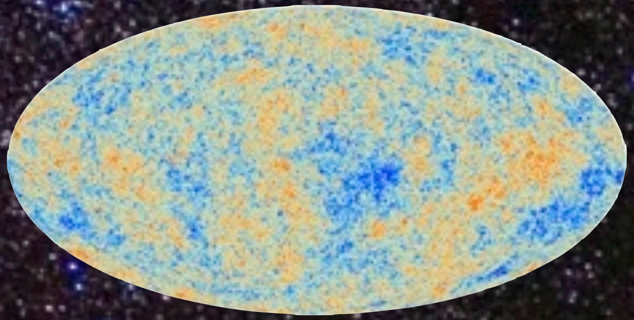
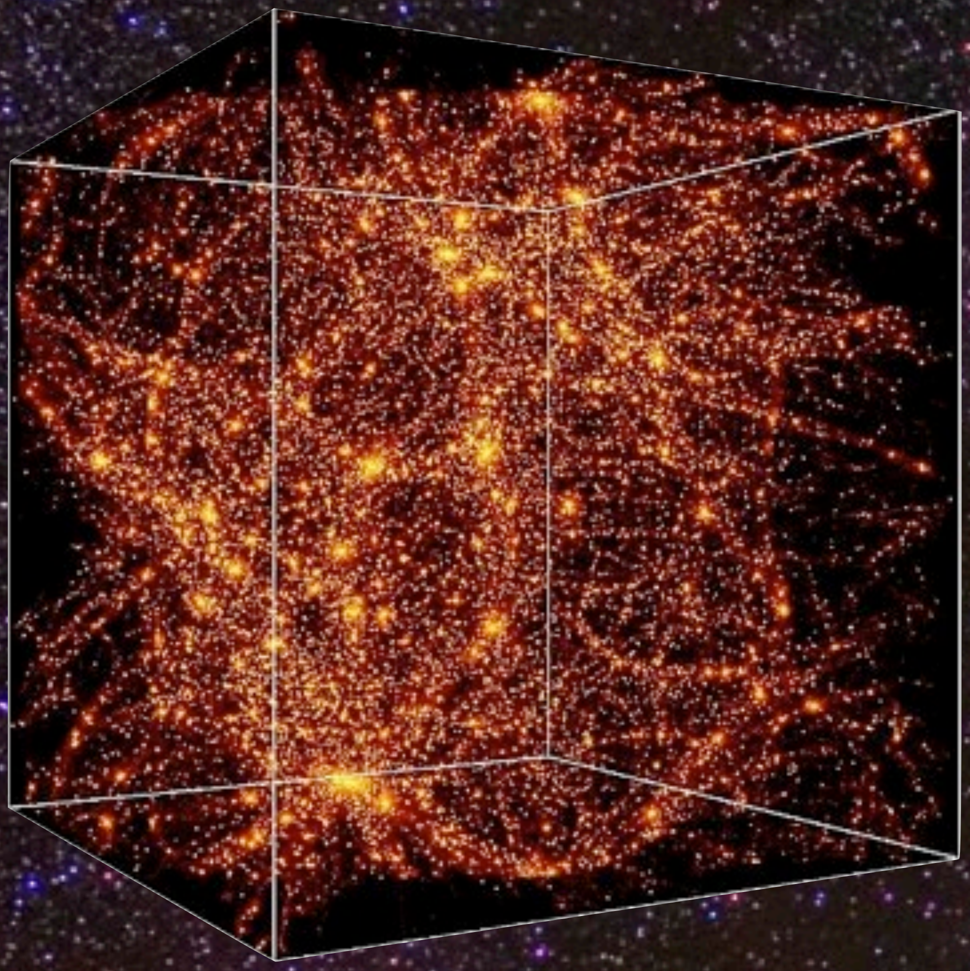
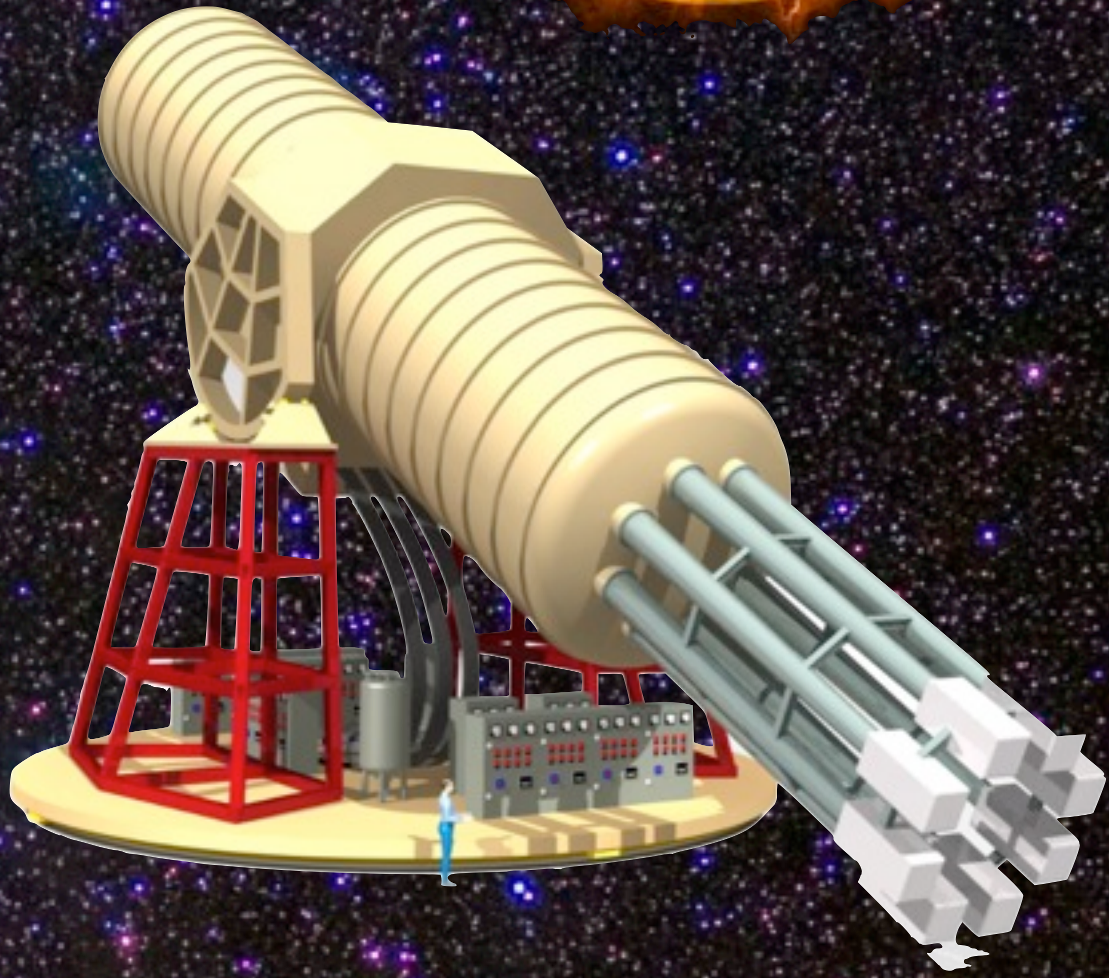
meV frontier of axion physics

Javier Redondo
(Zaragoza U & MPP)

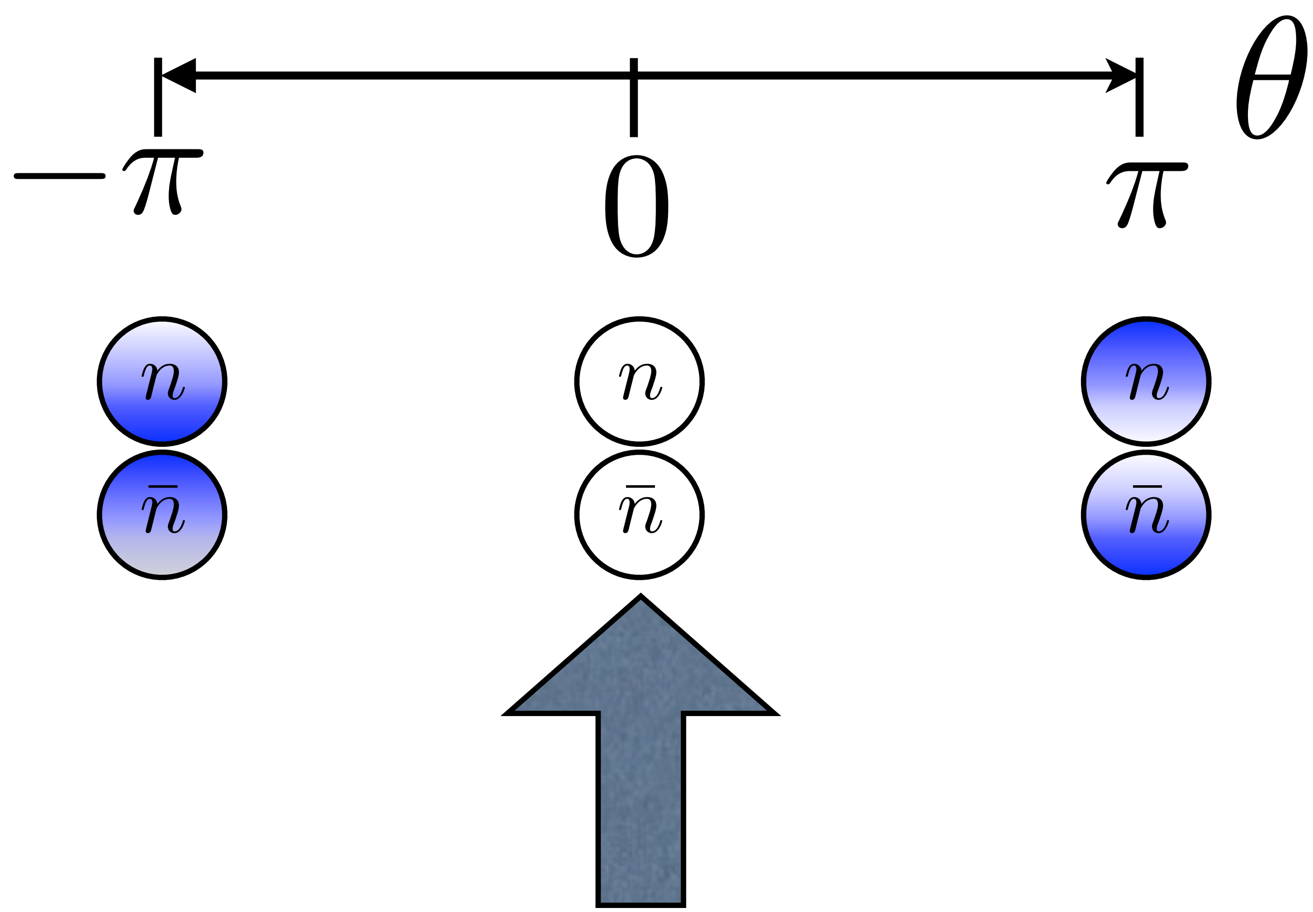






The theta angle of the strong interactions

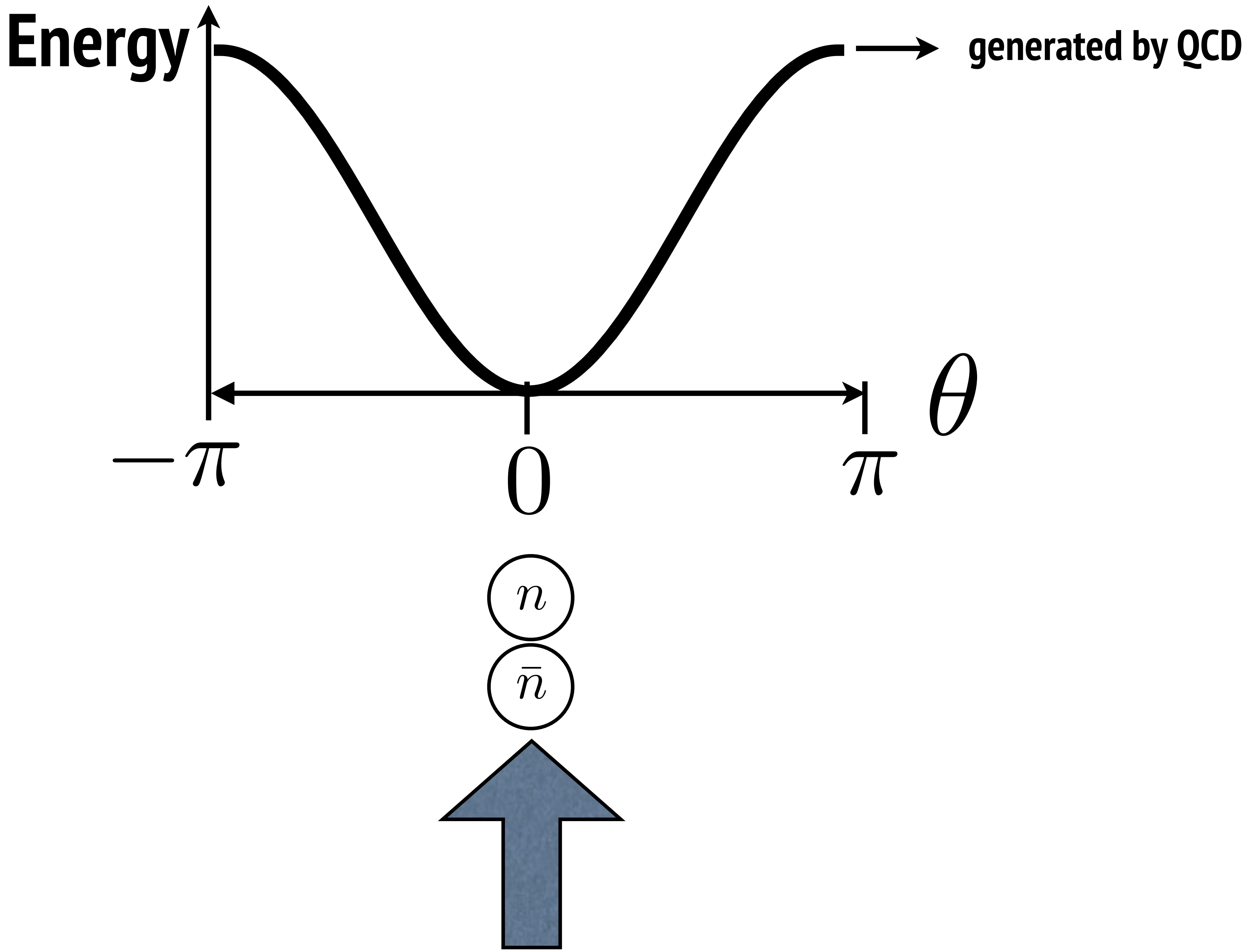
- The value of θ controls matter-antimatter differences in QCD



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

Axions

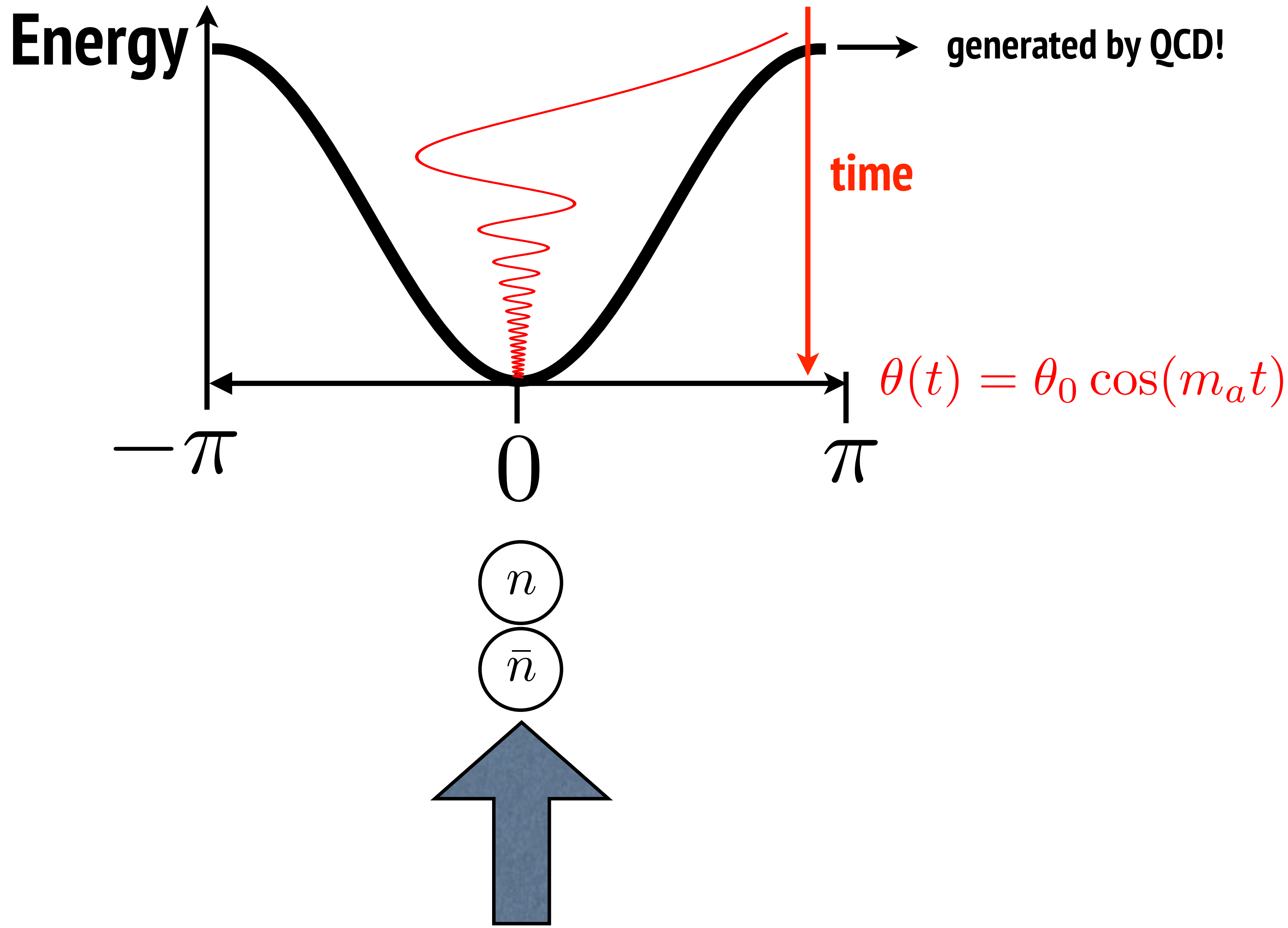
- **is it a dynamical field?** $\theta(t, \mathbf{x})$



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

Axions

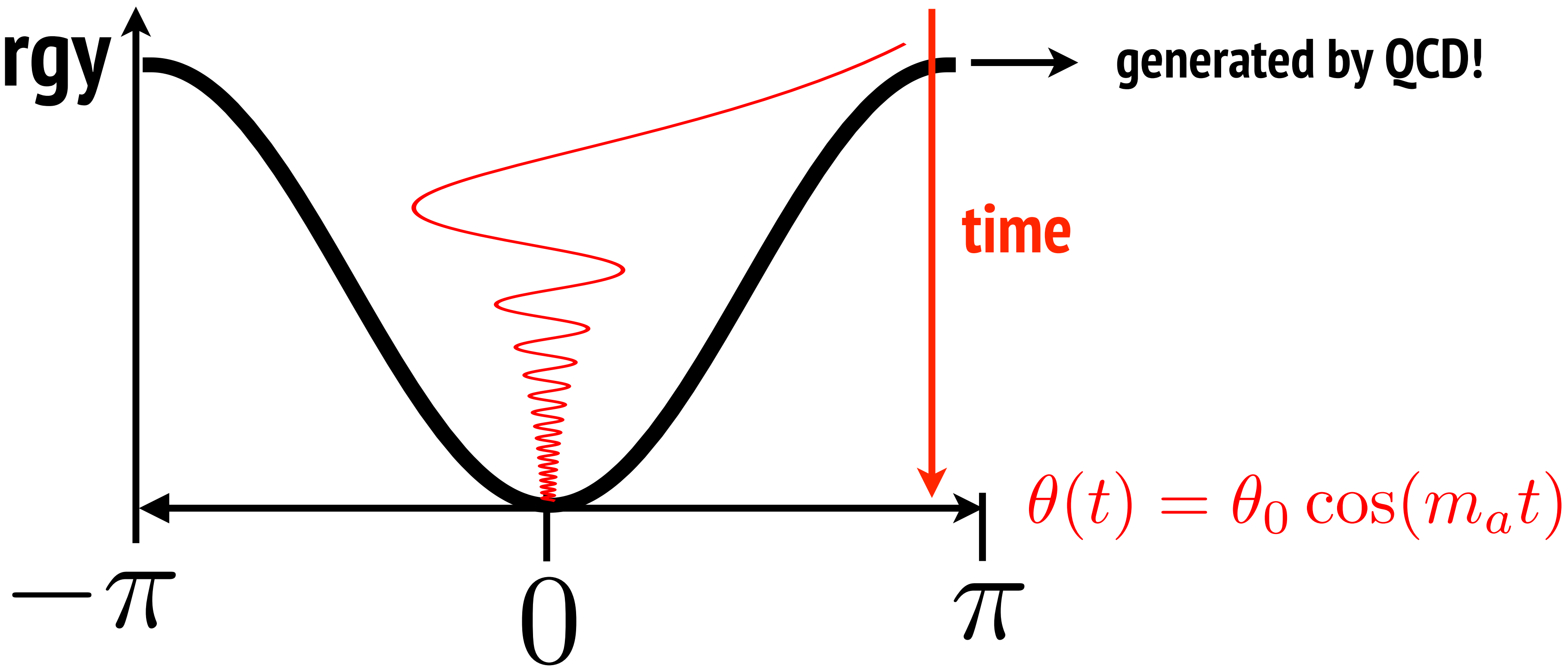
- is it a dynamical field? $\theta(t, \mathbf{x})$

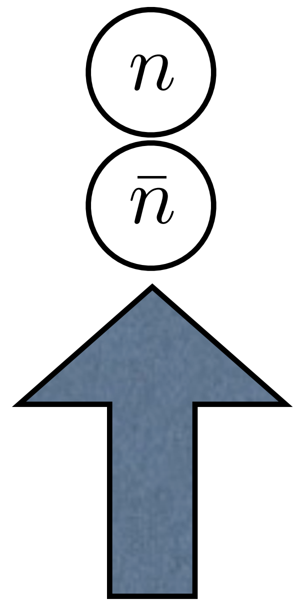


Measured today $|\theta| < 10^{-10}$ (strong CP problem)

Axions

- is it a dynamical field? $\theta(t, \mathbf{x})$





~ One parameter theory

$$\theta(t,x) = a(t,x)/f_a$$

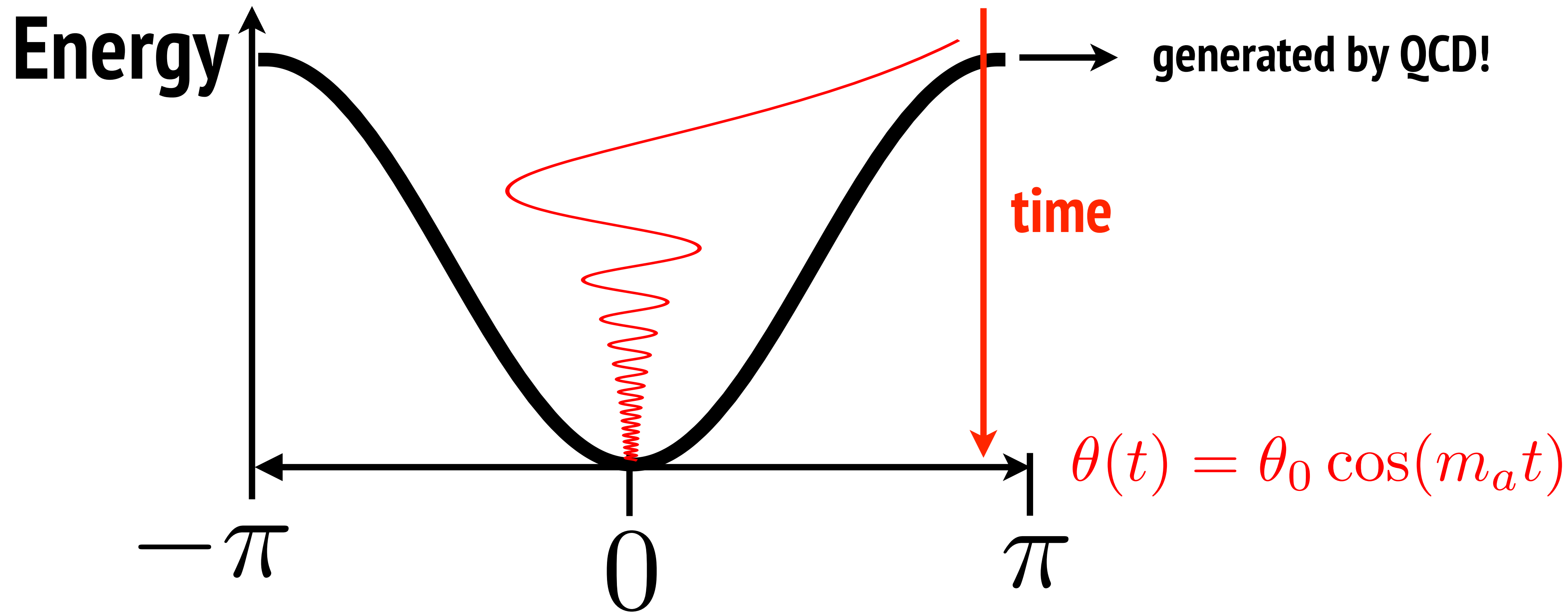
axion mass

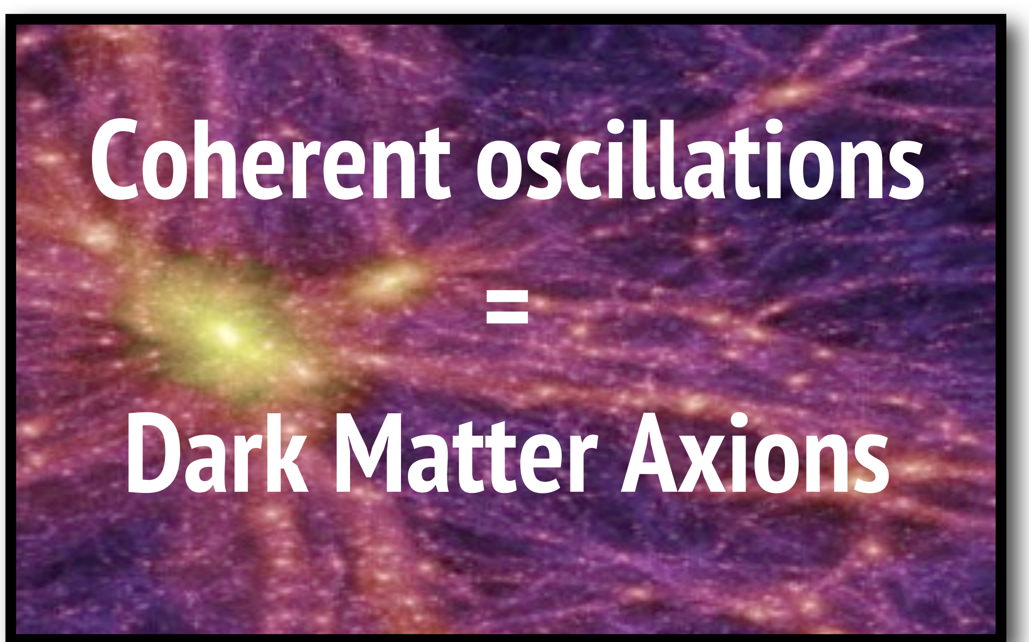
$$m_a = 6\,\mathrm{meV}\frac{10^9\,\mathrm{GeV}}{f_a}$$

