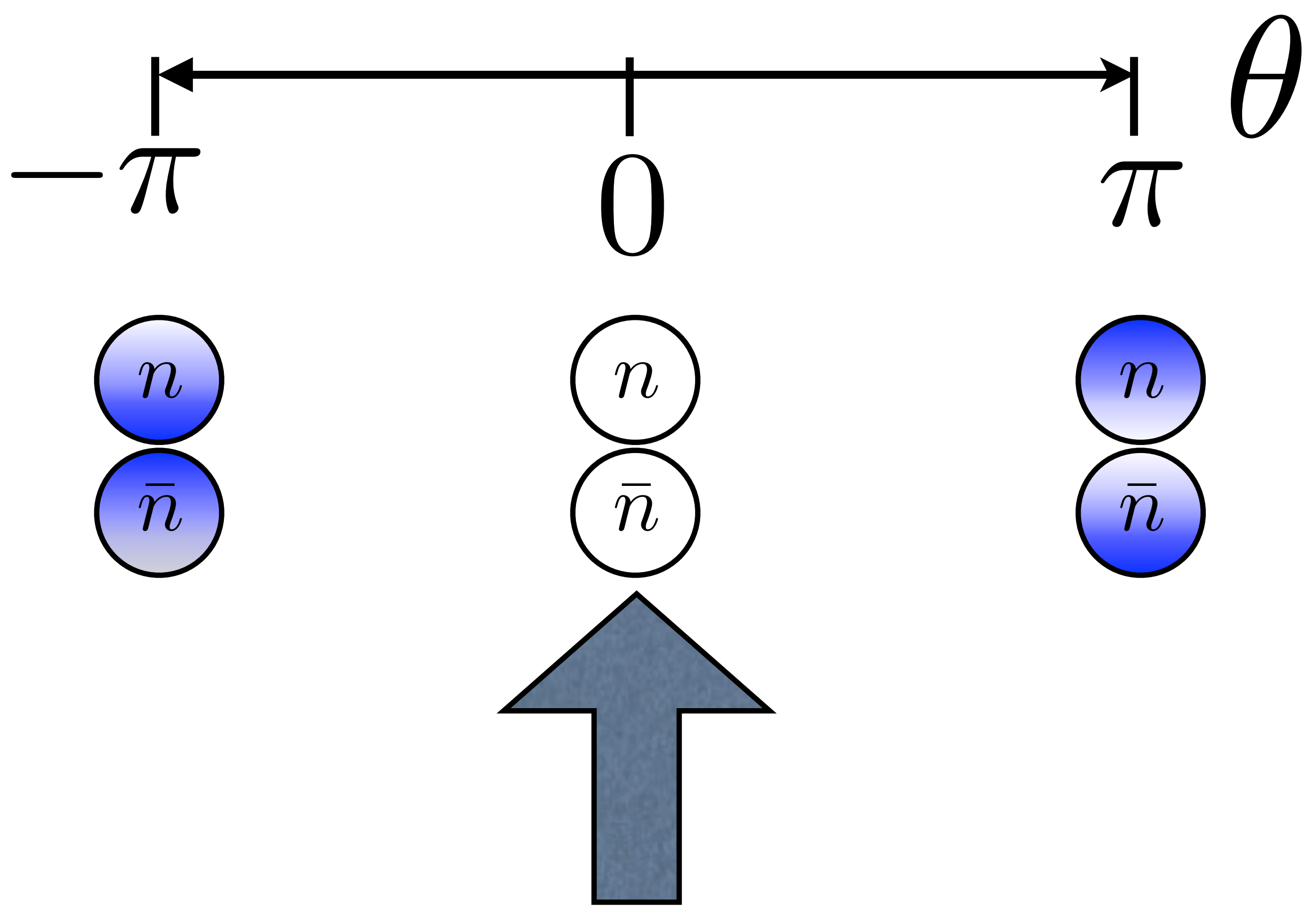
Axions, dark matter and all that MAD(MAX) stuff

Javier Redondo
(Zaragoza U & MPP)

Warsaw Workshop on Non-standard (?)
dark matter: multicomponent scenarios and beyond
4th June 2016

The theta angle of the strong interactions

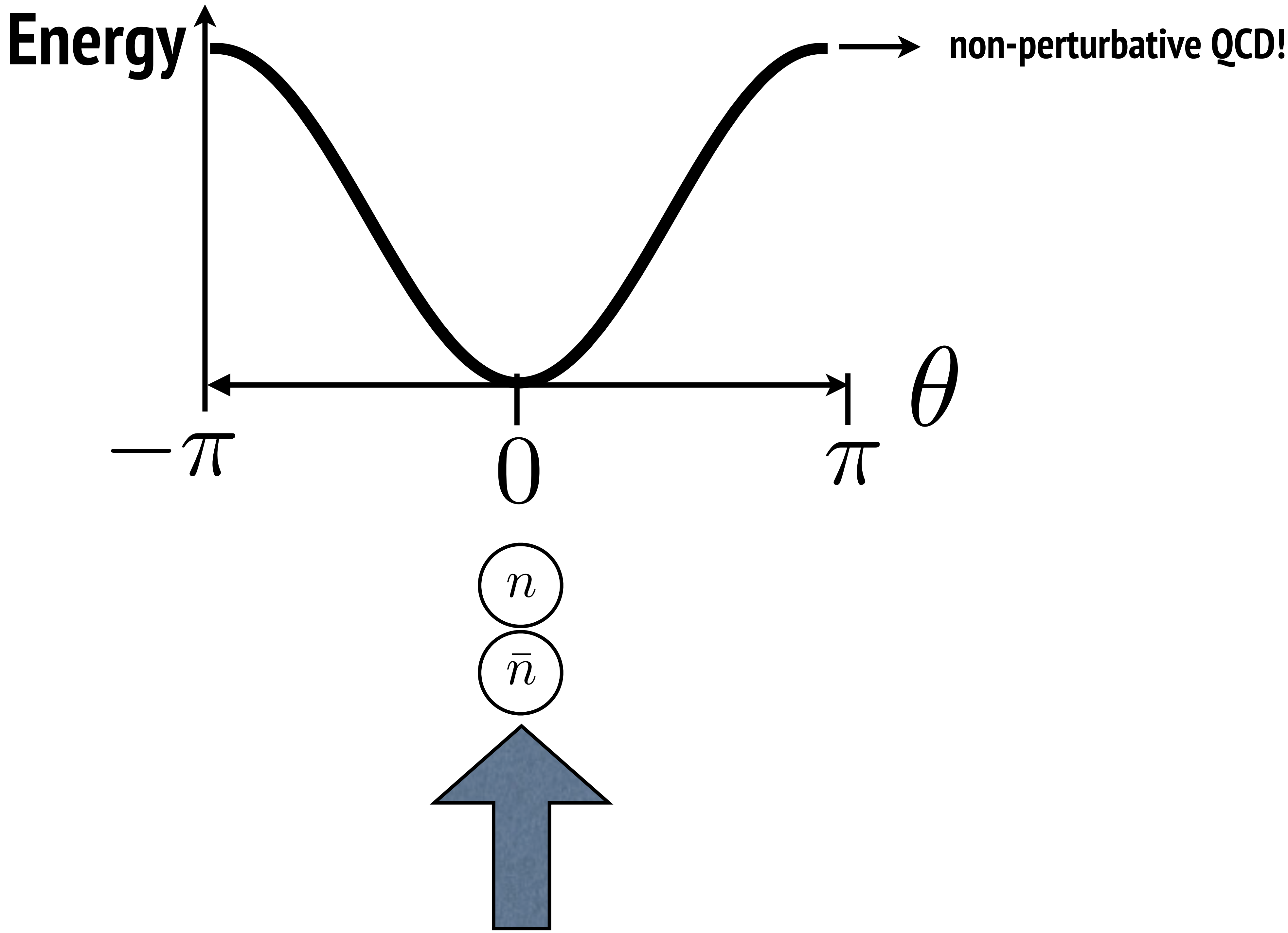
- The value of θ controls matter-antimatter differences in QCD



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

Axions

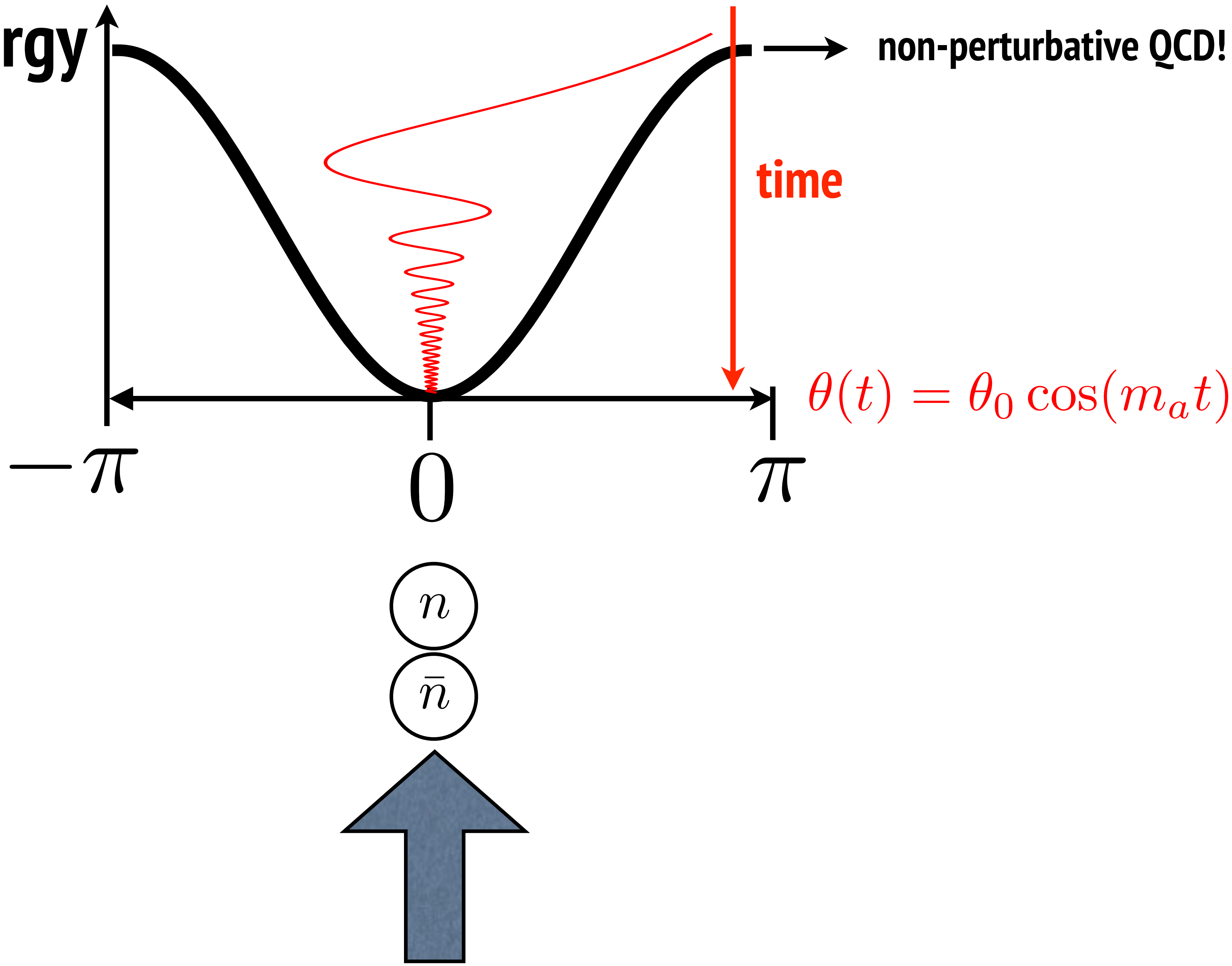
- is it a dynamical field? $\theta(t, \mathbf{x})$



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

Axions are necessarily dark matter

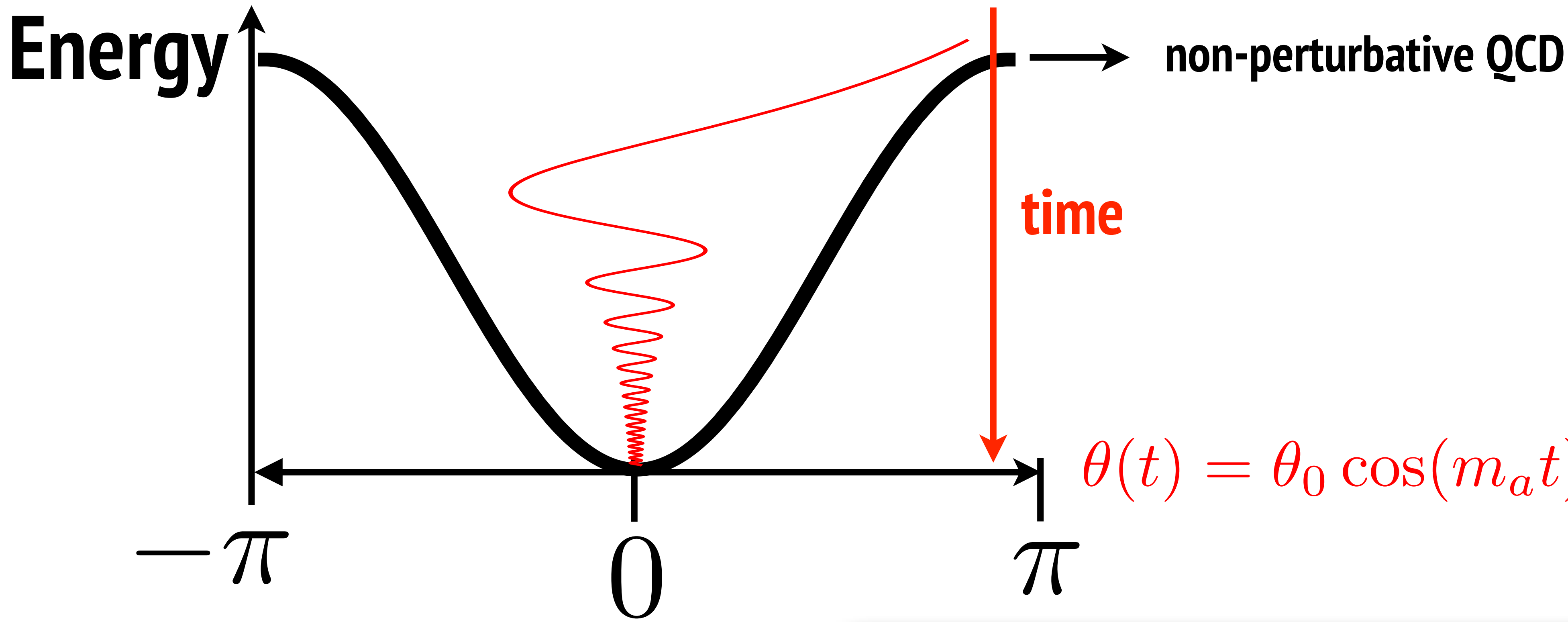
- is it a dynamical field? $\theta(t, \mathbf{x})$

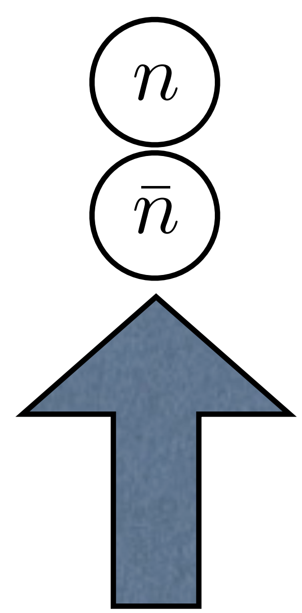


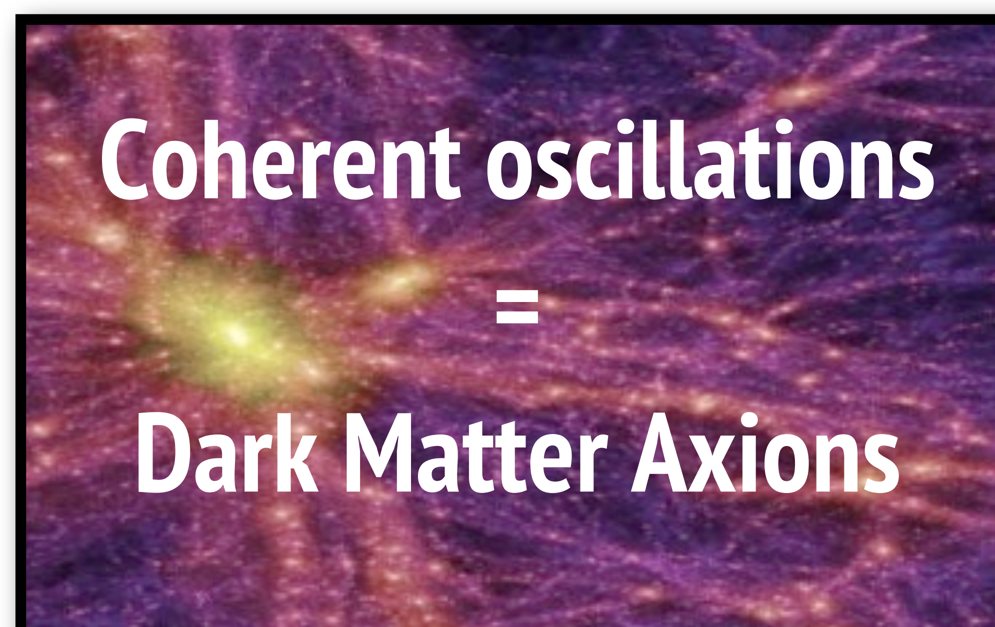
Measured today $|\theta| < 10^{-10}$ (strong CP problem)

Axions are necessarily dark matter

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



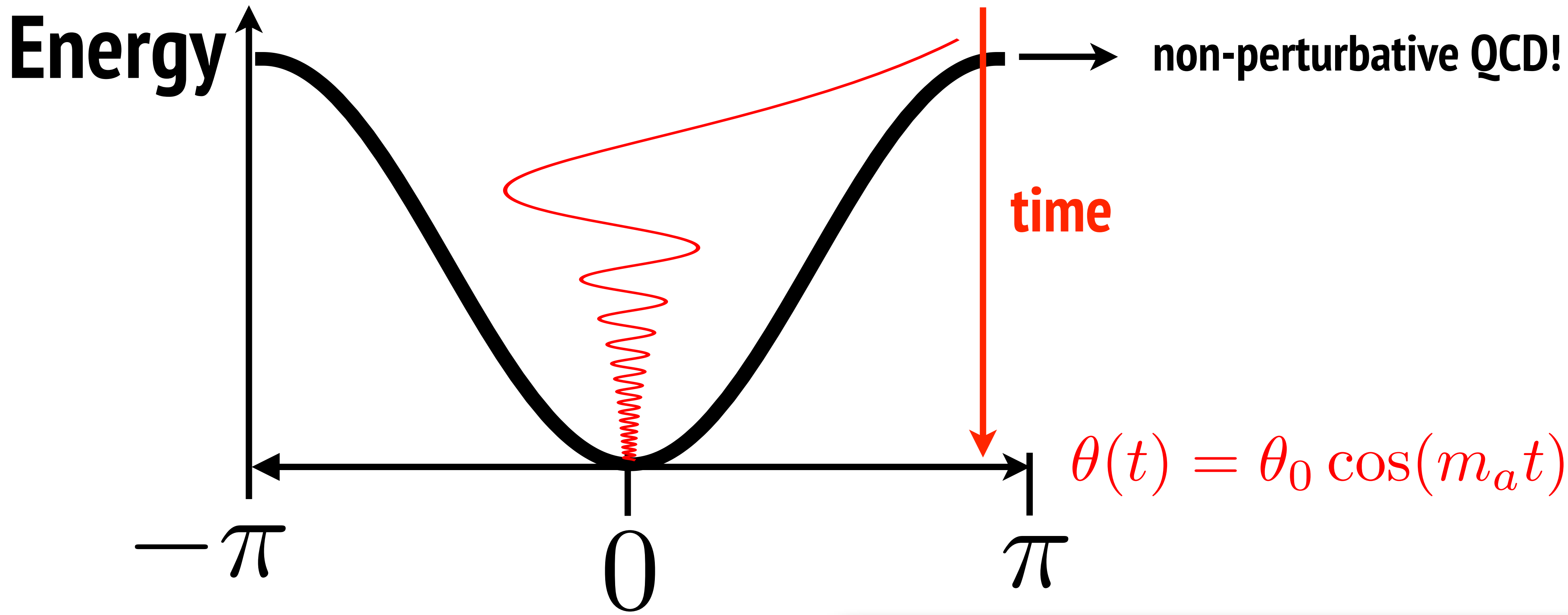




Measured today $|\theta| < 10^{-10}$ (strong CP problem)

