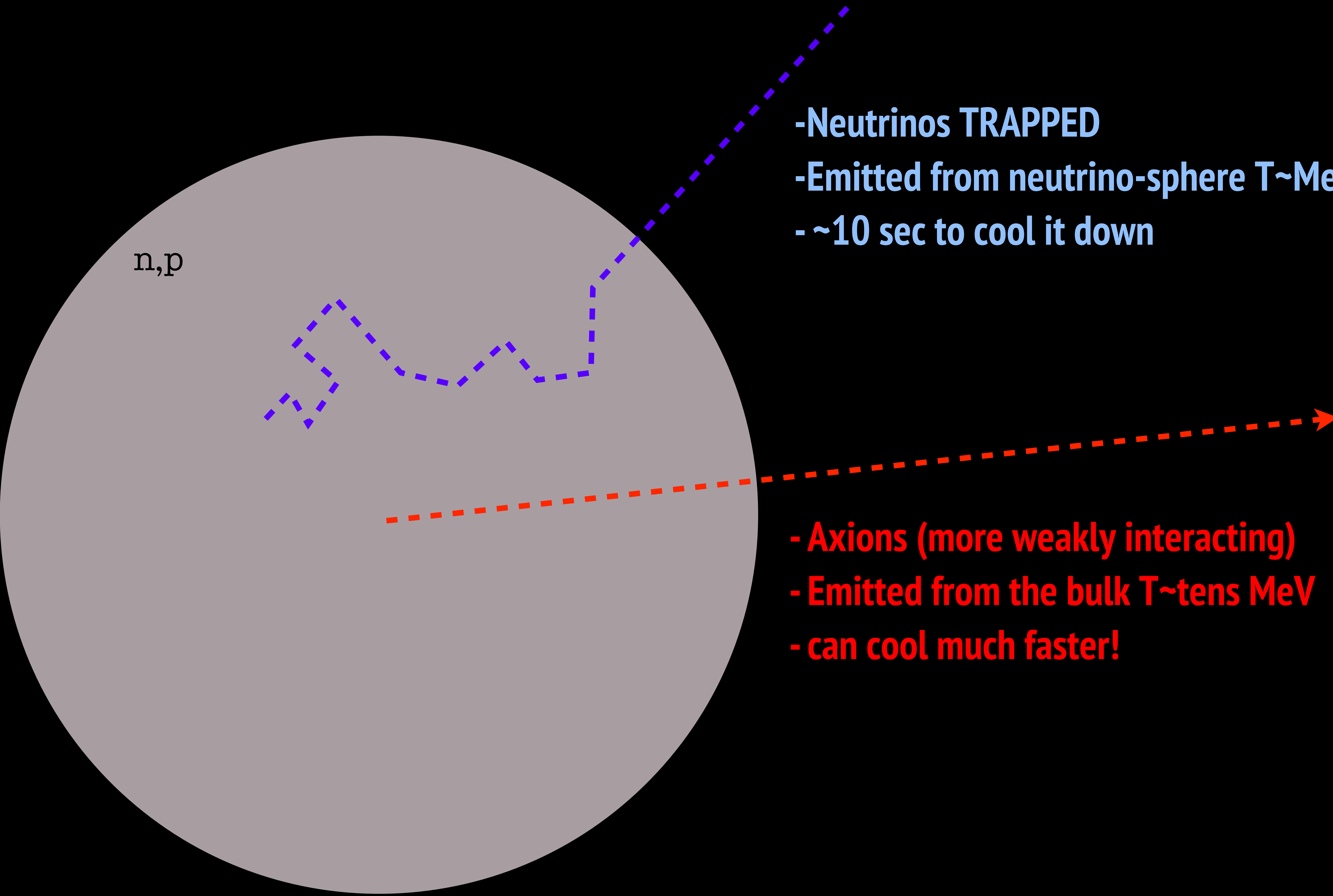
$$\mathcal{M}_{\rm core} \sim 1.4\mathcal{M}_\odot$$

The gravitational energy of the core is mainly to be radiated away in neutrinos

$$E = 3 \times 10^{53}\ {\rm erg}$$



Neutrino burst



-Neutrinos TRAPPED

-Emitted from neutrino-sphere T~MeV

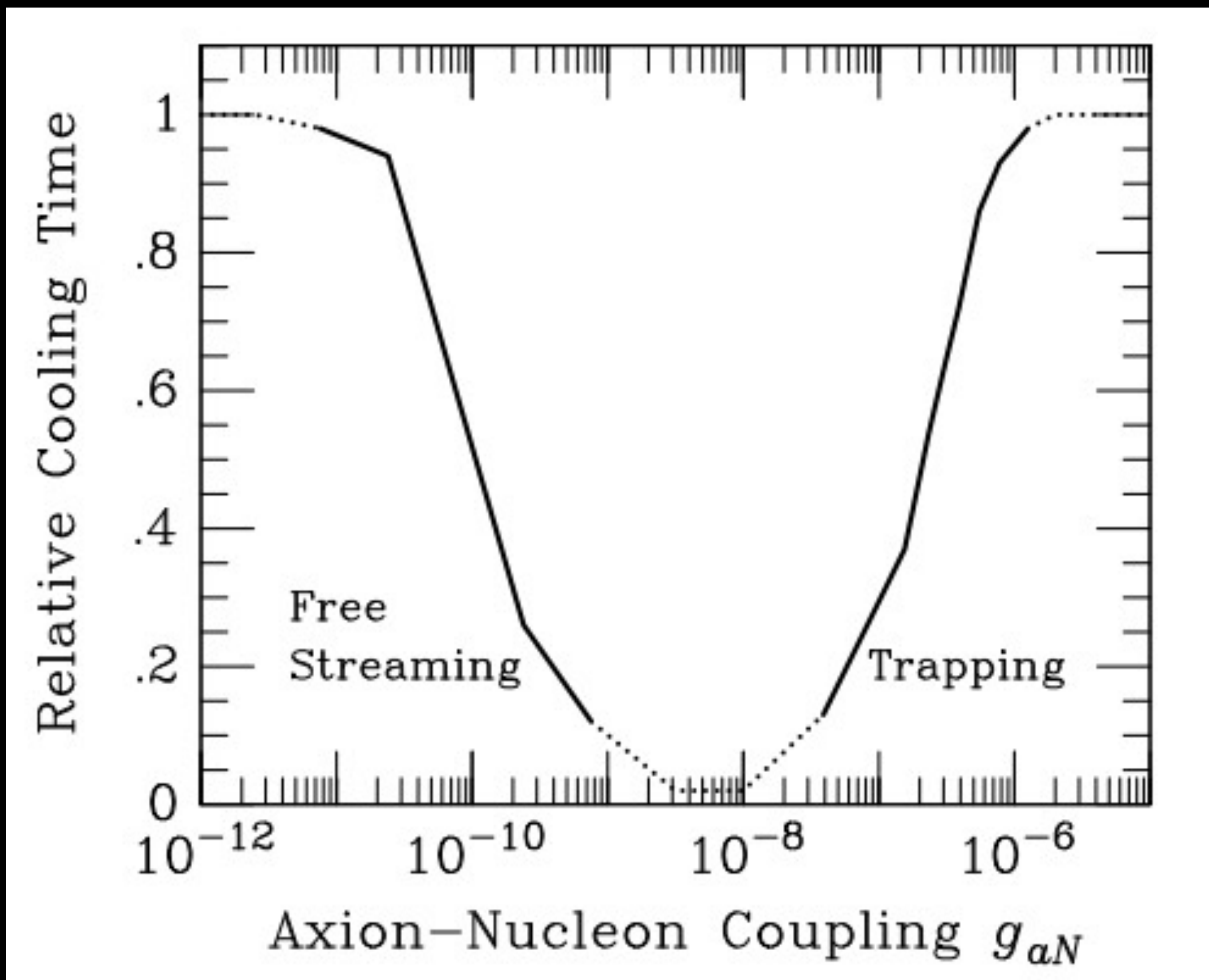
- ~10 sec to cool it down

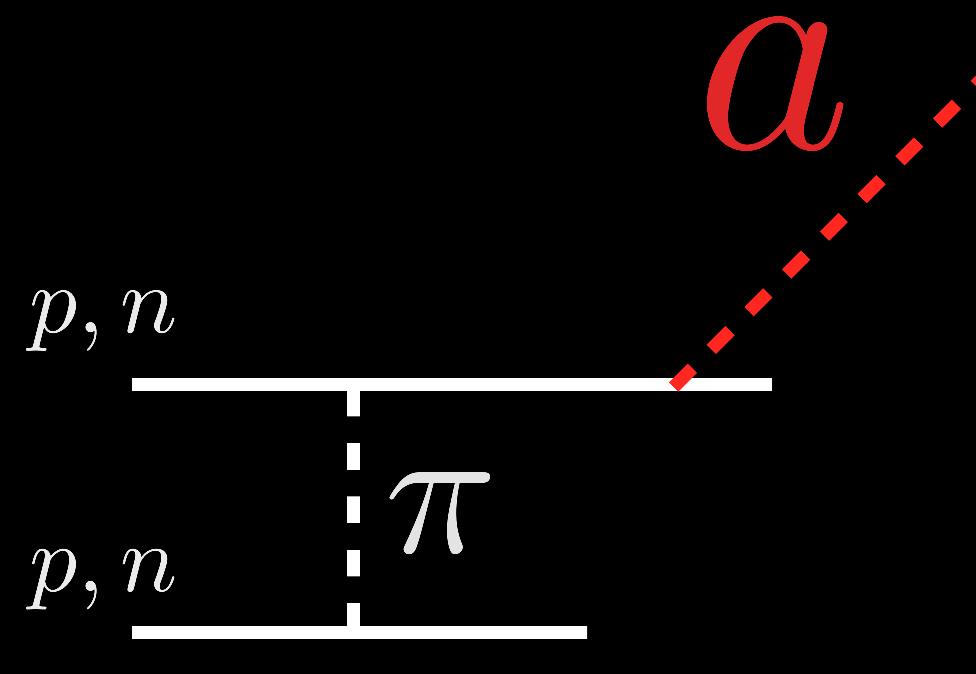
- Axions (more weakly interacting)

- Emitted from the bulk T~tens MeV

- can cool much faster!

Reduction of nu burst $N + N \rightarrow N + N + a$





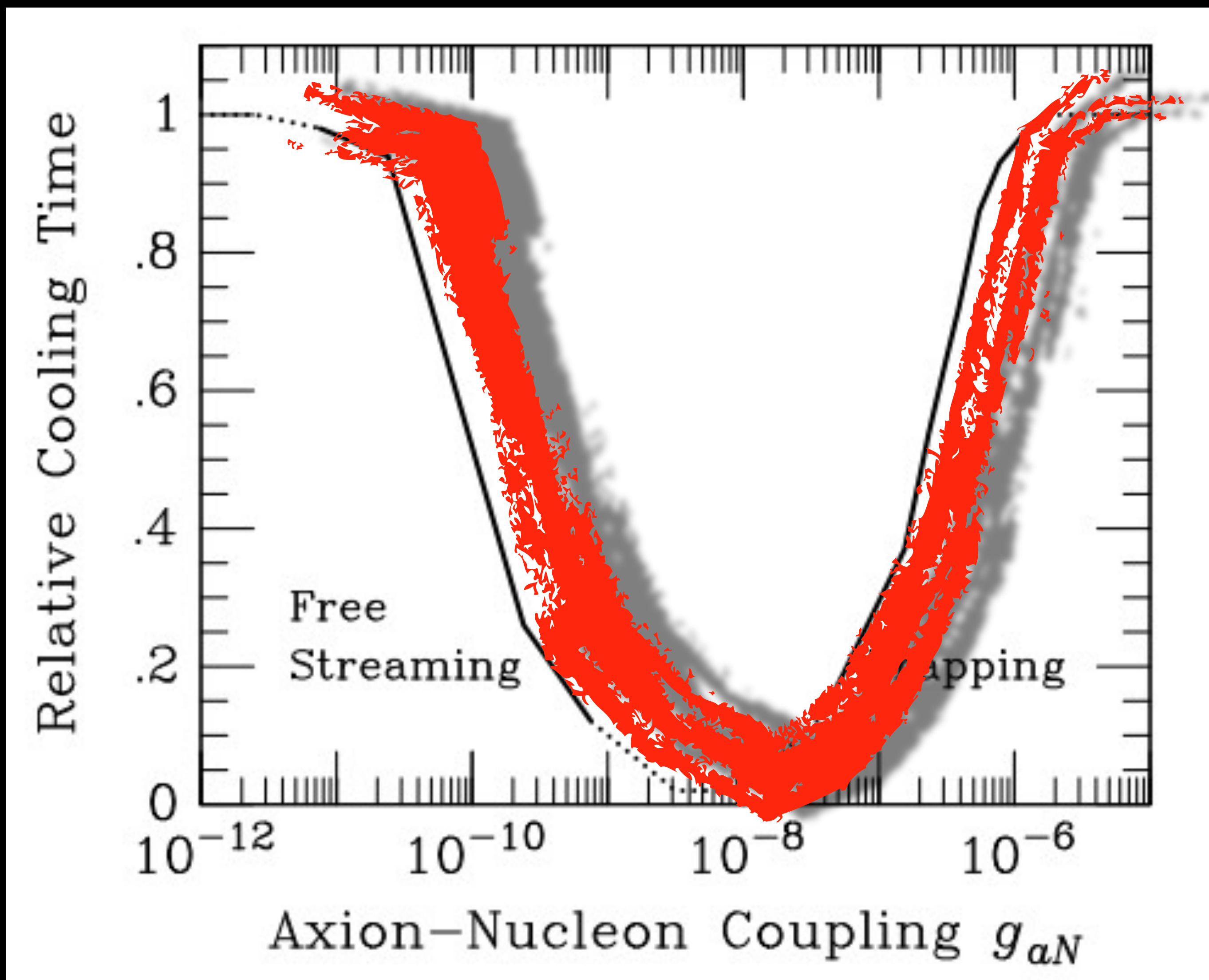
first approx. (pi pole too hard...)

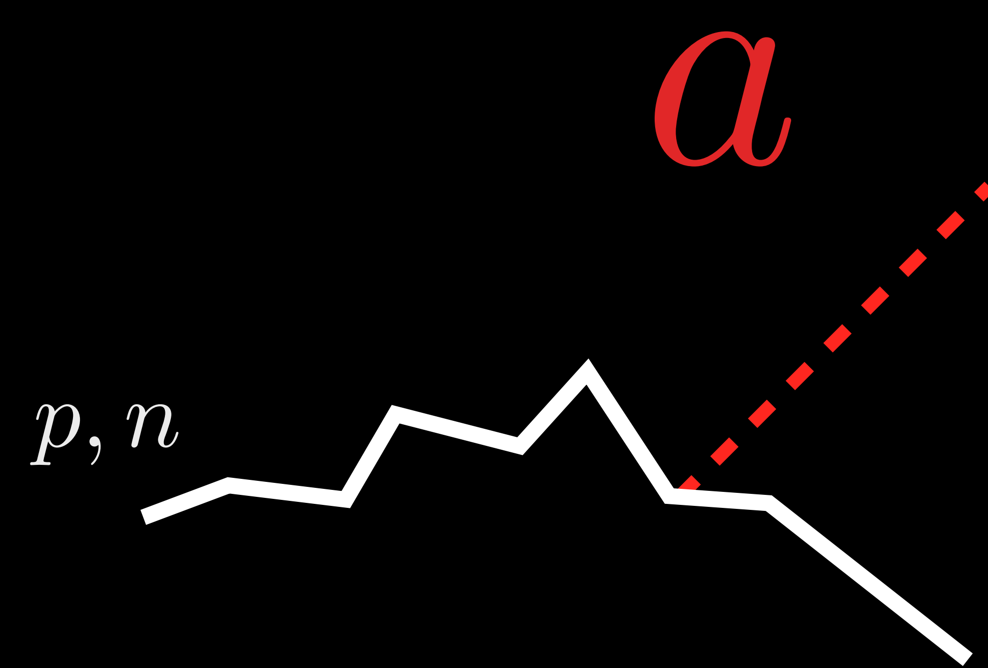
axion production not significant

Cool the PNS eficiently reduce the neutrino burst!

axions are reabsorbed inside the SN

Reduction of nu burst $N + N \to N + N + a$





axion emission is suppressed due to high density effects !

SN1987A

- Cooling ~ 10 s
- Exotics, Eloss/mass and time

$$\epsilon \lesssim 10^{19} \mathrm{erg/gs}$$

- Axion emission …

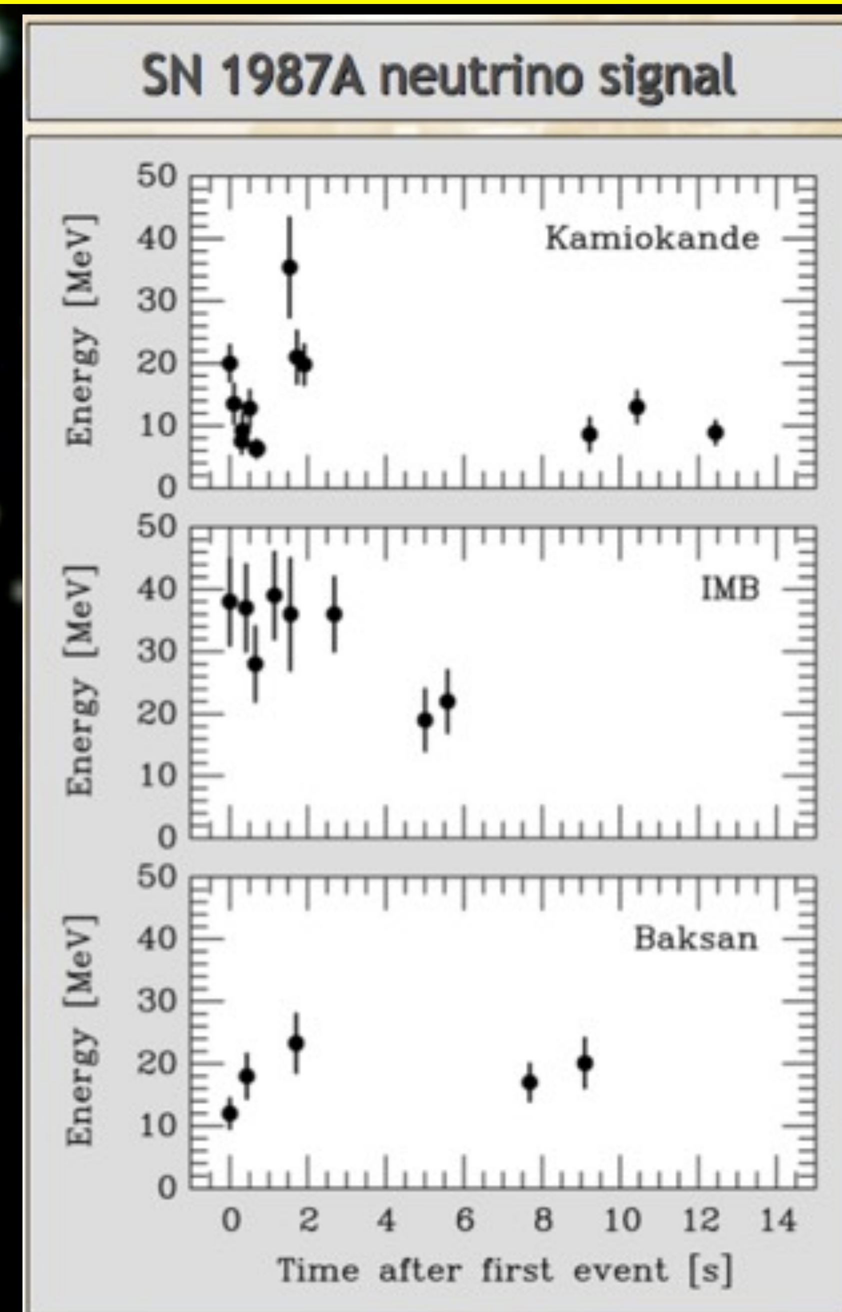
$$\epsilon_a \sim g_{ap}^2 1.6 \times 10^{37} \mathrm{erg/gs} \left(\frac{T}{30\mathrm{MeV}} \right)^4$$

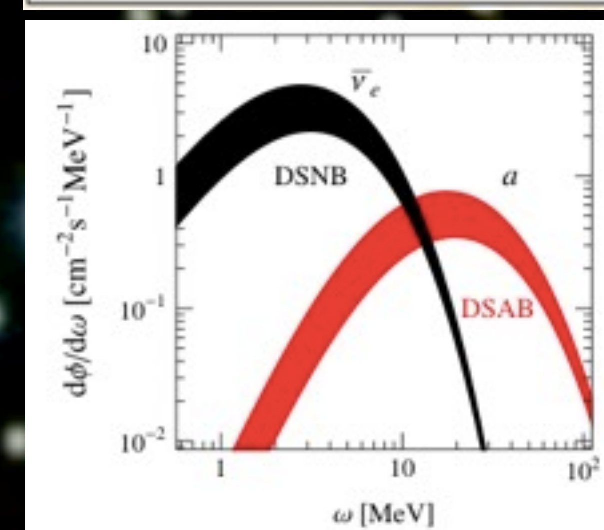
- Constraint …

$$g_{ap} \lesssim 8 \times 10^{-9}$$

- Axions saturating the bound take ~50% Ecore

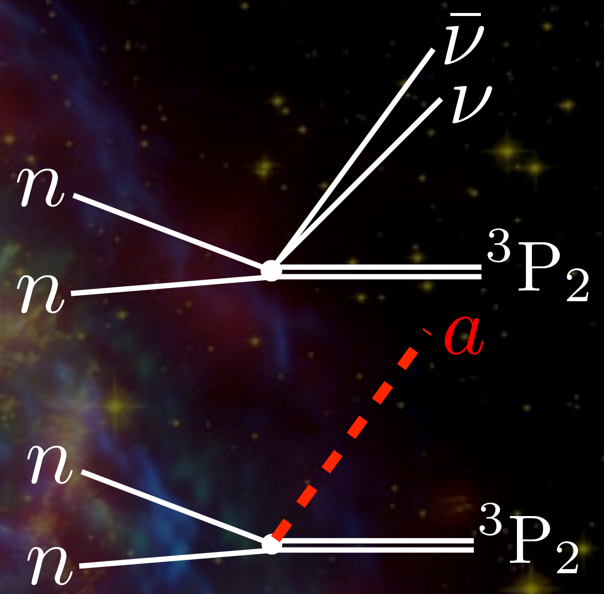
Diffuse Supernova Axion Background

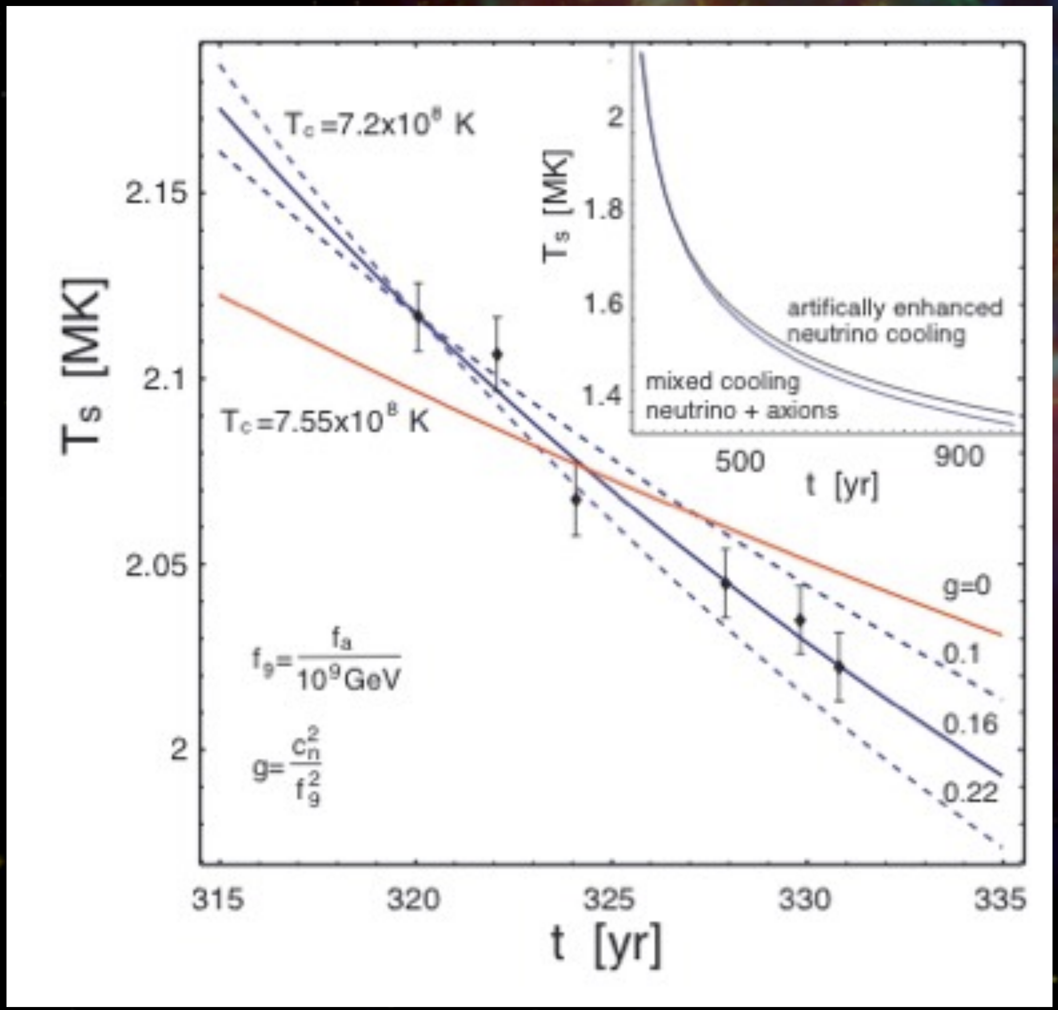




Cassiopeia A: neutron star cooling

- Cooling measured by Chandra, ~4% in ten years!
- Evidence of $\bar{\nu}\nu$ emission in n Cooper pair formation $^3P_2$
- Factor of ~2 extra cooling required, axions?





