MAD MAX

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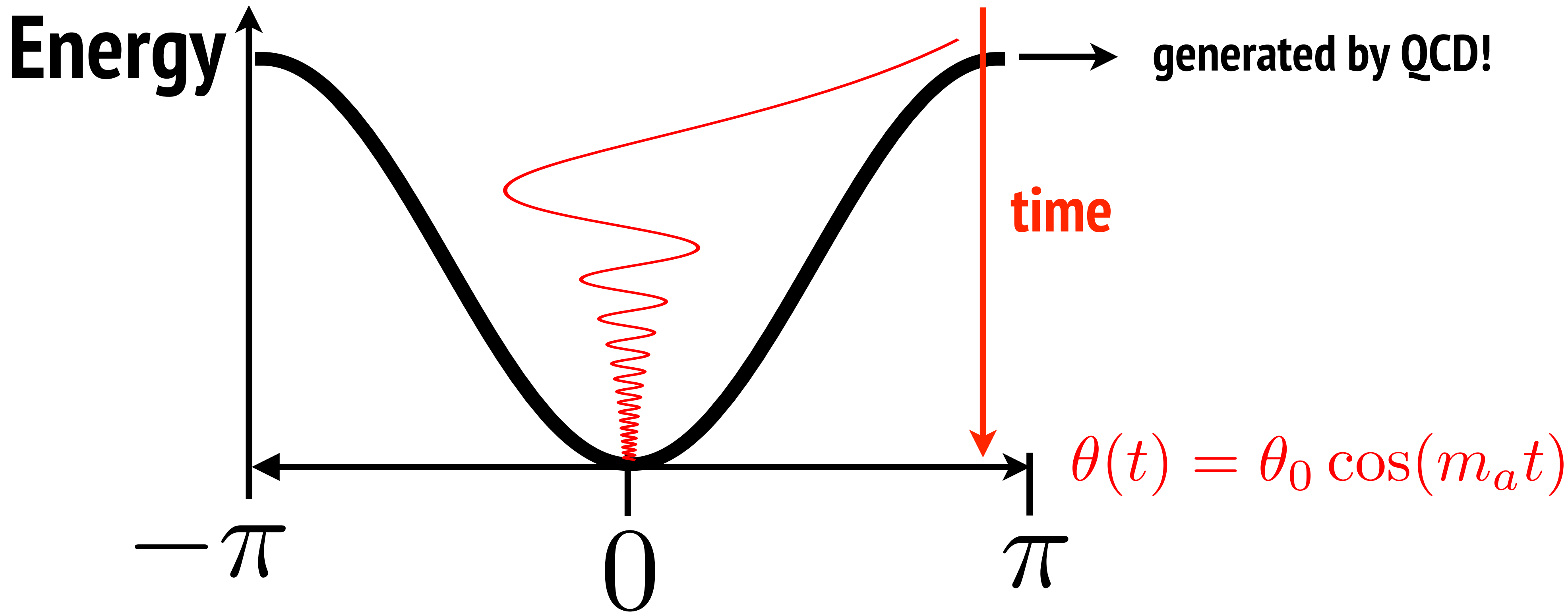
Axions are necessarily dark matter