Axions are necessarily dark matter

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

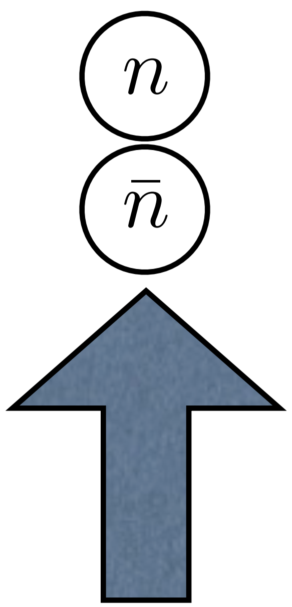


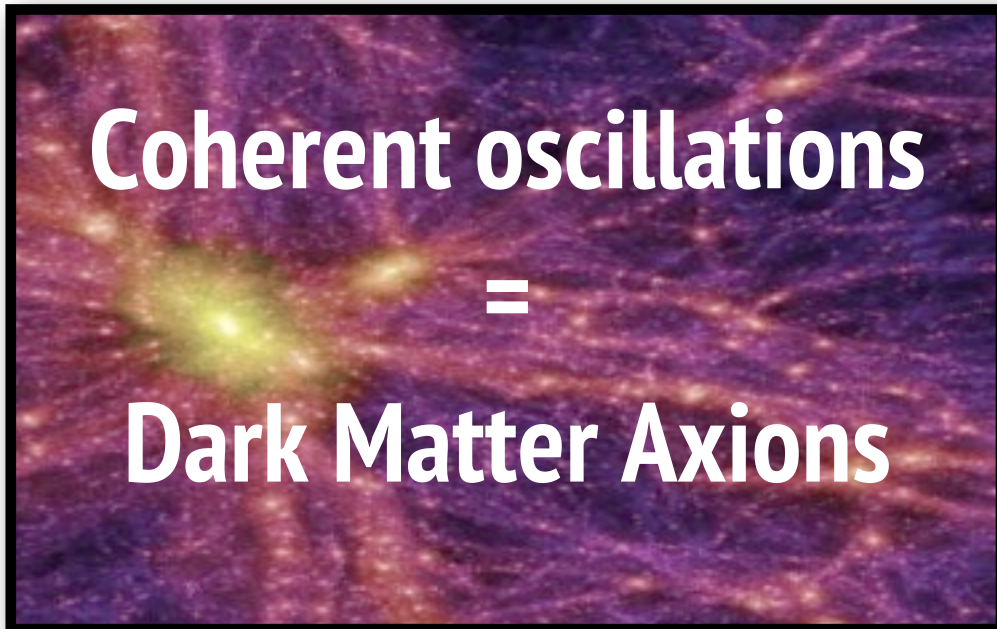
~ One parameter theory

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

axion mass

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



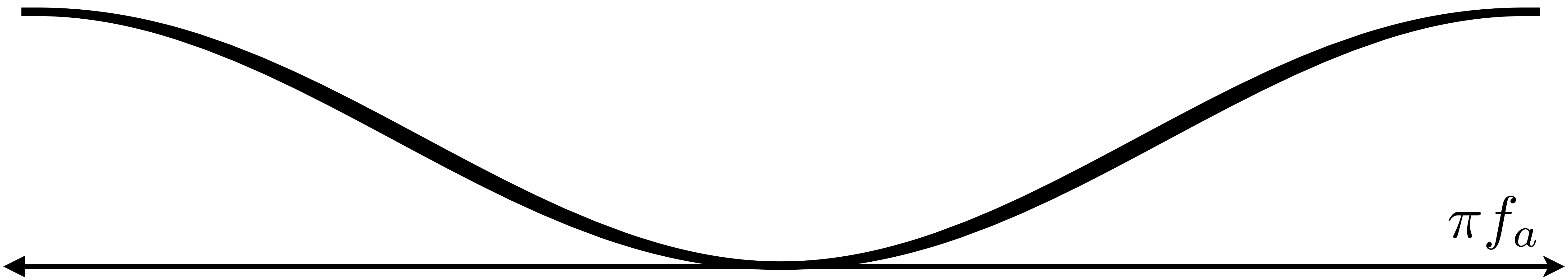


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

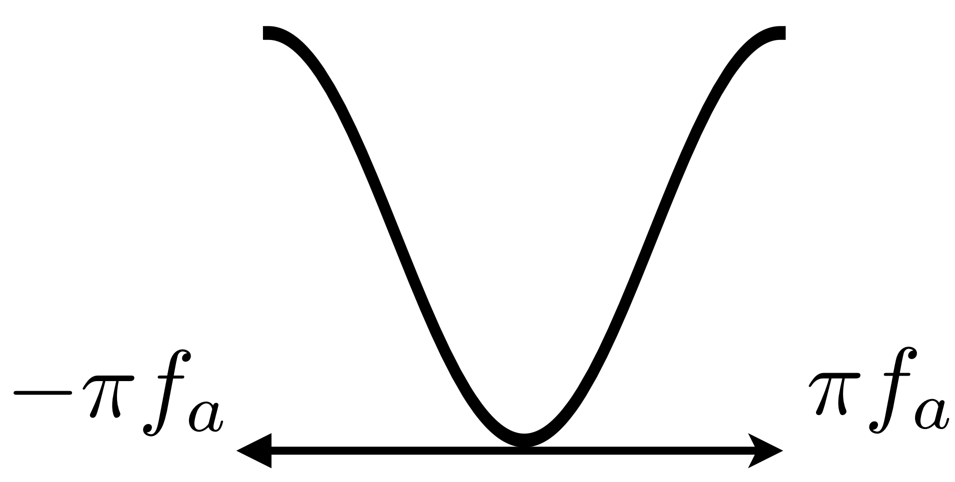
Axion dark matter

- The amount of axion DM produced depends on fa

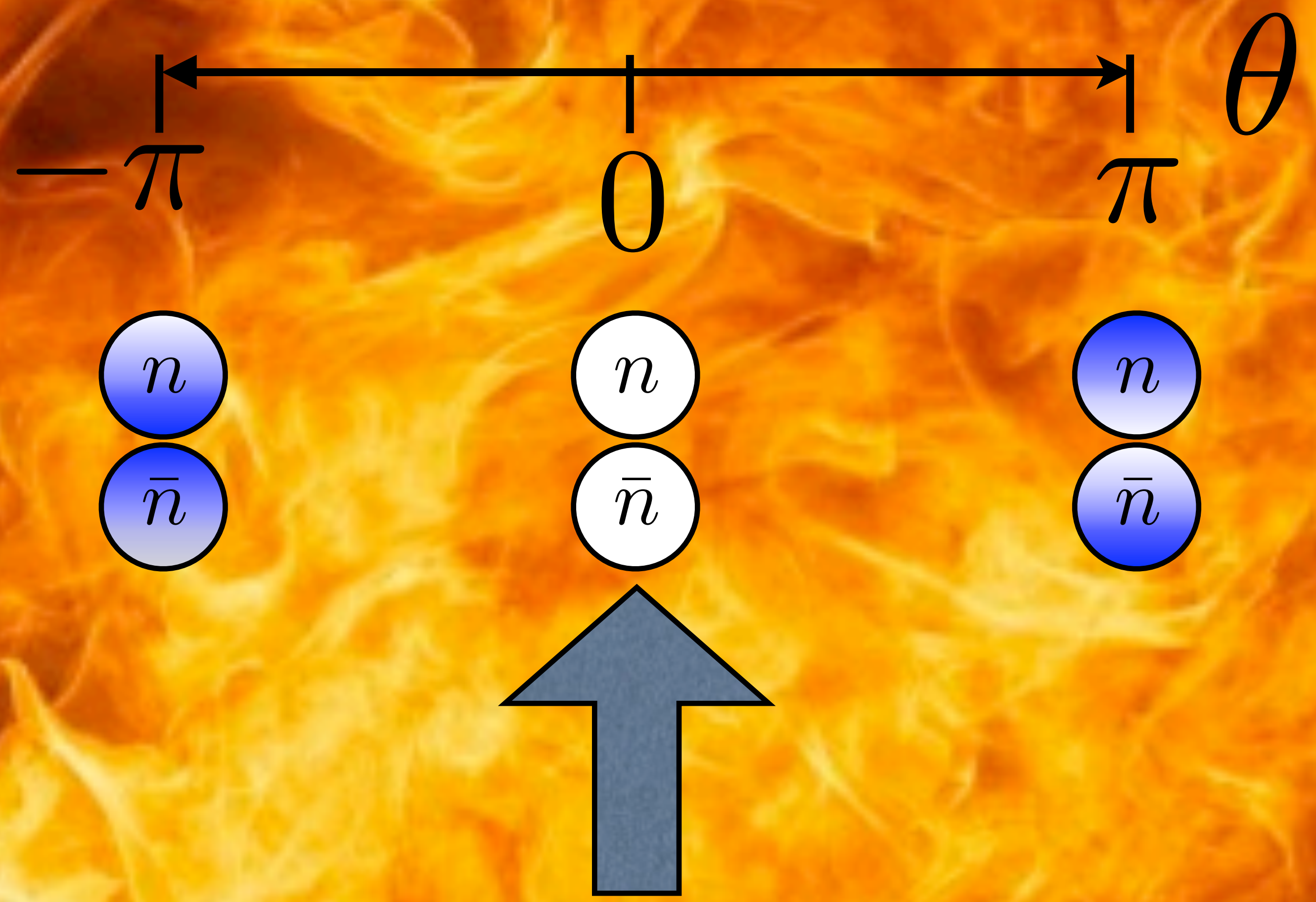
- large fa, small curvature, oscillations start later->more DM



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

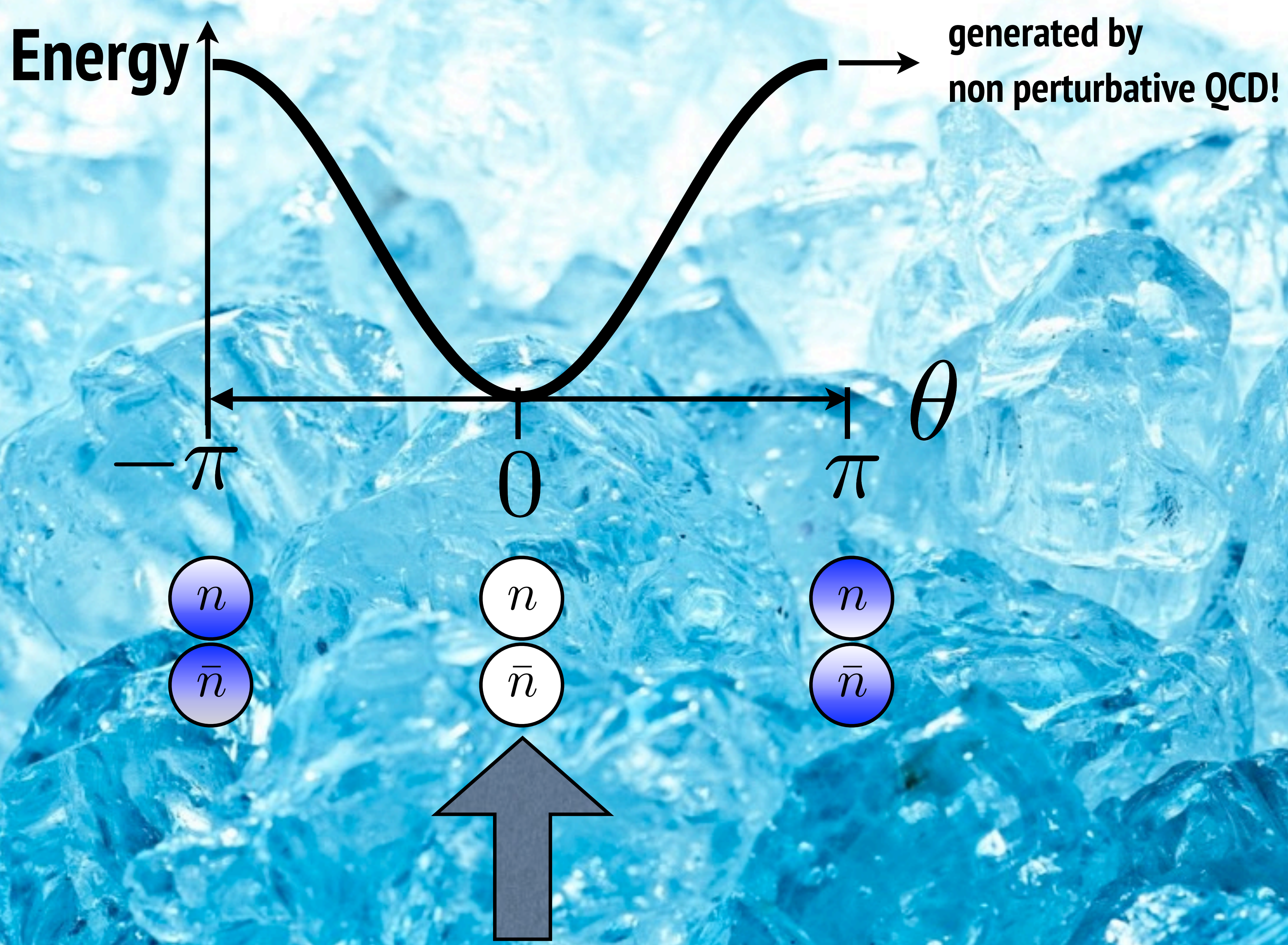


no preferred value at high Temperature ($T > \Lambda_{\mathrm{QCD}}$)



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

below confinement, theta = 0 minimises vacuum energy!



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

Simple model KSVZ

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

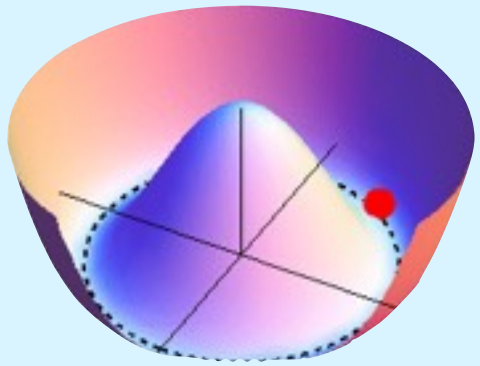
ENERGY

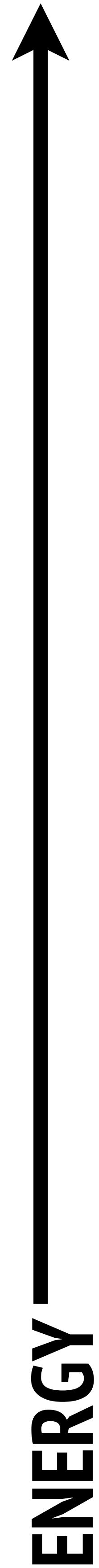
Simple model KSVZ

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

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

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



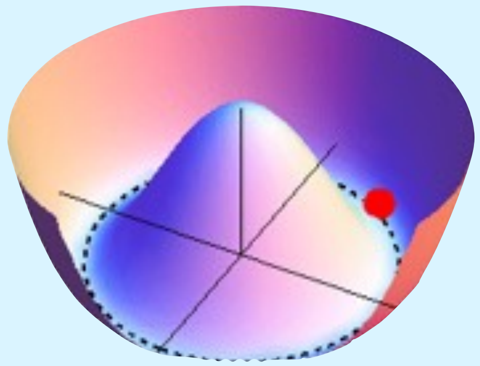


Simple model KSVZ

- 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)**

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

$\sim f_a$

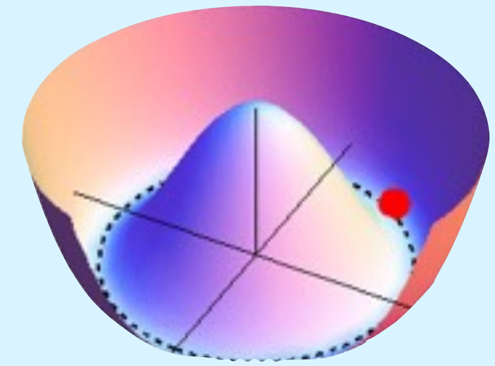
ENERGY

Simple model KSVZ

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

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

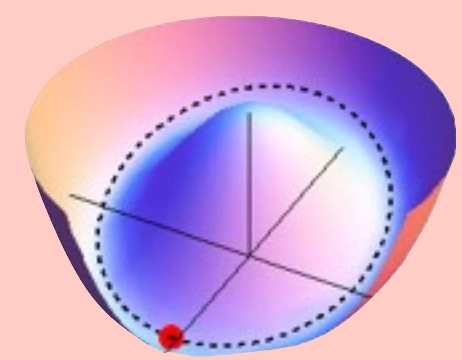
$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$



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

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

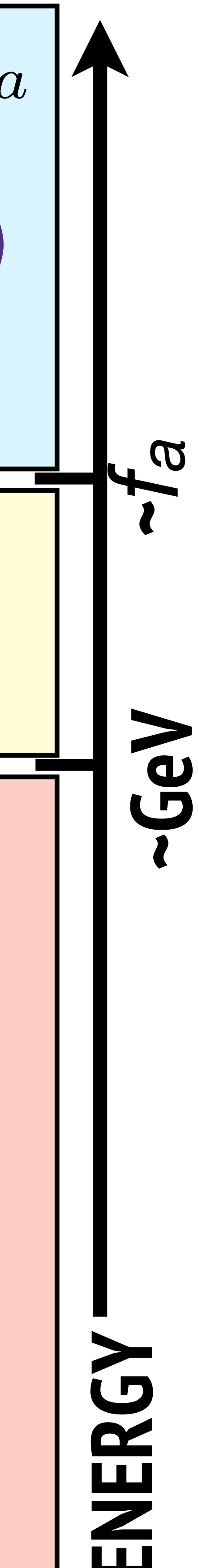
- At energies below $\Lambda_{\rm QCD}$**,** $a - \eta' - \pi^0 - \eta - \ldots$ **mixing**