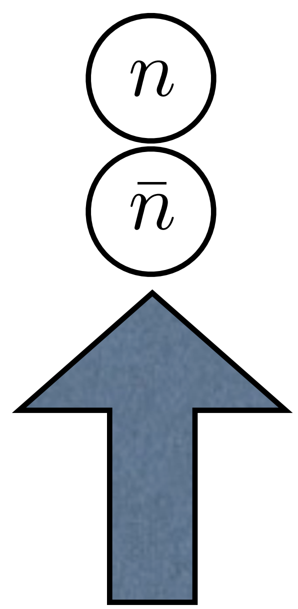
Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Axions

- is it a dynamical field? $\theta(t, \mathbf{x})$







~ One parameter theory

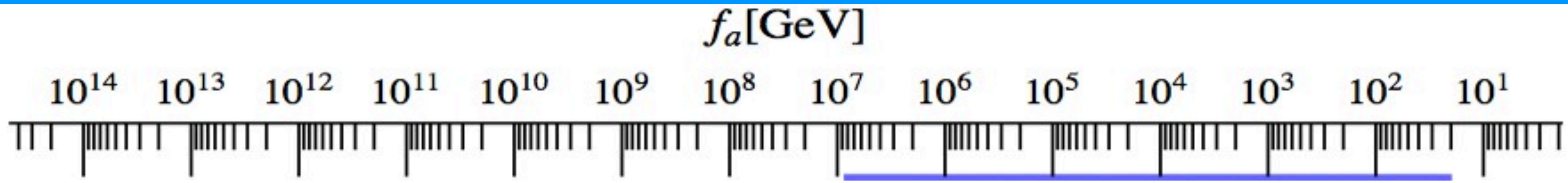
$$\theta(t, x) = a(t, x)/f_a$$

axion mass

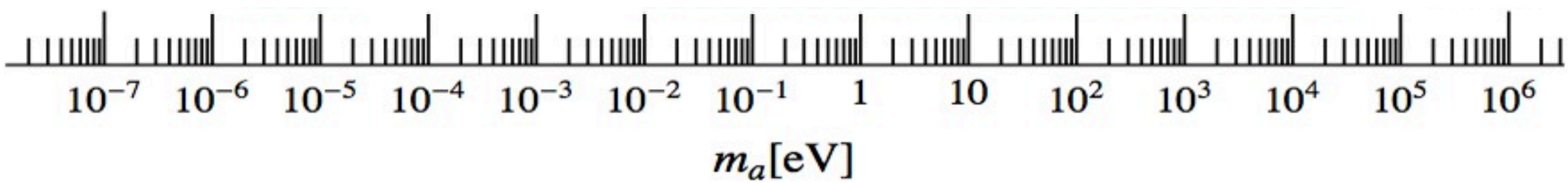
$$m_a = 6\,\mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a}$$

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

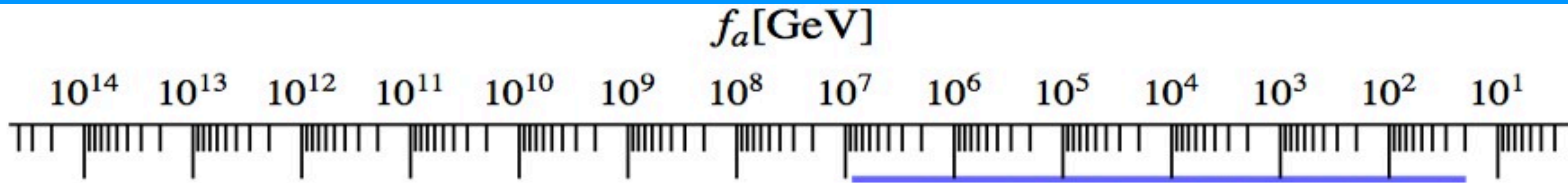
Axion dark matter



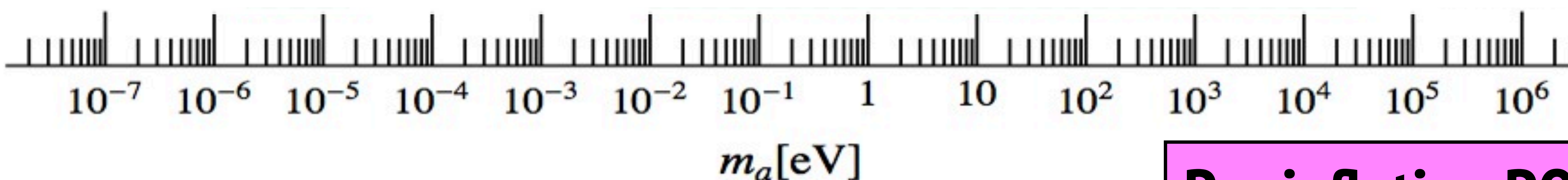
- Axion DM scenarios



Axion dark matter



- Axion DM scenarios

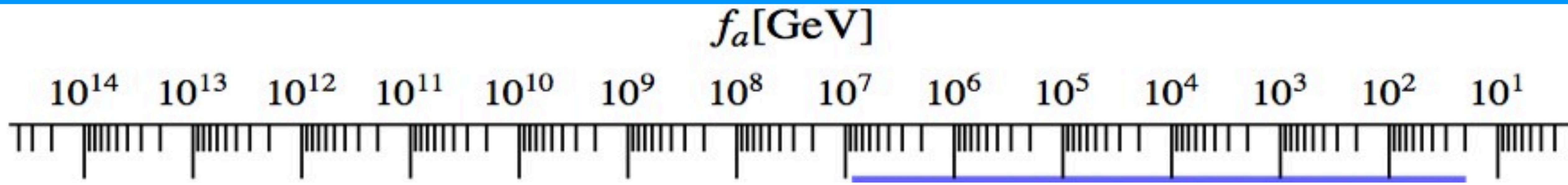


Pre inflation PQ

misalignment

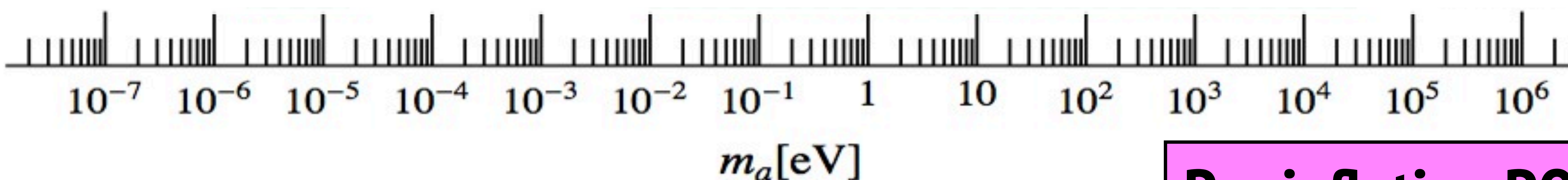
$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter



- Axion DM scenarios

tuned (anthropic?) | ok | tuned

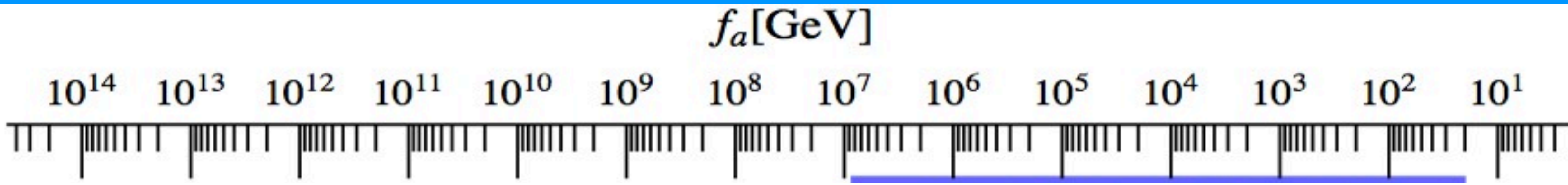


Pre inflation PQ

misalignment

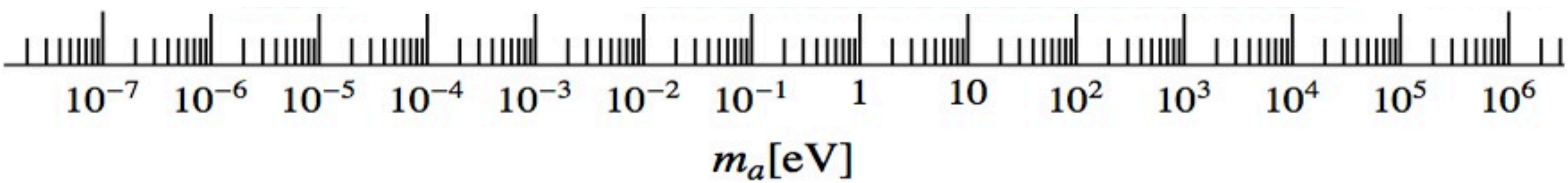
$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter



- Axion DM scenarios

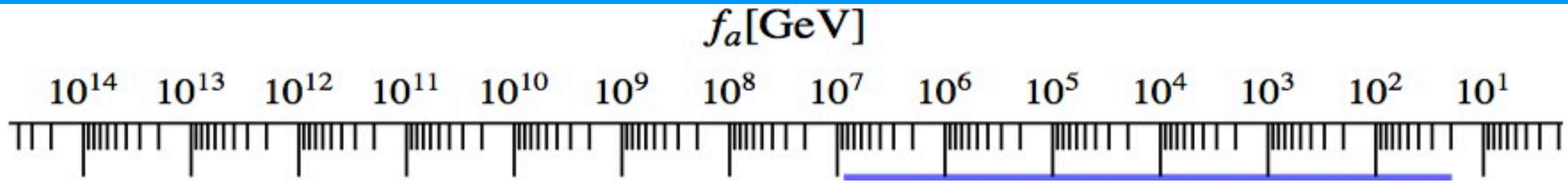
tuned (anthropic?) | **ok** | **tuned**



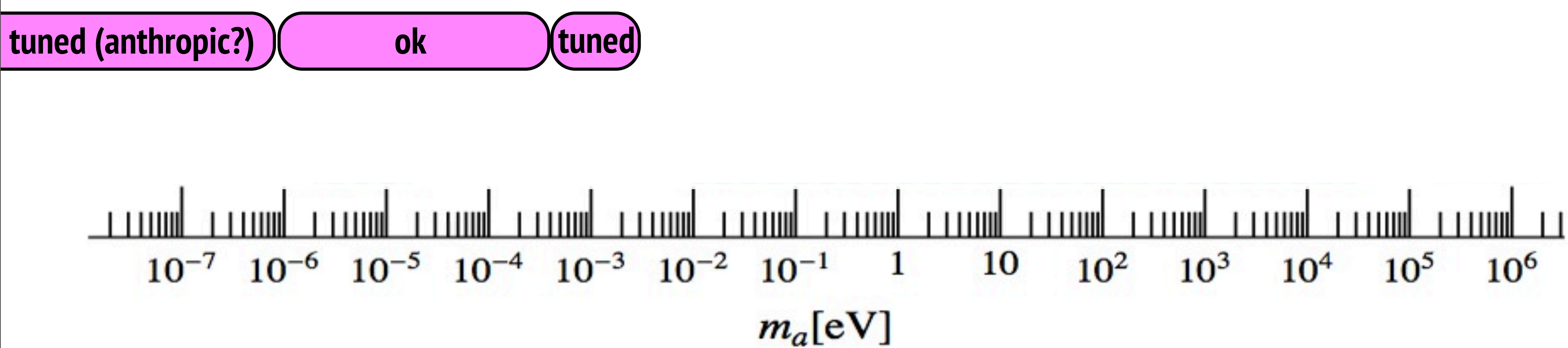
Pre inflation PQ

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter



- Axion DM scenarios



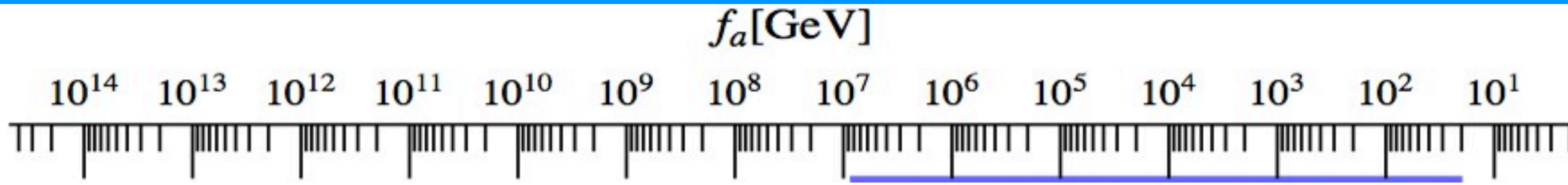
Post-inflation PQ (N=1)

strings+unstable DW's

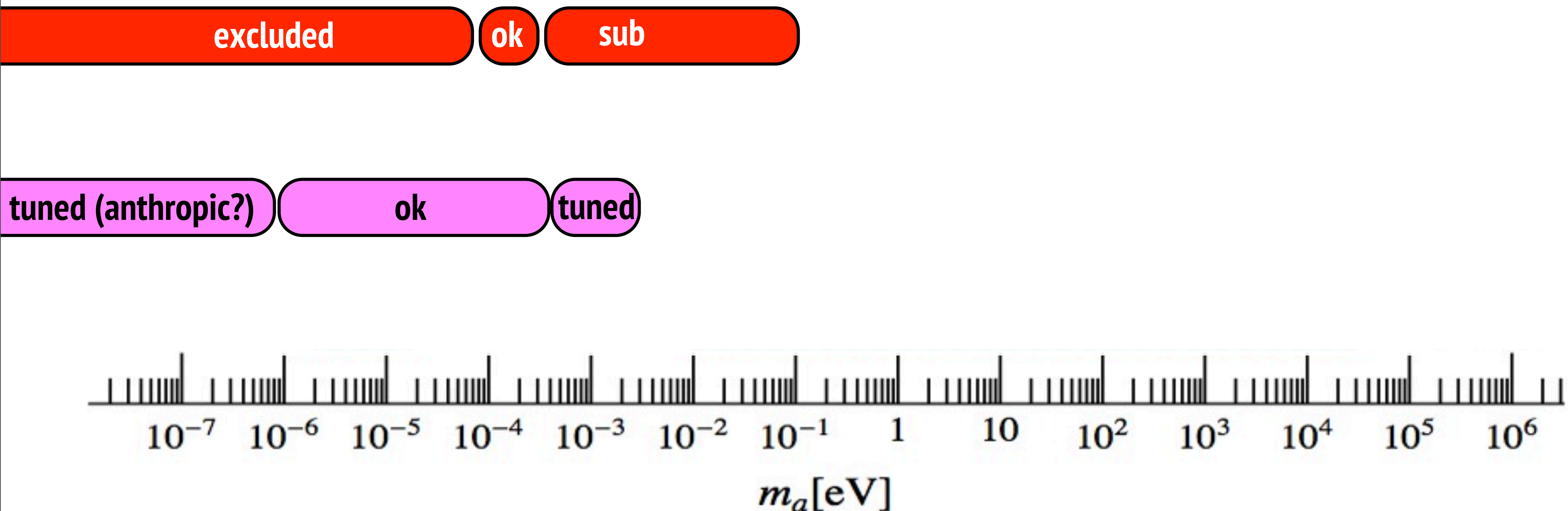
Pre inflation PQ

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter



- Axion DM scenarios



Post-inflation PQ (N=1)

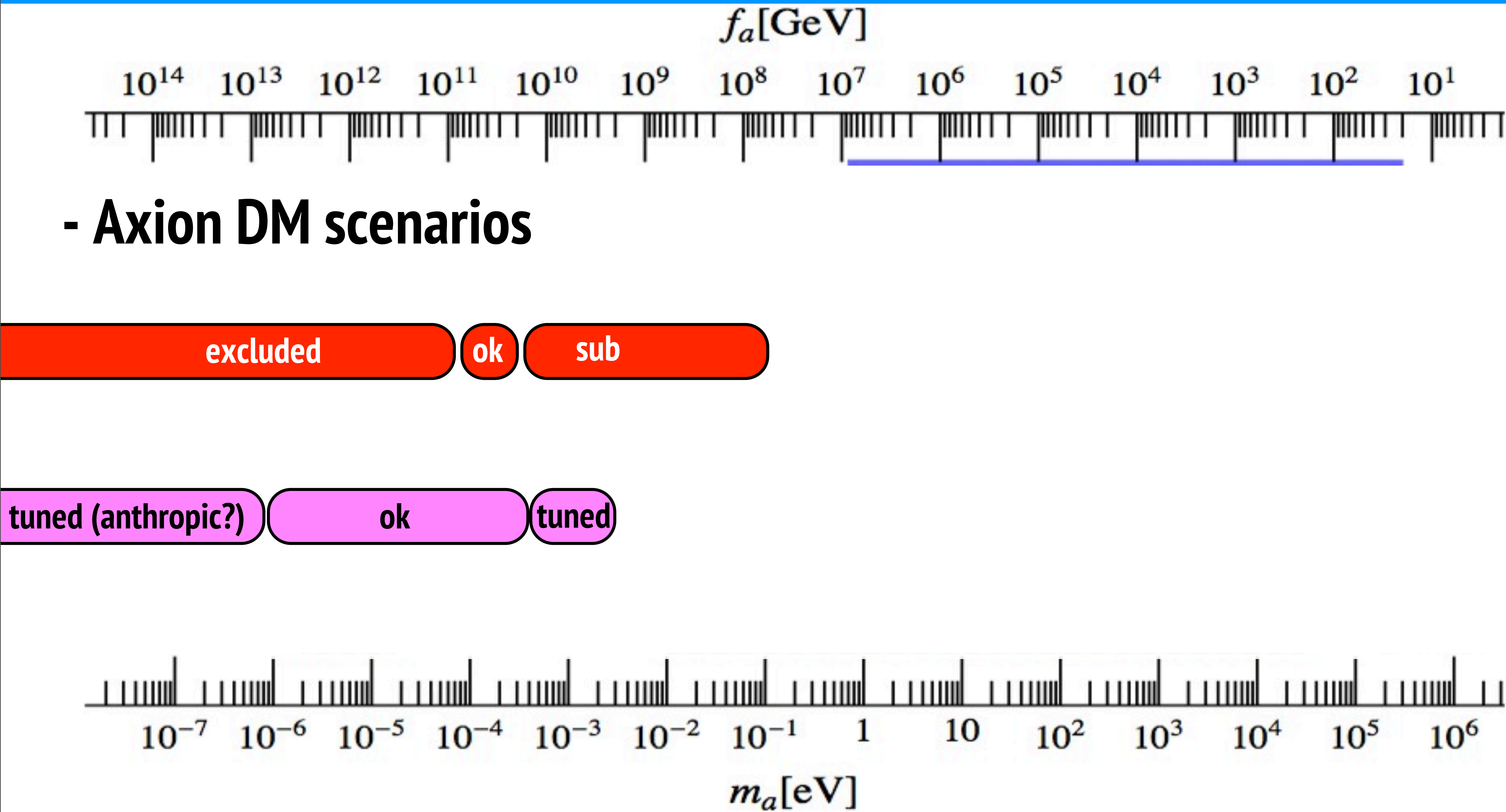
strings+unstable DW's

Pre inflation PQ

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

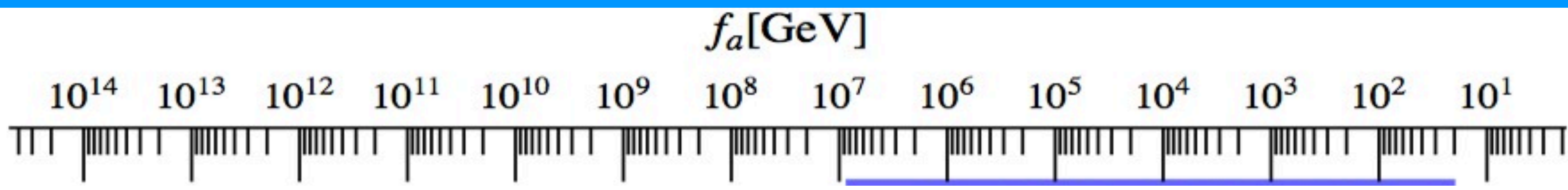
Axion dark matter

- Axion DM scenarios

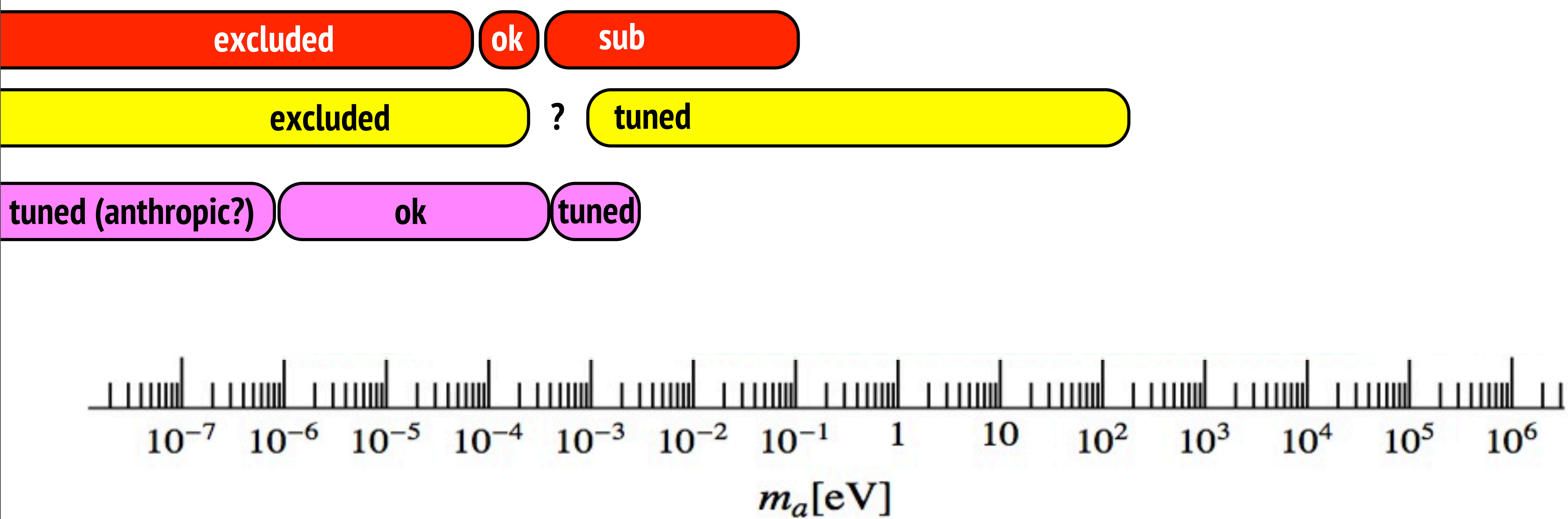


Post-inflation PQ (N=1)	Post inflation PQ (N>1)	Pre inflation PQ
strings+unstable DW's	strings+long-lived DWs	$\Omega_{\rm aDM}h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$