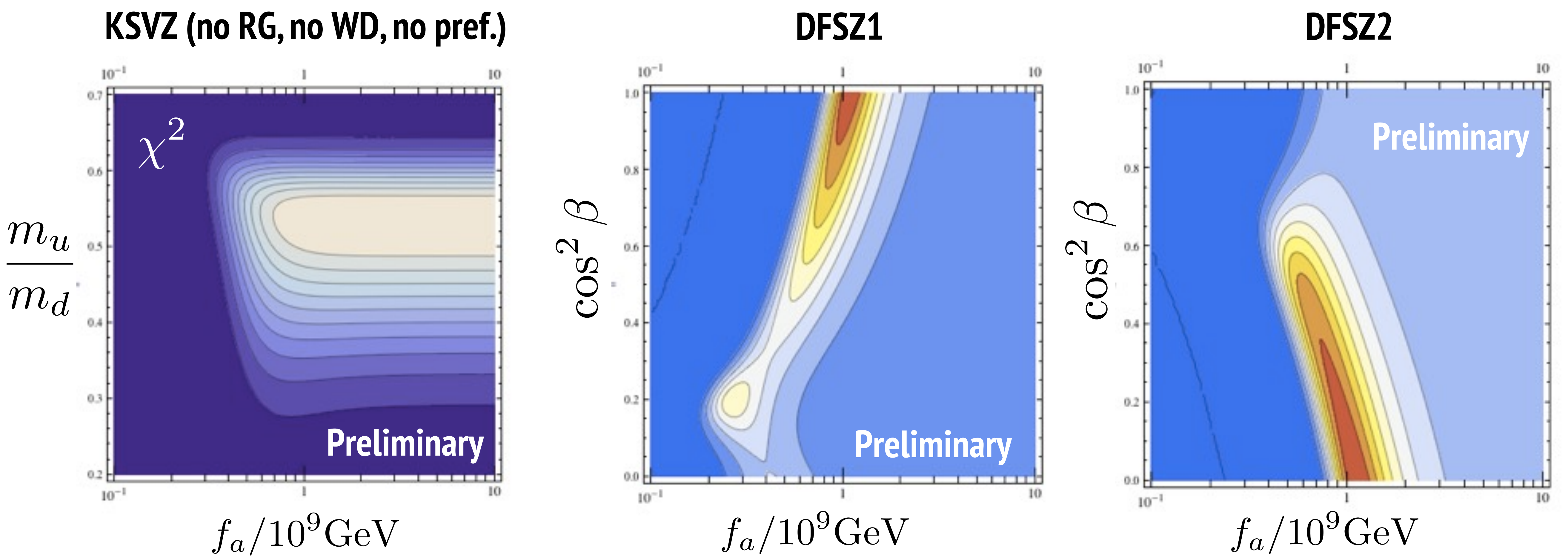
Hints, constraints and models ... any preference?

Tip of the Red Giant branch (M5) $$g_{ae} = C_{ae}\frac{m_e}{f_a} = (2 \pm 1.5) \times 10^{-13}$$

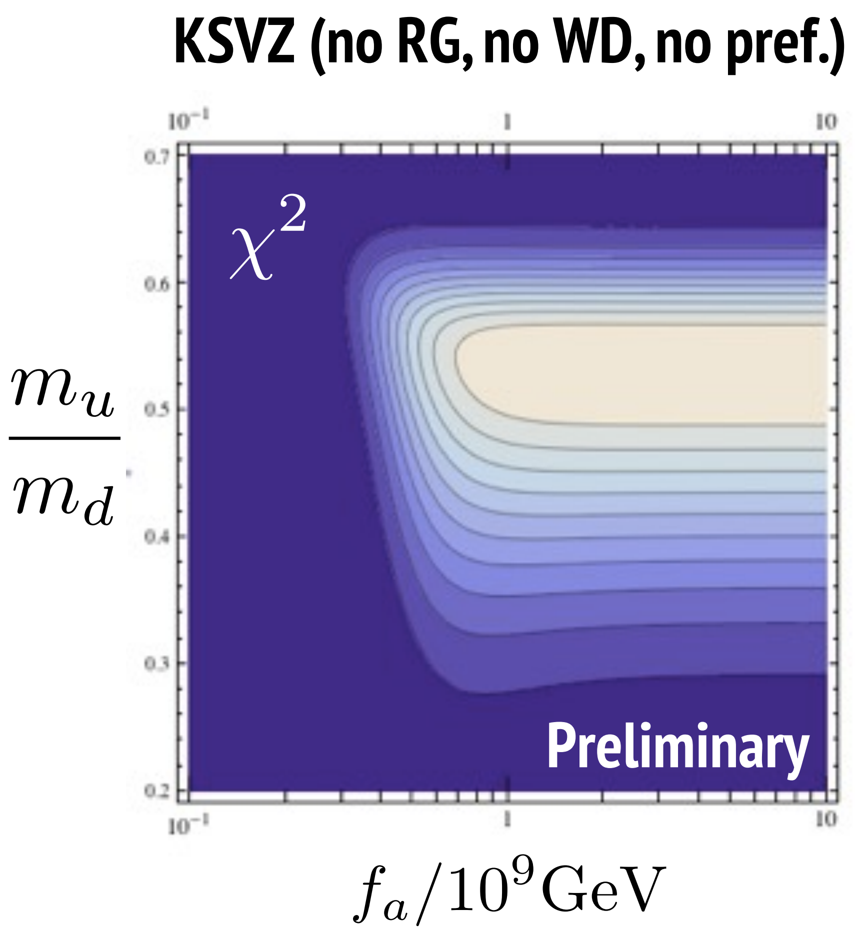
White dwarf luminosity function $$g_{ae} = C_{ae}\frac{m_e}{f_a} = (1.4 \pm 1.4) \times 10^{-13}$$

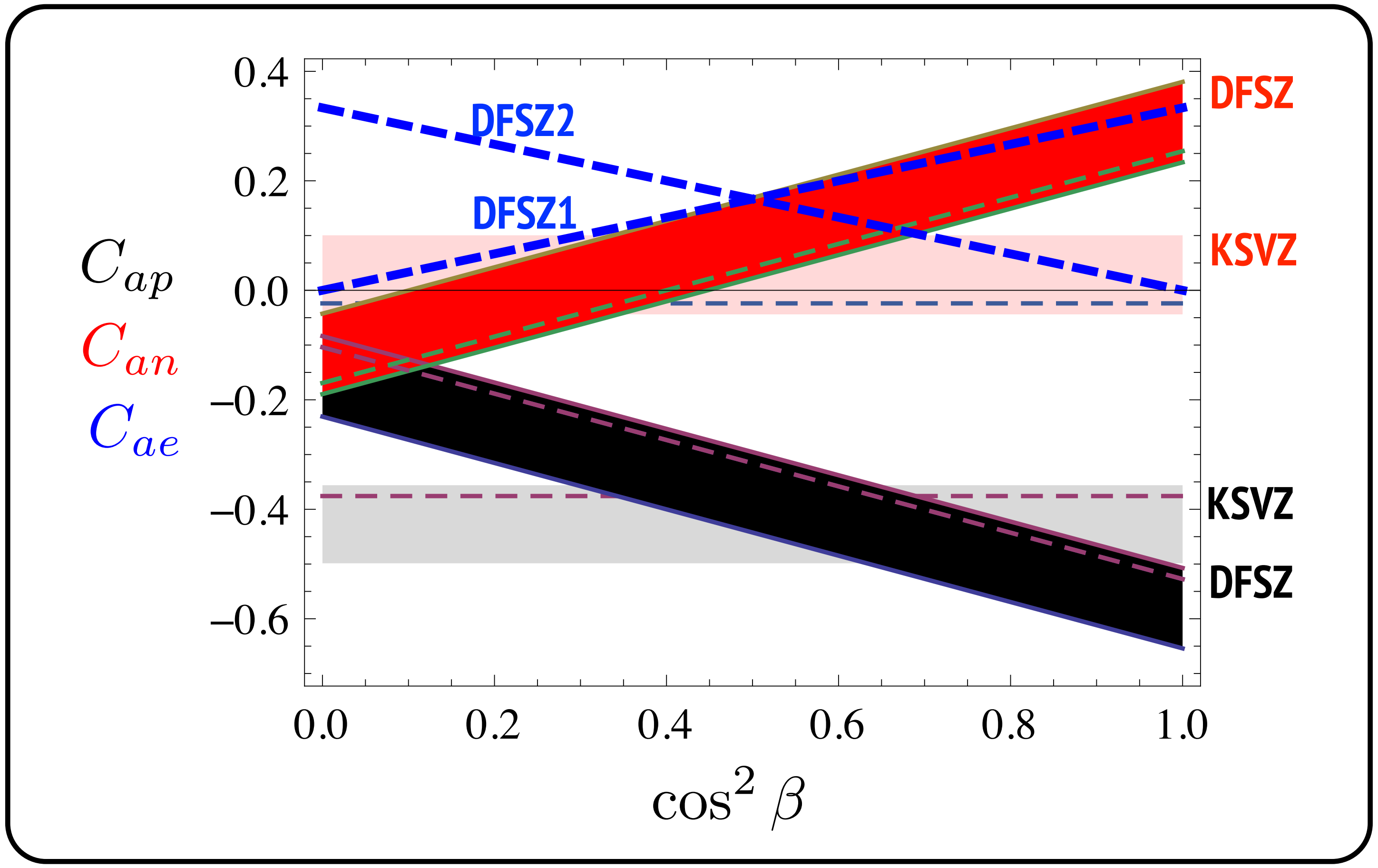
Cassiopeia A: neutron star cooling $$g_{an} = C_{an}\frac{m_n}{f_a} = (3.8 \pm 3) \times 10^{-10}$$

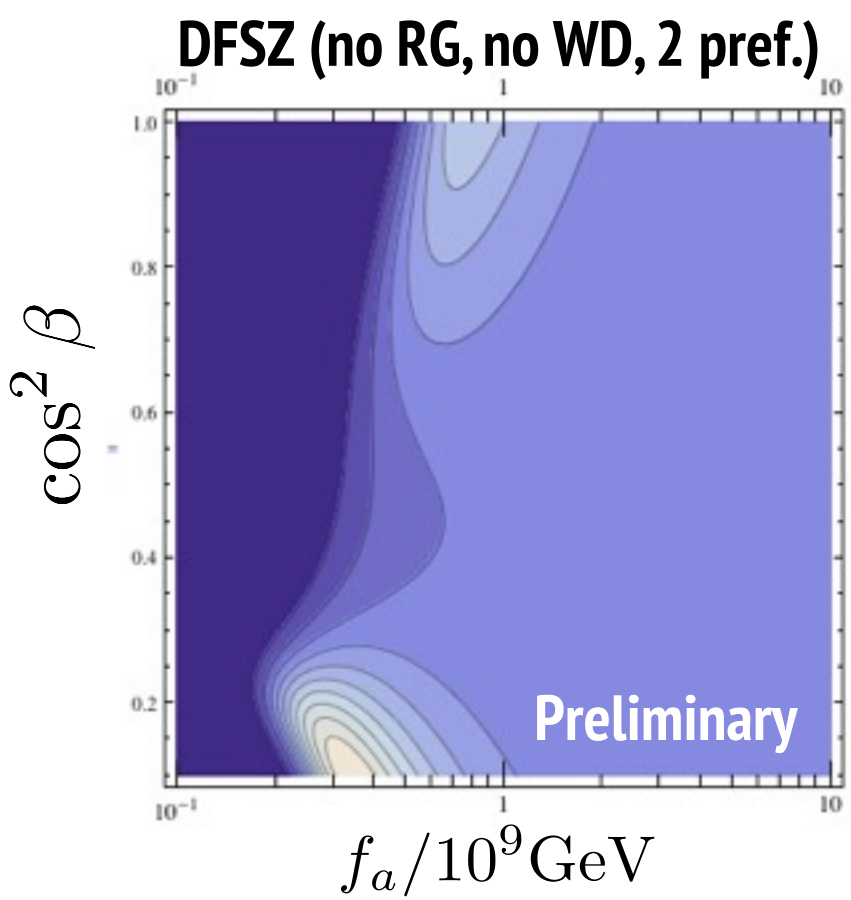
SN1987A $$g_{ap} = C_{ap}\frac{m_p}{f_a} < 0.8 \times 10^{-10}$$

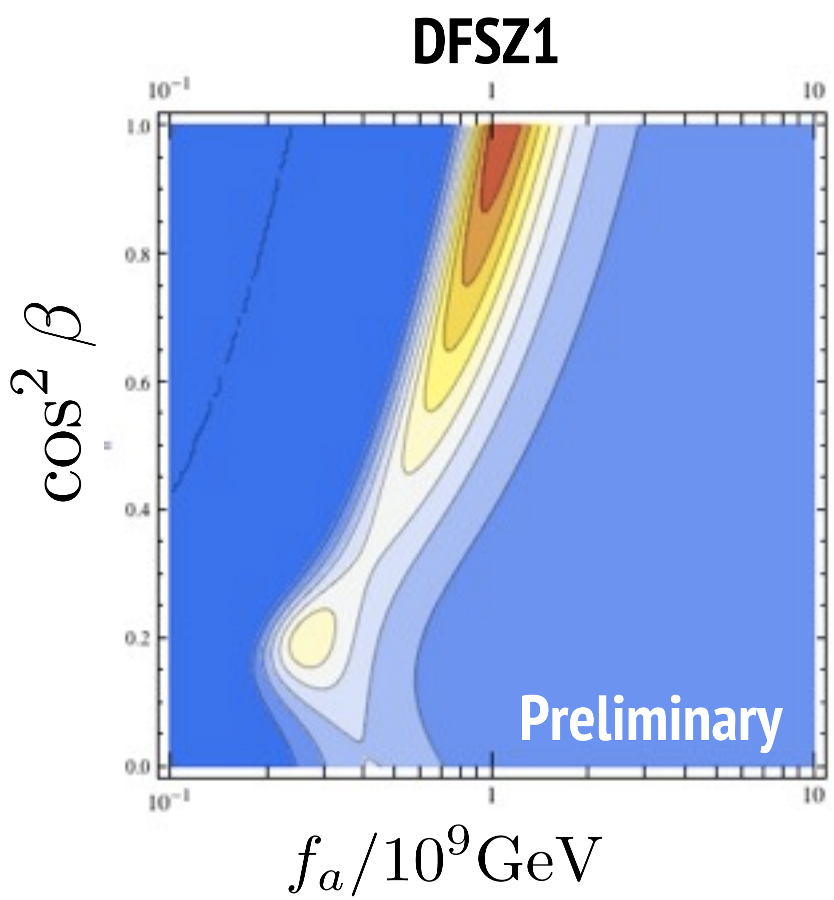


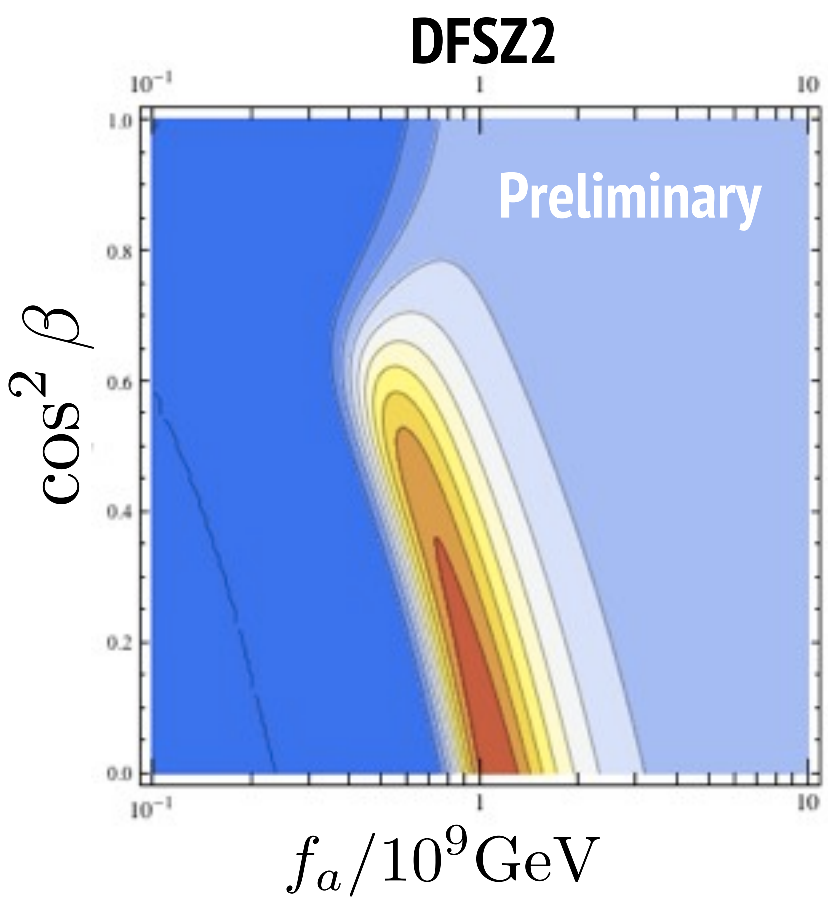
Hints, constraints and models ... any preference?