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 ...**



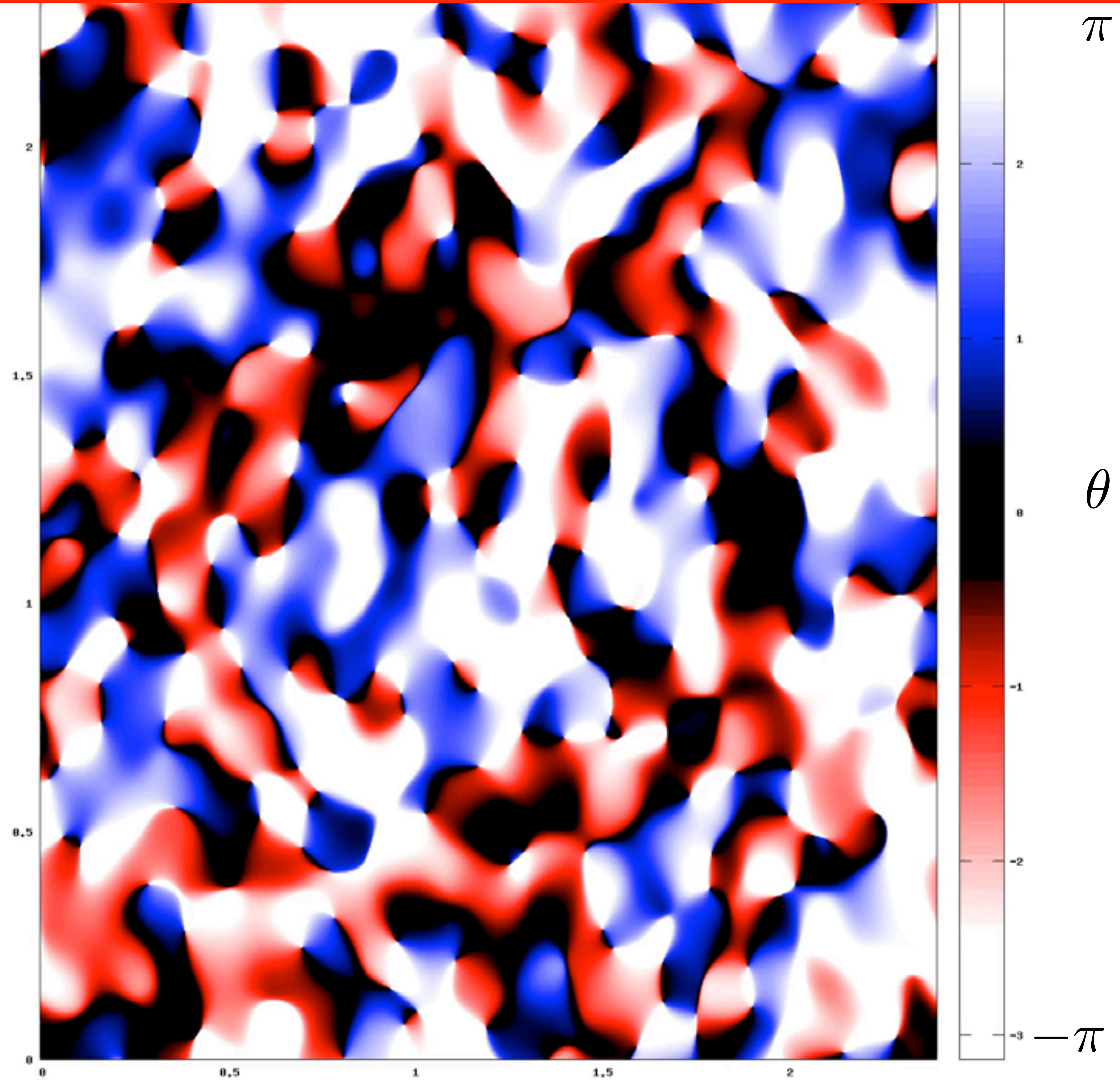
Theta evolution, Averaged SCENARIO I

π

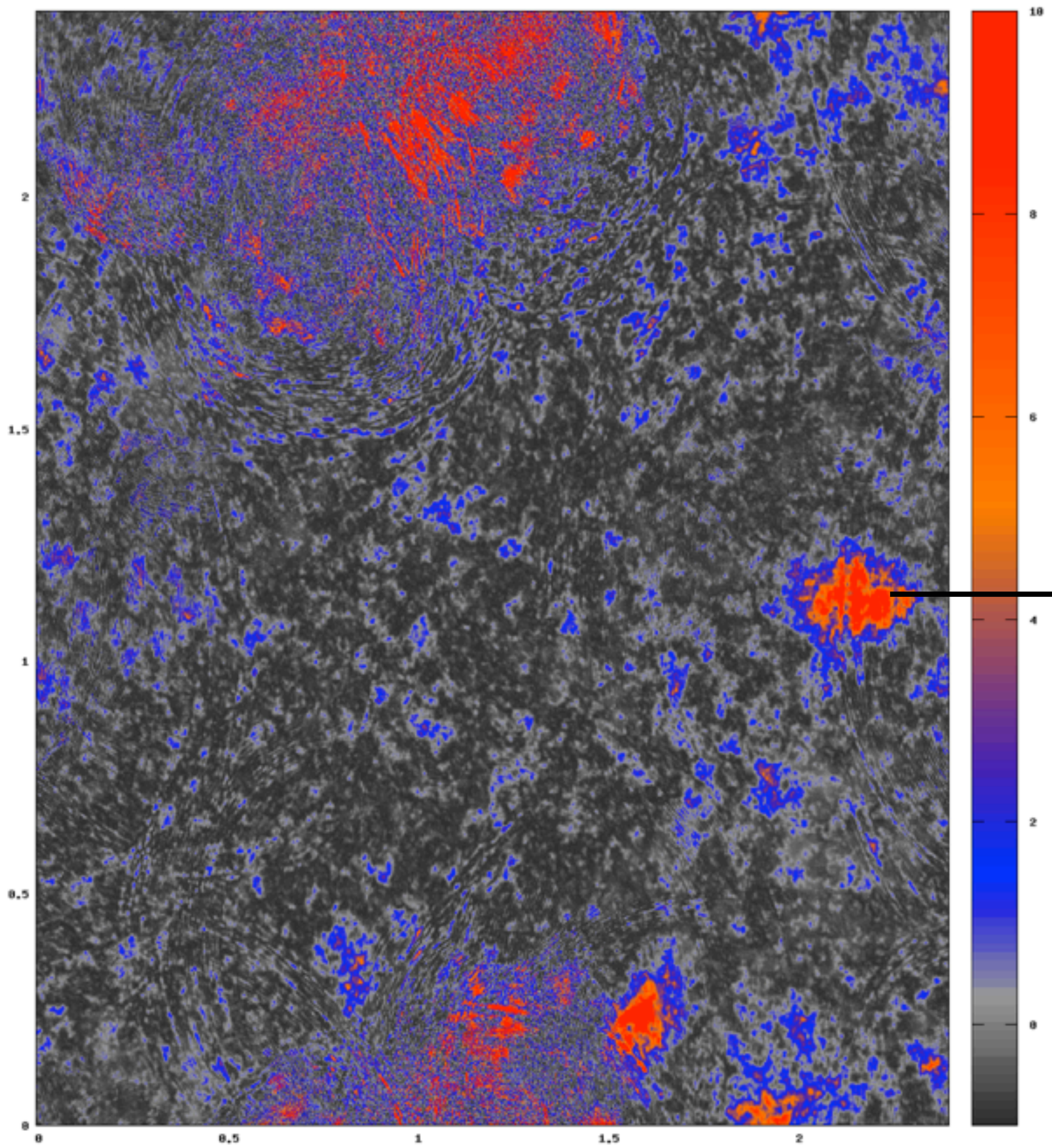
θ

$-\pi$

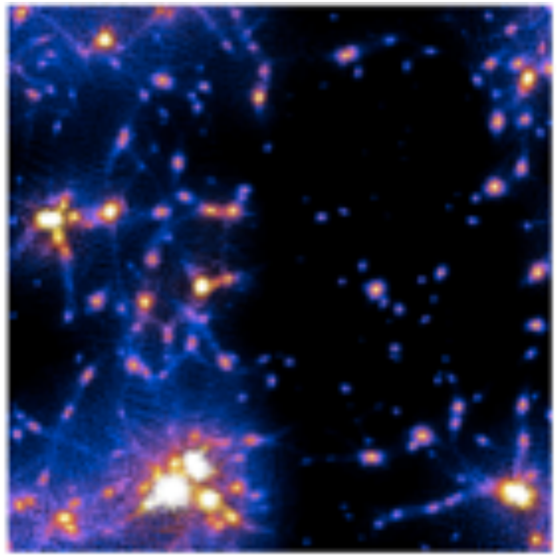
Theta evolution, Averaged SCENARIO I



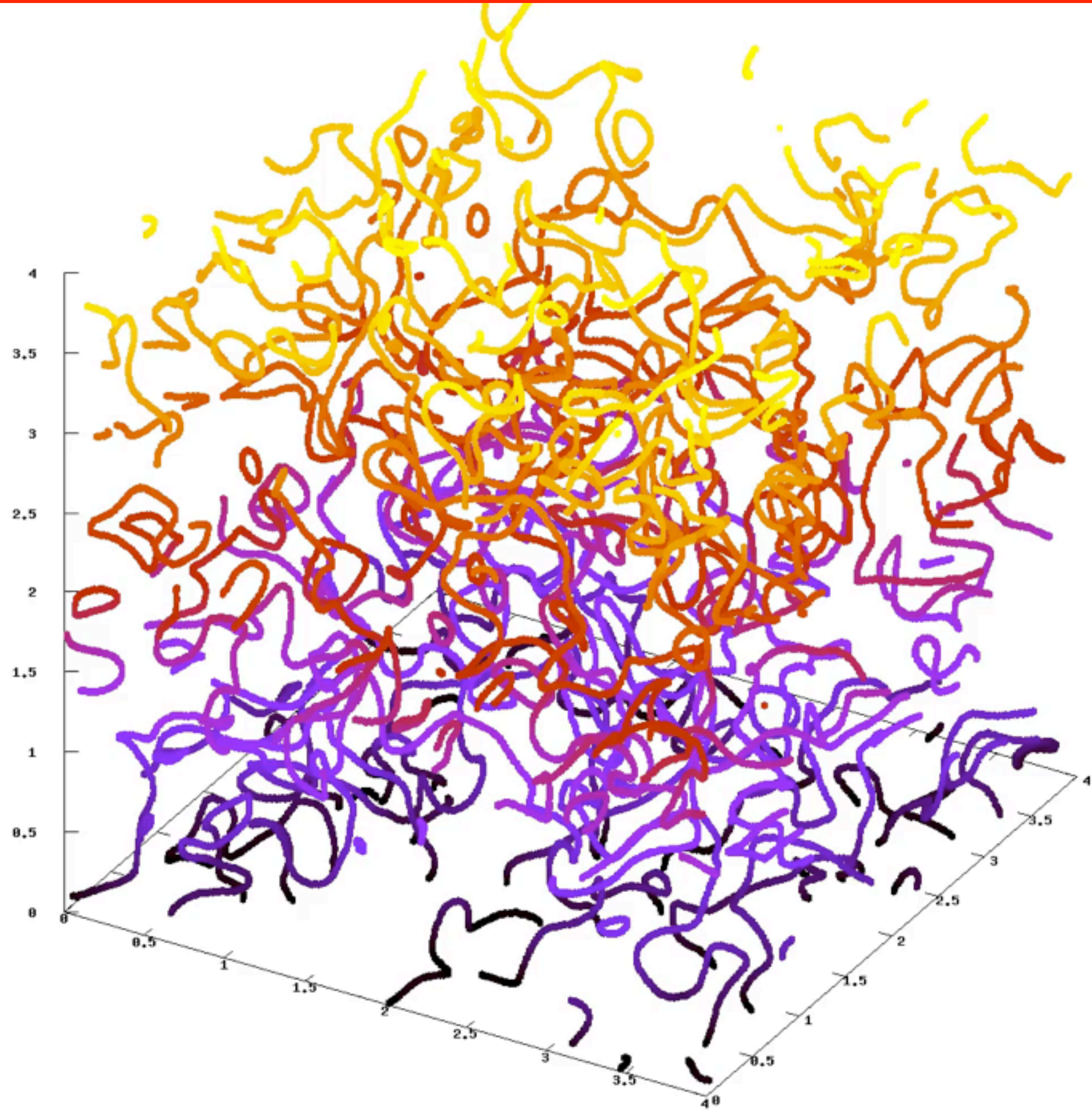
Dark matter density, inhomogeneous at comoving mpc scales



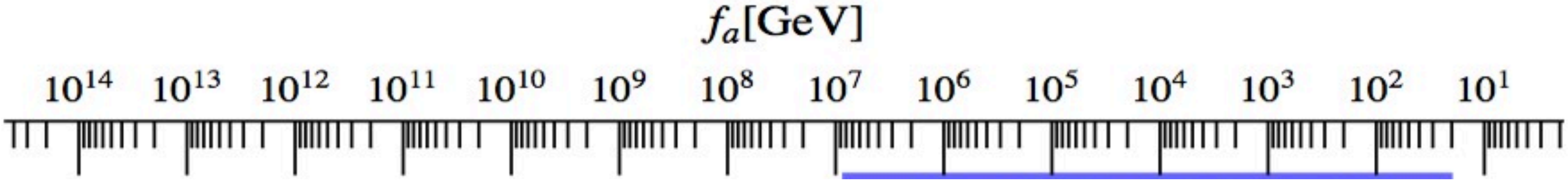
minicluster seed!



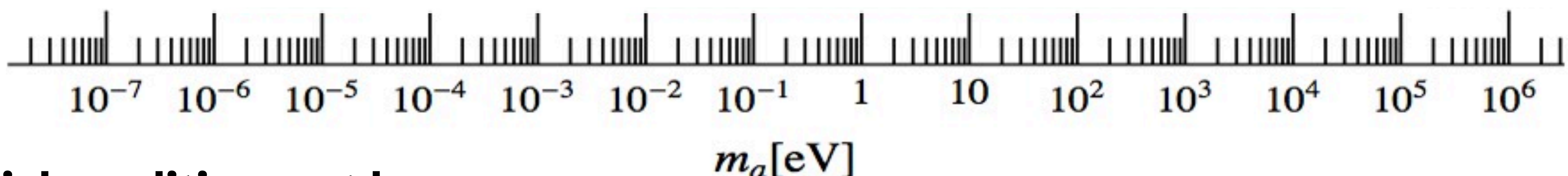
Strings



Axion dark matter (Scenario I)

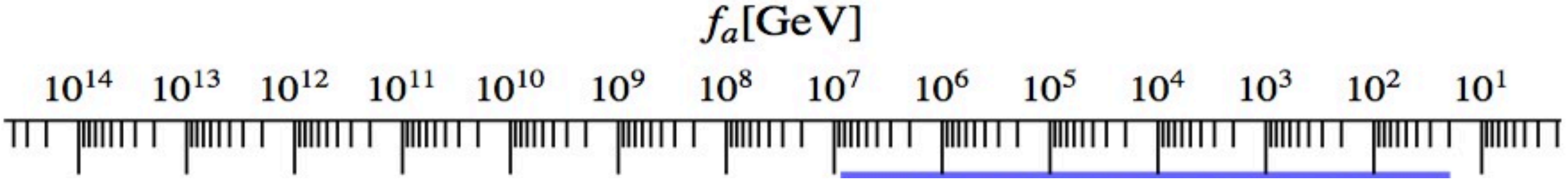


- **Axion DM scenarios**

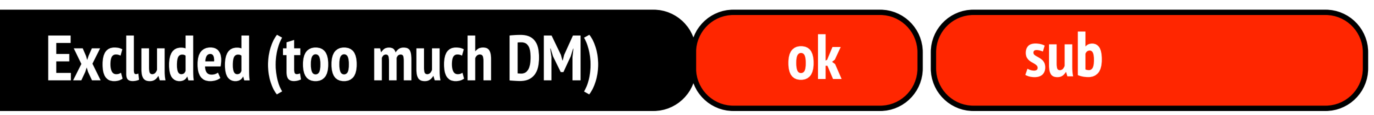


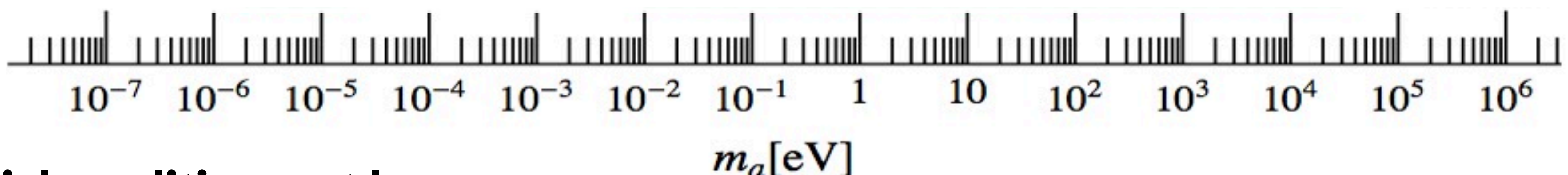
Initial conditions set by :

Axion dark matter (Scenario I)



- Axion DM scenarios



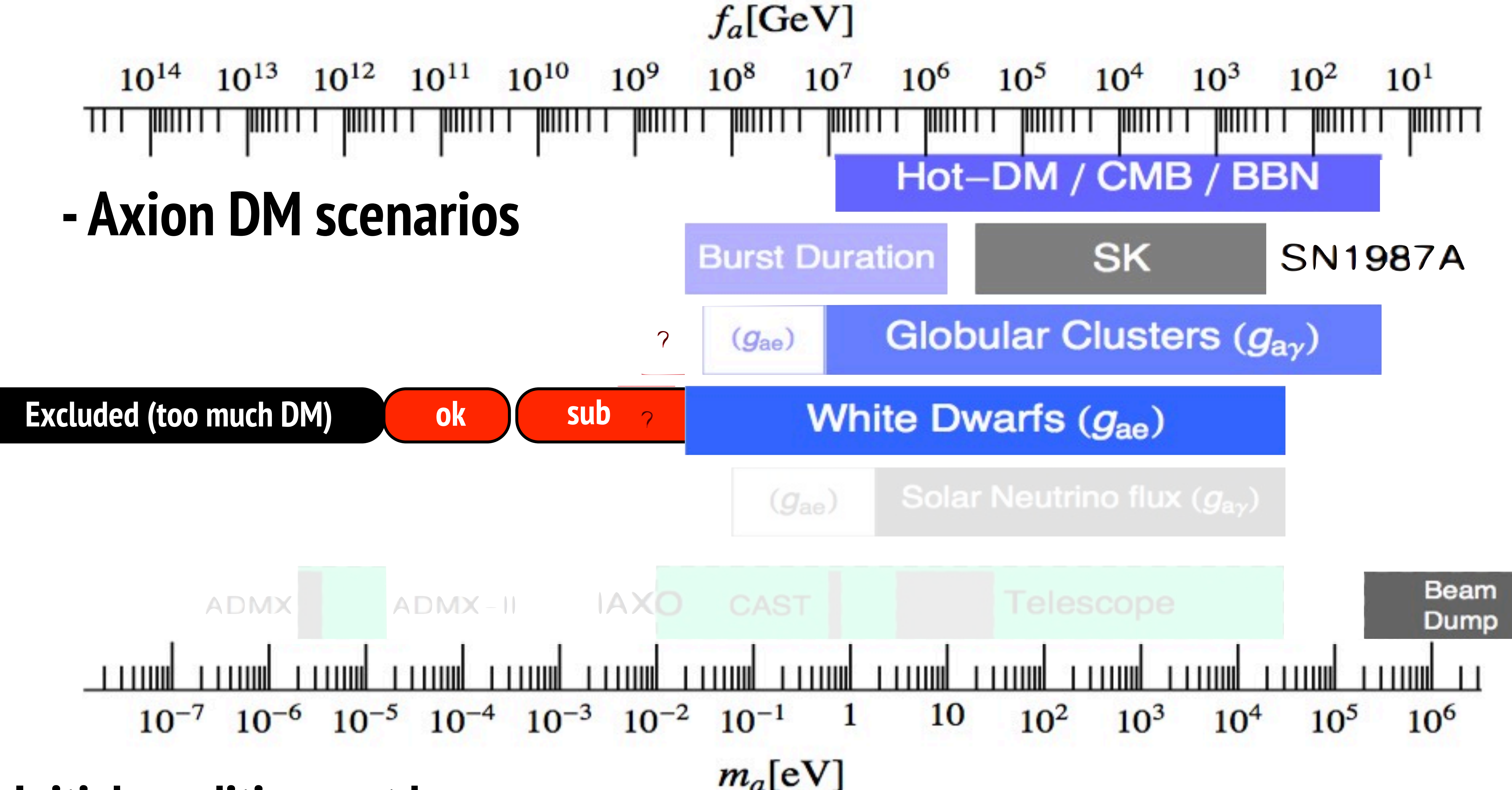


Initial conditions set by :

Phase transition (N=1)

strings+unstable DW's

Axion dark matter (Scenario I)



- Axion DM scenarios

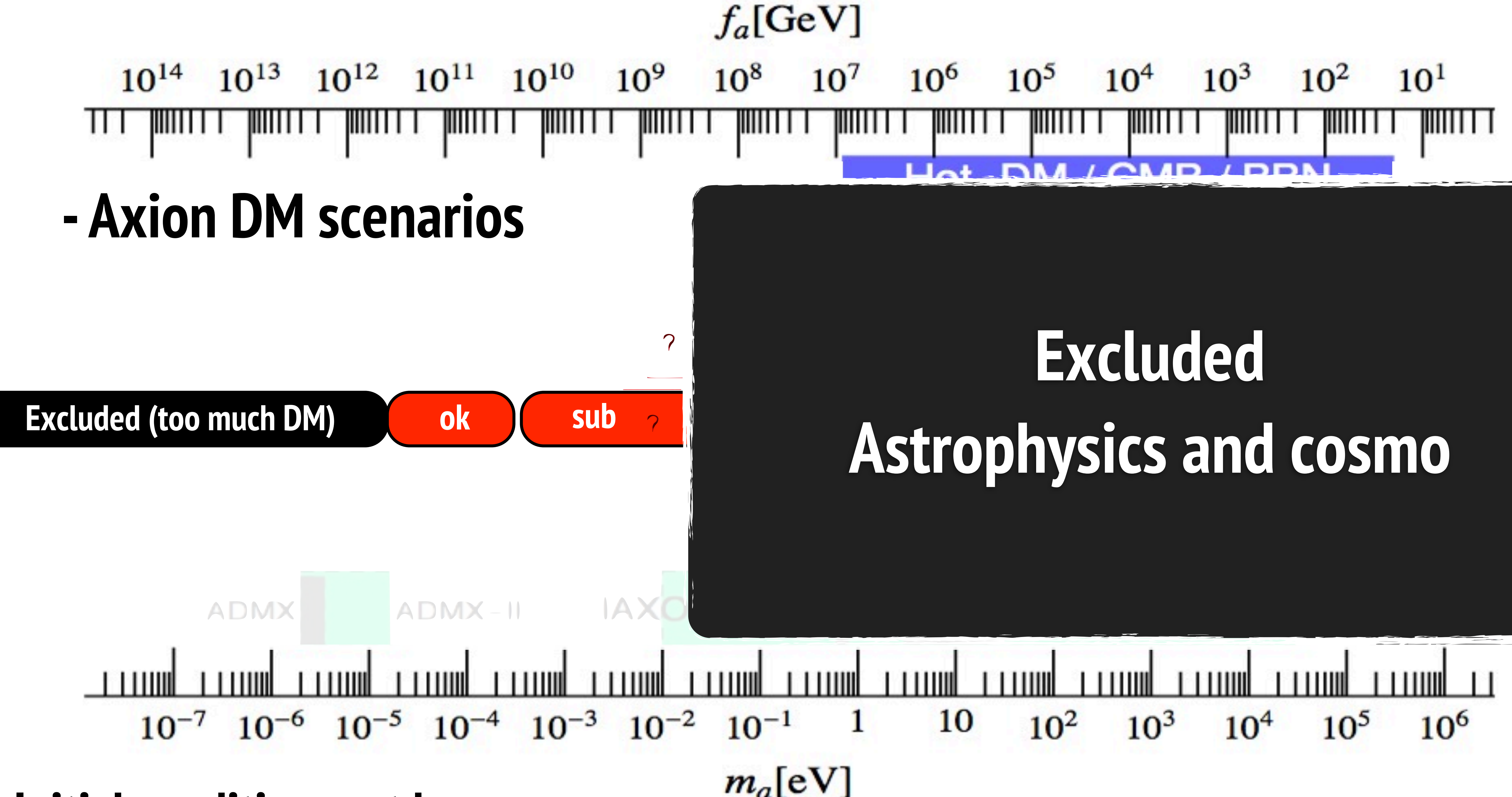
Initial conditions set by :