Axion dark matter



- Axion DM scenarios



Post-inflation PQ (N=1)
strings+unstable DW's

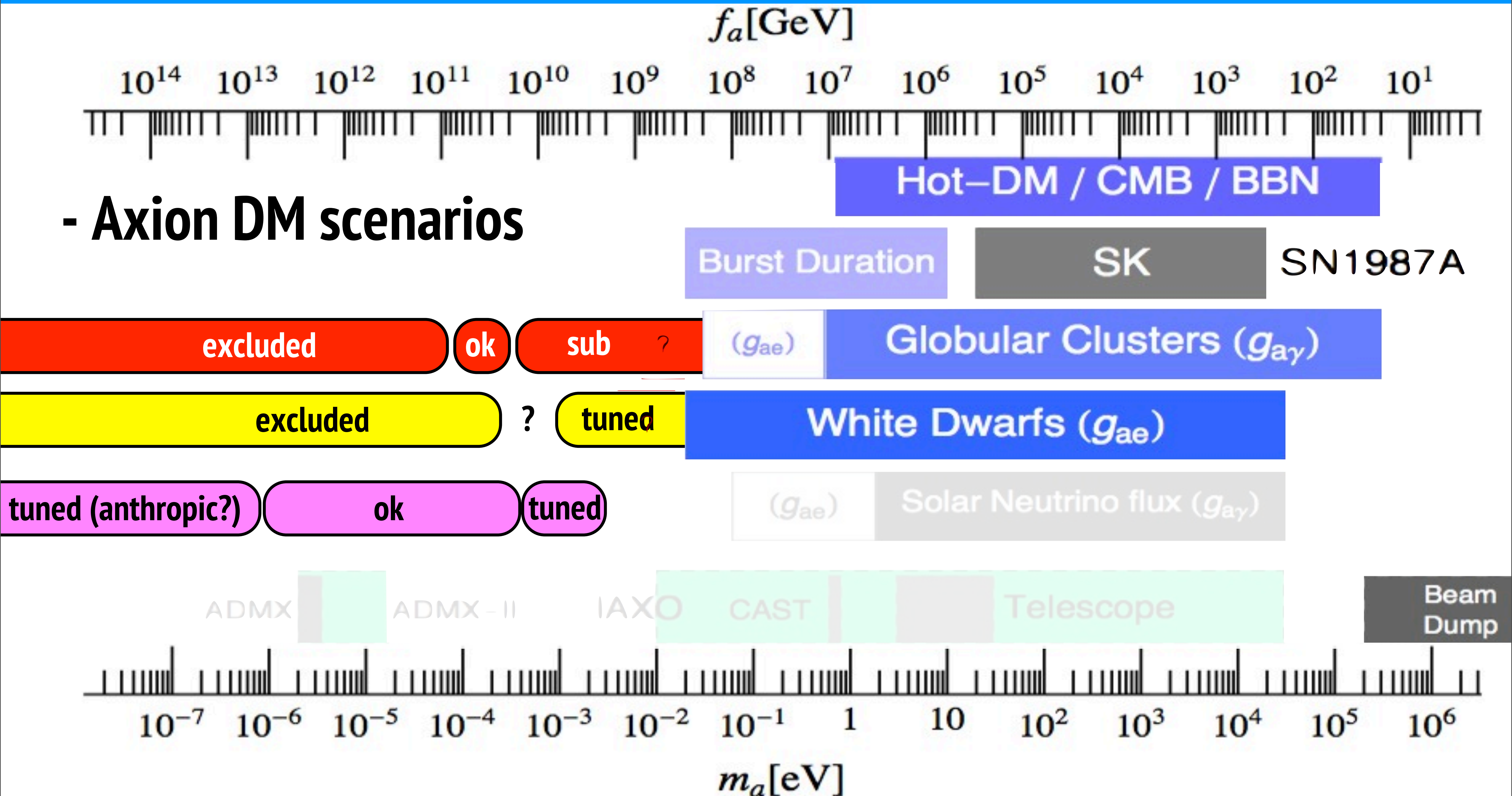
Post inflation PQ (N>1)
strings+long-lived DWs

Pre inflation PQ

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter

- Axion DM scenarios



Post-inflation PQ (N=1)
strings+unstable DW's

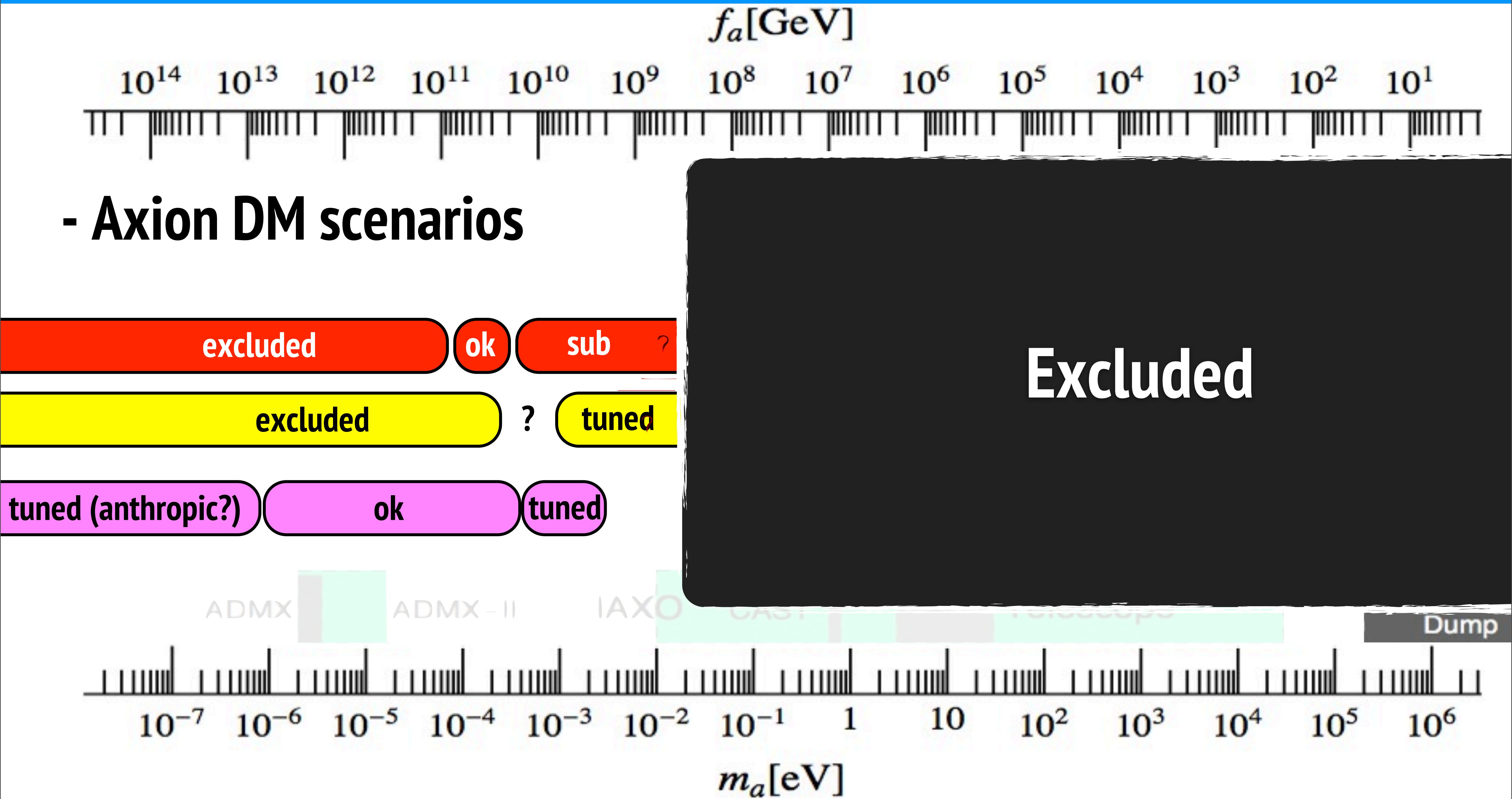
Post inflation PQ (N>1)
strings+long-lived DWs

Pre inflation PQ

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axion dark matter

- Axion DM scenarios



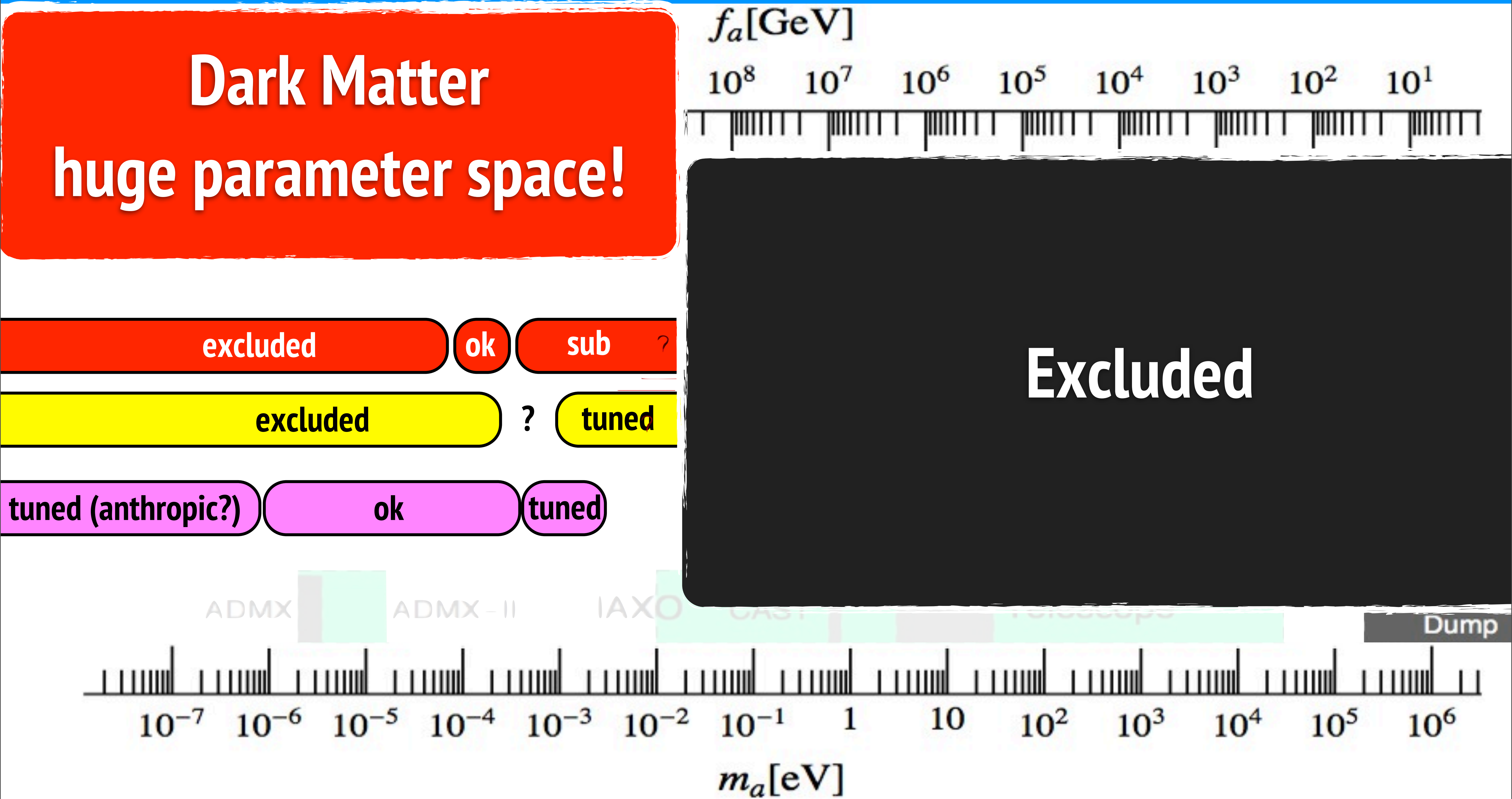
Post-inflation PQ (N=1)
strings+unstable DW's

Post inflation PQ (N>1)
strings+long-lived DWs

Pre inflation PQ
$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

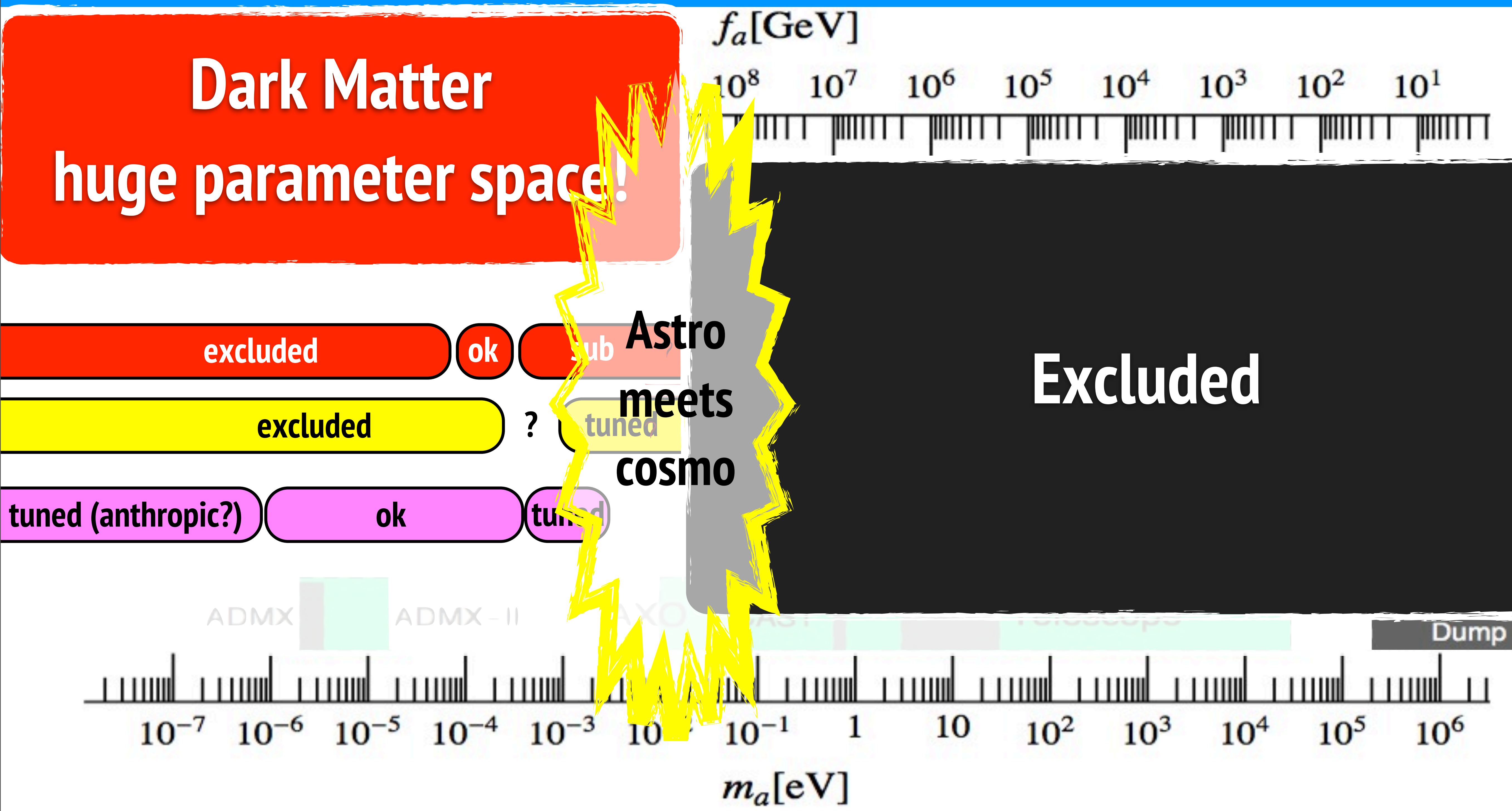
Axion dark matter

Dark Matter
huge parameter space!



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

Axion dark matter



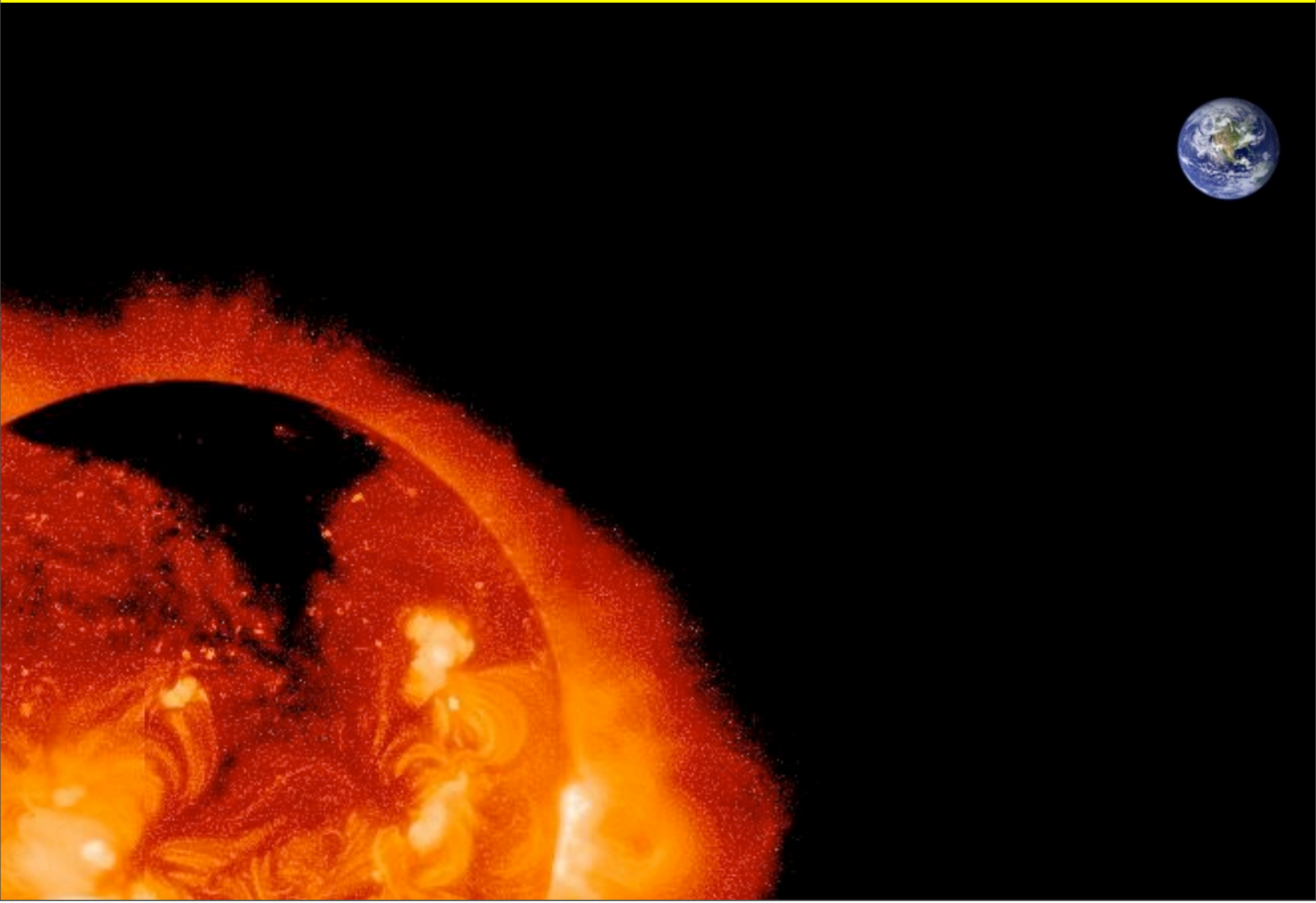
Post-inflation PQ (N=1)
strings+unstable DW's

Post inflation PQ (N>1)
strings+long-lived DWs

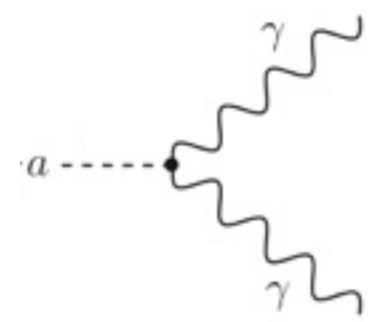
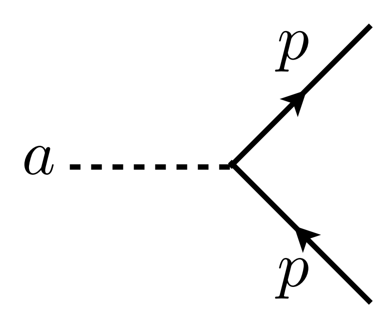
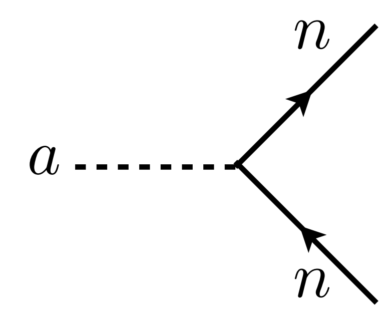
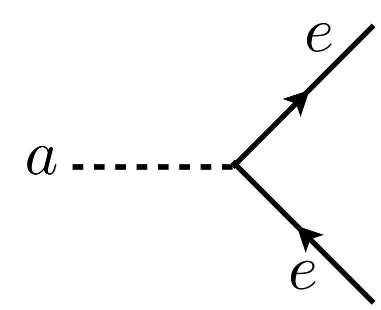
Pre inflation PQ

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Axions in stars



Axion Couplings and some models

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

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

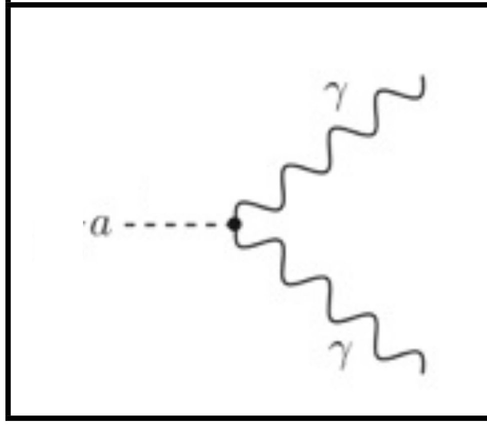
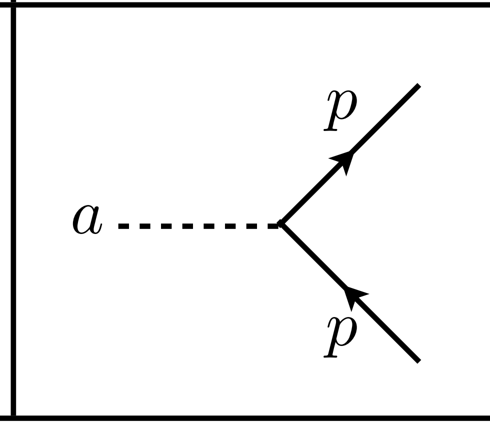
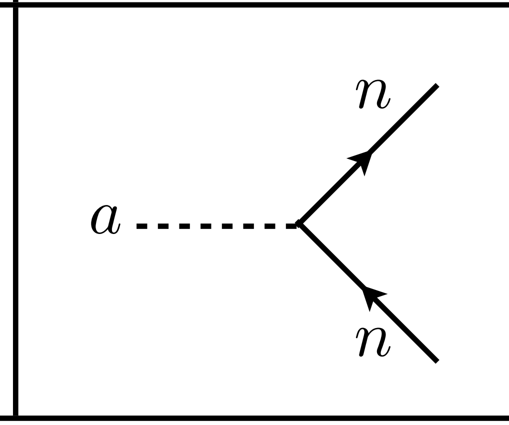
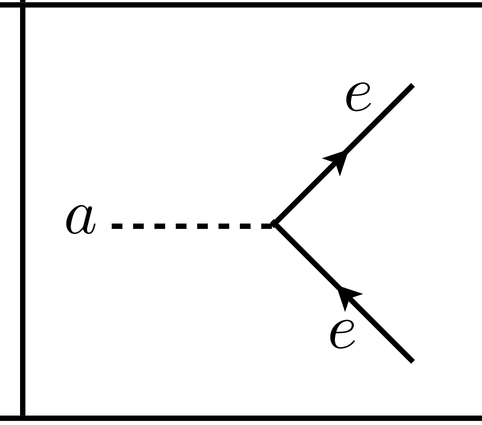
$$C_{ap} \simeq [C_{au} - \frac{m_d}{m_u + m_d}]\Delta u + [C_{ad} - \frac{m_u}{m_u + m_d}]\Delta d$$

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

		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

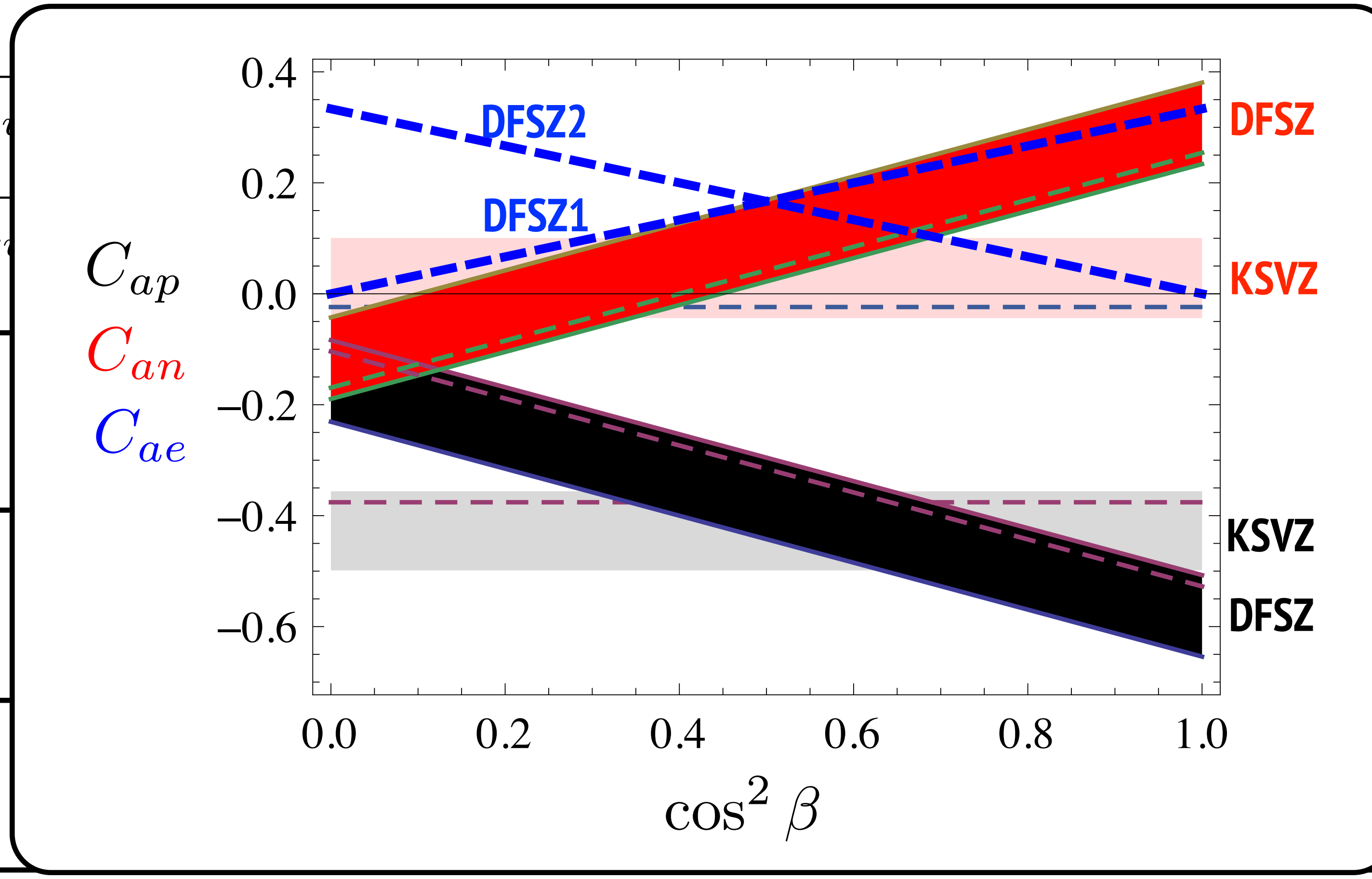
$$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu}\widetilde{G}^{\mu\nu} + \text{m.d.} \rightarrow$$

