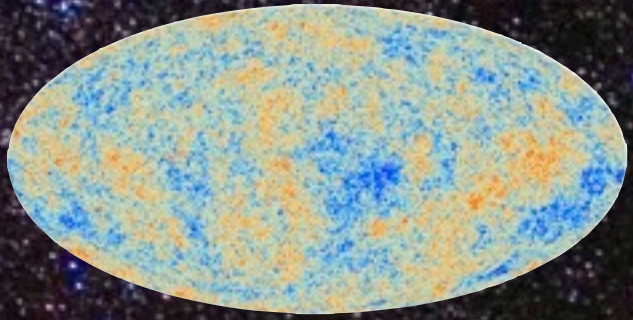
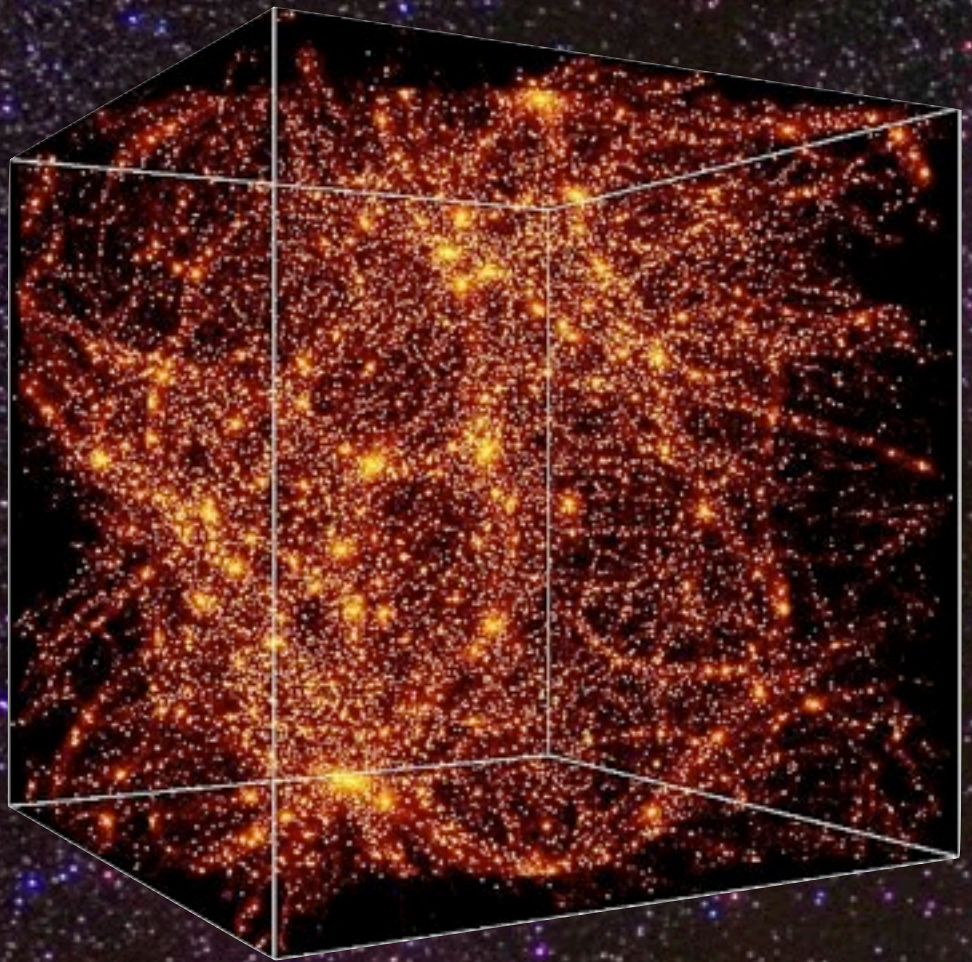
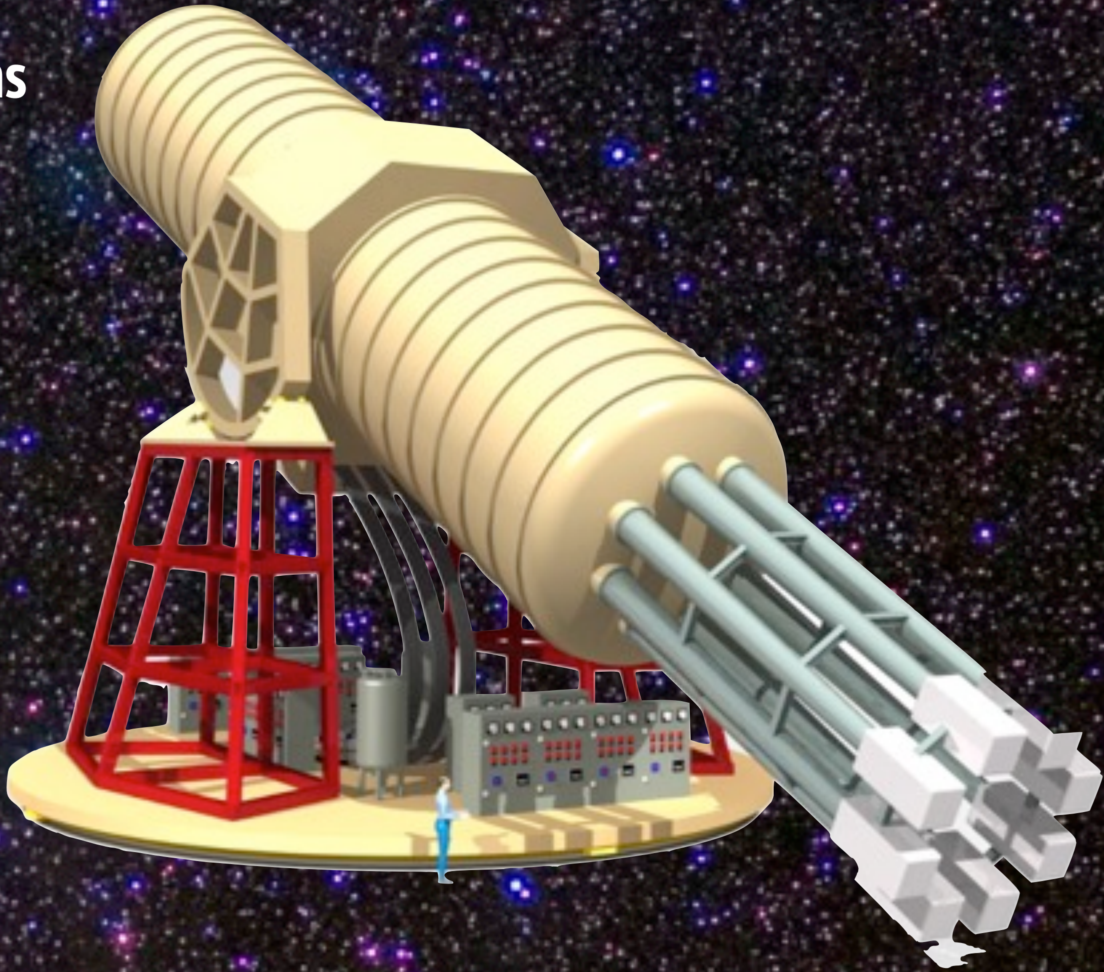
Axions, Dark Matter and Cosmology



Yavier Redondo
(Zaragoza U & MPP)

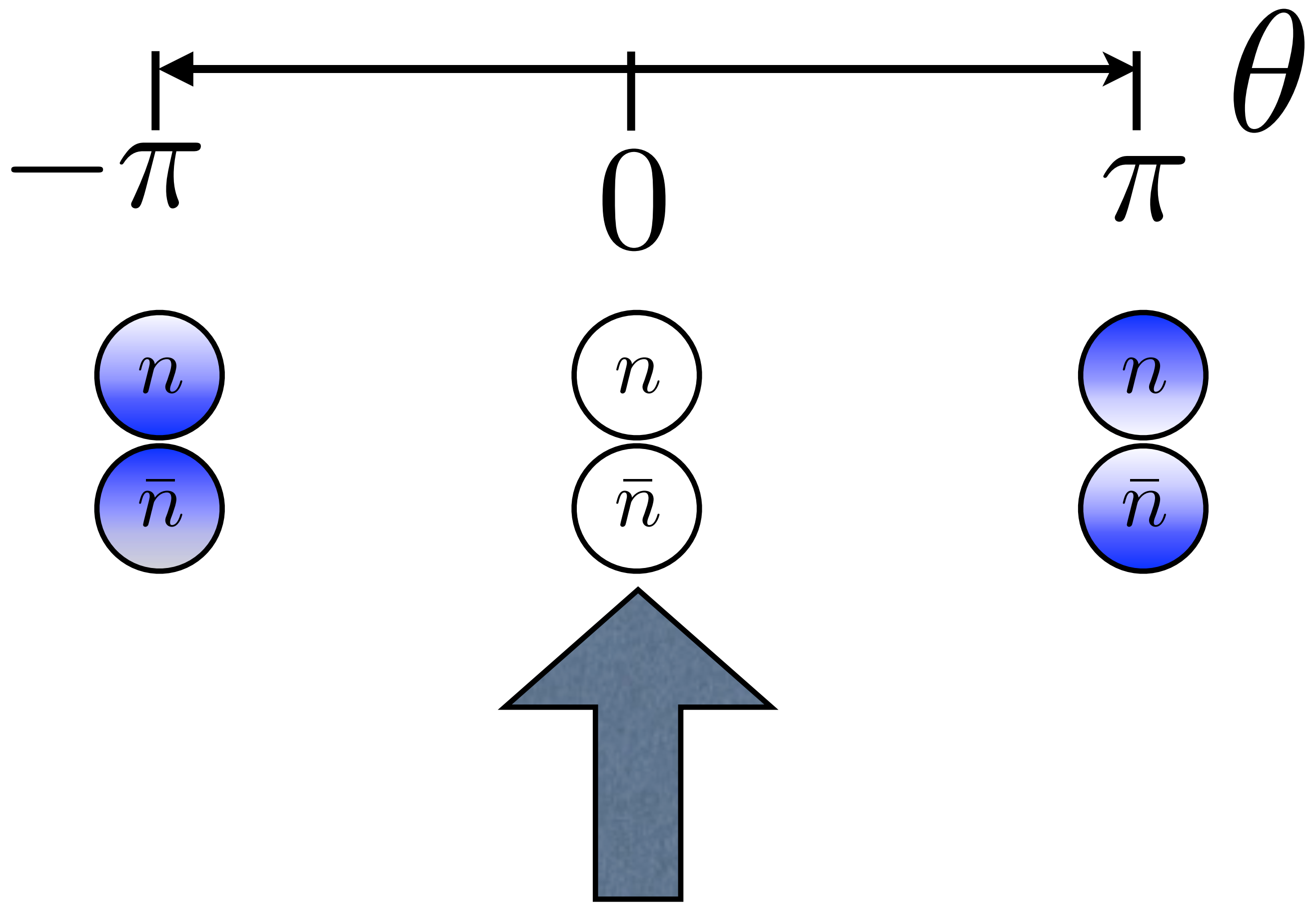


The Search for Axions
in the Universe
INFN Frascati
18-19 Aprile, 2016



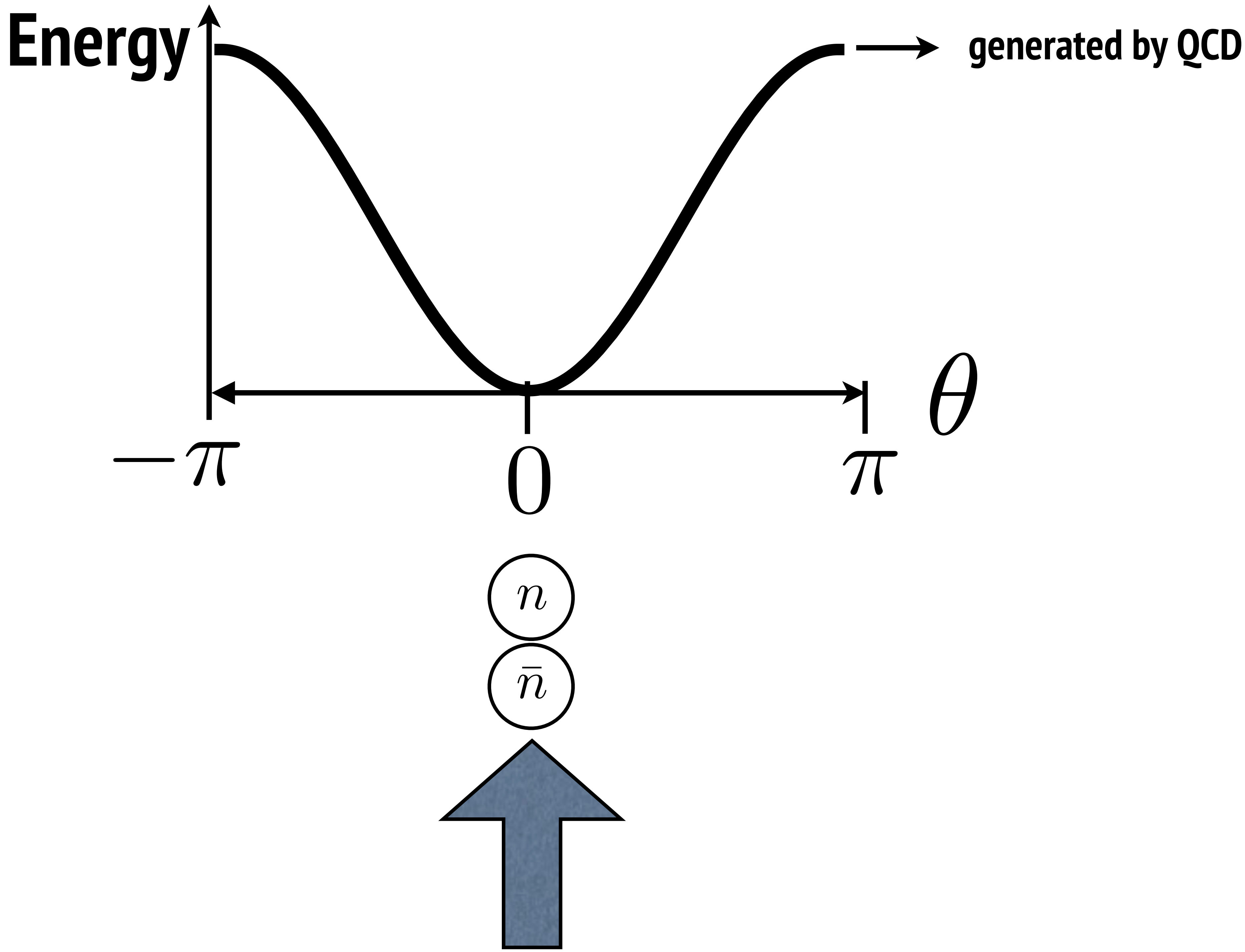
The theta angle of the strong interactions

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



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

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



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Axions are necessarily dark matter

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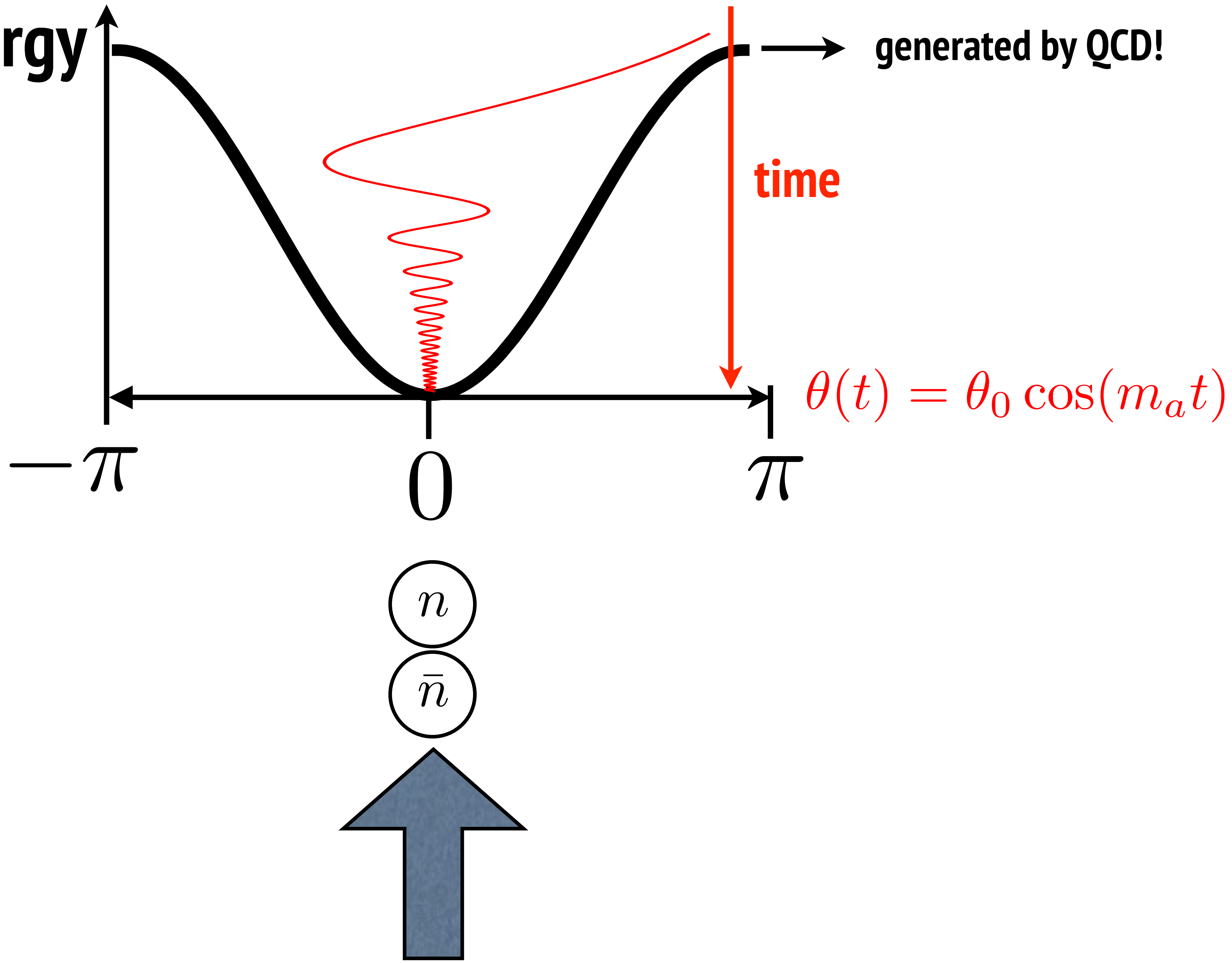

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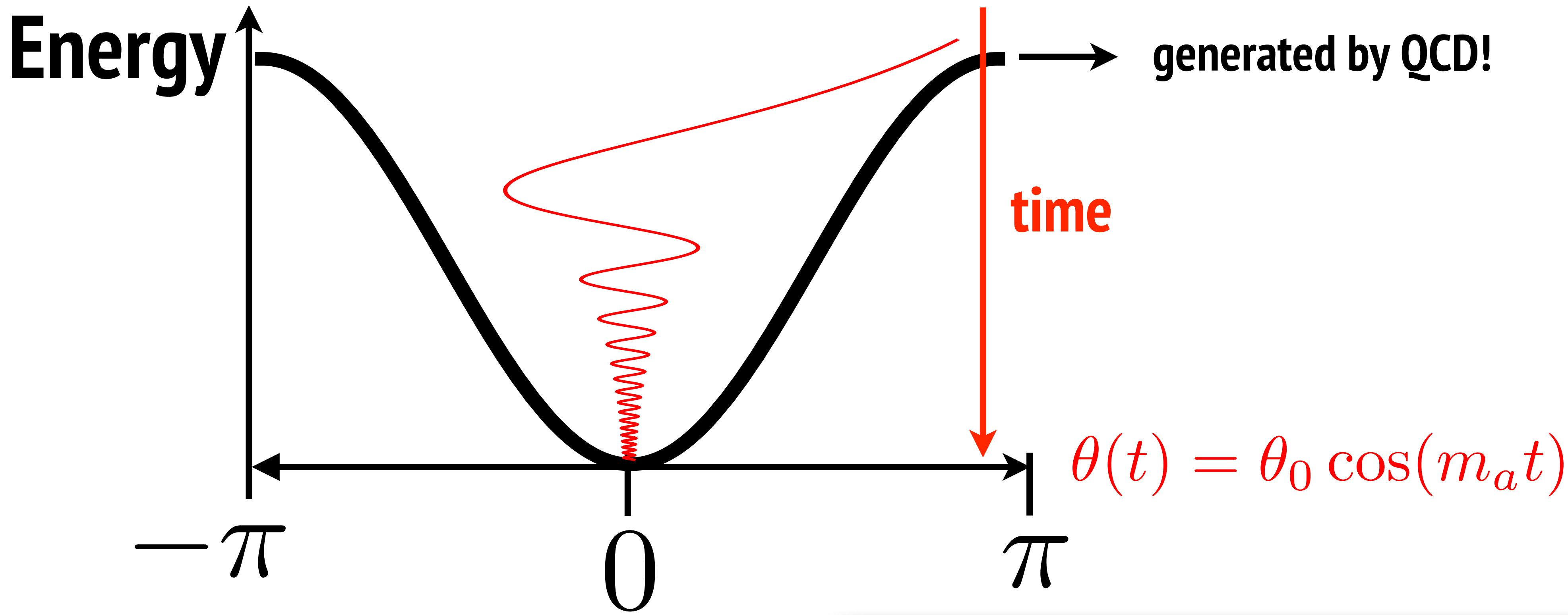

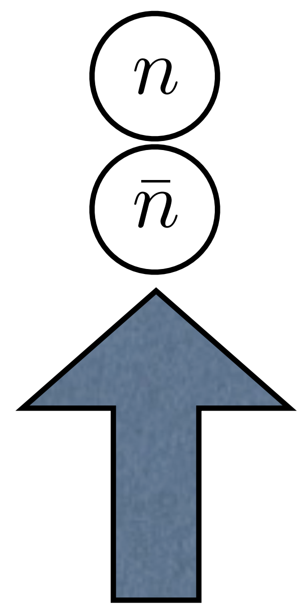

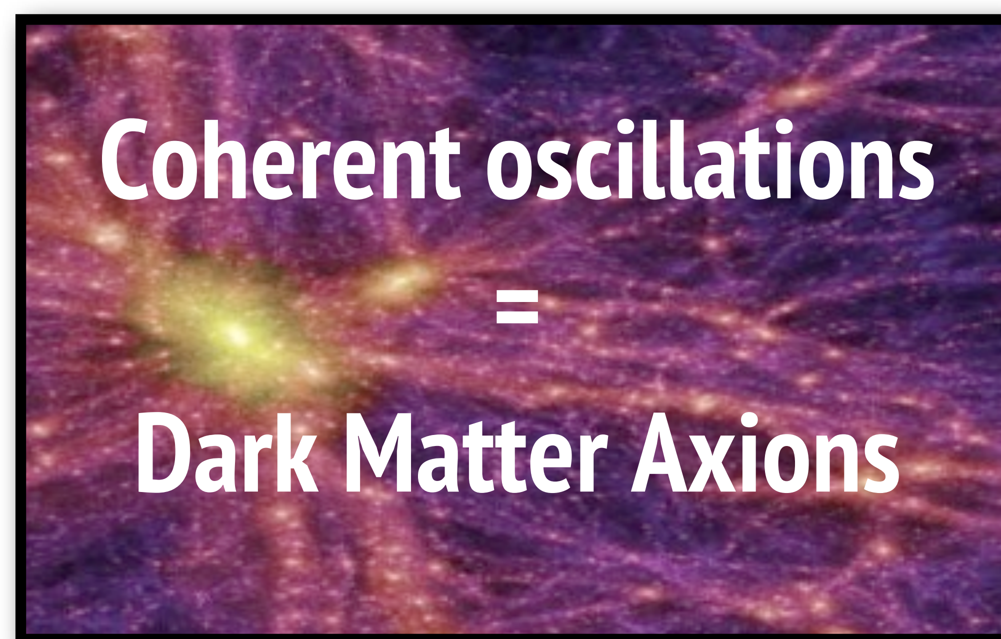

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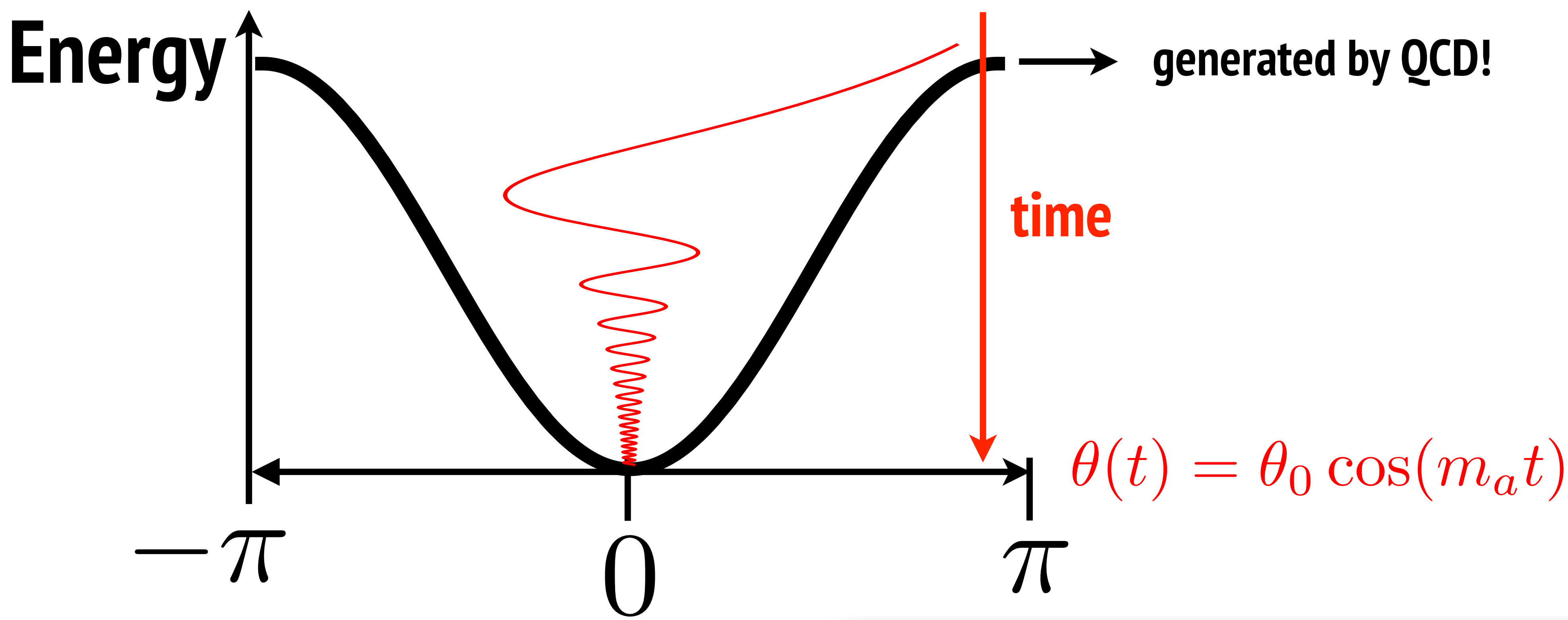
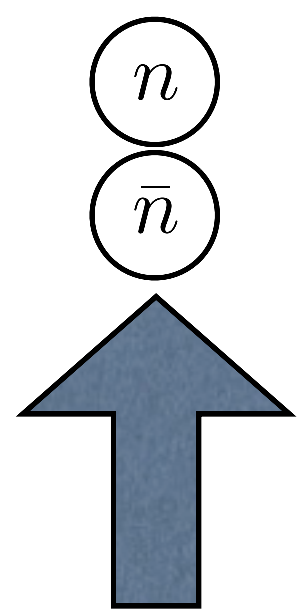