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

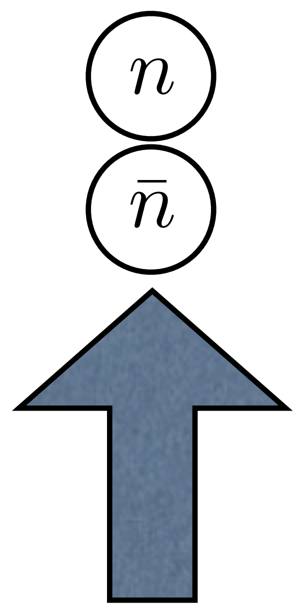


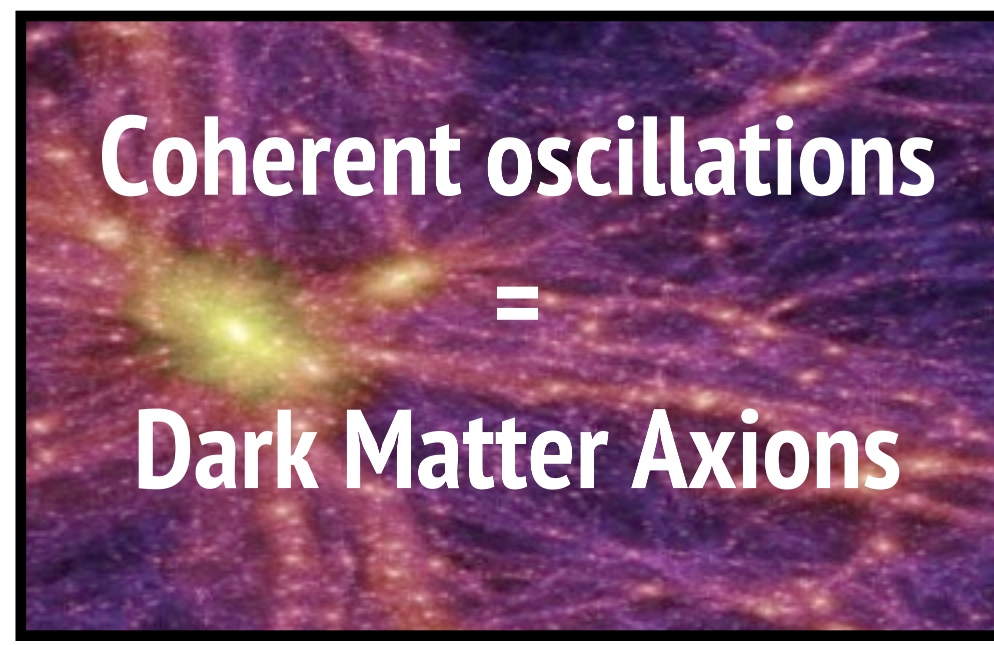
~ One parameter theory

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