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

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

$C_{ap} \simeq [C_{au} - \frac{}{m}$

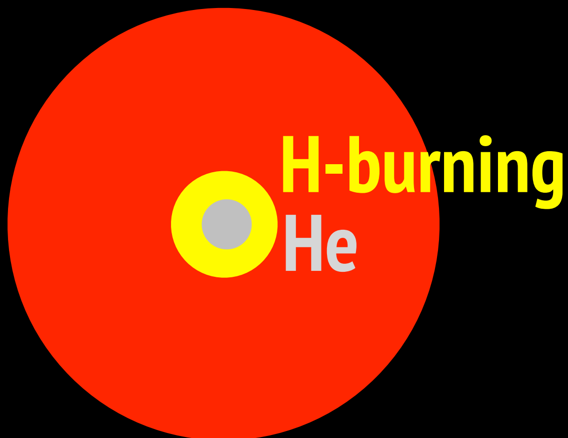
$C_{an} \simeq [C_{au} - \frac{}{m}$



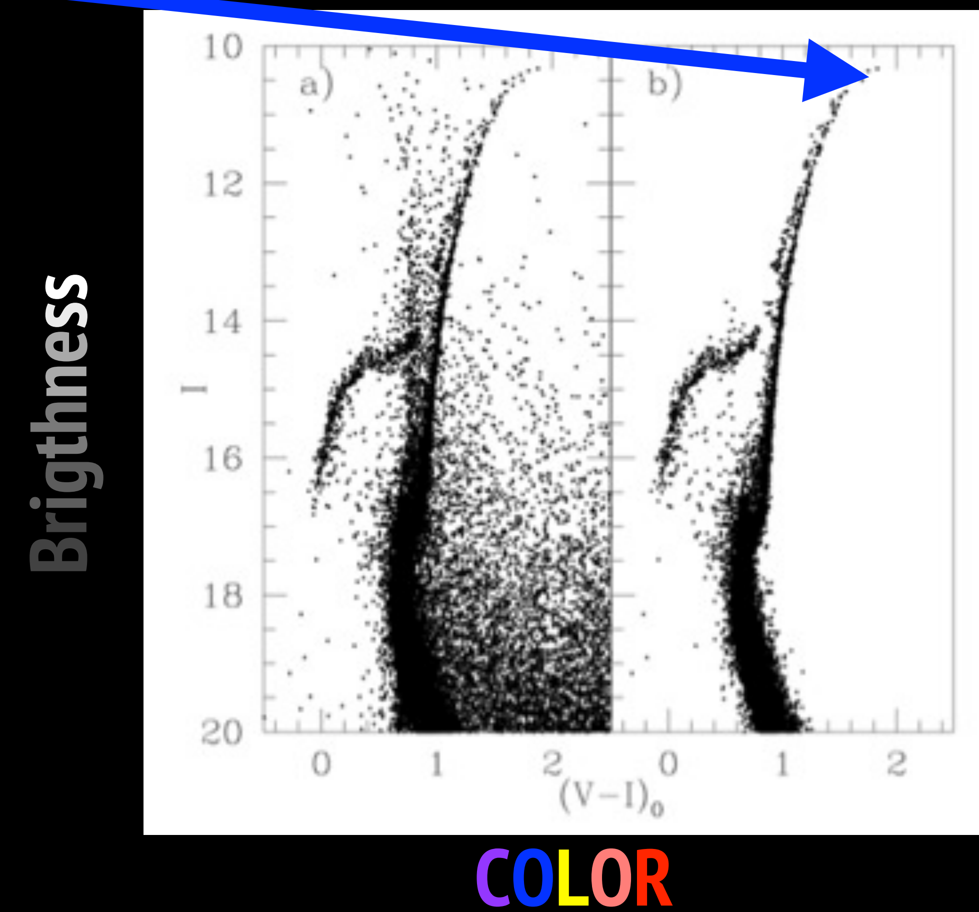
KSVZ	$C_{a(u,d,e)} = 0$	$C_{a\gamma} \simeq -1.92$
DFSZ1	$C_{au} = \frac{1}{3}\sin^2\beta$ $C_{a(d,e)} = \frac{1}{3}\cos^2\beta$	$C_{a\gamma} \simeq \frac{8}{3} - 1.92$
DFSZ2	$C_{a(u,e)} = \frac{1}{3}\sin^2\beta$ $C_{ad} = \frac{1}{3}\cos^2\beta$	$C_{a\gamma} \simeq \frac{2}{3} - 1.92$

Tip of the Red Giant branch (M5)

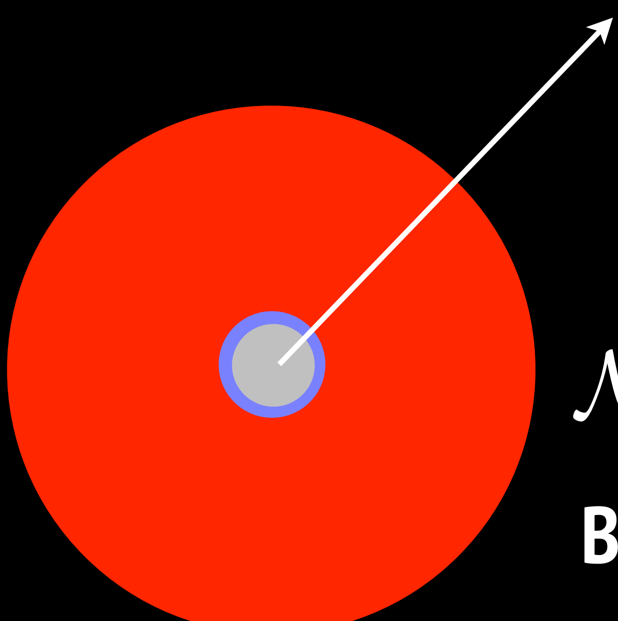
Increase He core until 3alpha ignition (T~8.6 KeV)

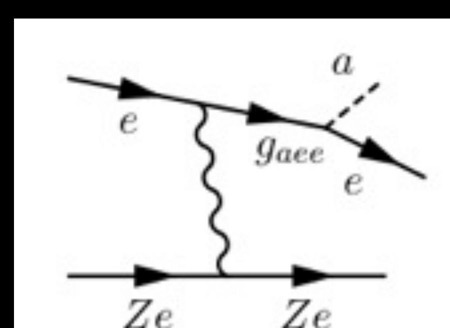


Globular ClusterM5



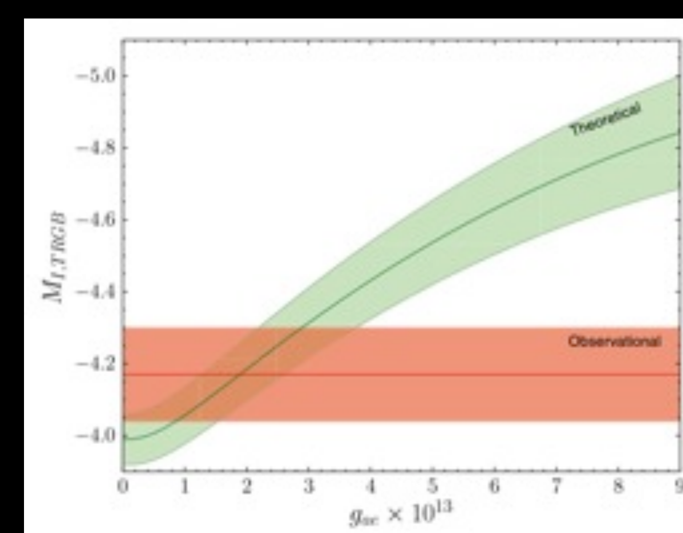
Axion emission cools down core, delays ignition





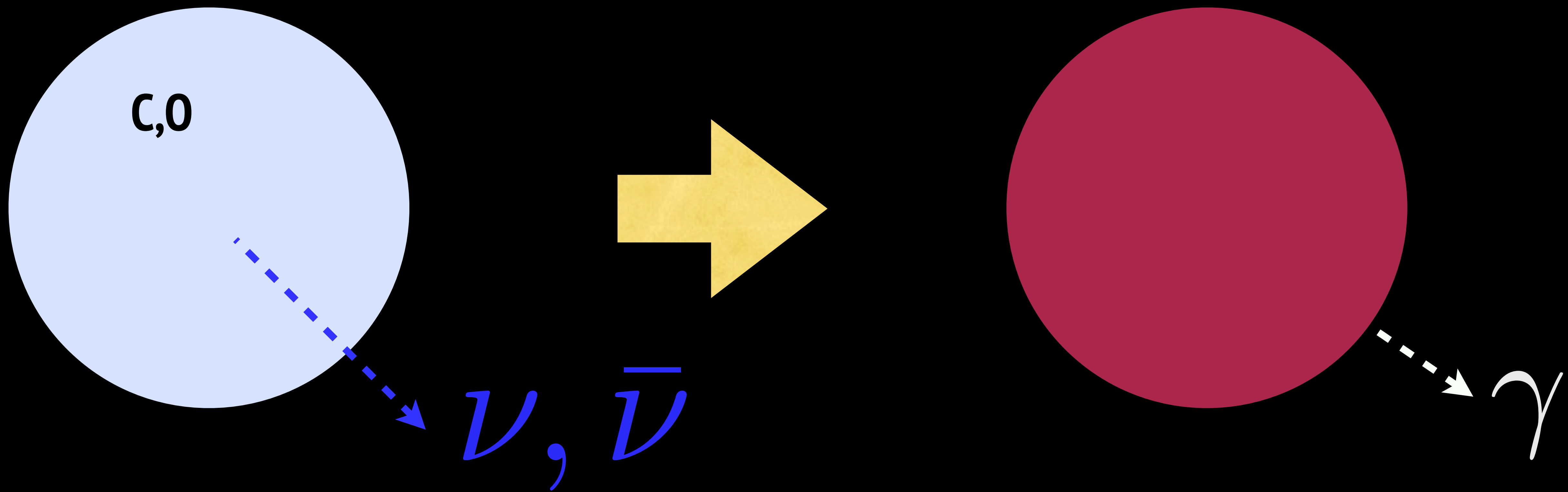
$$\mathcal{M}_{\rm core}\uparrow, T_{\rm H}\uparrow, \mathcal{L}\uparrow$$

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

Rate of WD production (simpified)

$$\frac{d\,N_{\rm WD}}{\rm Vol\,dt} = k$$

Luminosity decrease in time (~Cooling rate)

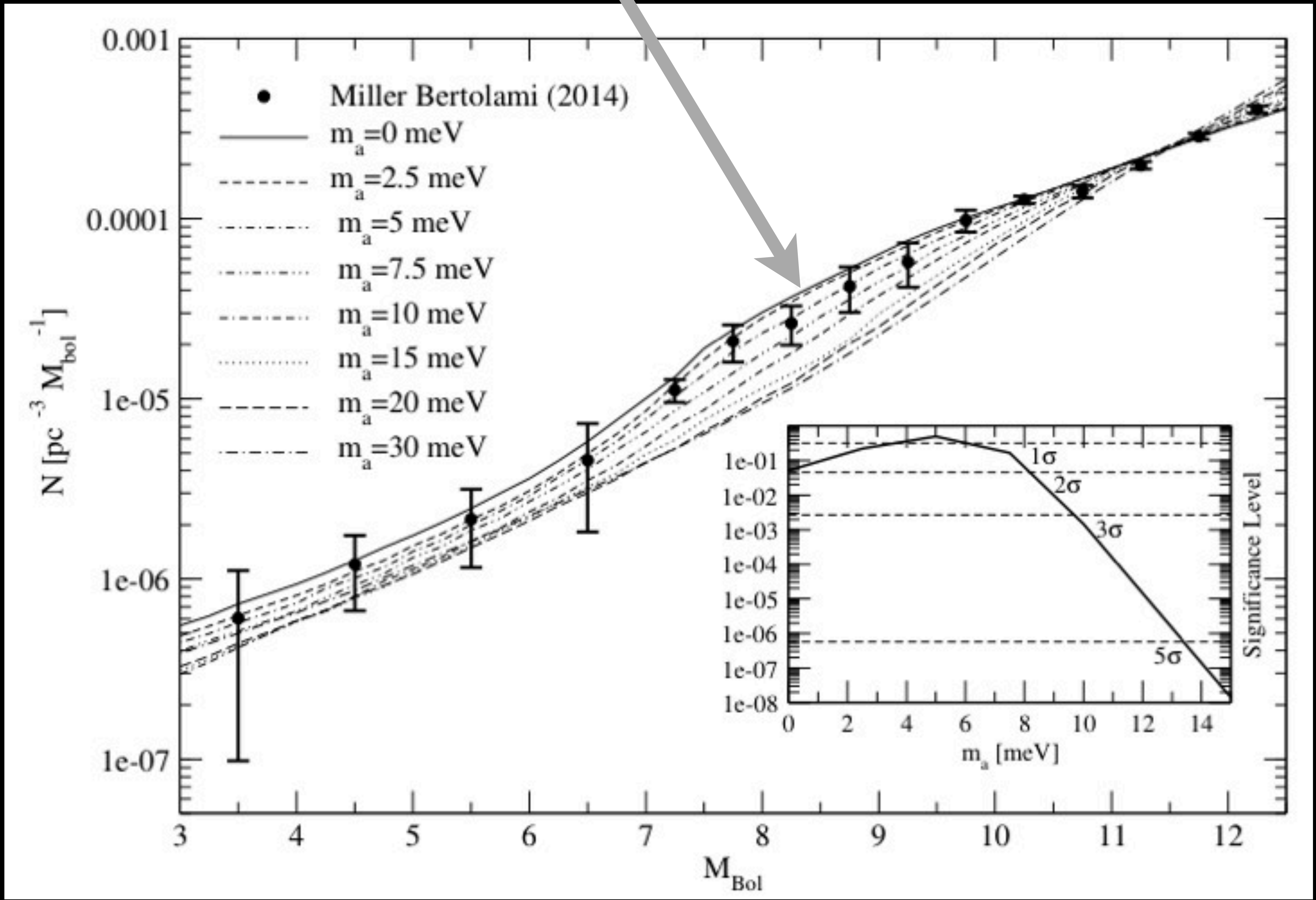
$$\frac{d\mathcal{L}}{dt} = f(t, ...)$$

Number of WDs per unit luminosity (LUMINOSITY FUNCTION)

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

White dwarf luminosity function

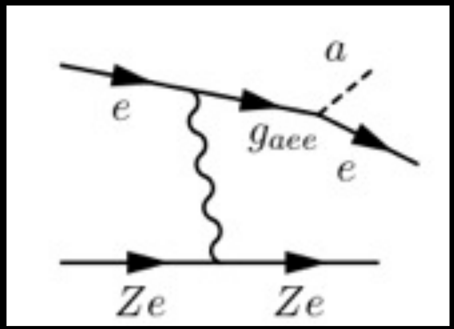
$$\frac{d\,N_{\mathrm{WD}}}{\mathrm{Vol}\,d\mathcal{L}} = \frac{k}{d\mathcal{L}/dt}$$

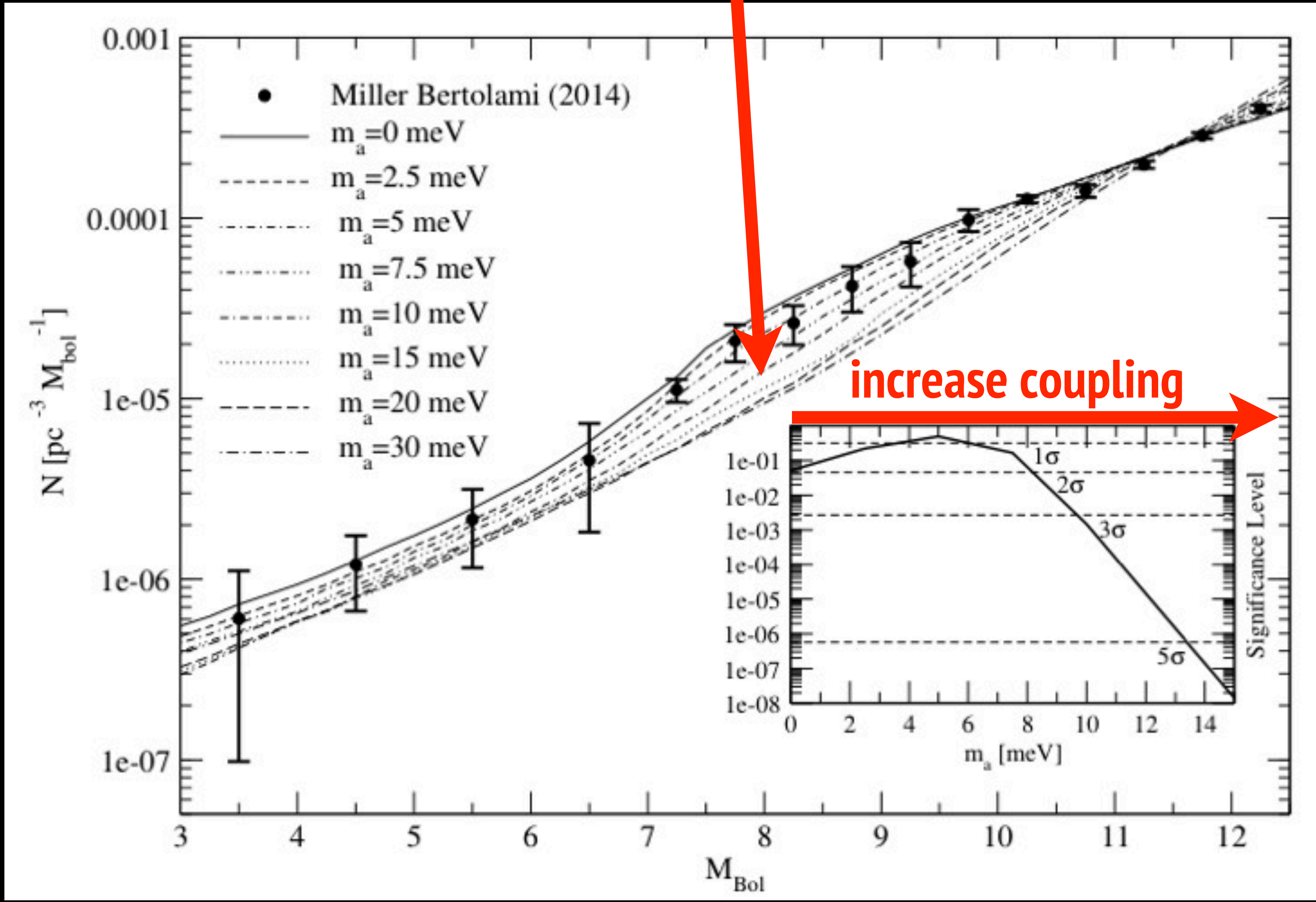


White dwarf luminosity function

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

with axion-electron bremsstrahlung





Strong constraint, small hint!

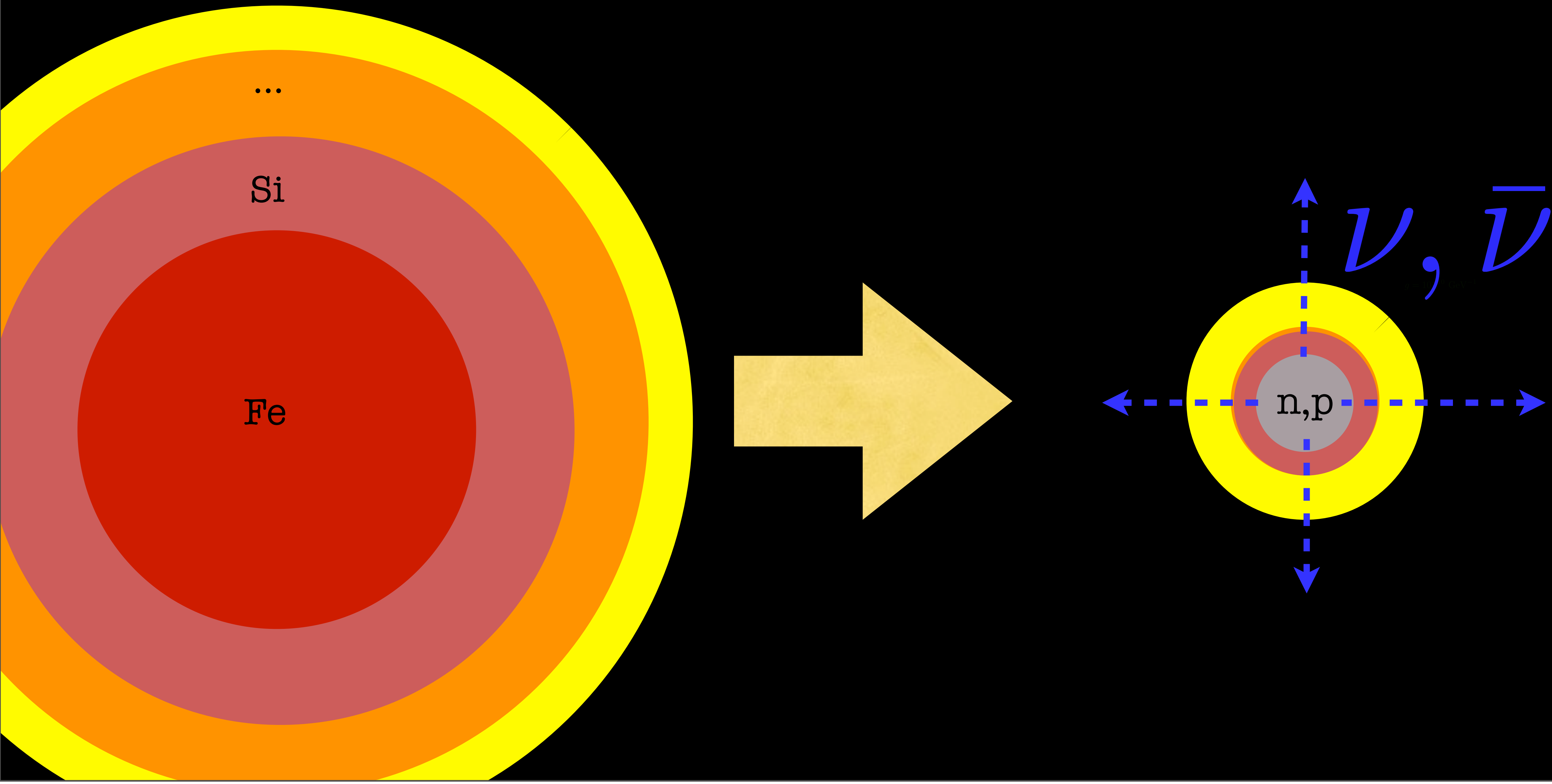
Core collapse SN

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

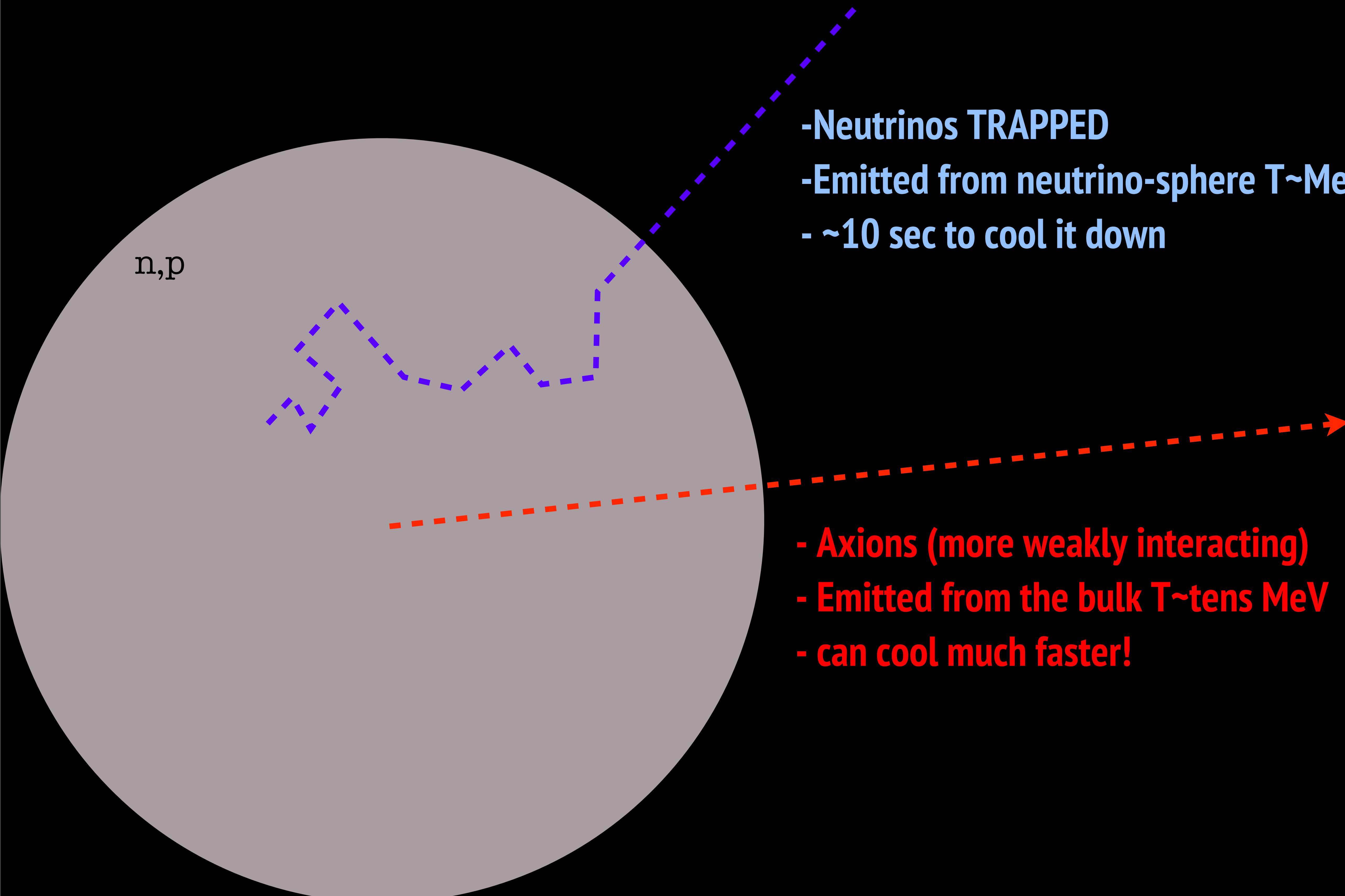
$$\mathcal{M}_{\rm core} \sim 1.4 \mathcal{M}_\odot$$