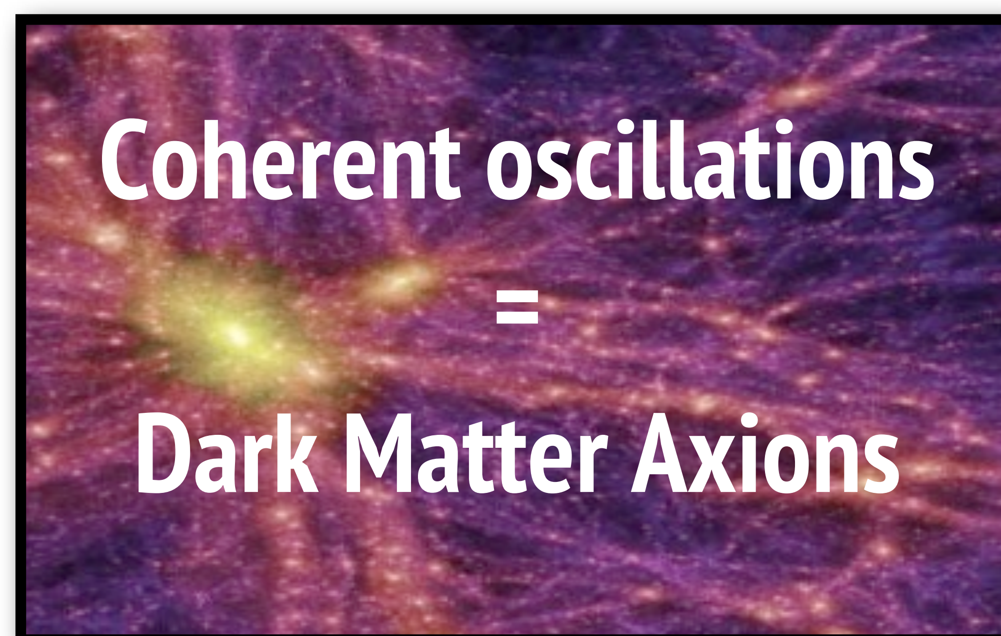
~ One parameter theory

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

axion mass

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



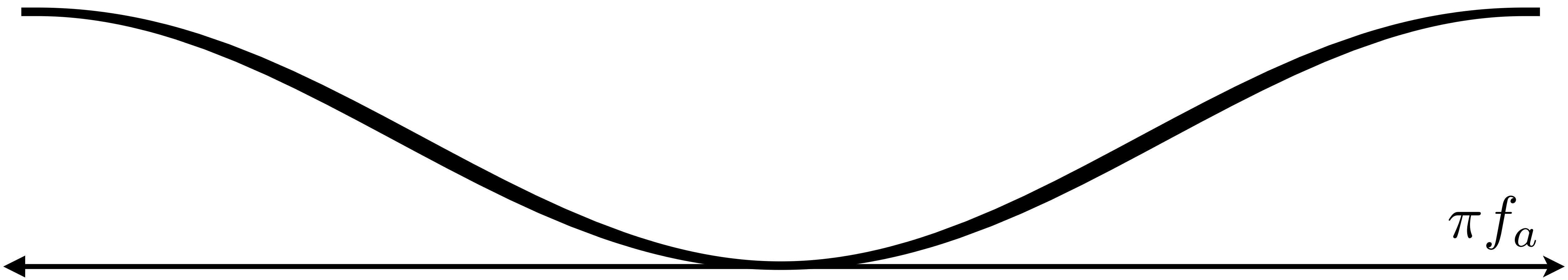


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

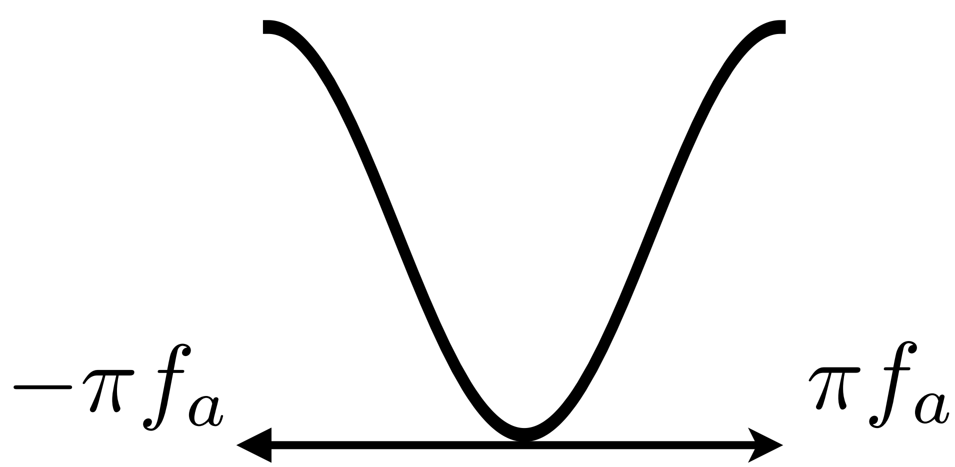
Axion dark matter

- The amount of axion DM produced depends on fa

- large fa, small curvature, oscillations start later->more DM



- small fa, large curvature, oscillations start earlier -> less DM



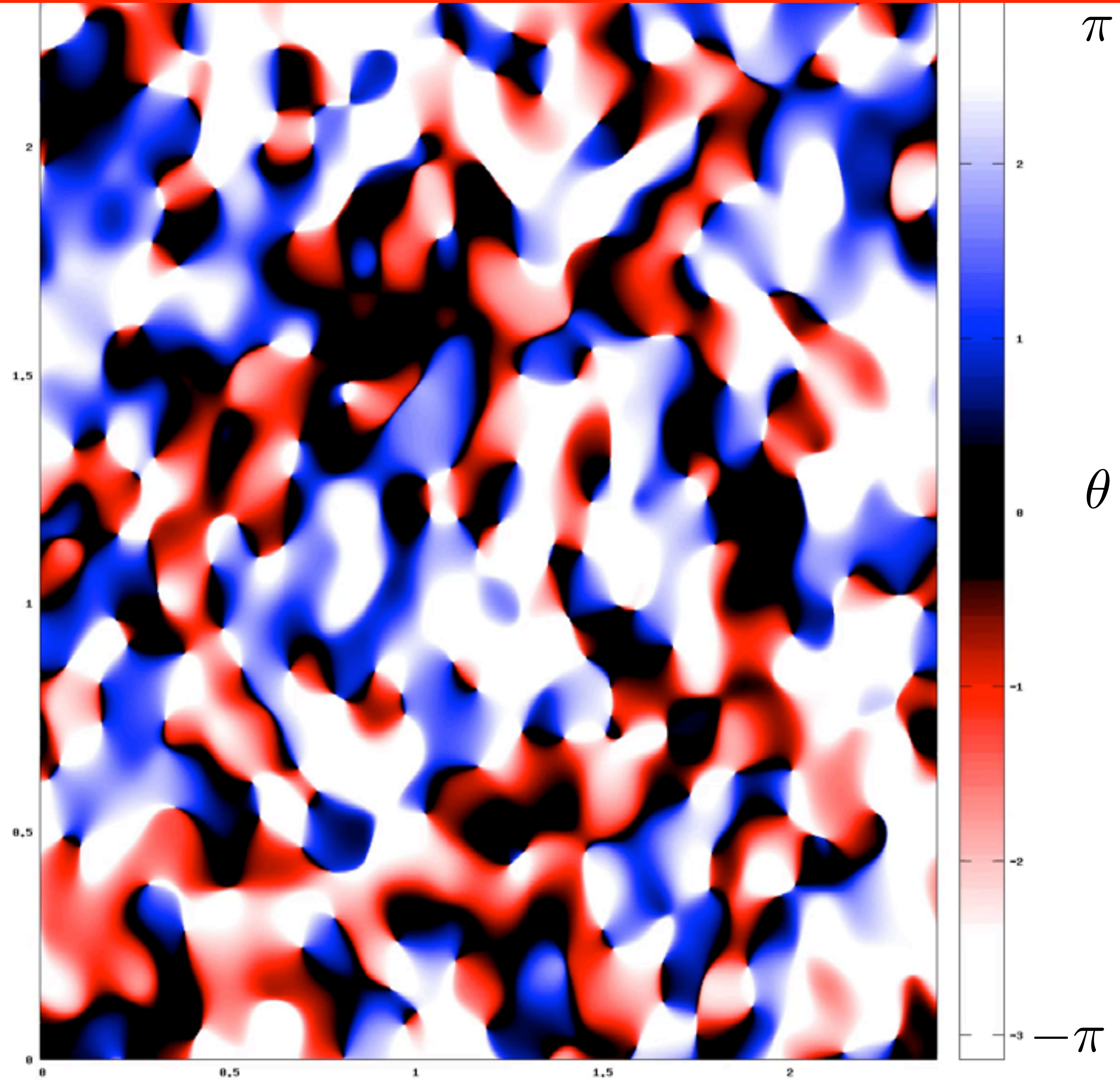
Theta evolution, Averaged SCENARIO I

π

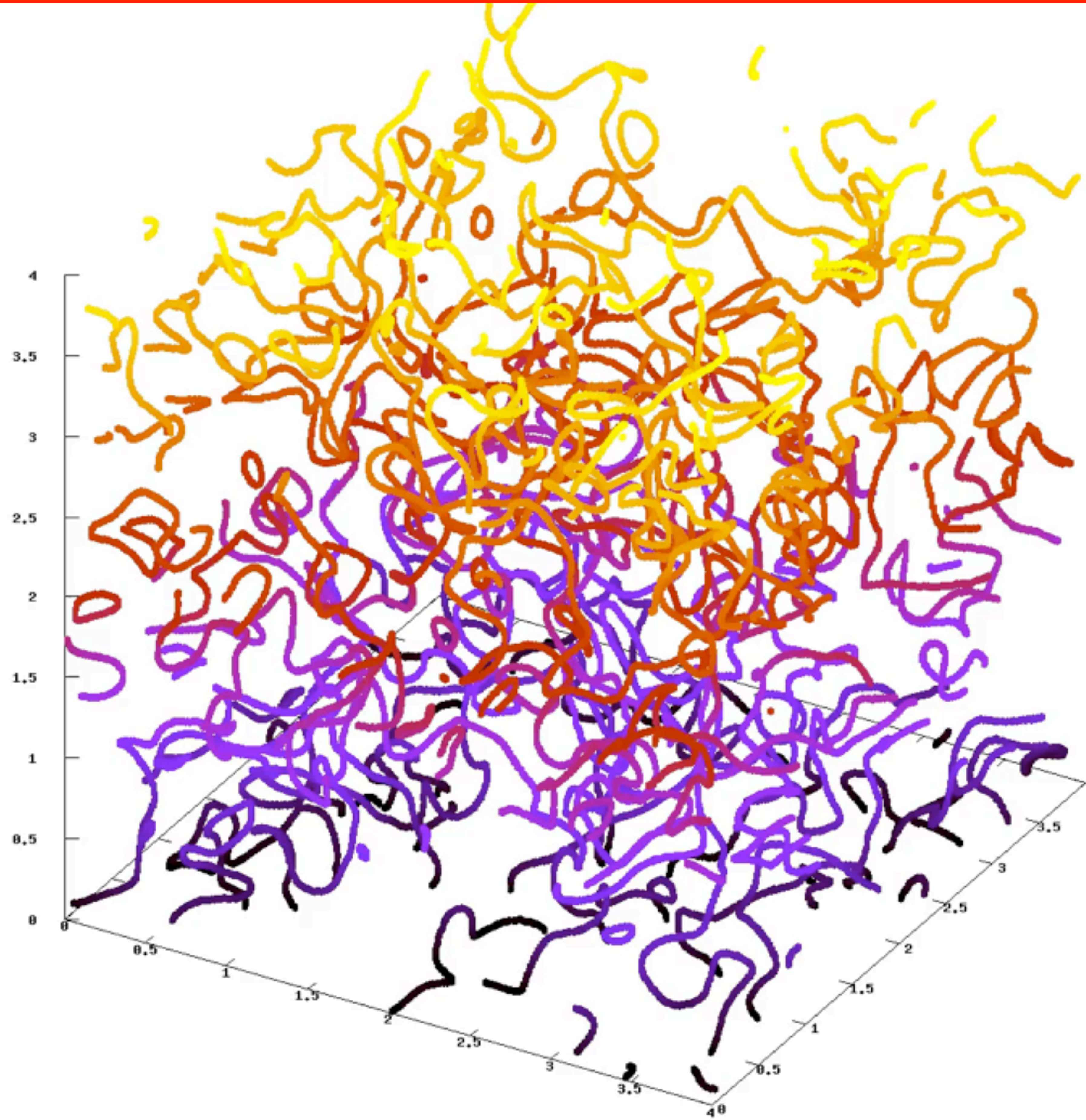
θ

$-\pi$

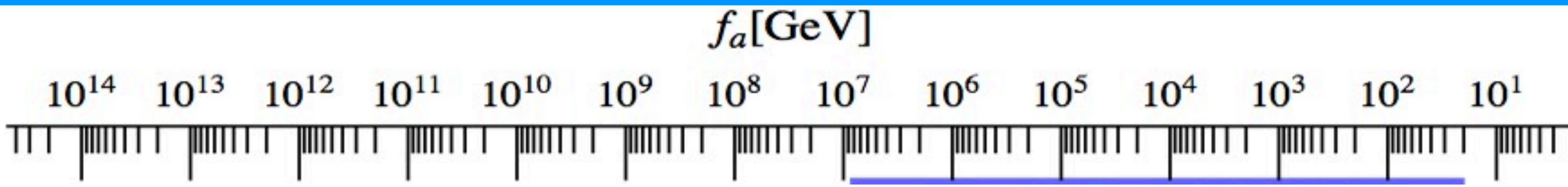
Theta evolution, Averaged SCENARIO I



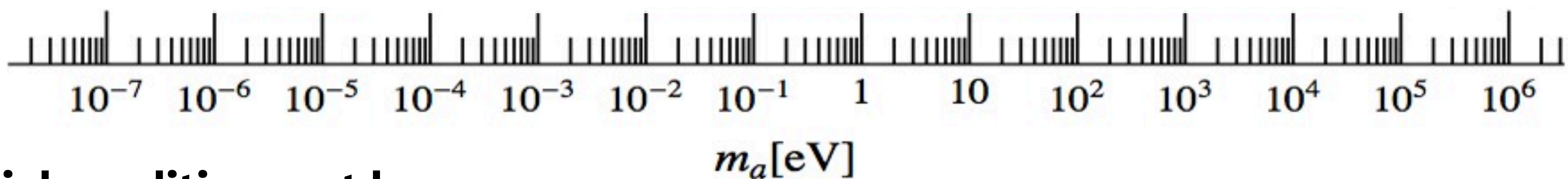
Strings



Axion dark matter

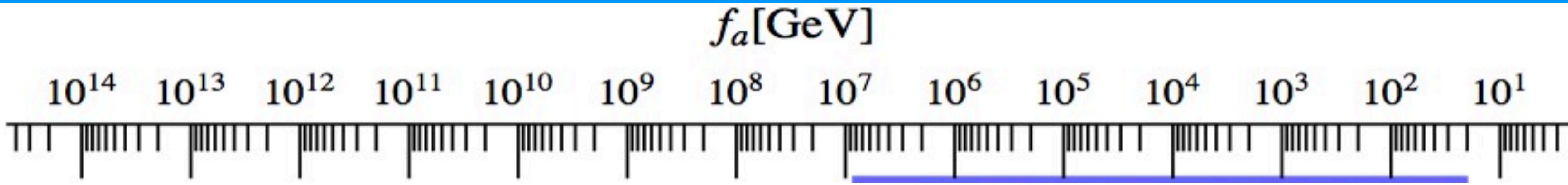


- Axion DM scenarios

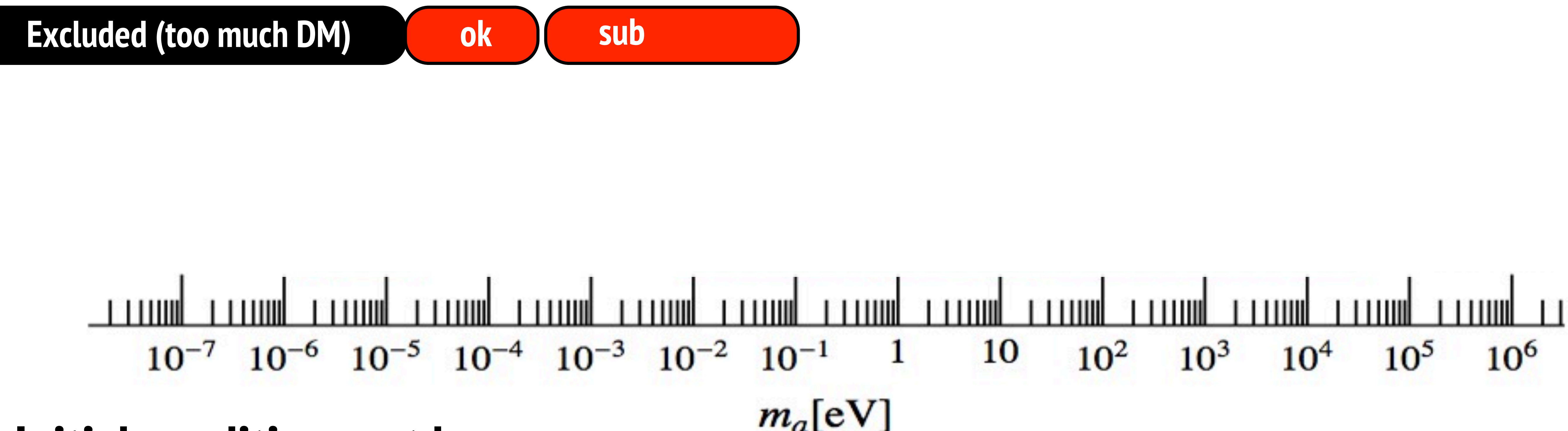


Initial conditions set by :

Axion dark matter



- Axion DM scenarios

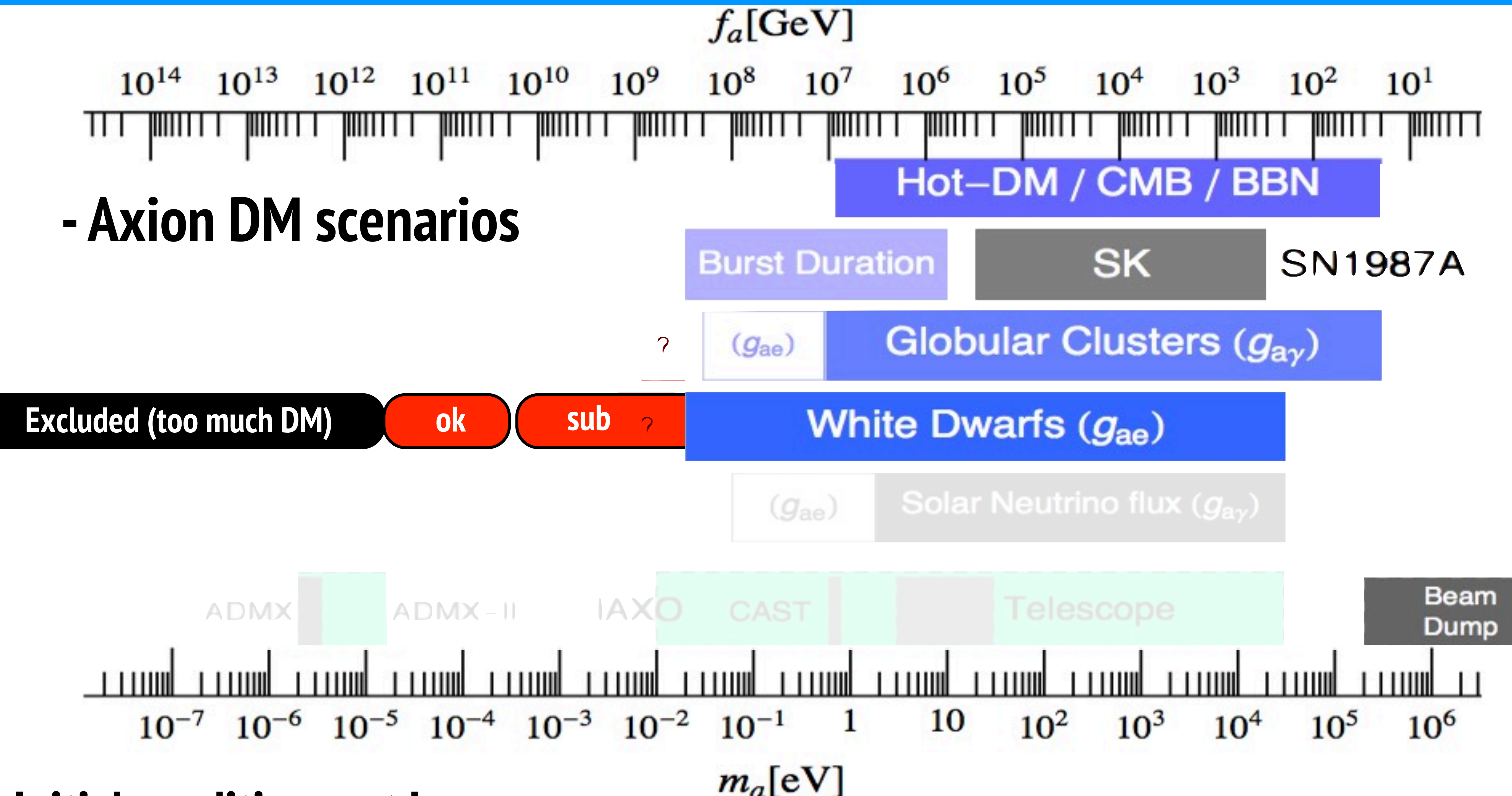


Initial conditions set by :

Phase transition (N=1)

strings+unstable DW's

Axion dark matter



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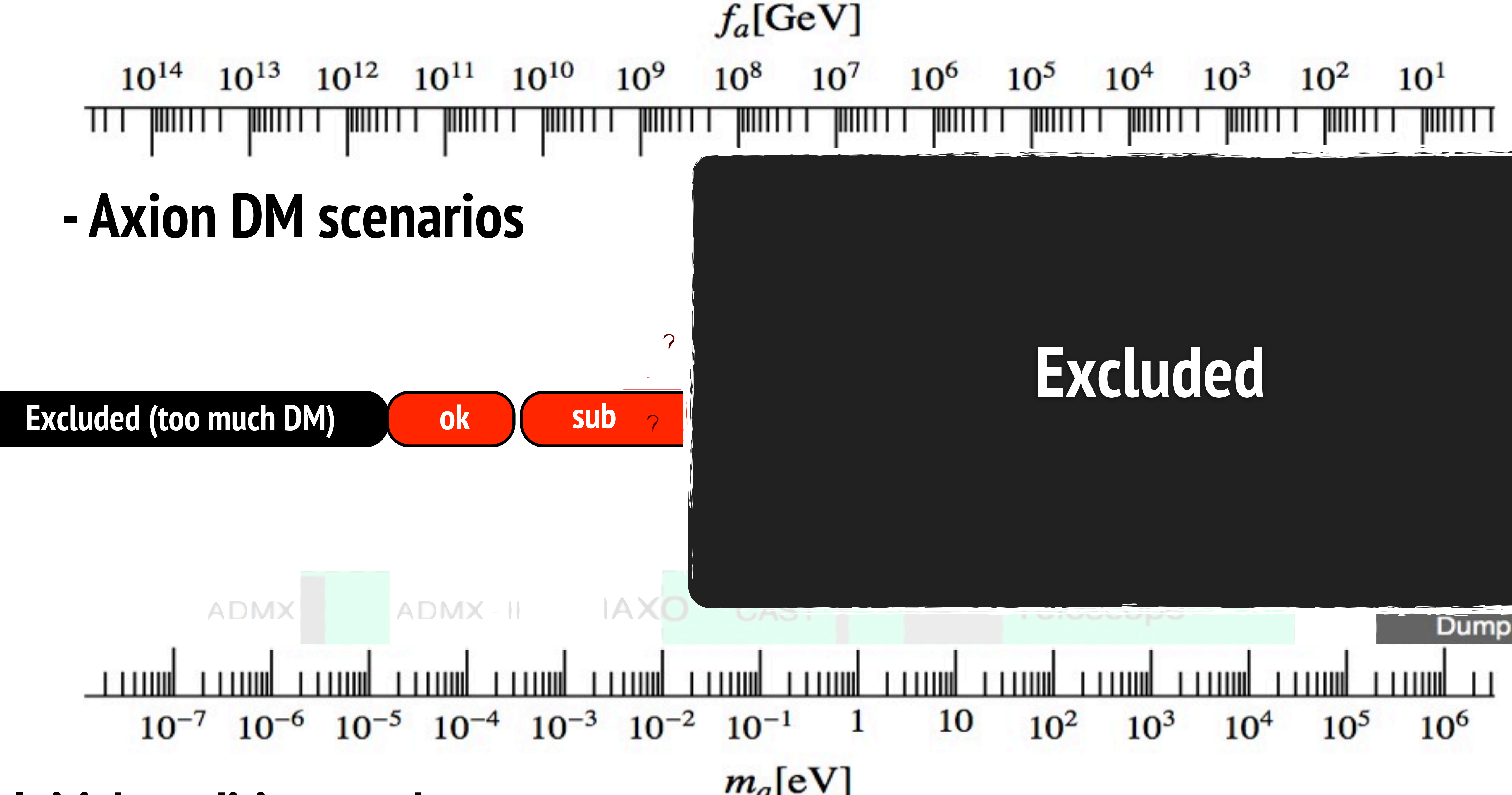


Initial conditions set by :

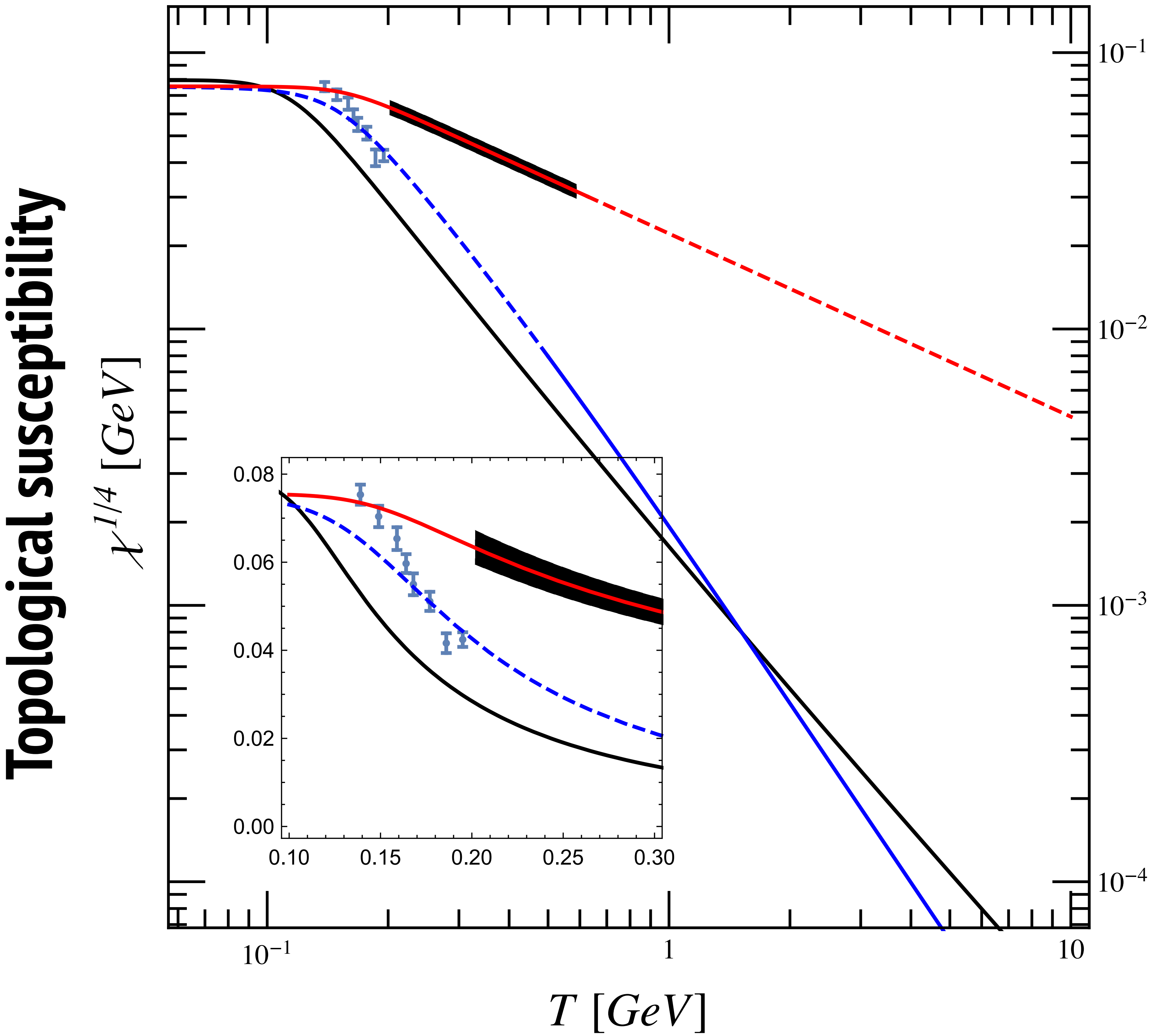
Phase transition (N=1)

strings+unstable DW's

Axion mass at high Temperature

- **Axion field starts to oscillate at T ~ GeV**

$$m_a = \frac{\sqrt{\chi}}{f_a}$$



$$\chi = \left(\frac{\Lambda}{T}\right)^n$$

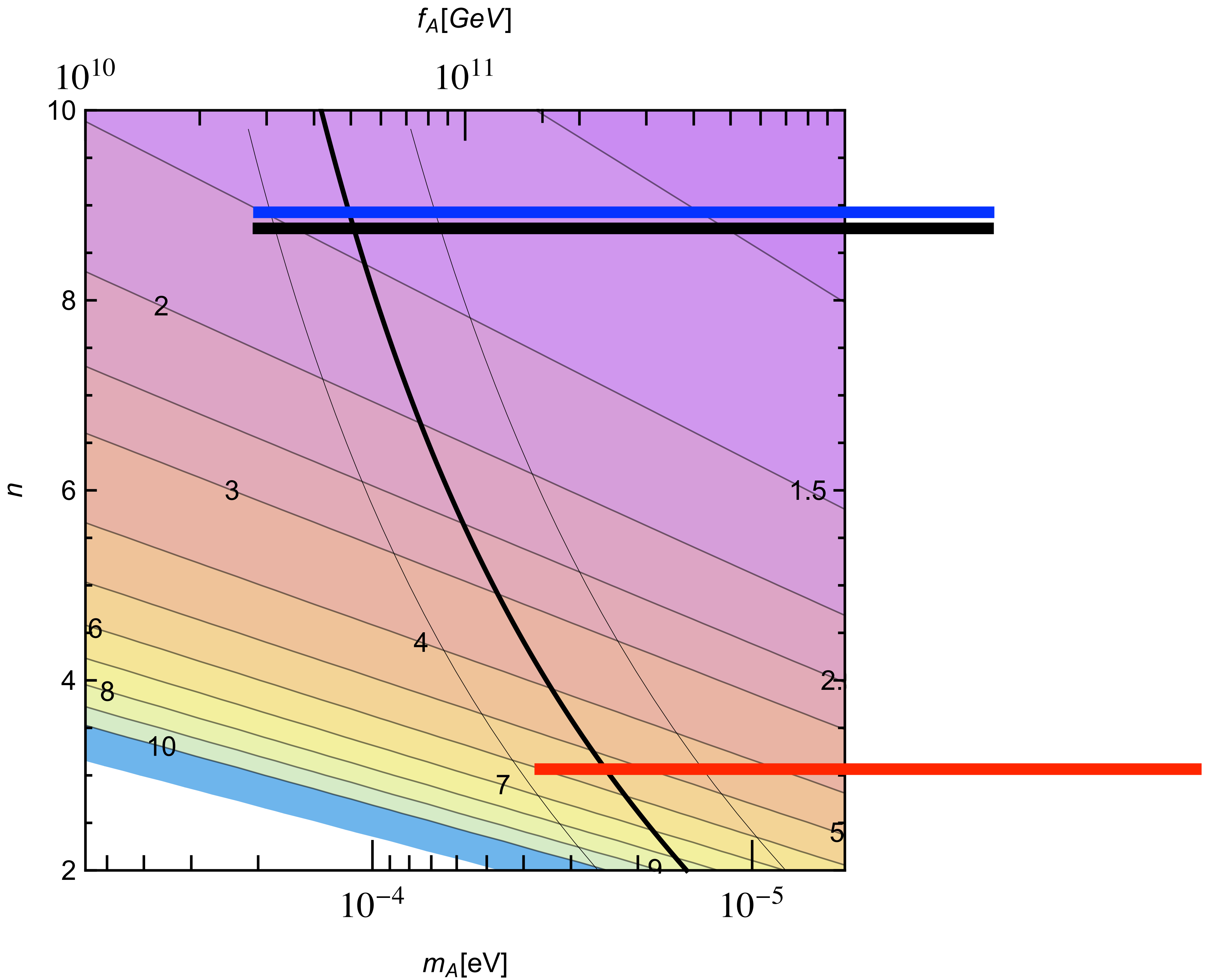
Lattice QCD 2+1 (T~Tc)
Bonati et al arXiv:1512.06746

DIGA (analytical) (valid T>>Tc)
Borsany at al PLB 2015

Lattice QCD (DWF) 2+1
Buchoff et al PRD 89 2014

Interacting Instanton Liquid (Model)
Wantz/Shellard PRD 82 2010

Axion mass at high Temperature

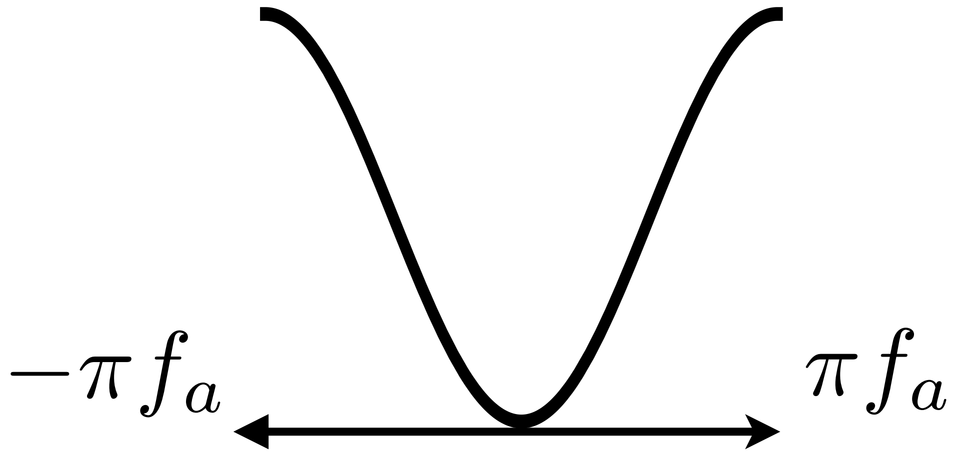


sub

ok

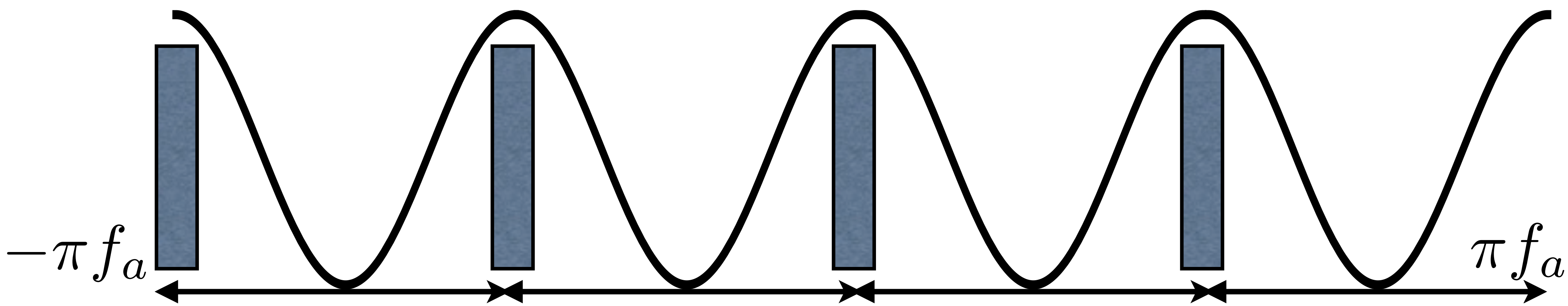
Excluded (too much DM)

SCENARIO I, N=1

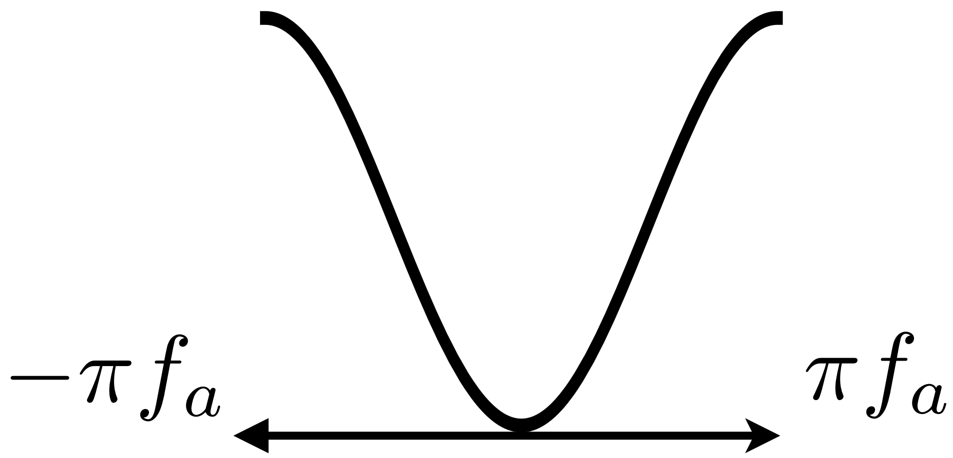


$$\frac{a}{f_a} = N\theta$$

SCENARIO I, N>1, Domain Walls stable-> cosmological disaster

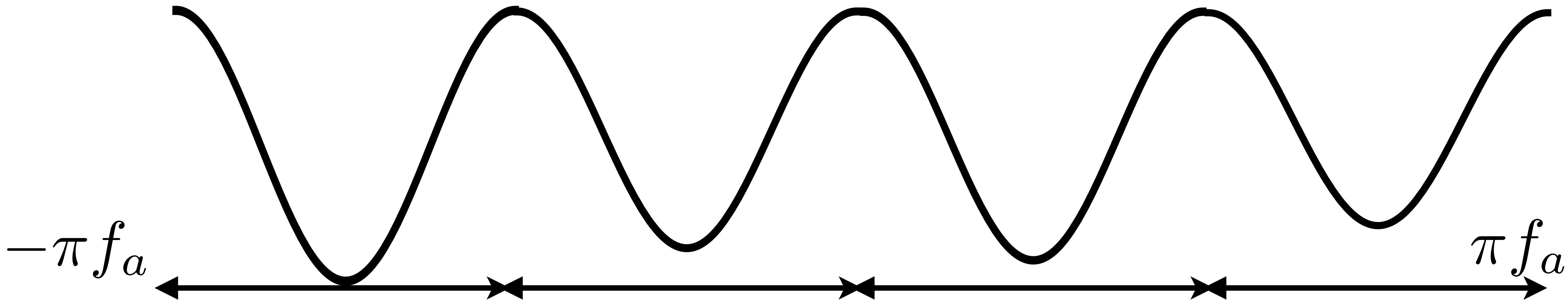


SCENARIO I, N=1



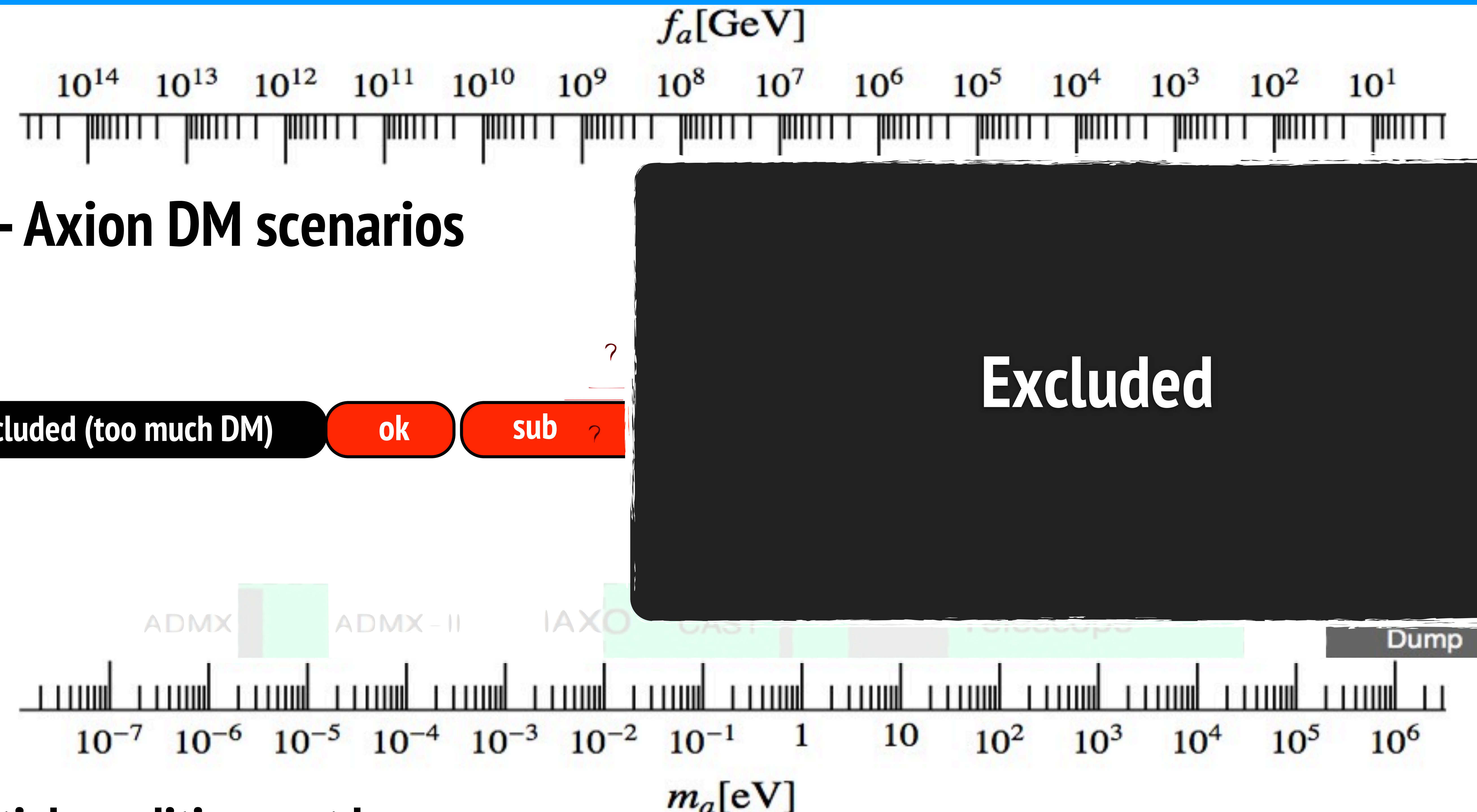
$$\frac{a}{f_a} = N\theta$$

SCENARIO I, N>1, break slightly degeneracy



Axion dark matter

- Axion DM scenarios



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Phase transition (N=1)