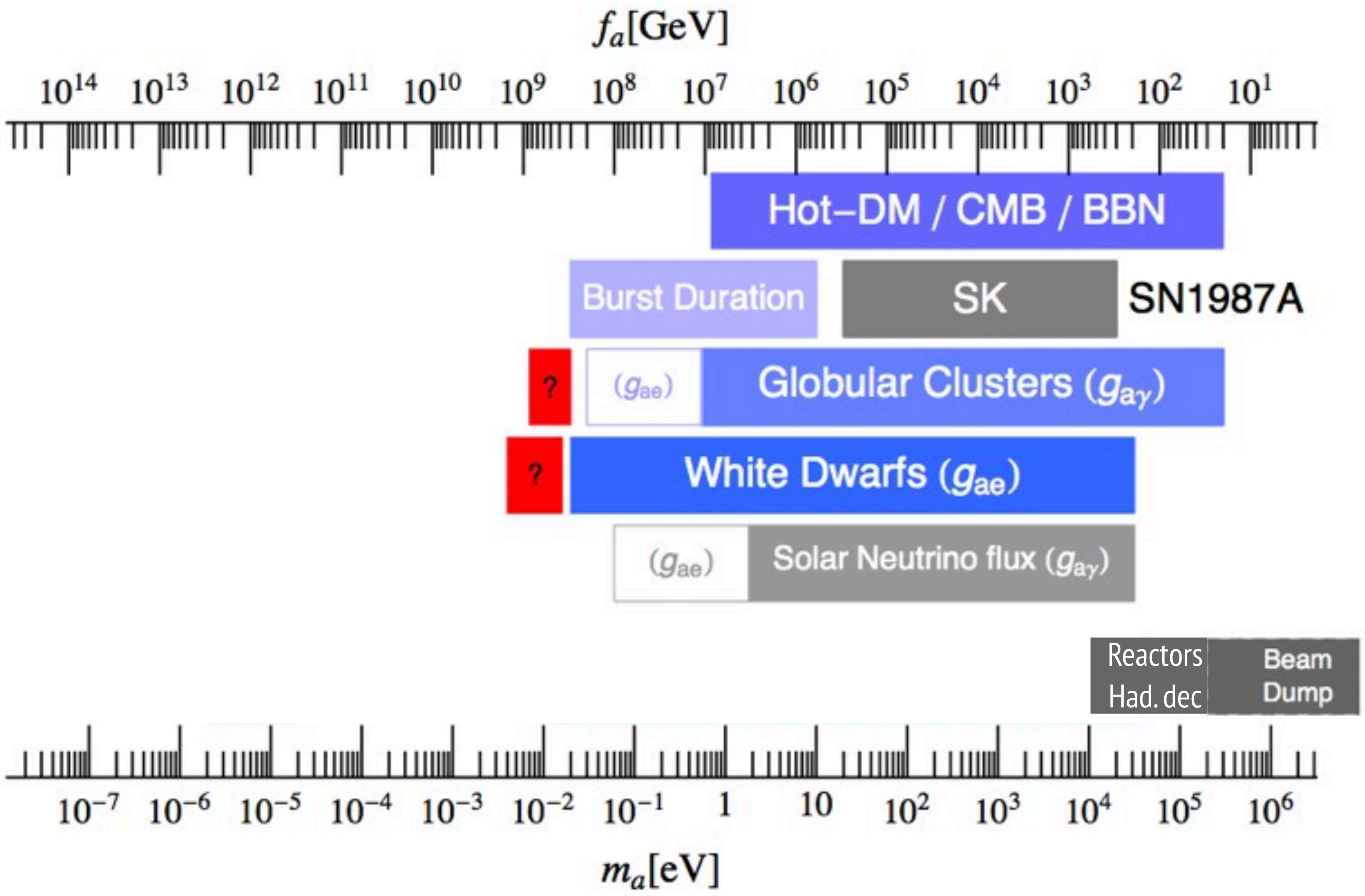




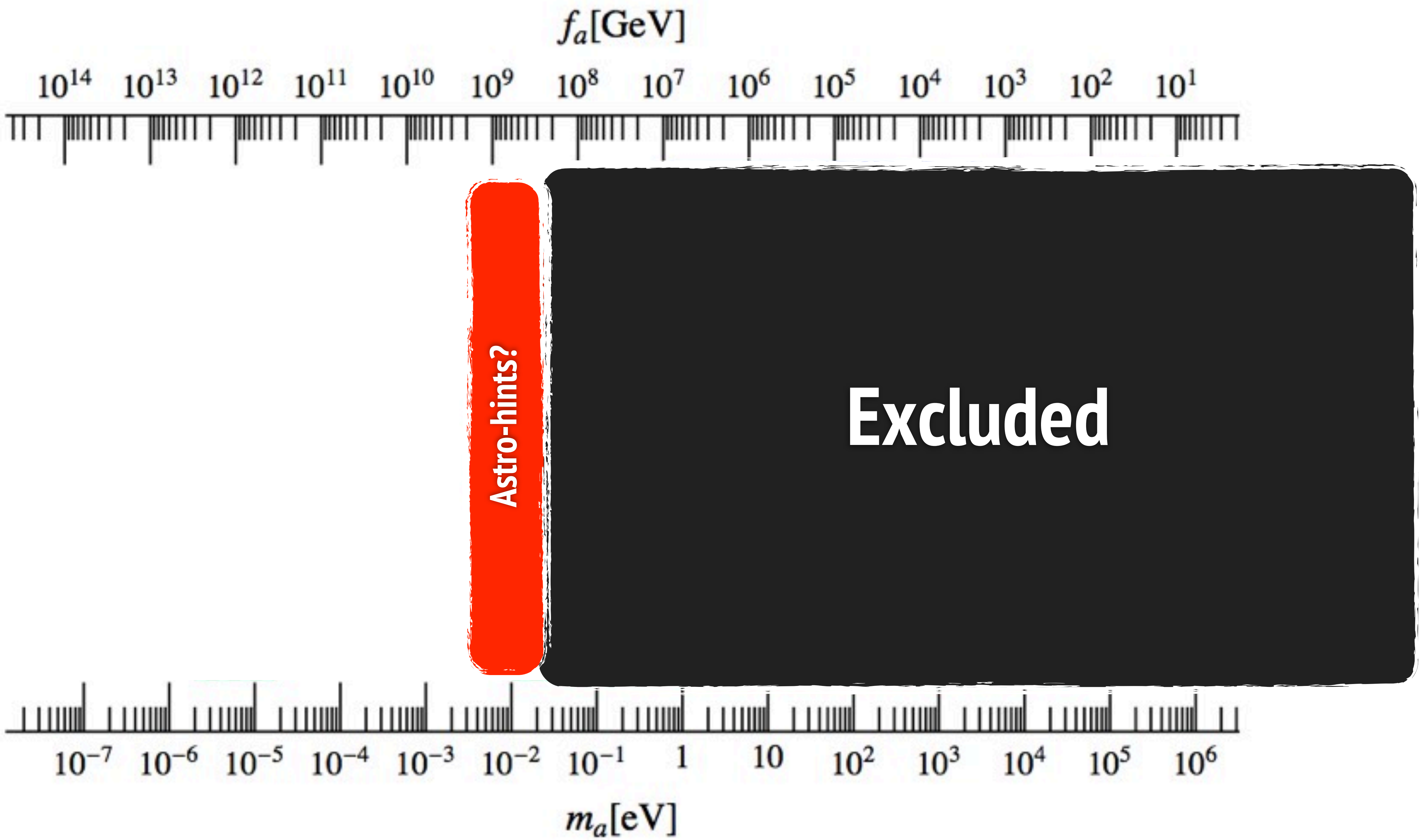




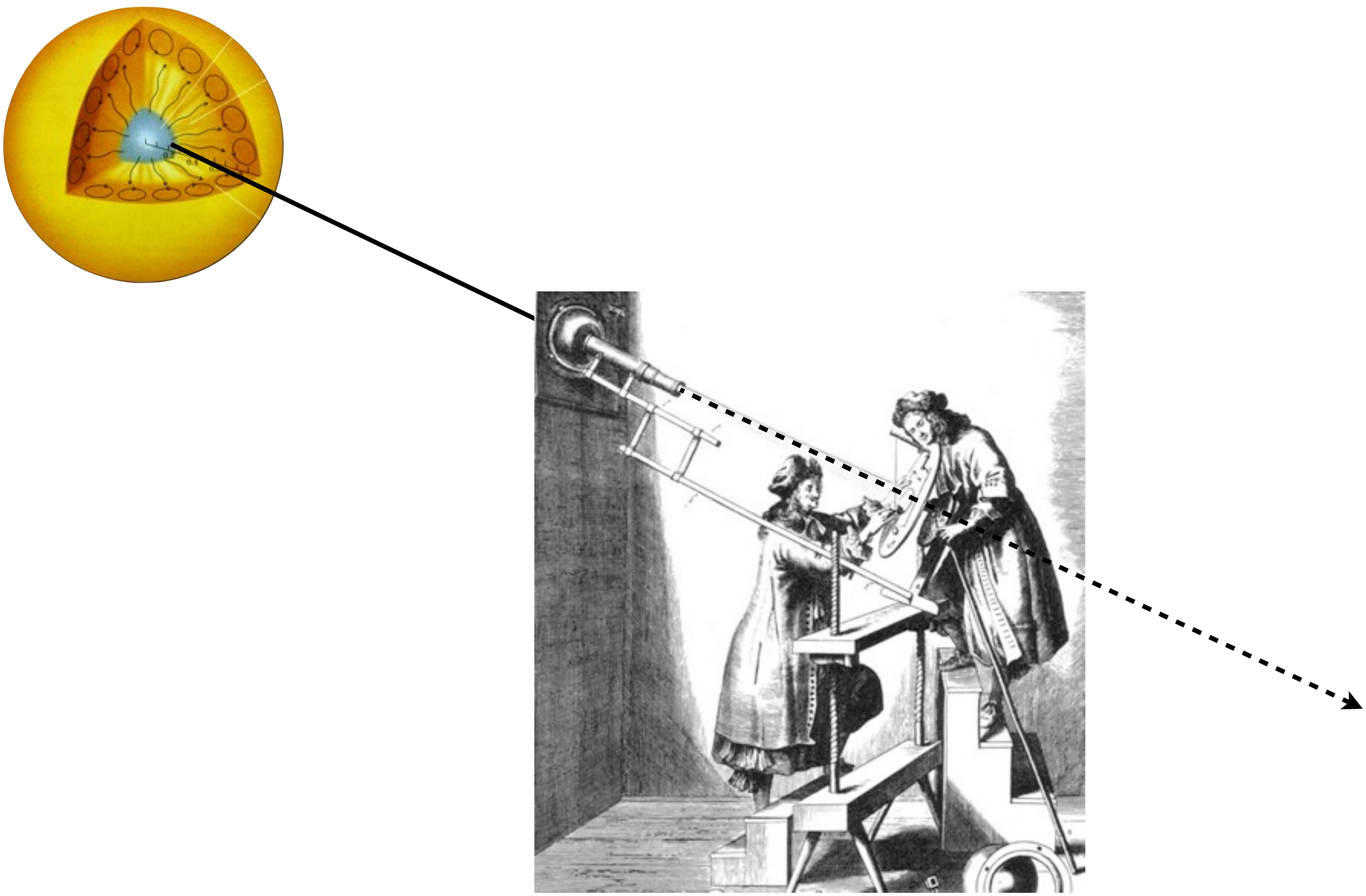
Axion Landscape



Axion Landscape

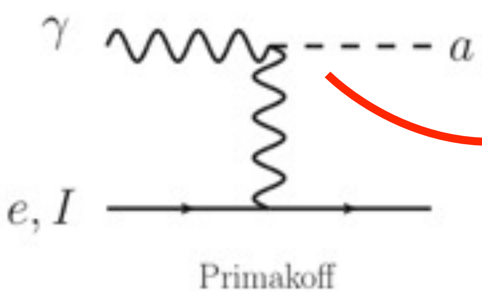


Detecting Solar Axions : Helioscopes



Axions from the Sun

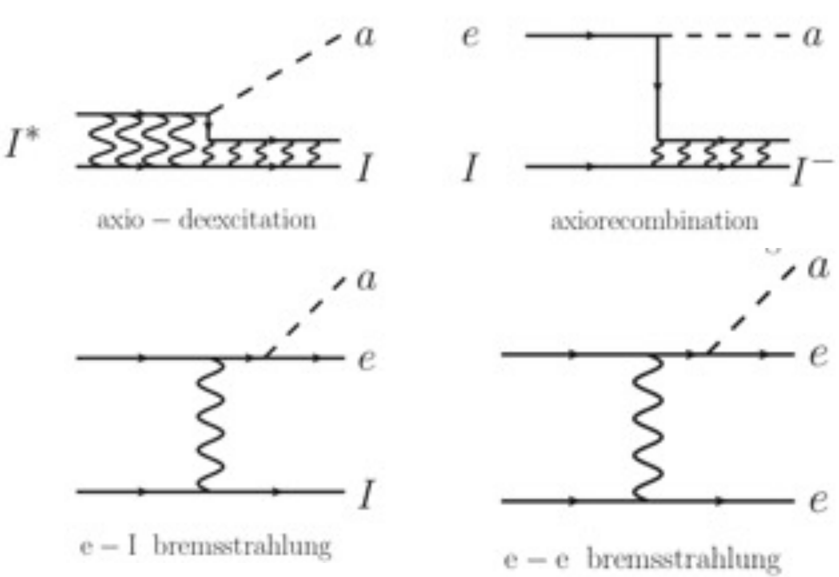
Hadronic axions (KSVZ)

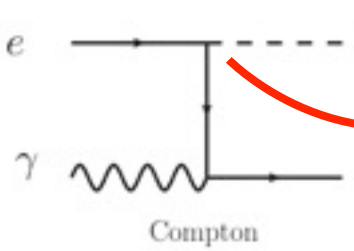


$$\frac{C_\gamma \alpha}{2\pi f_a} \frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4} a$$

$g_{a\gamma}$

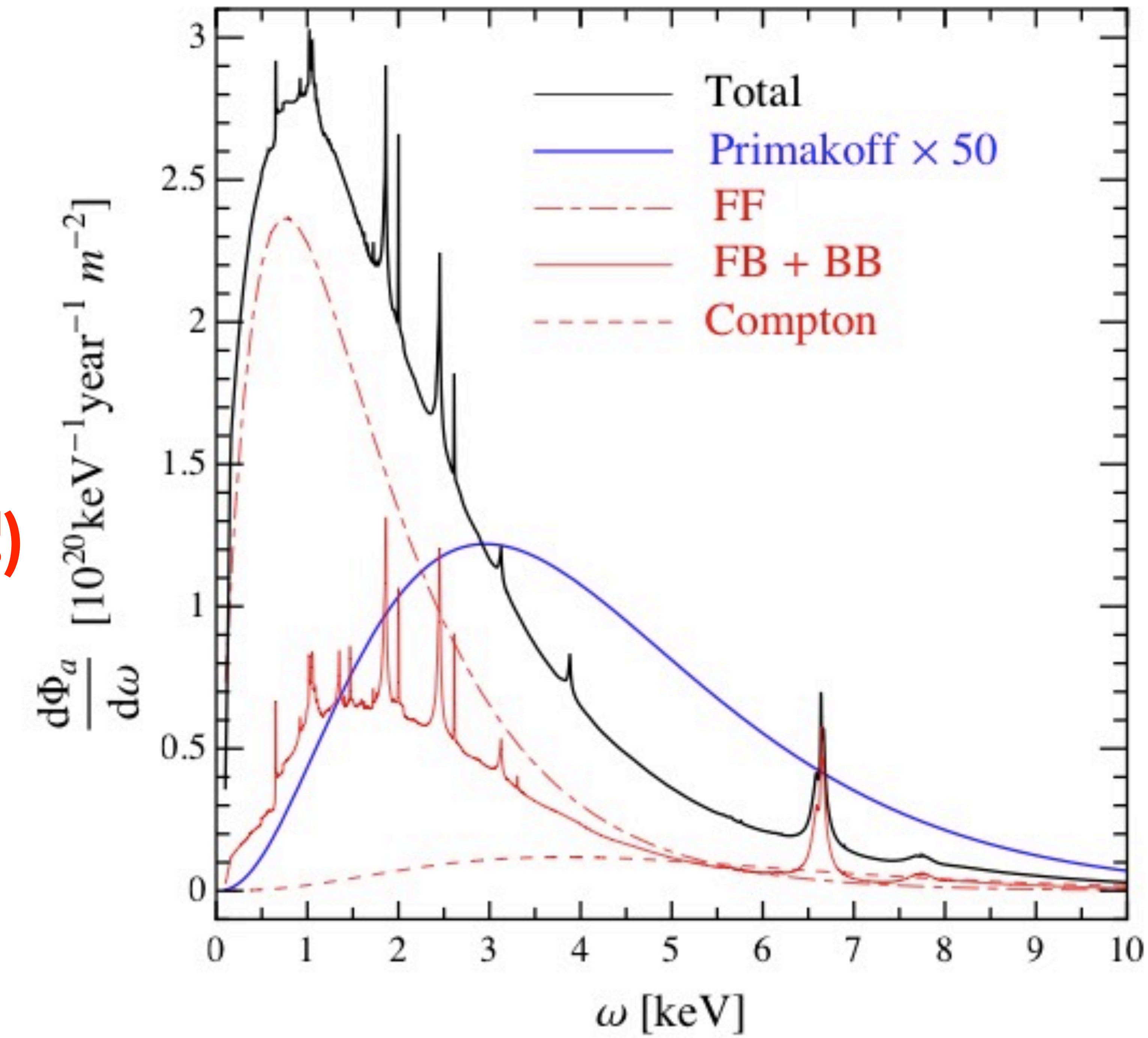
Non hadronic (DFSZ, e-coupling!)





$$\frac{C_e m_e}{f_a} i\bar{e}\gamma_5 e\, a$$

g_{ae}



$g_{ae} = 10^{-13}$

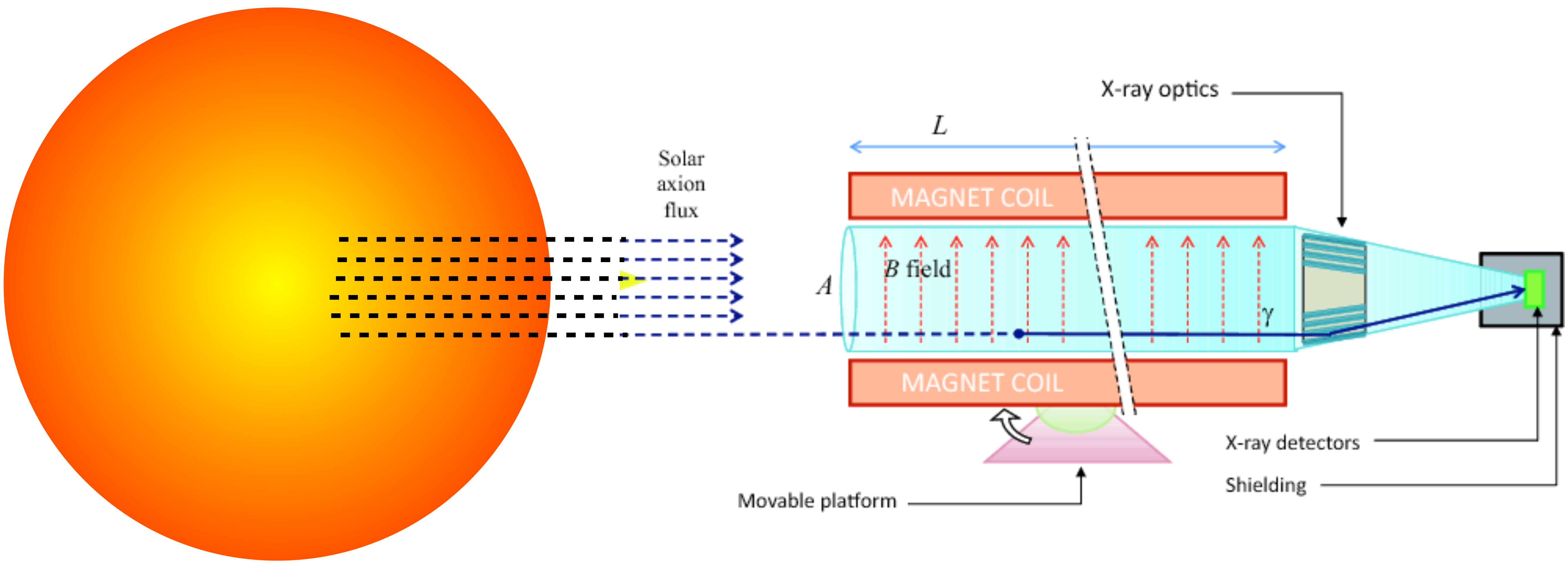
$g_{a\gamma} = 10^{-12}\mathrm{GeV}^{-1}$

typical of meV mass axions

Helioscopes

The Sun is a copious emitter of axions!

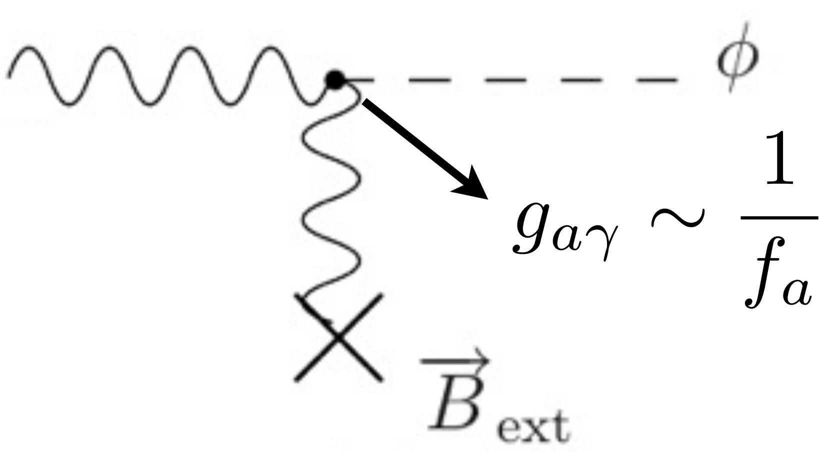
convert into X-rays   focus   detect



Conversion probability

$$P(a \leftrightarrow \gamma) = \left(\frac{2 g_{a\gamma} B_T \omega}{m_a^2}\right)^2 \sin^2\left(\frac{m_a^2 L}{4\omega}\right)$$

$$P(a \leftrightarrow \gamma) \sim 10^{-20} \left(\frac{B}{3\,\mathrm{T}}\frac{L}{20\,\mathrm{m}}\right)^2$$

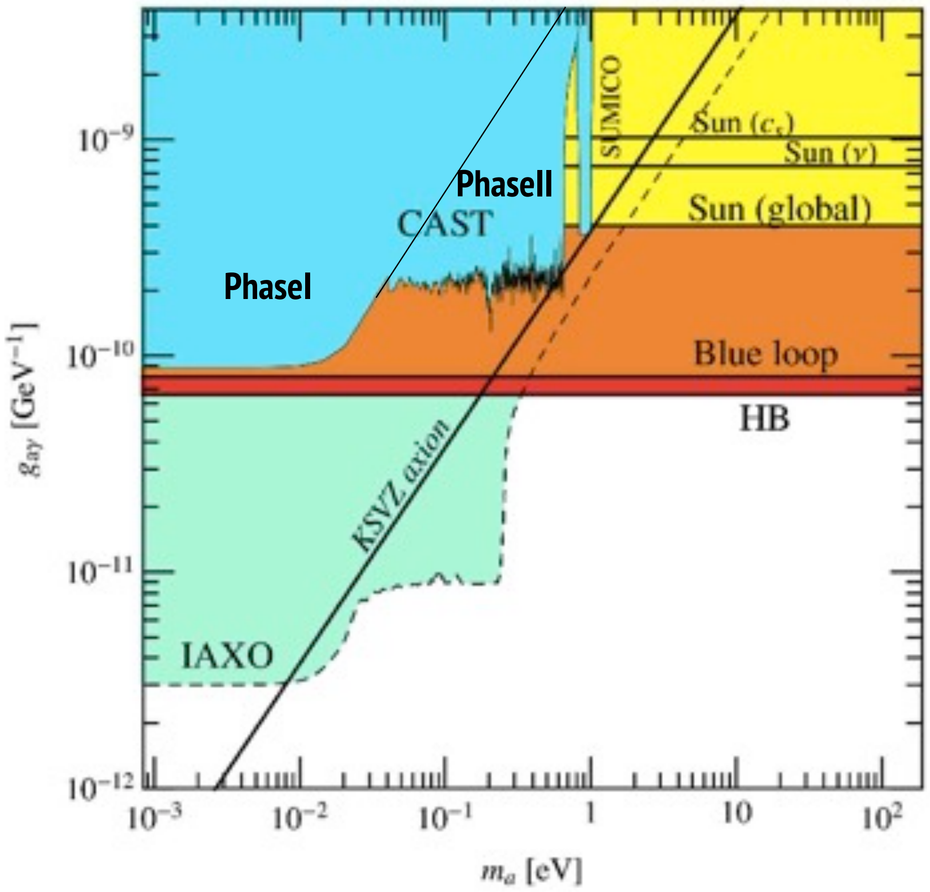


CAST Helioscope

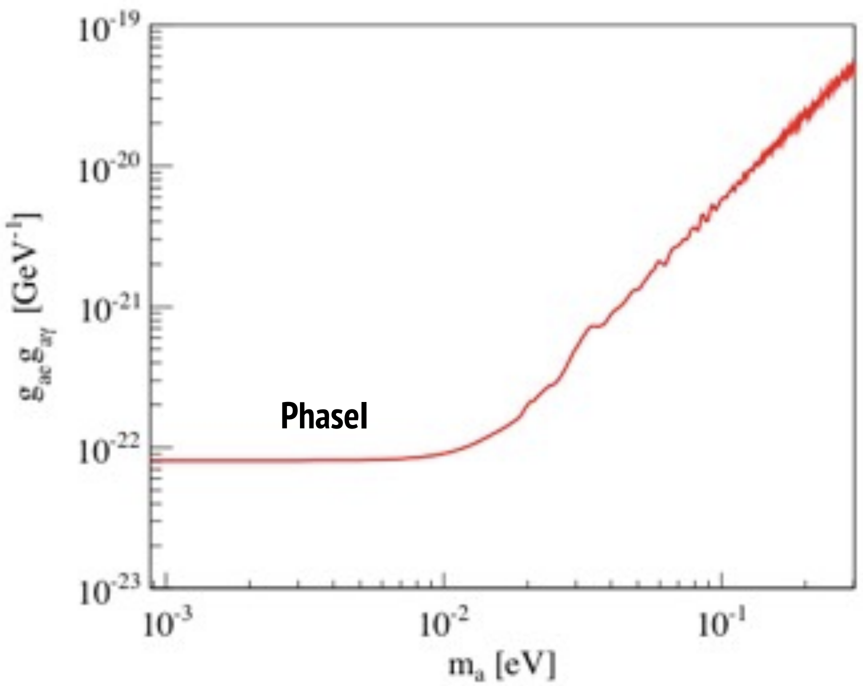
CAST (LHC dipole 9.3 m, 9T)

- 1~2 h tracking/day (sunset,dawn)
- 3 Detectors (2 bores)
  CCD, Micromegas
- X-ray optics

hadronic axions



non-hadronic axions



Next generation (proposed) IAXO

Boost parameters to the maximum

Large toroidal 8-coil magnet L = ~20 m

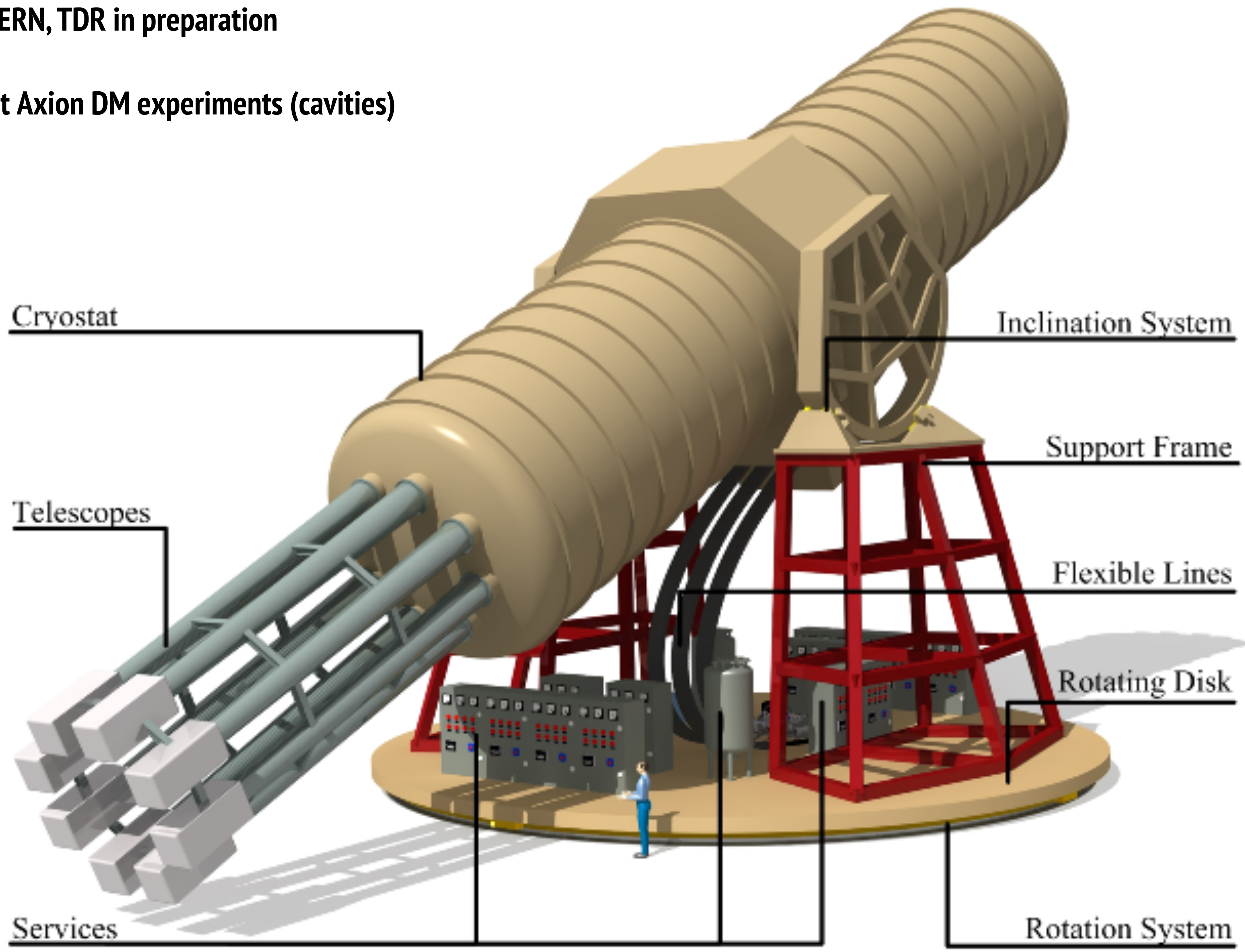
8 bores: 600 mm diameter each

8 x-ray optics + 8 detection systems

Rotating platform with services

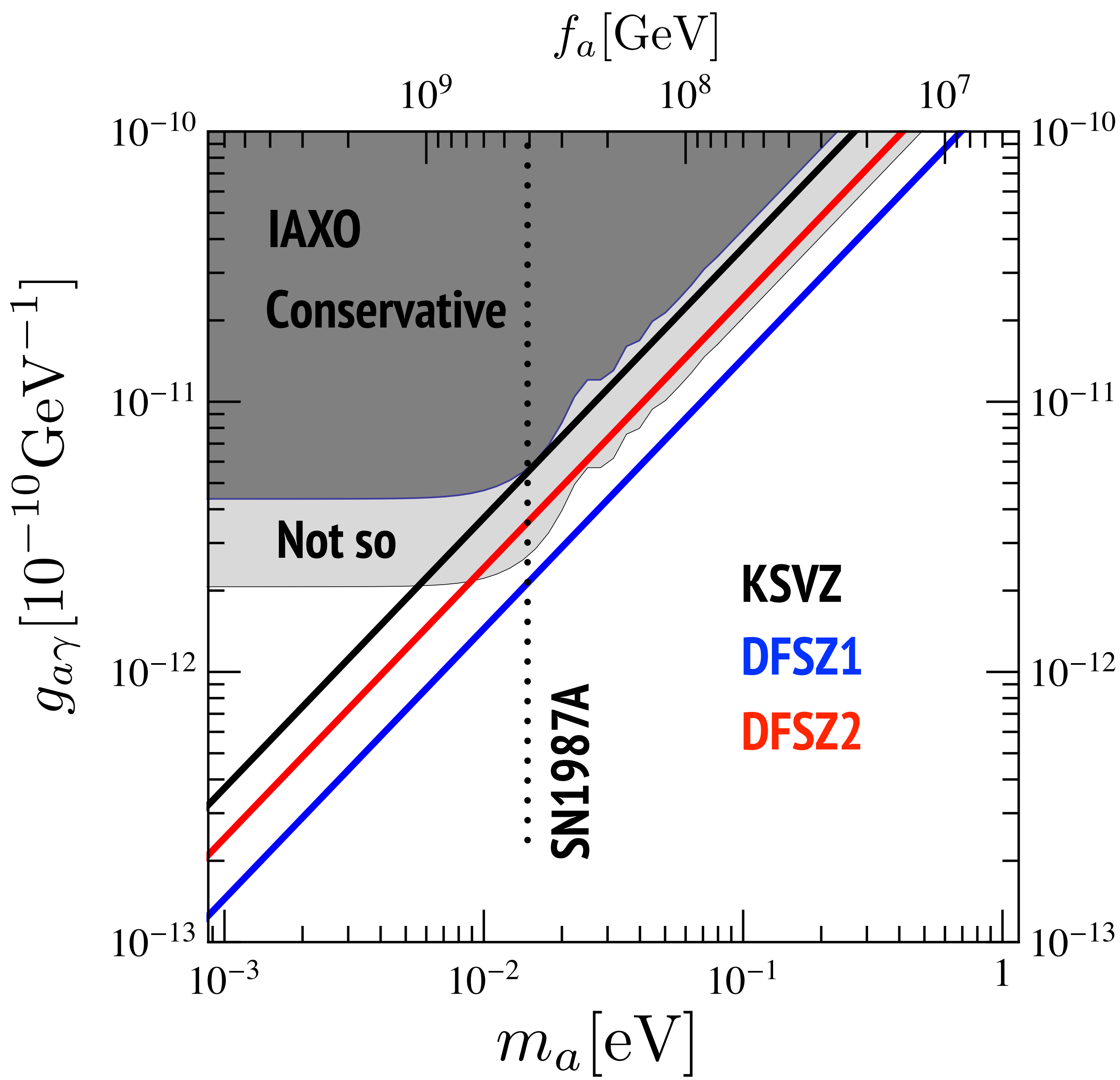
-NGAG paper JCAP 1106:013,2011
-Conceptual design report IAXO 2014 JINST 9 T05002
-LOI submitted to CERN, TDR in preparation