Phase transition (N=1)

strings+unstable DW's

Axion dark matter (Scenario I)

- Axion DM scenarios

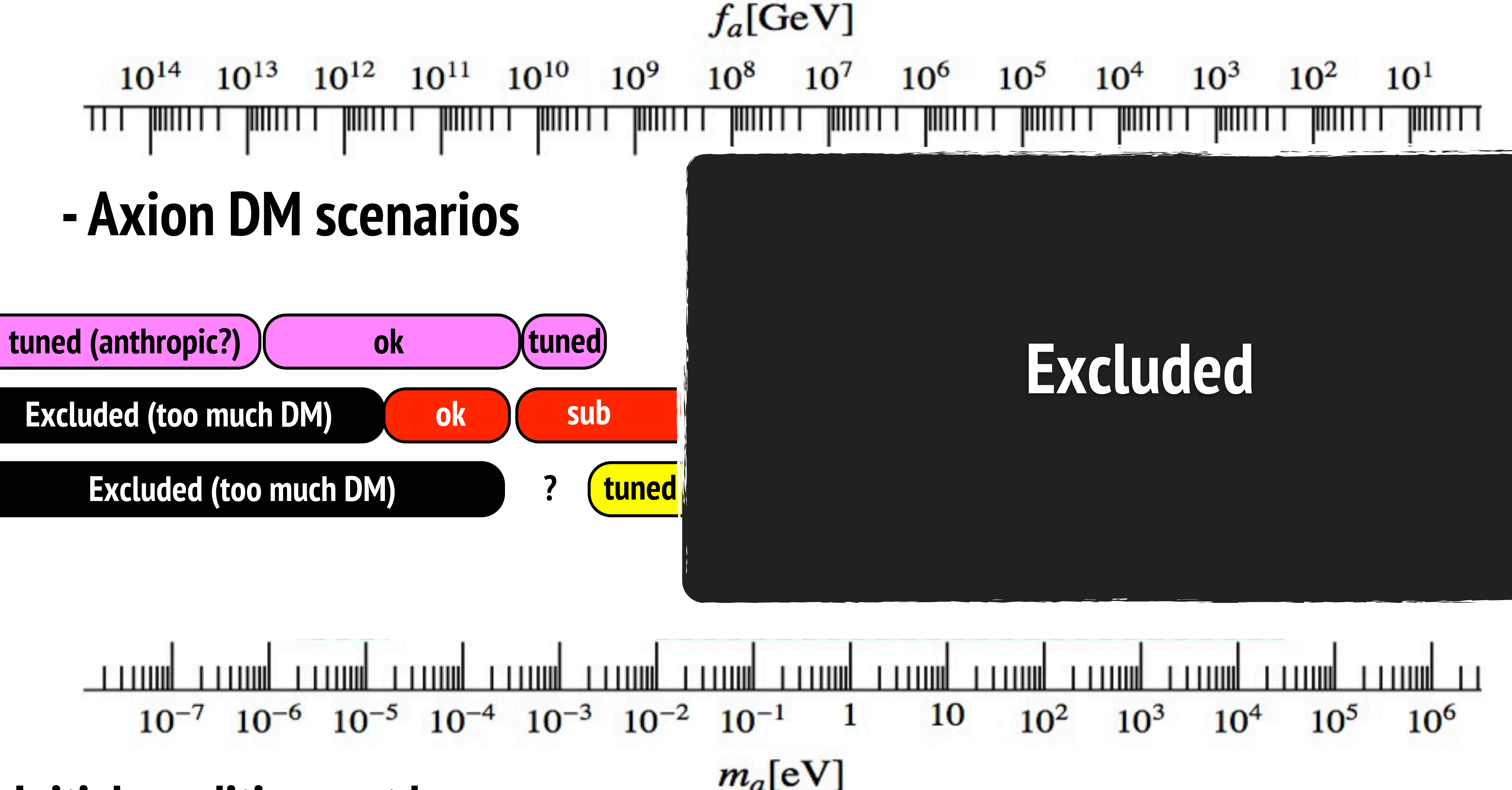


Initial conditions set by :

Phase transition (N=1)

strings+unstable DW's

Axion dark matter



Initial conditions set by :

Inflation smooth

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

Phase transition (N=1)

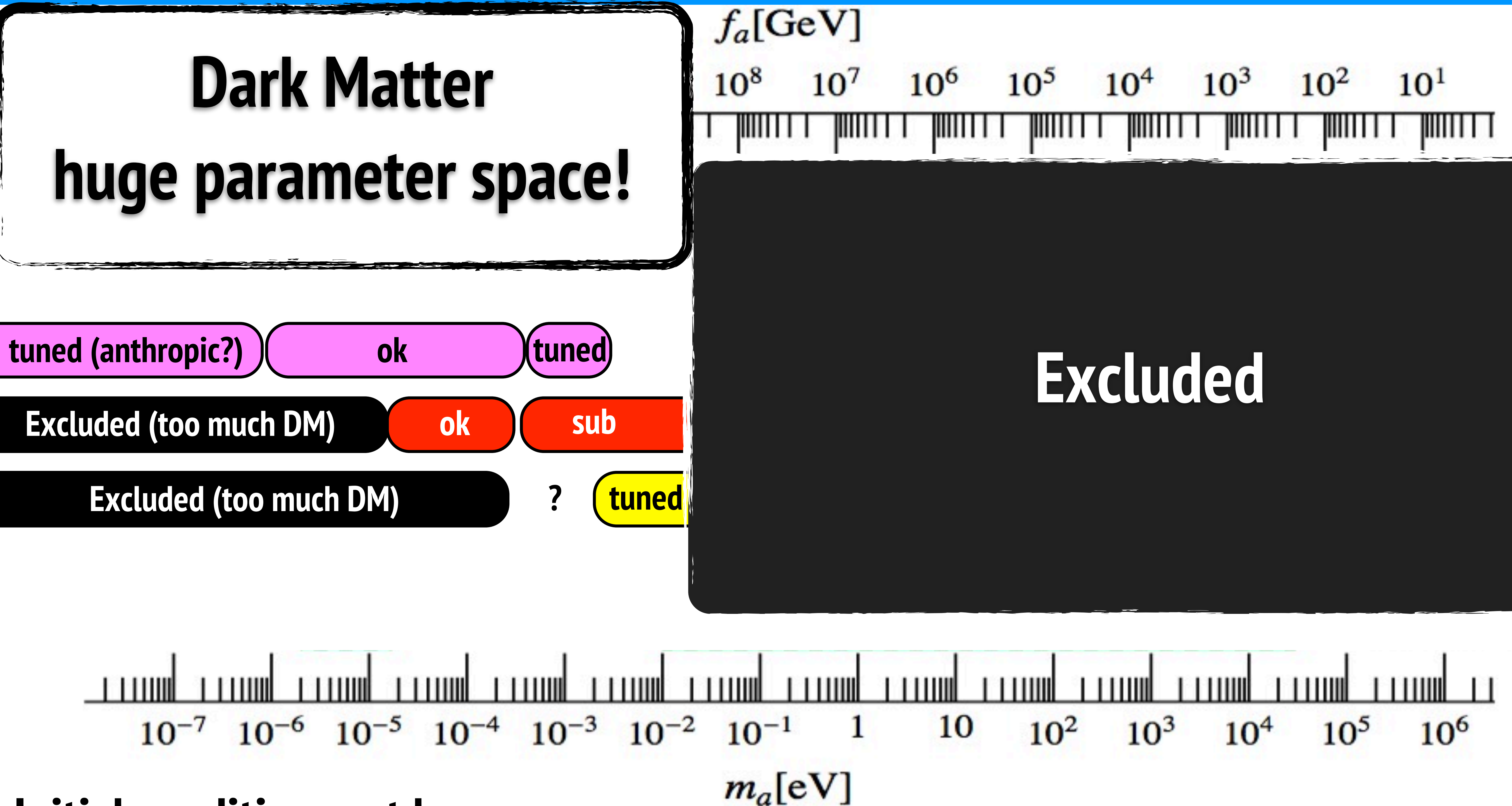
strings+unstable DW's

Phase transition (N>1)

strings+long-lived DWs

Axion dark matter

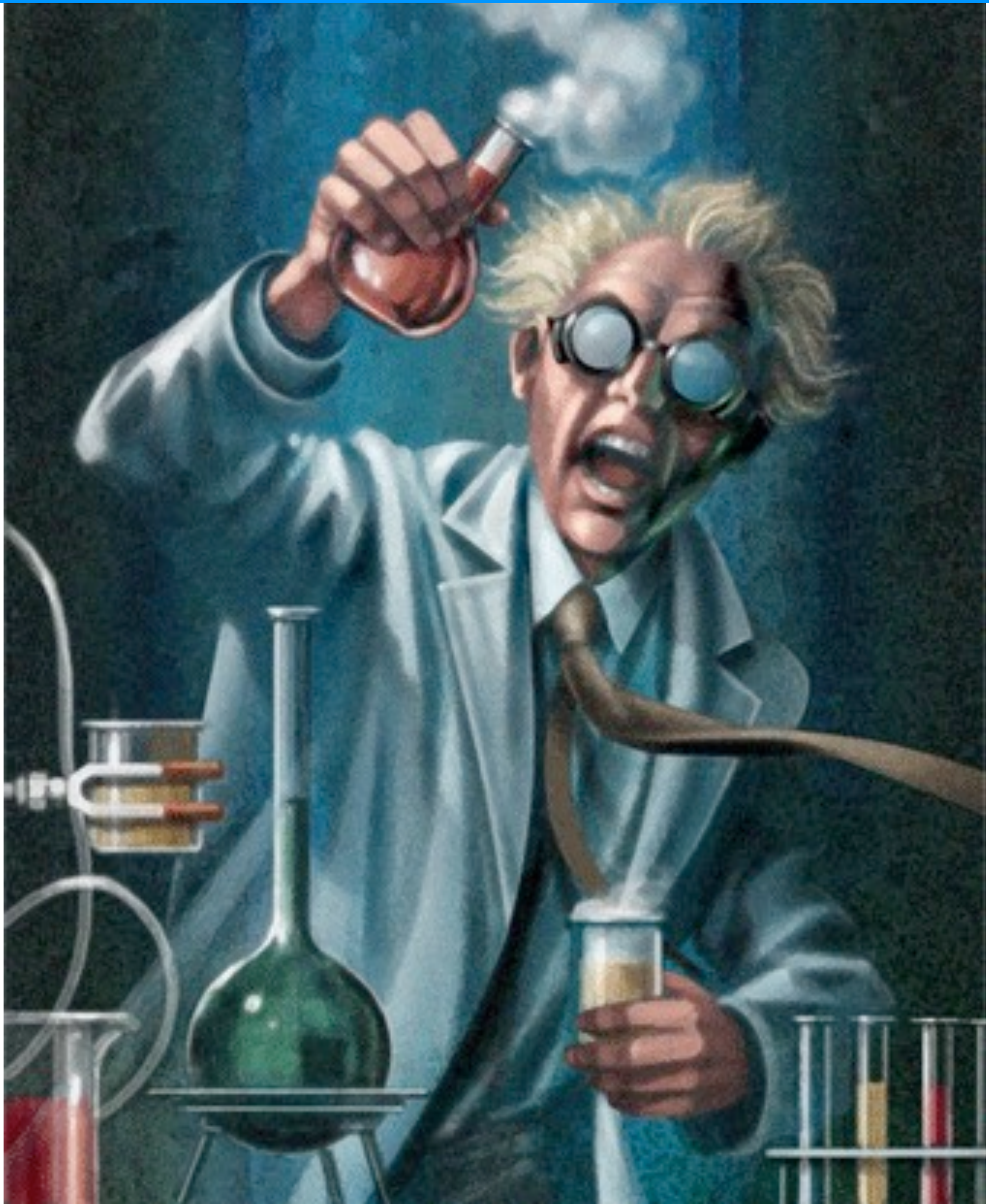
Dark Matter
huge parameter space!



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

Detecting SCI 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 $\quad v \lesssim 300\ \mathrm{km/s} \sim 10^{-3} c$

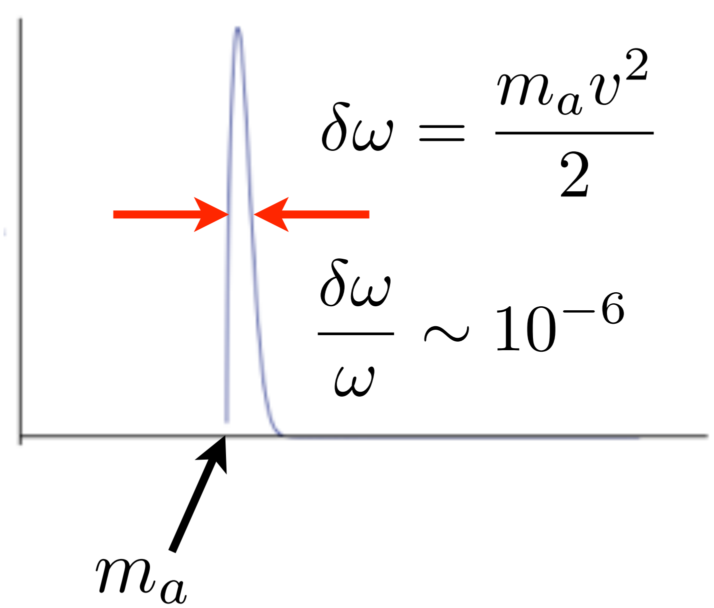
phase space density $\quad \dfrac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29} \left(\dfrac{\mu \mathrm{eV}}{m_a}\right)^4$

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

Roughly… $\quad a(t) = a_0 \cos(m_a t)$

Fourier-transform $a(x)$

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



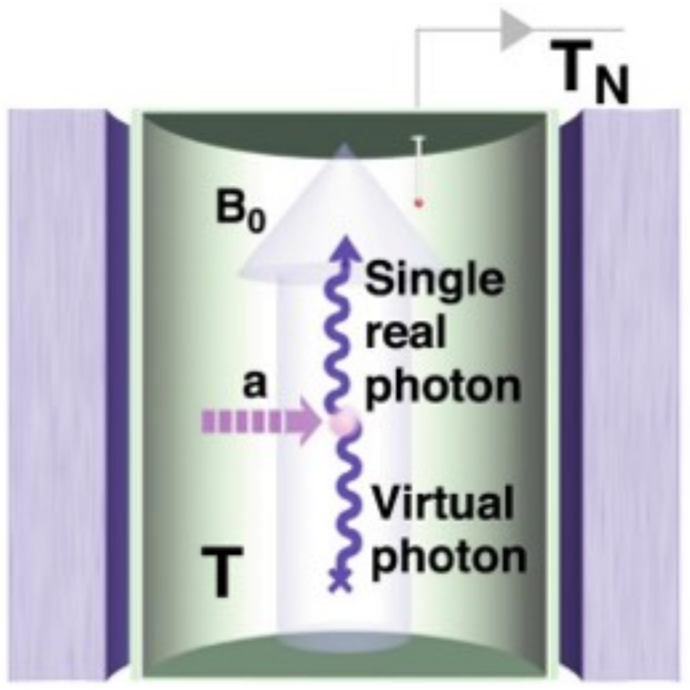
$$\delta\omega = \frac{m_a v^2}{2}$$

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

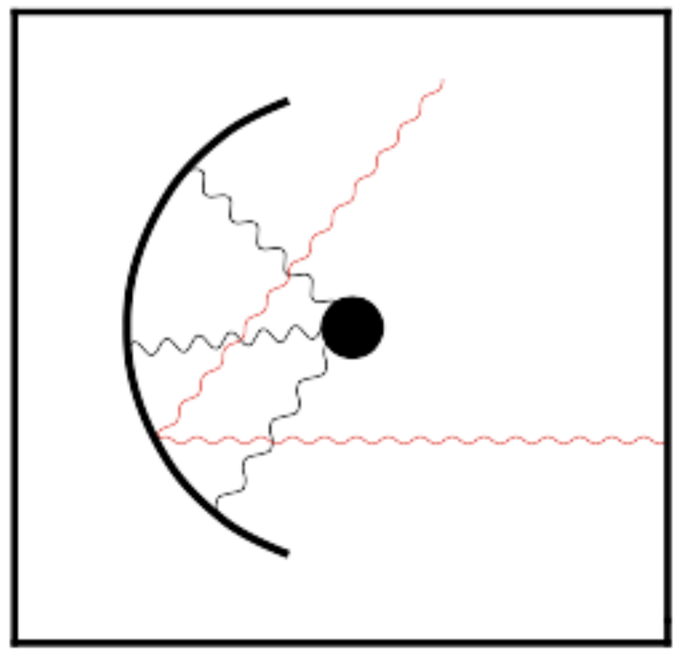
$$\delta t \sim \frac{1}{\delta\omega} \sim 0.13\mathrm{ms} \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)$$