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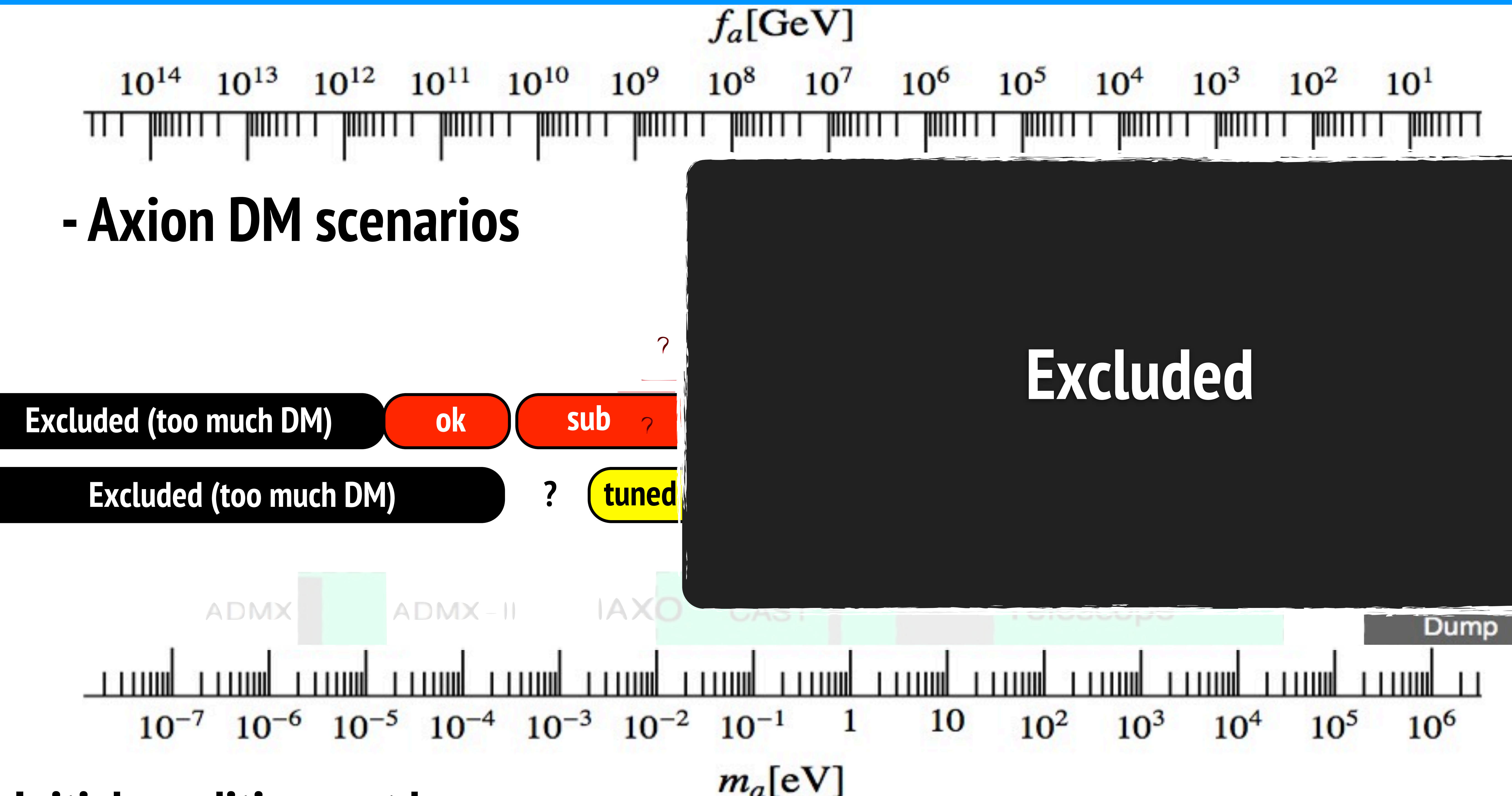
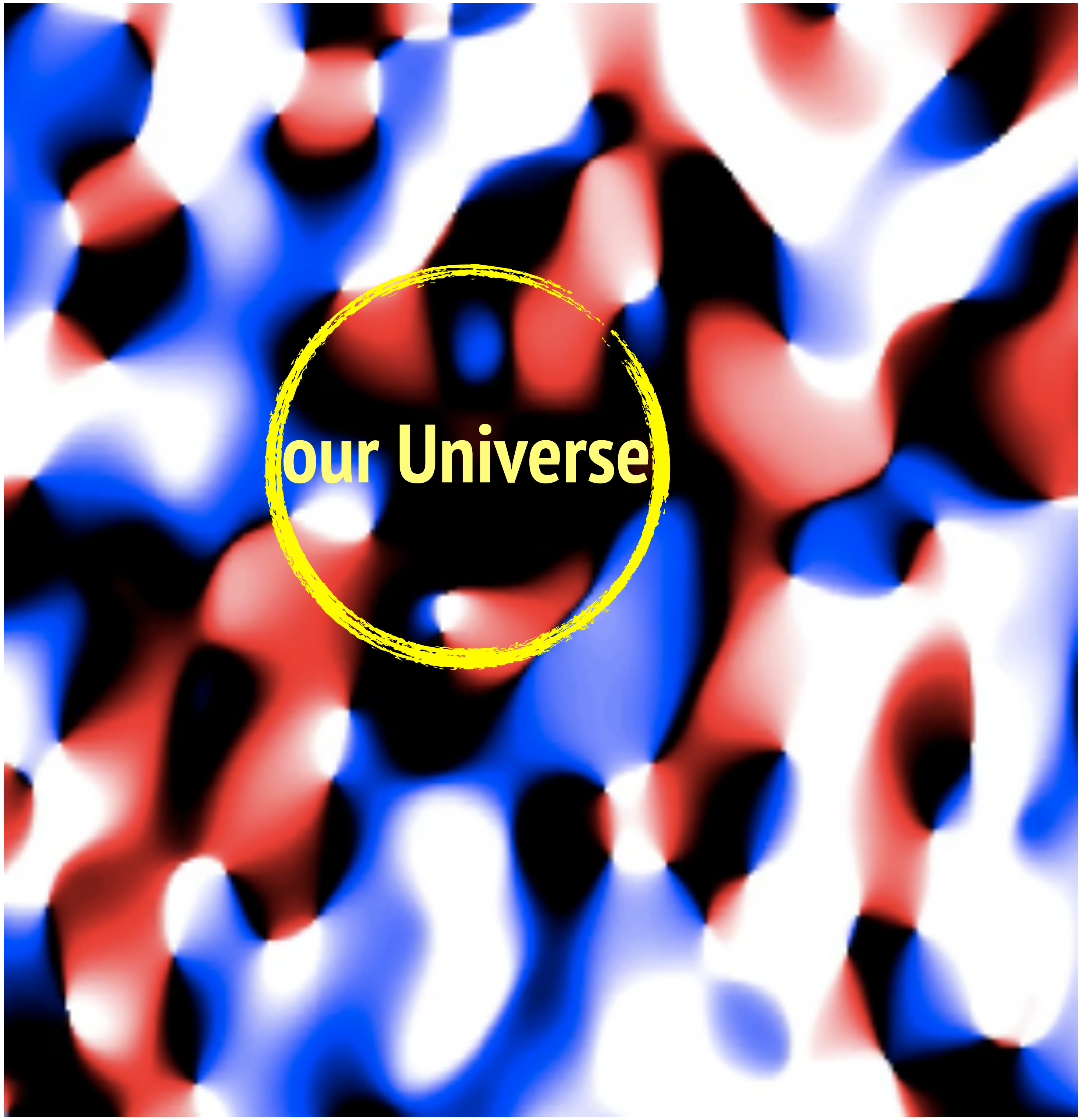


Initial conditions set by :

Phase transition (N=1)
strings+unstable DW's

Phase transition (N>1)
strings+long-lived DWs

Theta evolution, inflated SCENARIO I



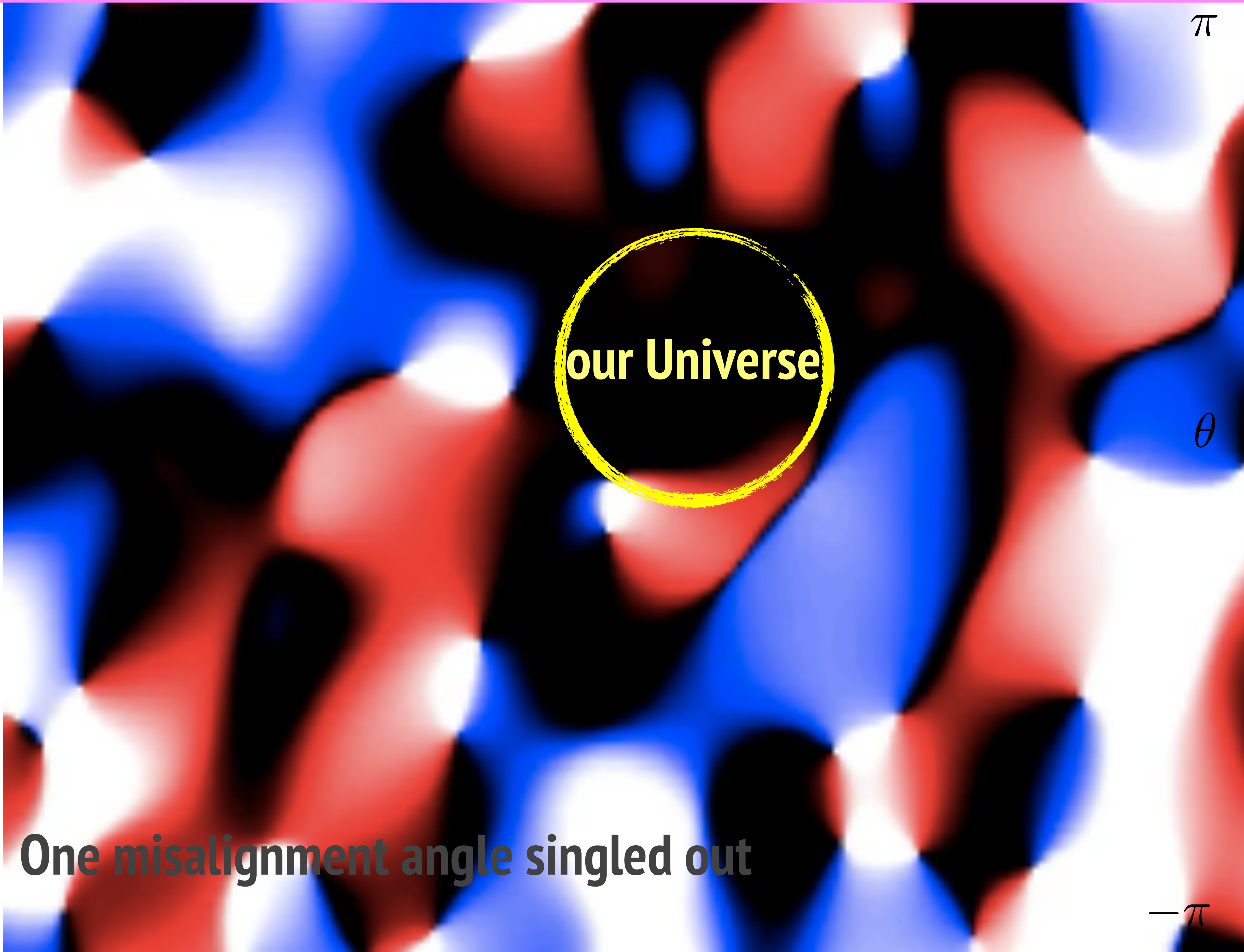
π

θ

$-\pi$

One misalignment angle singled out

Theta evolution, inflated SCENARIO I



Axion dark matter

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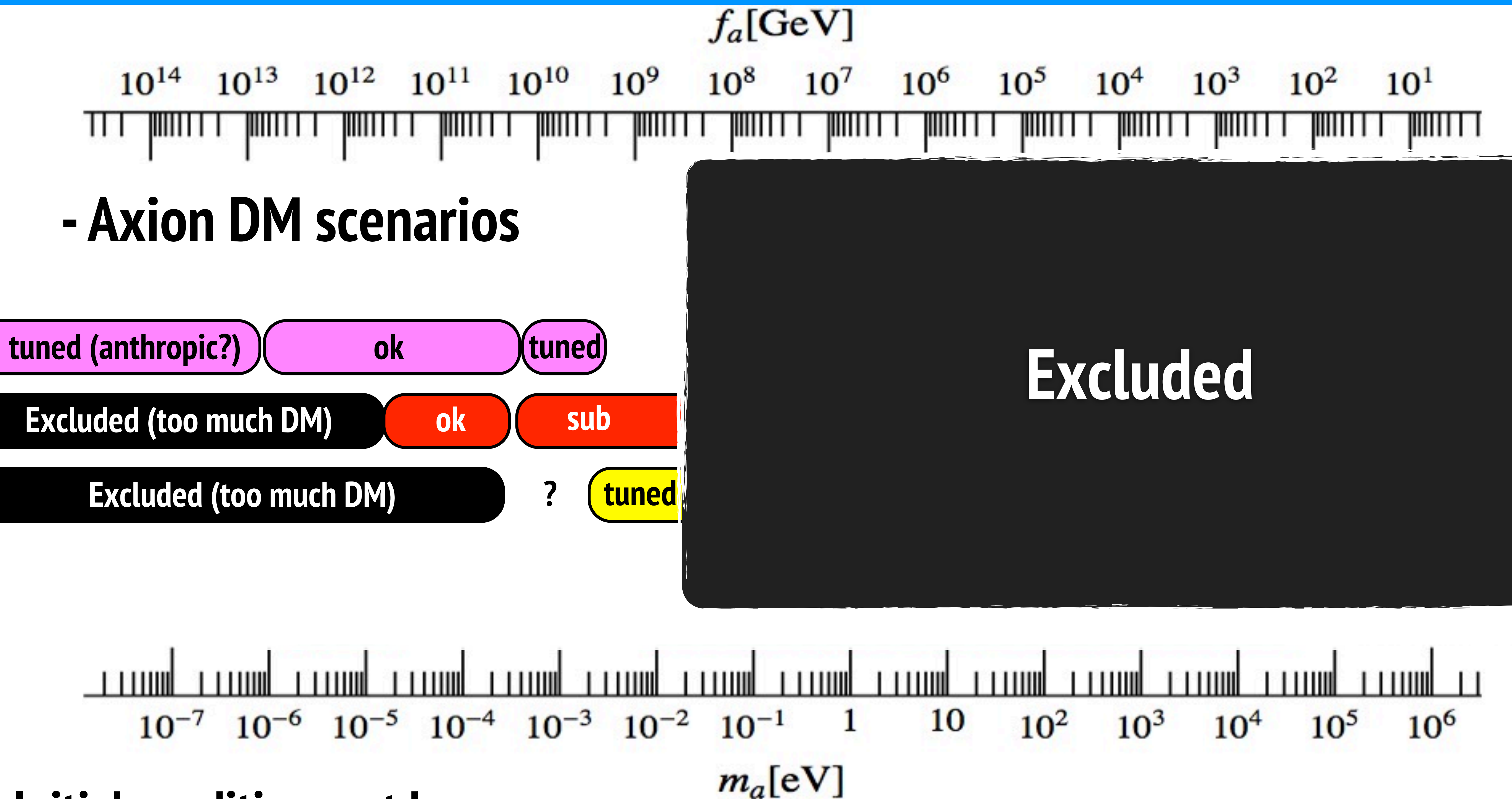
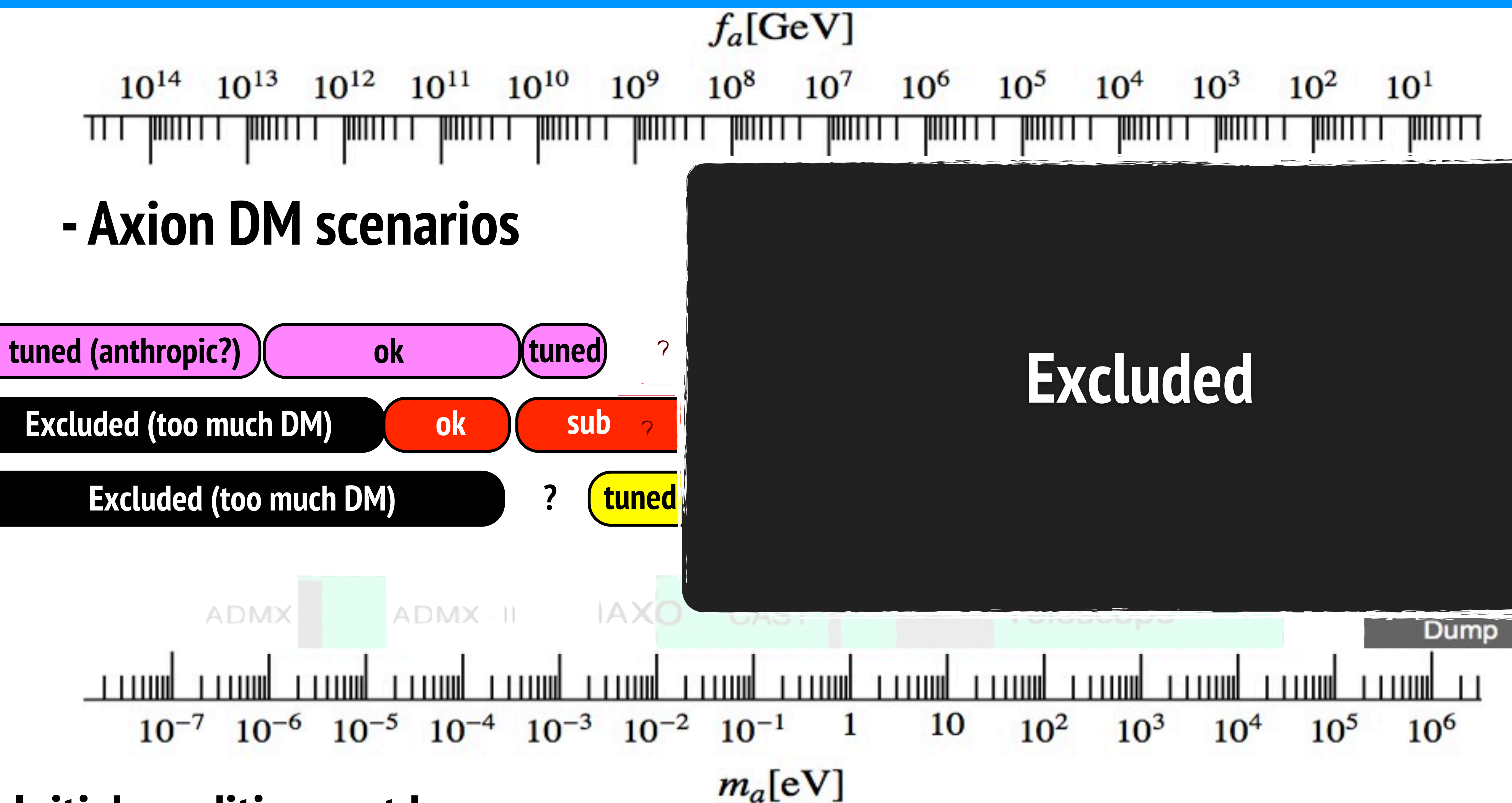


Initial conditions set by :

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

Axion dark matter

- Axion DM scenarios



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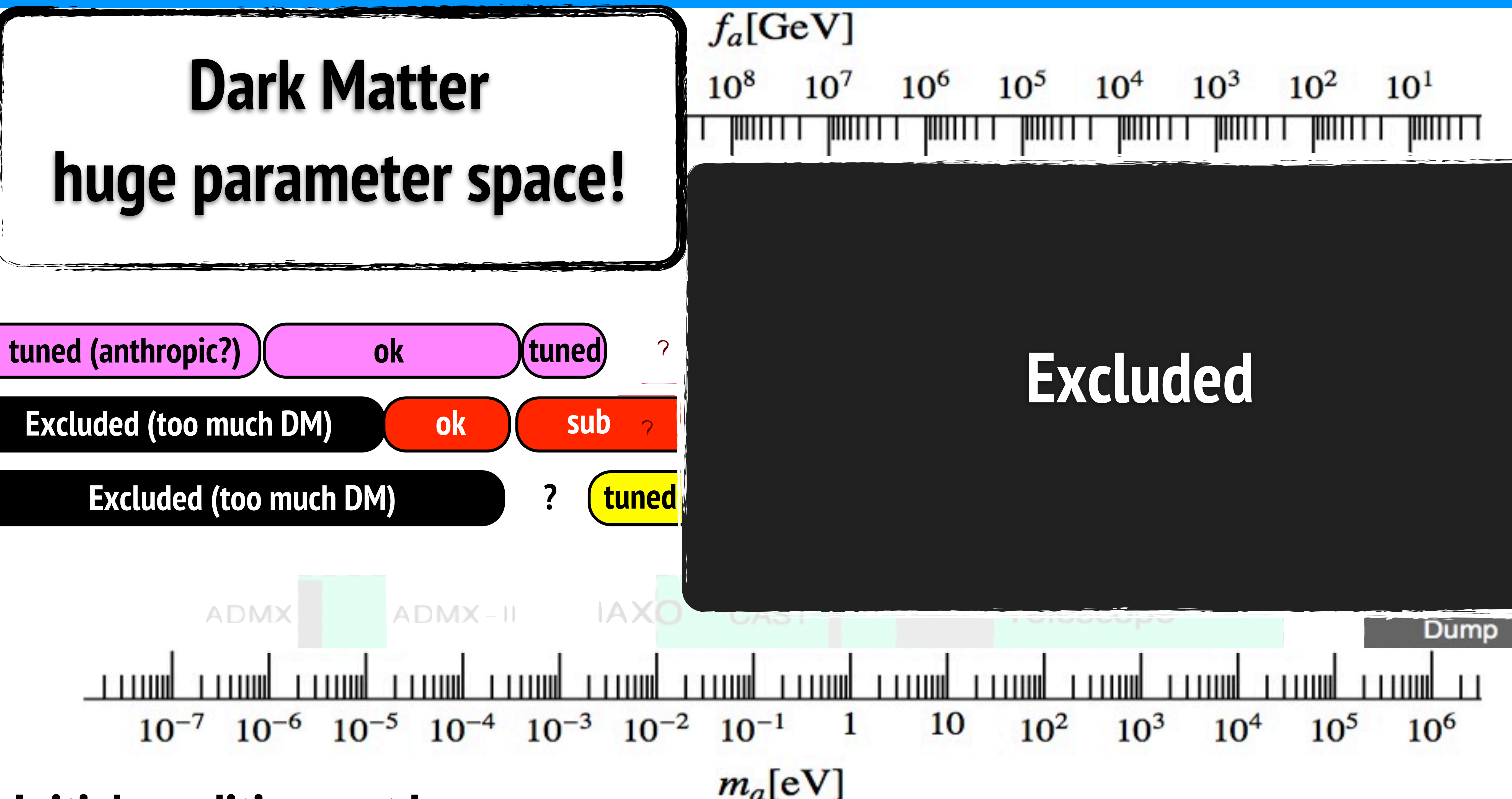
Axion dark matter

Dark Matter
huge parameter space!



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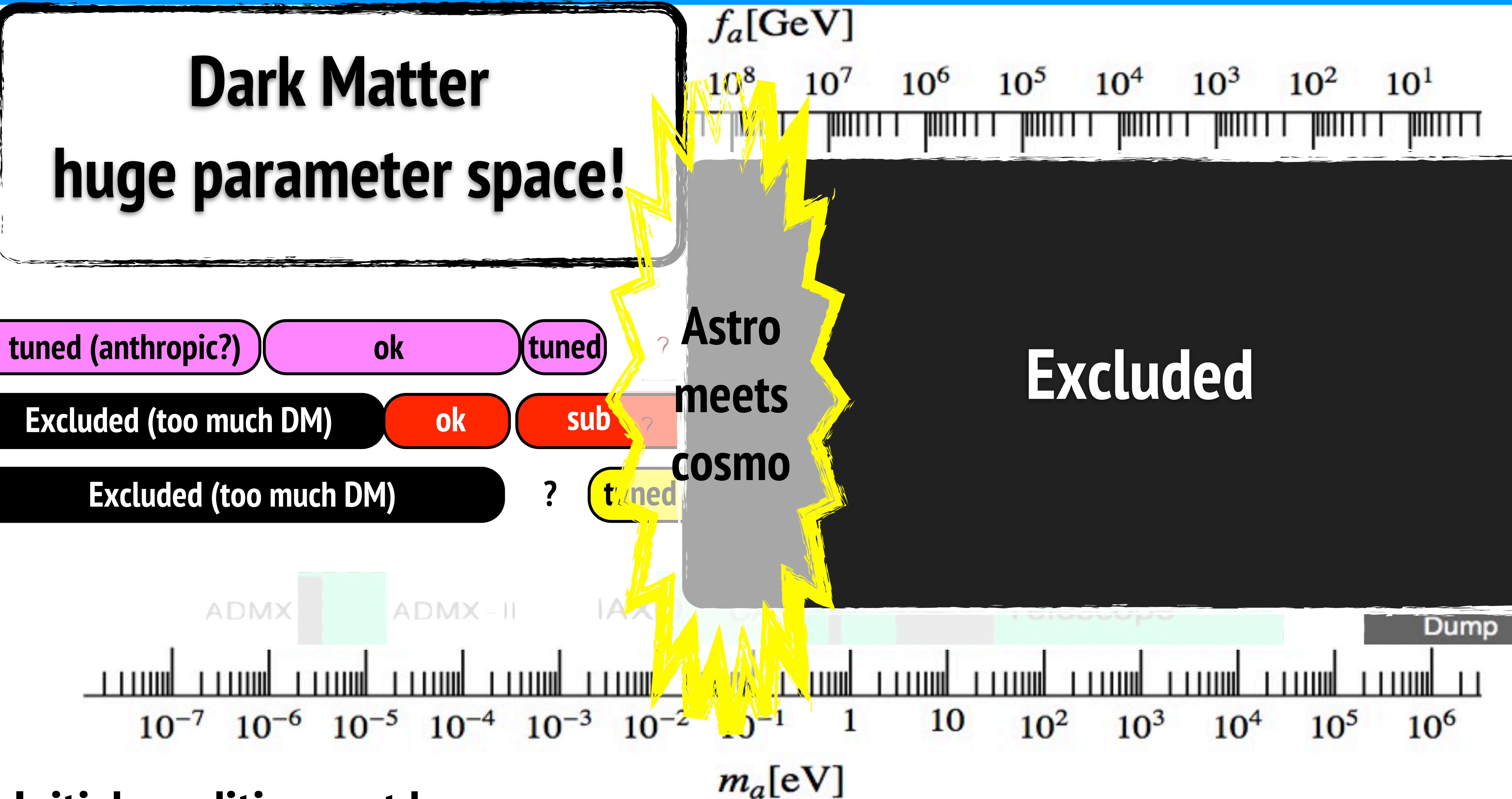
Axion dark matter



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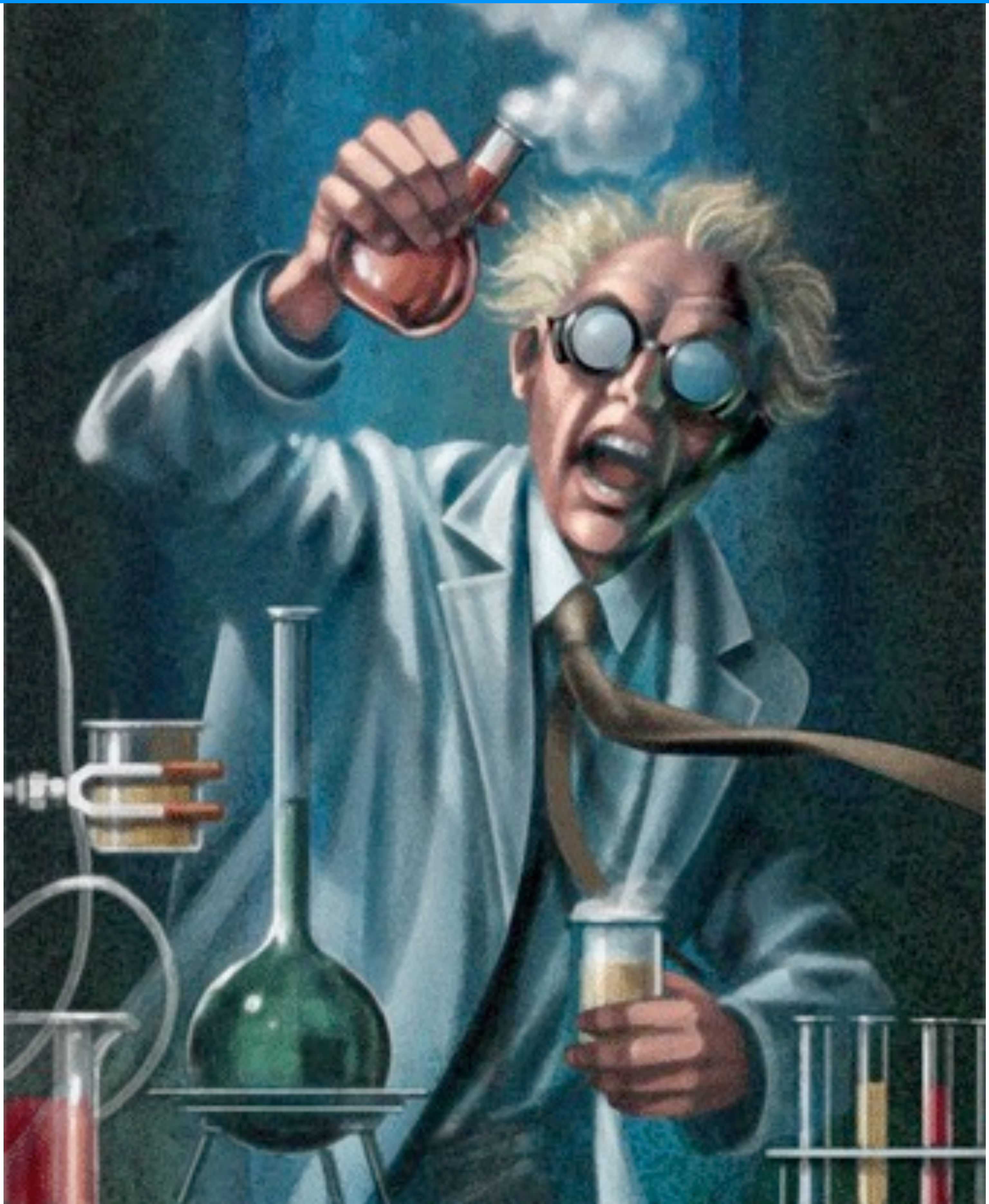
Detecting Axions



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

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

Detecting Axion (Dark Matter) in the lab

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

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

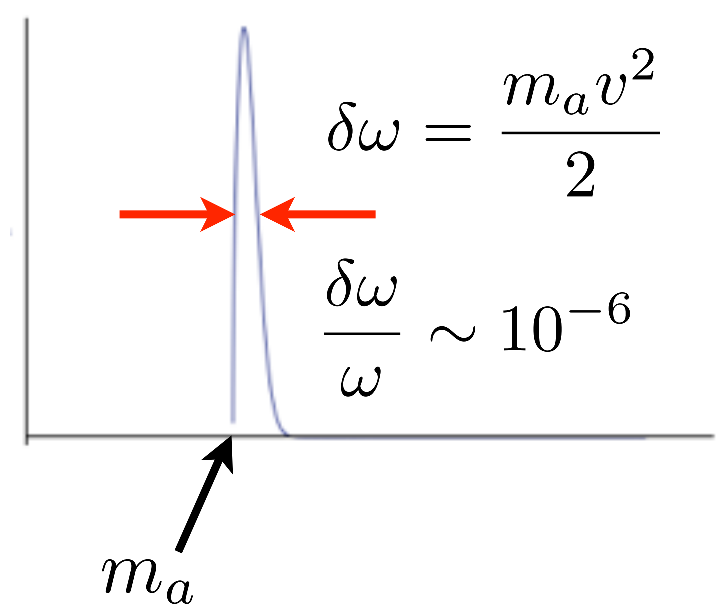
phase space density $\dfrac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29} \left(\dfrac{\mu \rm eV}{m_a} \right)^4$