-Possibility of Direct Axion DM experiments (cavities)

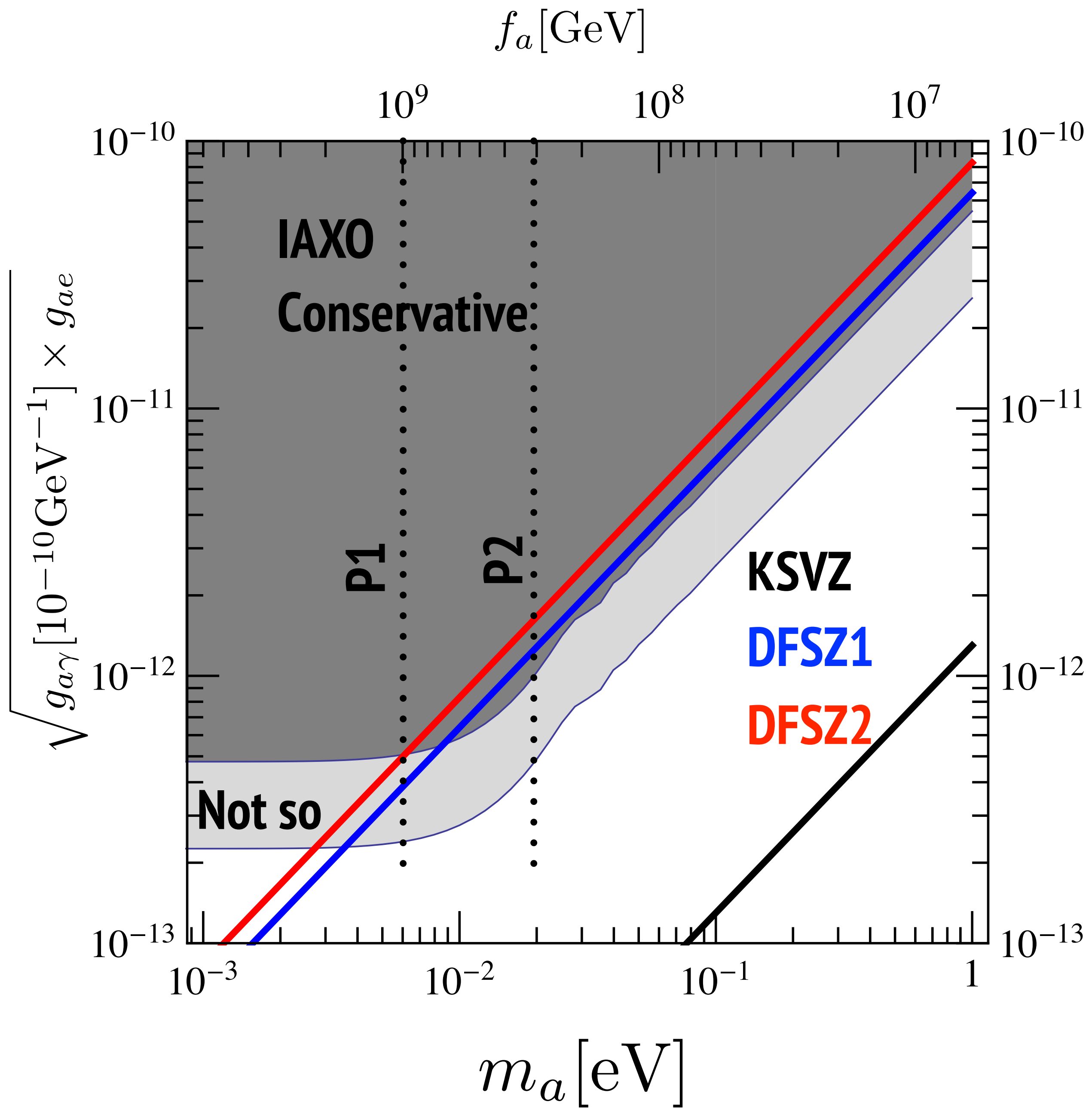


Physics reach (preliminary)

Hadronic axions (KSVZ)

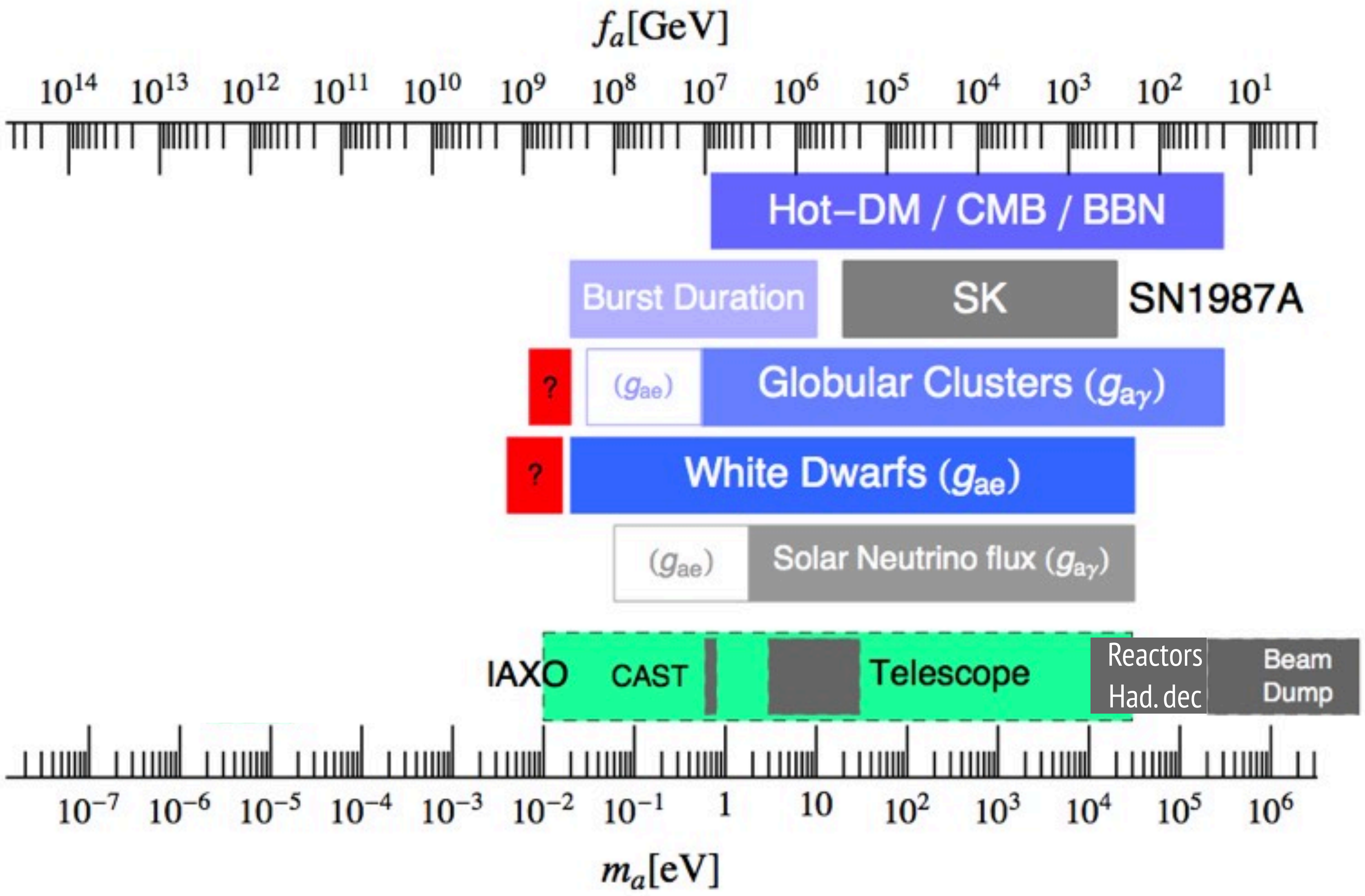


Non hadronic (DFSZ, e-coupling!)



Possibility to unveal the hints!

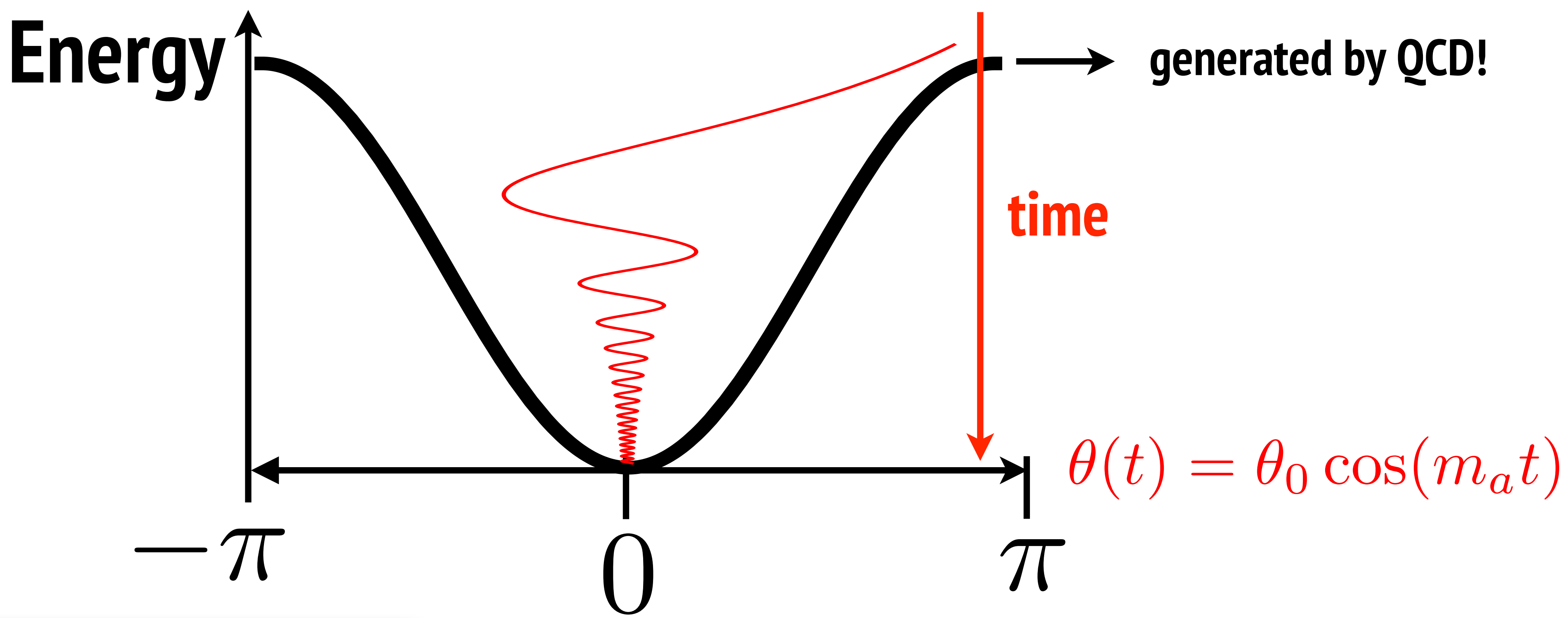
Axion Landscape

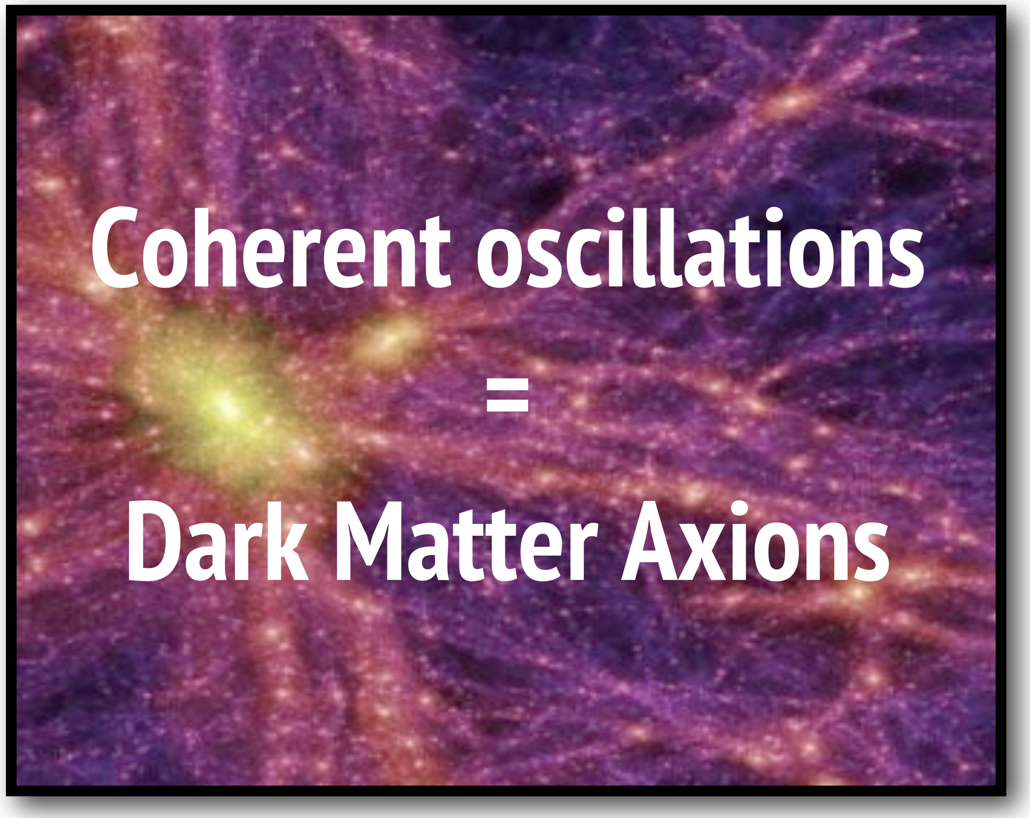


Dark Matters

Axions and dark matter

- ... if $\theta(t, \mathrm{x})$ is dynamical field, relaxes to its minimum





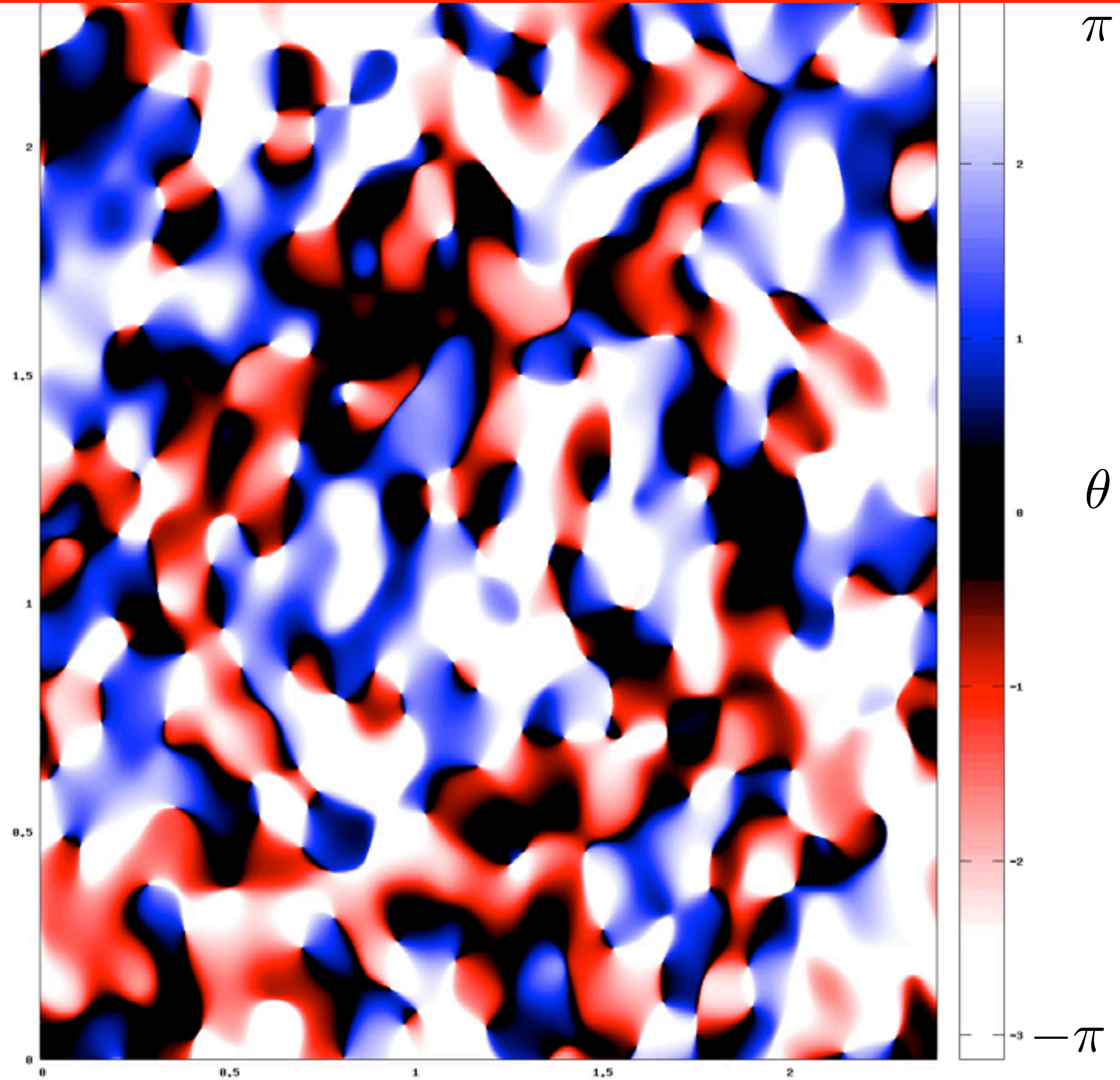
Oscillation frequency

$$\omega = m_a$$

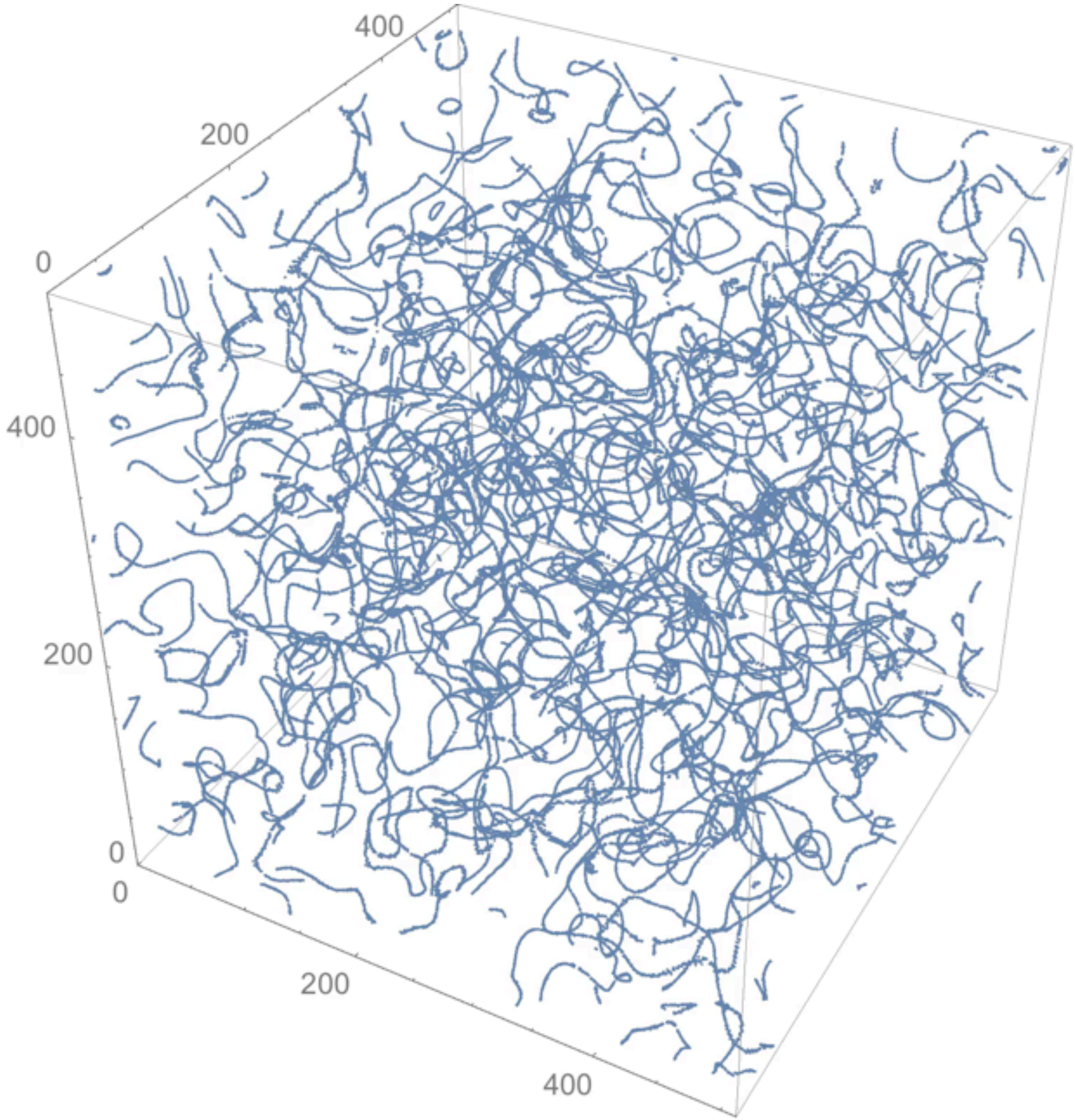
Energy density (harm. oscillator)

$$\rho_{\mathrm{aDM}} = \frac{1}{2} m_a^2 f_a^2 \theta_0^2 = \frac{1}{2} (75\mathrm{MeV})^4 \theta_0^2$$