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

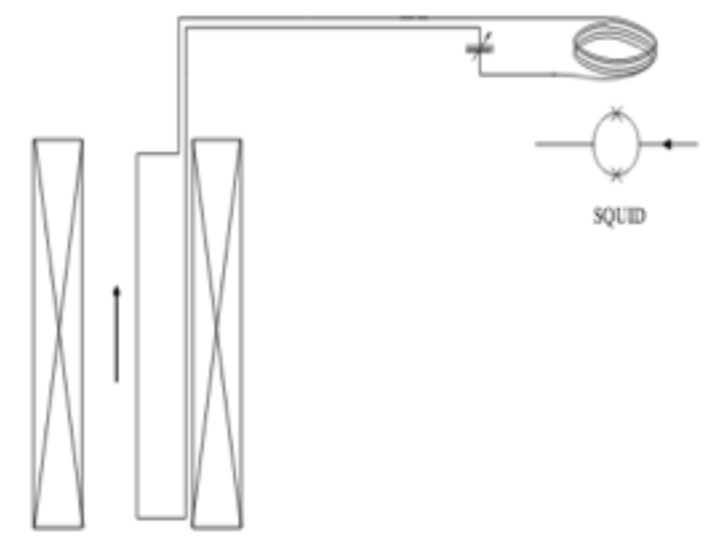
Cavities



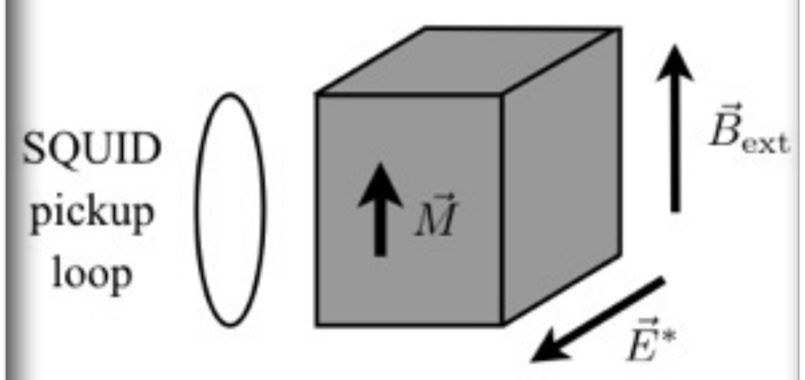
Mirrors



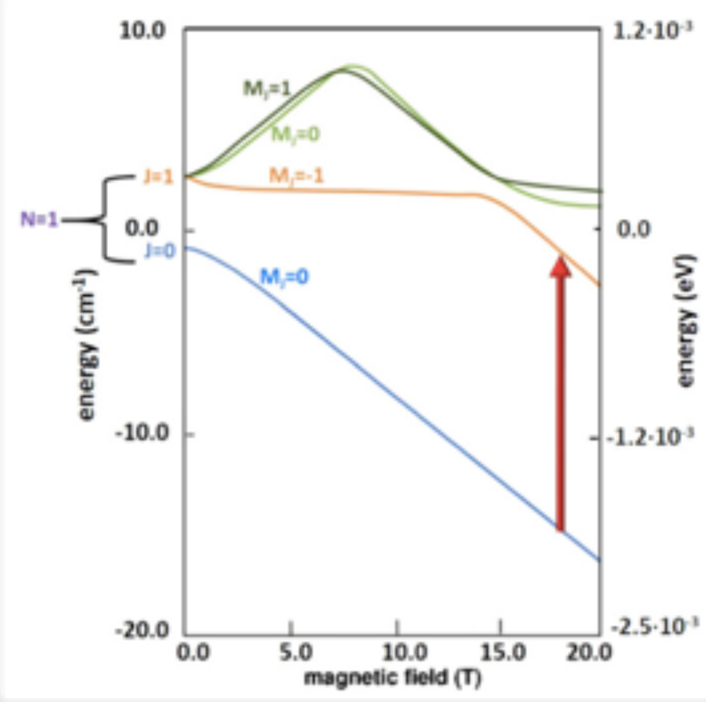
LC-circuit



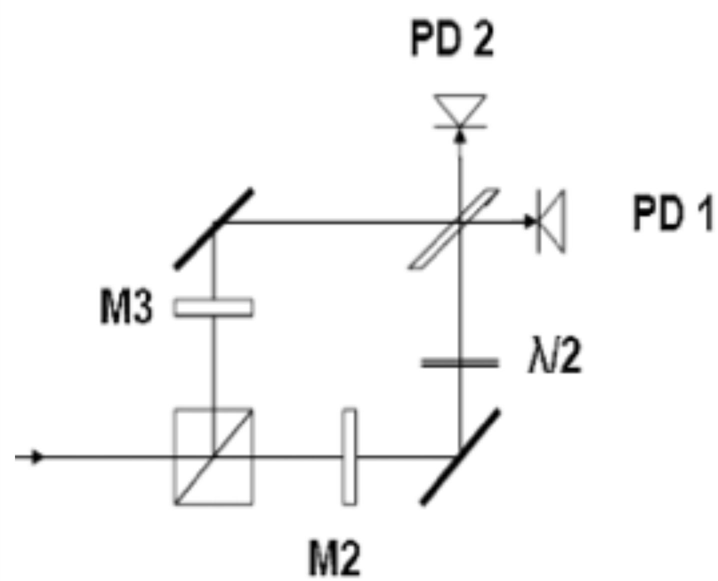
Spin precession



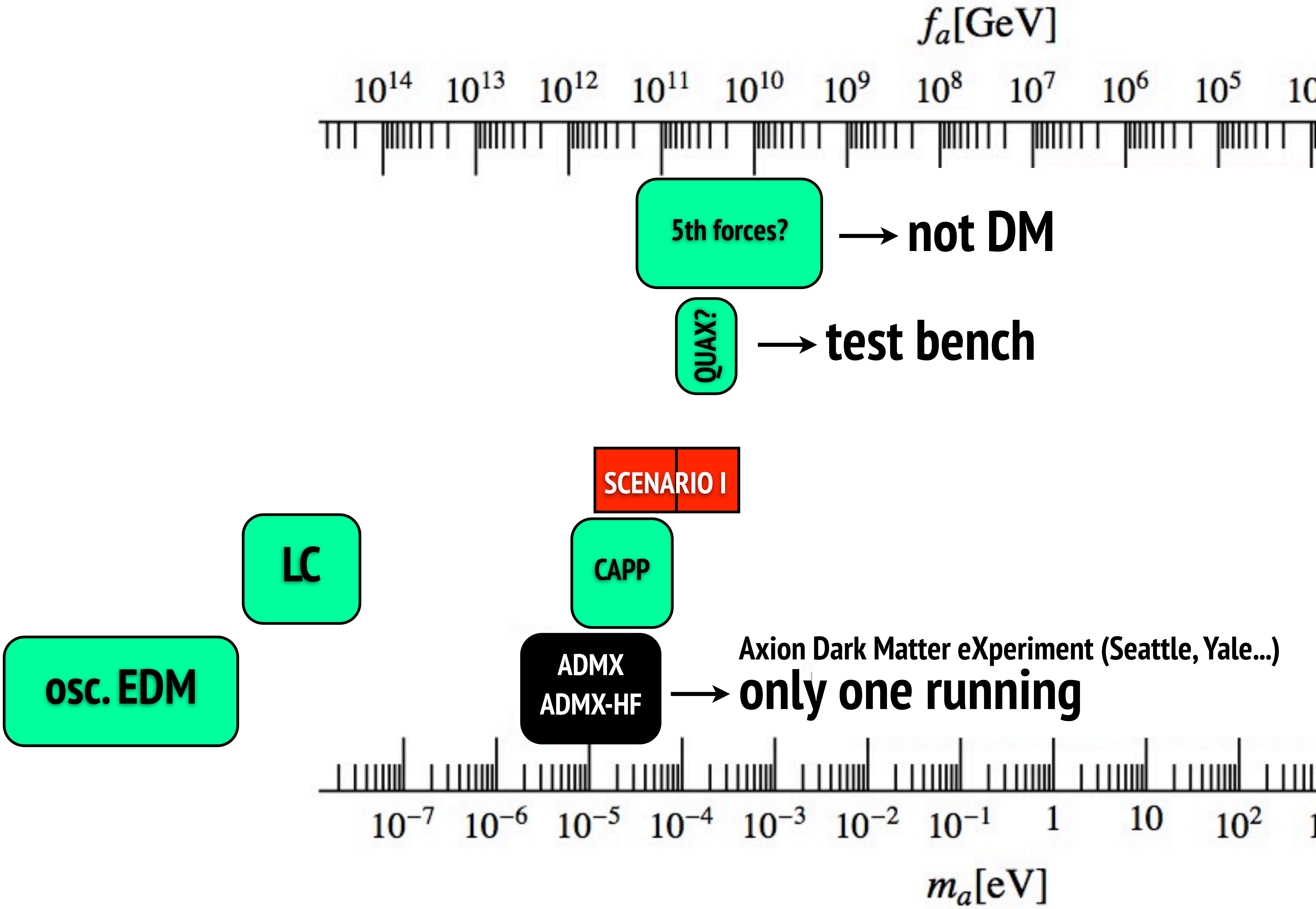
Atomic transitions



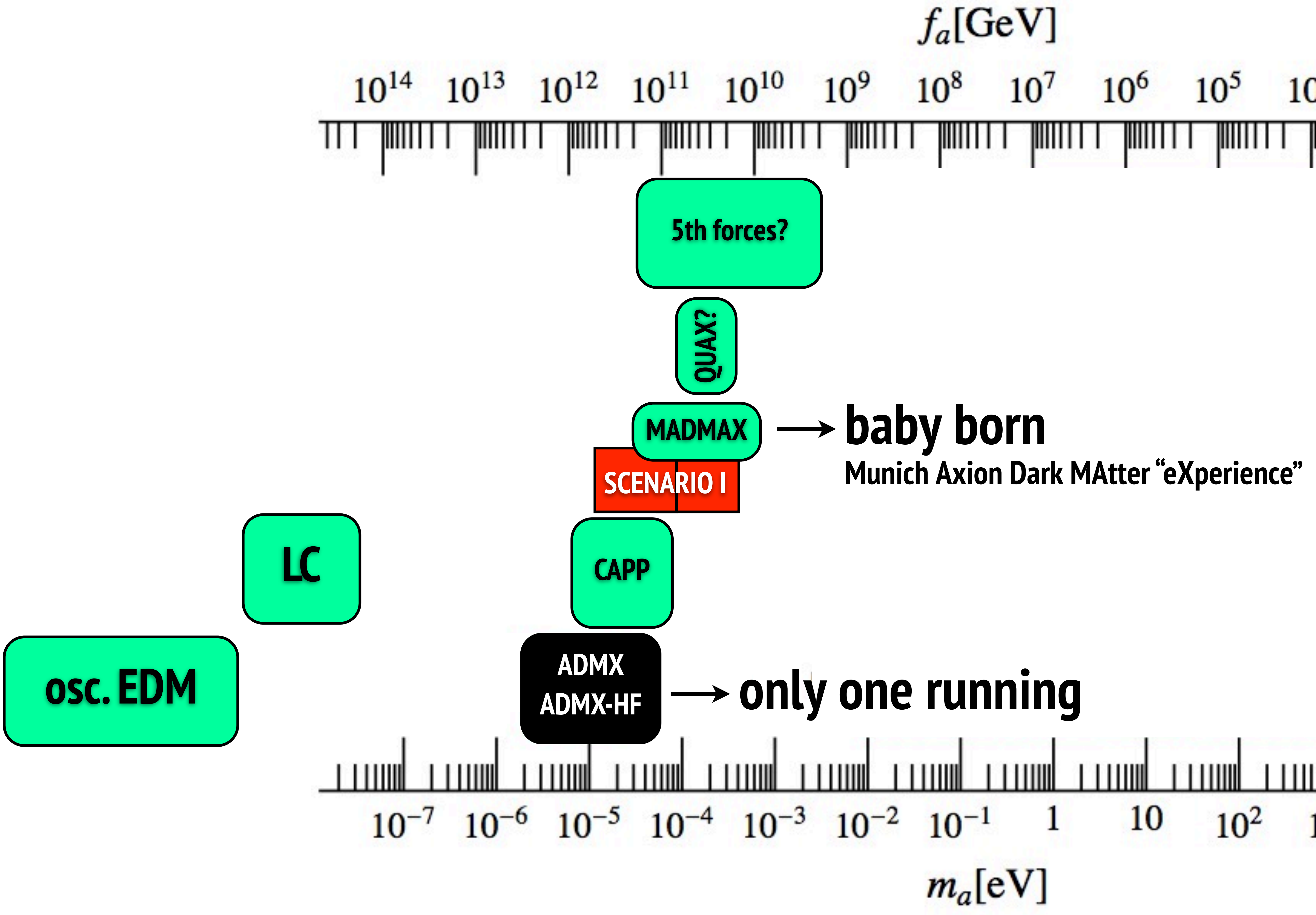
Optical



Axion Dark matter experiments (target areas)



Axion Dark matter experiments (target areas)



→ baby born

Munich Axion Dark MAtter “eXperience”

→ only one running

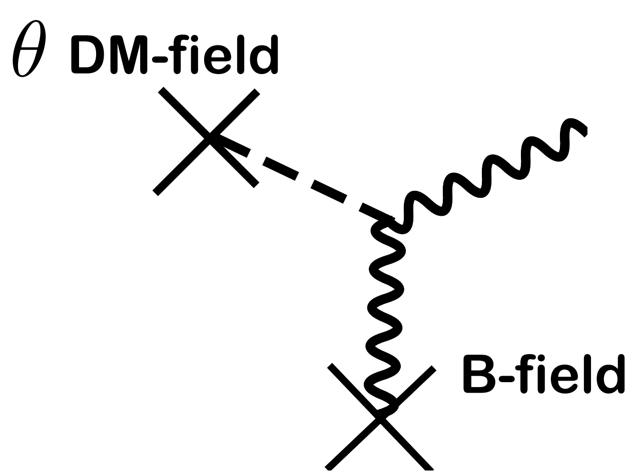
Axion DM in a B-field : two photon coupling

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

- 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



Detecting axion DM

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

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

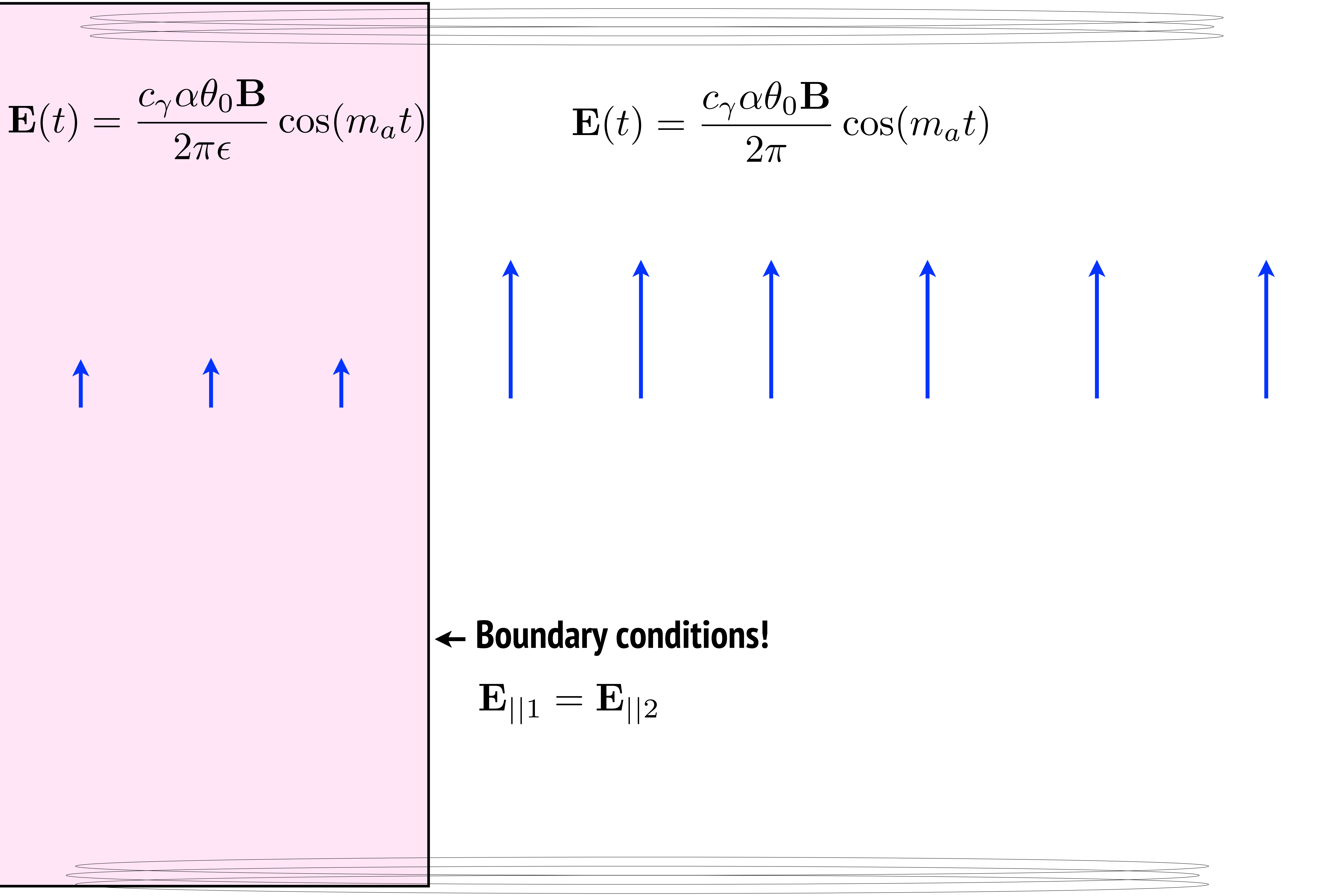
In a magnetised medium

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

- **Electric fields** $E = 1.3 \times 10^{-12}\ \mathrm{V/m}\ \frac{B_\mathrm{e}}{10\ \mathrm{T}} \frac{C_{a\gamma}}{\epsilon}$. **(amp independent of mass!)**

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

Radiation from a dielectric interface ...



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

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

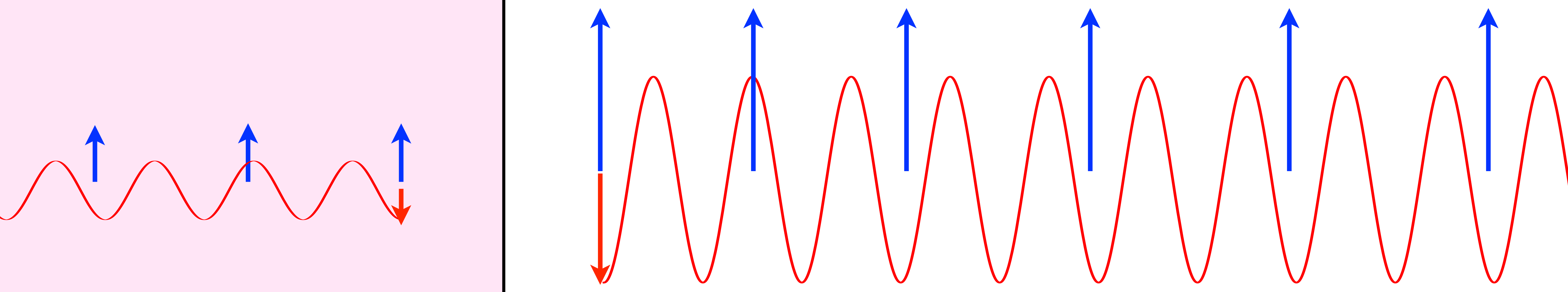
← **Boundary conditions!**

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

Radiation from a dielectric interface ...