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

Roughly… $a(t) = a_0 \cos(m_a t)$

Fourier-transform $a(x)$

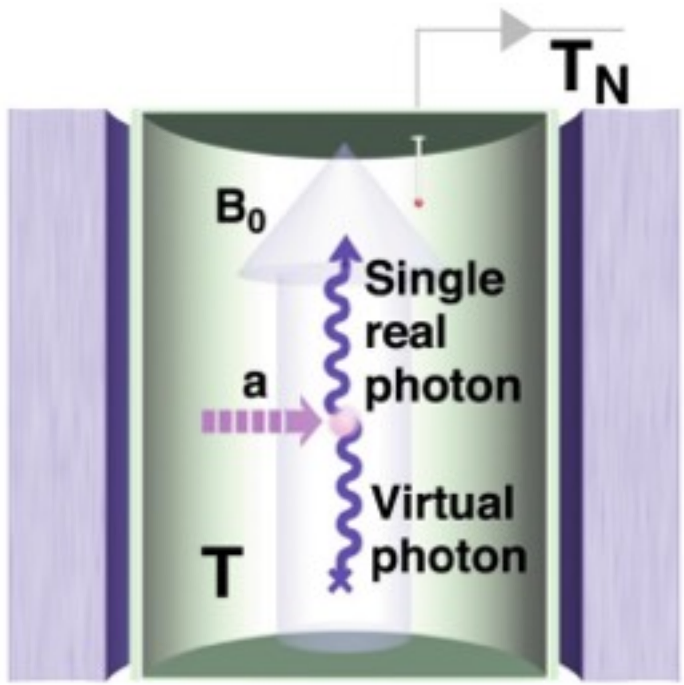
$$\omega \simeq m_a (1 + v^2/2 + \ldots)$$



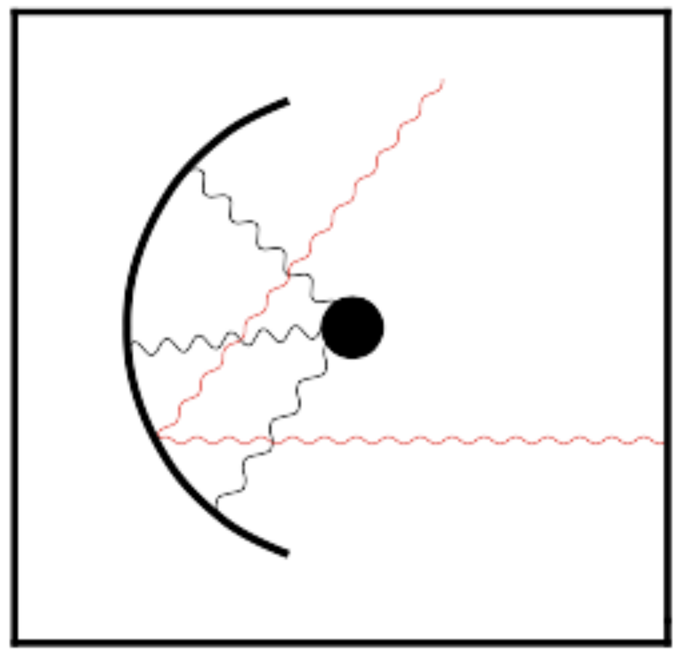
$$\delta t \sim \frac{1}{\delta\omega} \sim 0.13 {\rm ms} \left(\frac{10^{-5} {\rm eV}}{m_a} \right)$$

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

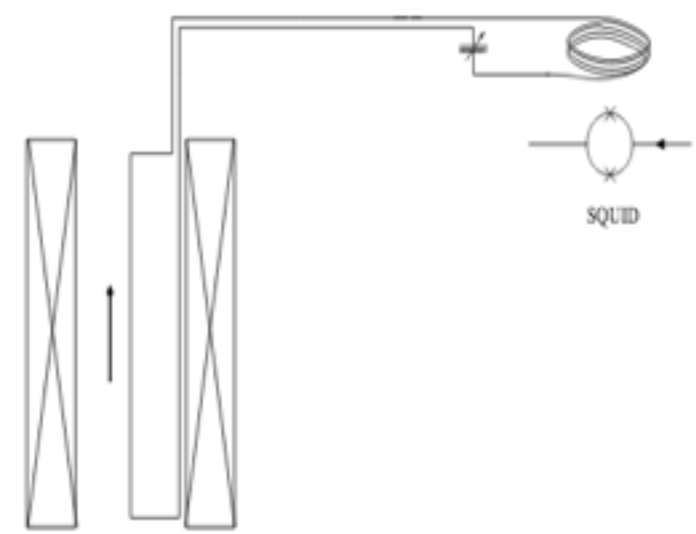
Cavities



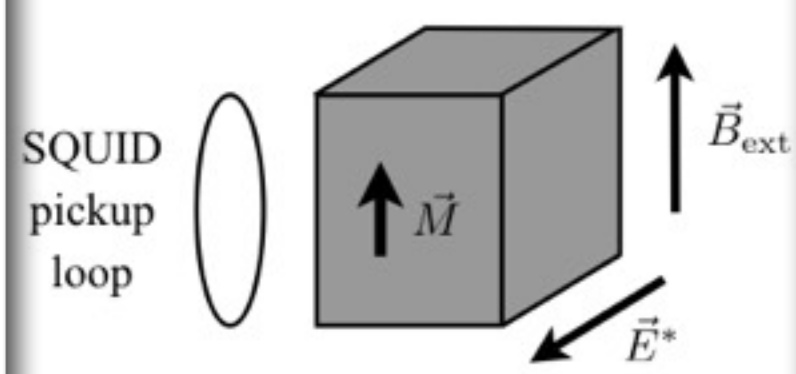
Mirrors



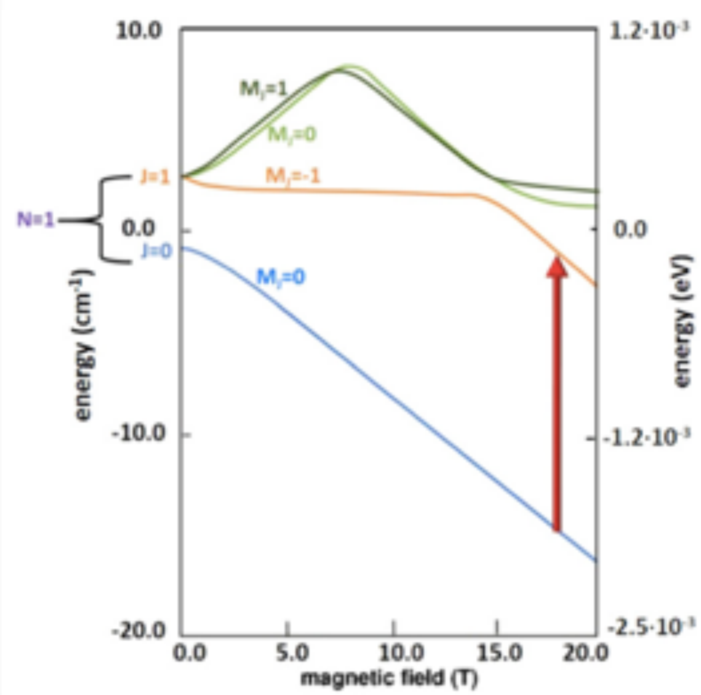
LC-circuit



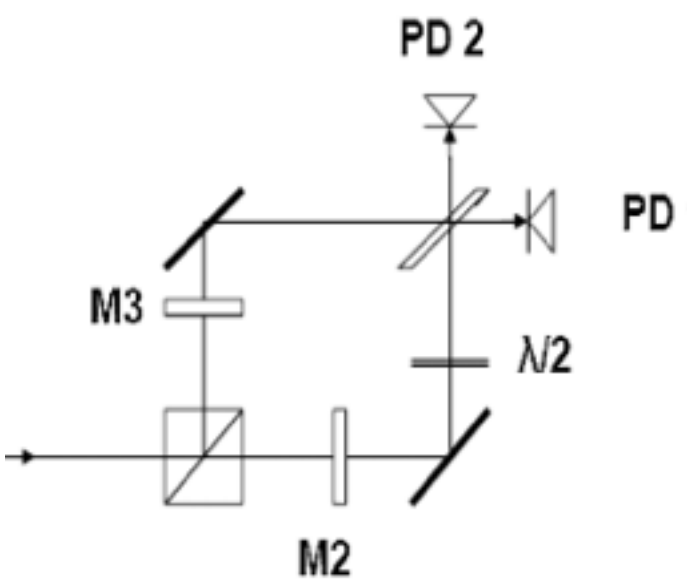
Spin precession



Atomic transitions



Optical



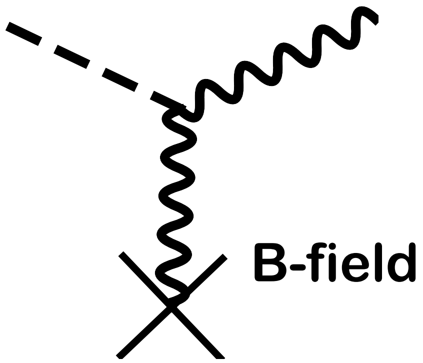
Axion DM in a B-field

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

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

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

source

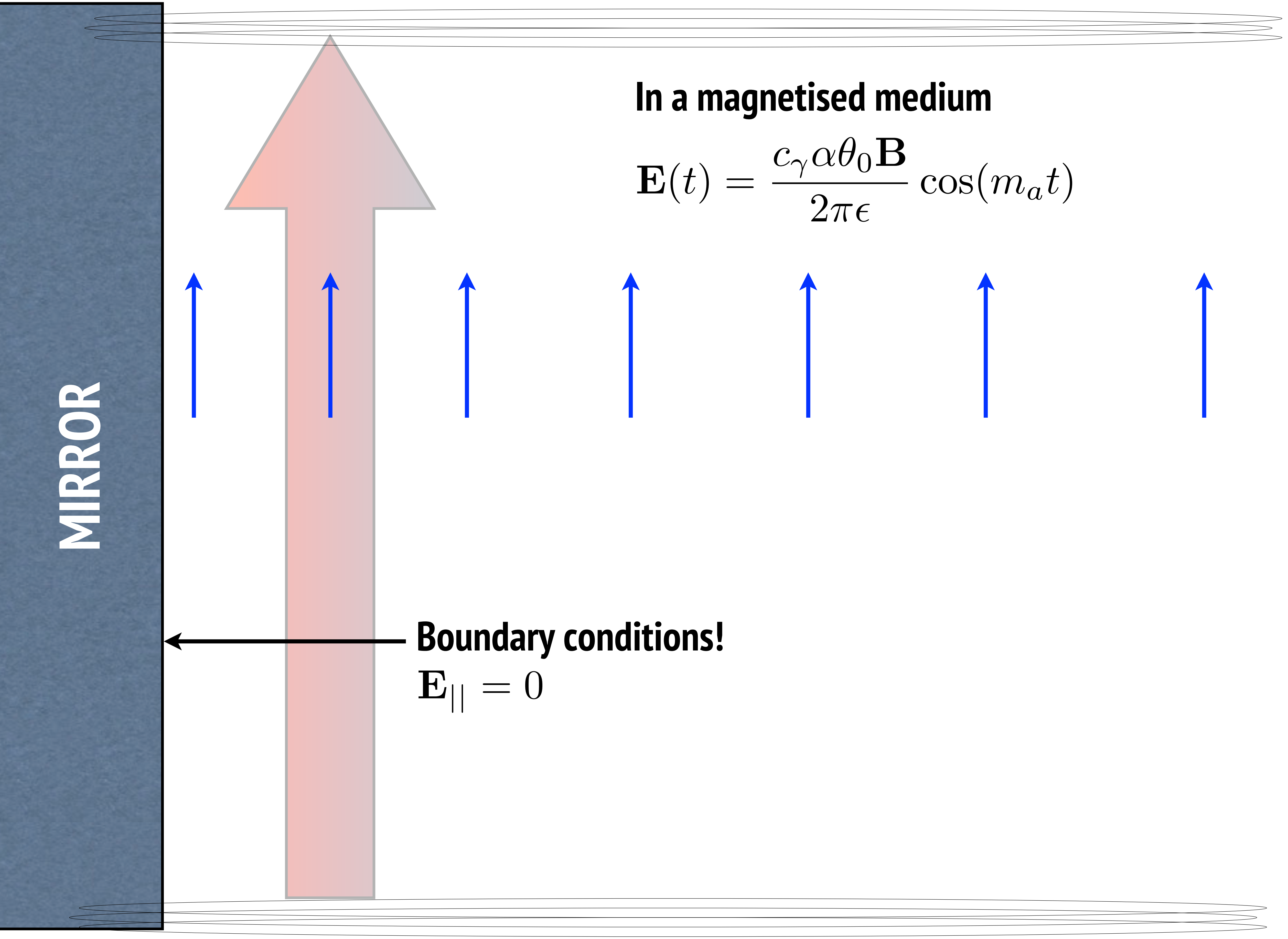


- Electric fields $\mathbf{E}_a = C_{a\gamma}\frac{\alpha\mathbf{B}_{\rm ext}}{2\pi}\theta_0\cos(m_a t)$ (amp independent of mass!)

- Oscillating at a frequency $\omega \simeq m_a$

- B-fields $\propto \nabla\theta$ $|\mathbf{B}_a| \sim \langle v\rangle|\mathbf{E}_a|$

Radiation from a magnetised mirror



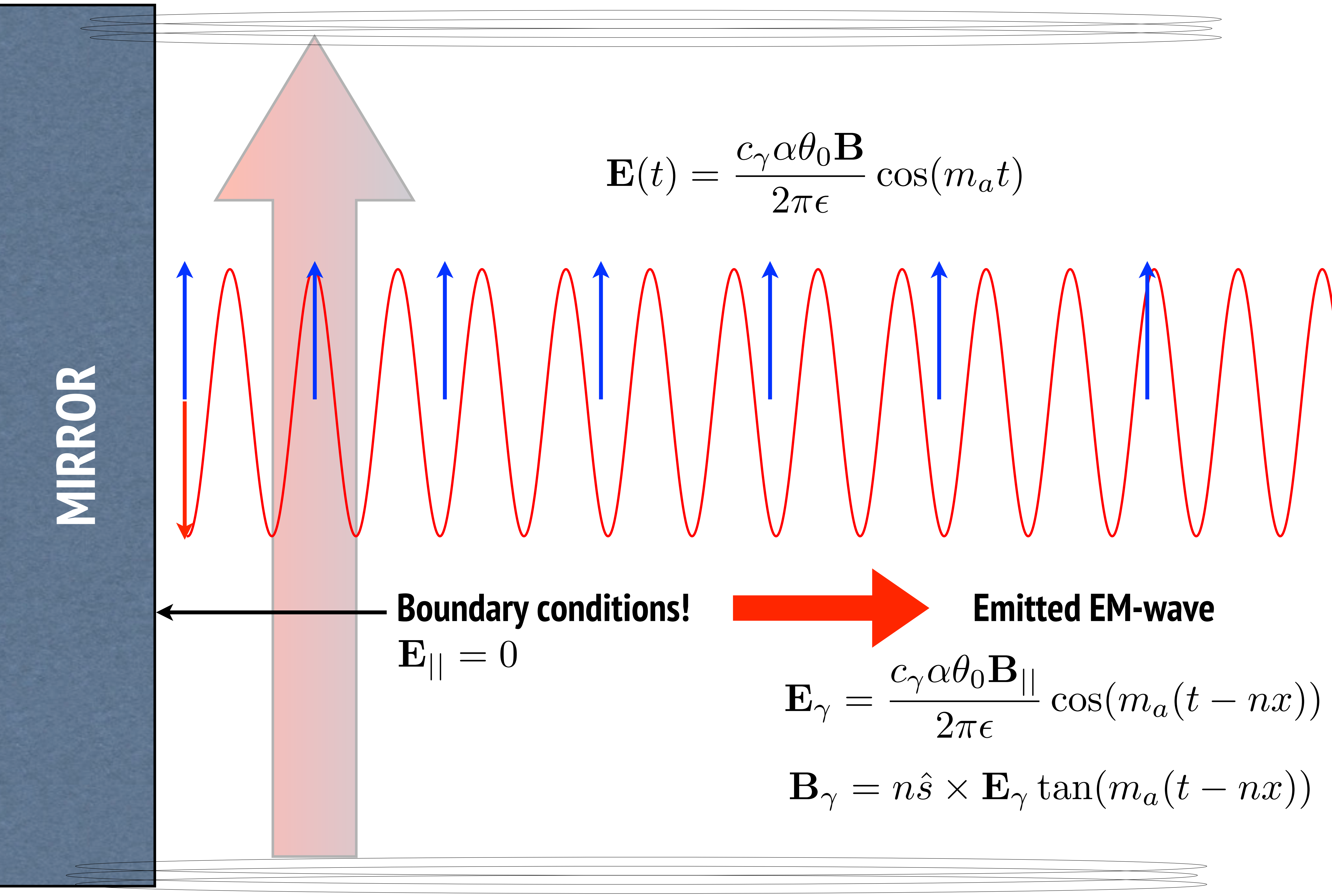
In a magnetised medium

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

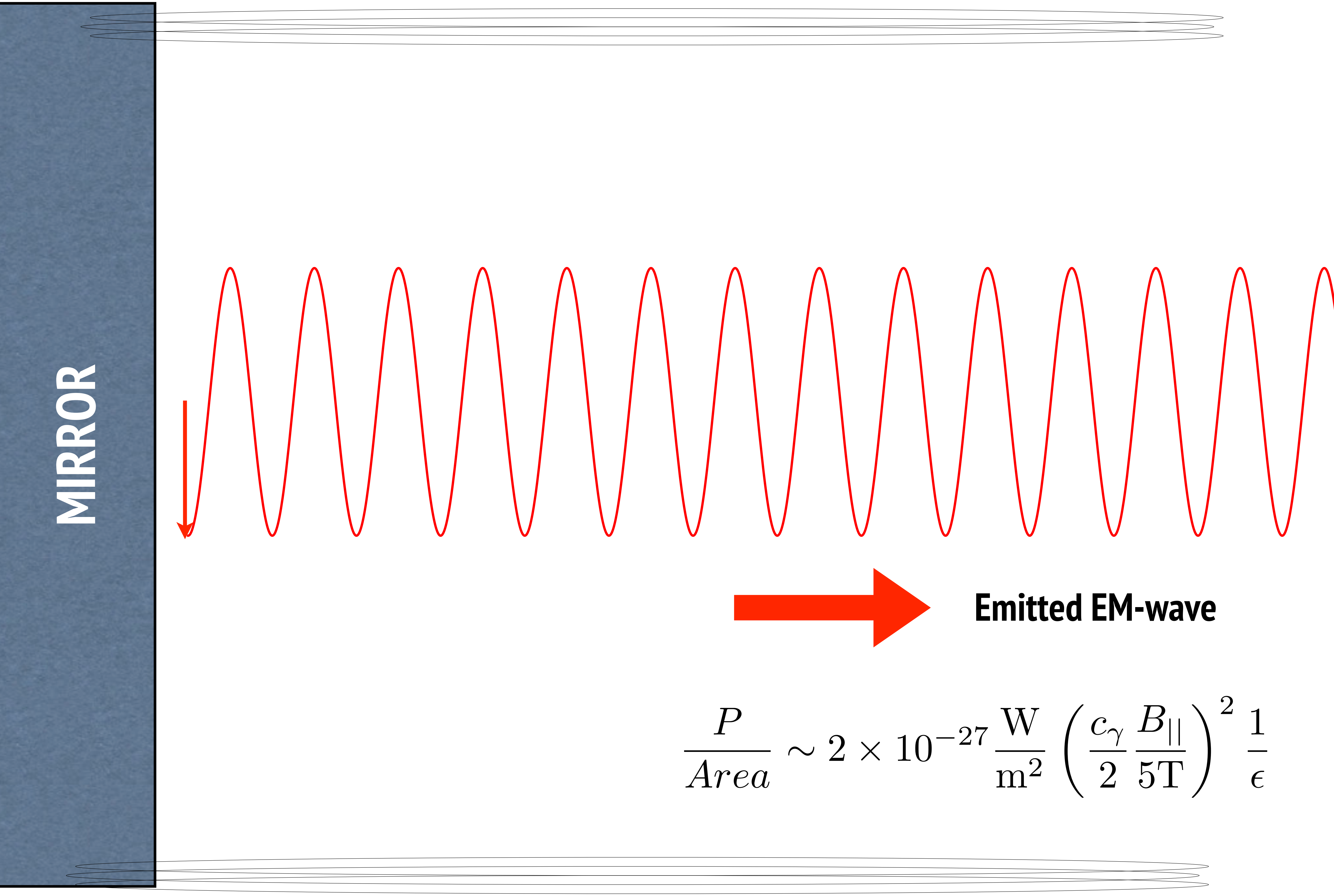
Boundary conditions!

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

Radiation from a magnetised mirror

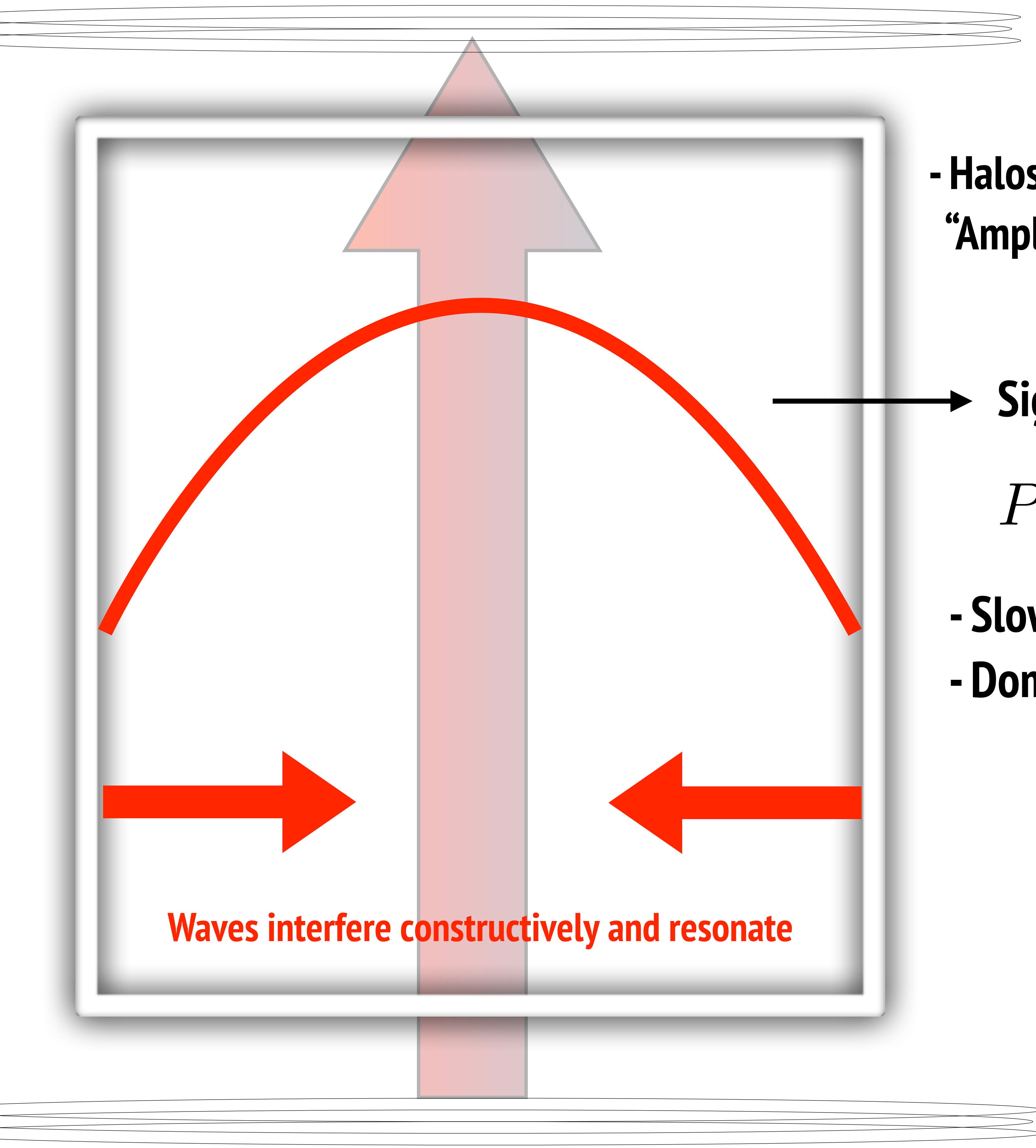


Radiation from a magnetised mirror : Power



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

Cavity experiments



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

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

$$P \to P \times Q$$

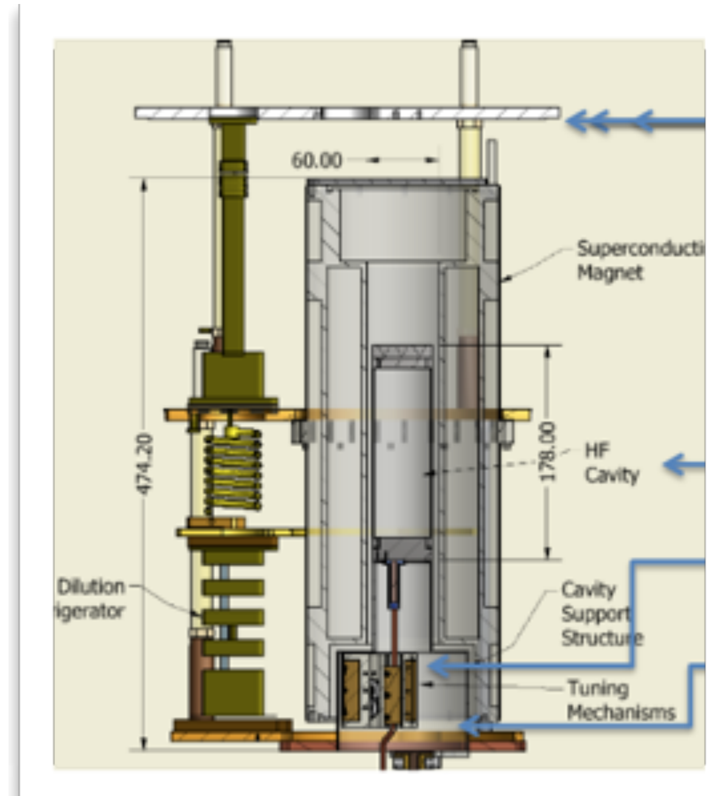
- Slow scan over frequencies
- Dominated by thermal+preamp noise

Cavity experiments

ADMX

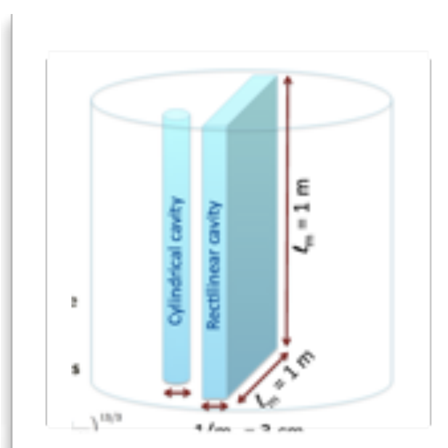
CARRACK (discontinued)