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

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



Neutrino burst



-Neutrinos TRAPPED

-Emitted from neutrino-sphere T~MeV

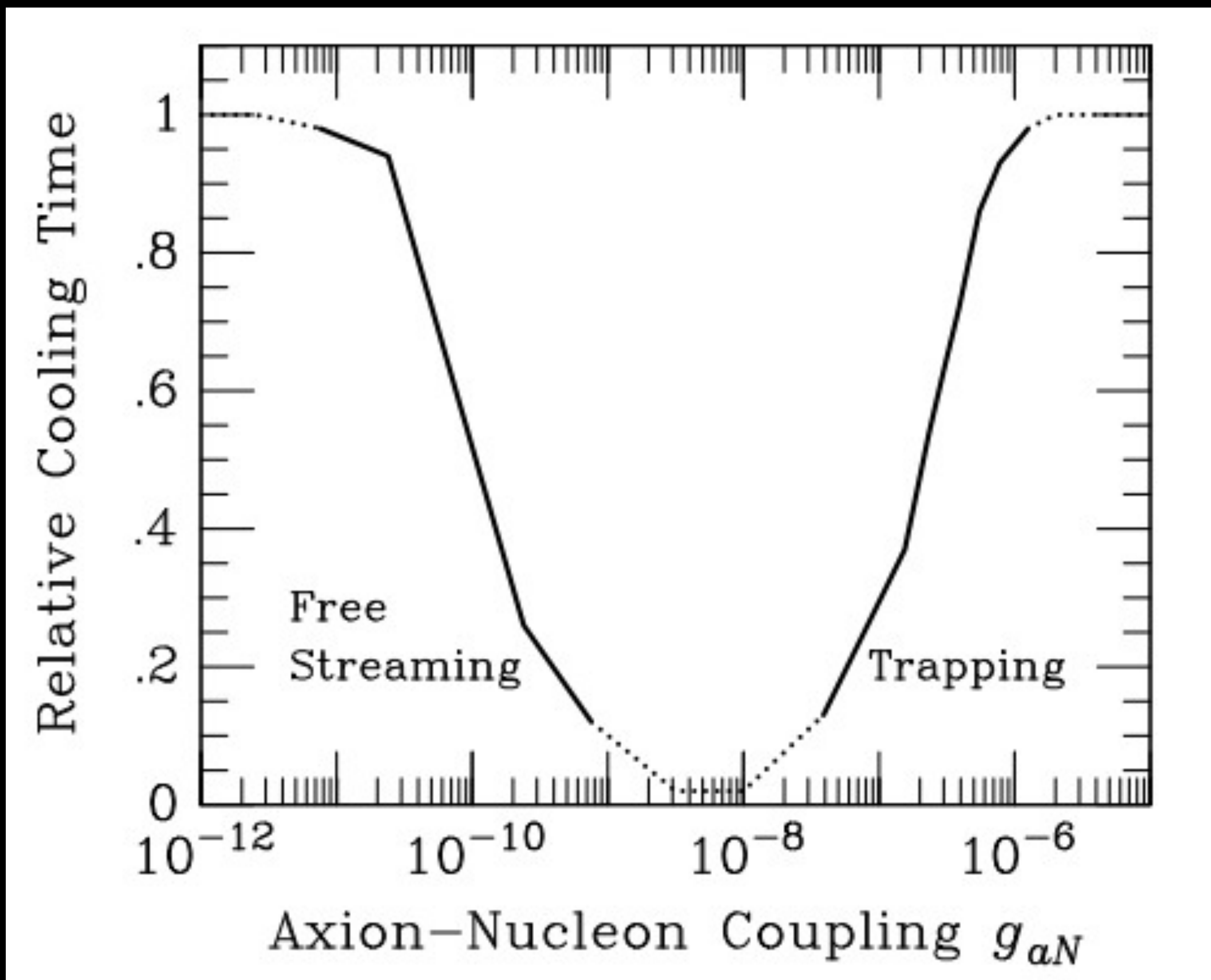
- ~10 sec to cool it down

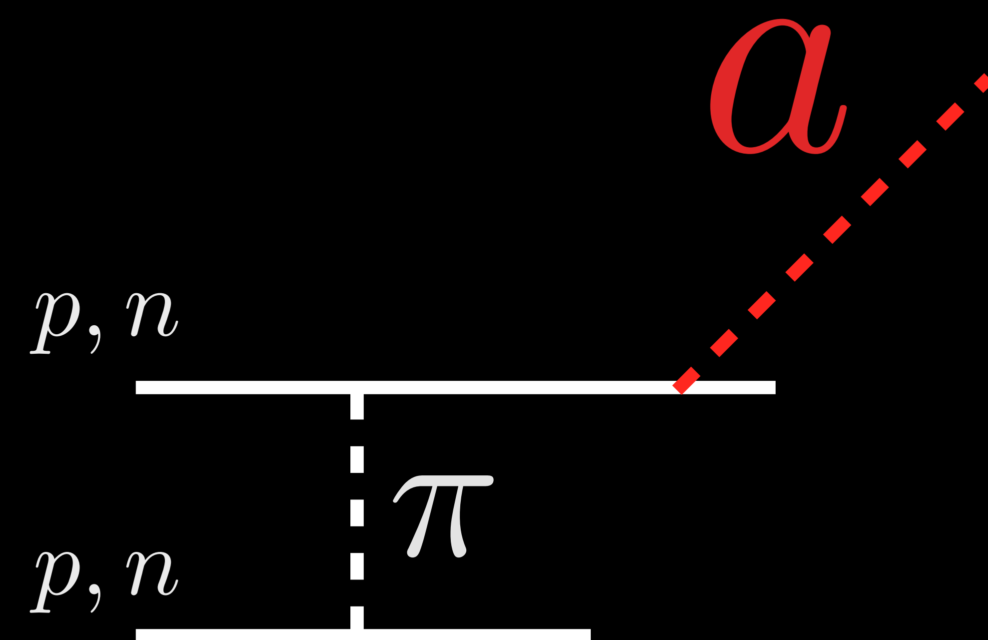
- Axions (more weakly interacting)

- Emitted from the bulk T~tens MeV

- can cool much faster!

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





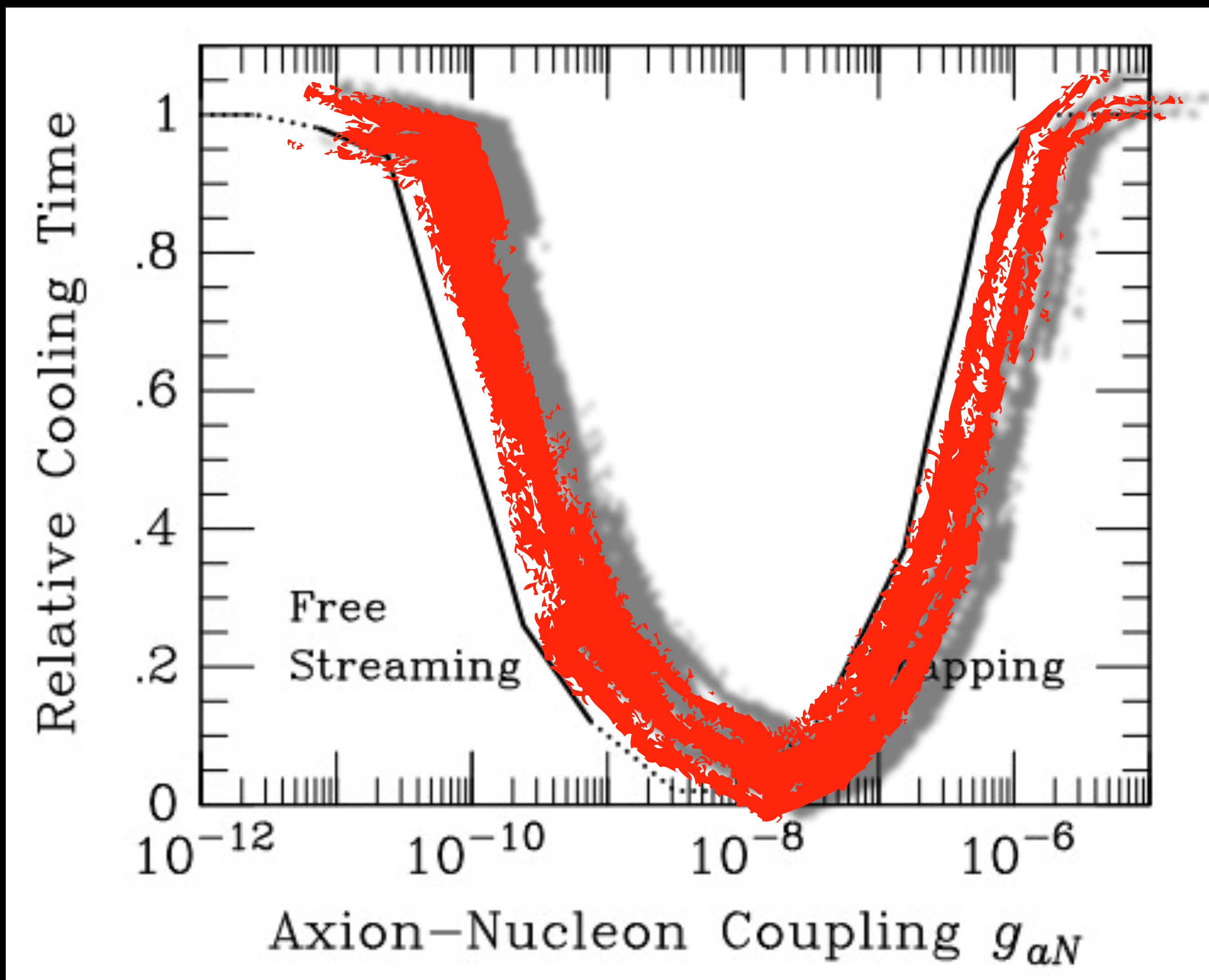
first approx. (pi pole too hard...)

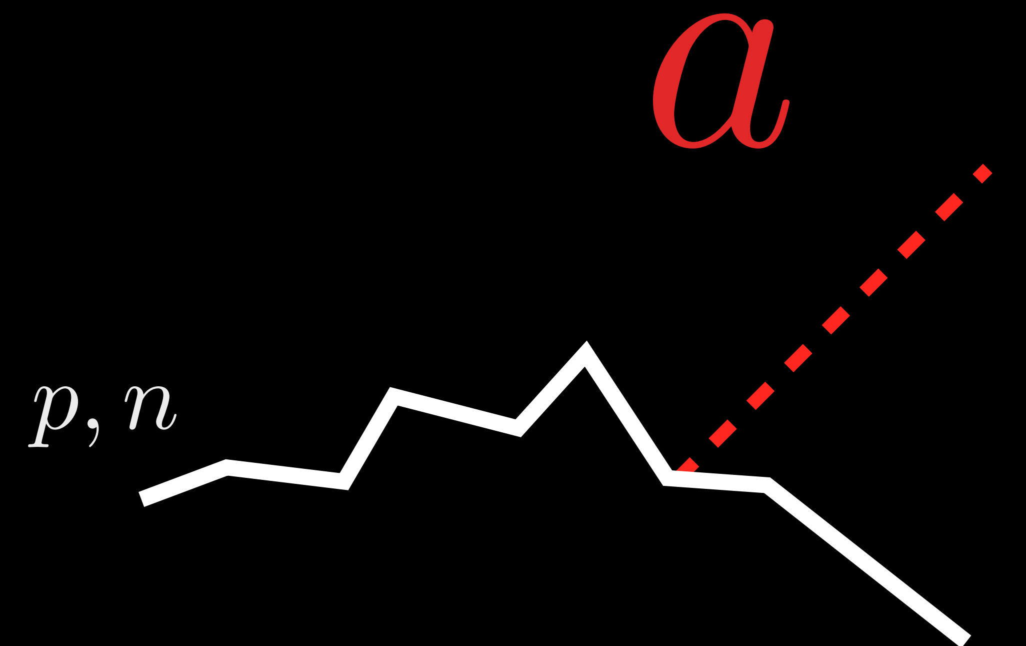
axion production not significant

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 . . .

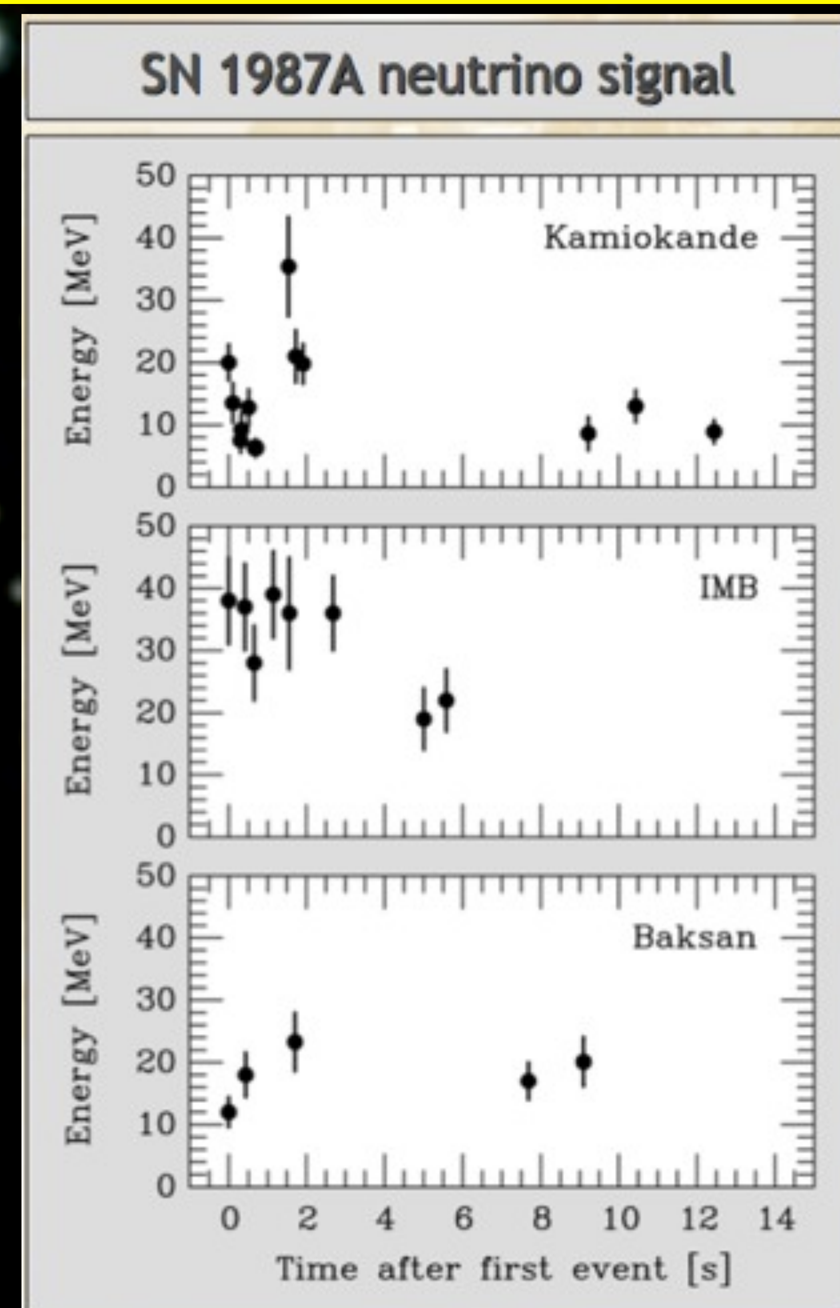
$$\epsilon_a \sim g_{ap}^2 1.6 \times 10^{37} \mathrm{erg/gs} \left(\frac{T}{30 \mathrm{MeV}} \right)^4$$

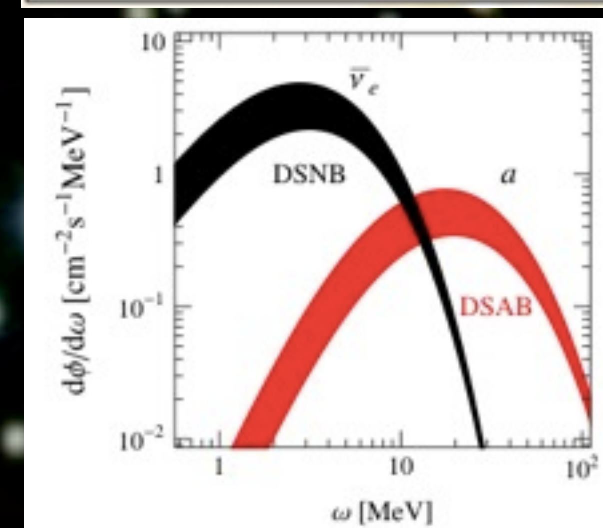
- Constraint . . .

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

- Axions saturating the bound take ~50% Ecore

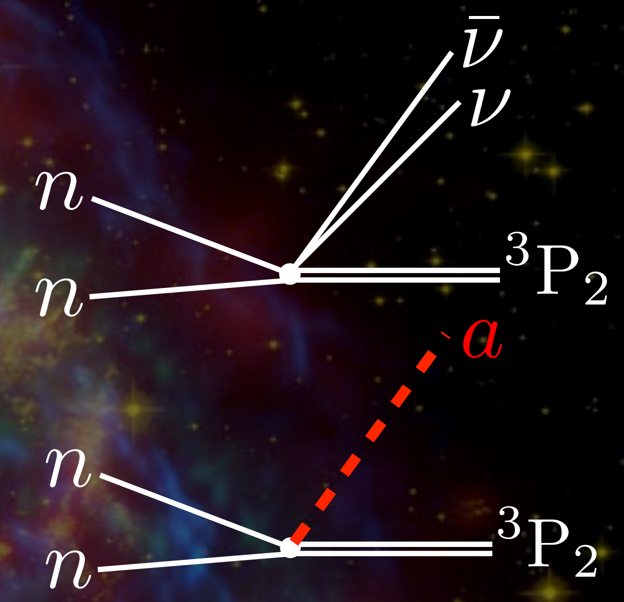
Diffuse Supernova Axion Background

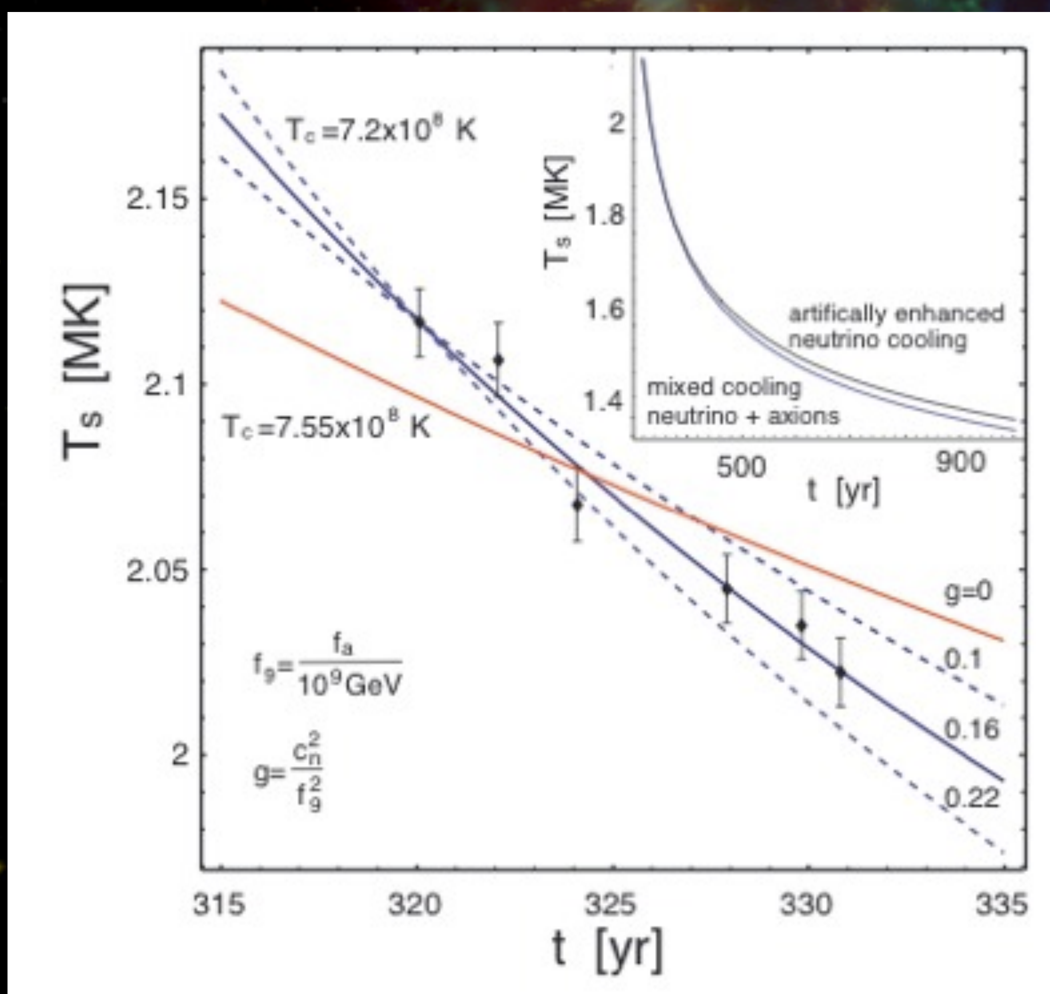




Cassiopeia A: neutron star cooling

- 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?

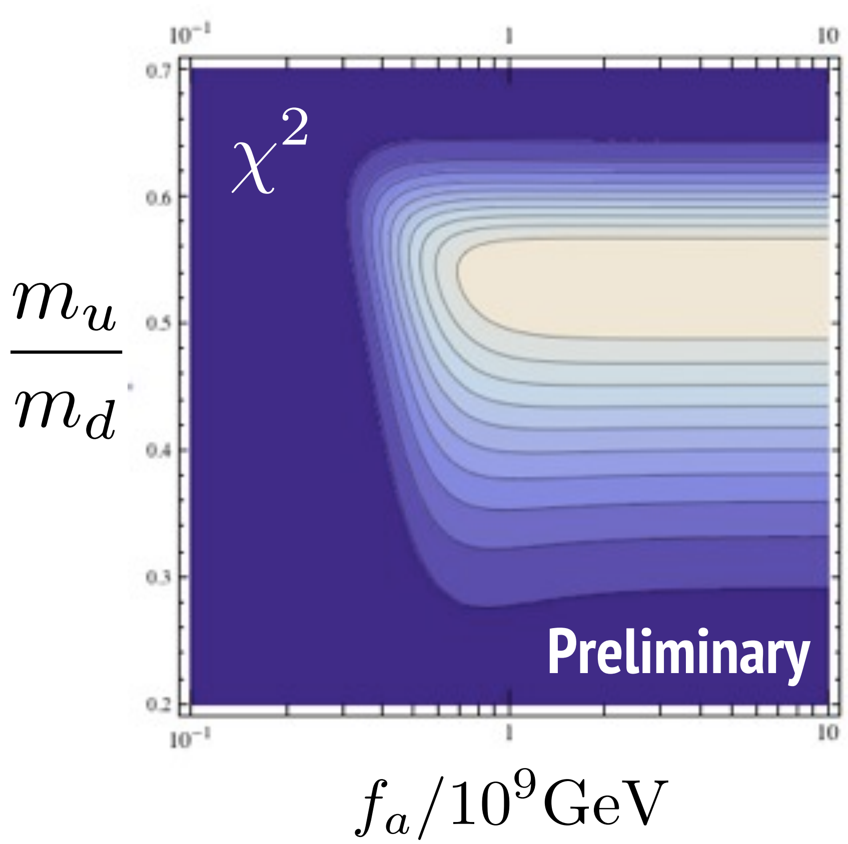




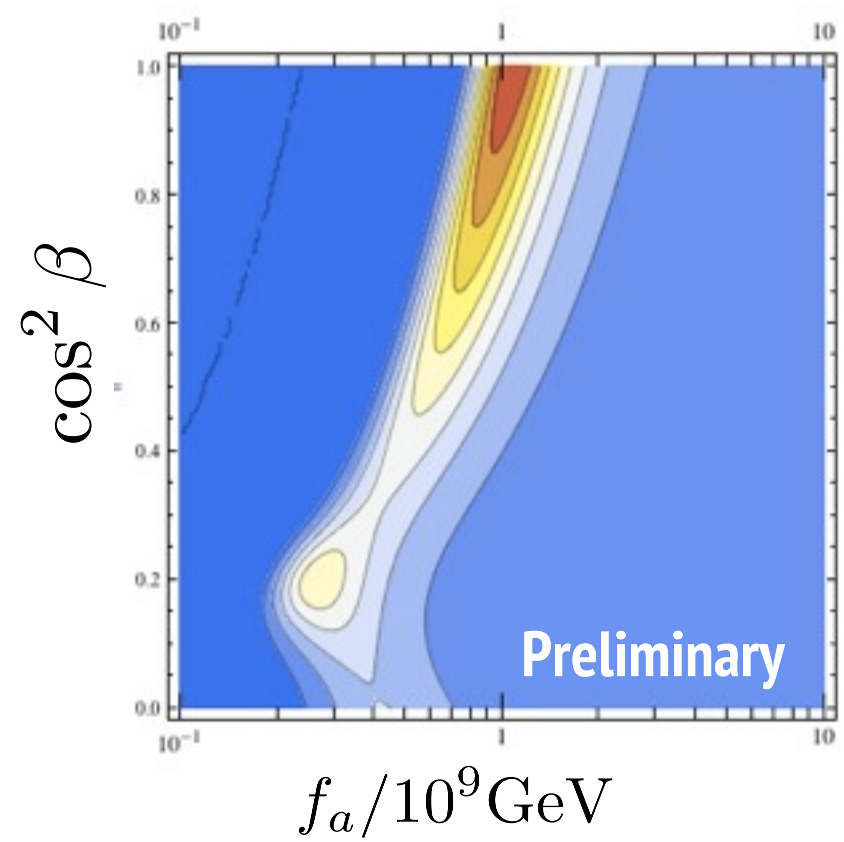
Hints, constraints and models ... any preference?