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

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



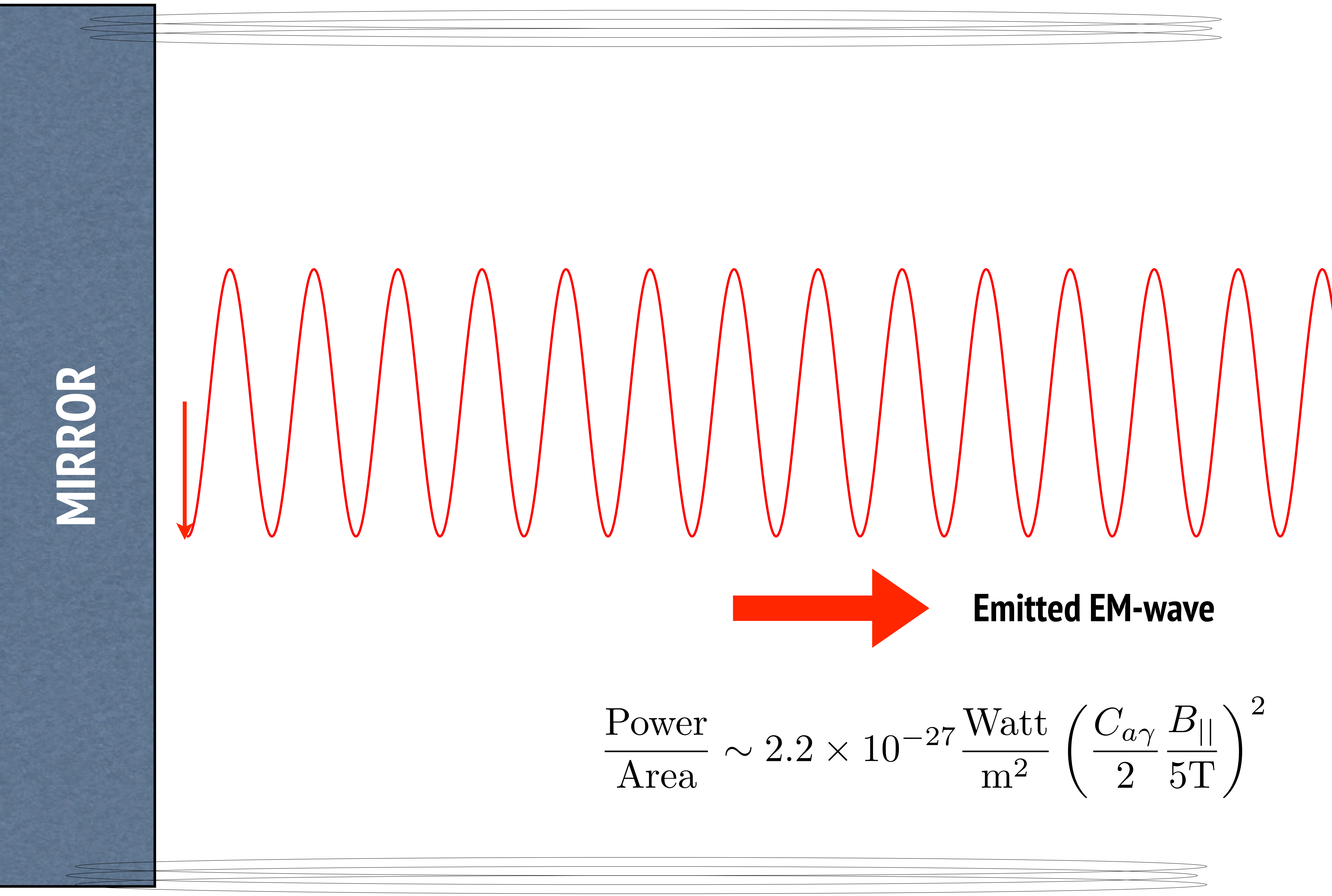
← **Boundary conditions!**

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

Emitted EM-wave

Emitted EM-wave

Radiation from a magnetised mirror : Power

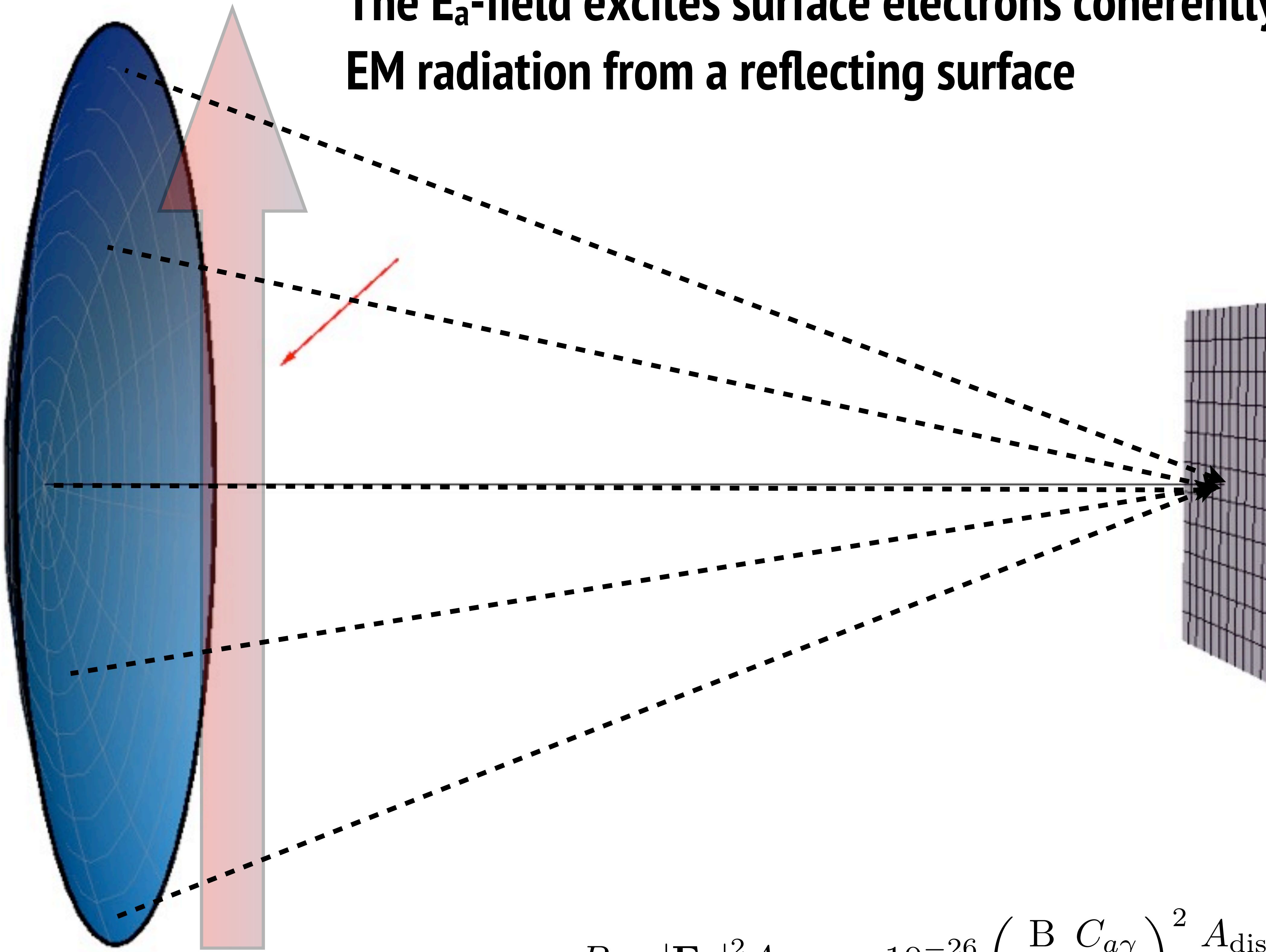


$$\frac{\text{Power}}{\text{Area}} \sim 2.2 \times 10^{-27} \frac{\text{Watt}}{\text{m}^2} \left(\frac{C_{a\gamma}}{2} \frac{B_{||}}{5\text{T}} \right)^2$$

Dish antenna experiment?

Horns 2012

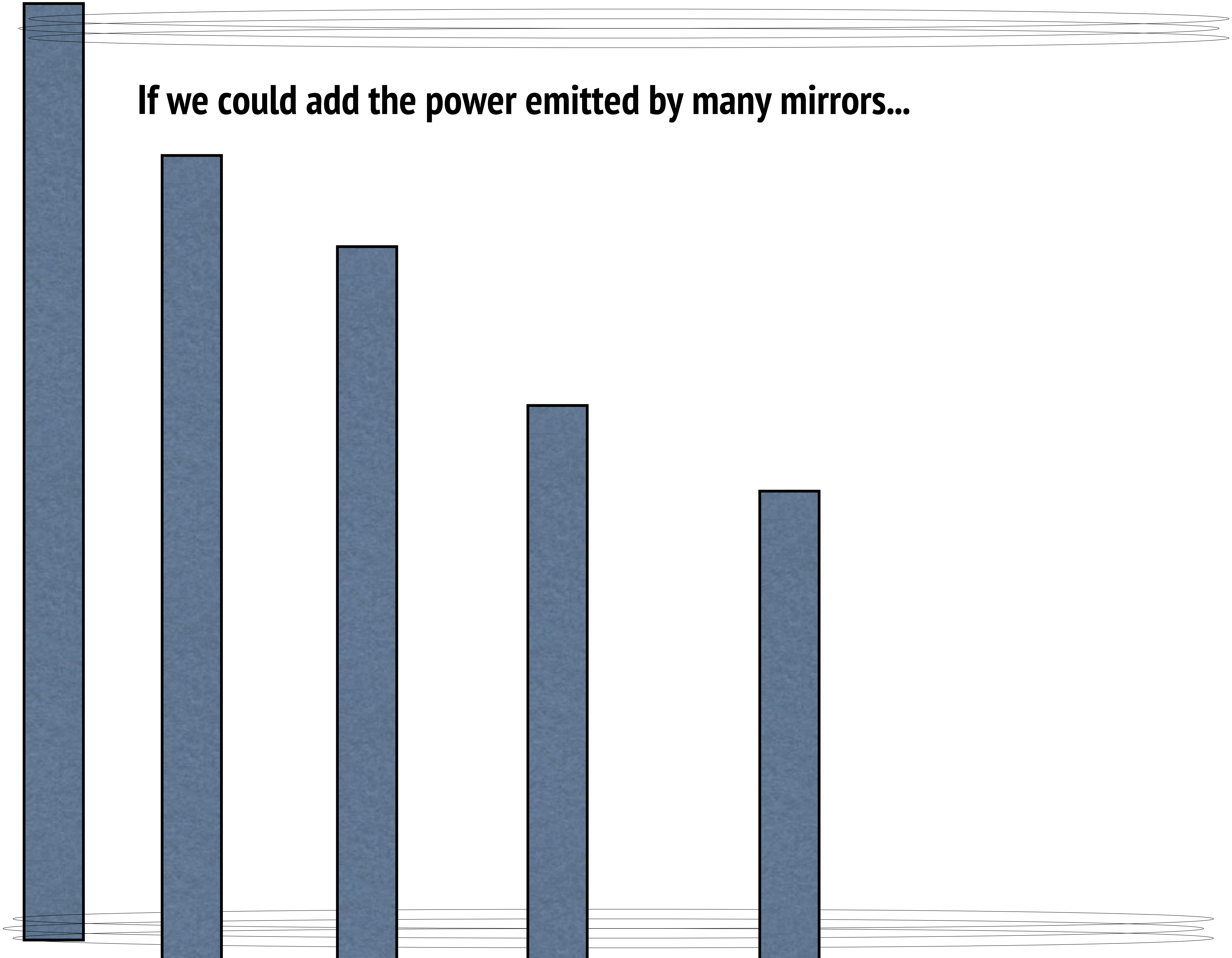
The E_a-field excites surface electrons coherently
EM radiation from a reflecting surface



spherical reflecting dish

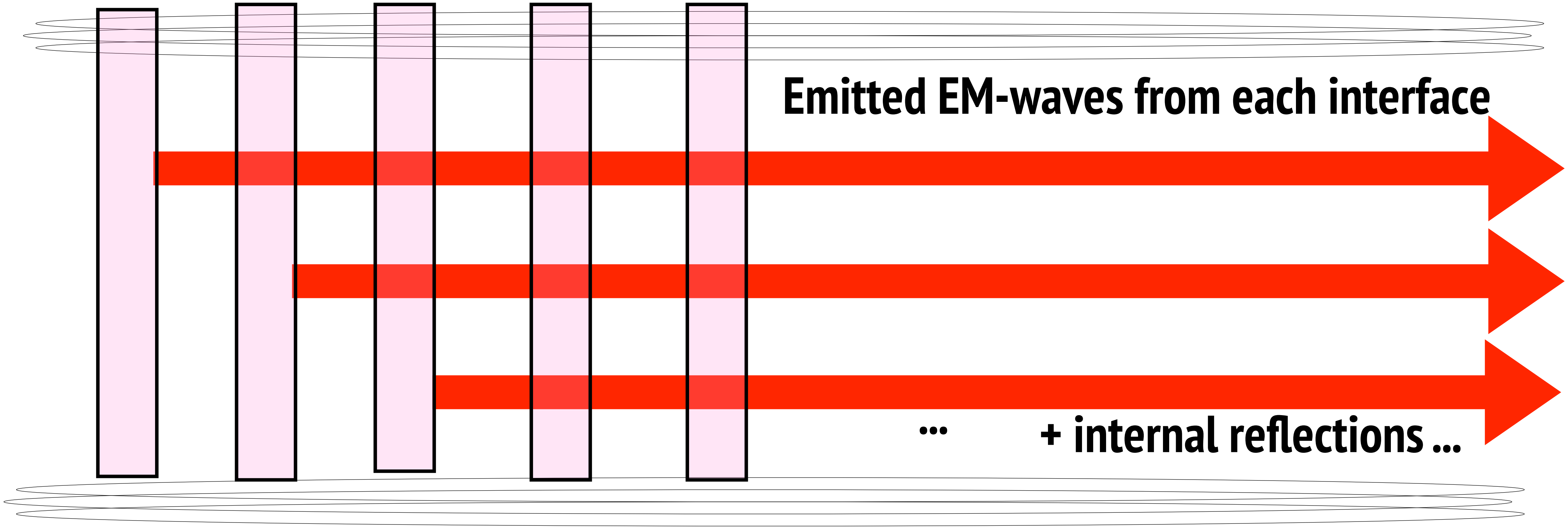
$$P \sim |\mathbf{E}_a|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\,\frac{C_{a\gamma}}{2}\right)^2 \frac{A_{\rm dish}}{1\,\rm m^2}\,{\rm Watt}$$

Mixed scheme?



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

Many dielectrics : MADMAX at MPP Munich

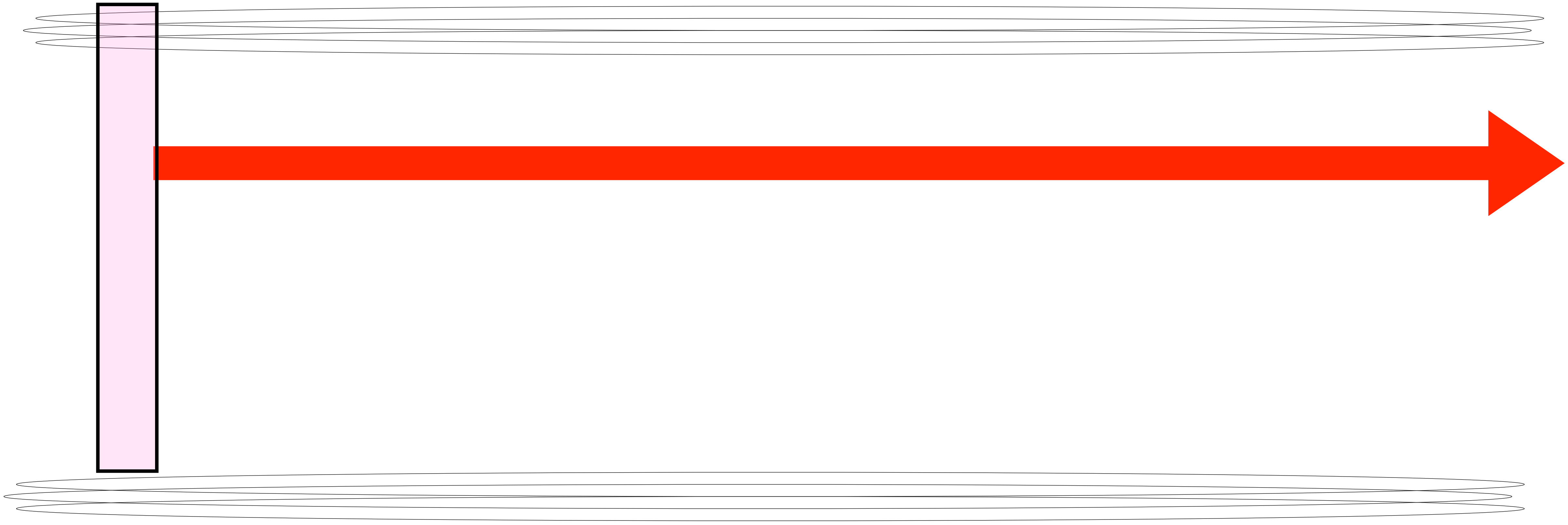


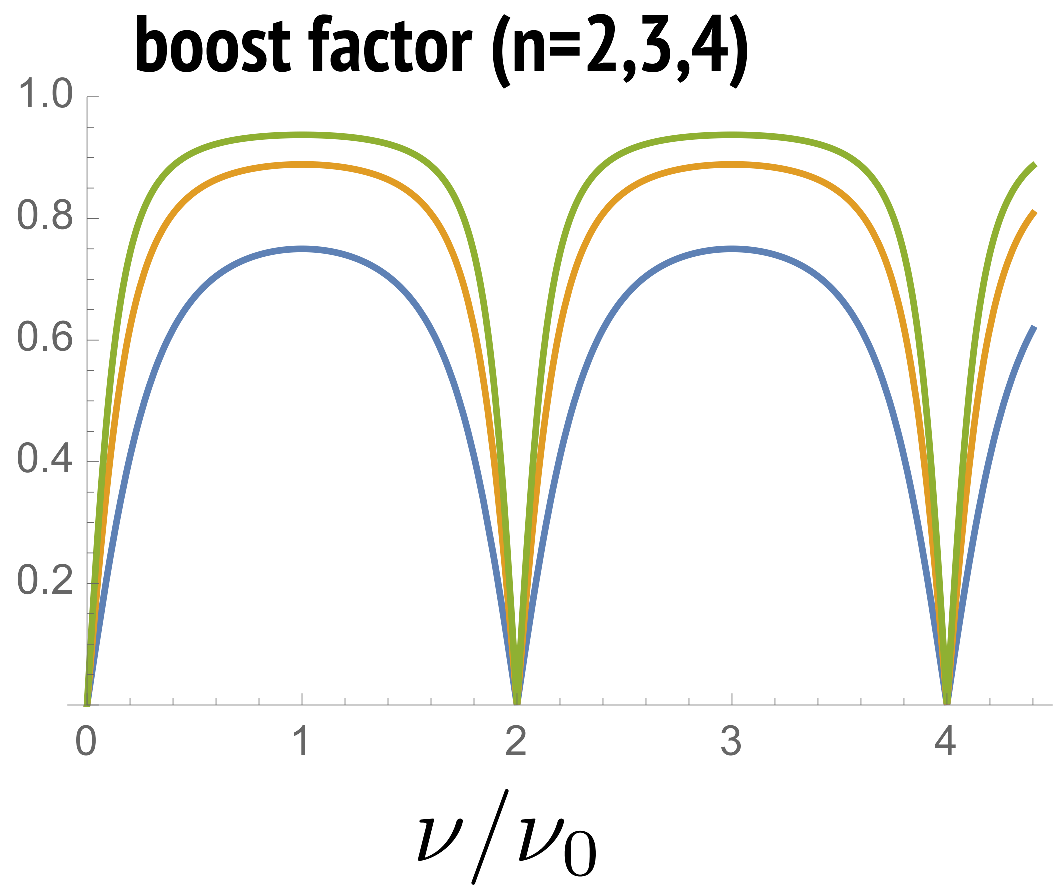
- Emission has large spatial coherence; adjusting plate separation -> coherence

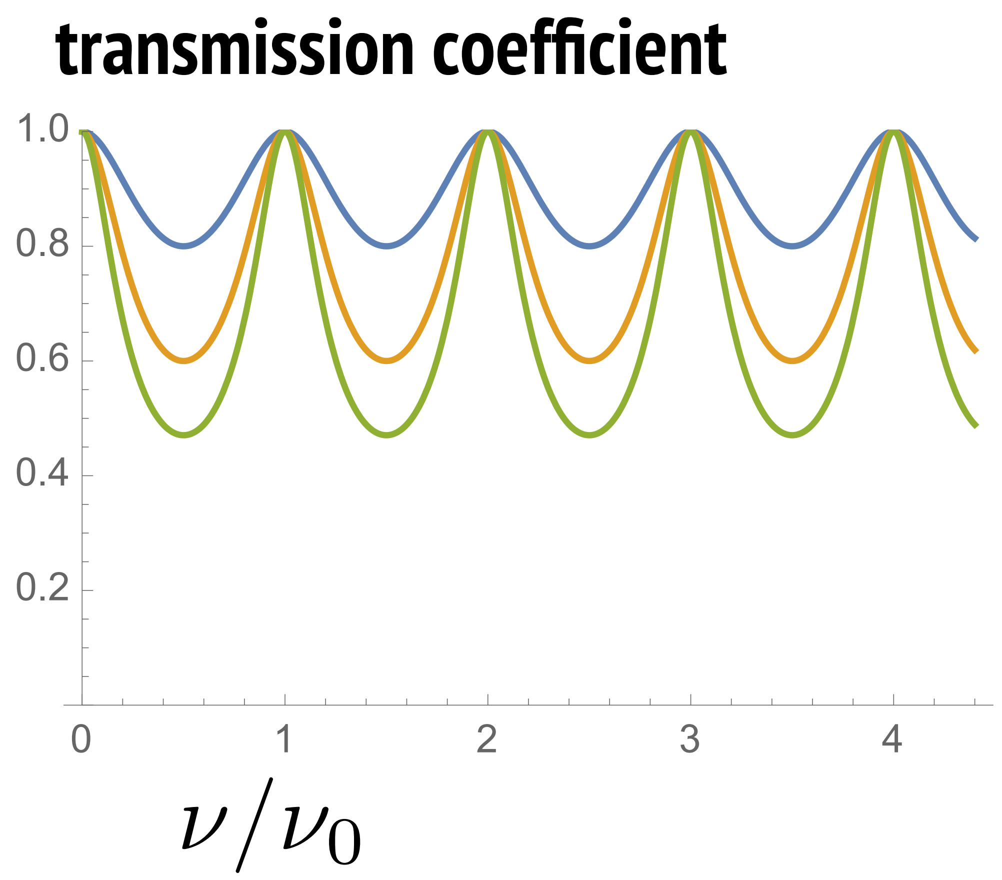
$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(c_\gamma \frac{B_{||}}{10\mathrm{T}} \right)^2 \times \beta^2(\omega)$$ **boost factor**