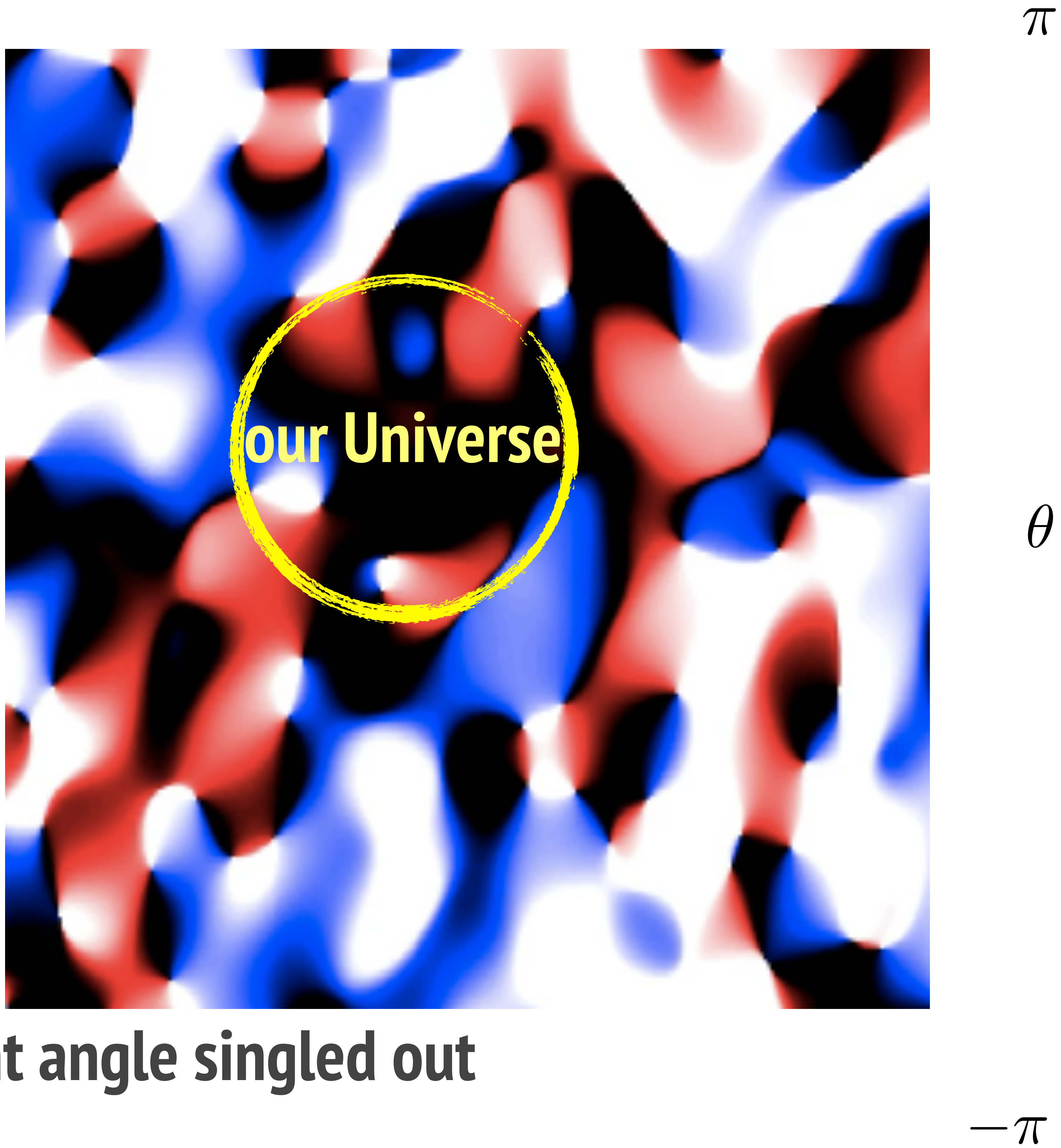
Theta evolution, Averaged SCENARIO I



Strings

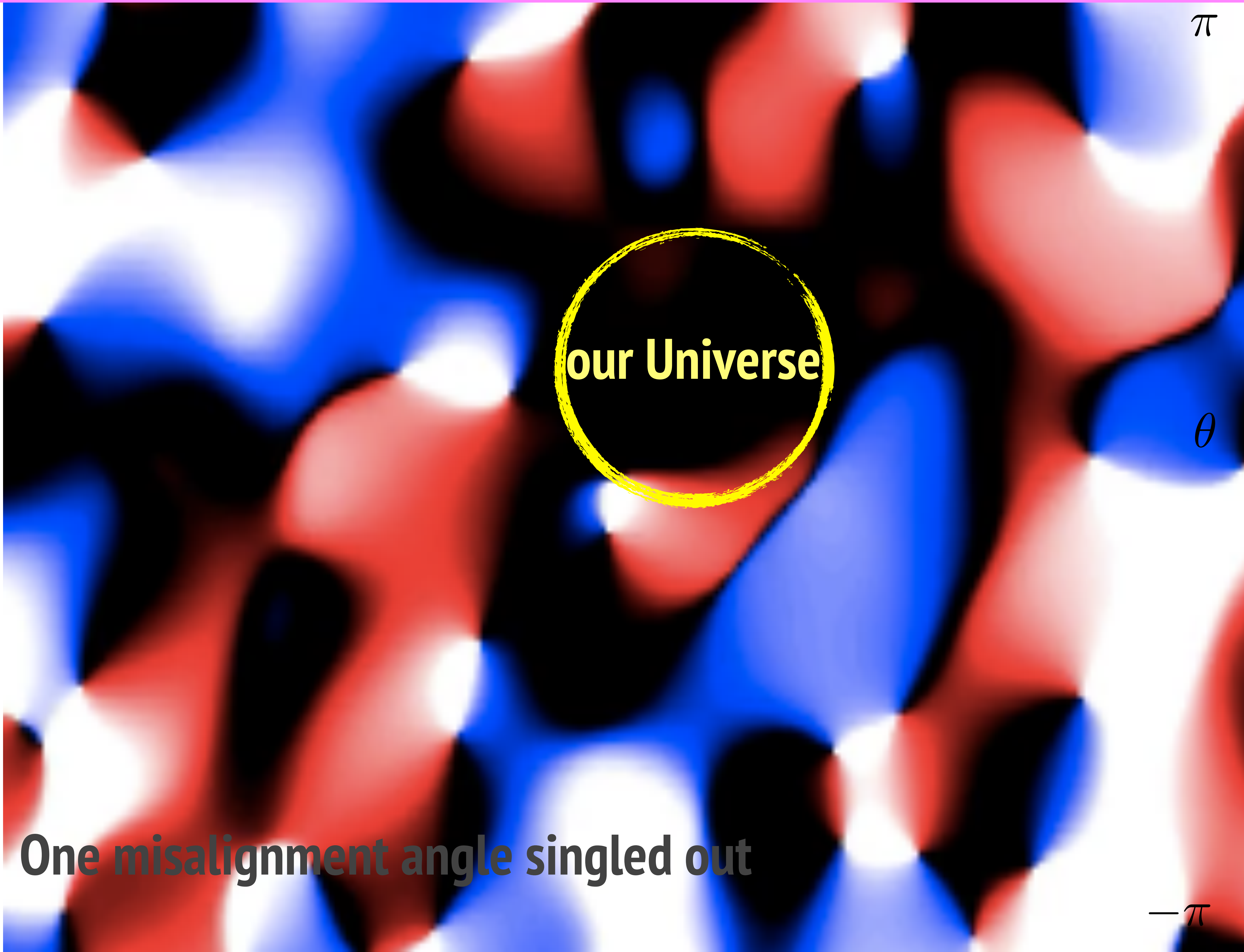


Theta evolution, inflated SCENARIO I



One misalignment angle singled out

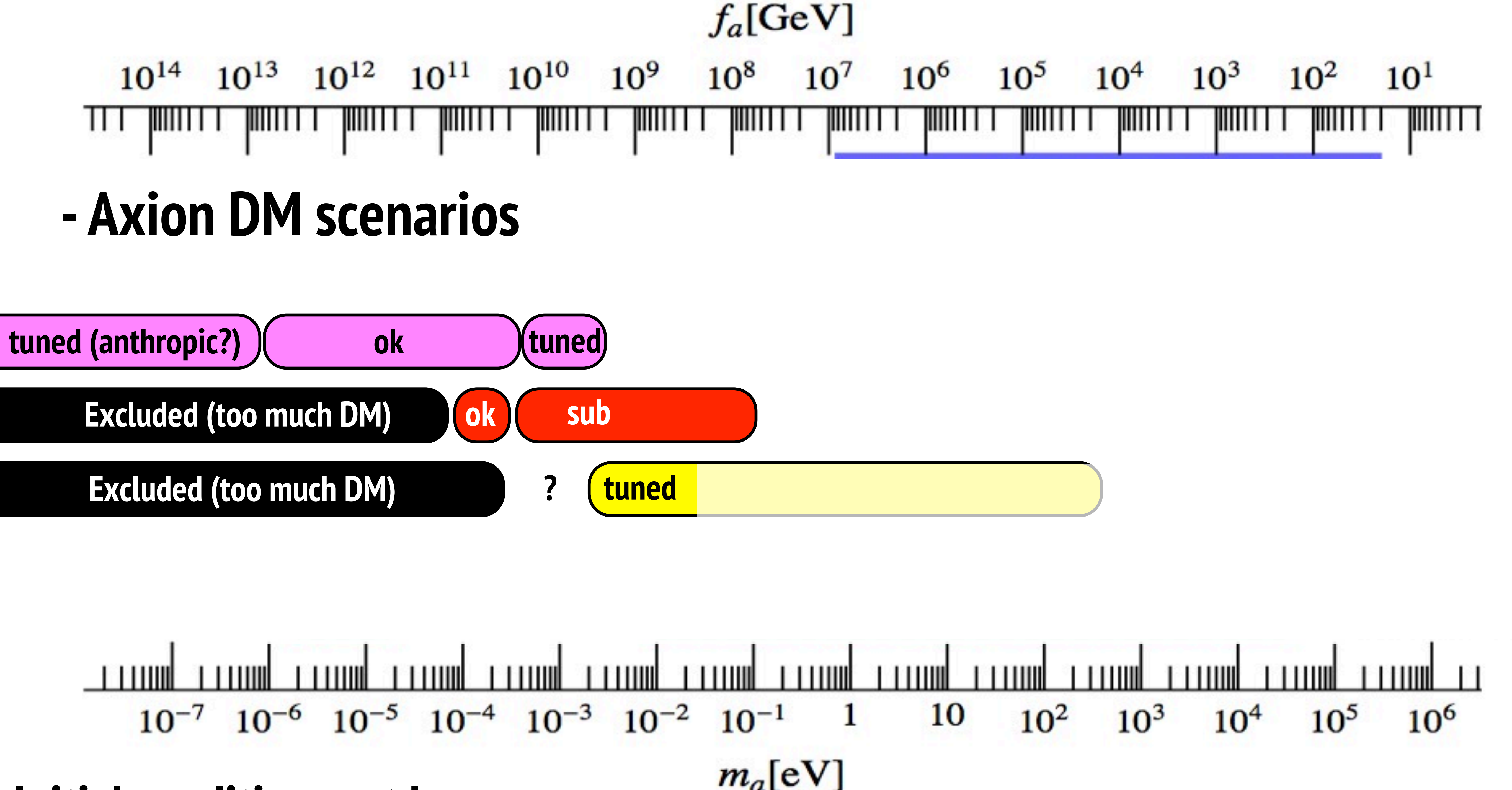
Theta evolution, inflated SCENARIO I



One misalignment angle singled out

Axion dark matter

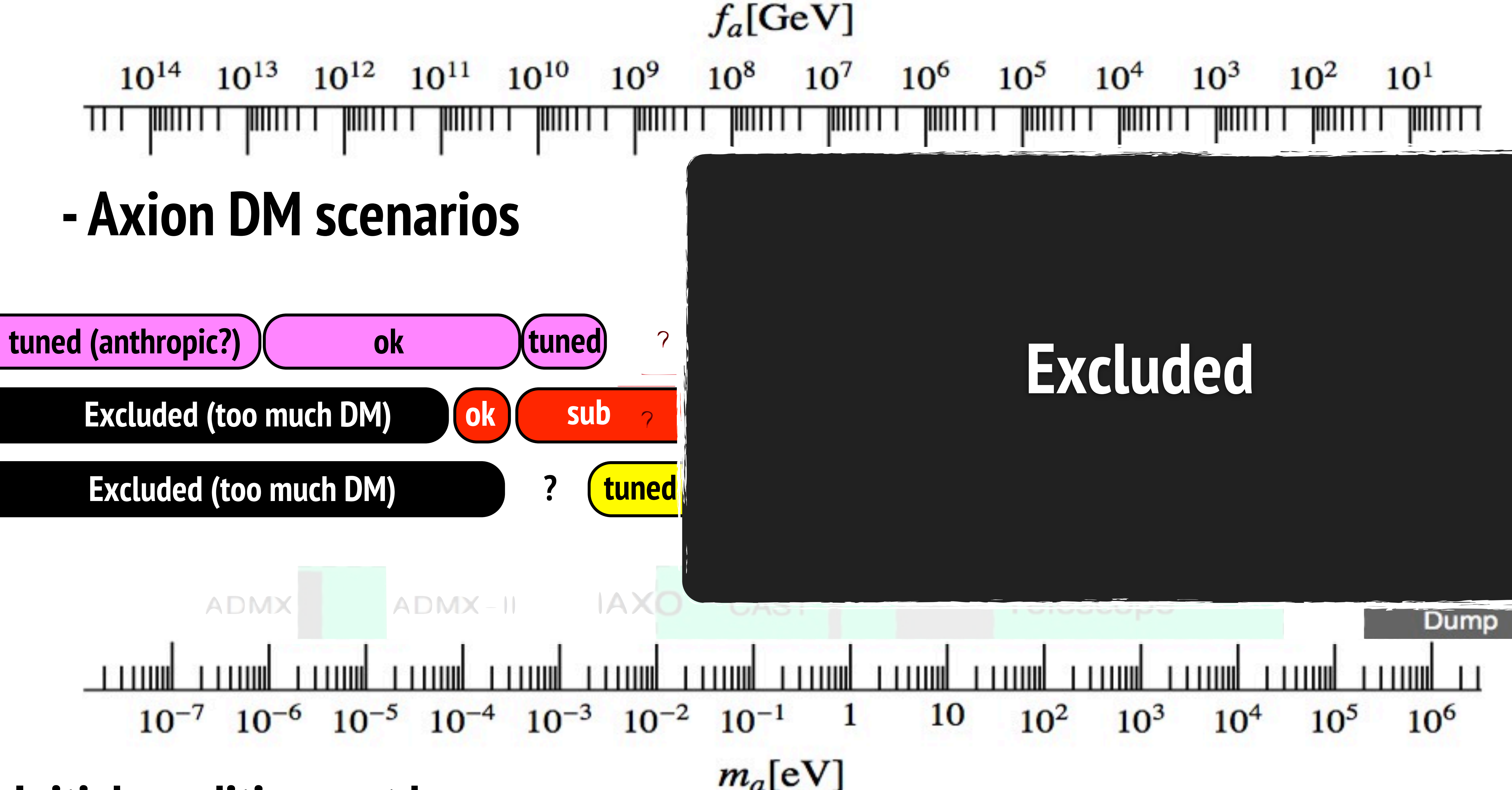
- Axion DM scenarios



Initial conditions set by :

Inflation smooth	Phase transition (N=1)	Phase transition (N>1)
$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu\text{eV}}{m_a}\right)^{1.19}$	strings+unstable DW's	strings+long-lived DWs

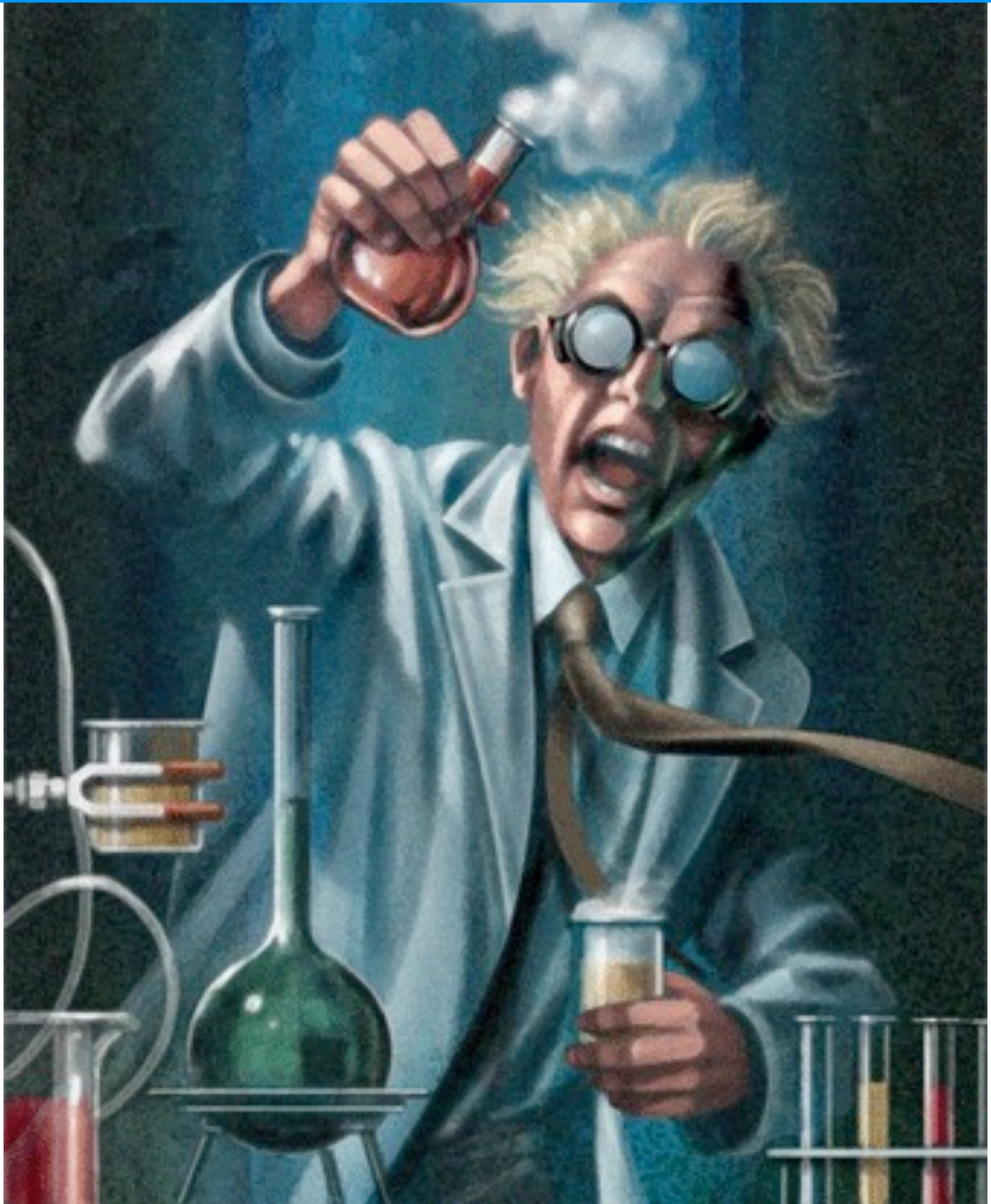
Axion dark matter



Initial conditions set by :

Inflation smooth	Phase transition (N=1)	Phase transition (N>1)
$\Omega_{\mathrm{aDM}} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu\mathrm{eV}}{m_a}\right)^{1.19}$	strings+unstable DW's	strings+long-lived DWs