CULTASK - CAPP -Korea

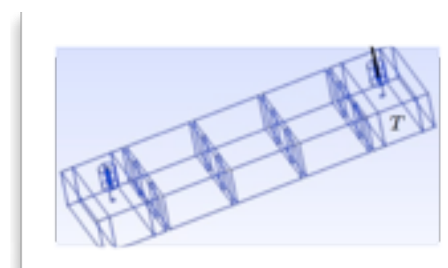


ADMX-HF

ADMX-Fermilab

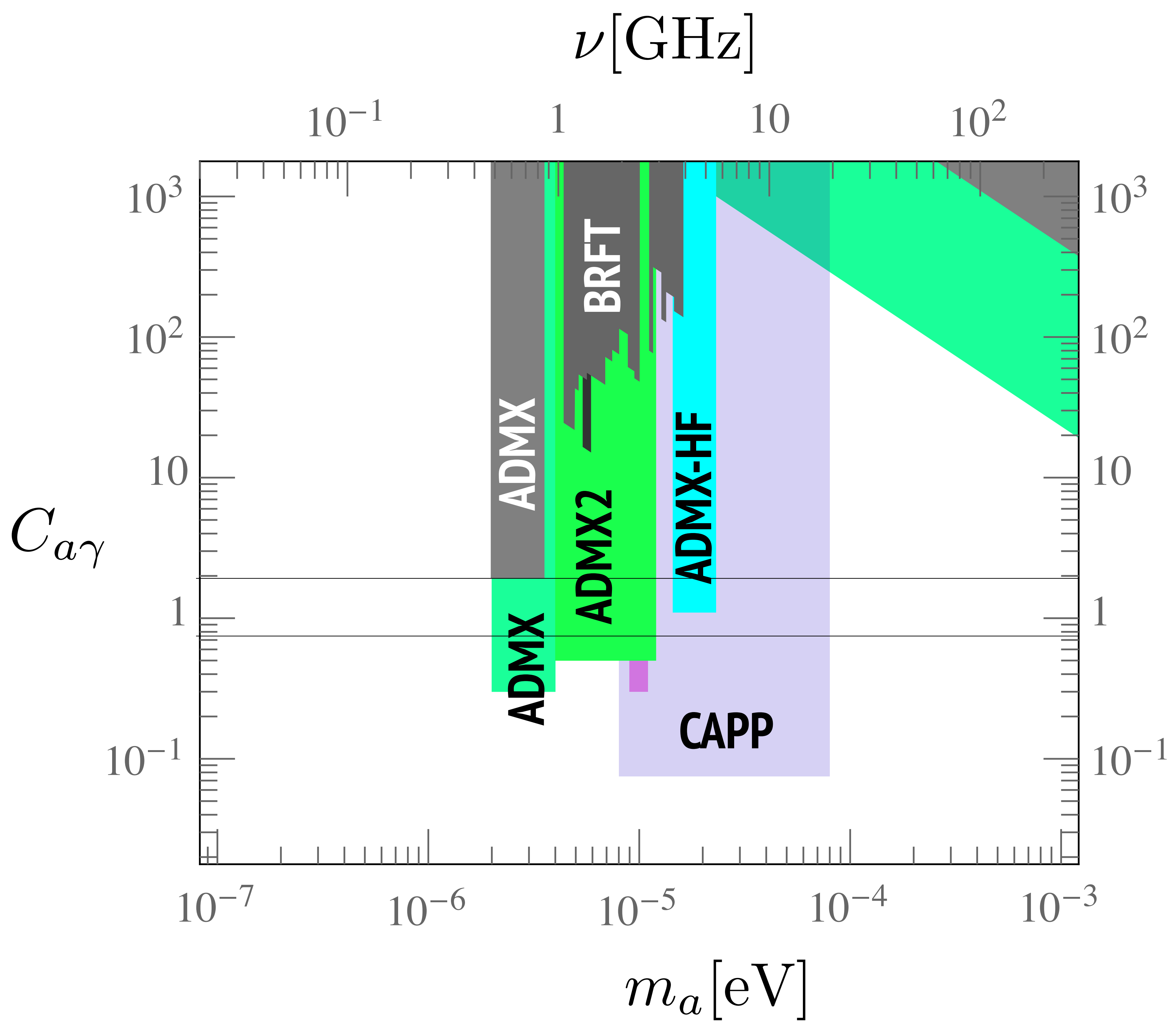


RADES

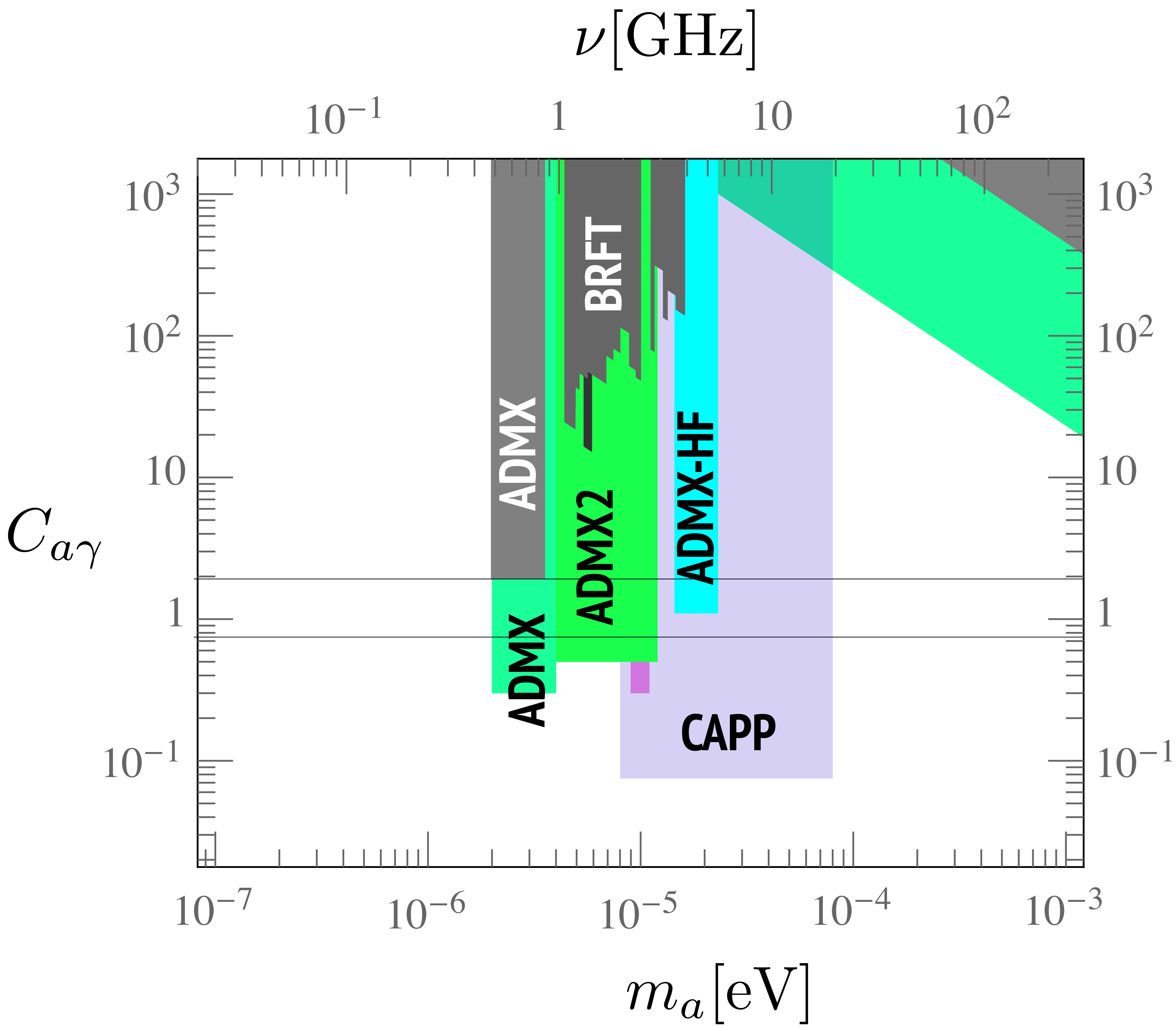


CAST-CAPP

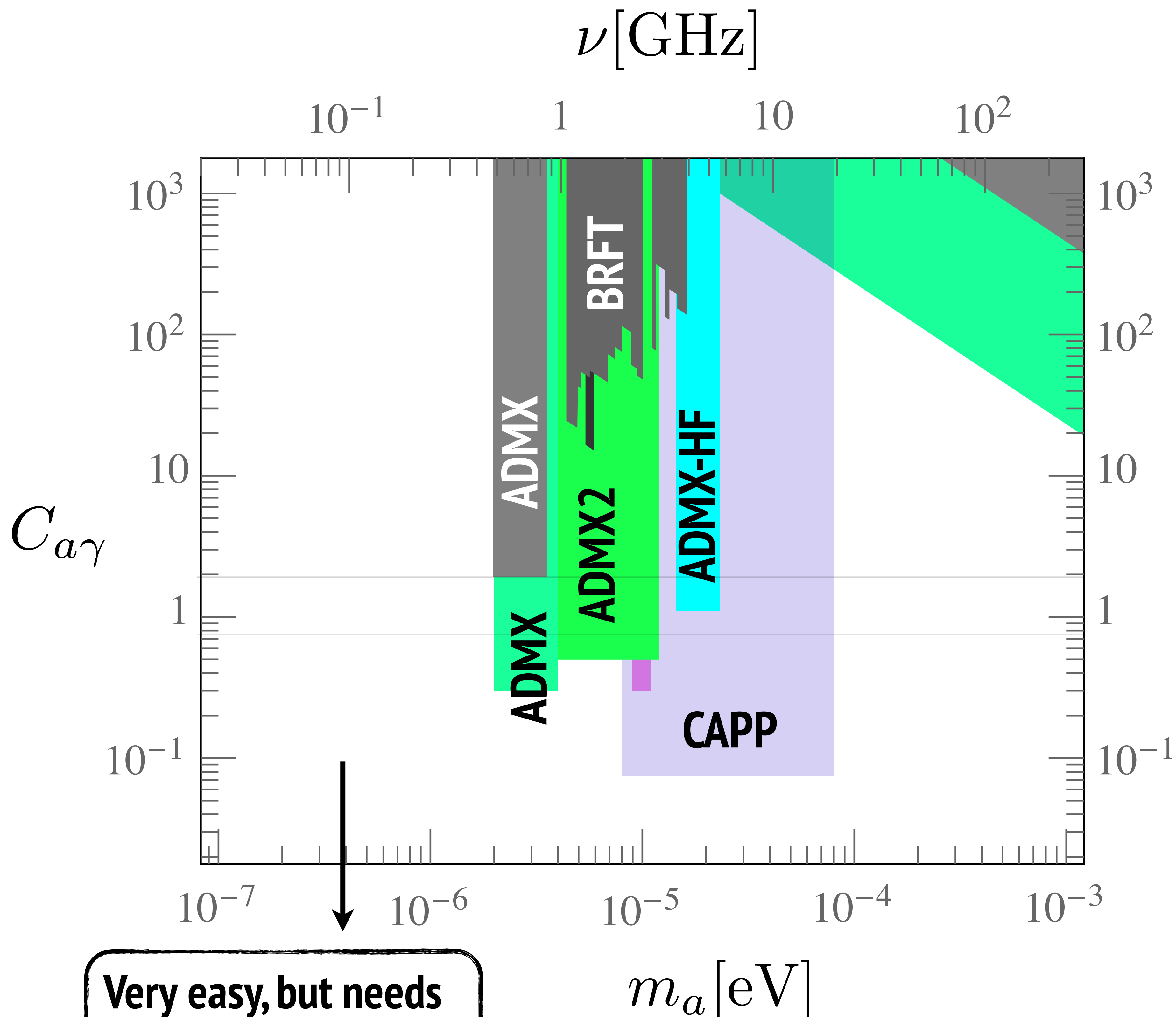
Cavity experiments



Cavity experiments ... and beyond

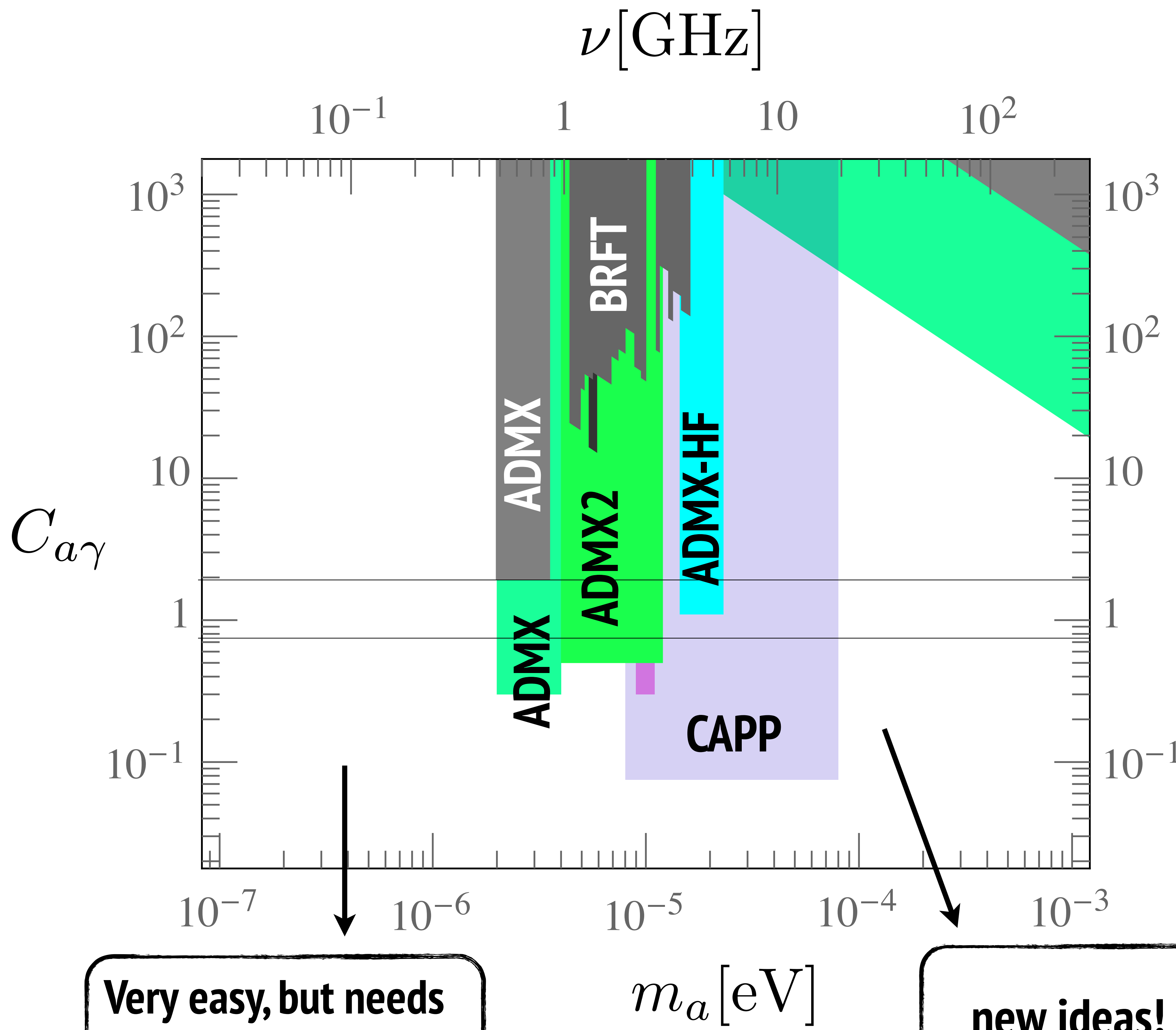


Cavity experiments ... and beyond



Very easy, but needs large magnet volume!

Cavity experiments ... and beyond



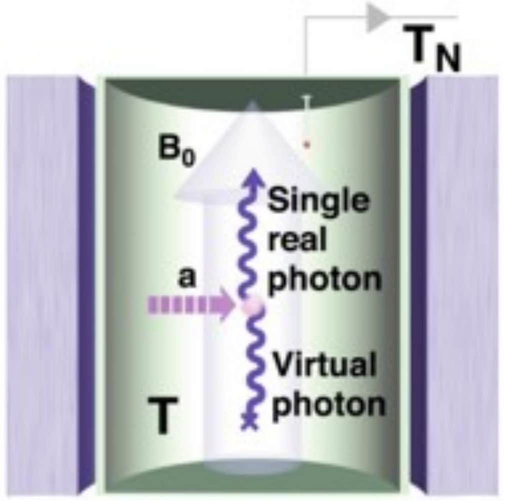
Very easy, but needs large magnet volume!

new ideas!

Cavity experiments (if time)

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

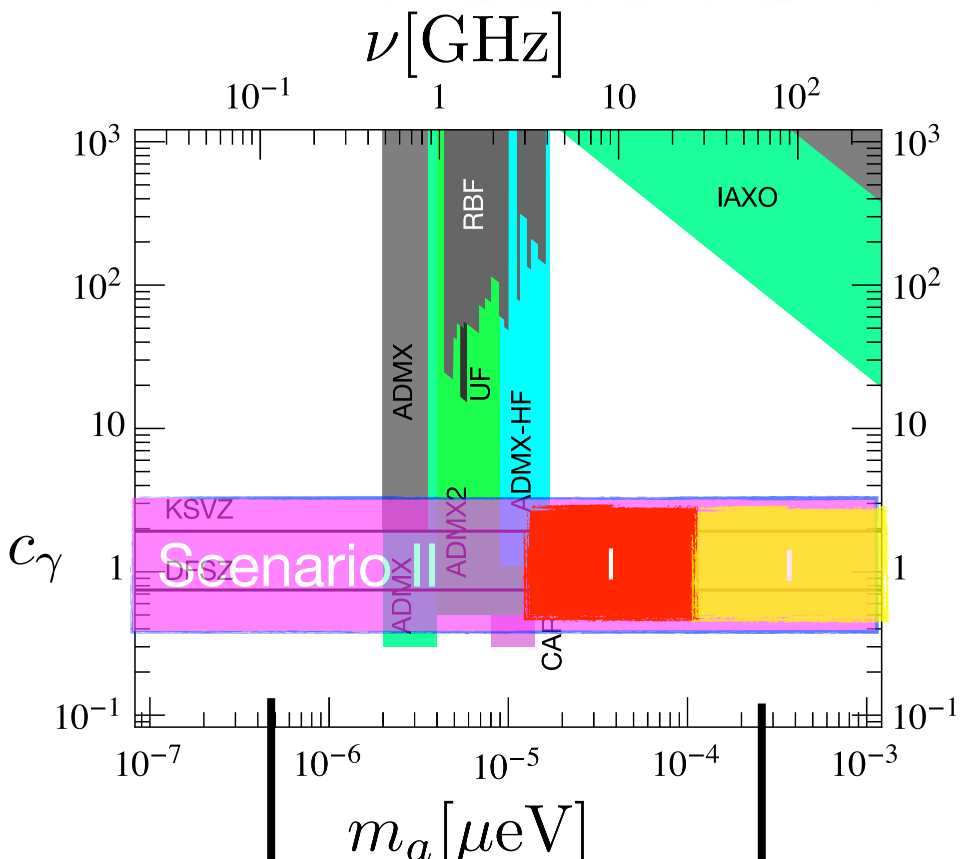
$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa \quad \text{(on resonance)}$$



- **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**

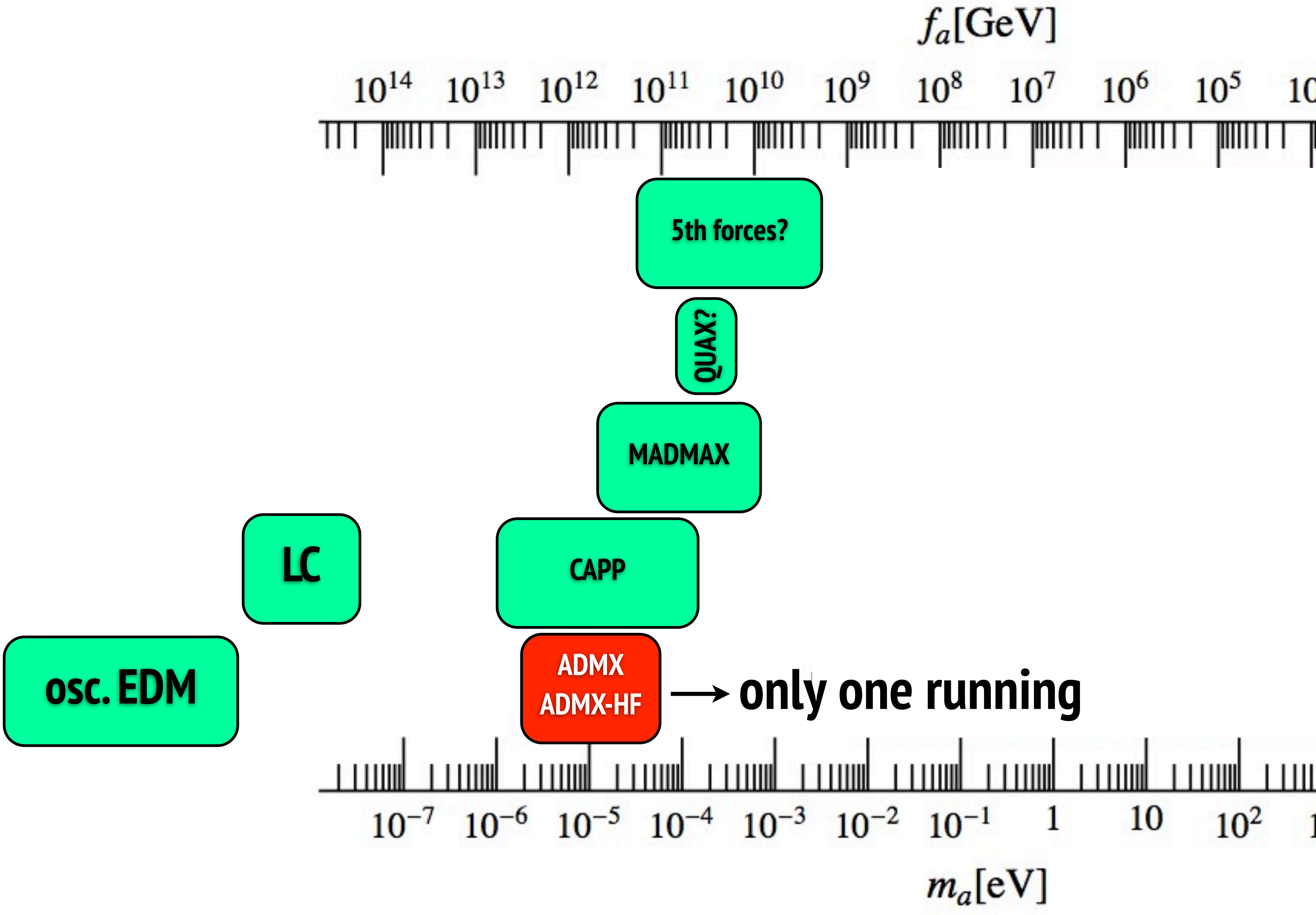
- Signal $(V \propto m_a^{-3})$ $\quad P_{\rm out} \propto V m_a \sim \frac{1}{m_a^2}$
- Noise $\quad P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$
- Signal/noise in $\Delta\nu_a$ of time, *t*, $\quad \frac{S}{N} = \frac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$
- Scanning rate $\quad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



Very easy, but needs large magnet volume!

Very complicated, needs new ideas...

Axion Dark matter experiments (target areas)



Conclusions

- Axion exists -> axion dark matter guaranteed

- 3 main scenarios -> huge DM parameter space m < meV

- meV frontier extremely challenging for direct detection

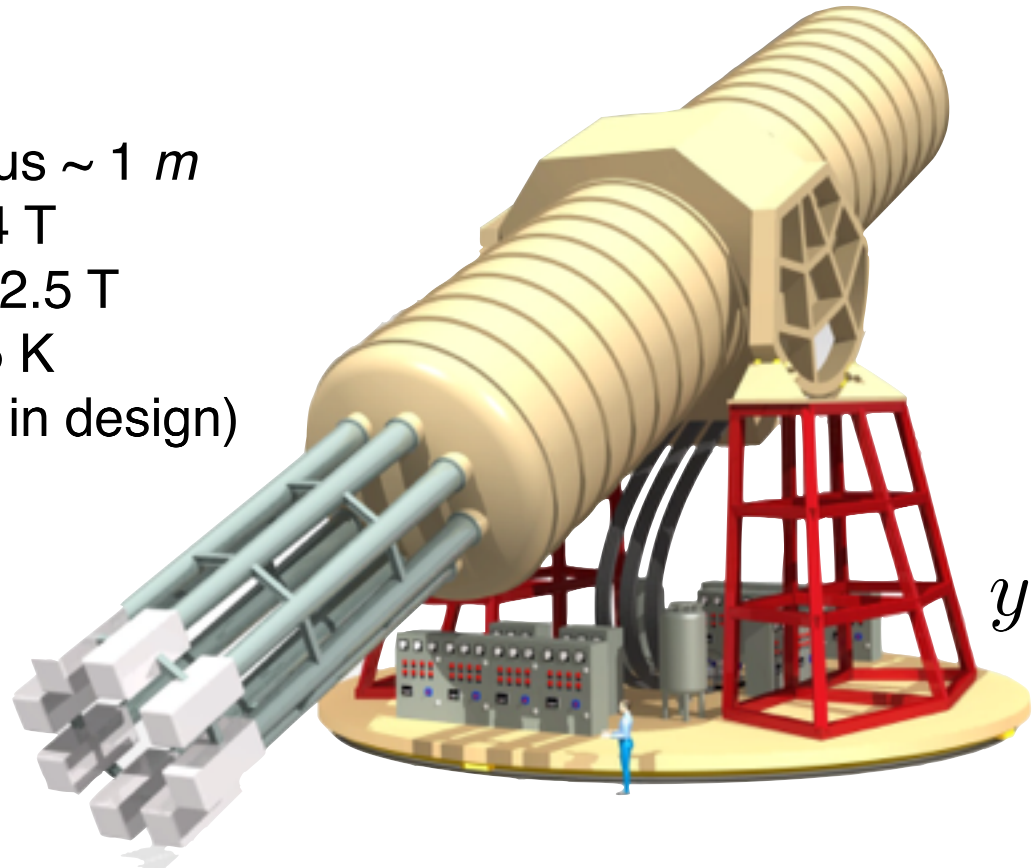
- Axion dark matter experiments, more and better

... But still under critical

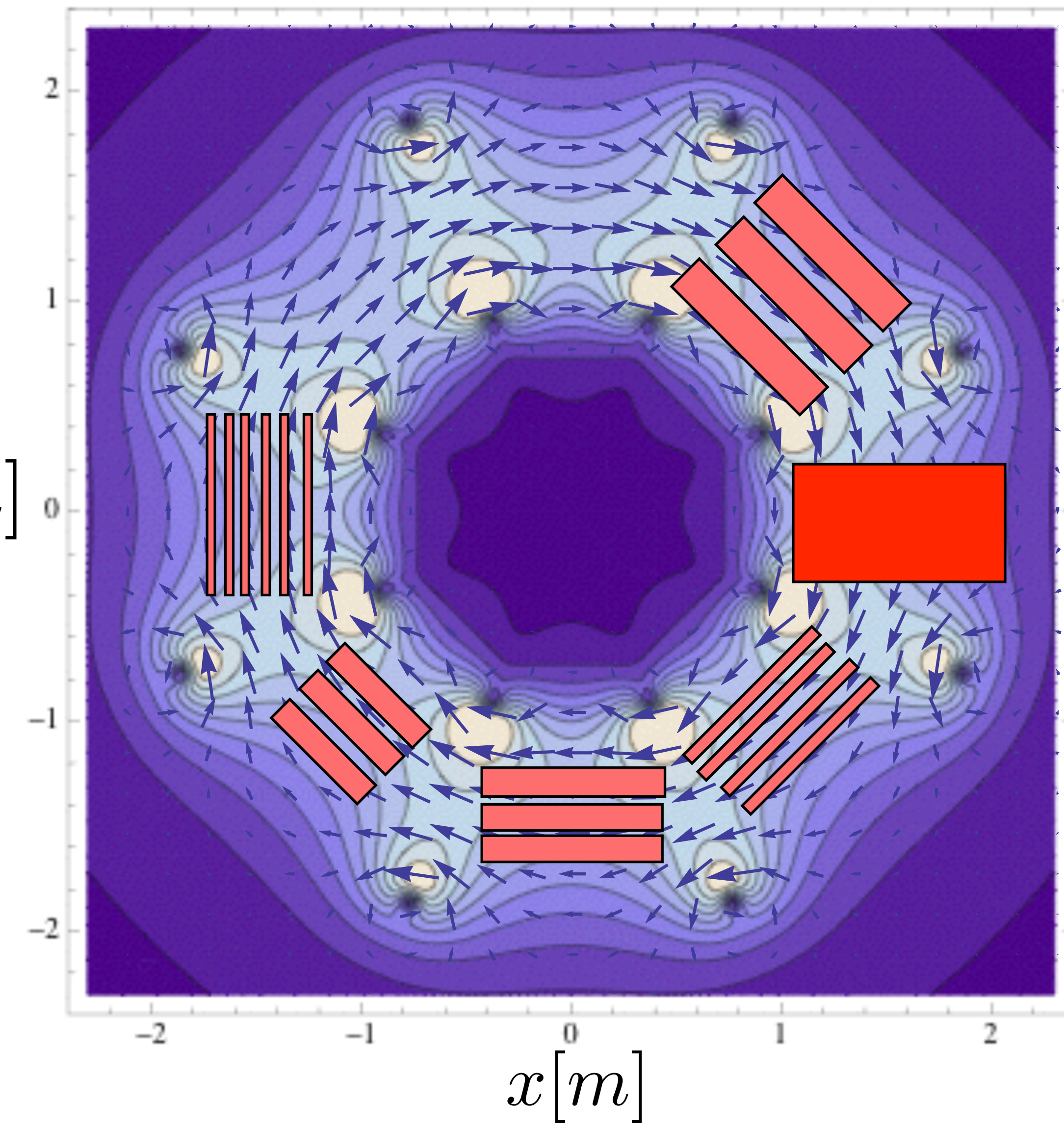
- IAXO huge magnet could host new EXPERIMENTS

Axion DM searches with IAXO?

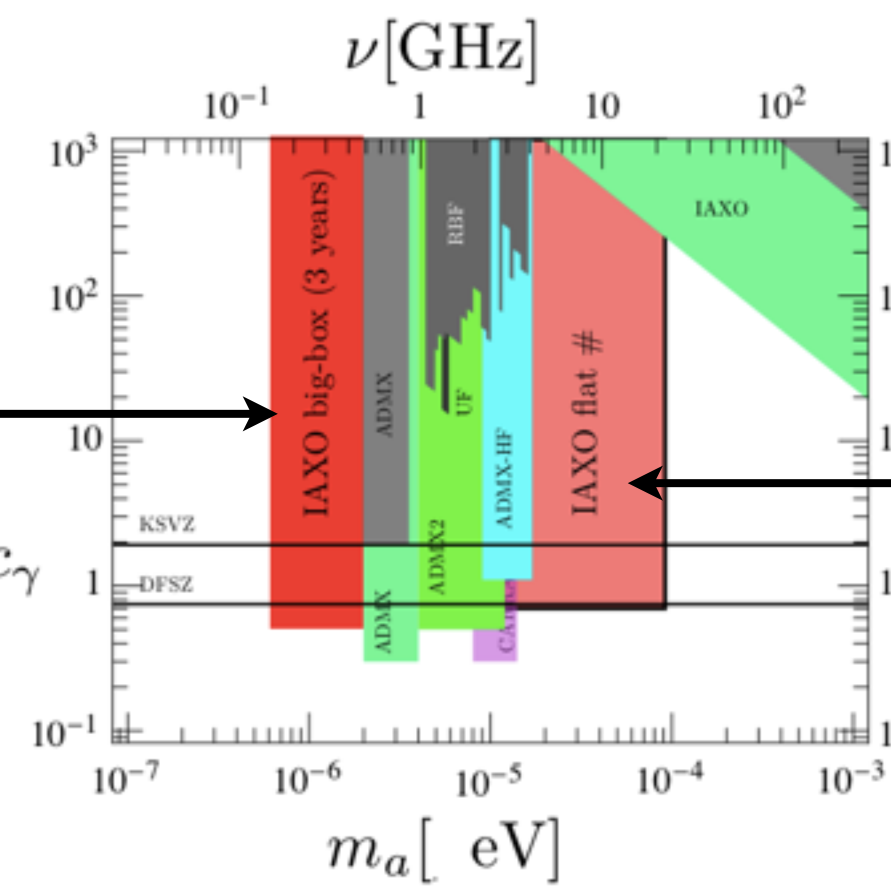
- Length = 20 *m*
- Magnetised radius ~ 1 *m*
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K
  (but warm bores in design)



field map of transverse cut



- Sensitivity



Big cavity (realistic)

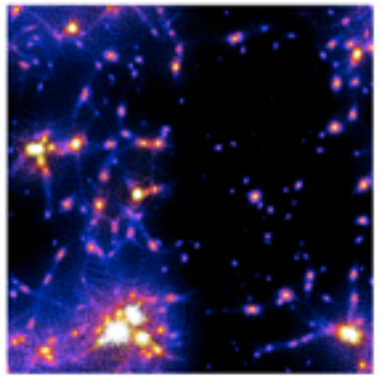
Many flat (exploit the huge volume)
(very speculative, R&D needed!)

Dish antenna and miniclusters

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

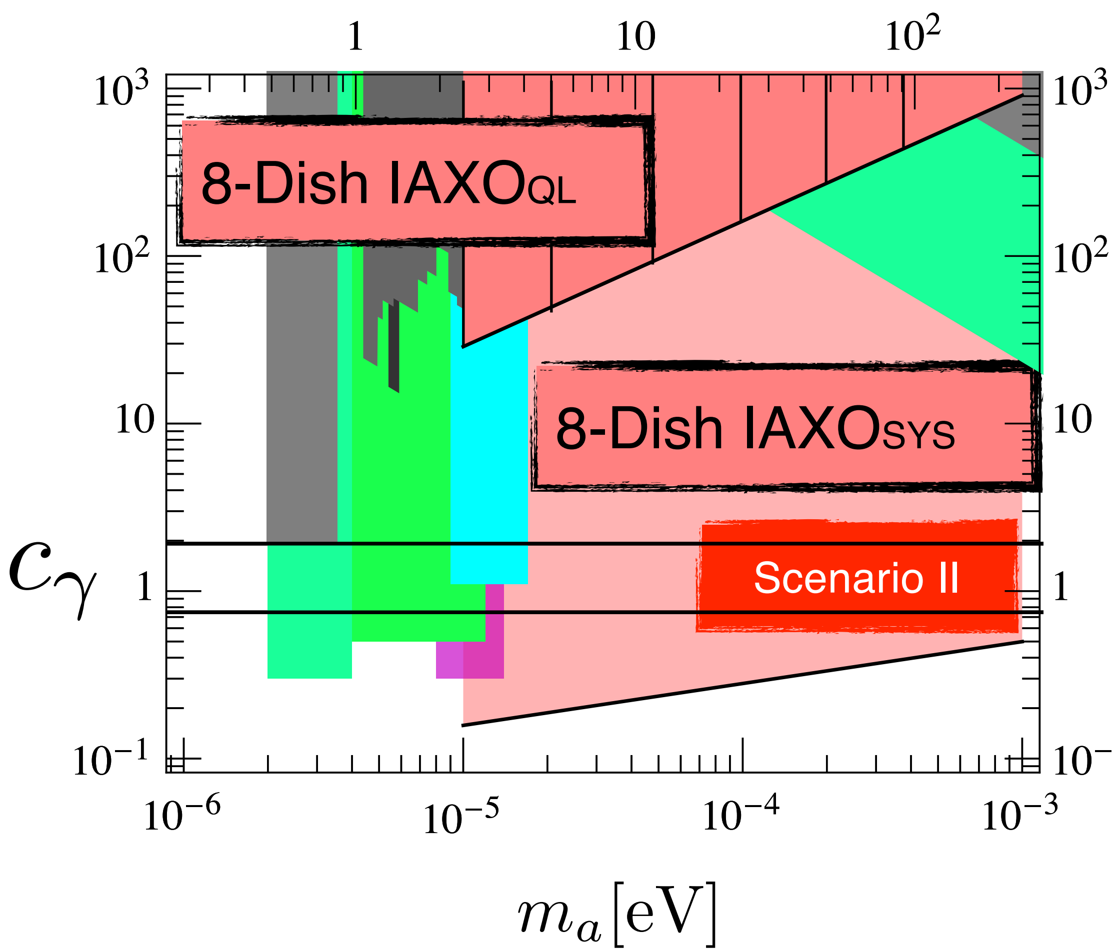
- 0.1-1 meV range is most interesting in **Scenario-II**

- 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...)

Second END

- Axion exists -> axion dark matter guaranteed

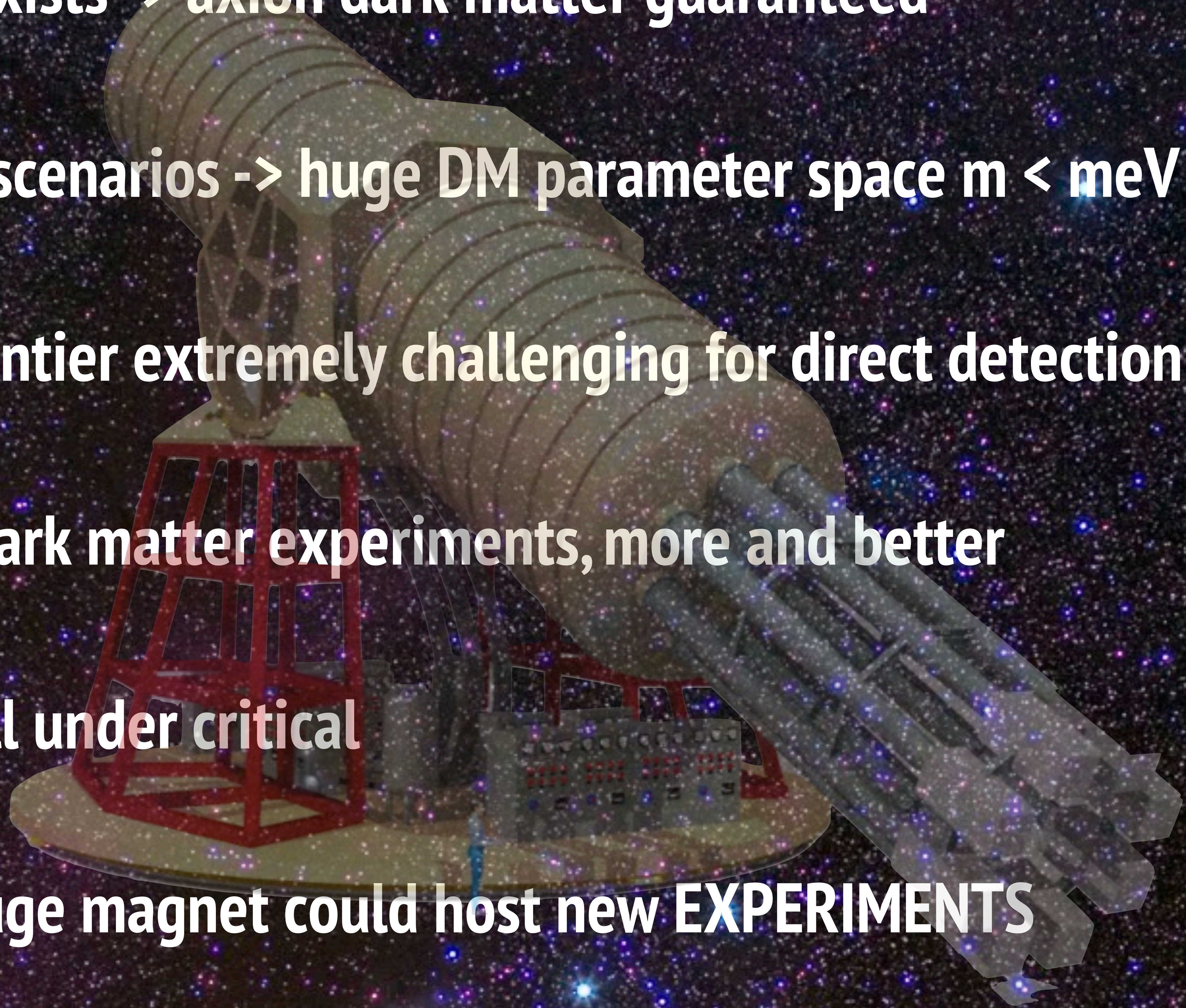
- 3 main scenarios -> huge DM parameter space m < meV

- meV frontier extremely challenging for direct detection

- Axion dark matter experiments, more and better

... But still under critical

- IAXO huge magnet could host new EXPERIMENTS



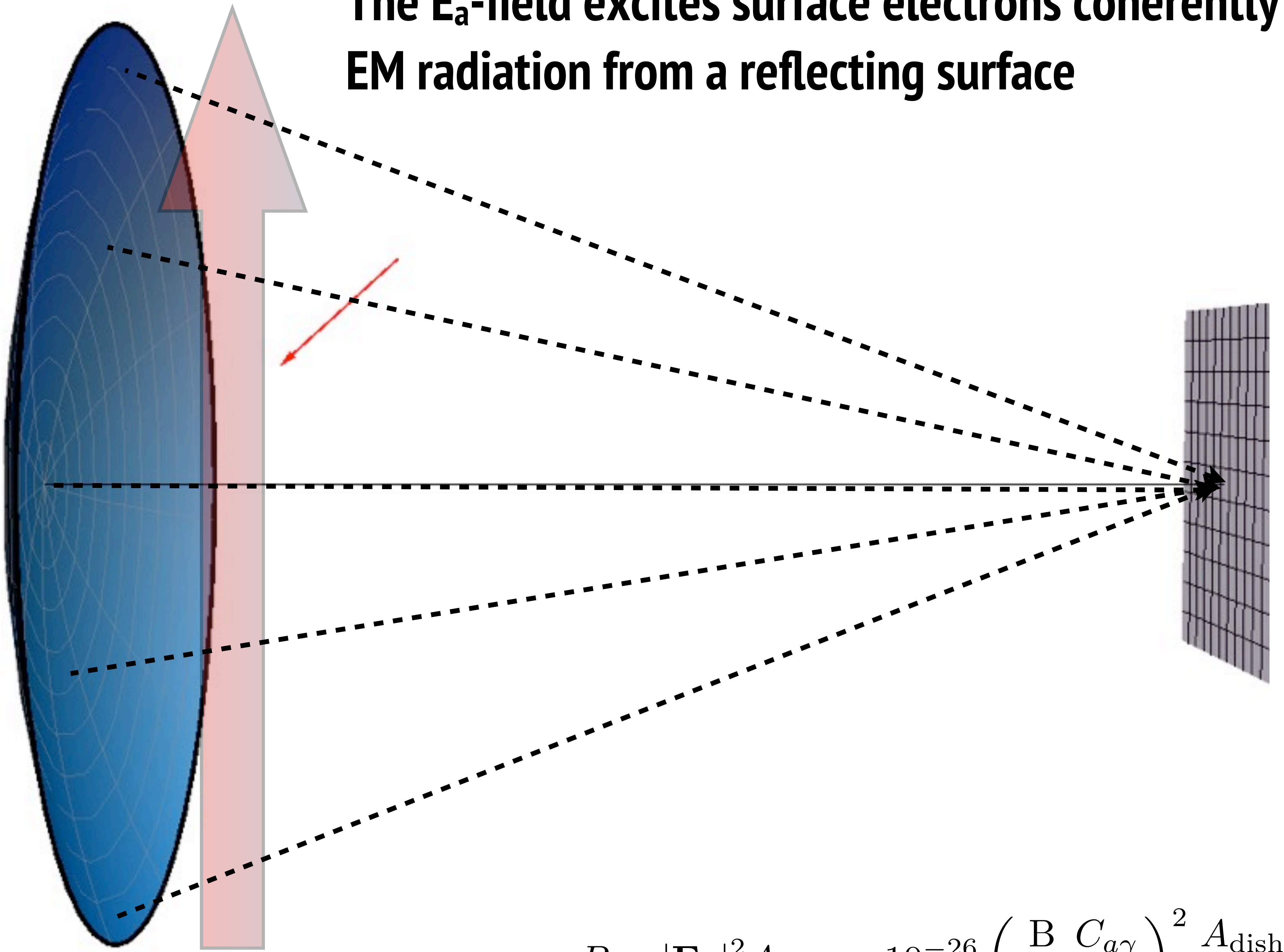
do not go beyond this point

Dish antenna experiment?