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

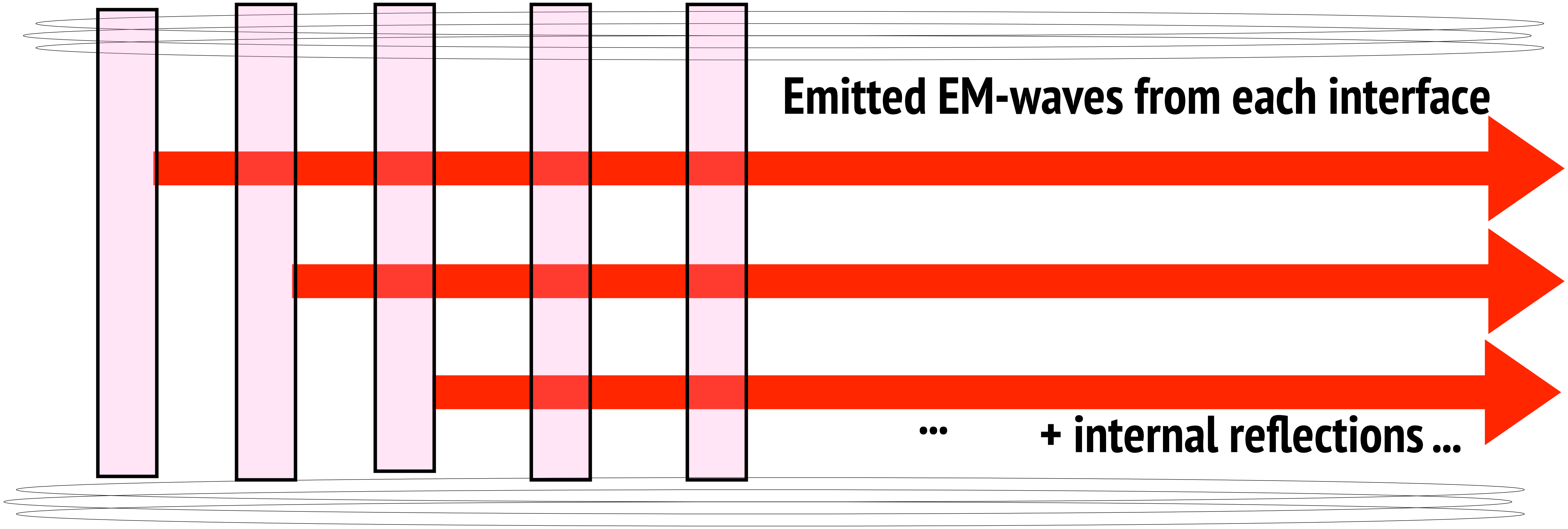
One dielectric



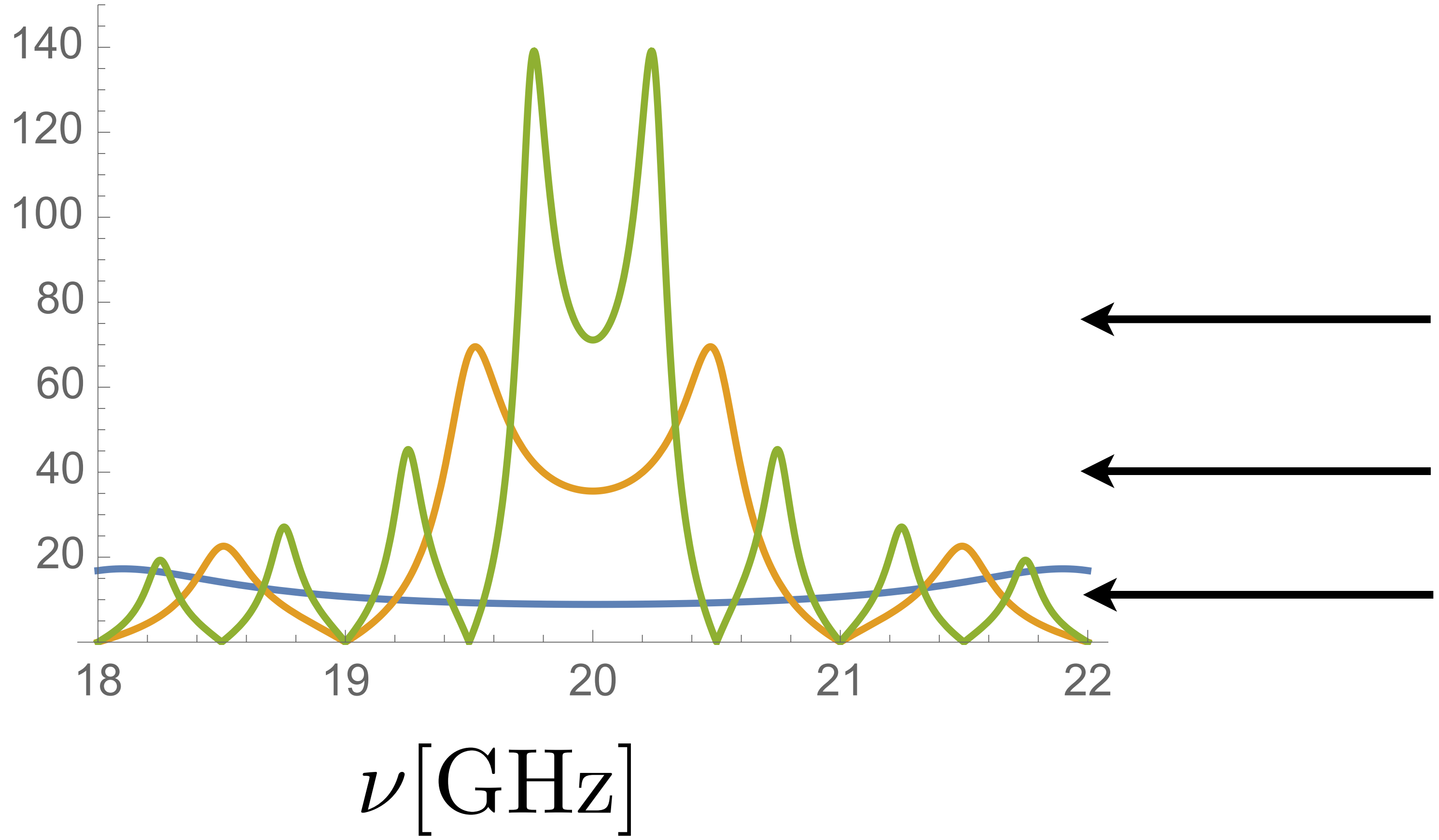




Close to nu0, many layers



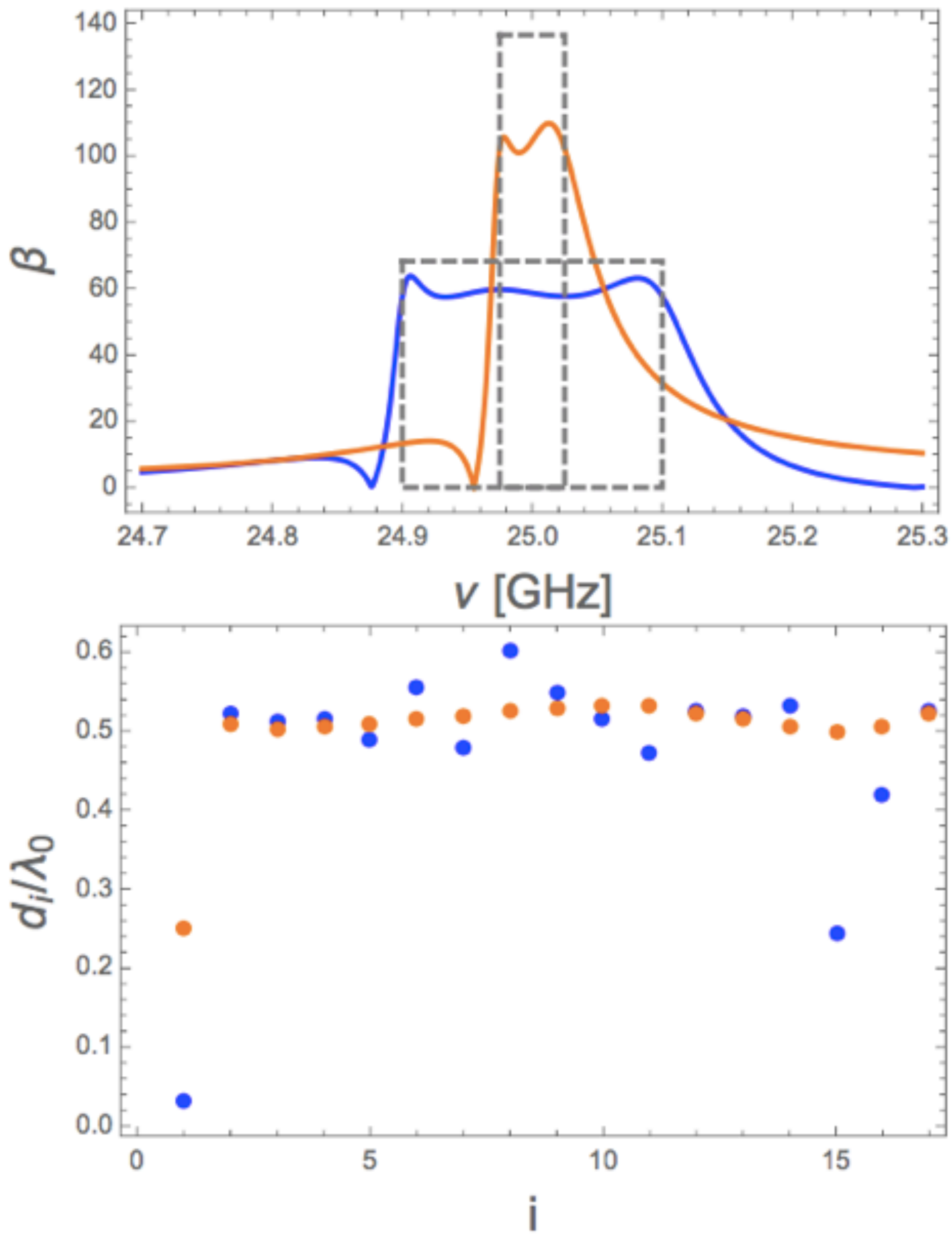
boost factor (N=10,40,80; n=3,nu0=20 GHz)



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

Even larger boosts are possible (small resonant enhancement)

Numerical optimisation of distance between 17 layers n=5 (flat response)



Conceptual paper in preparation:

Prepared for submission to JCAP (ALMOST)

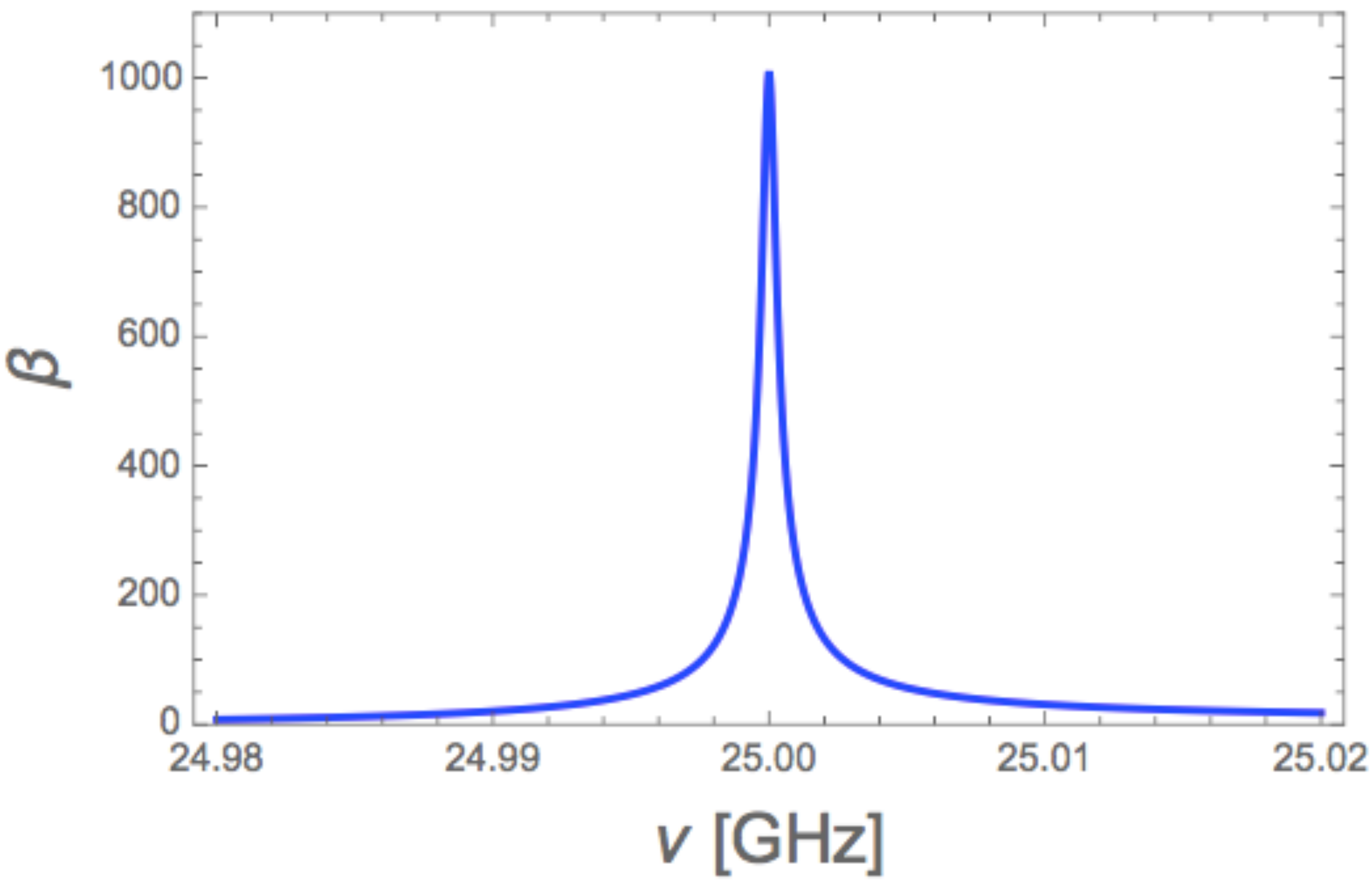
MPP-2016-XXX

Layered dielectric haloscopes: a new way to detect axion dark matter

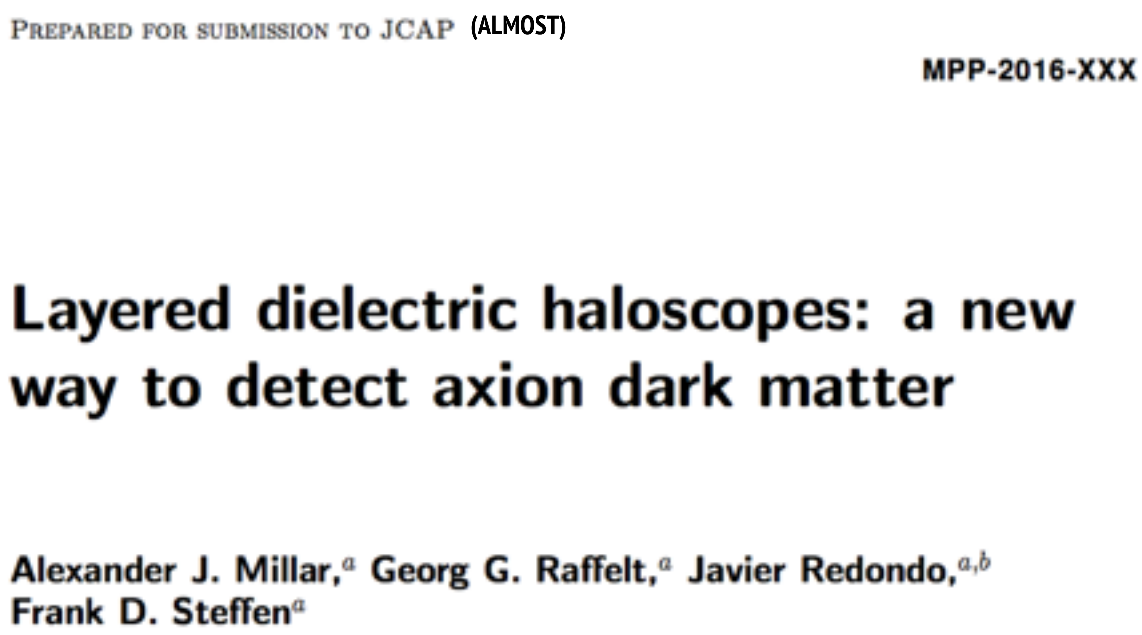
Alexander J. Millar,[a] Georg G. Raffelt,[a] Javier Redondo,[a,b] Frank D. Steffen[a]

and if a candidate is found ...

Numerical optimisation of distance between 17 layers n=5 (max response)



Conceptual paper in preparation:

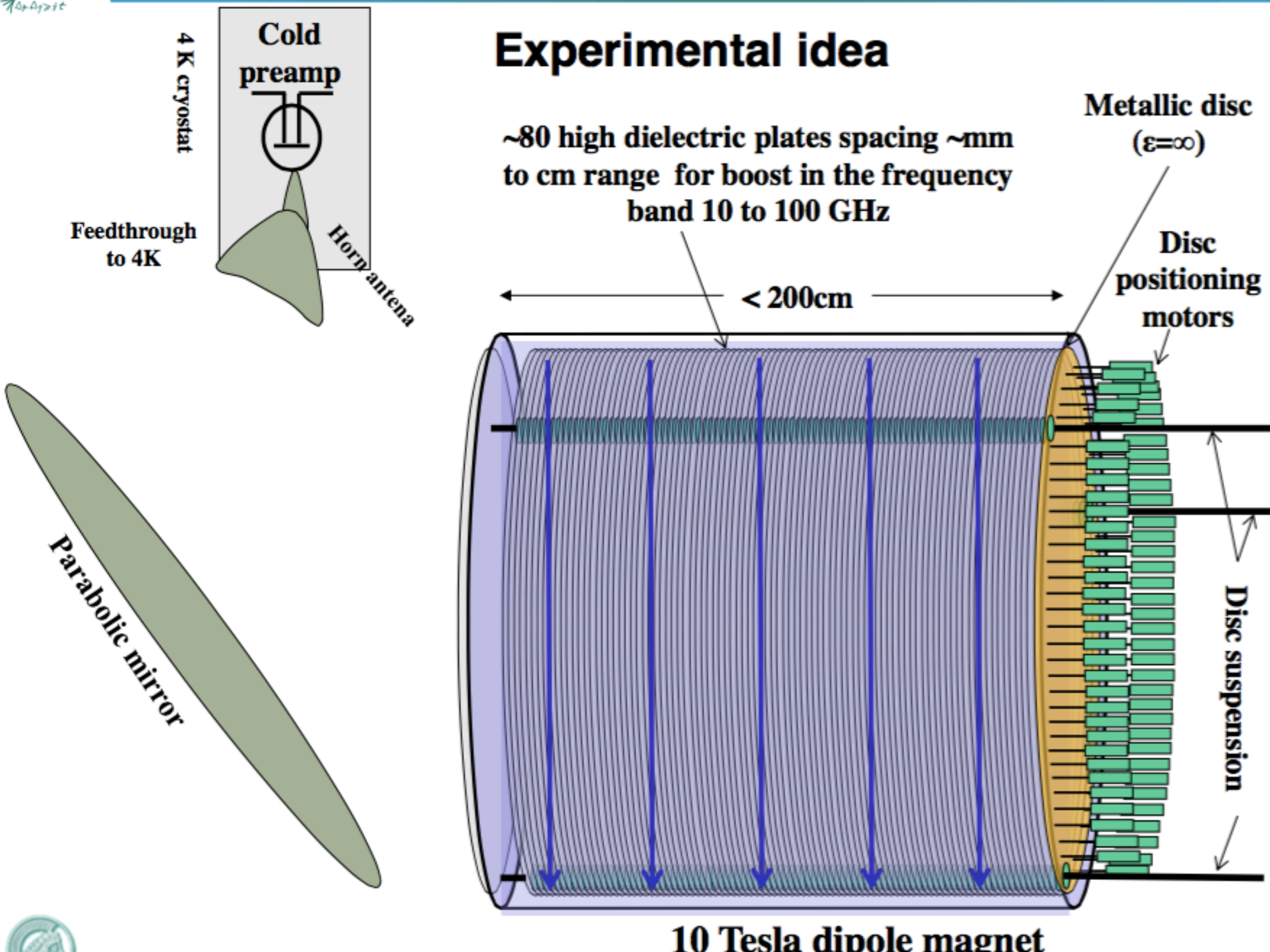

Prepared for submission to JCAP (ALMOST)

MPP-2016-XXX

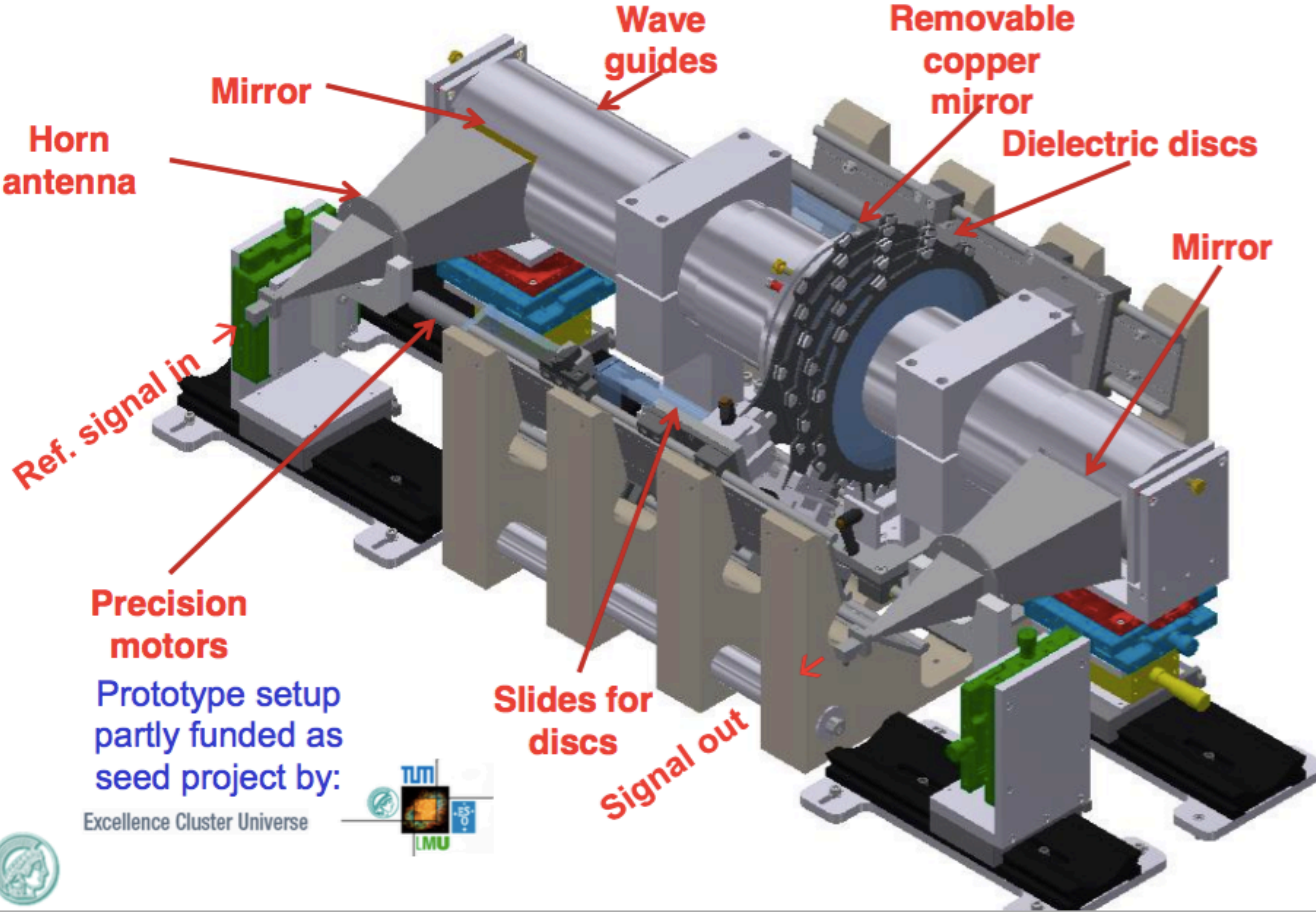
Layered dielectric haloscopes: a new way to detect axion dark matter