Detecting Axions

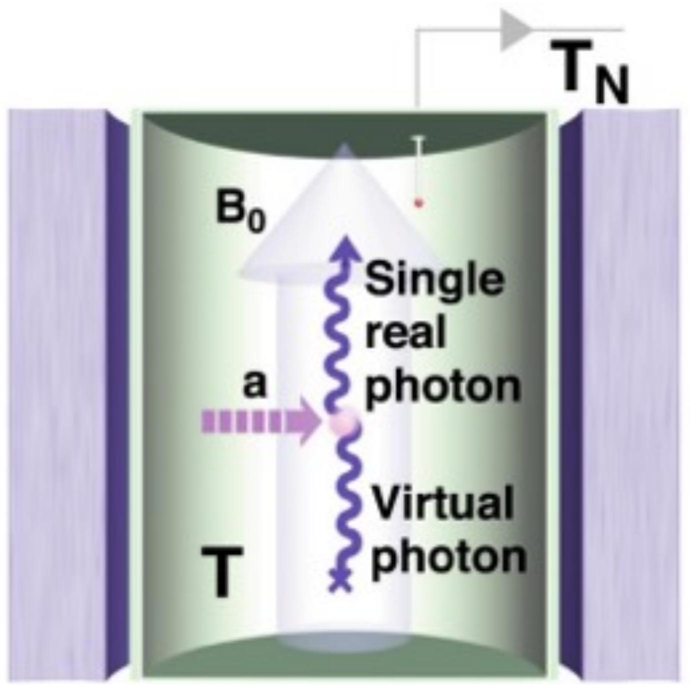


$$\rho_{\mathrm{aDM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

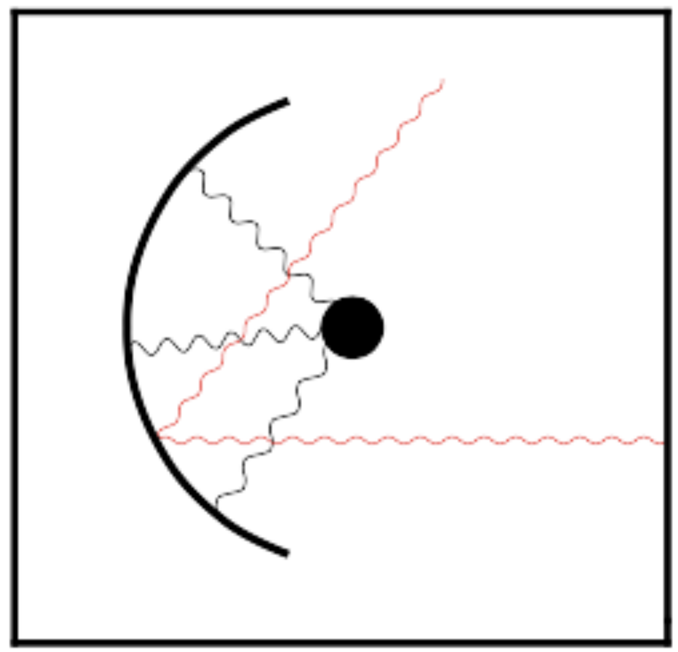
$$\Downarrow$$

$$\theta_0 = 3.6 \times 10^{-19}$$

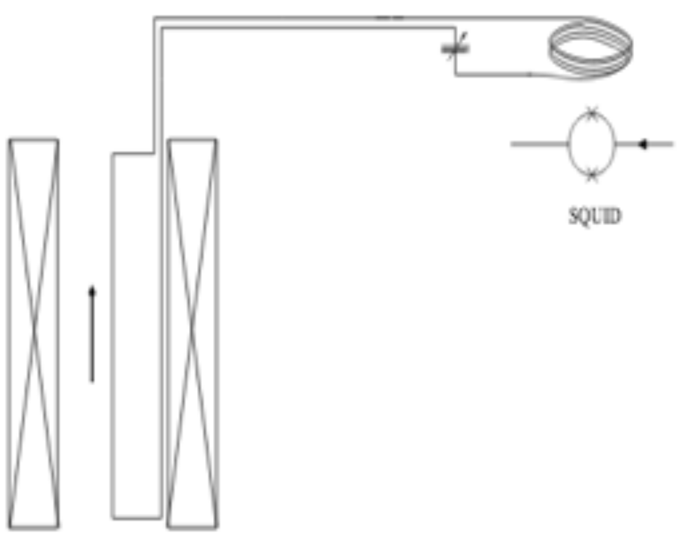
Cavities



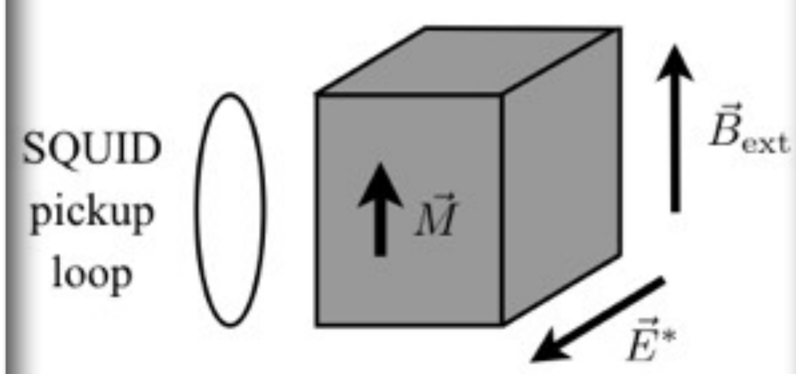
Mirrors



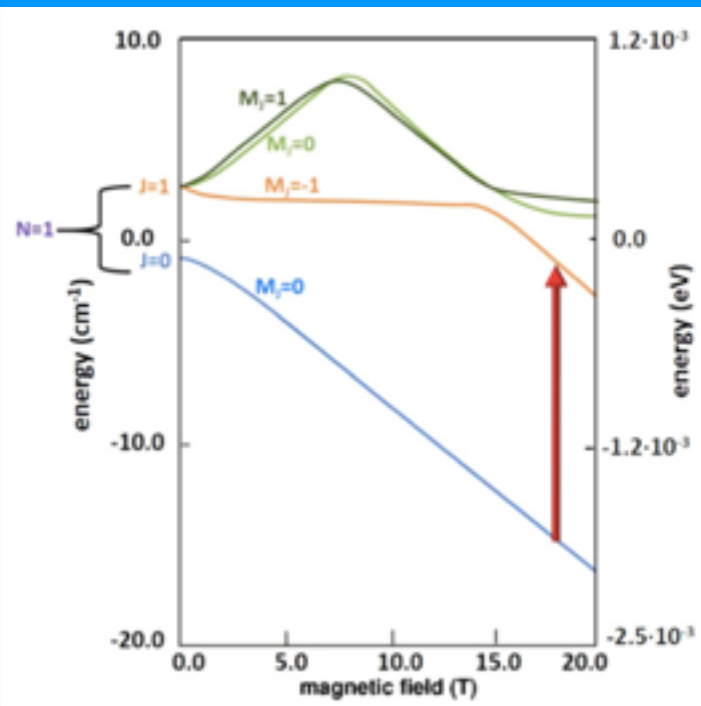
LC-circuit



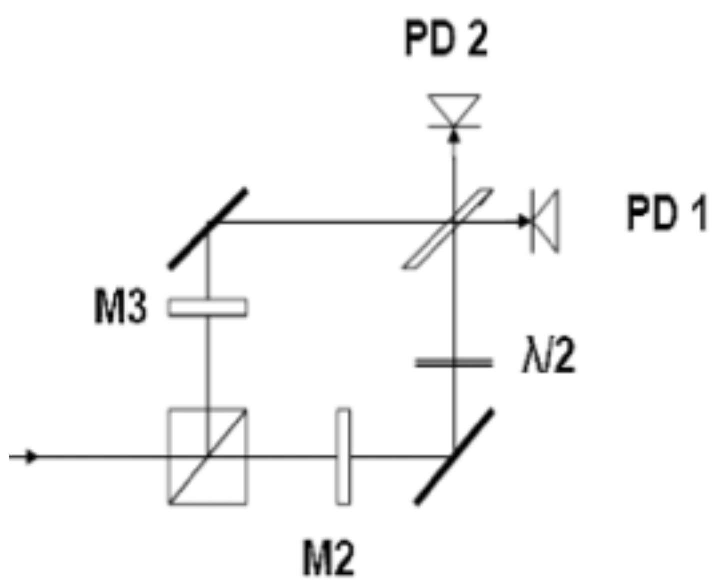
Spin precession



Atomic transitions

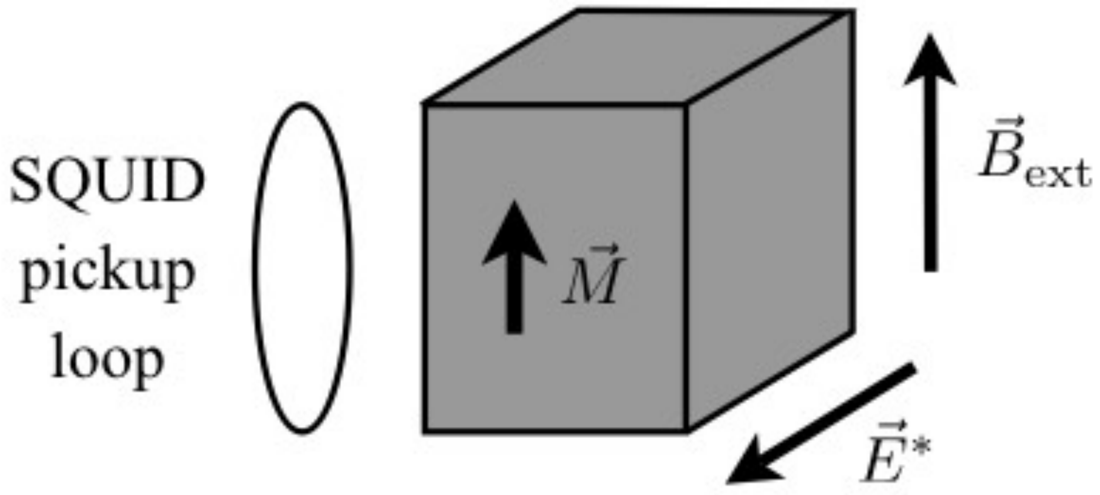


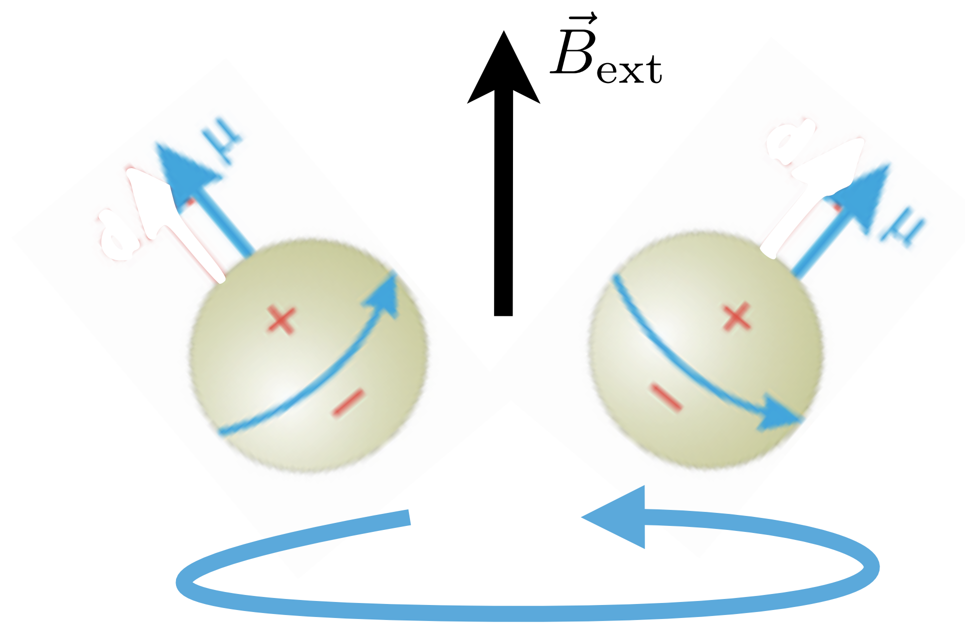
Optical



CASPER: Cosmic Axion Spin Precession exPERiment

Graham 2012



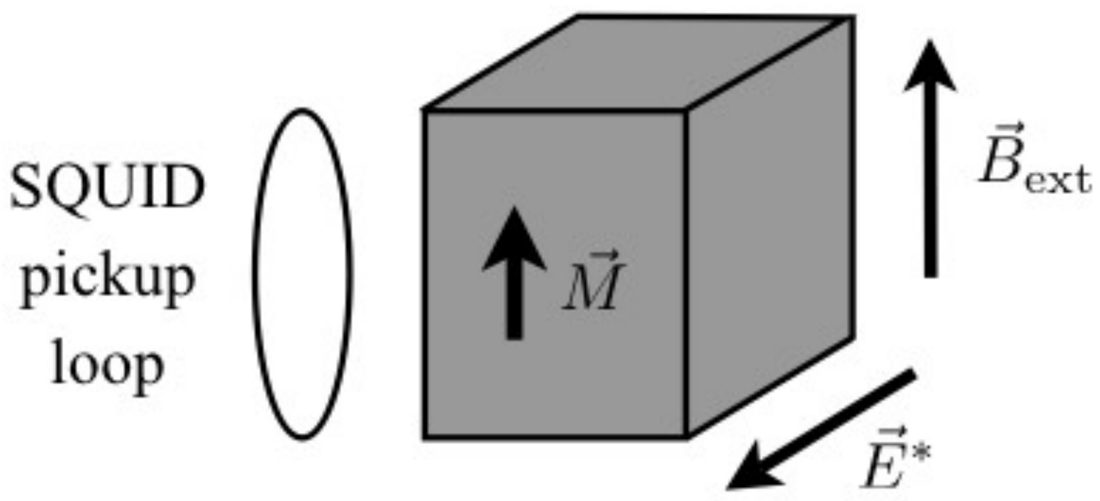


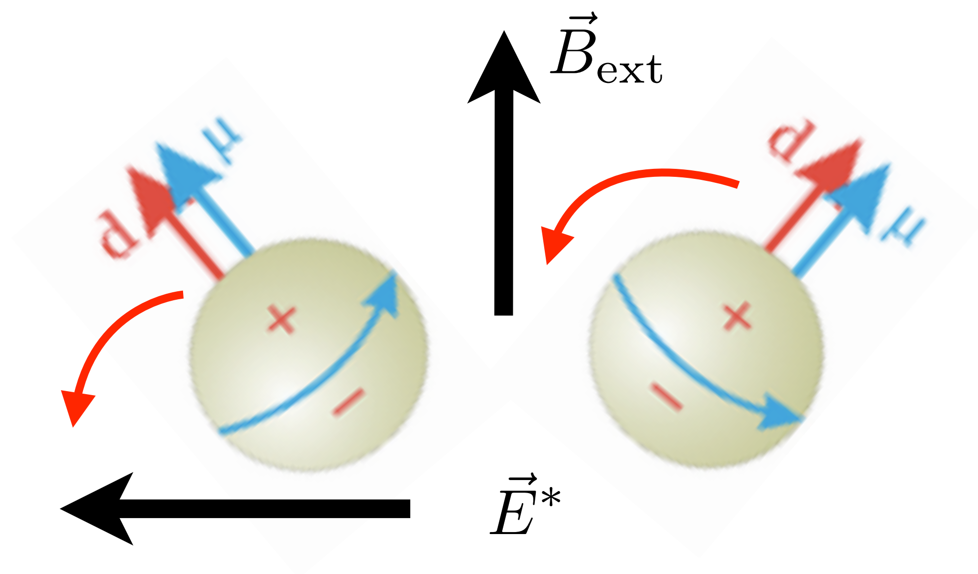
Spin precesion

$$\omega = \mu|\vec{B}_{\text{ext}}|$$

CASPER : Spin precession

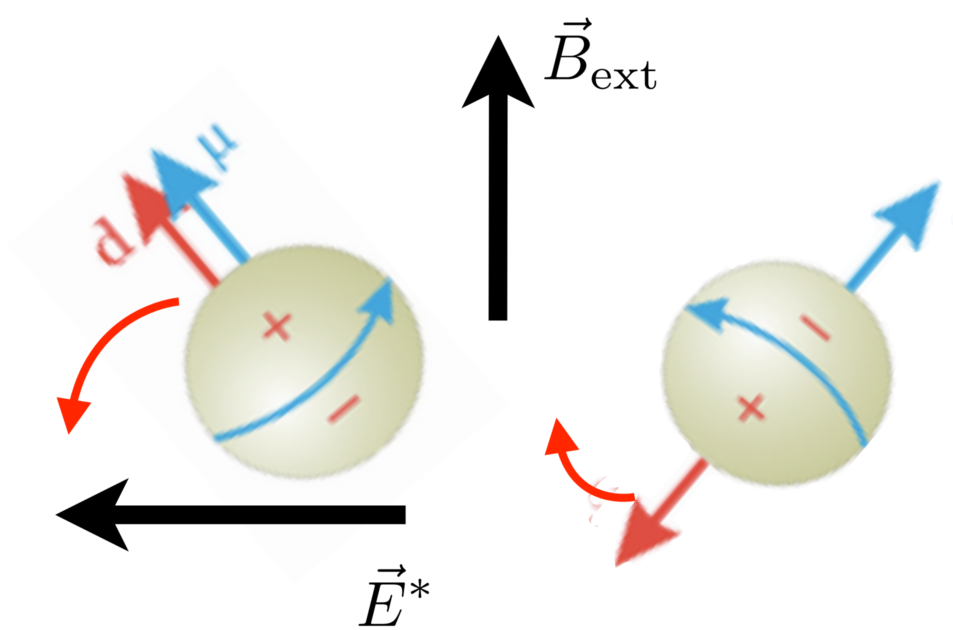
Mainz, Berkeley





Static EDM, effects cancel in a period

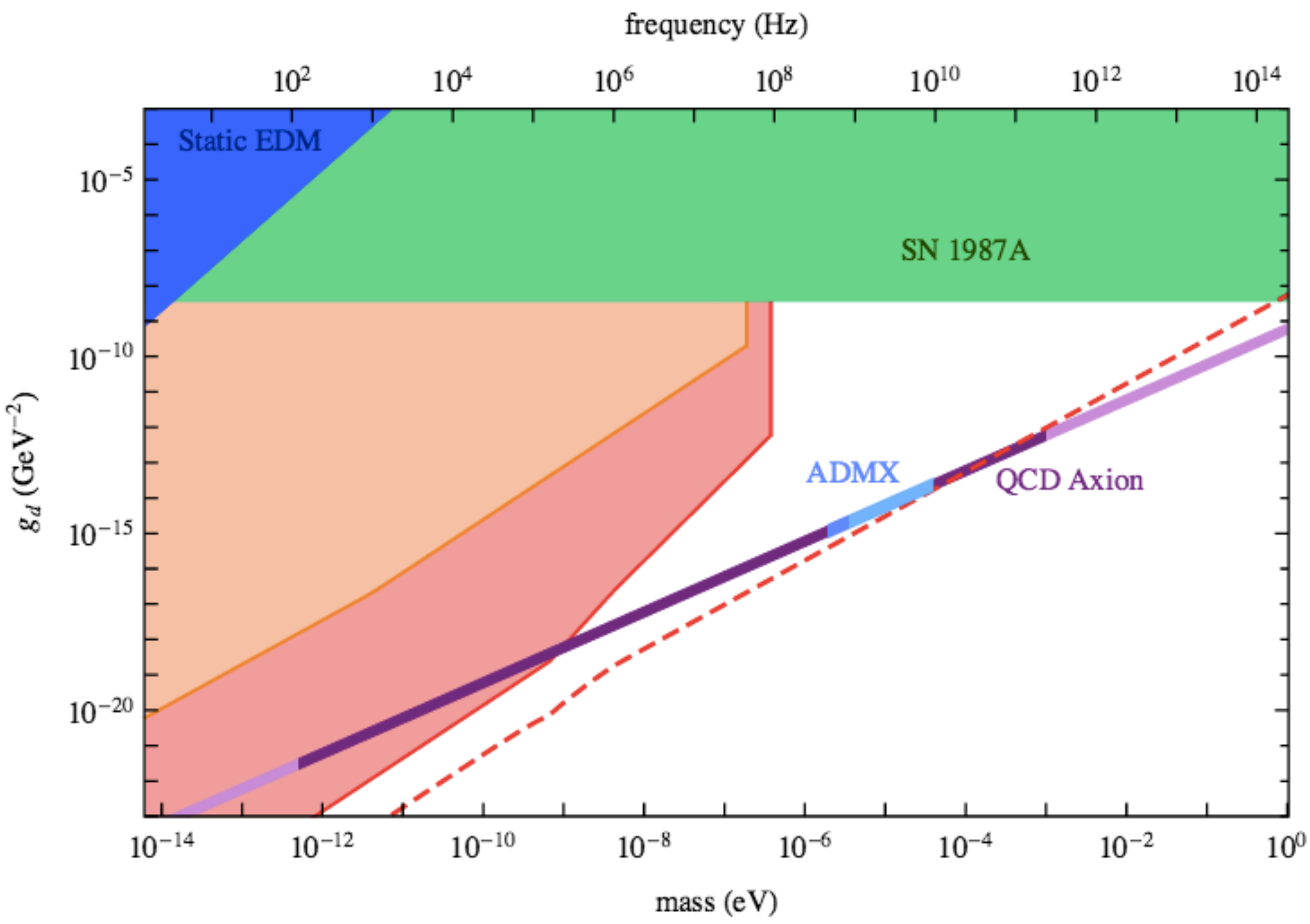
- EDM + Large E-fields in PbTiO3
- Scan over frequencies, with Bext
- Mainz (D. Budker's group) & Berkeley
- Phase I starts in 2016, Phase II physics results
- Mass range limited by B-field strength



Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\rm ext}|$

CASPER : Spin precession

Mainz, Berkeley

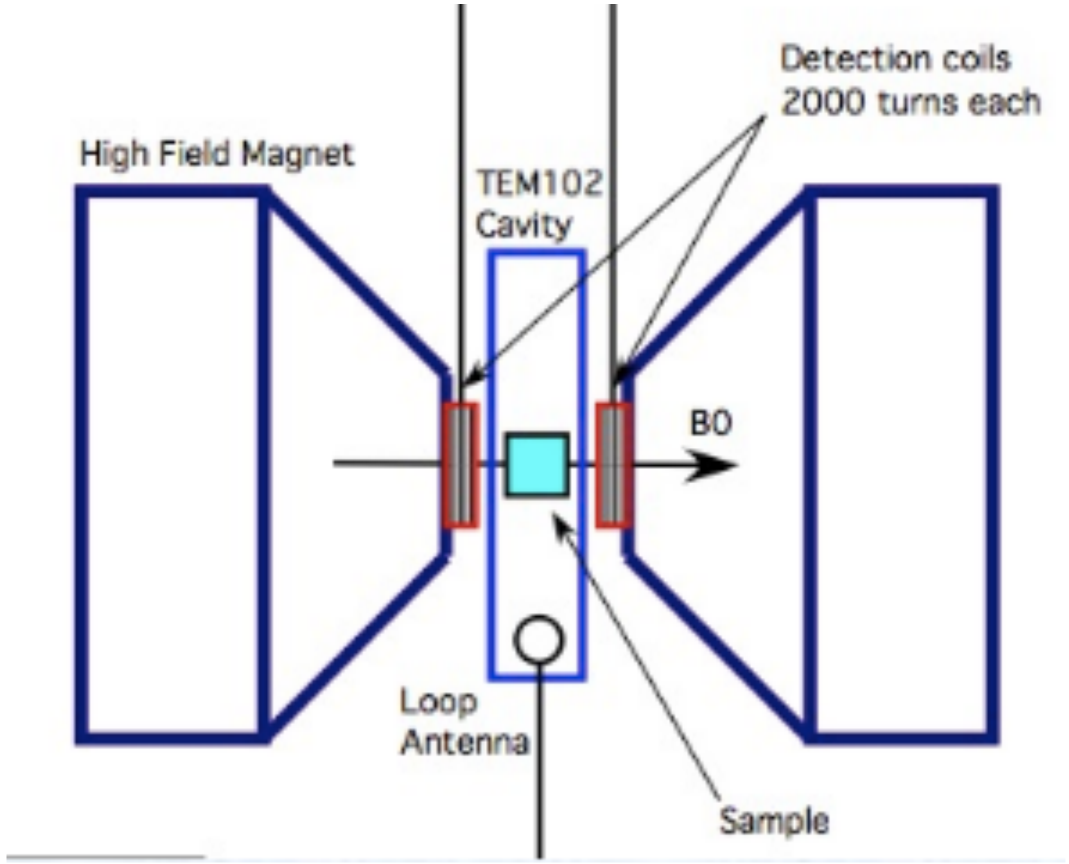


QUAX : electron Spin precession

- Electron coupling in the non-relativistic limit, Electron spin - axion "wind"

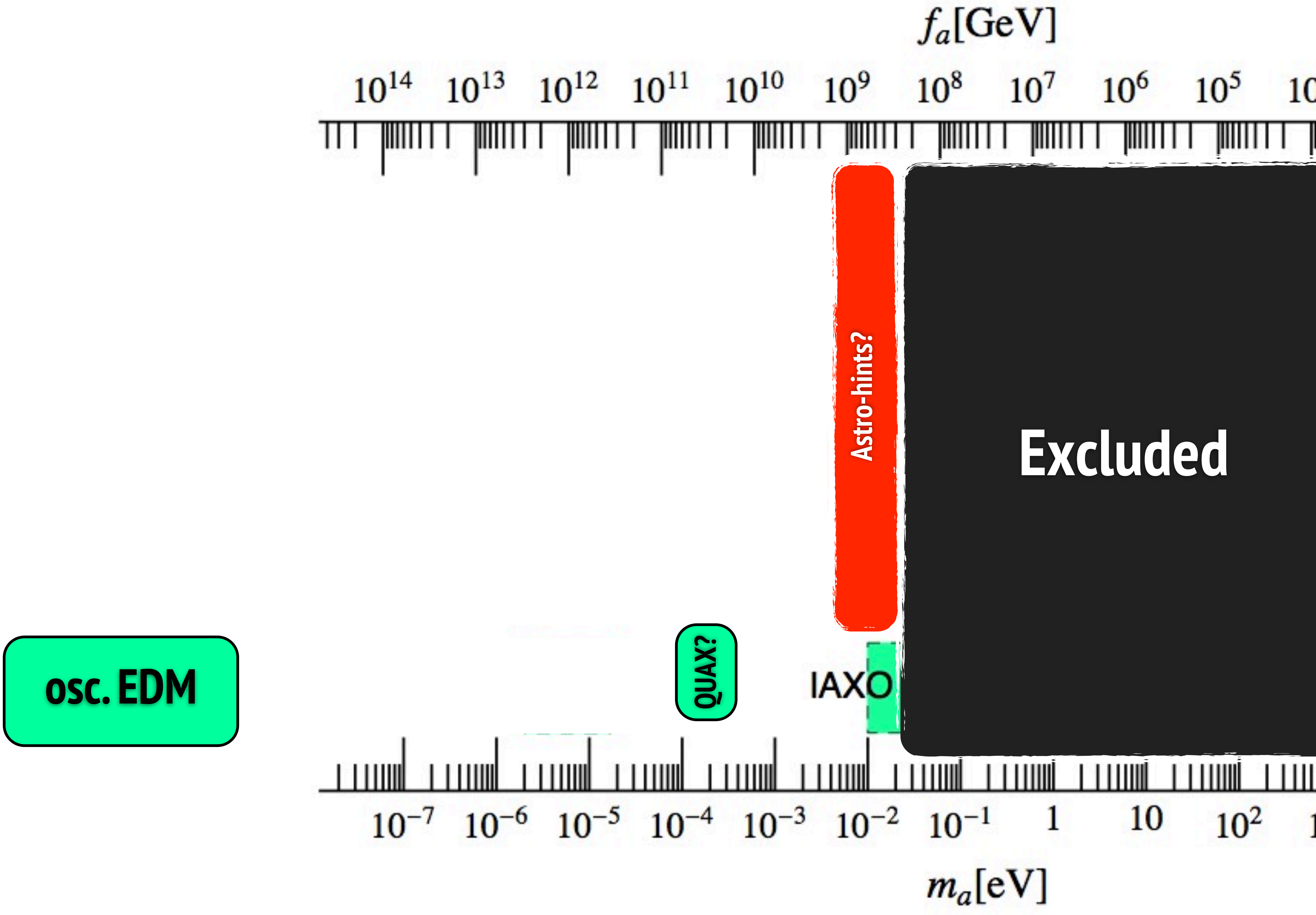
$$\mathcal{L}_{ae} = C_{ae}[\bar{e}\gamma^{\mu}\gamma_5 e]\partial_{\mu}\theta \quad \rightarrow \quad C_{ae}(\nabla\theta)\cdot\sigma_e\mu_B \quad \sim \quad \underbrace{C_{ae}m_a\langle\vec{v}\rangle\theta}\cdot\sigma_e\mu_B$$

Effective Magnetic field



- Use Electron Spin Resonance (similar to NMR but with electrons) $\omega = \mu_B \vec{B}_{\rm ext} = m_a$
- Bohr magneton much larger, smaller B-fields required for large axion mass
- Short coherence times, radiation damping (R+D)
- HF detection ? Use non-linearity and search for LF oscillations $\omega \sim \mu_B|\vec{B}_{\rm ext}| - m_a$

Future sensitivity



Detecting axion DM

- **Axion DM,** $\theta = \theta_0 \cos(m_a t)$**, in a B-field is a source in Maxwell's eq.**