Tip of the Red Giant branch (M5)	$g_{ae} = C_{ae}\dfrac{m_e}{f_a} = (2 \pm 1.5) \times 10^{-13}$
White dwarf luminosity function	$g_{ae} = C_{ae}\dfrac{m_e}{f_a} = (1.4 \pm 1.4) \times 10^{-13}$
Cassiopeia A: neutron star cooling	$g_{an} = C_{an}\dfrac{m_n}{f_a} = (3.8 \pm 3) \times 10^{-10}$
SN1987A	$g_{ap} = C_{ap}\dfrac{m_p}{f_a} < 0.8 \times 10^{-10}$

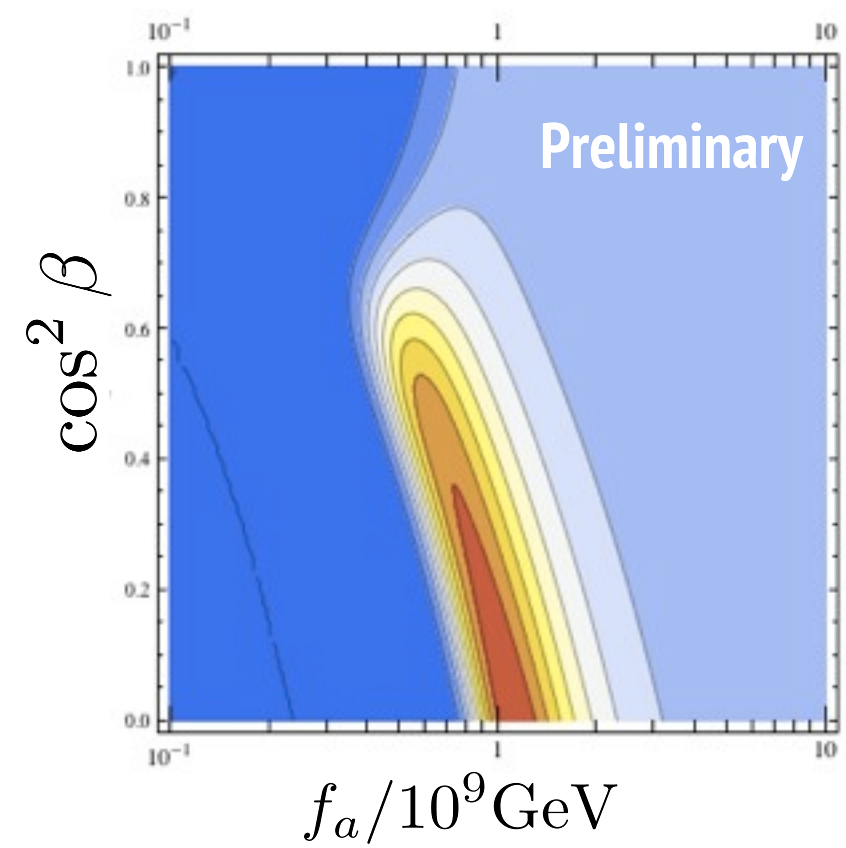
KSVZ (no RG, no WD, no pref.)



DFSZ1

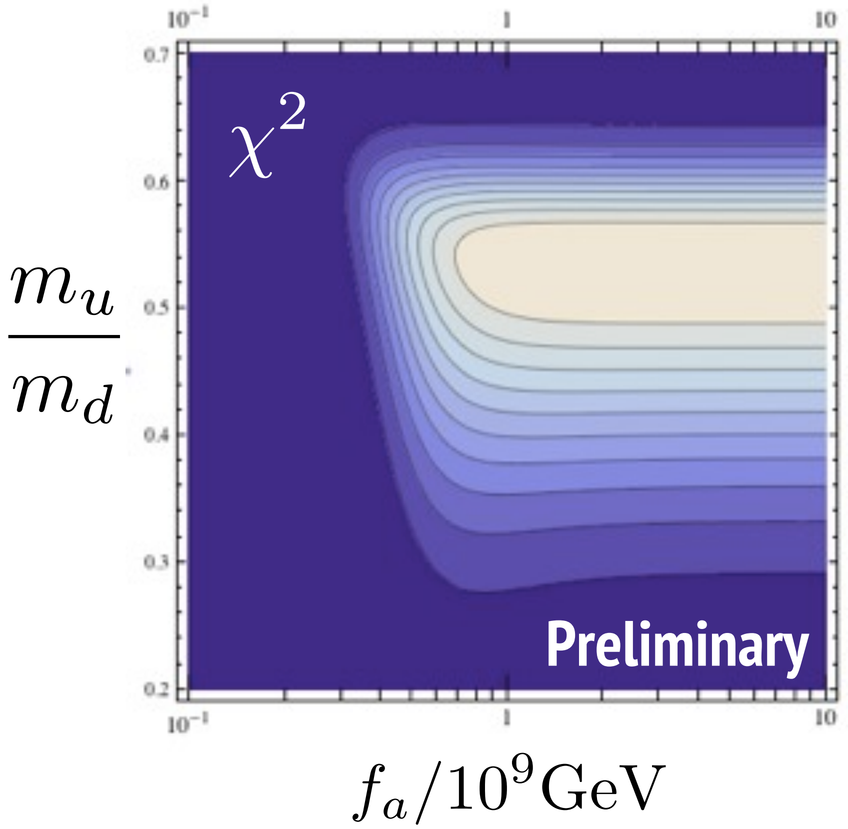


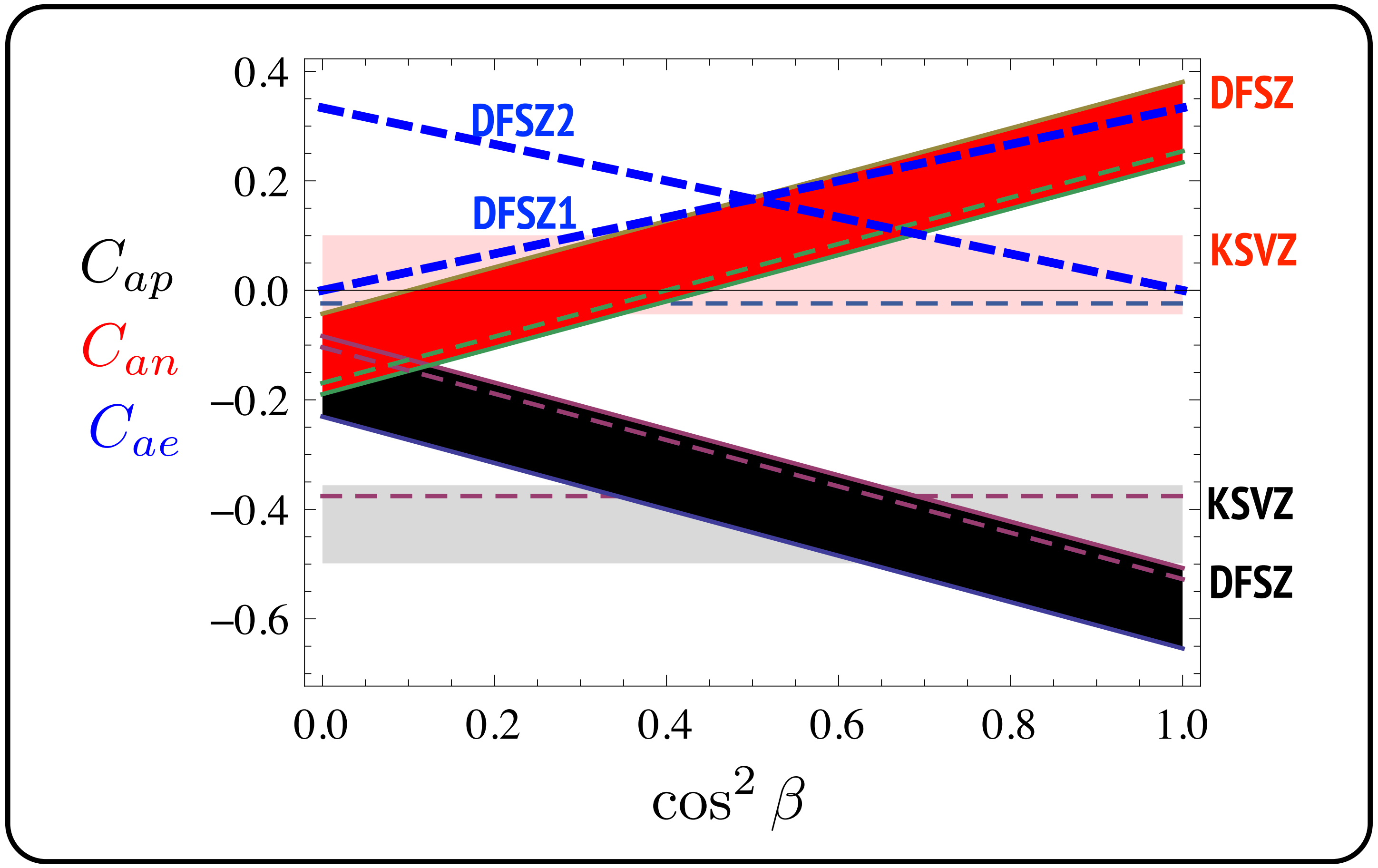
DFSZ2



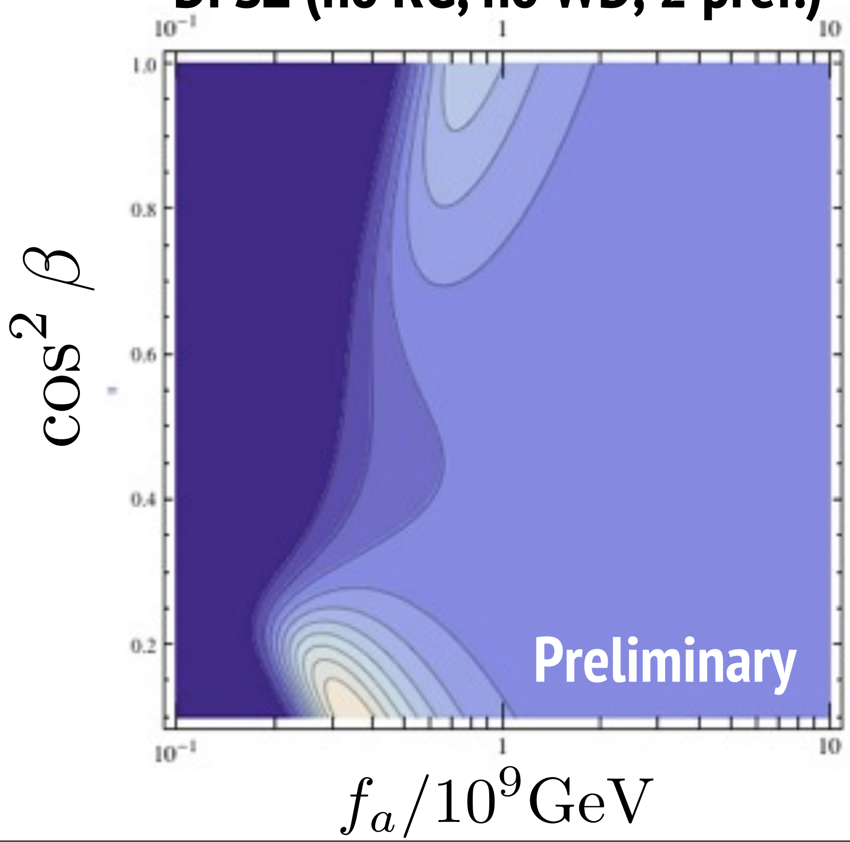
Hints, constraints and models ... any preference?

KSVZ (no RG, no WD, no pref.)

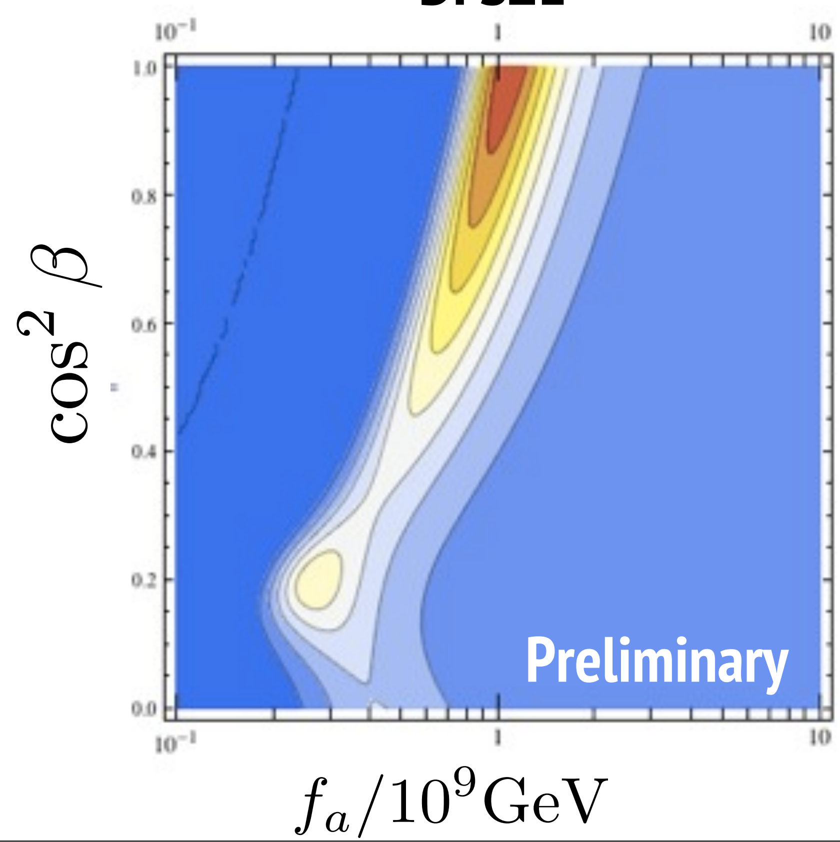




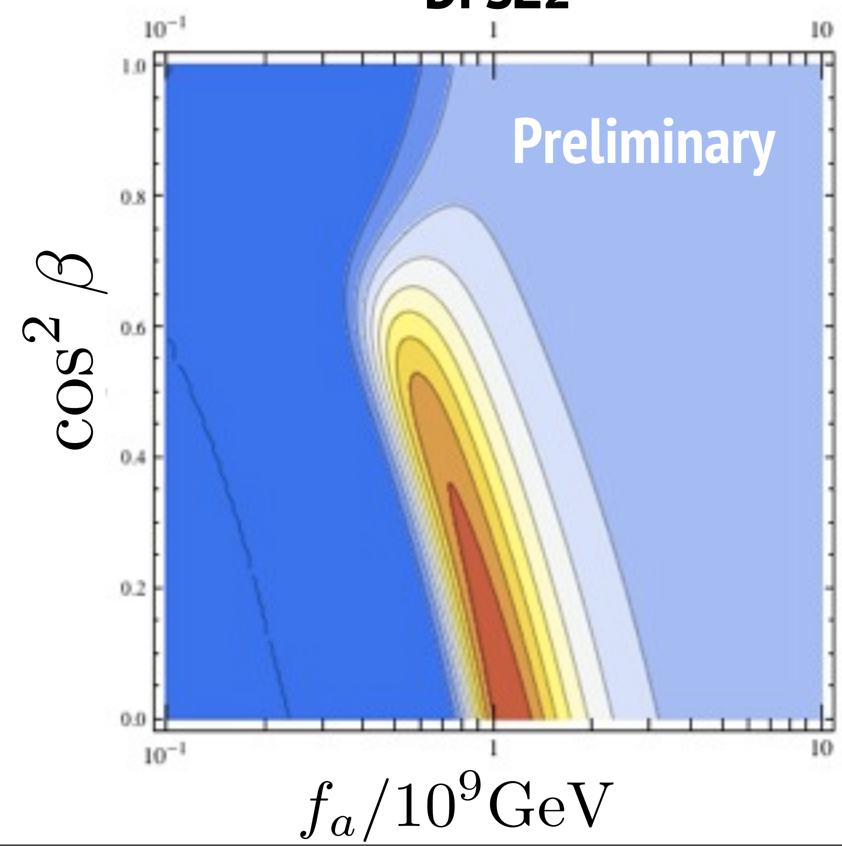
DFSZ (no RG, no WD, 2 pref.)



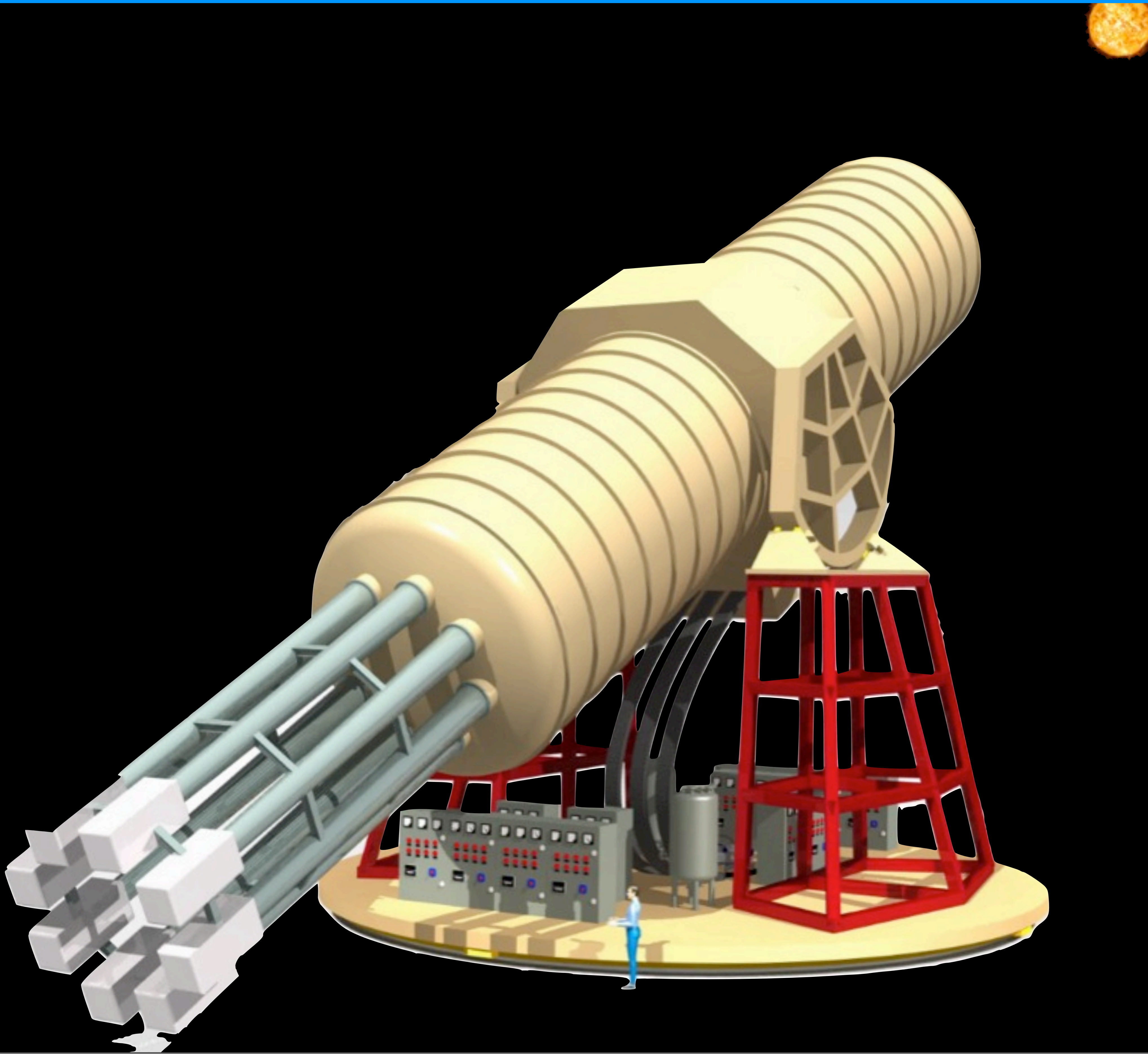
DFSZ1



DFSZ2



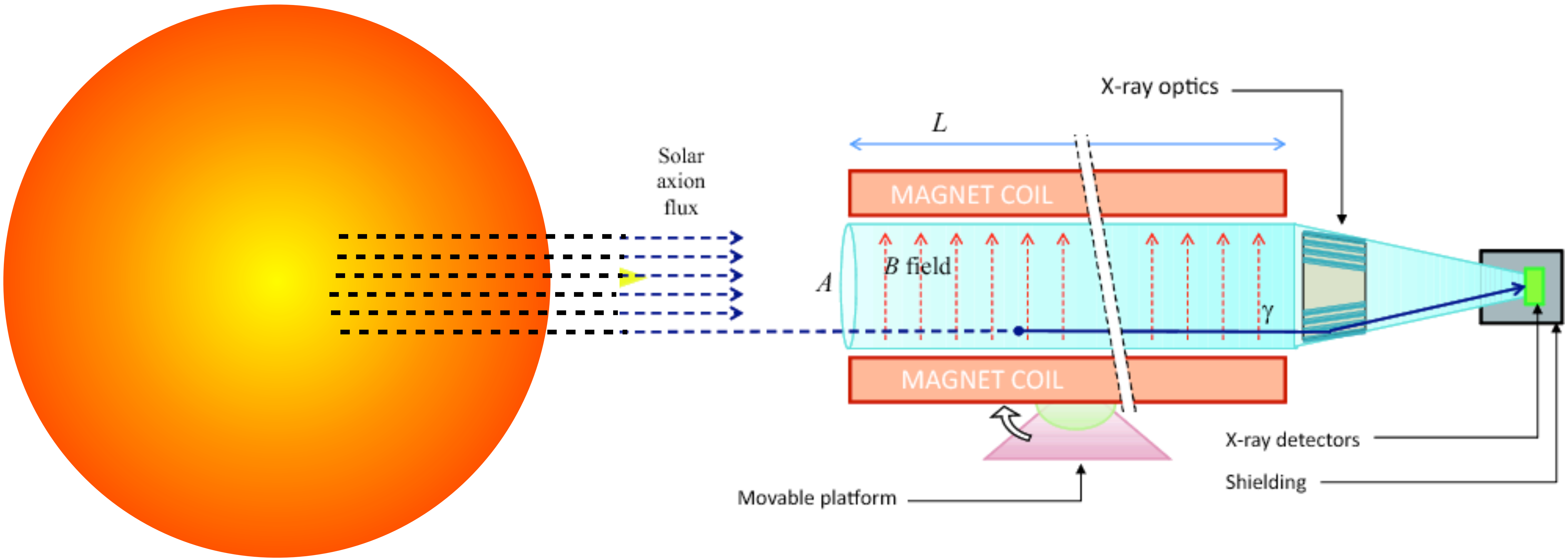
IAXO: The international axion observatory



Helioscopes

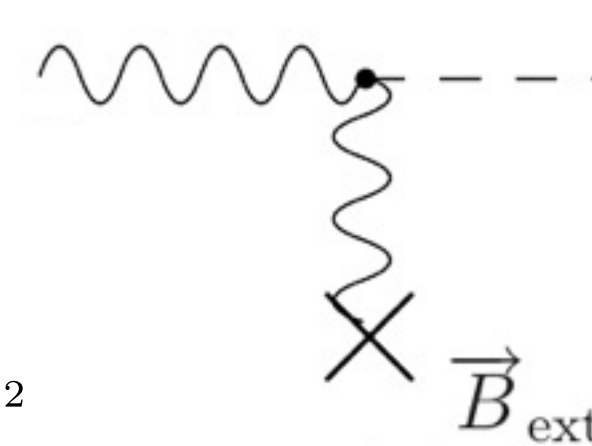
The Sun is a copious emitter of axions!

convert into X-rays **focus** **detect**



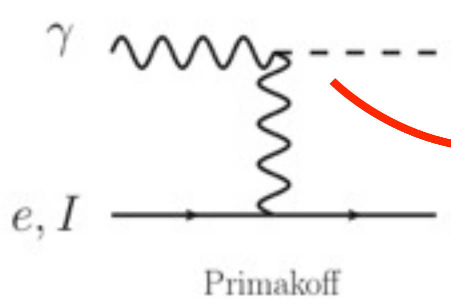
Conversion probability

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



$m_a \to 0, P \to \left(\frac{g_{a\gamma}B_T L}{2}\right)^2$ $m_a \to \text{large}, P \to \left(\frac{2g_{a\gamma}B_T\omega}{m_a^2}\right)^2$

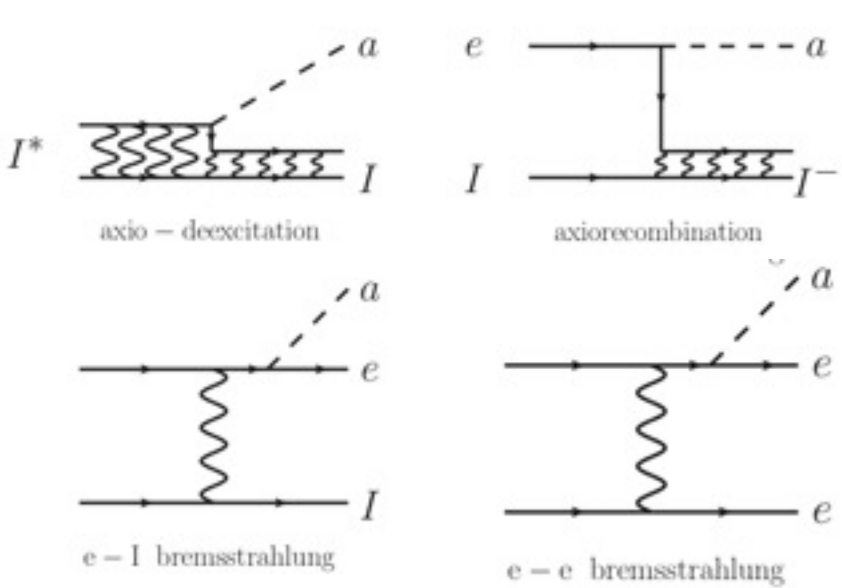
Hadronic axions (KSVZ)

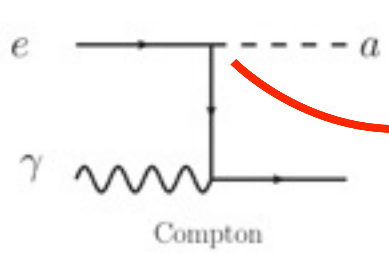


$$\frac{C_\gamma \alpha}{2\pi f_a} \frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4} a$$

$g_{a\gamma}$

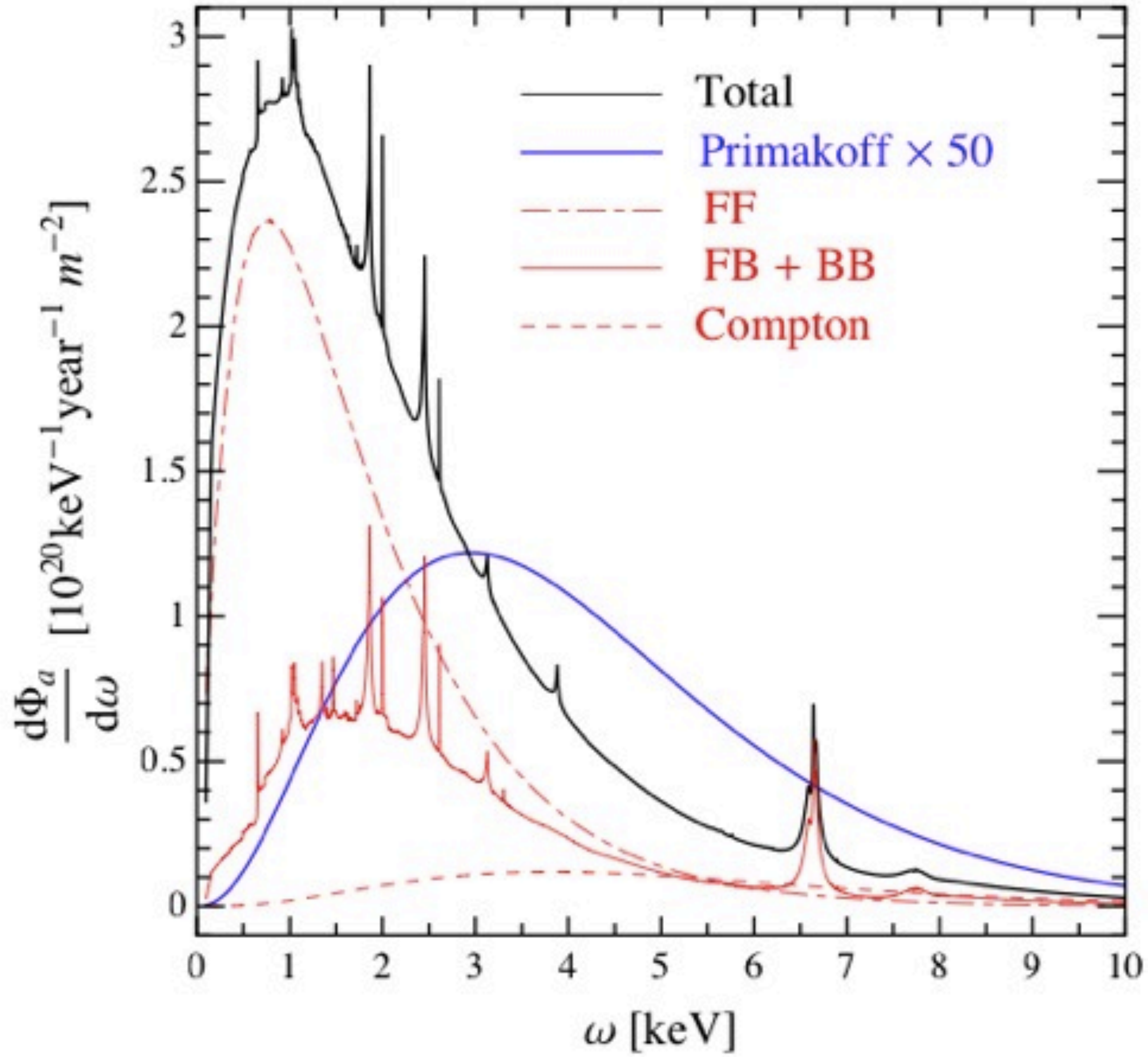
Non hadronic (DFSZ, e-coupling!)