Alexander J. Millar,[a] Georg G. Raffelt,[a] Javier Redondo,[a,b] Frank D. Steffen[a]

Experimental idea



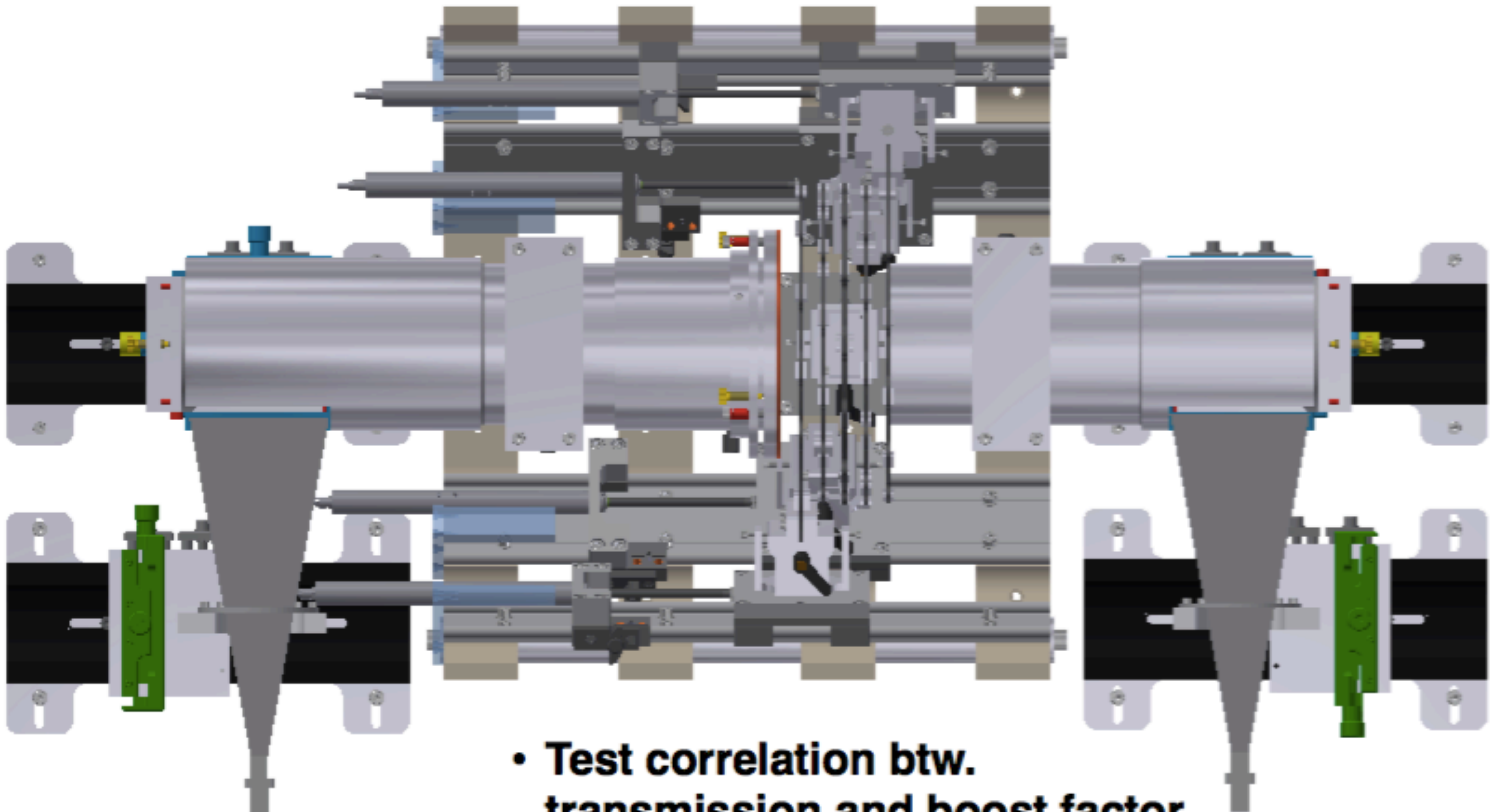
First prototype setup at MPI



Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First prototype setup at MPI

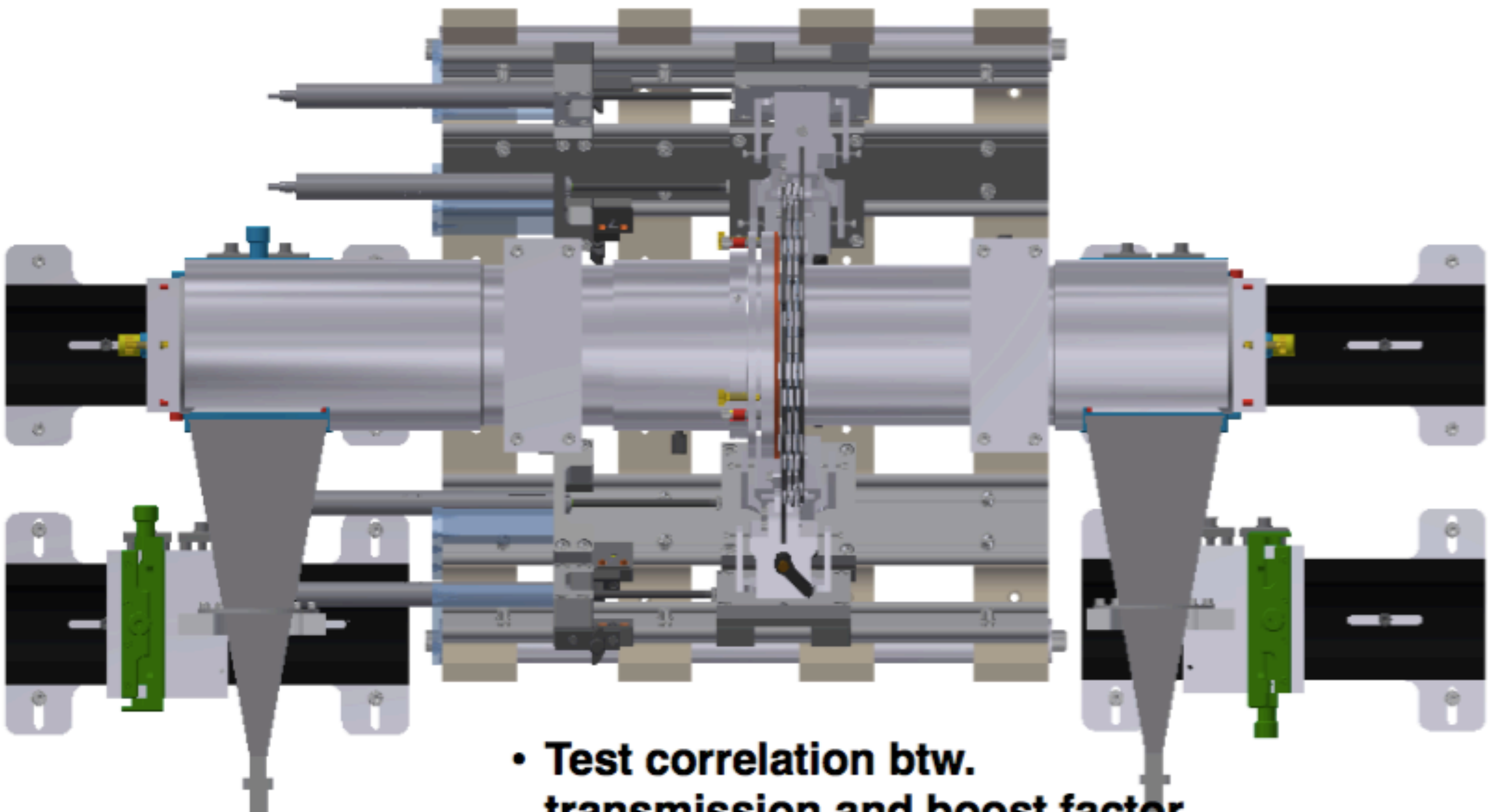


- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
- R&D on tiling

Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First prototype setup at MPI

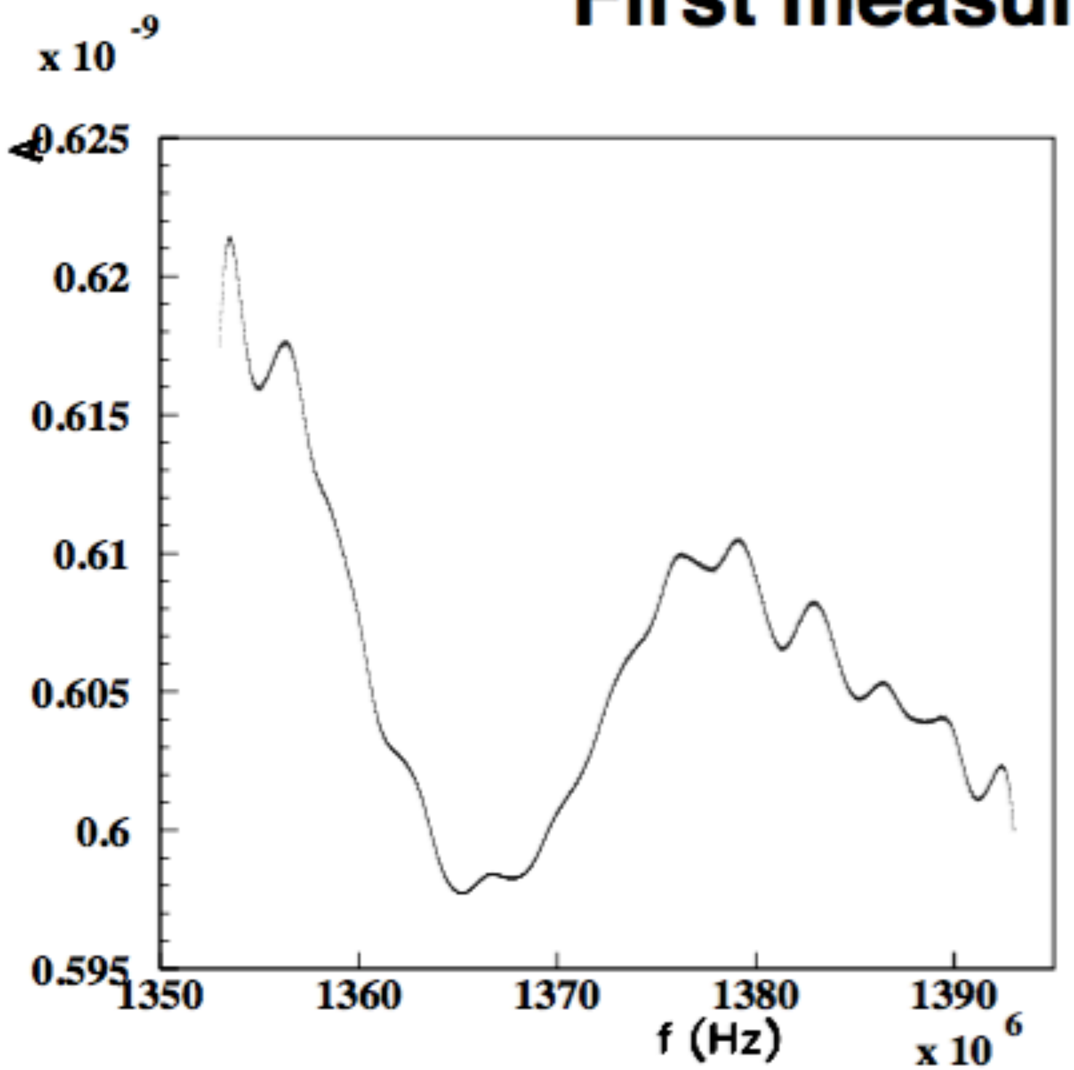


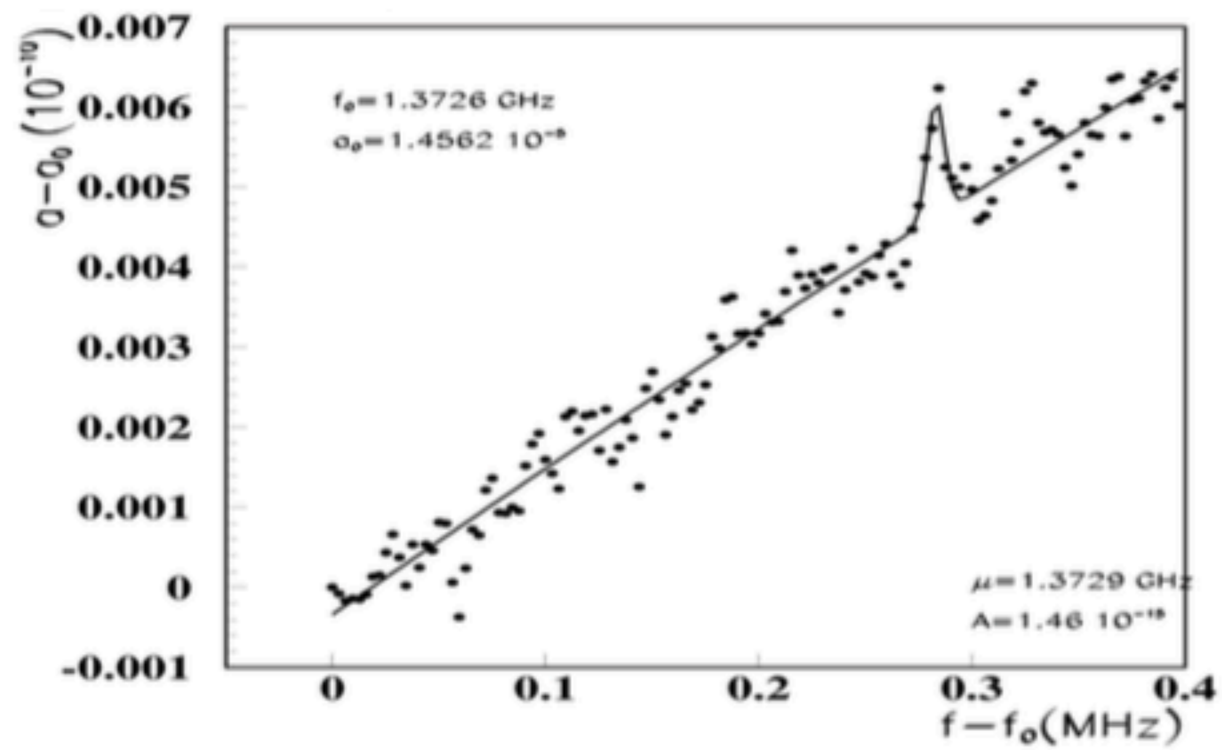
- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
- R&D on tiling

Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First measurements: sensitivity



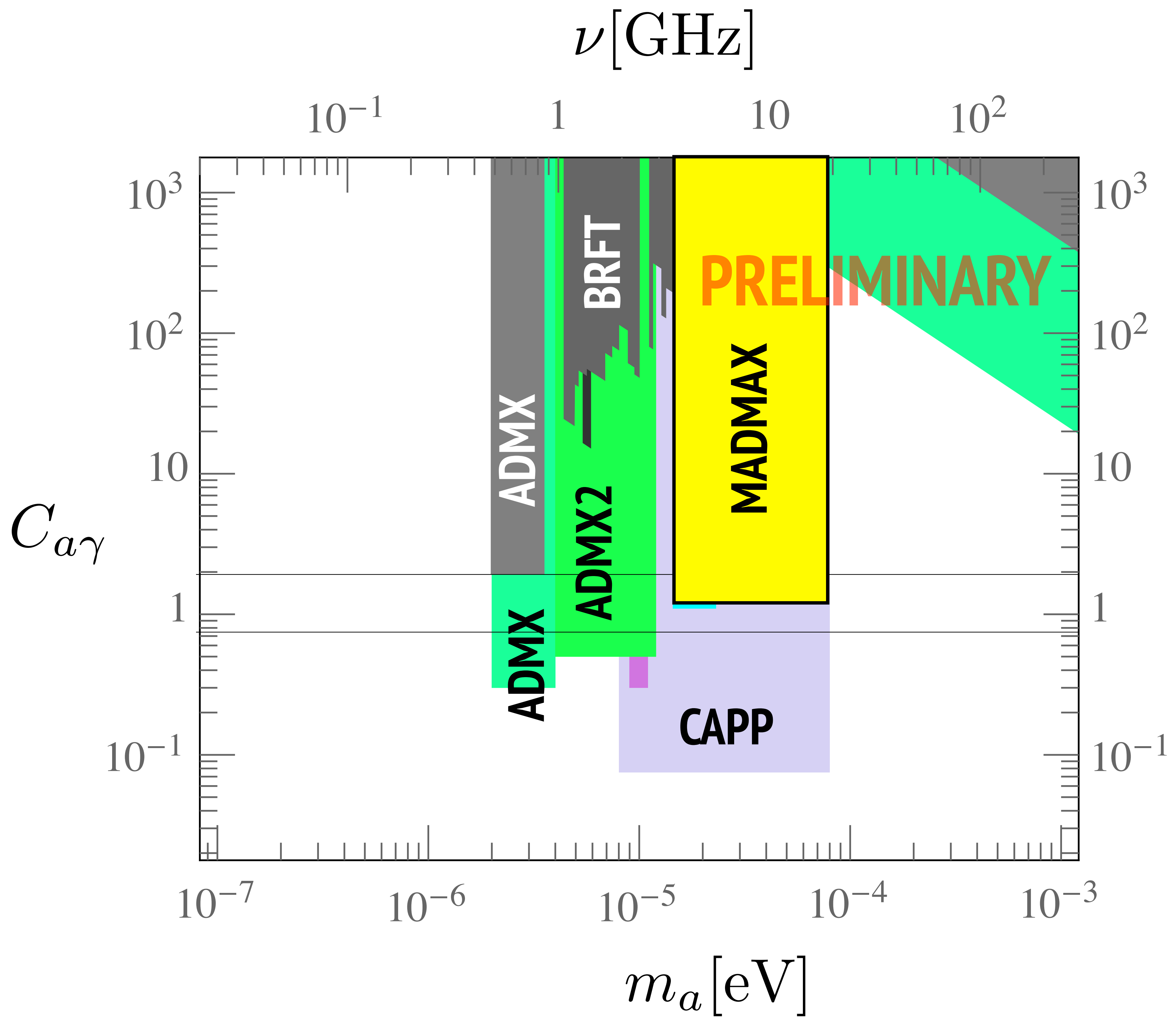


- Inject fake axion signal with **3·10^{-21}** W power
- Mesurement for one week (integrate signal): Receiver at Room Temp.

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

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

Sensitivity (10 T, 1 m^2, 5K, 5 years, boost=100)



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

Conclusions

- Strong CP problem and dark matter motivate <u>Axions</u>

- Most predictive model (N=1) mass~ 0.1 meV (fa ~ 10^11 GeV)

- Many experimental efforts, solid player missing in that range

- MW emission from interfaces is weak , make layered haloscope

- Munich Axion Dark MAtter eXperiment

SMASH : Standard Model Axion See-saw Hidden scalar inflation