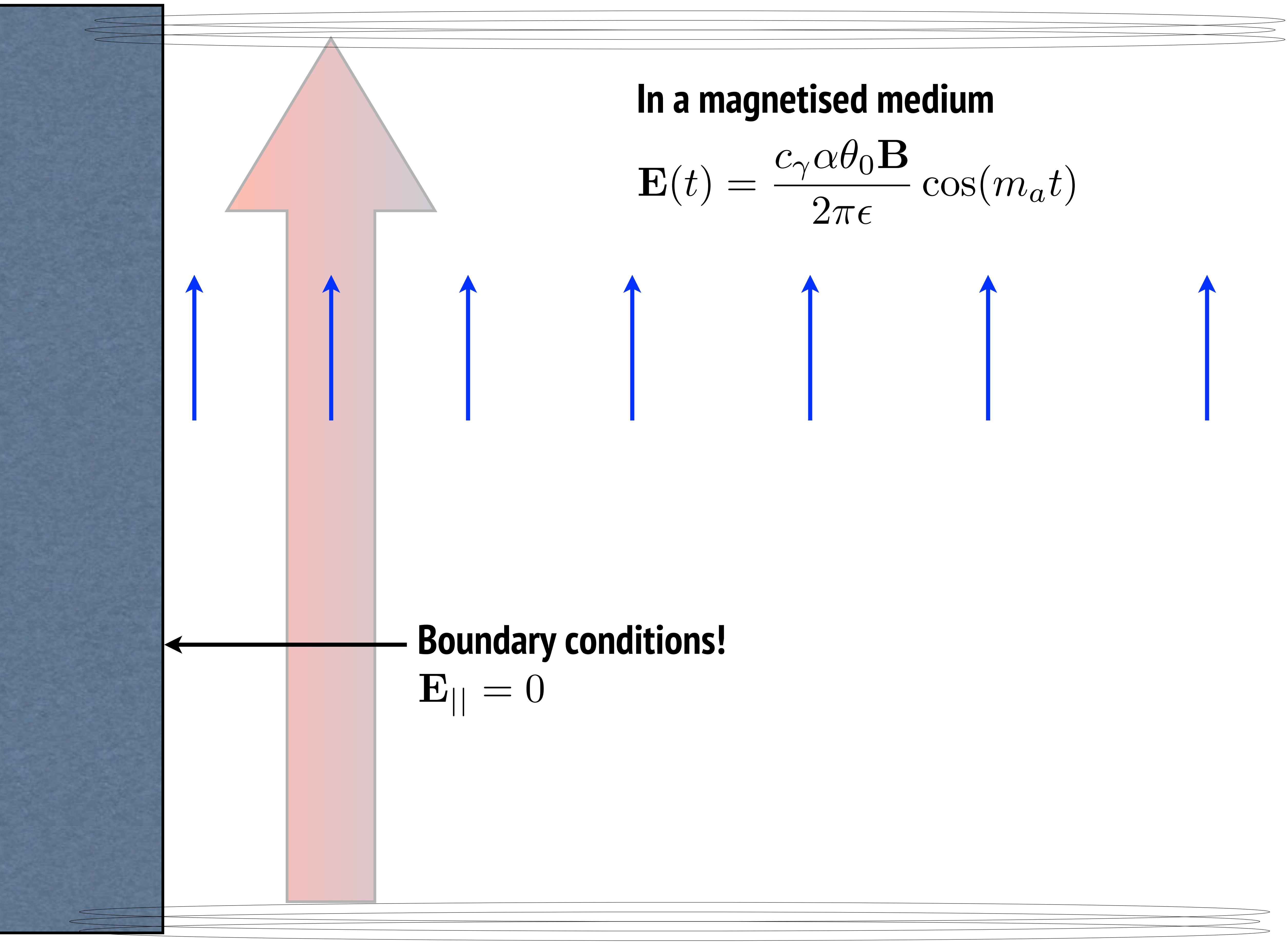
$$
\begin{aligned}
\nabla \cdot \mathbf{D} &= \rho_f \\
\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J}_f - c_\gamma \frac{\alpha}{2\pi} \mathbf{B} \frac{\partial \theta}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} &= 0
\end{aligned}
$$

→

In a magnetised medium

$$
\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)
$$

Radiation from a magnetised mirror



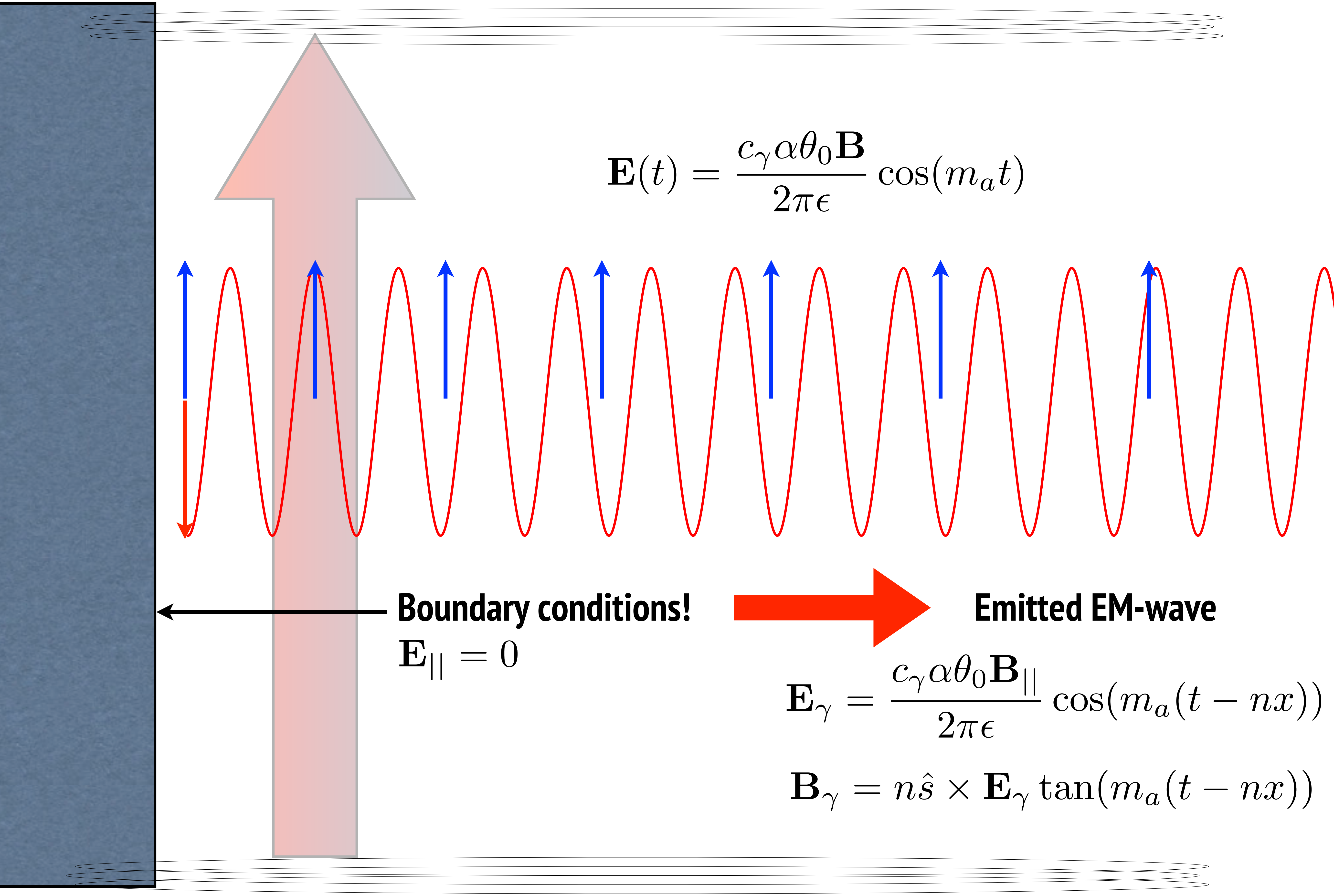
In a magnetised medium

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

Boundary conditions!

$$\mathbf{E}_{||} = 0$$

Radiation from a magnetised mirror



$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

Boundary conditions!

$\mathbf{E}_{||} = 0$

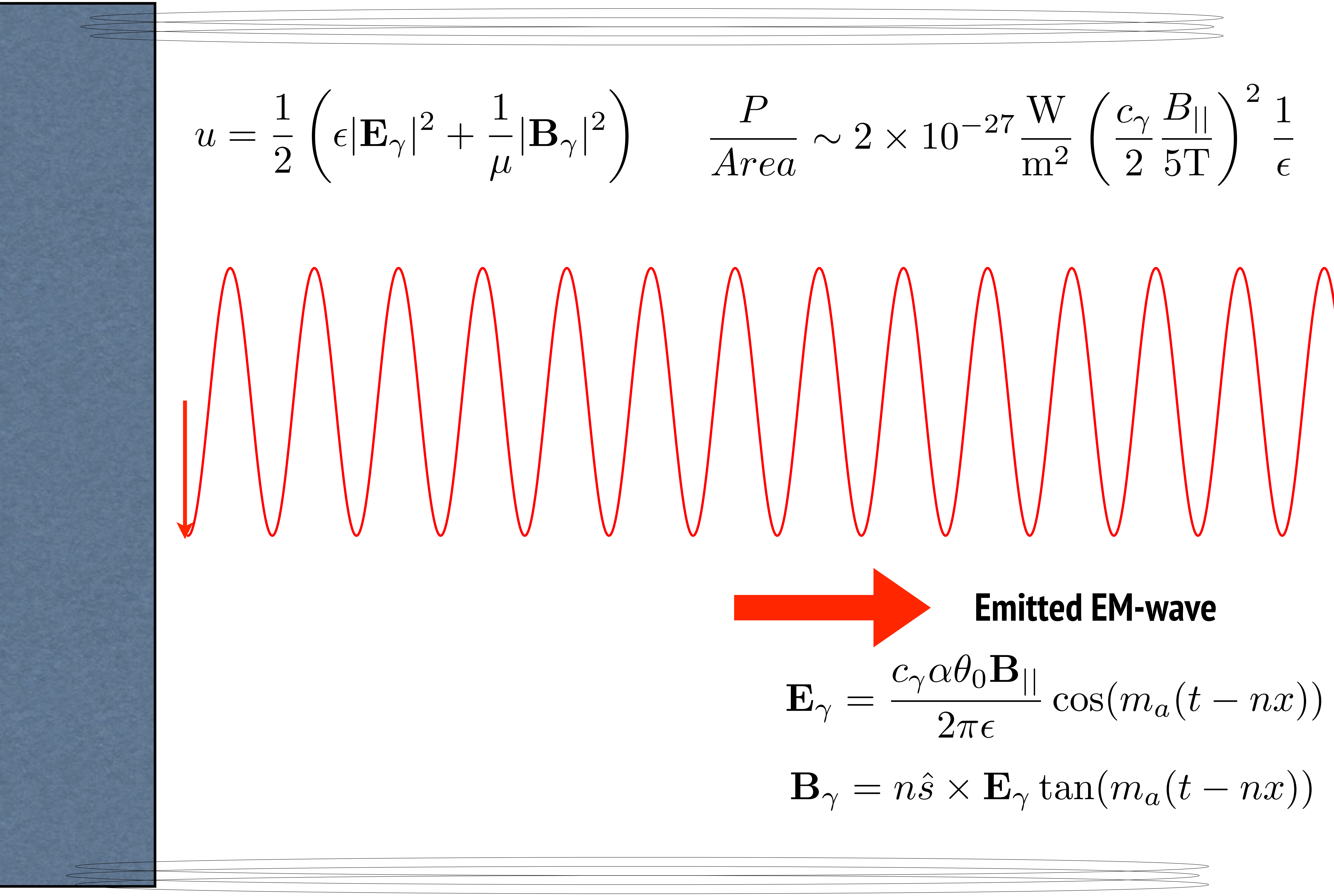
Emitted EM-wave

$$\mathbf{E}_\gamma = \frac{c_\gamma \alpha \theta_0 \mathbf{B}_{||}}{2\pi\epsilon} \cos(m_a(t - nx))$$

$$\mathbf{B}_\gamma = n\hat{s} \times \mathbf{E}_\gamma \tan(m_a(t - nx))$$

Radiation from a magnetised mirror : Power

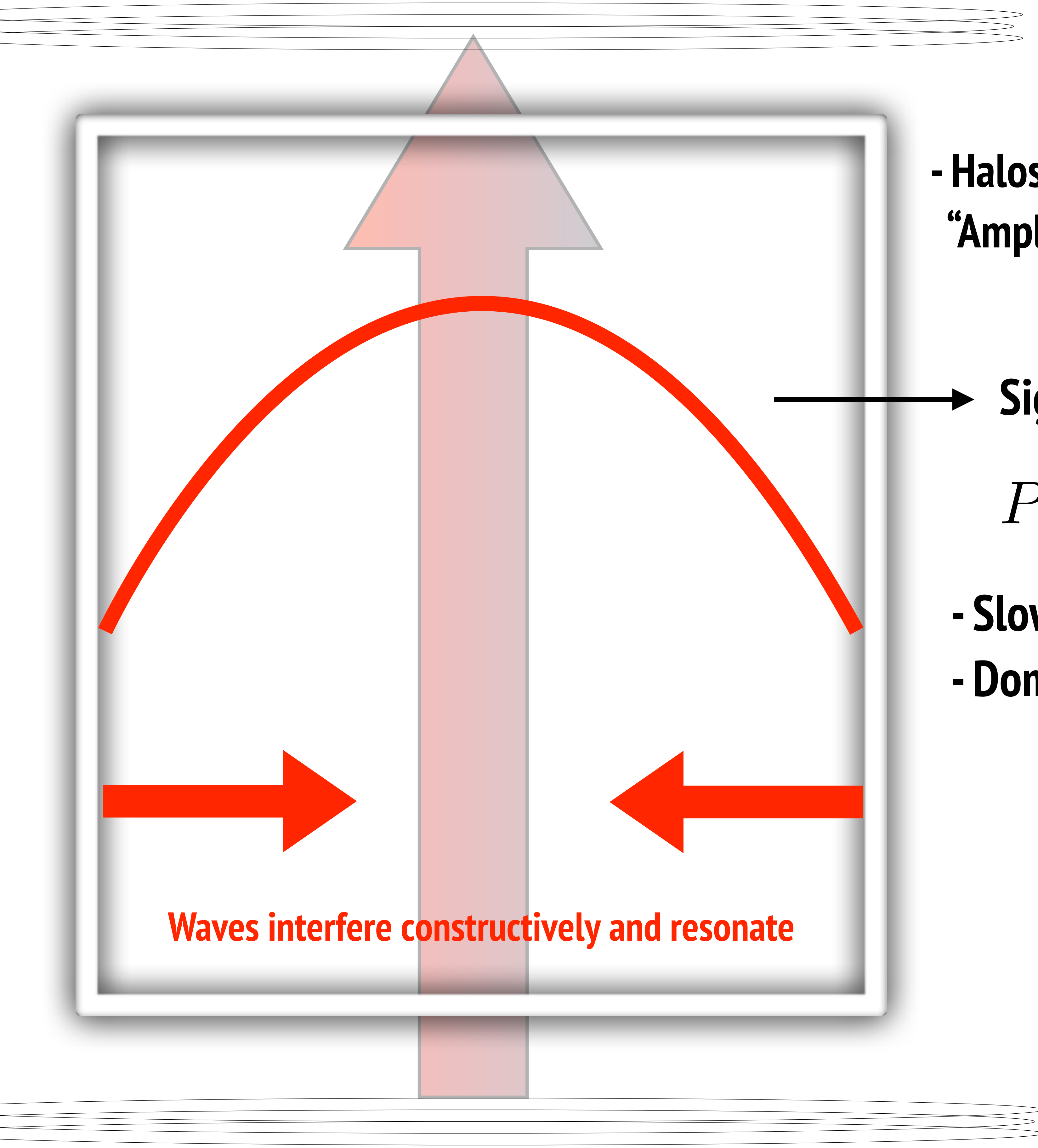
$$u = \frac{1}{2}\left(\epsilon|\mathbf{E}_\gamma|^2 + \frac{1}{\mu}|\mathbf{B}_\gamma|^2\right) \qquad \frac{P}{Area} \sim 2 \times 10^{-27}\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\frac{B_{||}}{5\mathrm{T}}\right)^2\frac{1}{\epsilon}$$



$$\mathbf{E}_\gamma = \frac{c_\gamma \alpha \theta_0 \mathbf{B}_{||}}{2\pi\epsilon}\cos(m_a(t - nx))$$

$$\mathbf{B}_\gamma = n\hat{s} \times \mathbf{E}_\gamma \tan(m_a(t - nx))$$

Cavity experiments



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

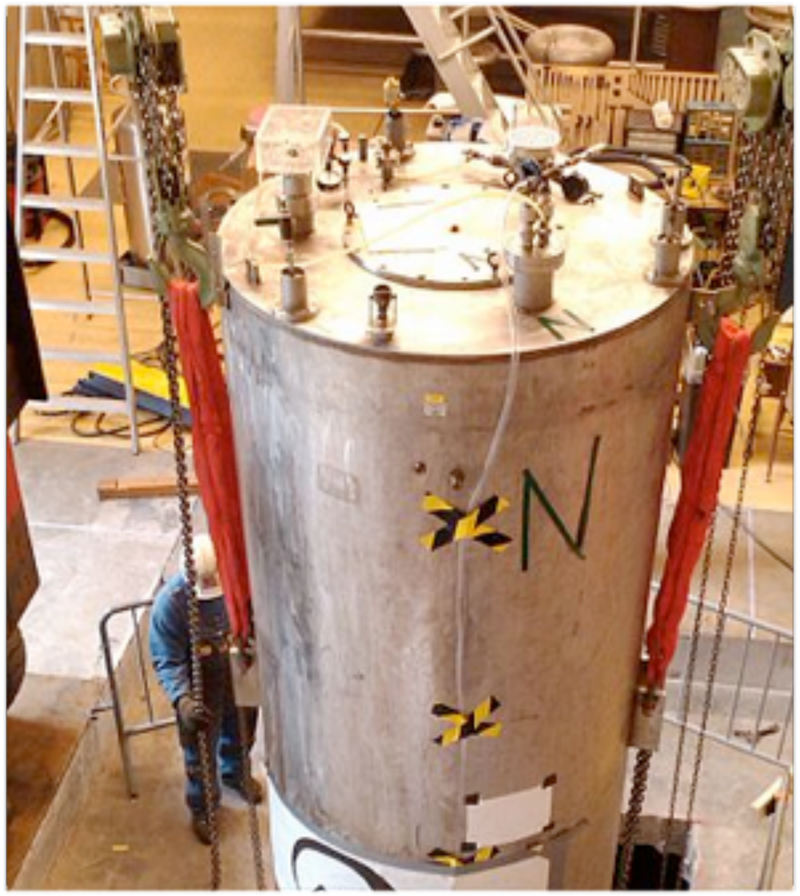
Signal if tuned $m_a = \omega_{\rm res}$

$$P \to P \times Q$$

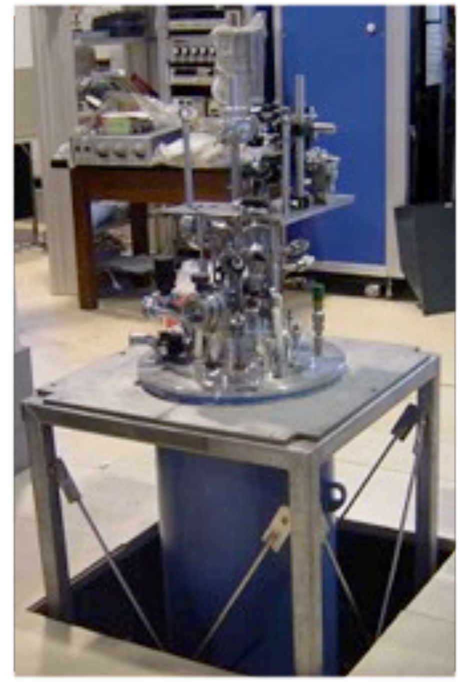
- Slow scan over frequencies
- Dominated by thermal+preamp noise

Cavity experiments

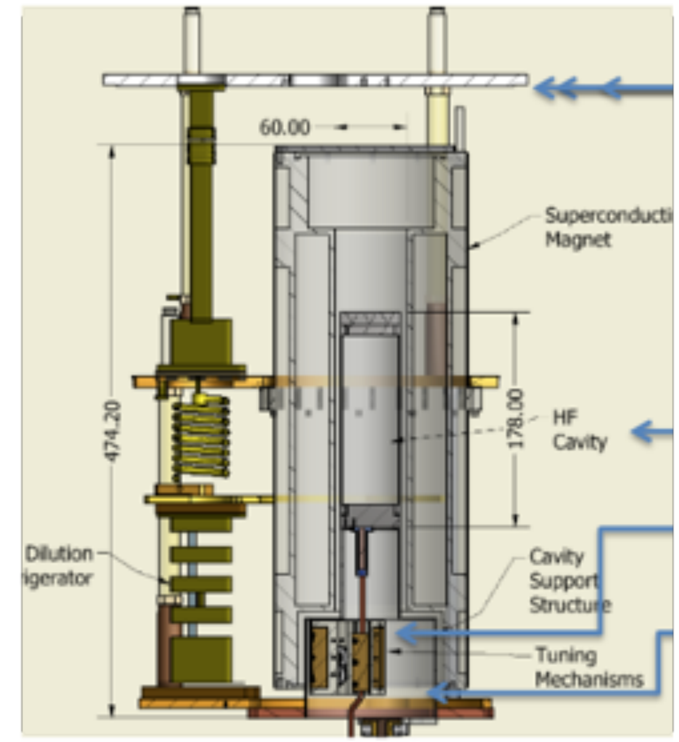
ADMX



CARRACK (discontinued)