Horns 2012

The E_a-field excites surface electrons coherently

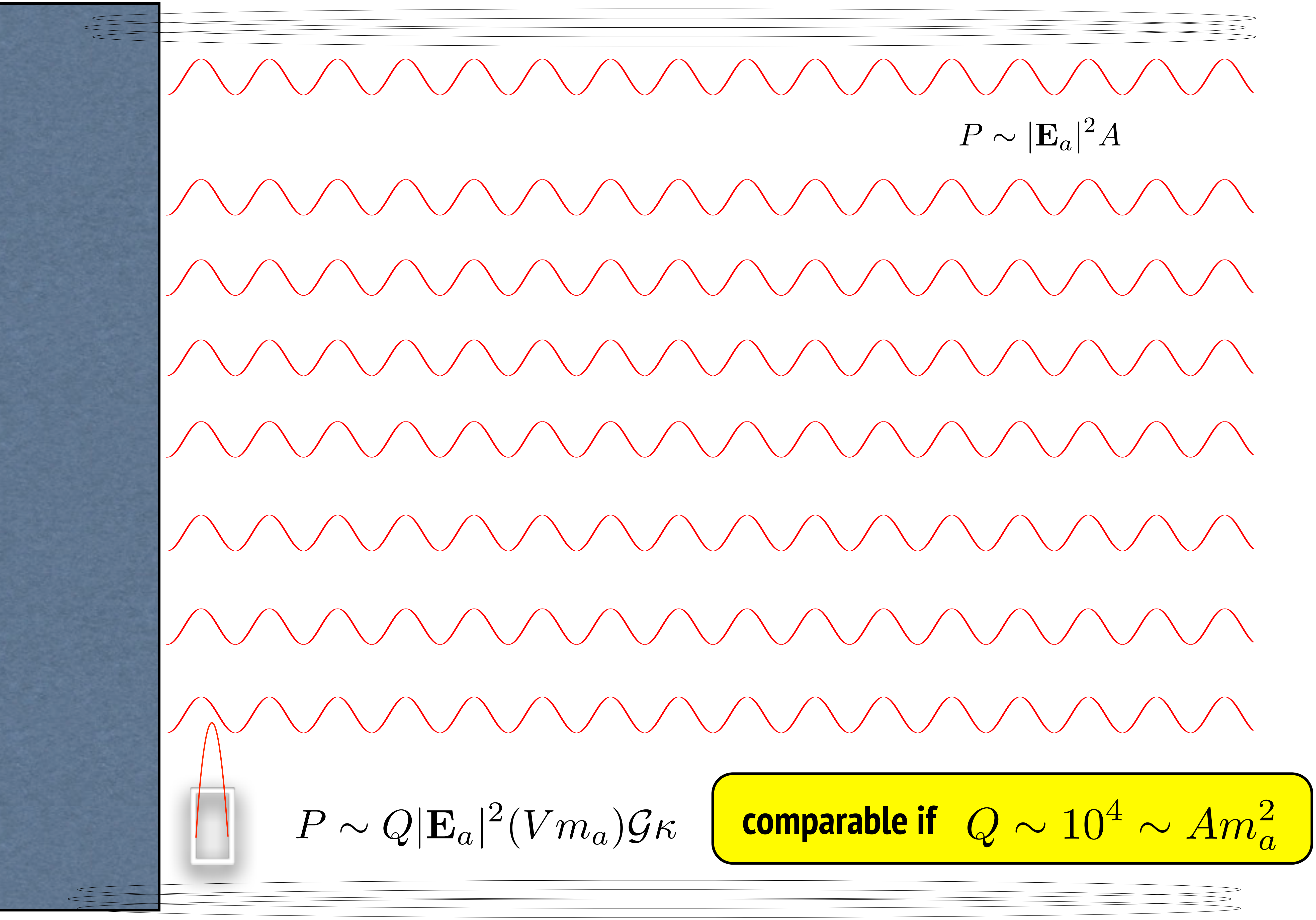
EM radiation from a reflecting surface



spherical reflecting dish

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

Large freq ... Area vs volume



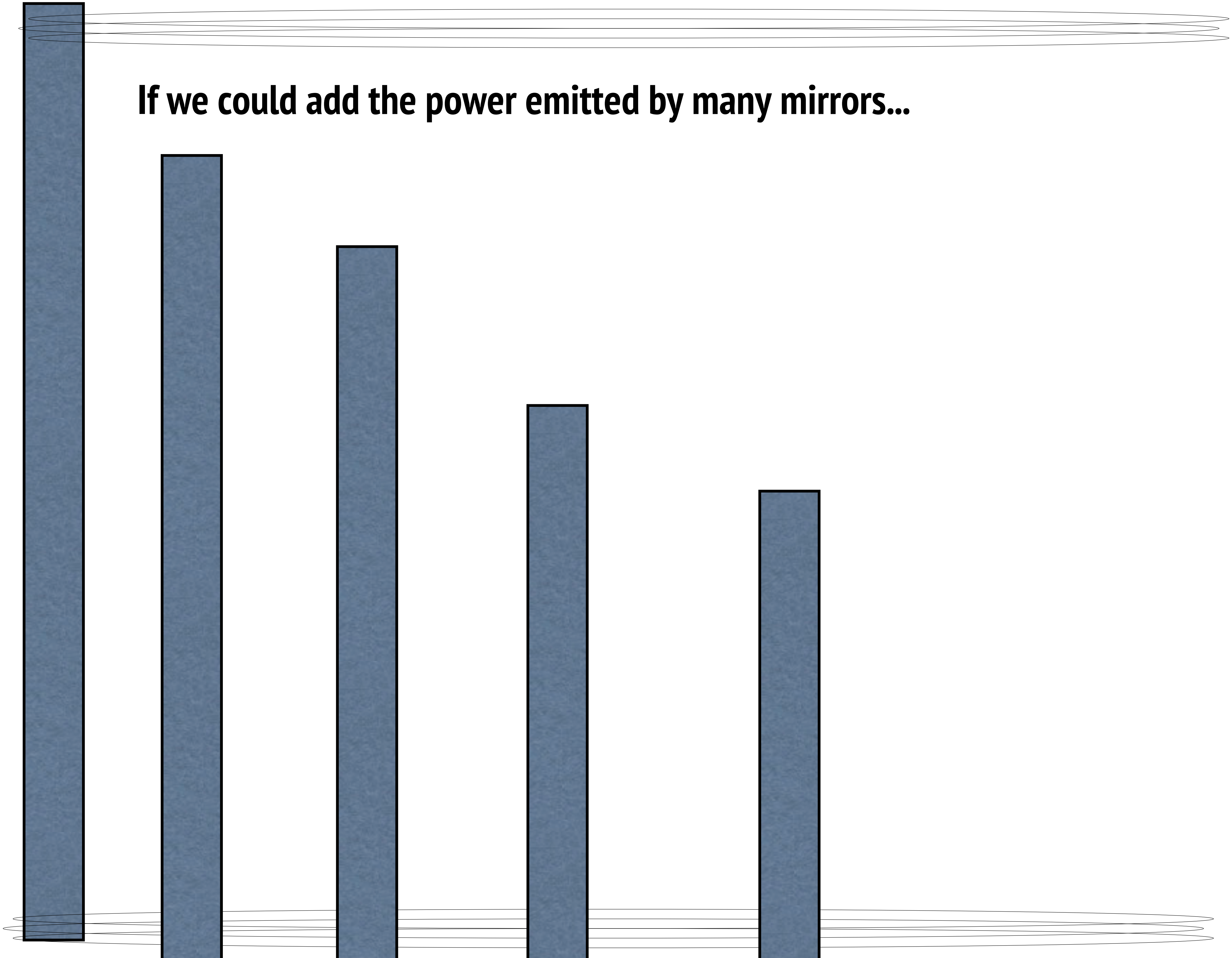
$$P \sim |\mathbf{E}_a|^2 A$$

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

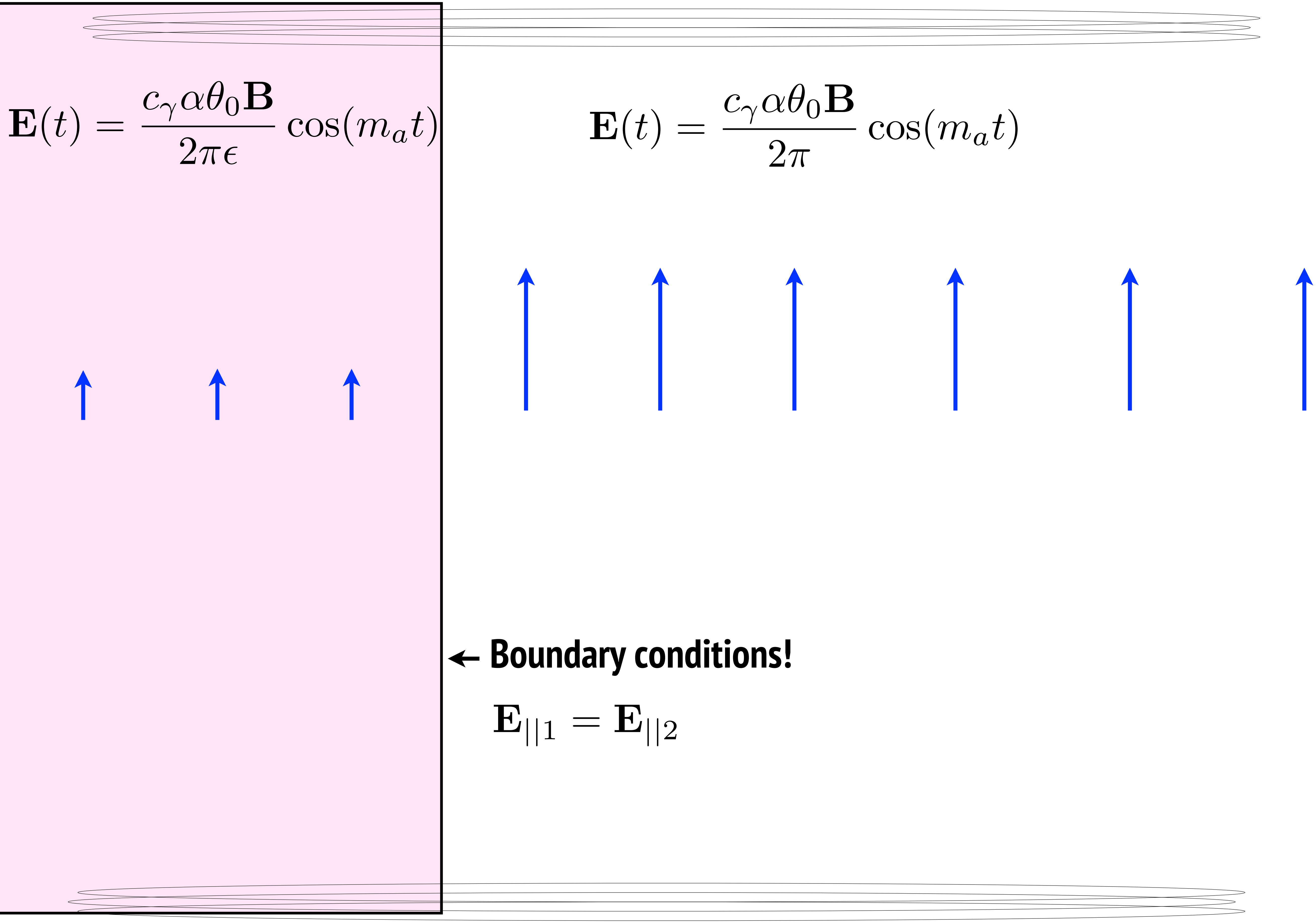
comparable if $Q \sim 10^4 \sim A m_a^2$

Mixed scheme?

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



Radiation from a dielectric interface ...



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

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

← **Boundary conditions!**

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

Radiation from a dielectric interface ...

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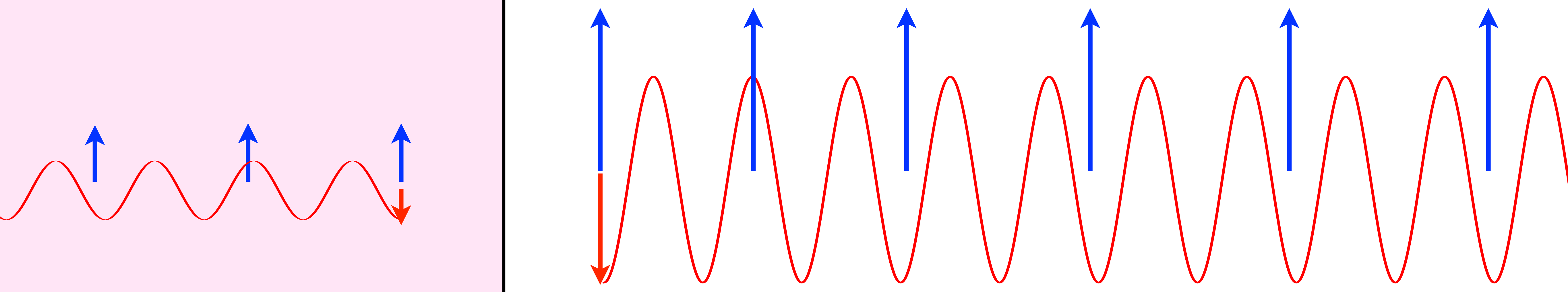


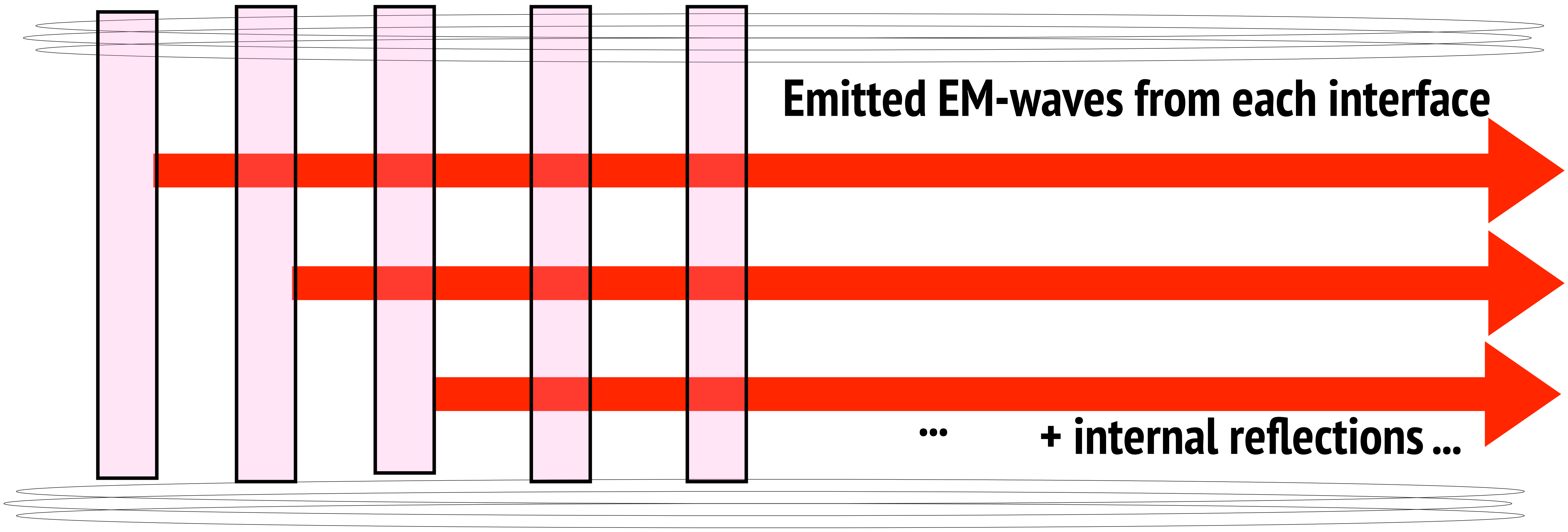
← **Boundary conditions!**

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

Emitted EM-wave

Emitted EM-wave

Many dielectrics : MADMAX at MPP Munich



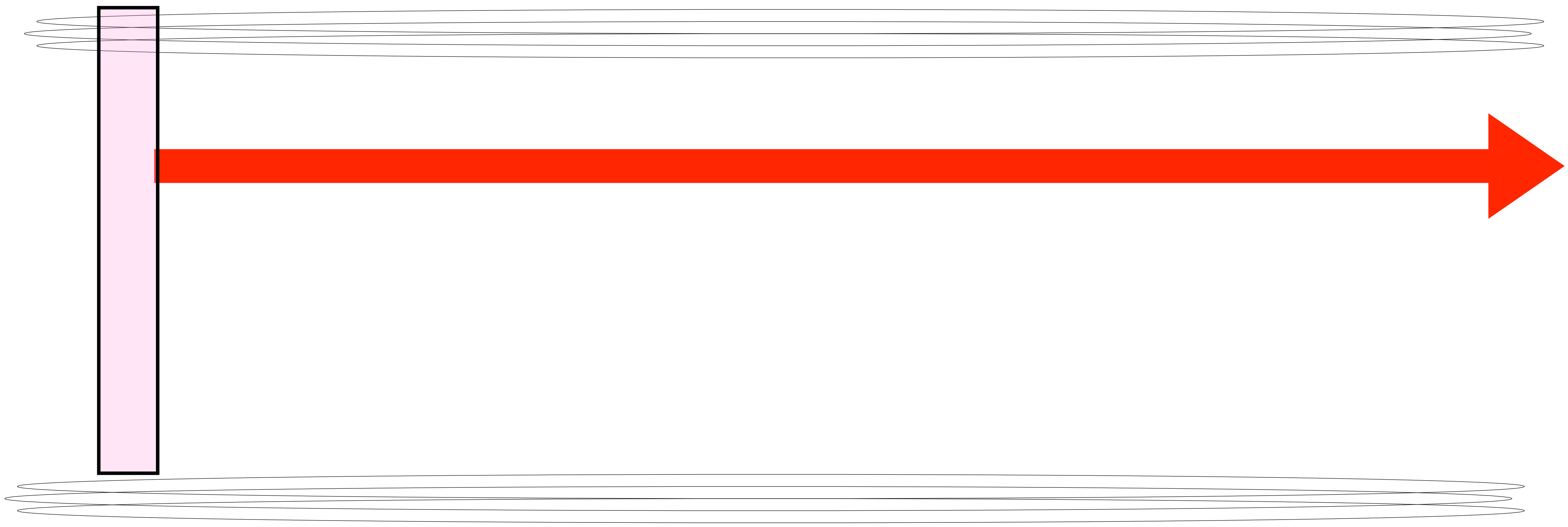
- Emission has large spatial coherence; adjusting plate separation -> coherence

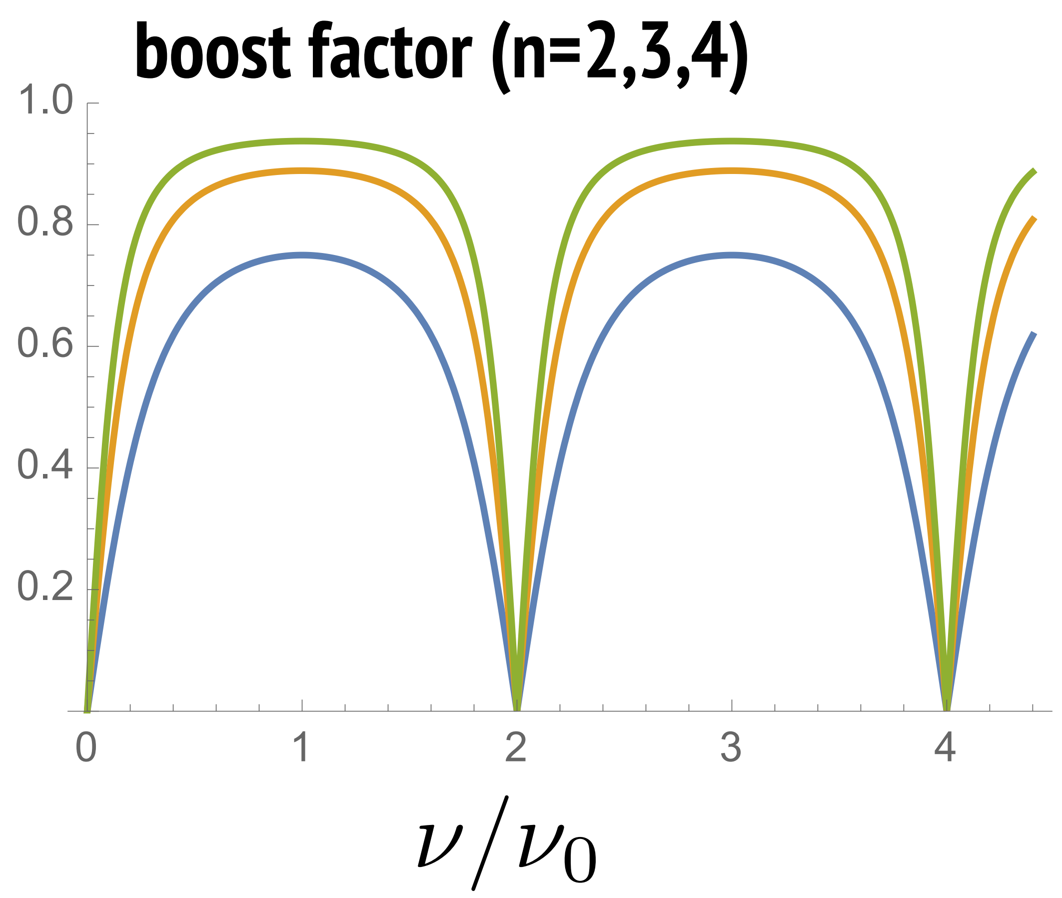
$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(c_\gamma \frac{B_{||}}{10\mathrm{T}} \right)^2 \times \beta^2(\omega)$$

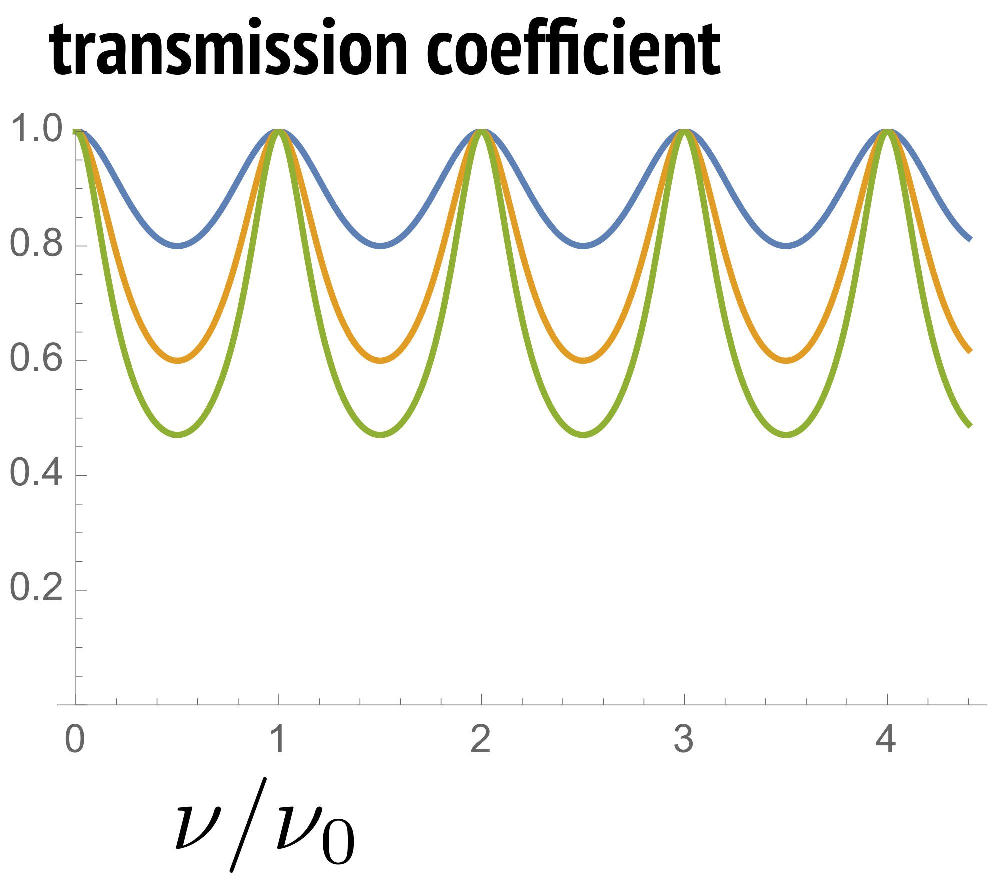
boost factor

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

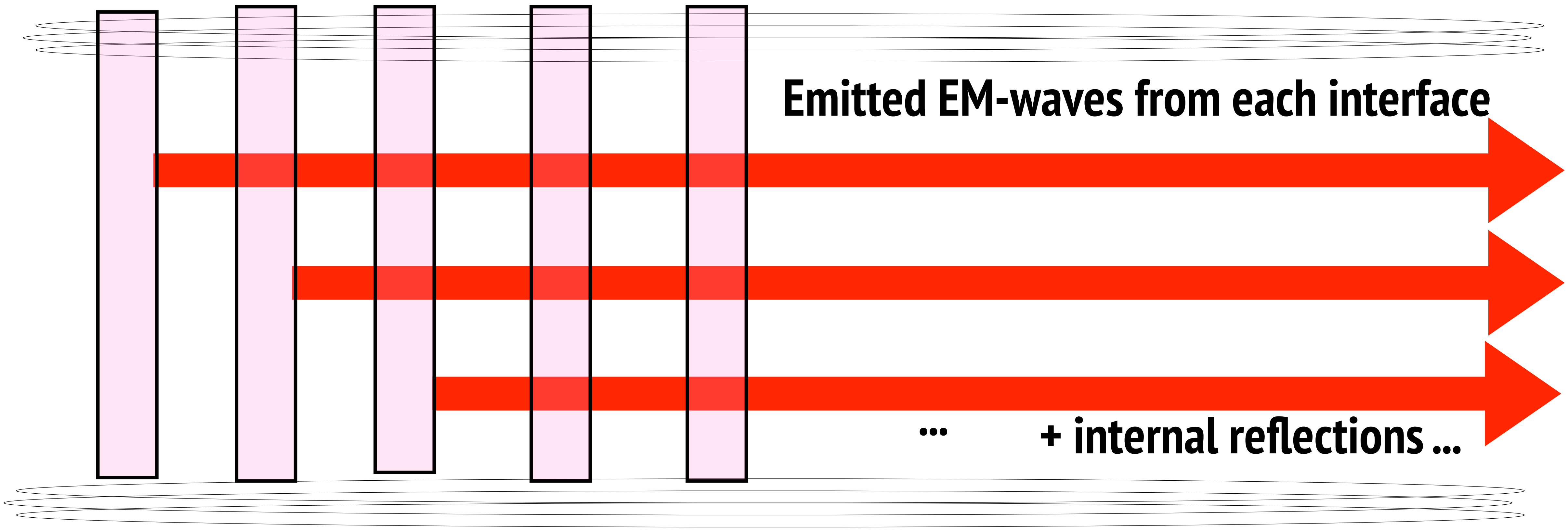
One dielectric



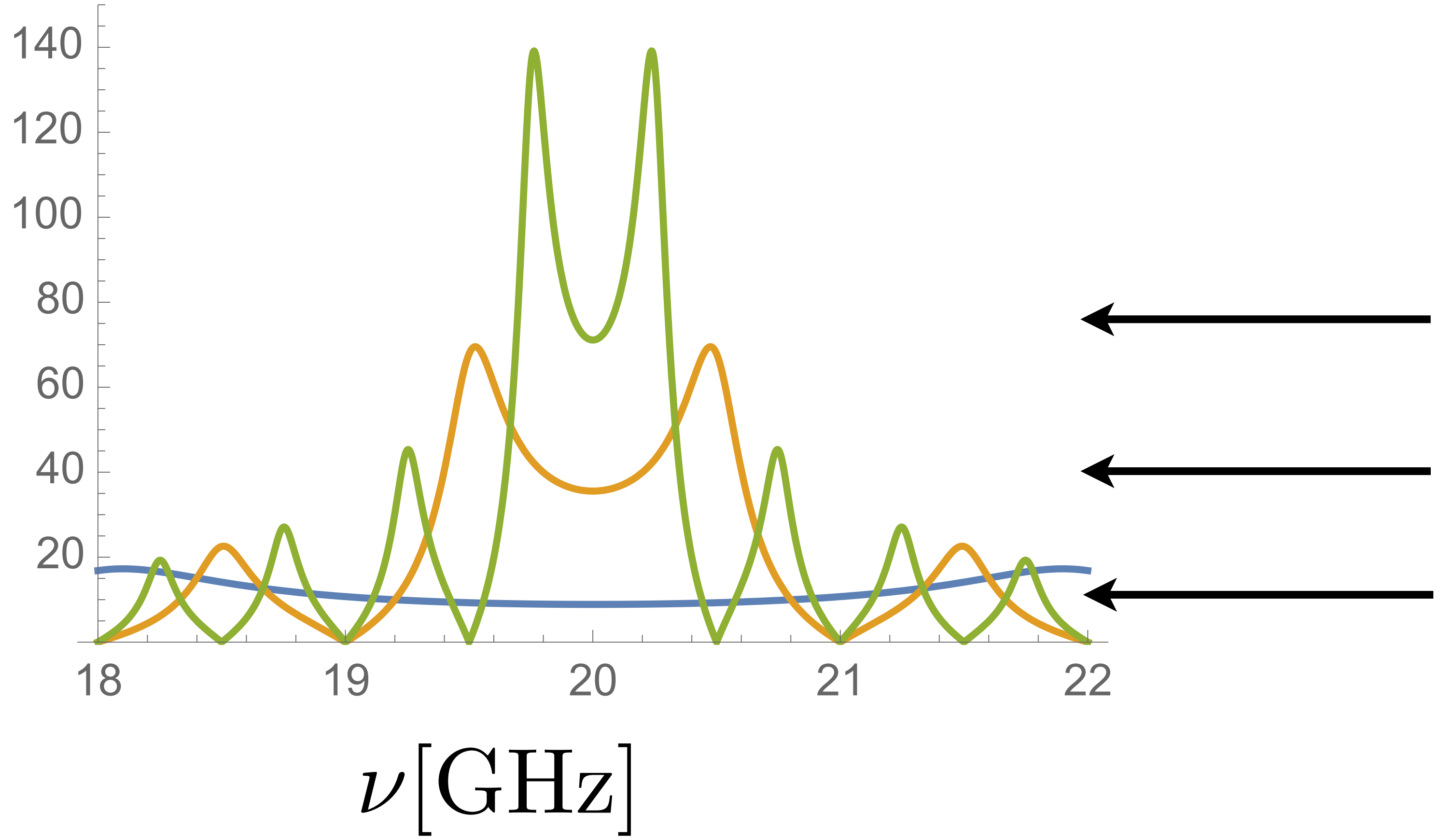




Close to nu0, many layers



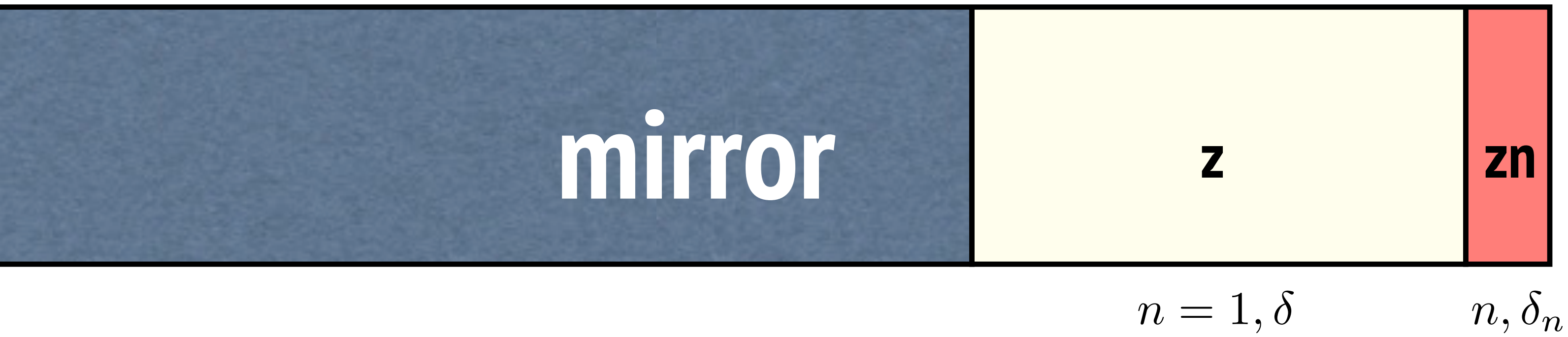
boost factor (N=10,40,80; n=3,nu0=20 GHz)