axion mass

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

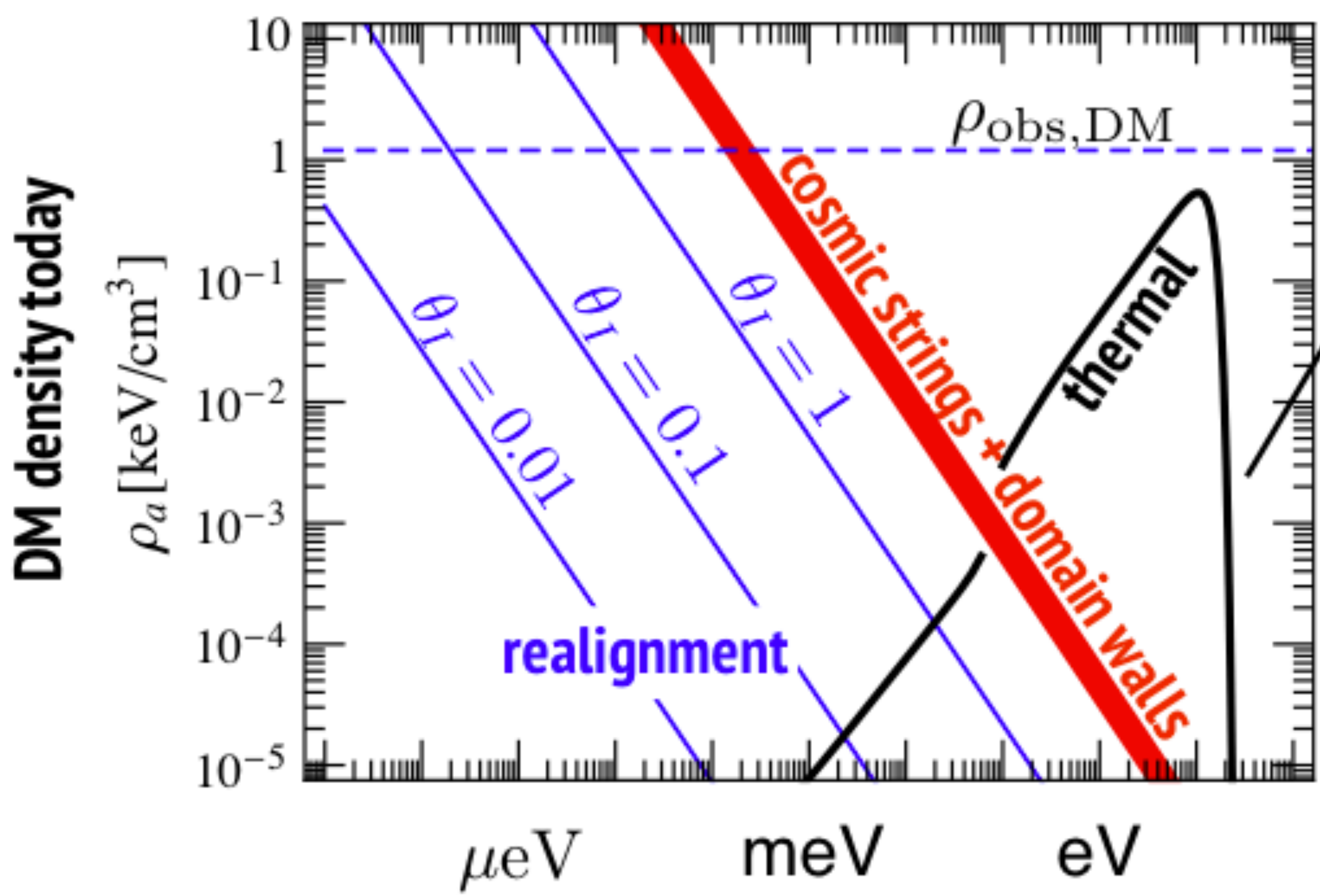


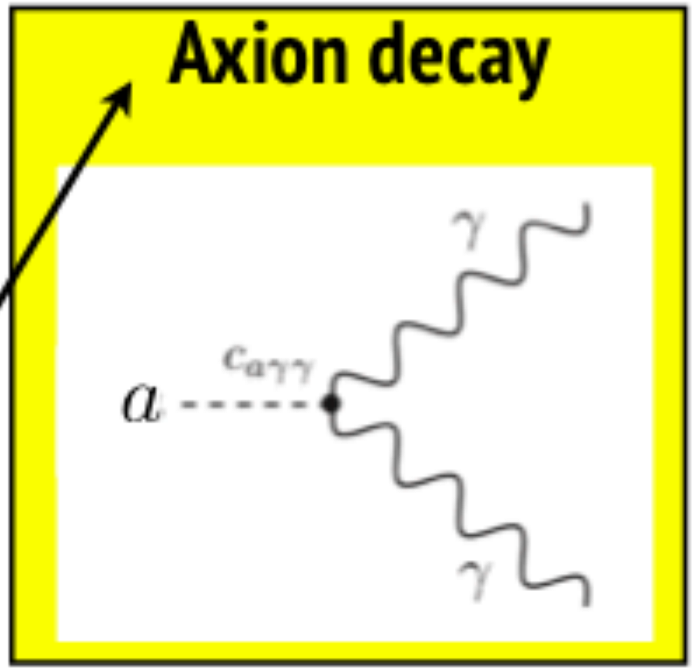


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