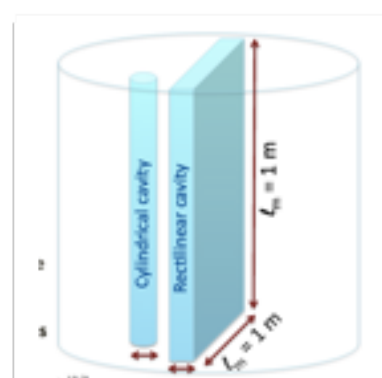


CULTASK - CAPP -Korea

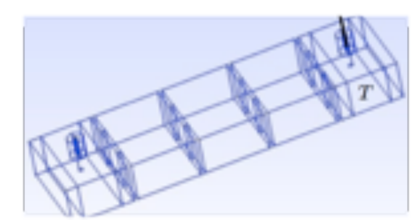


ADMX-HF

ADMX-Fermilab

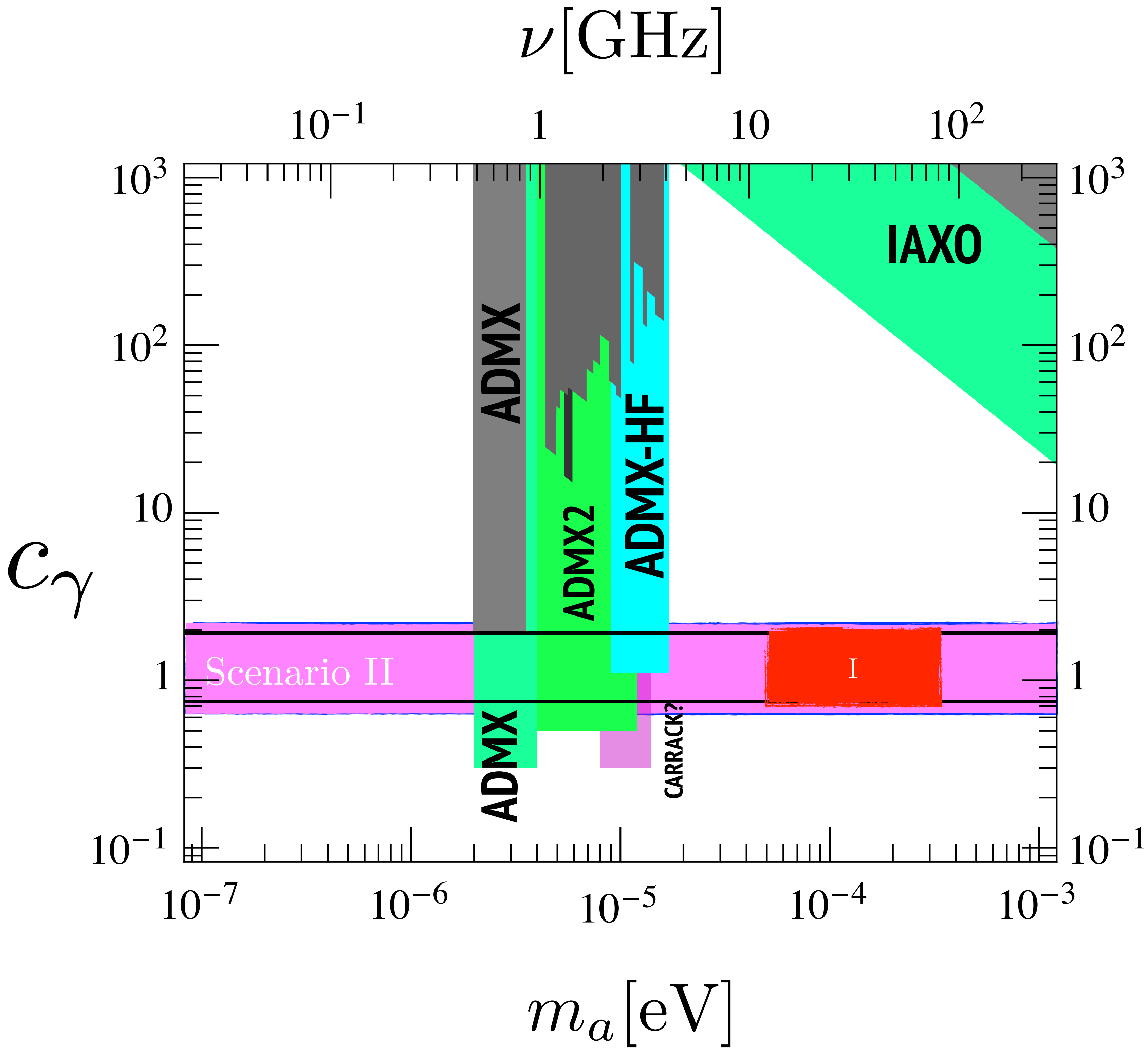


RADES



CAST-CAPP

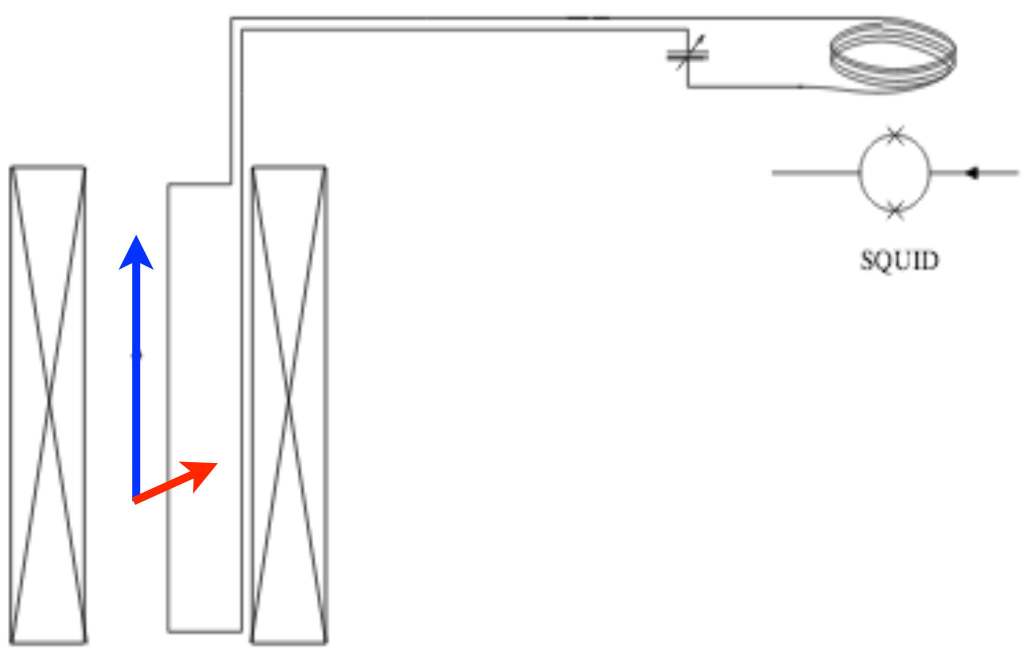
Cavity experiments



LC- circuit

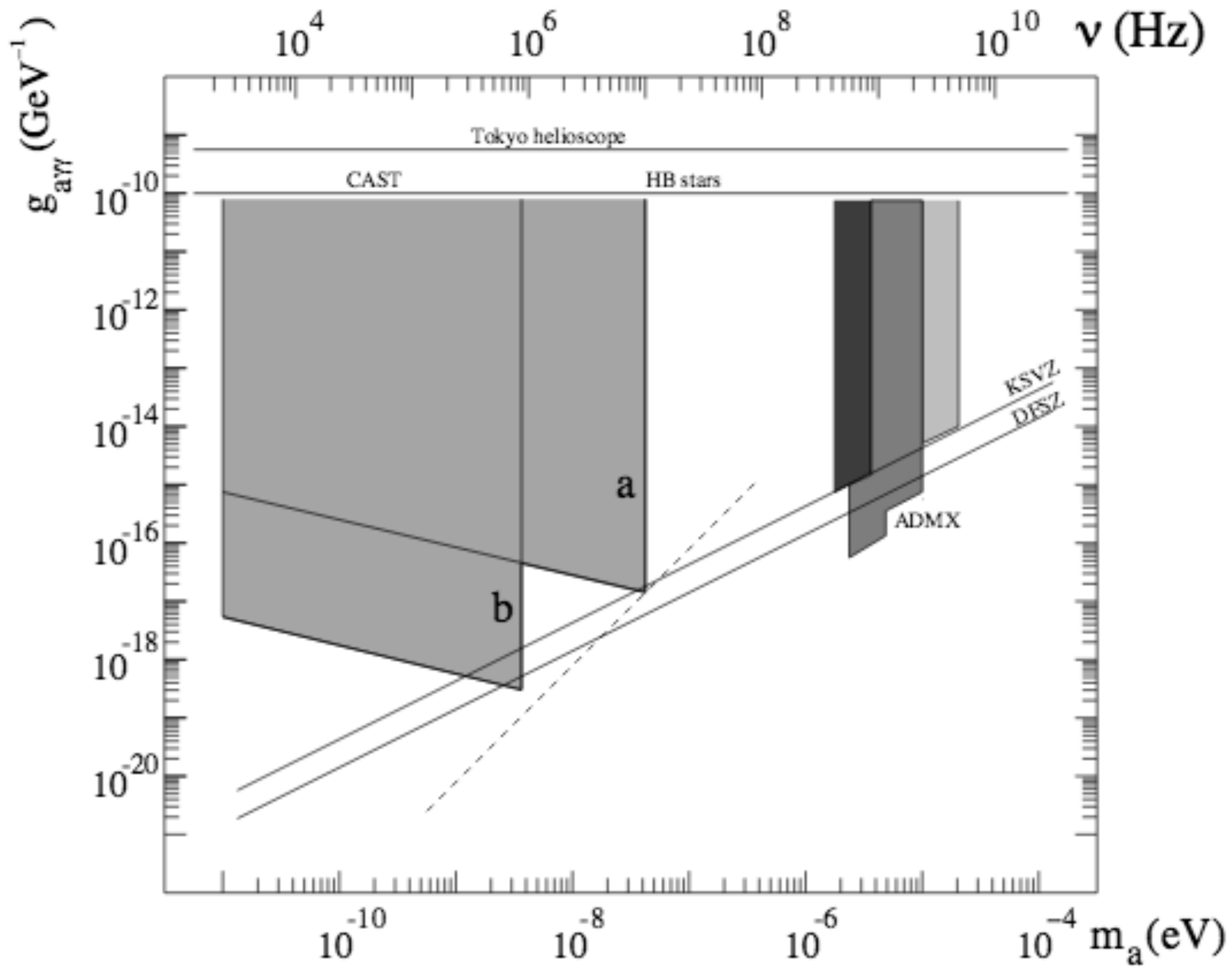
Sikivie 2012

- Detect low-frequency B-field with a tunable LC
- First moves in Florida U.

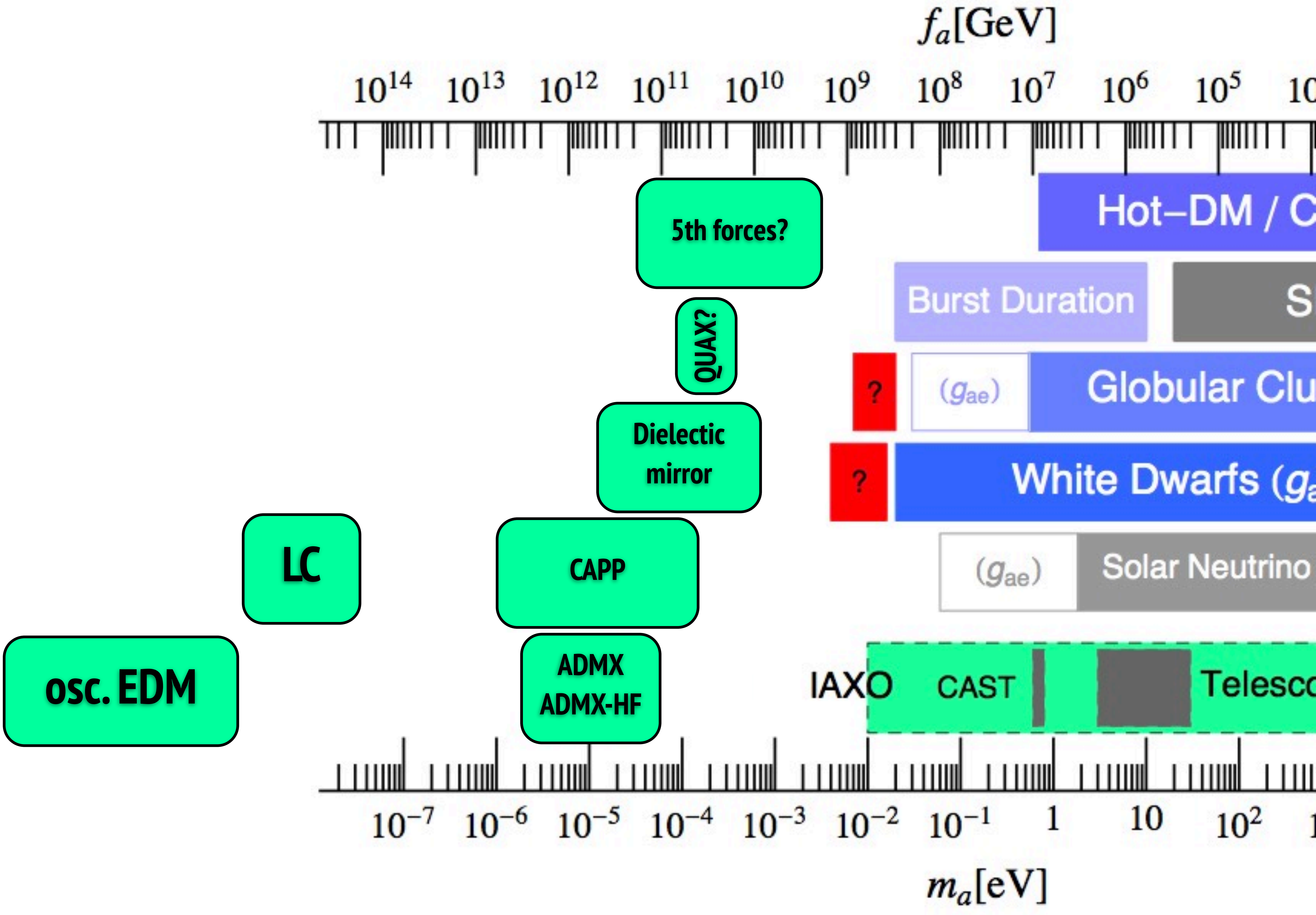


$$|\mathbf{B}_a| \sim \langle v \rangle |\mathbf{E}_a|$$

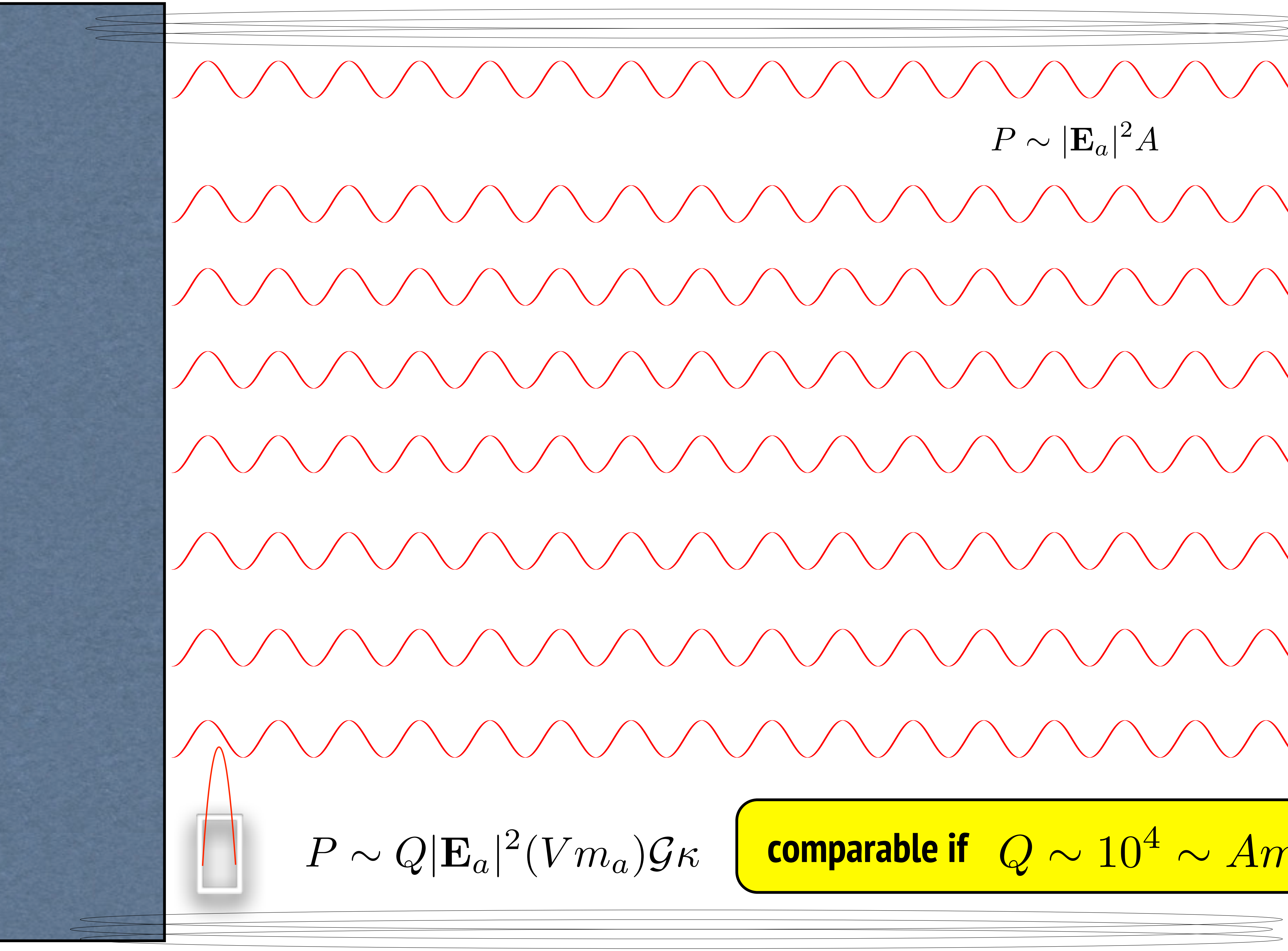
Earth-DM relative velocity



Axion DM : A developing picture



Large freq ... Area vs volume



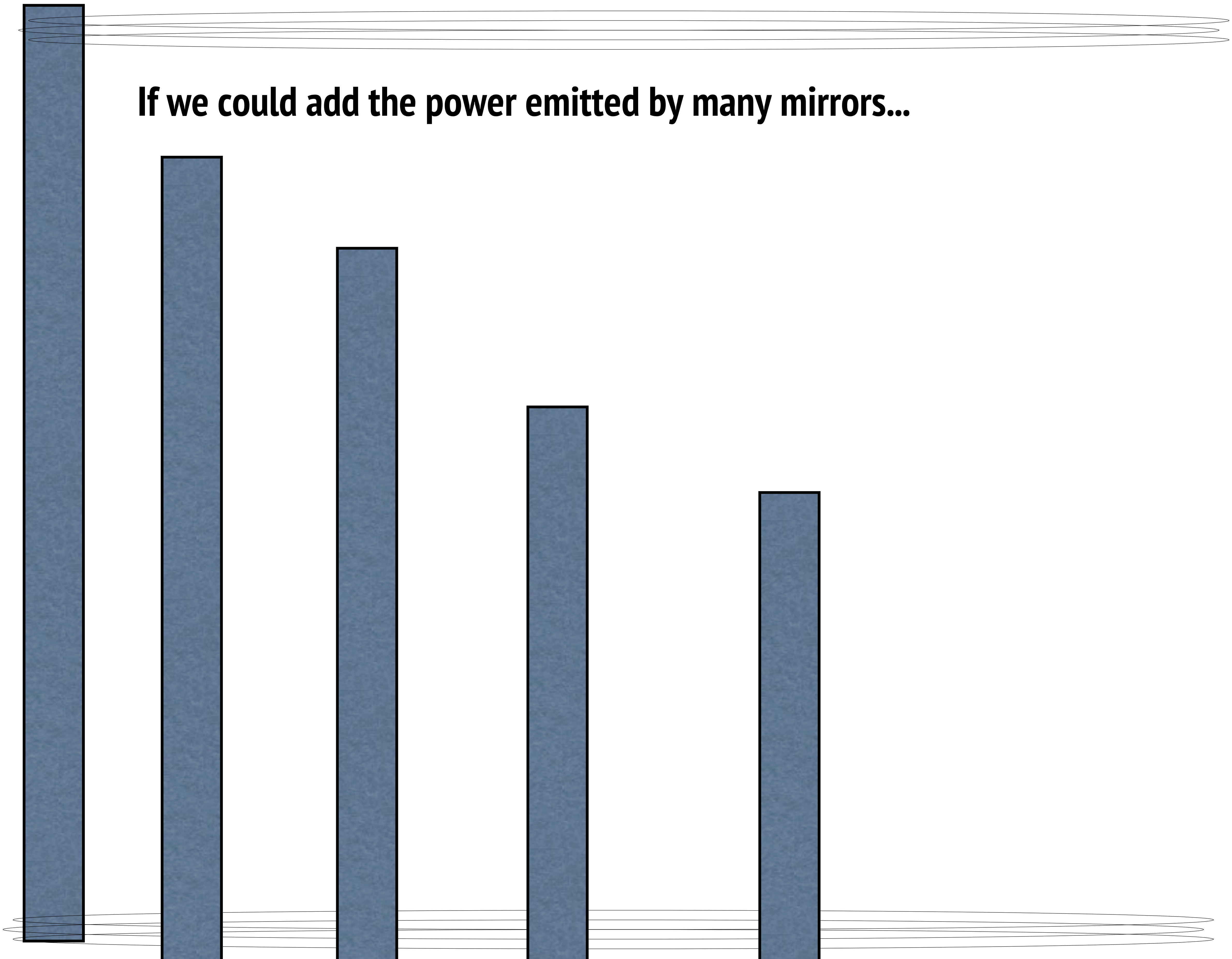
$$P \sim |\mathbf{E}_a|^2 A$$

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

comparable if $Q \sim 10^4 \sim A m_a^2$

Mixed scheme?

If we could add the power emitted by many mirrors...



Radiation from a dielectric interface ...

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

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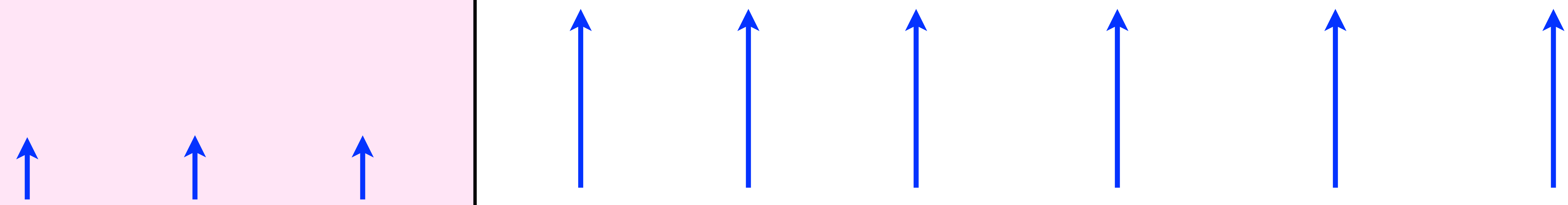

← **Boundary conditions!**

$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

Radiation from a dielectric interface ...

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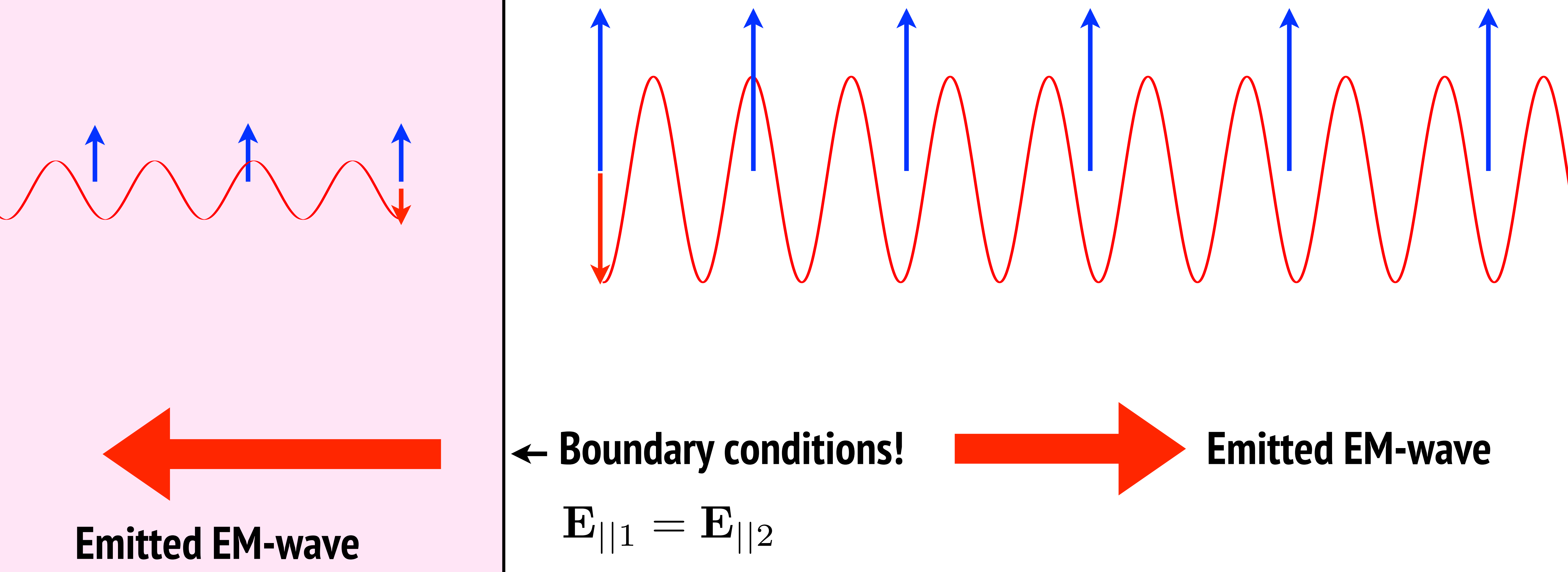
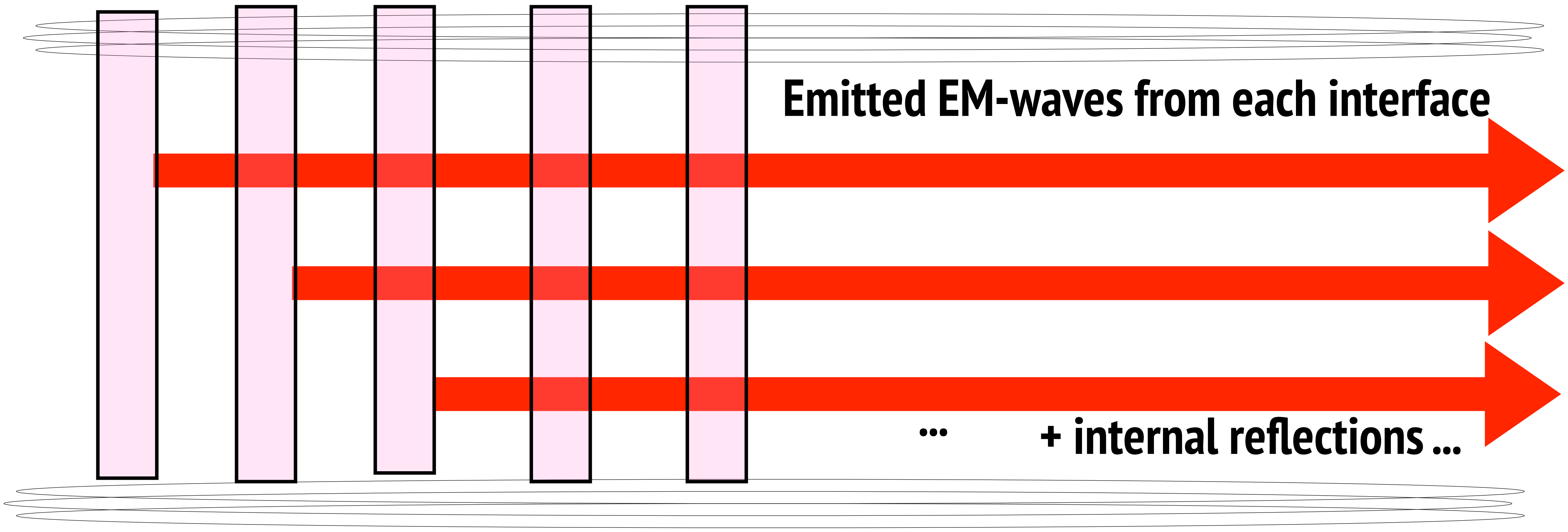


$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

Many dielectrics : MADMAX at MPP Munich



- Emission has large spatial coherence; adjusting plate separation -> coherence

$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{c_\gamma}{2} \frac{B_{||}}{5\mathrm{T}} \right)^2 \frac{1}{\epsilon} \times \beta(\omega)$$

boost factor

- Work in progress at Max Planck Institute fur Physik (Conceptual design)