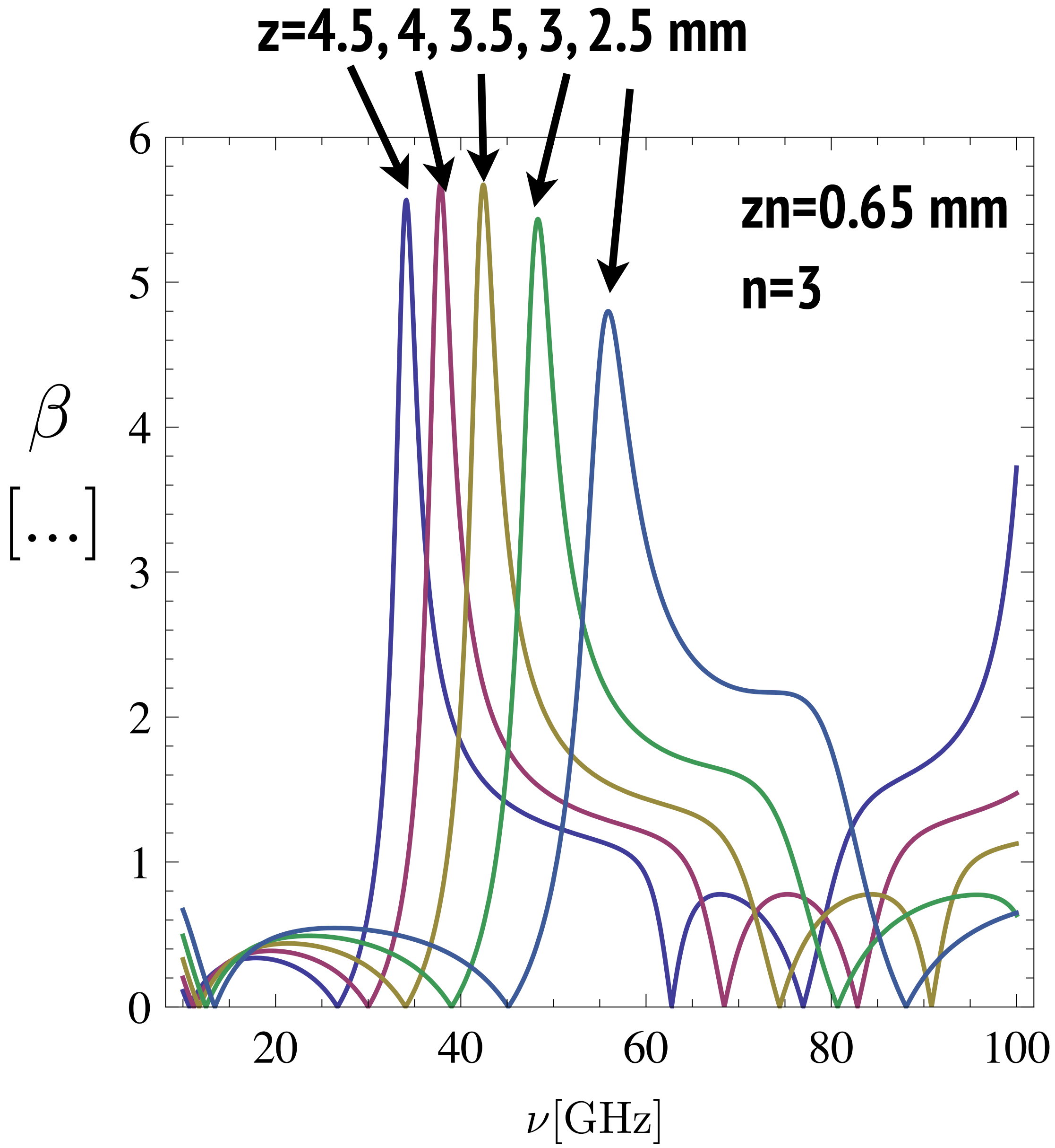


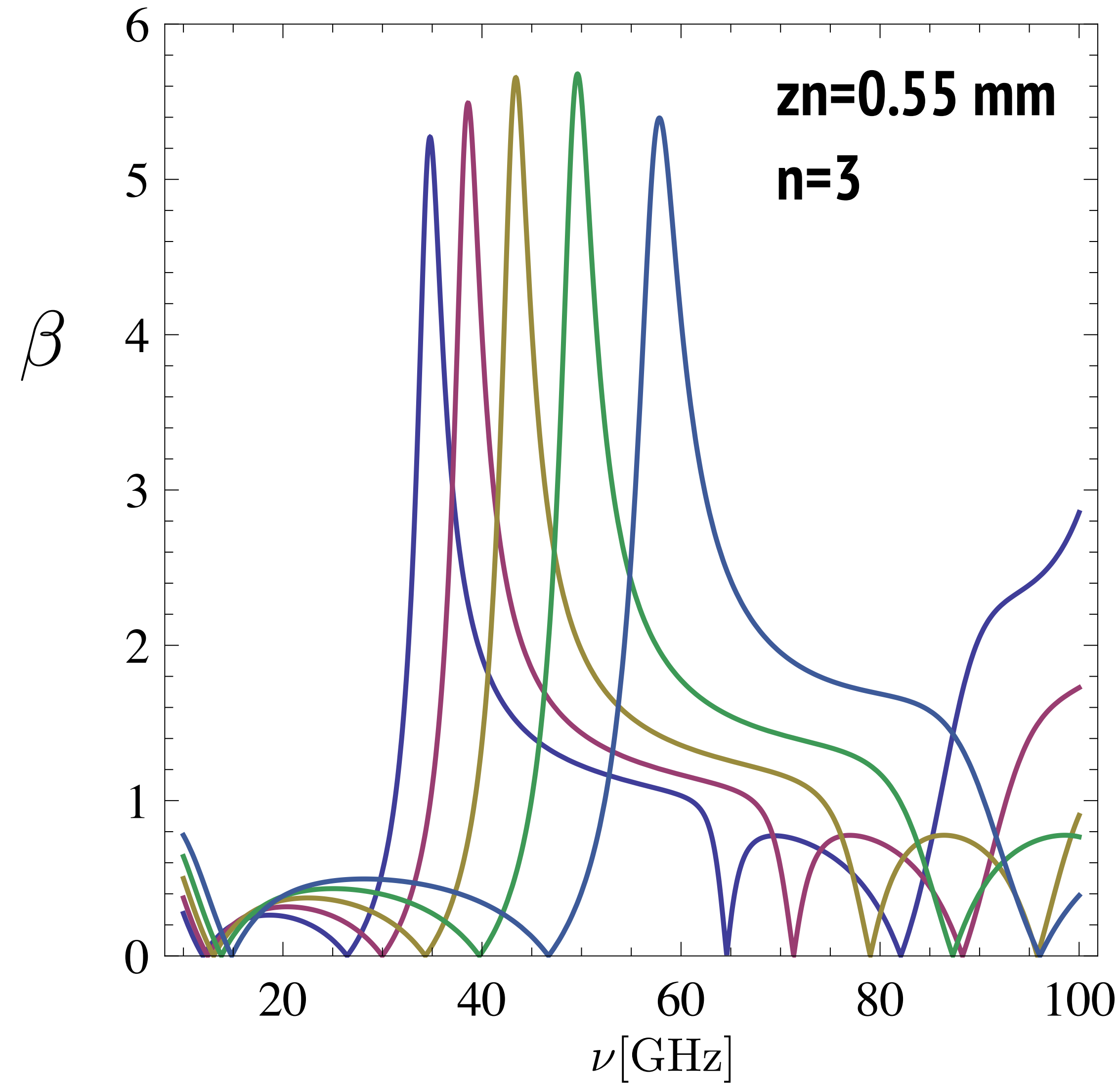
$$\beta_N \sim N \times \beta_1$$

Outside nu0

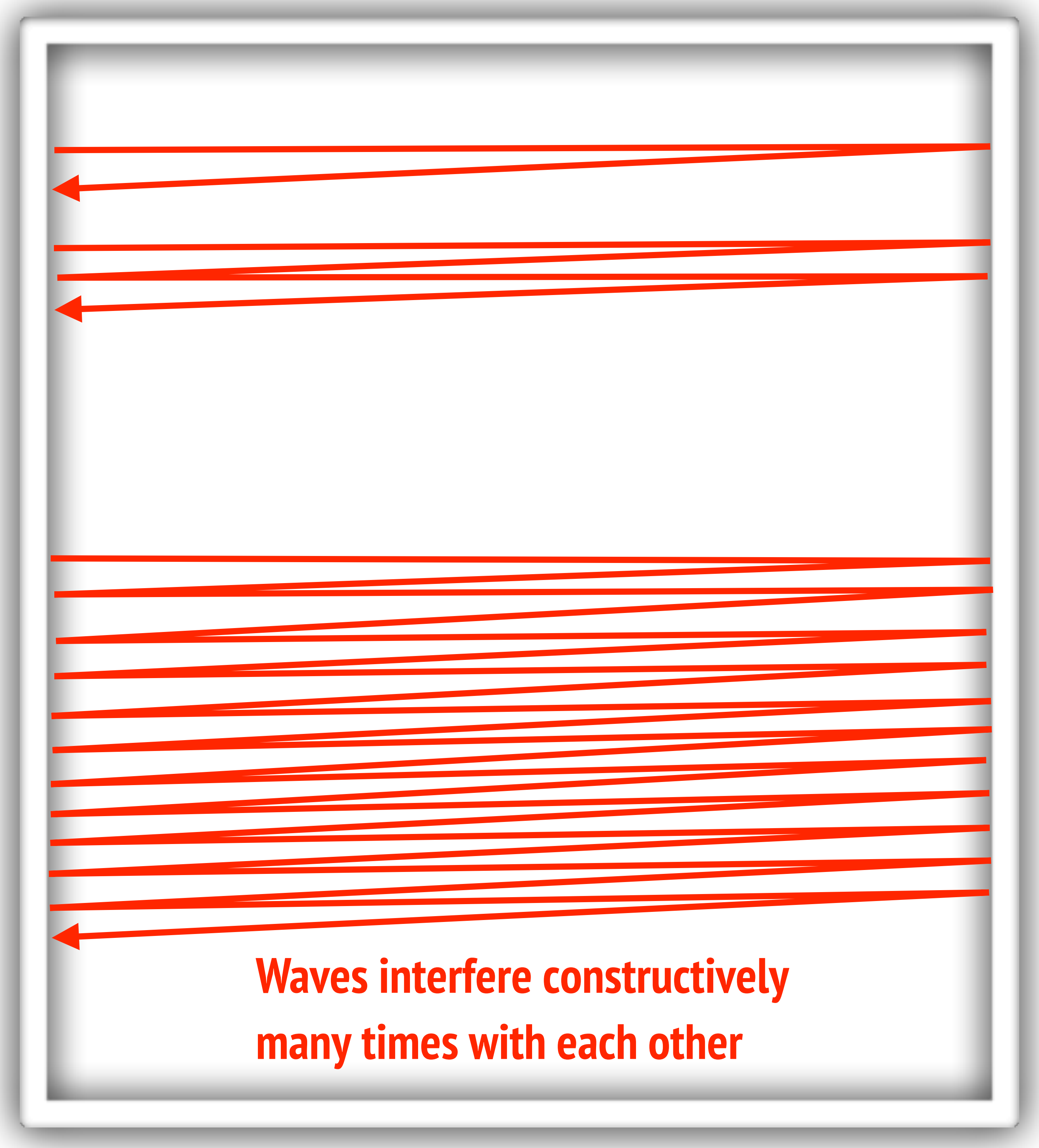
When dielectrics are non-transparent, mild resonances appear that allow higher boosts



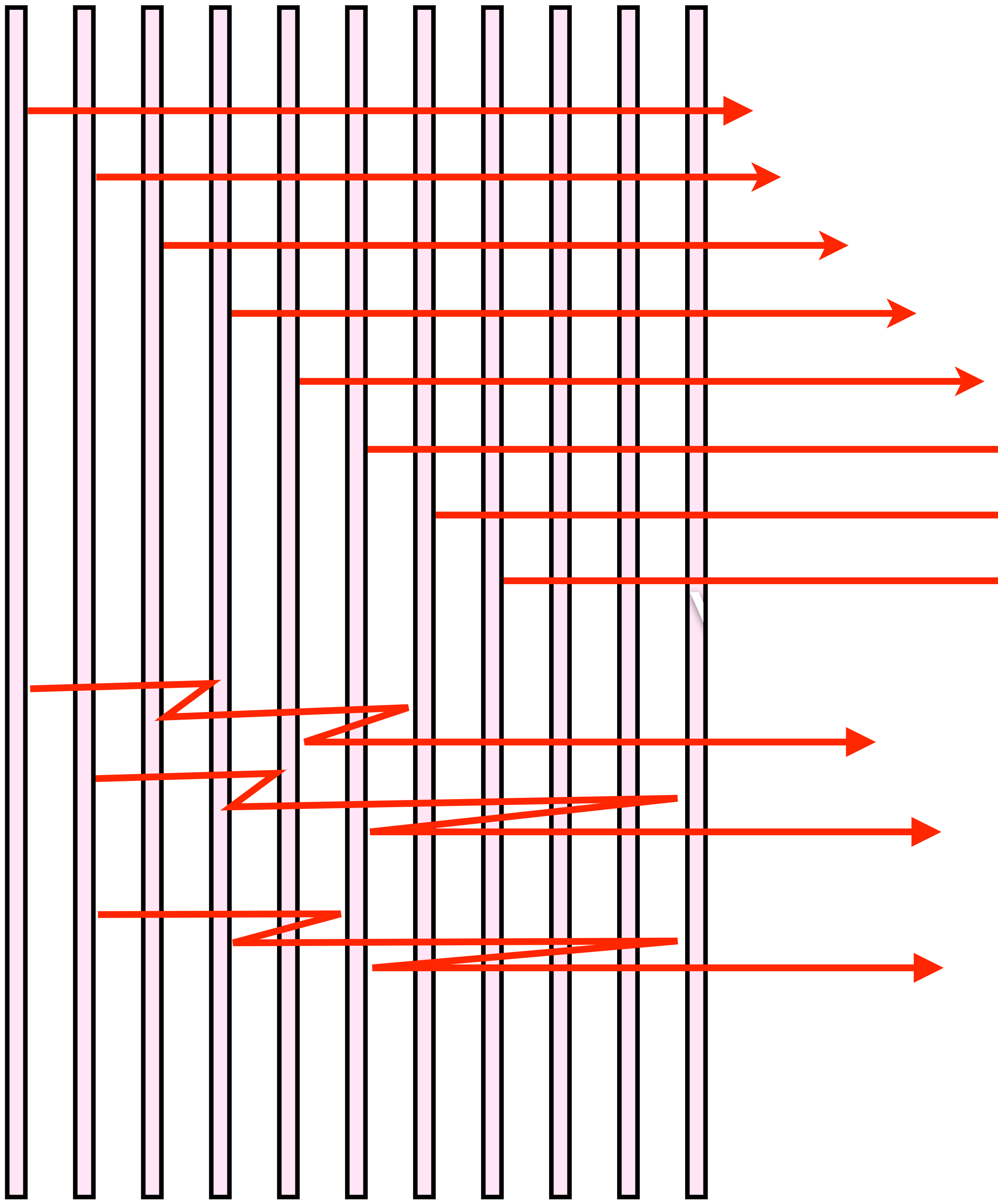




Comparison with cavities

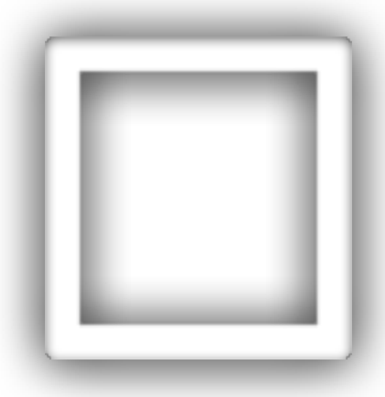


Mechanical tolerances amplified

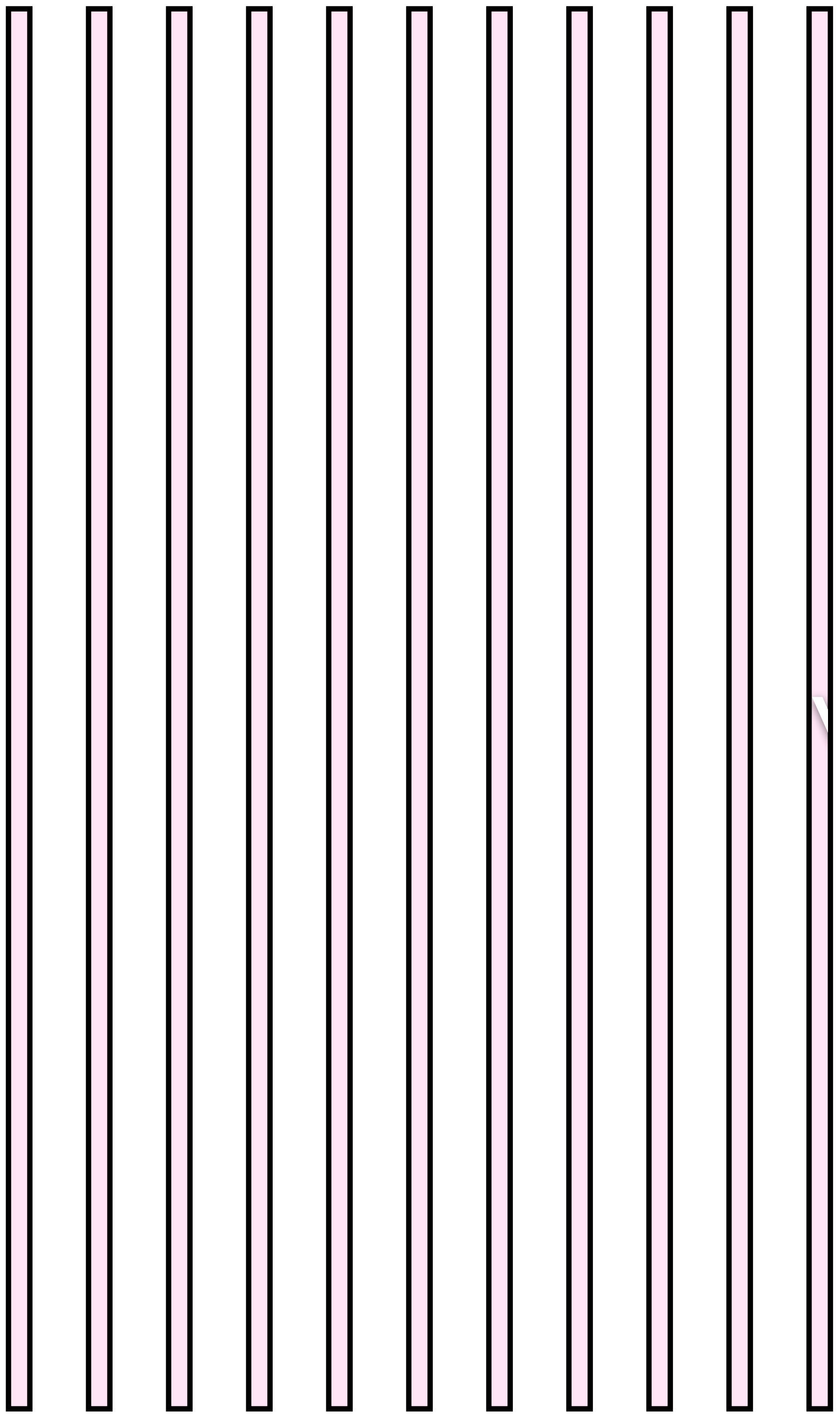


Many layers, Errors averaged to some extent
smaller cavity-effect contribution

Comparison with cavities, at high frequency



Cavities become small,



In principle, dielectric stacks can be kept quite wide
(Area effect)

MADMAX

A new QCD Dark Matter Axion search using a dielectric resonant cavity

A. Caldwell, C. Gooch, A. Hambarzumjan, B. Majorovits, A. Millar, G. Raffelt, J. Redondo, O. Reimann, F. Simon, F. Steffen
MPI für Physik, München, Germany

J. Redondo
University of Zaragoza, Spain

- Recap: Axion to photon conversion at surfaces
- The open cavity idea
- Simulations of boost factor and transmission
- Seed project at MPP
- Proposed design for final experiment, plans

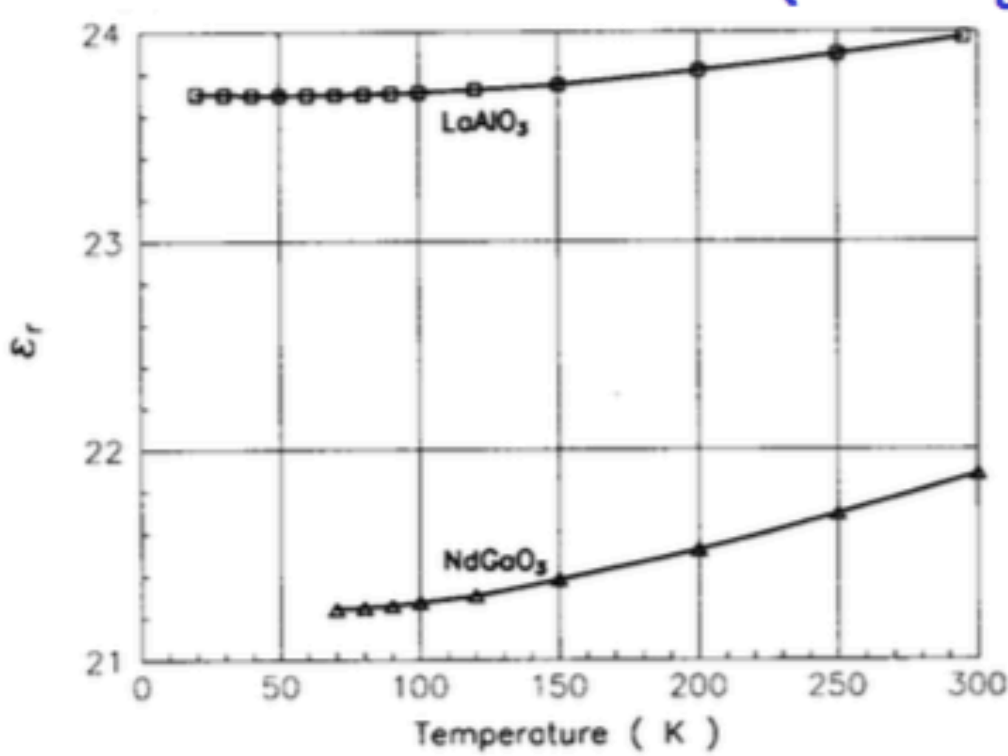
Experimental idea

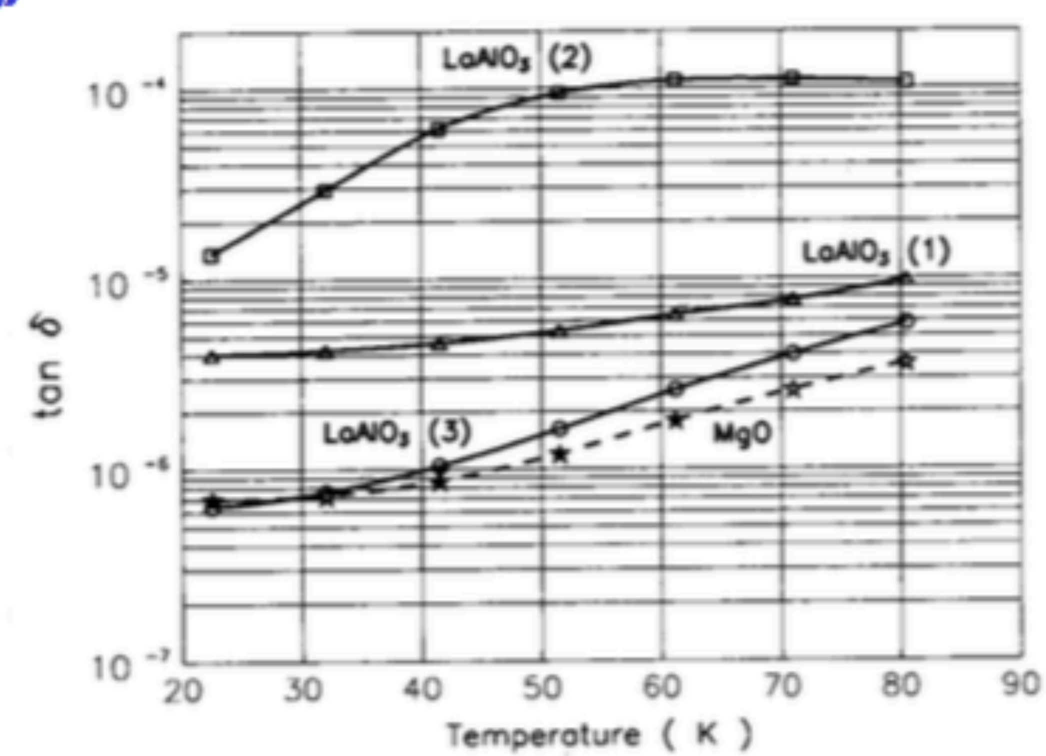
Chose dielectric material:

- **High dielectric constant (for large axion/photon conversion factor)**
  - **Low loss → low tan δ (in order to reduce photon loss)**
    - **Stable**
    - **Cheap**

→ **Sapphire (Al_2O_3)** @23 C, 10 GHz: $\varepsilon_{\perp} = 9.35$; $\tan\delta_{\perp} = 3\cdot10^{-5}$
$\varepsilon_{=} = 11.53$; $\tan\delta_{=} = 8.6\cdot10^{-5}$

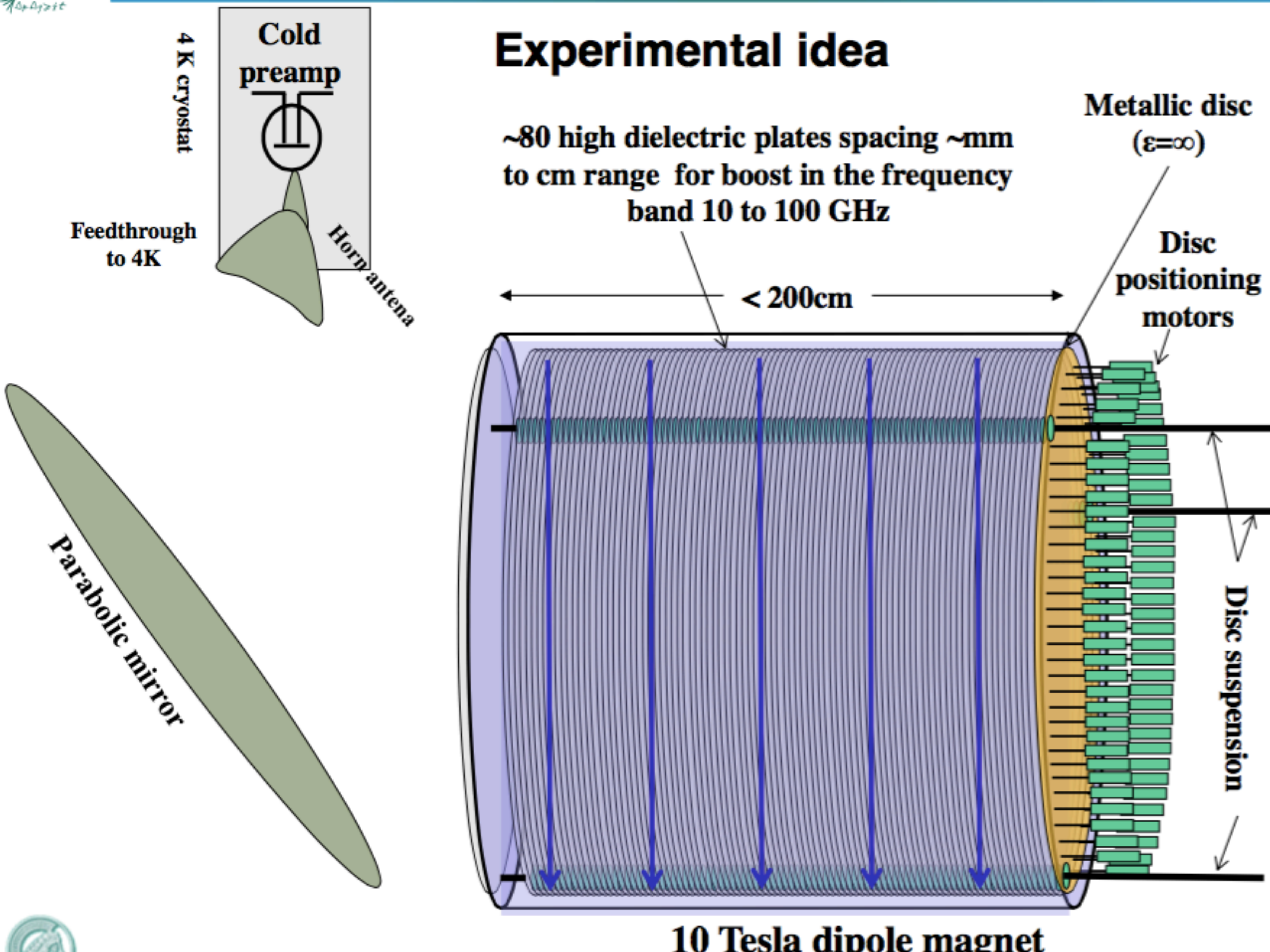
→ **Lanthanide Aluminate ($LaAlO_3$)**



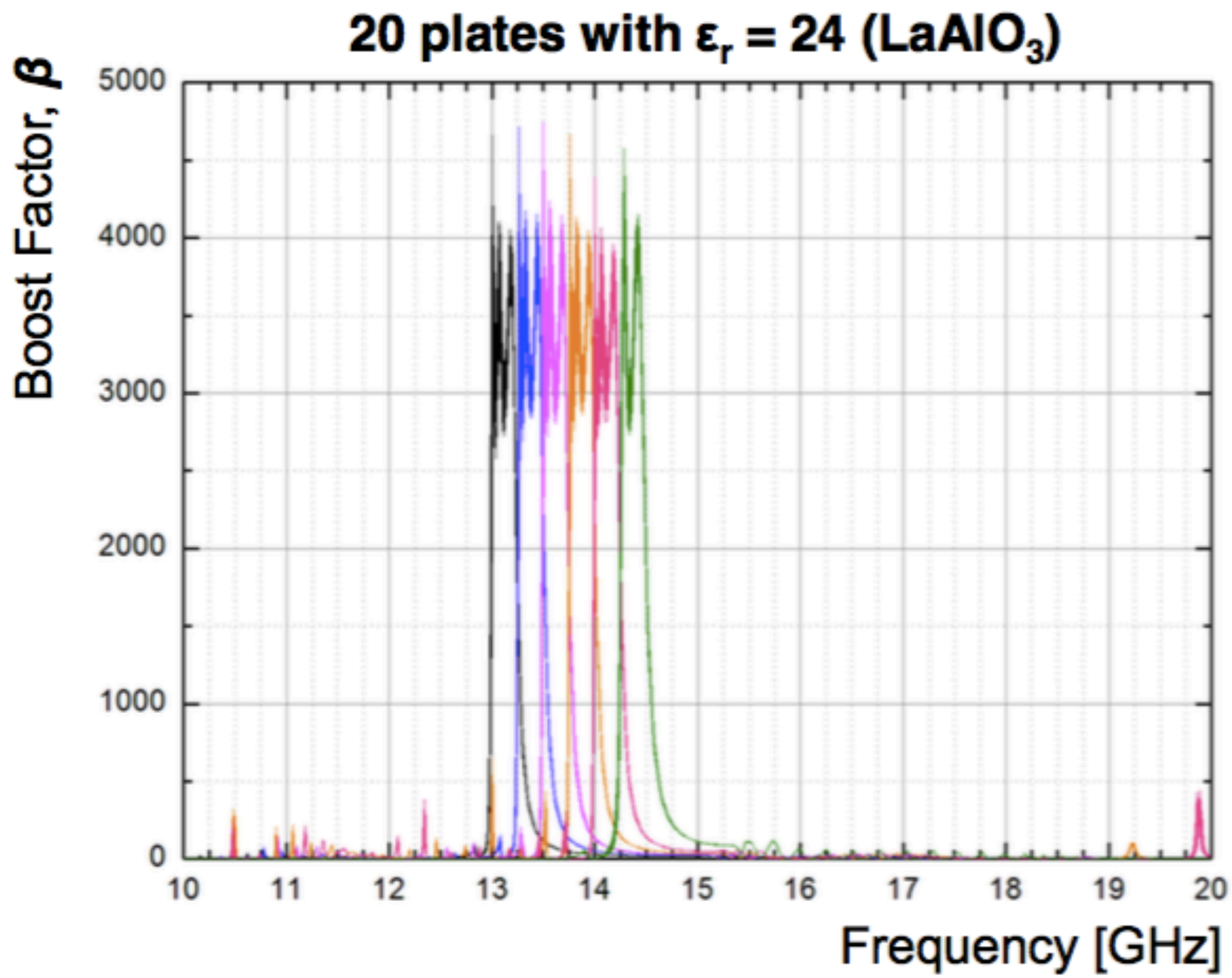


→ **Titanium dioxide – Rutil (TiO_2)** $\varepsilon \sim 100$; $\tan\delta = ?$
being investigated