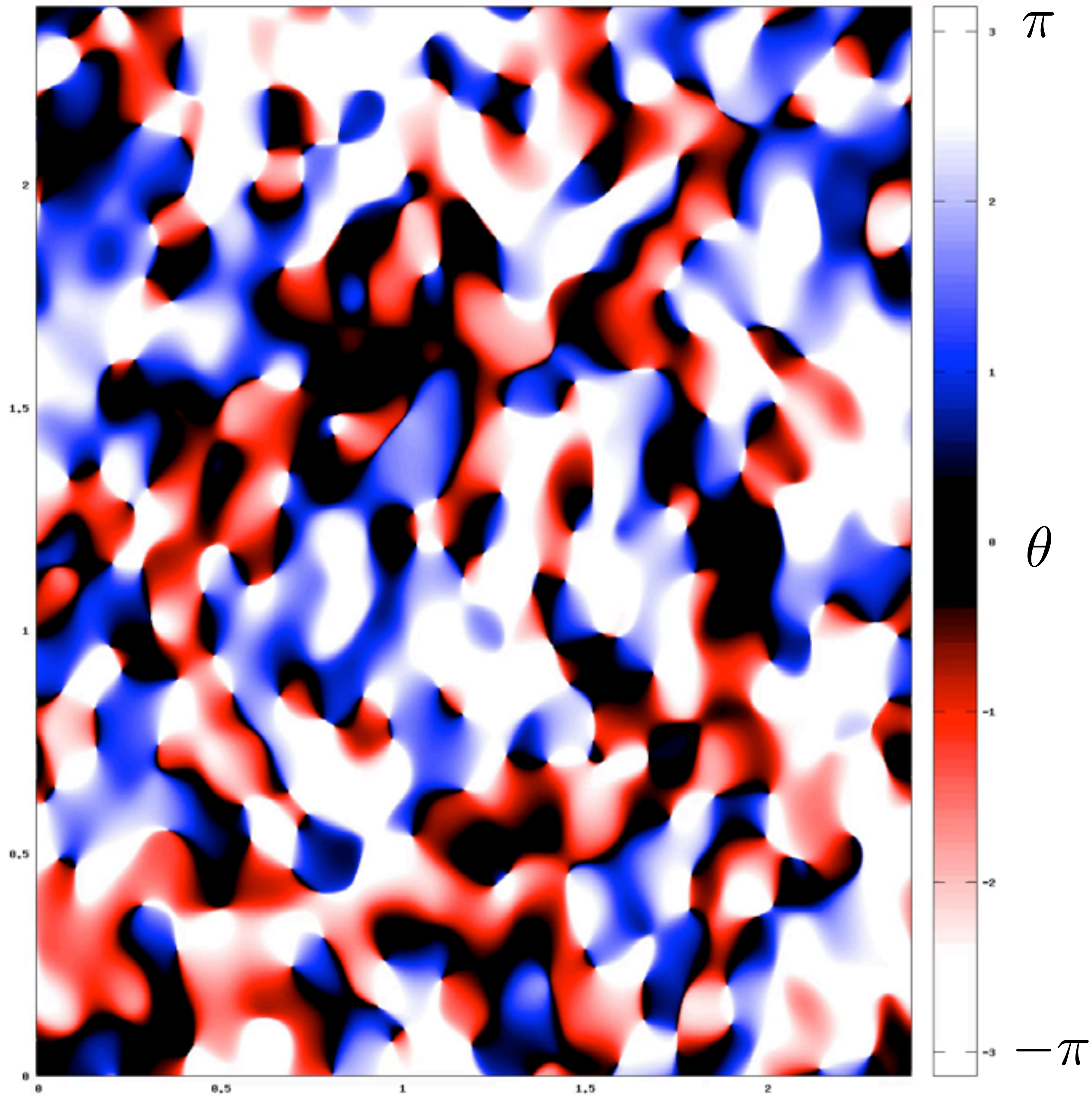
Relic density as function of mass

- Random IC (after a phase transition)
- One Universal IC (inflation smoothens the axion field)