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

g_{ae}



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

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

typical of non-hadronic meV mass axions

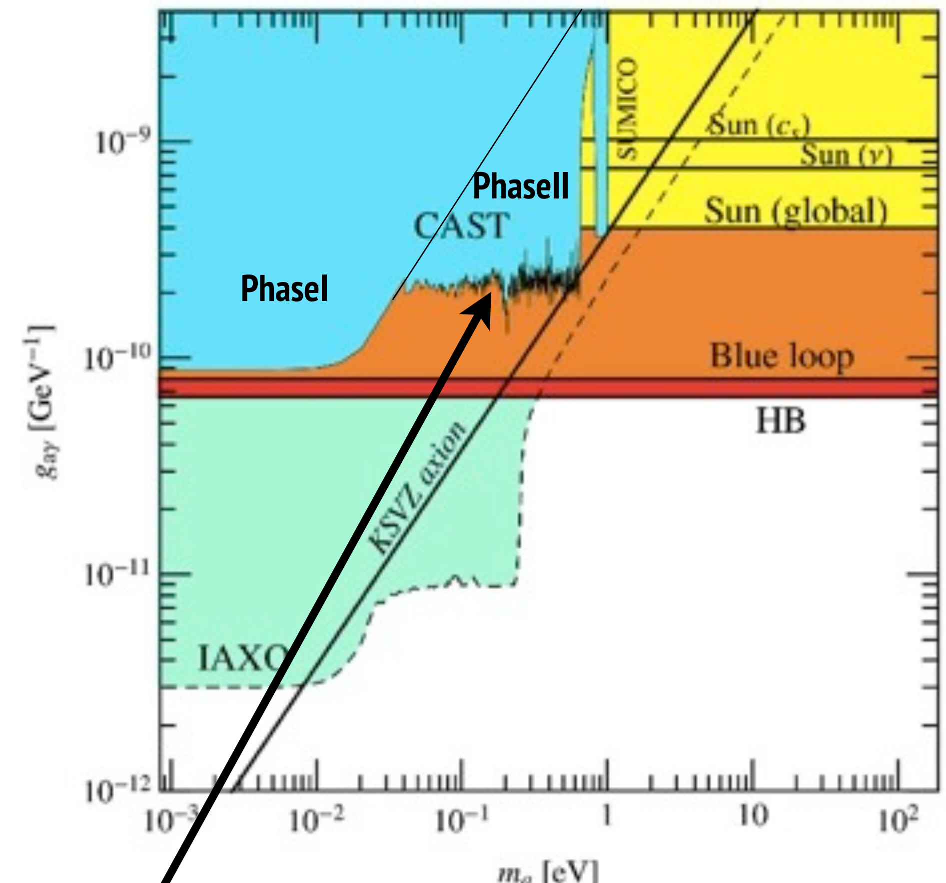
CAST Helioscope

CAST (LHC dipole 9.3 m, 9T)

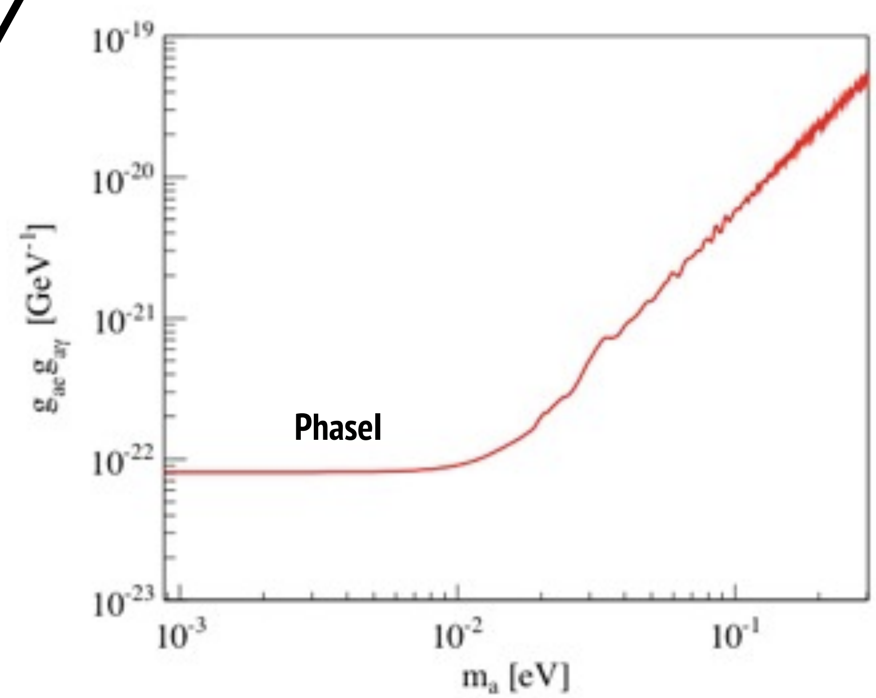
- 1~2 h tracking/day (sunset,dawn)
- 3 Detectors (2 bores)
  CCD, Micromegas
- X-ray optics
- He gas for large masses

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

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

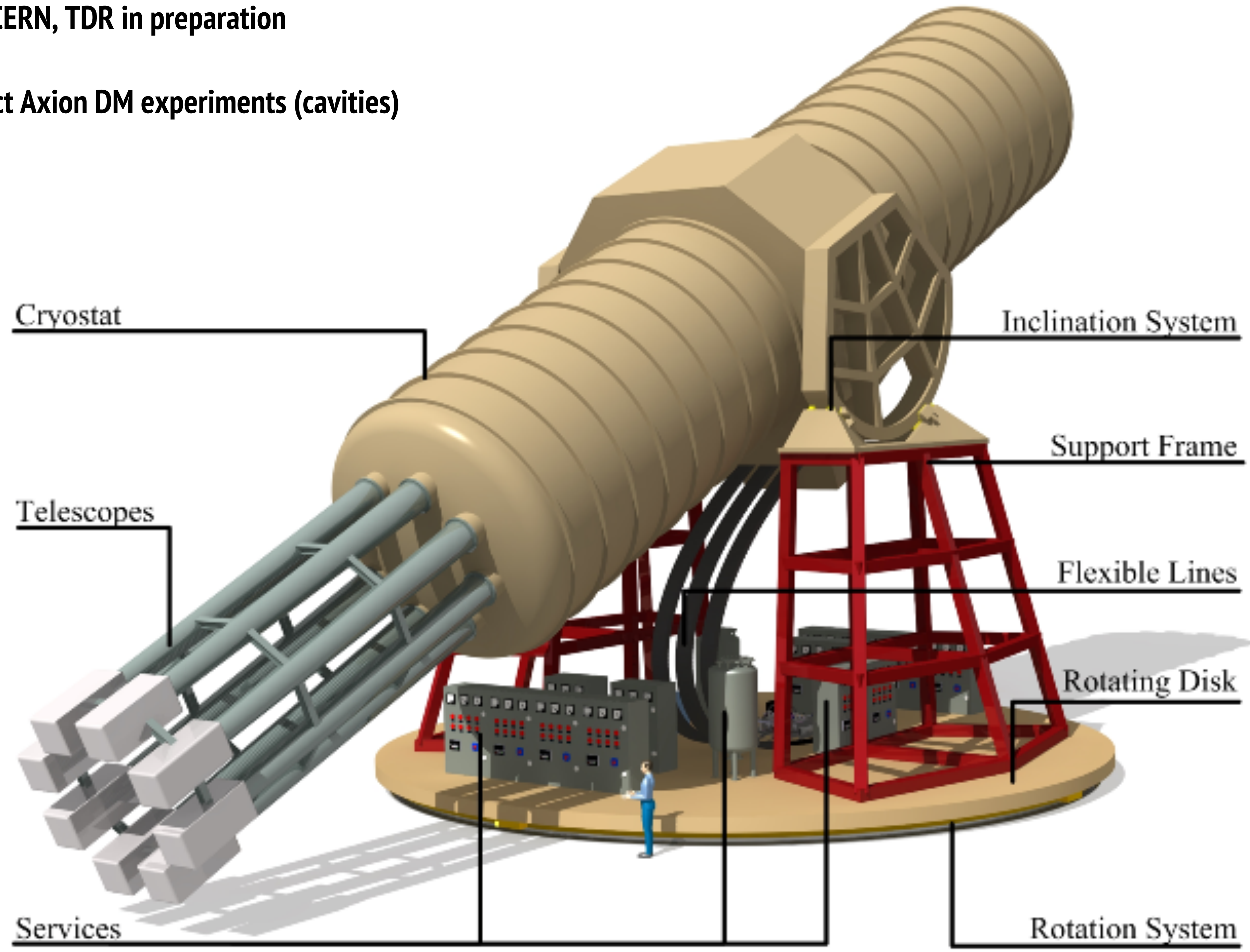
Rotating platform with services

-NGAG paper JCAP 1106:013,2011

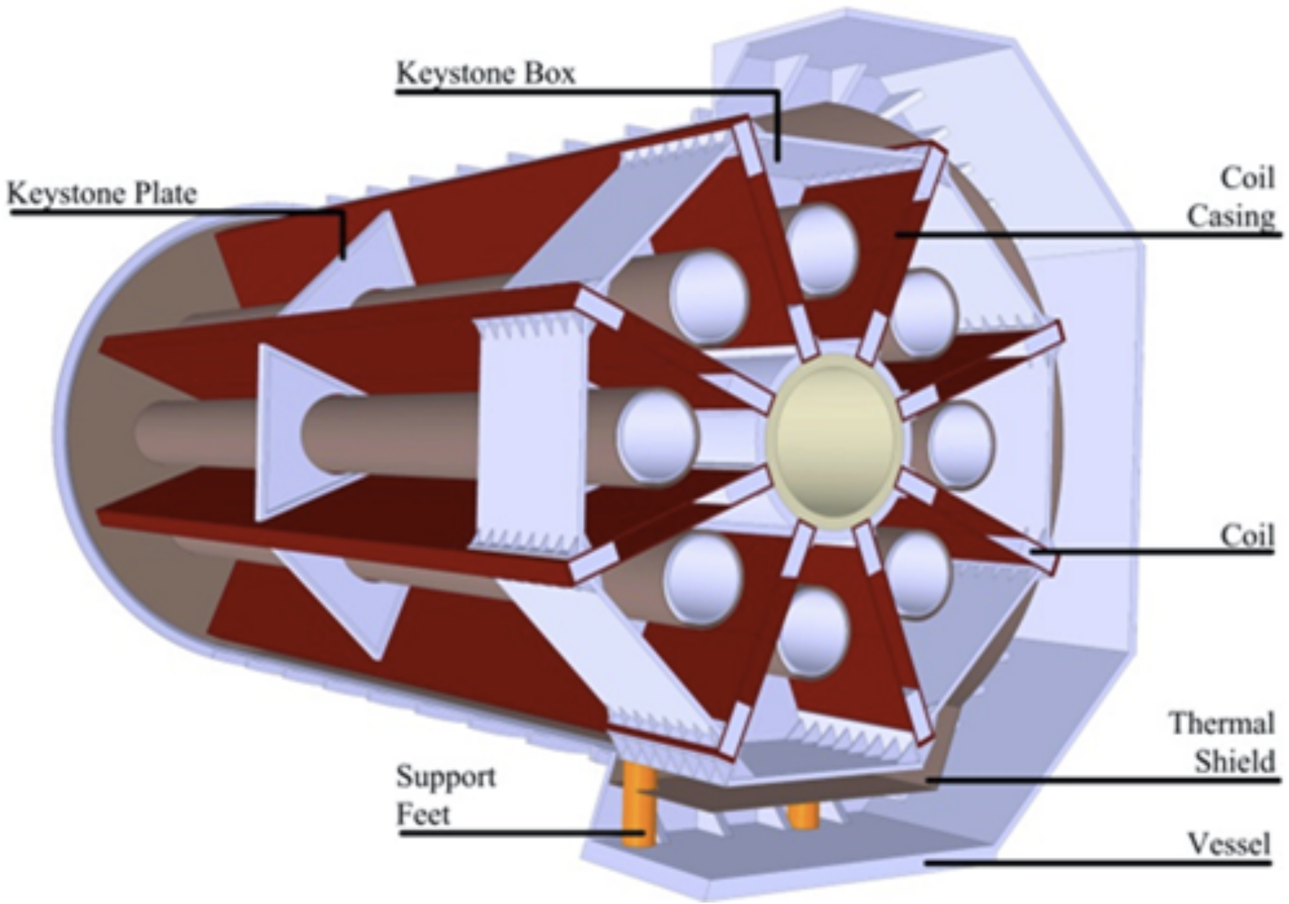
-Conceptual design report IAXO 2014 JINST 9 T05002

-LOI submitted to CERN, TDR in preparation

-Possibility of Direct Axion DM experiments (cavities)



IAXO magnet (under development)



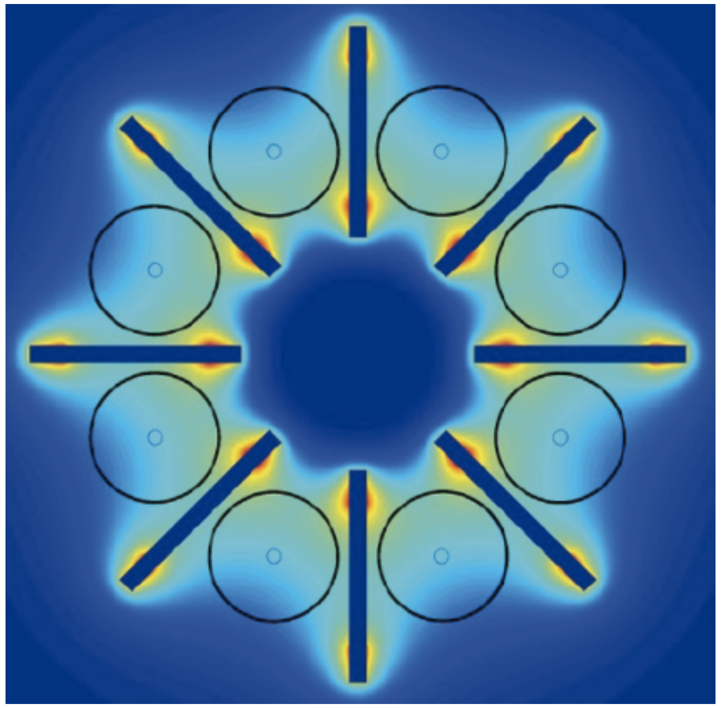
IAXO magnet concept presented in:

IEEE Trans. Appl. Supercond. 23 (ASC 2012)

Adv. Cryo. Eng. (CEC/ICMC 2013)

IEEE Trans. Appl. Supercond. (MT 23)

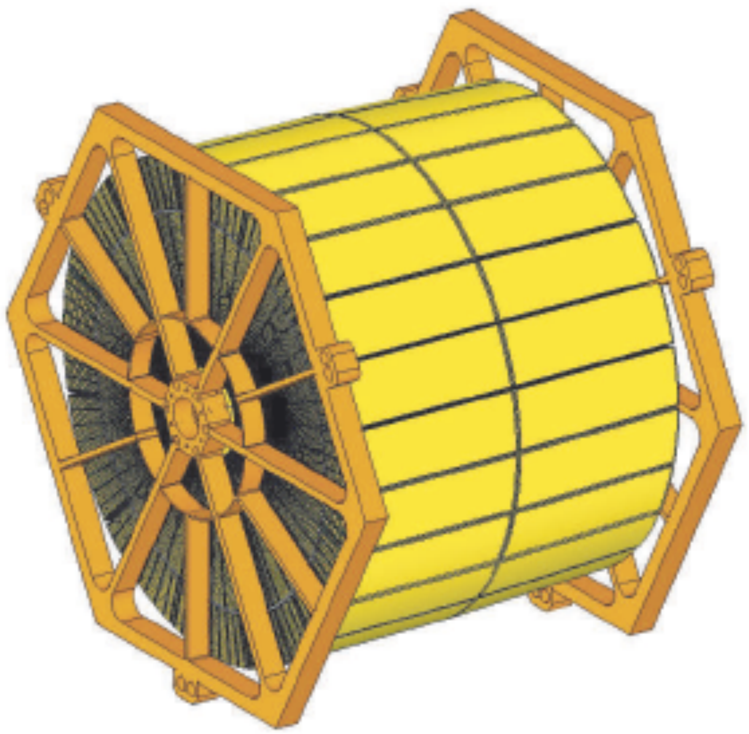
Transverse B-field (peak 5T, average 2.5T)

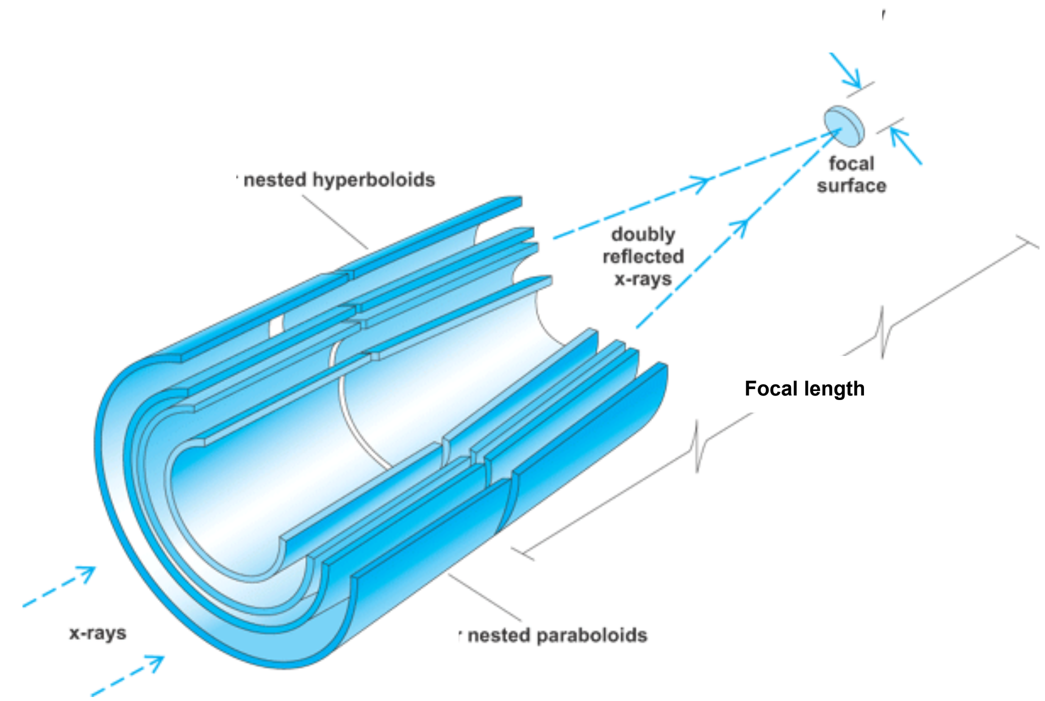


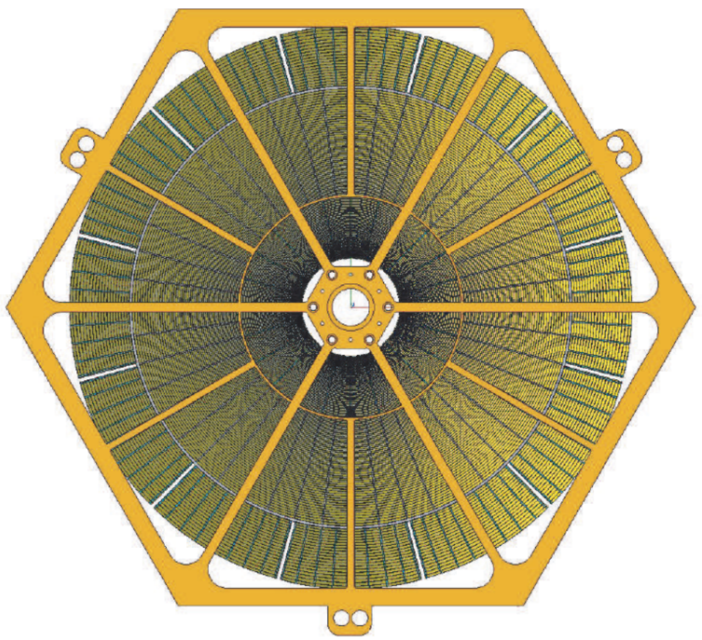
Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	$\sim$ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	$\sim$ 250
Coils:	Number of racetrack coils	8
	Winding pack width (mm)	384
	Winding pack height (mm)	144
	Turns/coil	180
	Nominal current, I_{op} (kA)	12.0
	Stored energy, E (MJ)	500
	Inductance (H)	6.9
	Peak magnetic field, B_p (T)	5.4
	Average field in the bores (T)	2.5
Conductor:	Overall size (mm^2)	35×8
	Number of strands	40
	Strand diameter (mm)	1.3
	Critical current @ 5 T, I_c (kA)	58
	Operating temperature, T_{op} (K)	4.5
	Operational margin	40%
	Temperature margin @ 5.4 T (K)	1.9
Heat Load:	at 4.5 K (W)	$\sim$150
	at 60-80 K (kW)	$\sim$1.6

IAXO optics

- IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)
- NuSTAR optics groups LLNL, Columbia U., DTU Denmark all in IAXO







Telescopes	8
N, Layers (or shells) per telescope	123
Segments per telescope	2172
Geometric area of glass per telescope	0.38 m^2
Focal length	5.0 m
Inner radius	50 mm
Outer Radius	300 mm
Minimum graze angle	2.63 mrad
Maximum graze angle	15.0 mrad
Coatings	W/B_4C multilayers
Pass band	1–10 keV
IAXO Nominal, 50% EEF (HPD)	0.29 mrad
IAXO Enhanced, 50% EEF (HPD)	0.23 mrad
IAXO Nominal, 80% EEF	0.58 mrad
IAXO Enhanced, 90% EEF	0.58 mrad
FOV	2.9 mrad

IAXO detectors

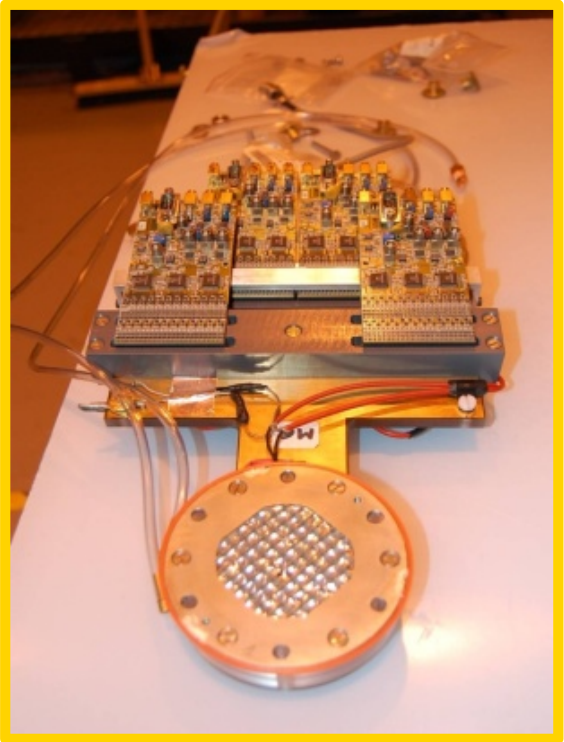
- Small Micromegas-TPC chambers:
  - Shielding
  - Radiopure components
  - Offline discrimination