Experimental idea



First simulations: the boost factor



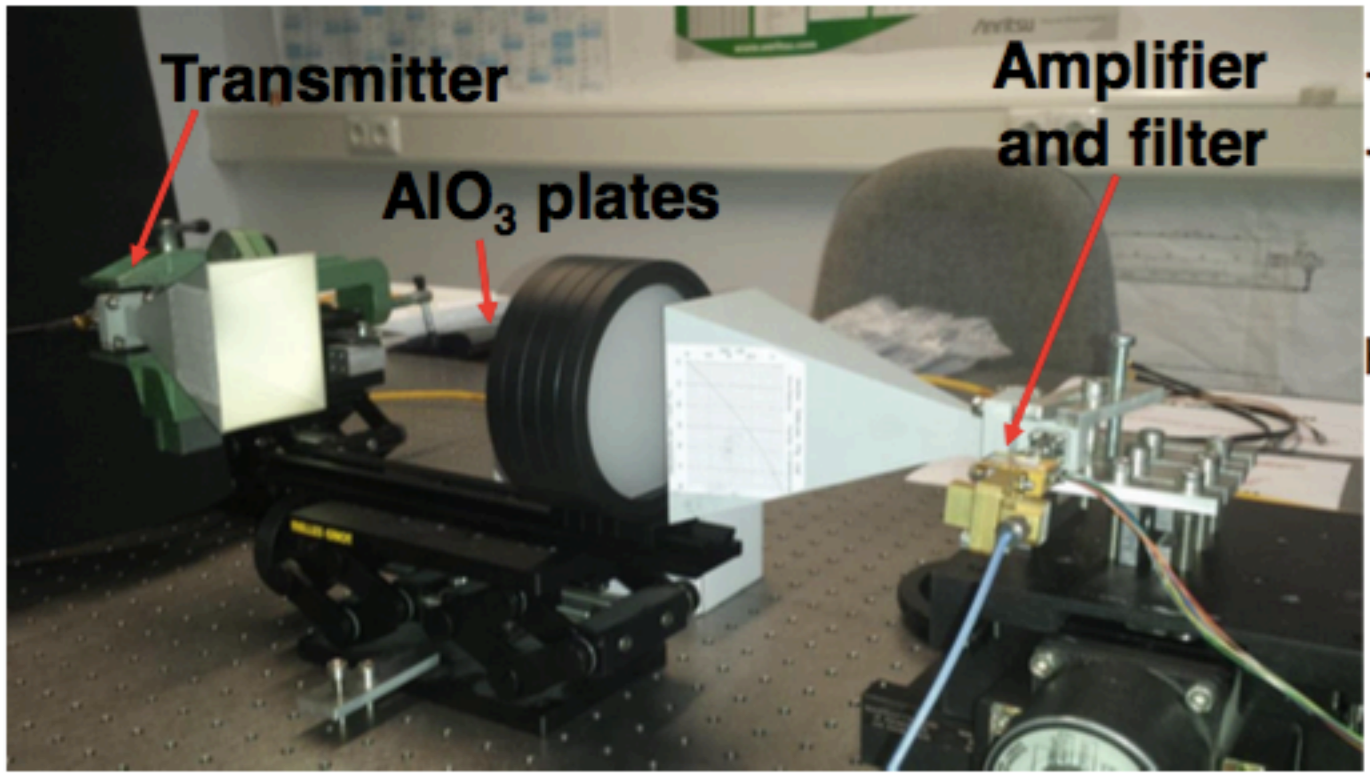
It is possible to adjust disc setting to reach sizeable *β* over broad bandwidth

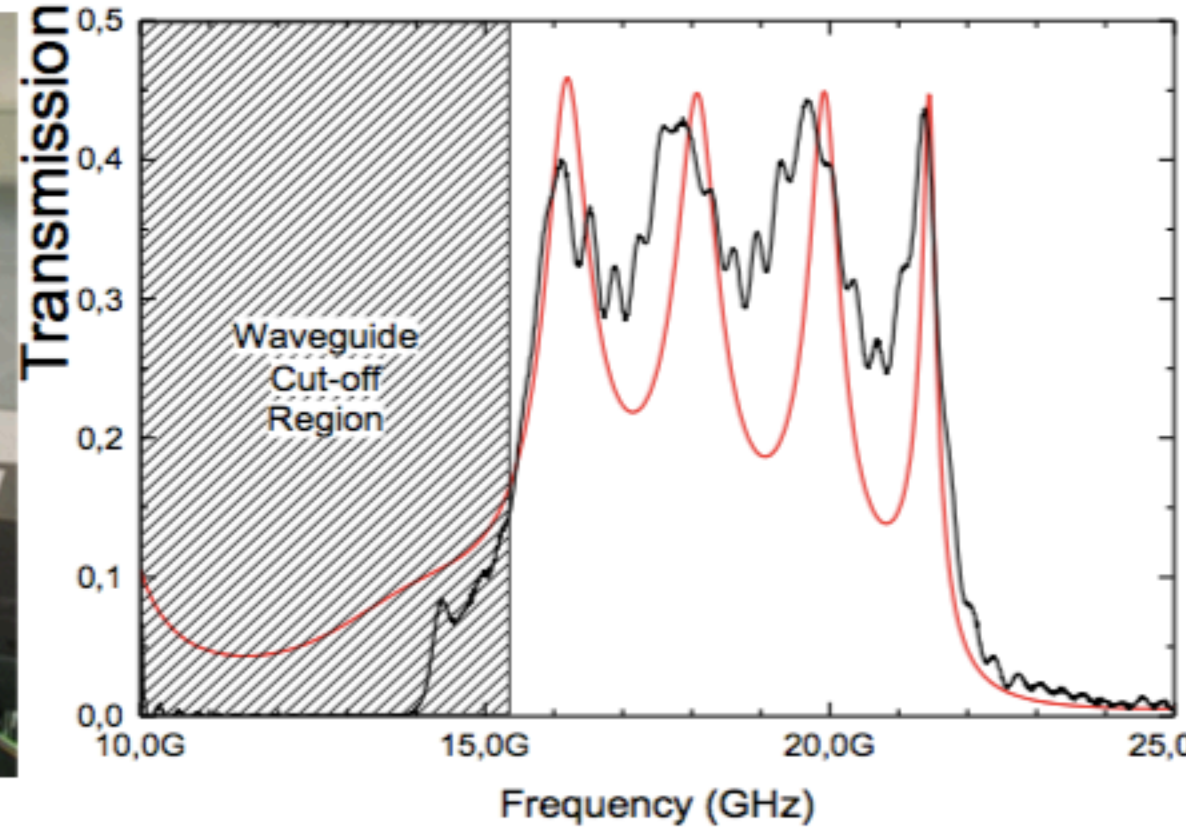
Bandwidth per setting: ~250MHz

Precision of placement of high ε plates needed: ~few μm

First measurements: transmission

Boost factor is coupled to transmission behavior

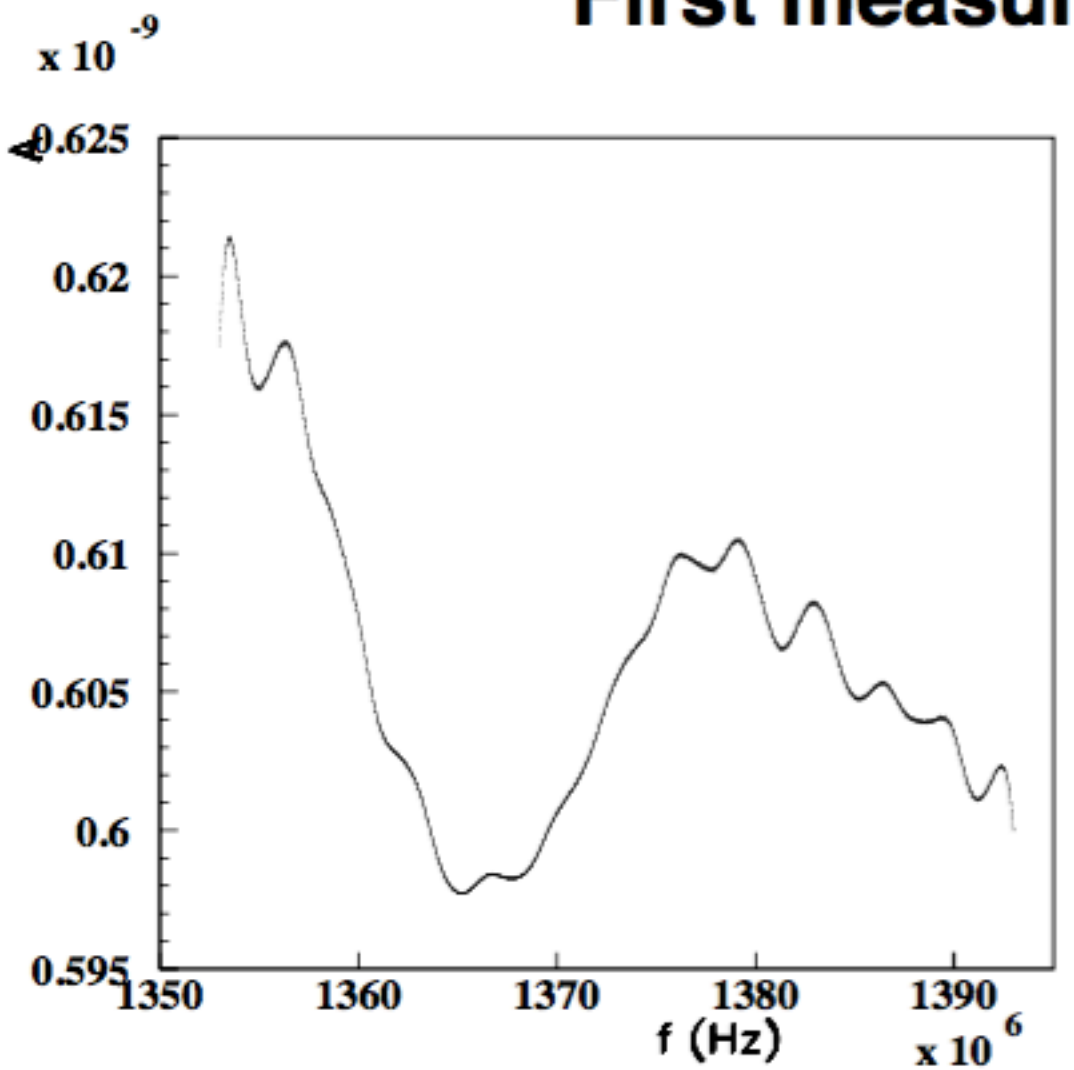


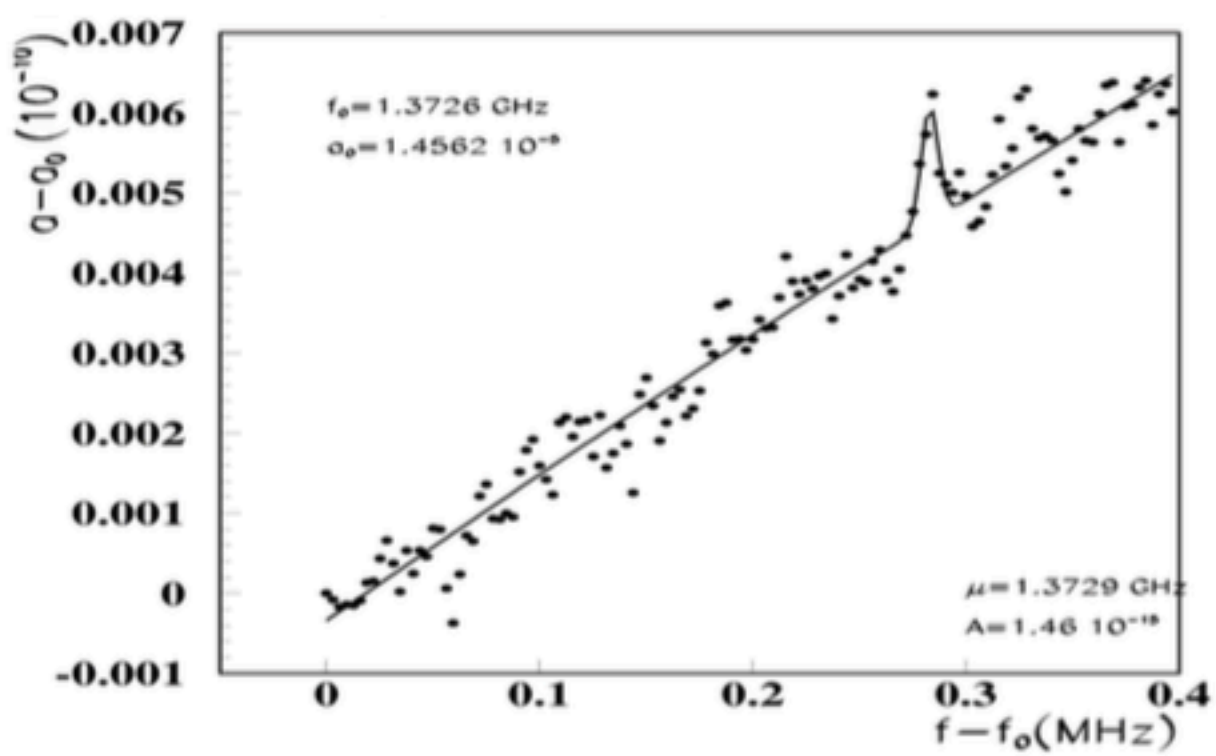


- 5 AlO_3 discs with diameter 100mm positioned within uncertaintiy ~ 1mm
  - Disc positions determine **transmission, reflection** and **boost factor** (**β**) curves
  - Prediction (red) fits measurement (black) well.

→ Verification of boost by transmission measurement!

First measurements: sensitivity



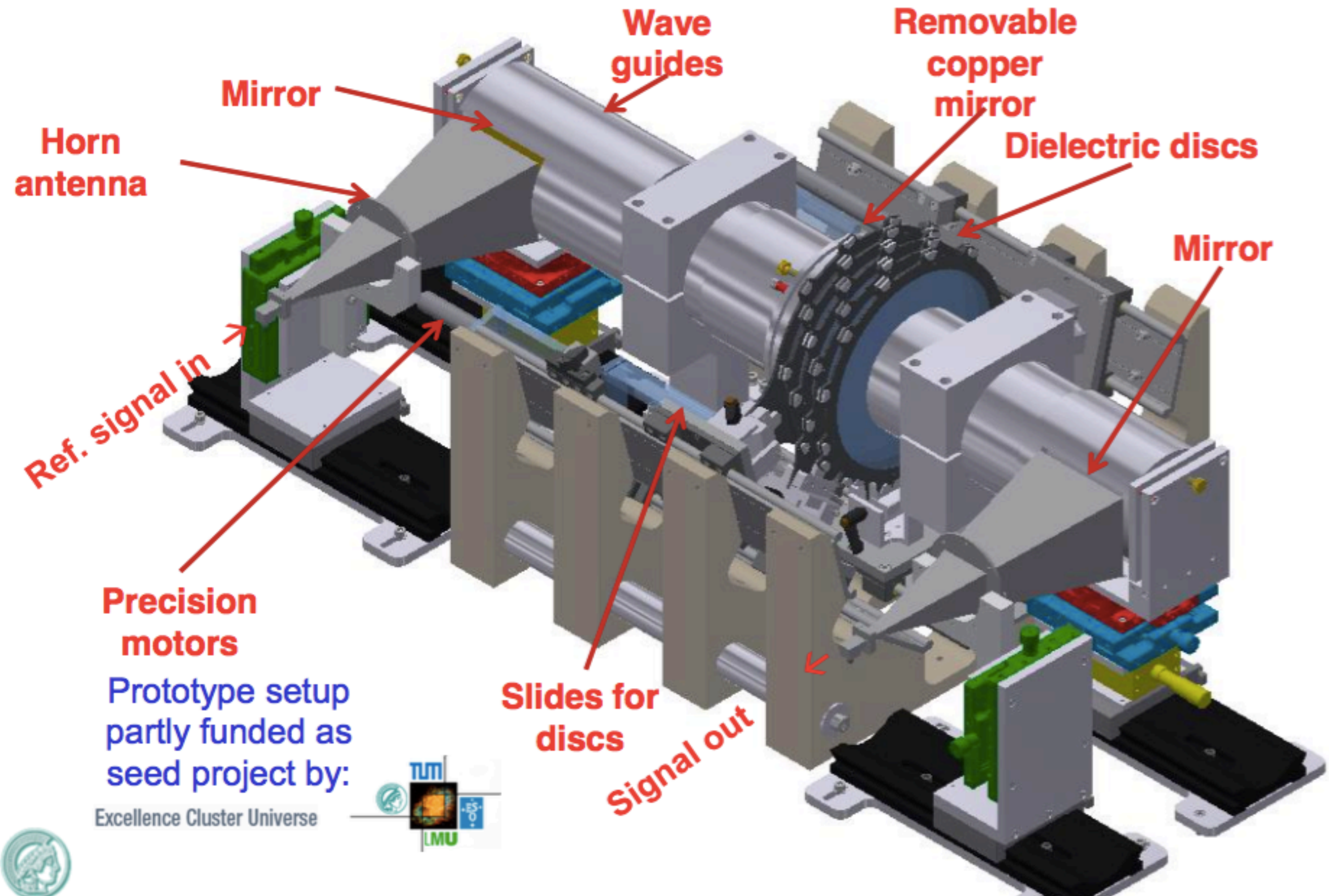


- Inject fake axion signal with **3·10^{-21}** W power
- Mesurement for one week (integrate signal): Receiver at Room Temp.

→ Independent „blind“ analysis
→ found > 6σ signal succesfully

→ At LHe: noise level factor 100 better
→ Sensitivity at the level of 10^{-23} W expected

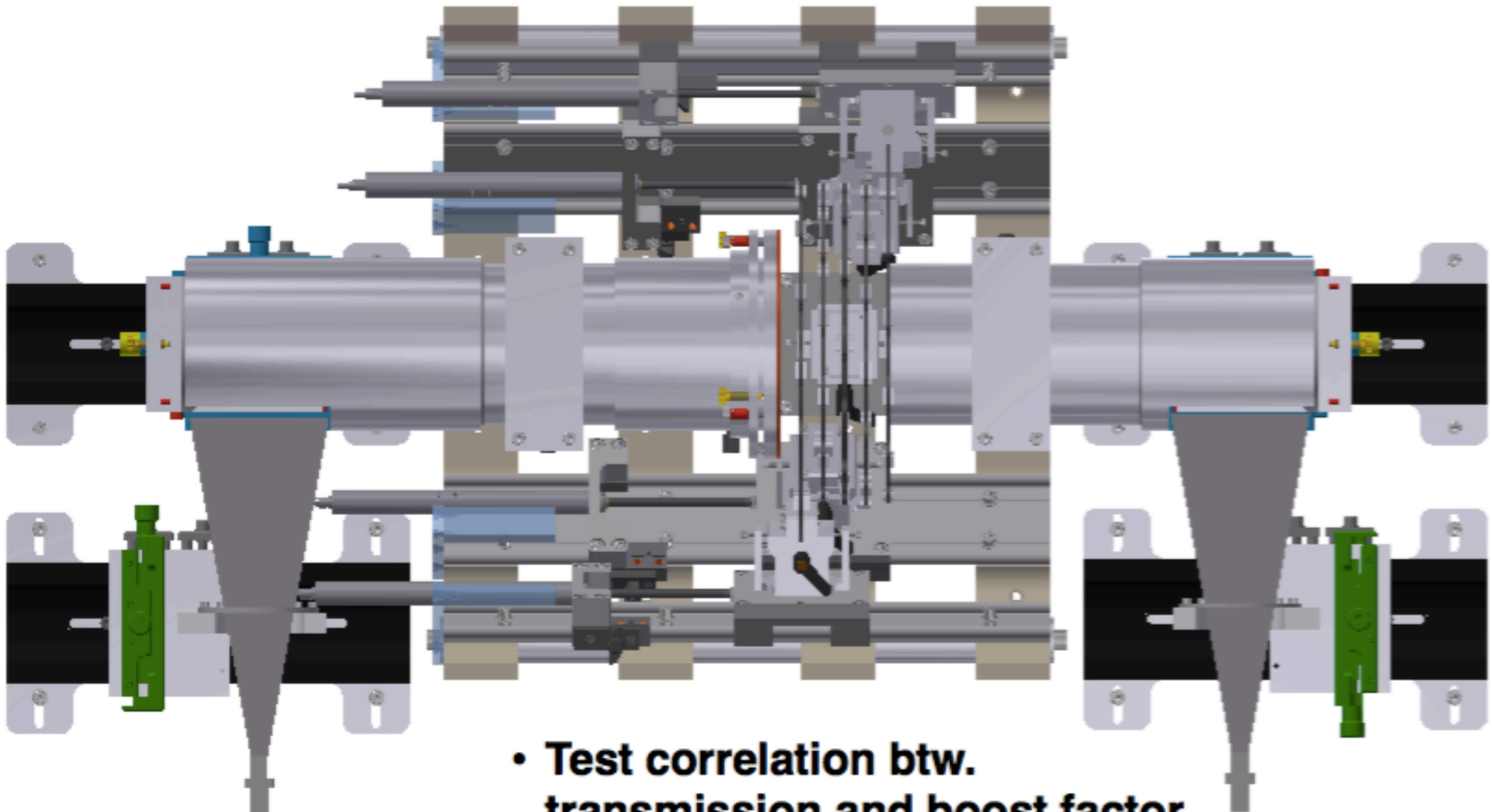
First prototype setup at MPI



Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First prototype setup at MPI



- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
- R&D on tiling

Prototype setup partly funded as seed project by:
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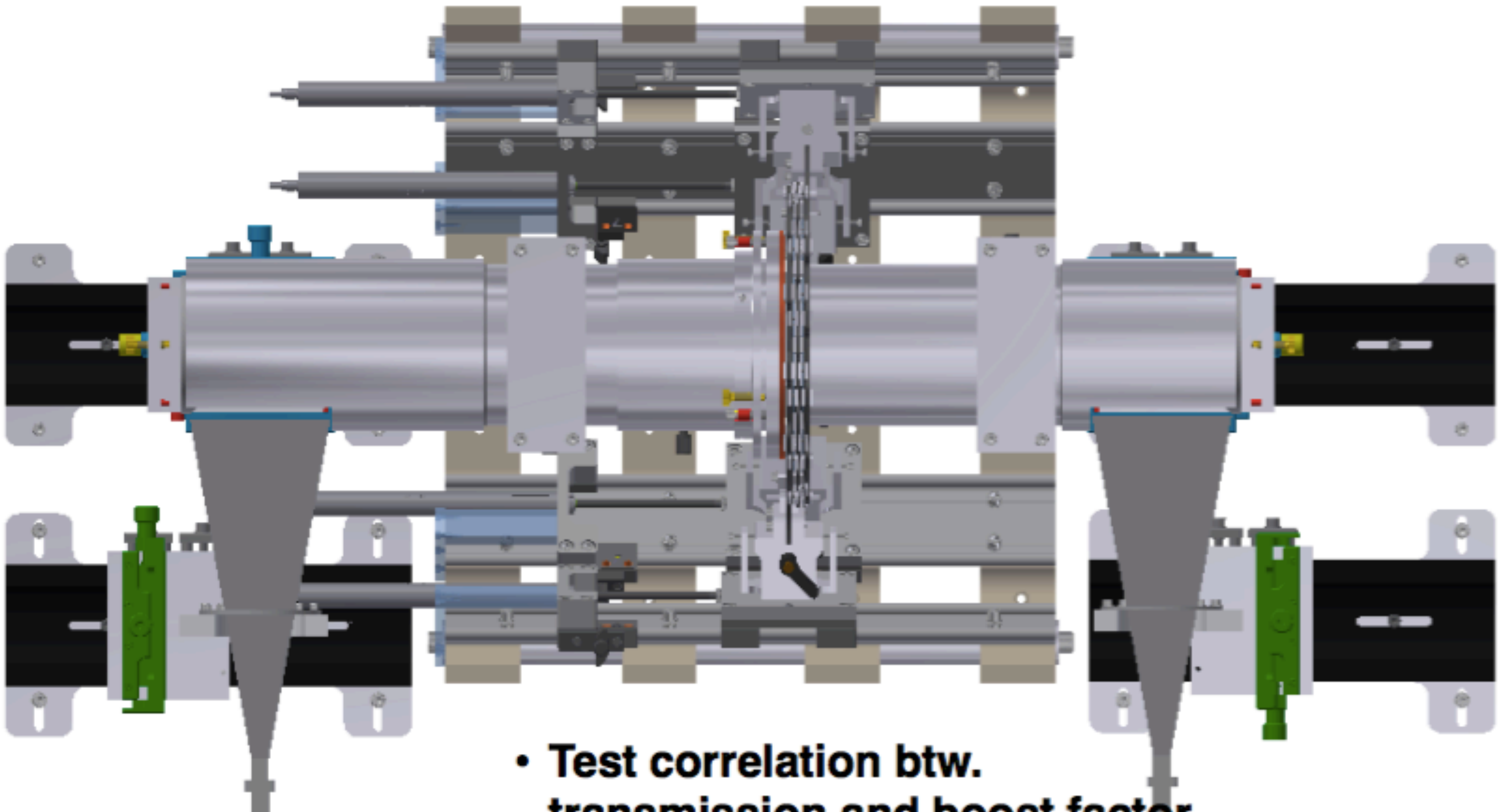
First prototype setup at MPI



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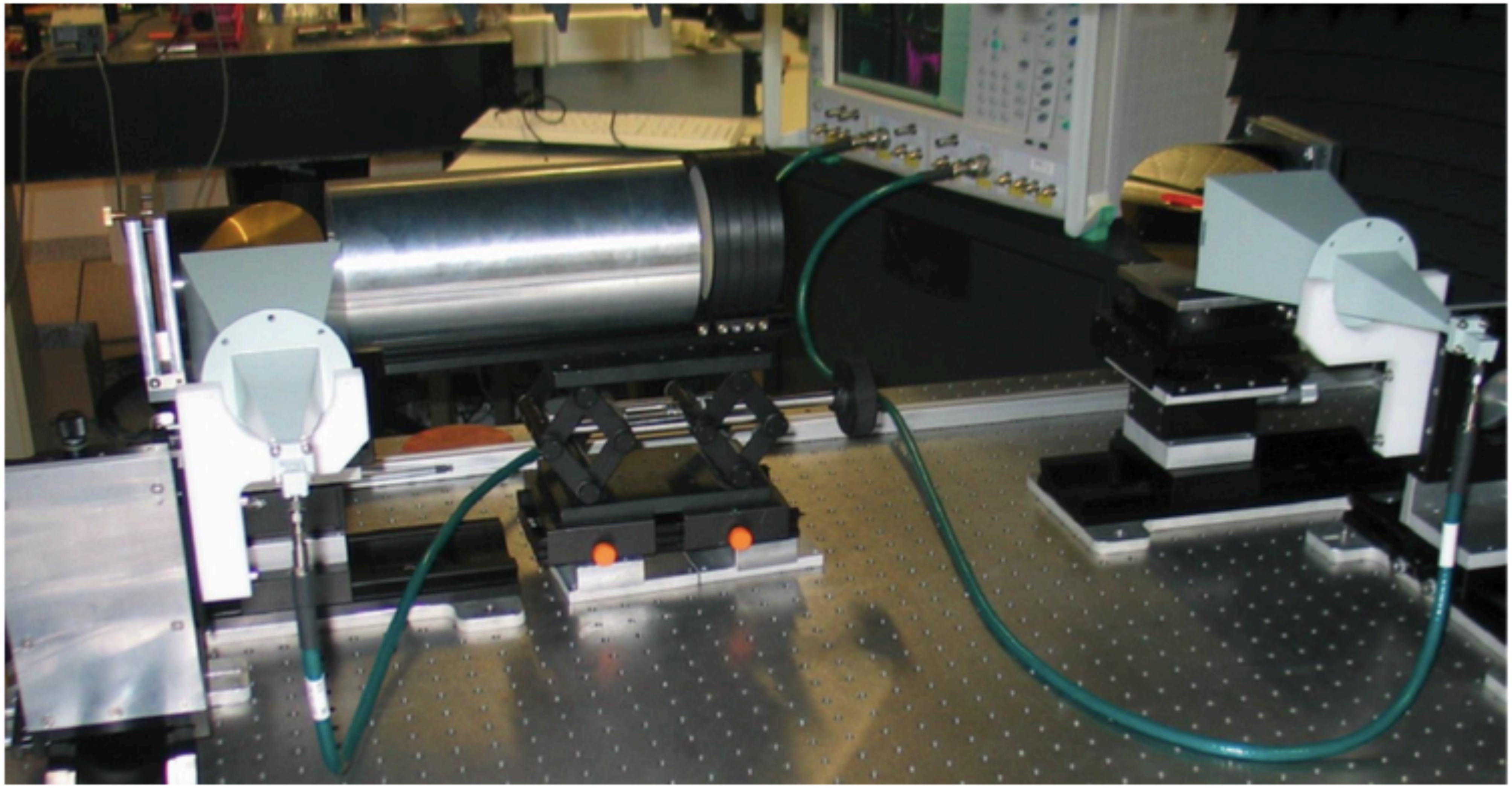

- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
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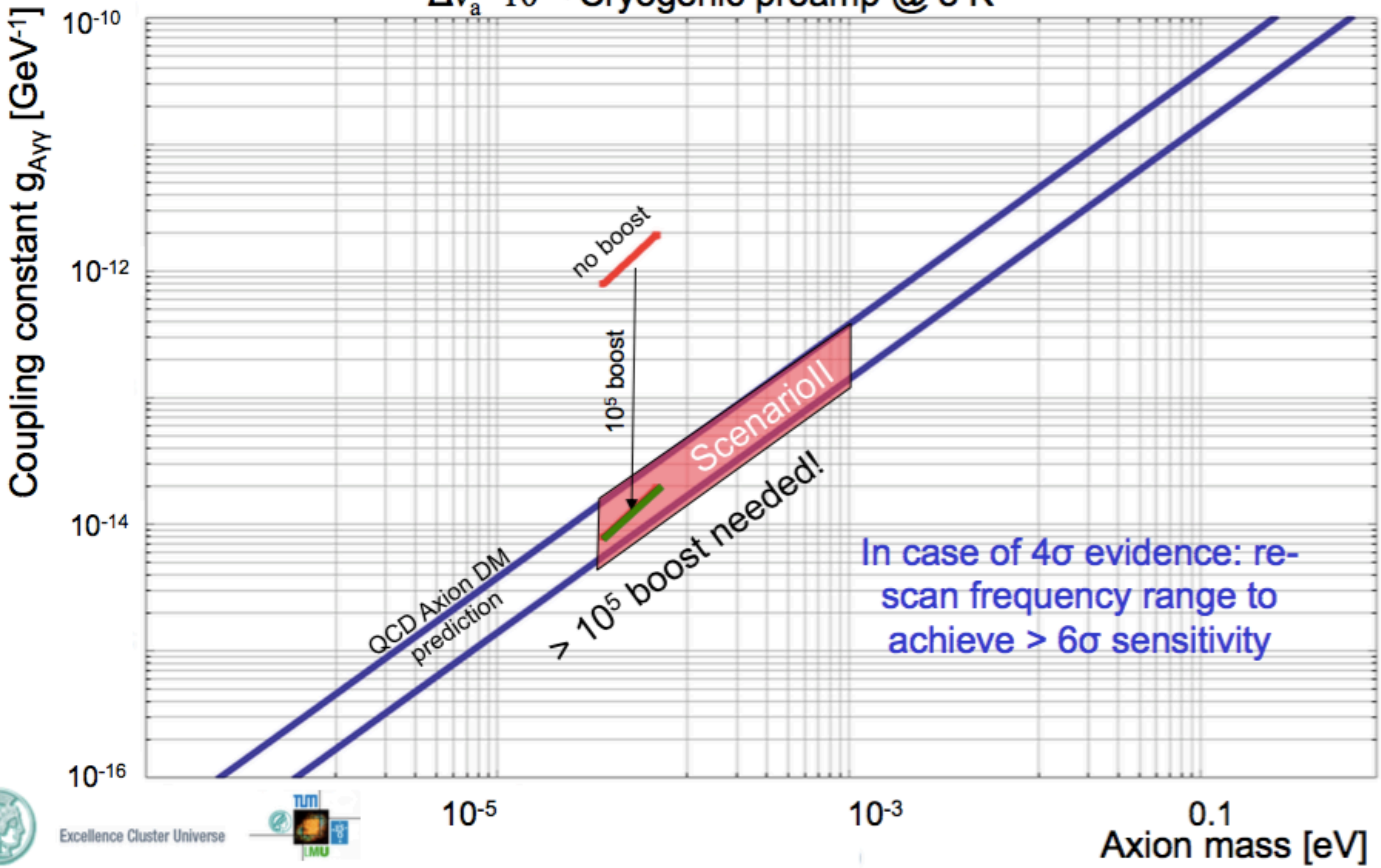
Prototype setup partly funded as seed project by:
Excellence Cluster Universe

First measurements: sensitivity

Expected 4σ detection sensitivity with and without boost

for 80 discs, $1m^2$ surface, 10T B-field, τ=200h, 50MHz boost andwidth,

$\Delta\nu_a = 10^{-6}$; Cryogenic preamp @ 8 K



Further plans

2016:

- Finish first test measurements at room temperature at MPI
- Test noise of preamplifier at LHe temperature
- Find additional collaborators for specific parts of project
- Start design of 10T magnet
- Develope technique to cover frequencies above 30 GHz
- R&D on production of large diameter high-ε discs

2017-2020:

- Demonstrate low noise performance, operation with many discs, scalability to 1m diameter, work in ~10 T environment
- Build prototype with preamp in LHe in cryostat and resonator in magnetic field

2020 :

- Start building full scale experiment