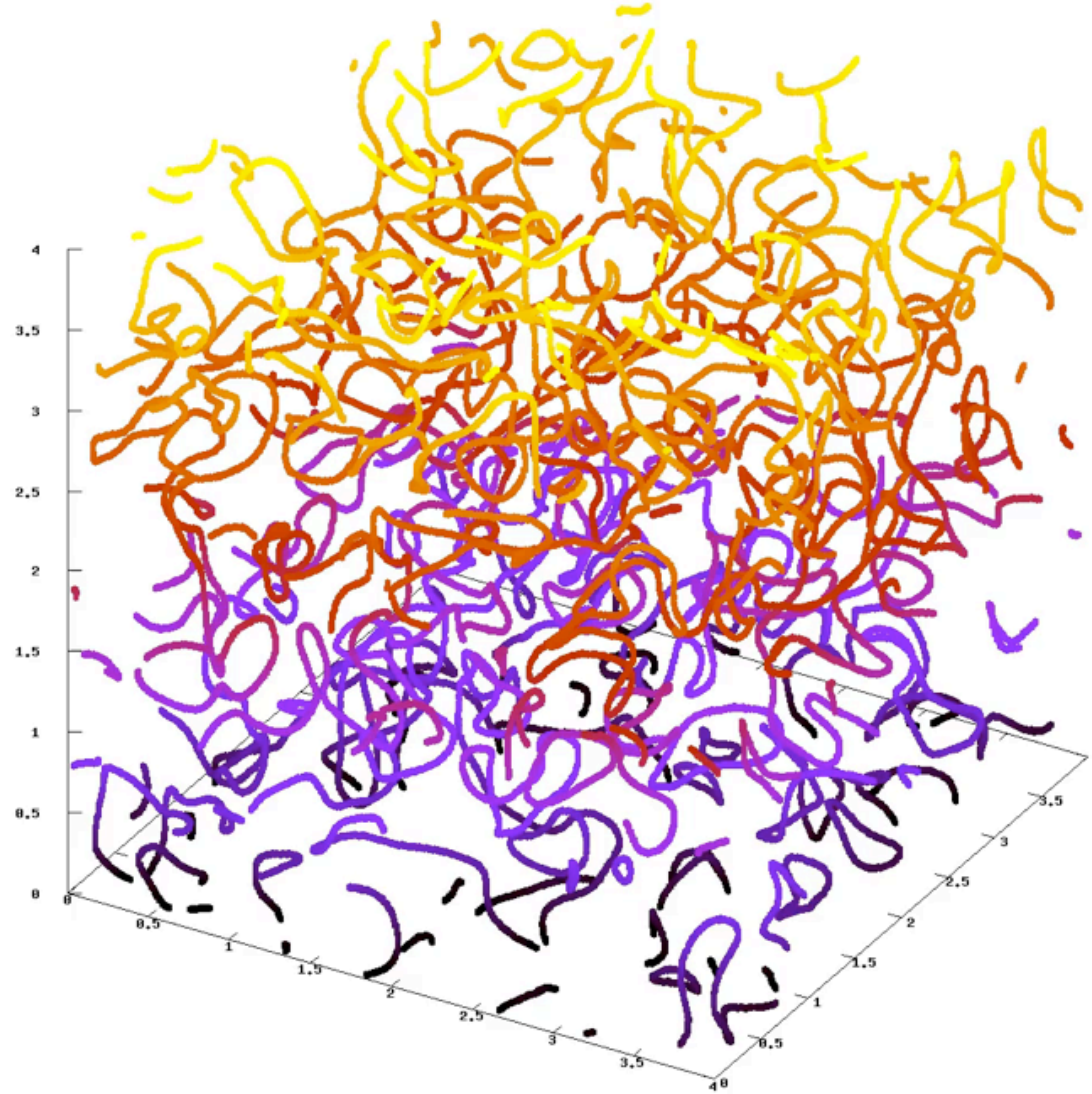




Theta evolution, Averaged SCENARIO I

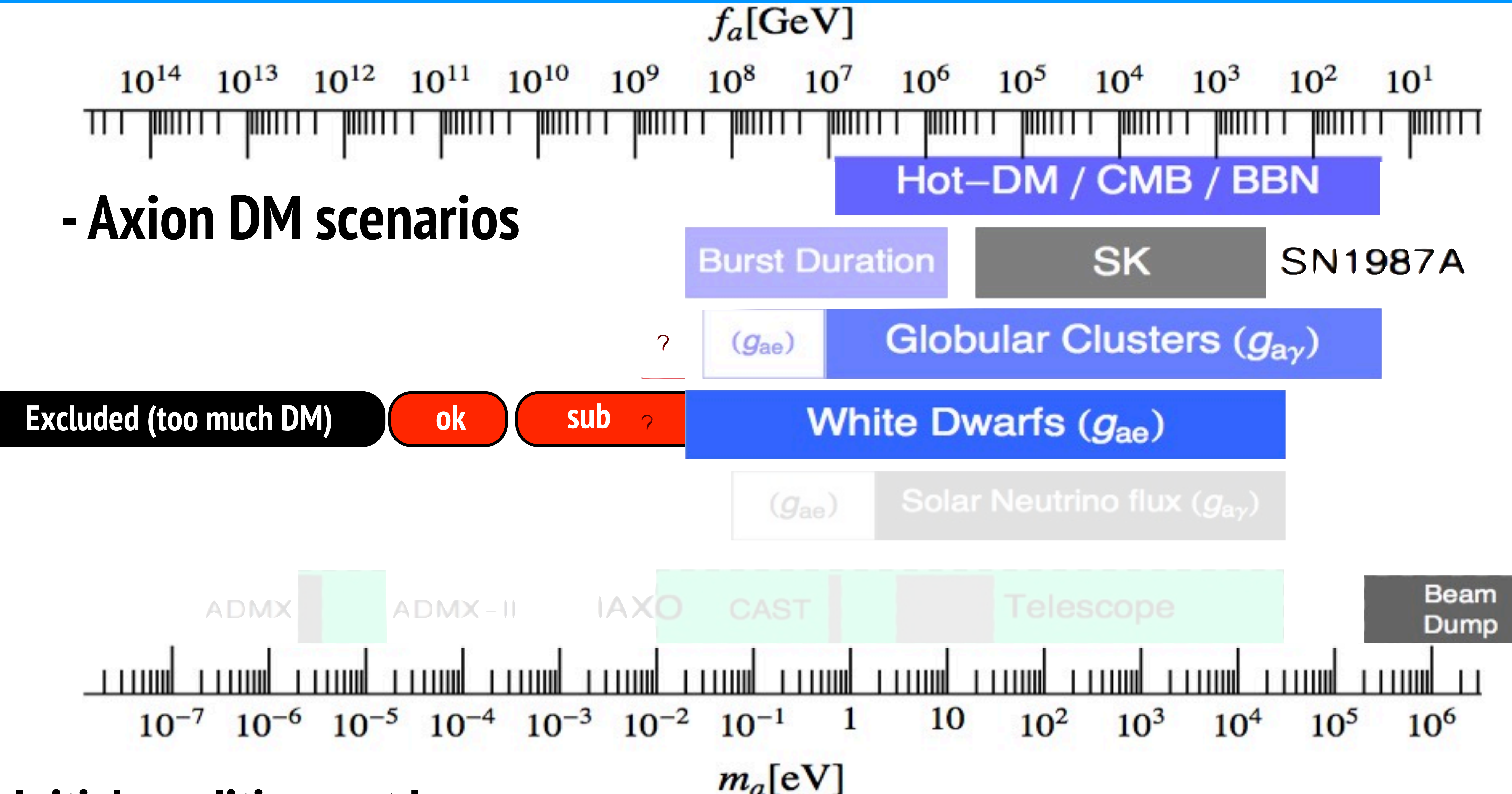


DM dominated by string radiation



Axion dark matter