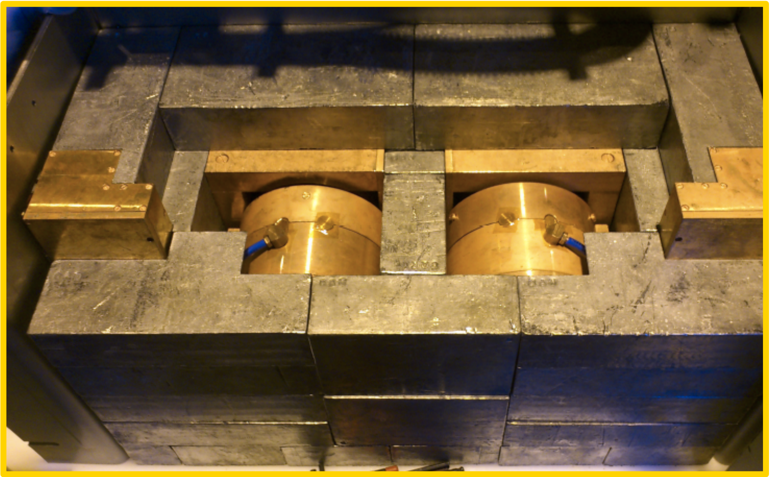
Goal background level for IAXO:
  10-7 – 10-8 c keV-1 cm-2 s-1

Already demonstrated:
~8×10-7 c keV-1 cm-2 s-1
  (in CAST 2014 result)
10-7 c keV-1 cm-2 s-1
  (underground at LSC)

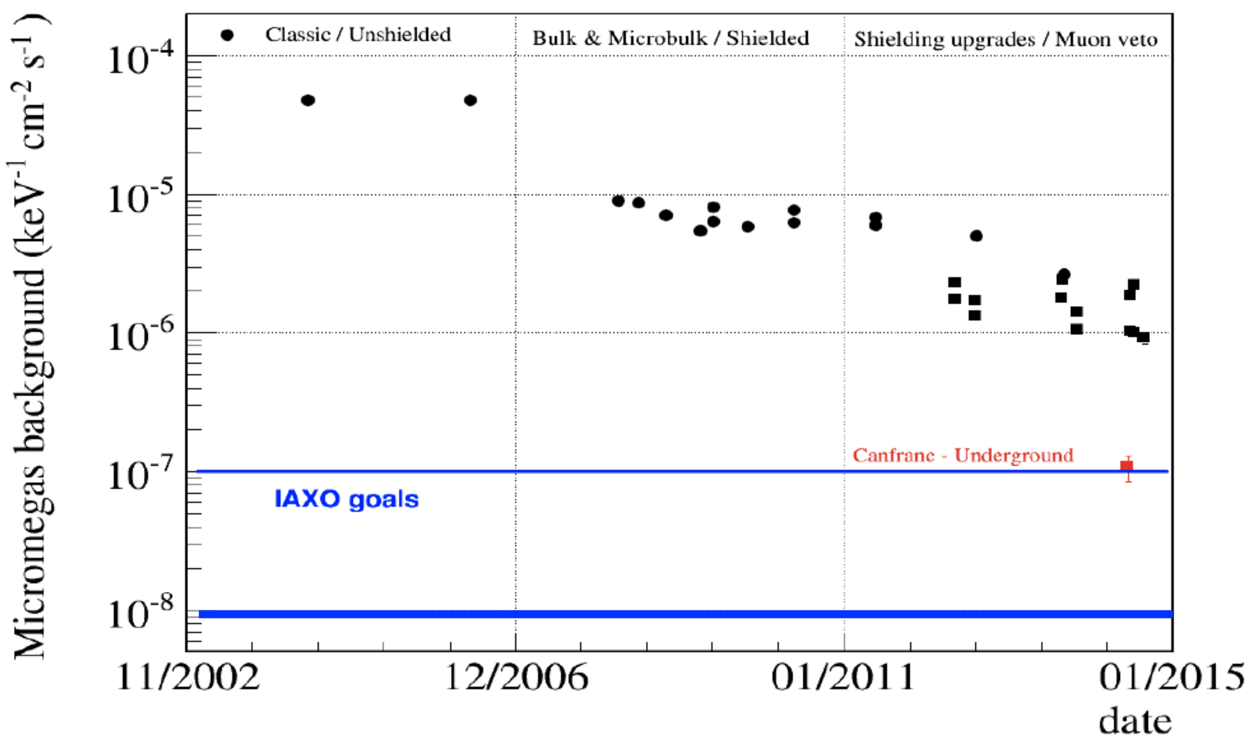
Active program of development. Clear roadmap for improvement

- Other detectors, Gridpix/InGrid, MMC,CCDs



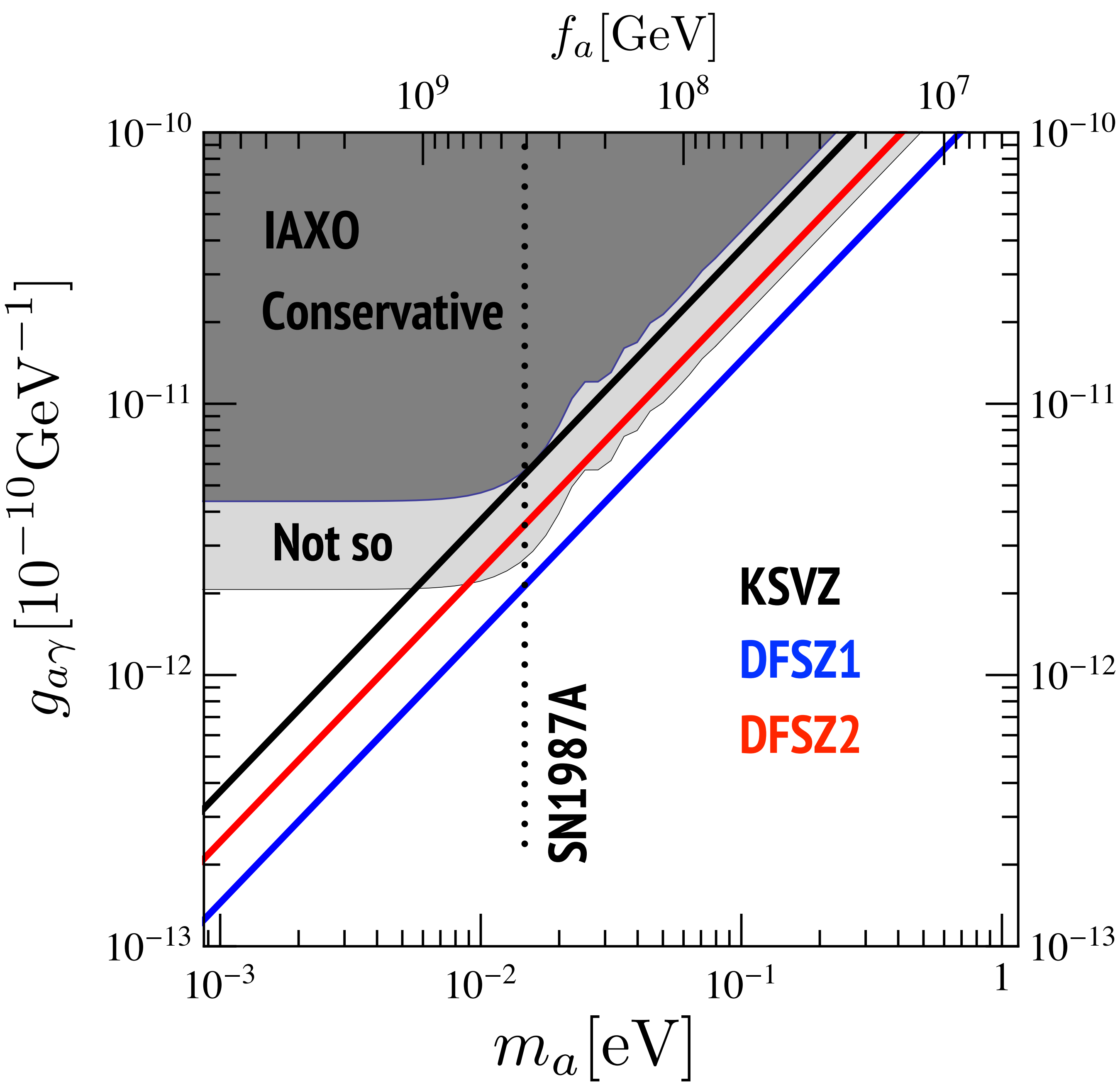


history

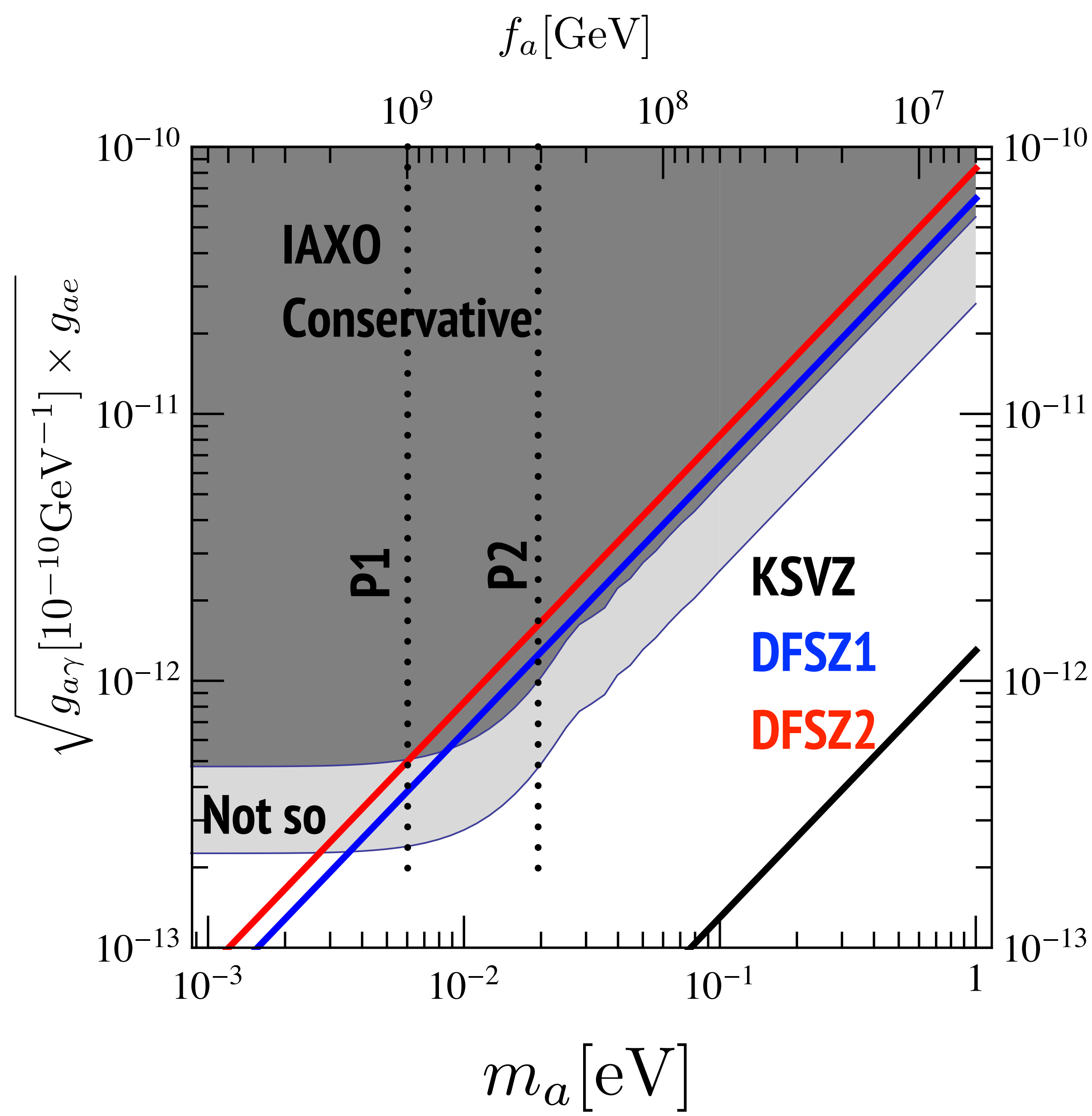


Physics reach (preliminary)

Hadronic axions (KSVZ)

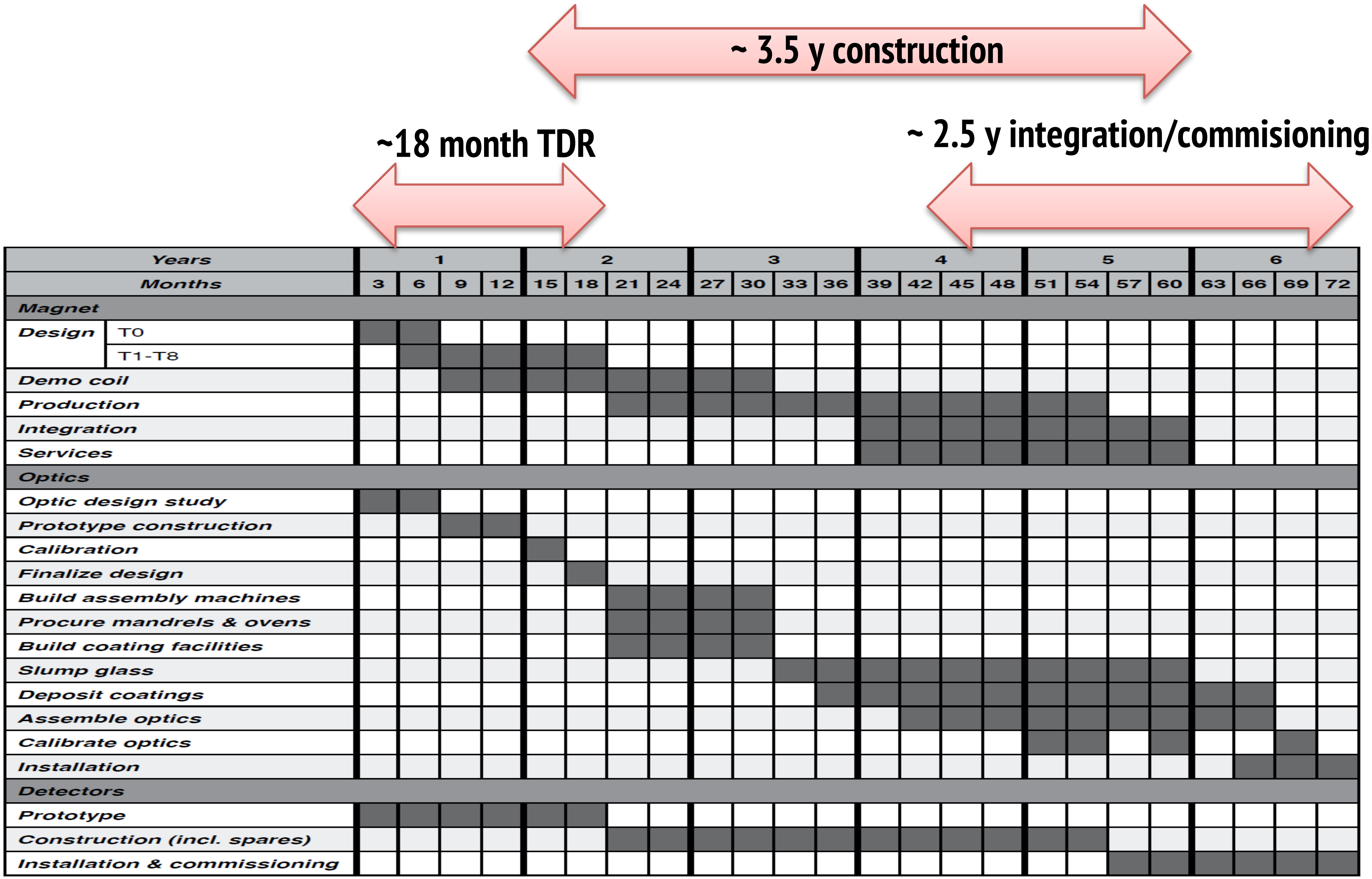


Non hadronic (DFSZ, e-coupling!)



Possibility to unveal the hints!

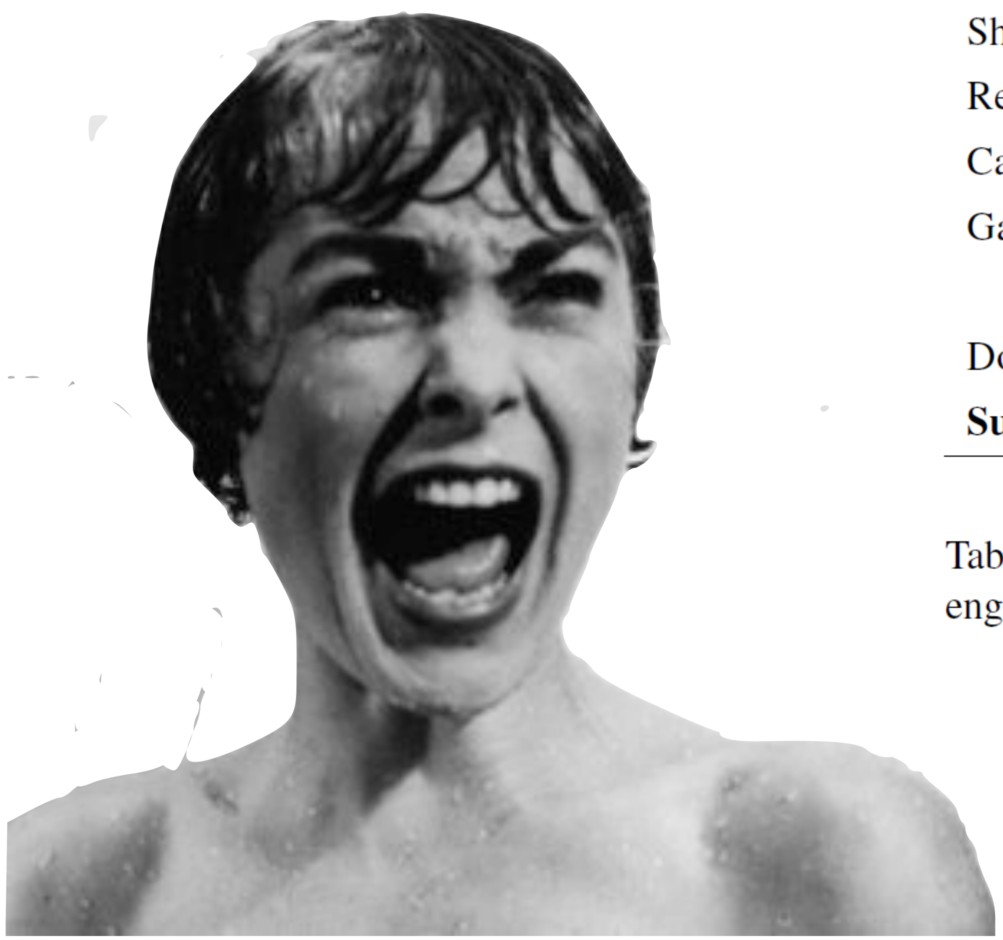
IAXO timeline



IAXO costs

Item	Cost (MCHF)	Subtotals (MCHF)
Magnet		31.3
Eight coils based assembled toroid	28	
Magnet services	3.3	
Optics		16.0
Prototype Optic: Design, Fabrication, Calibration, Analysis	1.0	
IAXO telescopes (8 + 1 spare)	8.0	
Calibration	2.0	
Integration and alignment	5.0	
Detectors		5.8
Shielding & mechanics	2.1	
Readouts, DAQ electronics & computing	0.8	
Calibration systems	1.5	
Gas & vacuum	1.4	
Dome, base, services building and integration		3.7
Sum		**56.8**

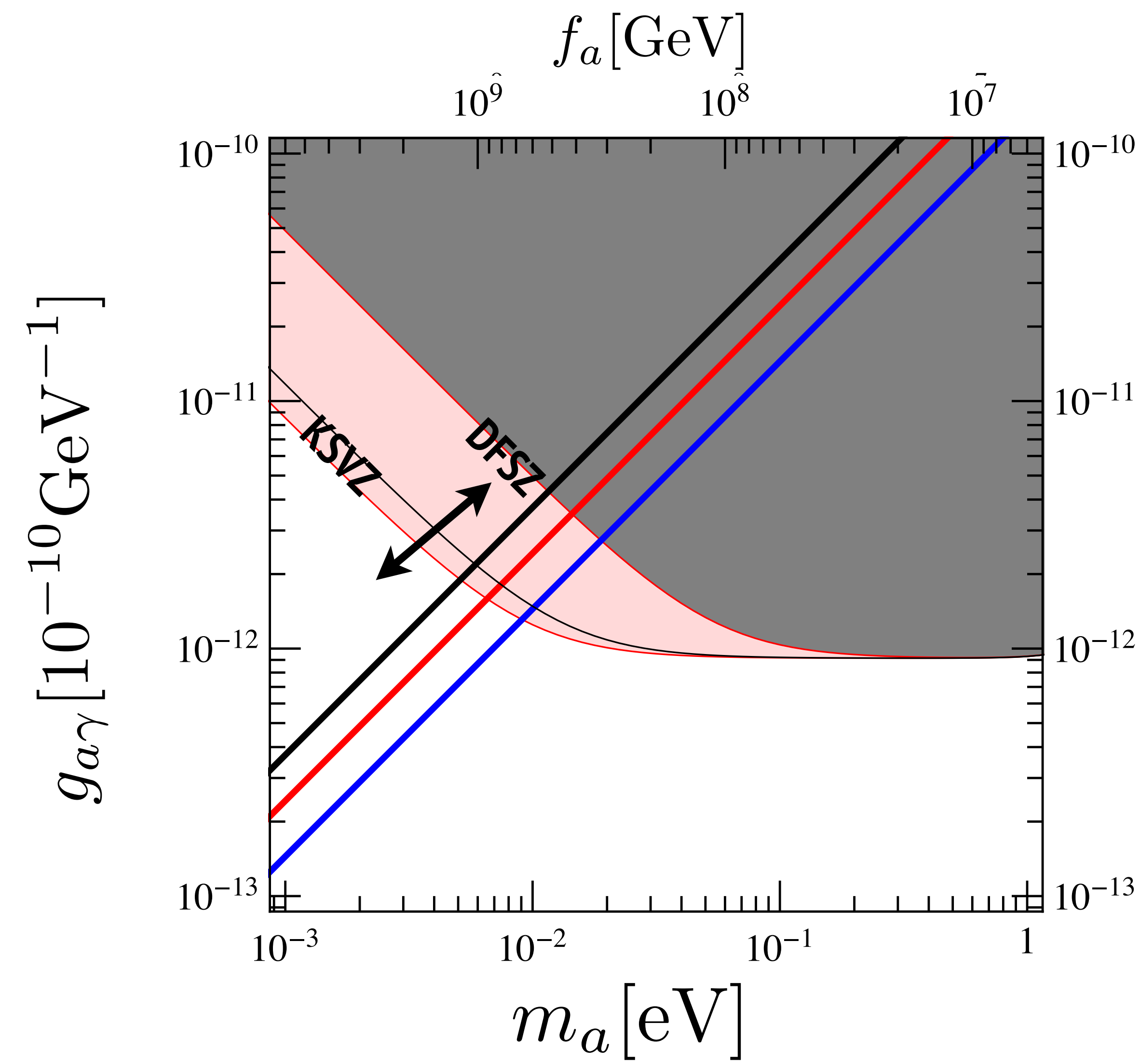
Table 5: Estimated costs of the IAXO setup: magnet, optics and detectors. It does not include laboratory engineering, as well as maintenance & operation and physics exploitation of the experiment.



Physics case +

Betelgeuse is the next galactic SN

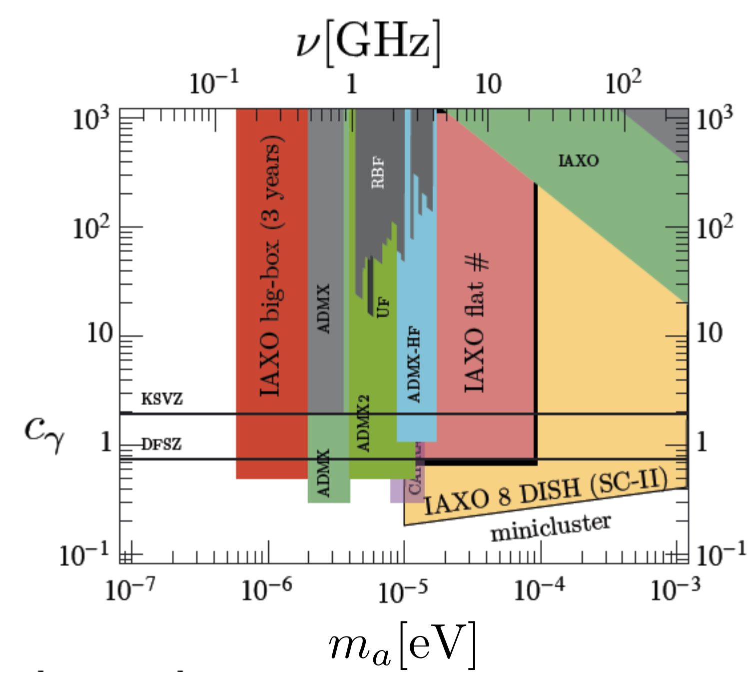
- up to 5 10^{14} a's (E~80 MeV) in 10 sec
- Early warning (Si nu's)
- check visibility
- 50-100 MeV detectors
- needs a boost ~30



DM detectors inside IAXO volume

- huge magnetic volume
- low masses than ADMX is straightforward
- high masses, combine cavities
- dish antennas (miniclusters)

see Redondo, talk at Patras 2014



Conclusions

meV frontier

- Astro hints (RGs,WD,NS)

- Experiment: IAXO

- Axion DM (hard to test otherwise)