- Axion DM scenarios

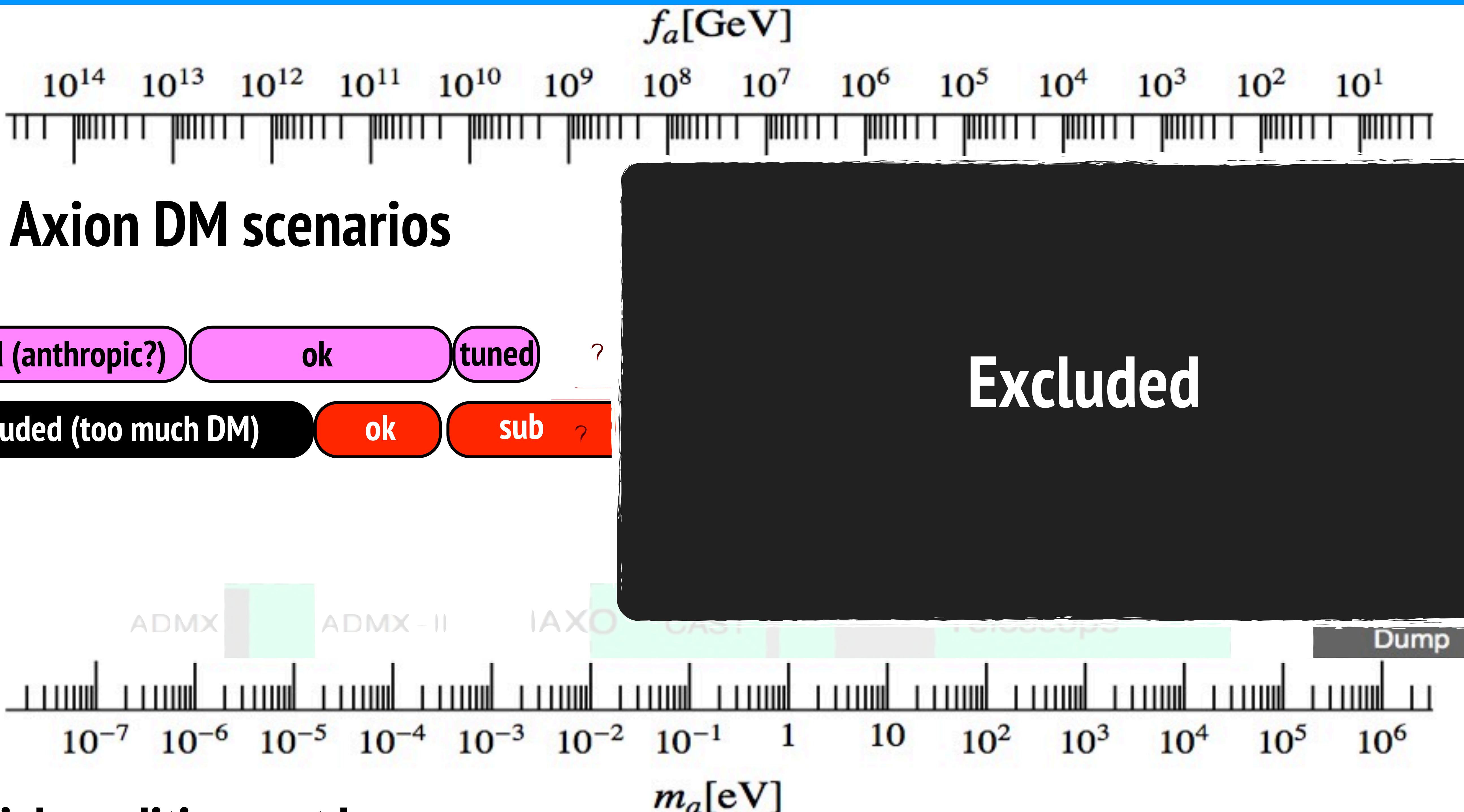


Initial conditions set by :

Phase transition (N=1)

strings+unstable DW's

Axion dark matter



Initial conditions set by :

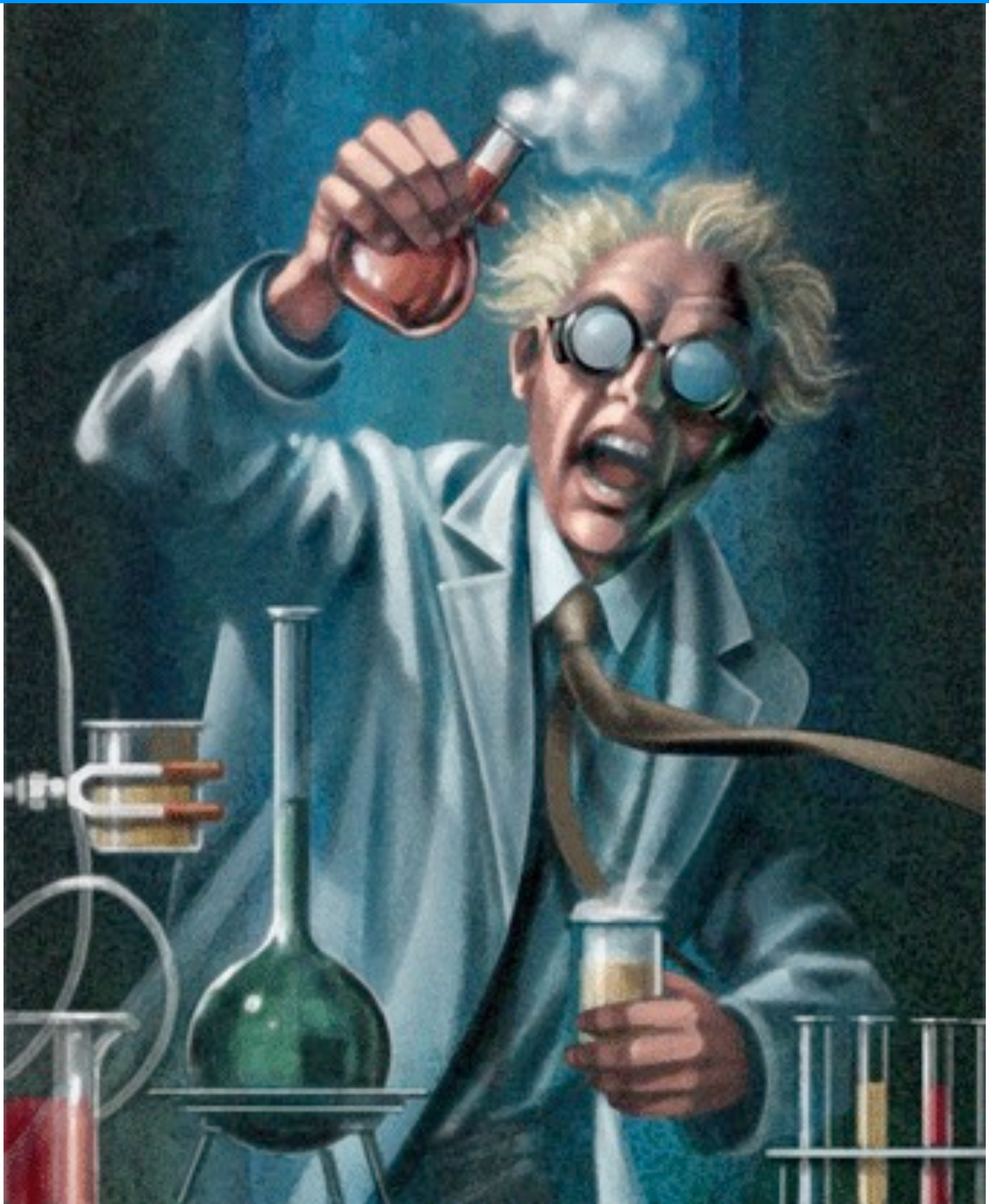
Inflation smooth

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

Phase transition (N=1)

strings+unstable DW's

Detecting Axions



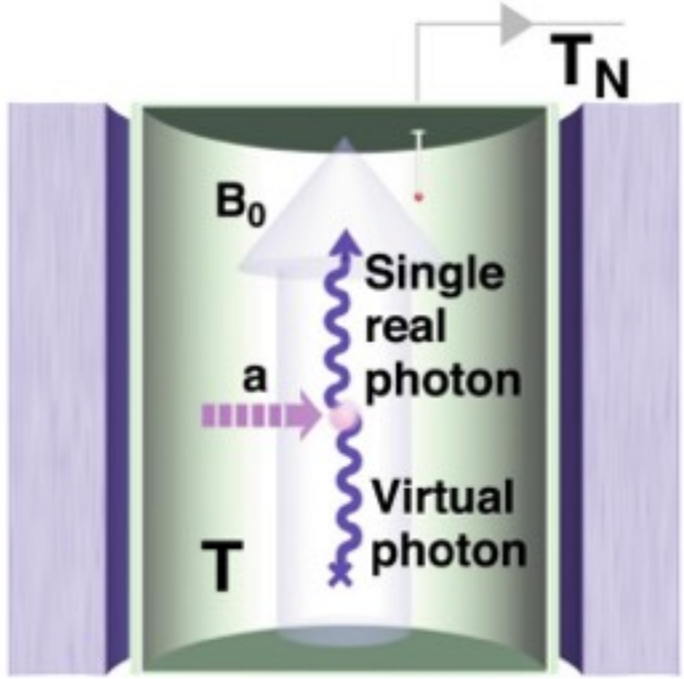
$$\rho_{\mathrm{aDM}} = 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

$$\rho_a = \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2 = \frac{1}{2}m_a^2 f_a^2 \theta_0^2$$

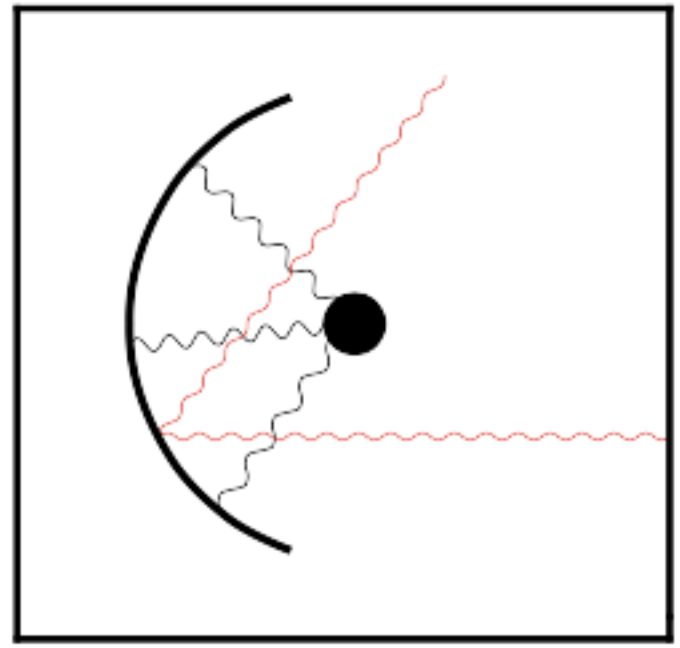
$$V_{\theta\theta}$$

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

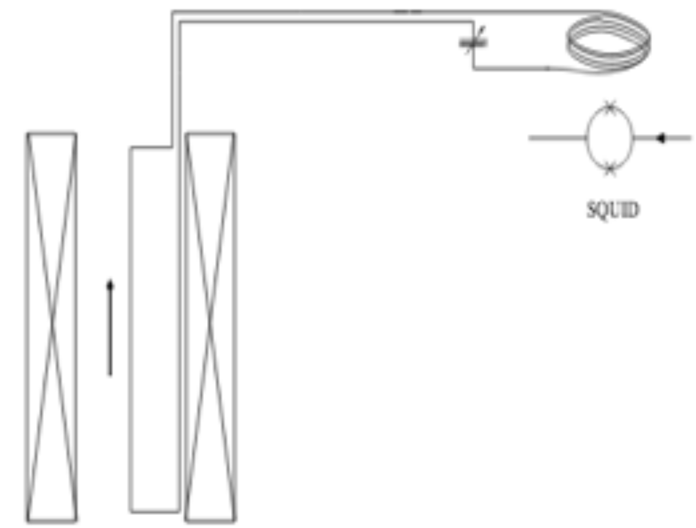
Cavities



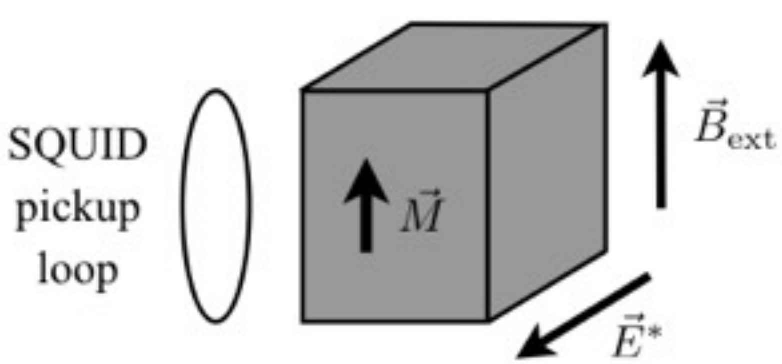
Mirrors



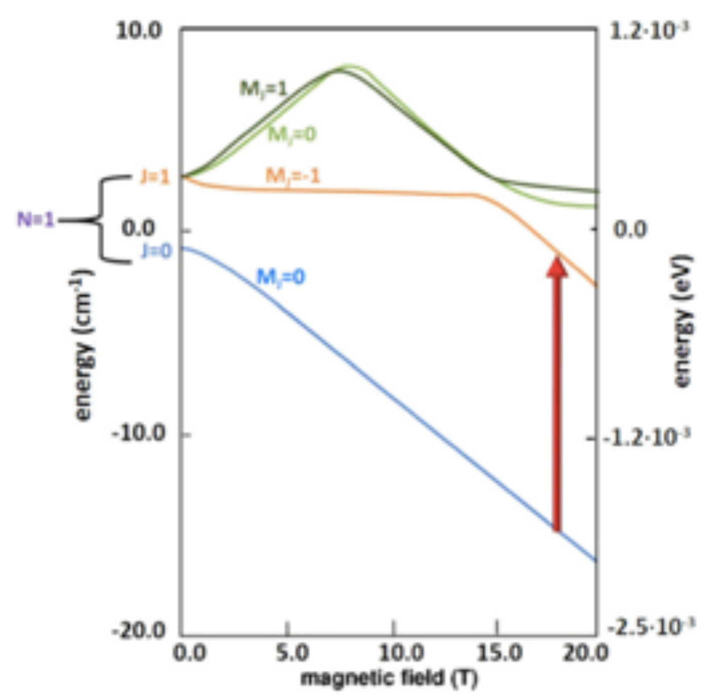
LC-circuit



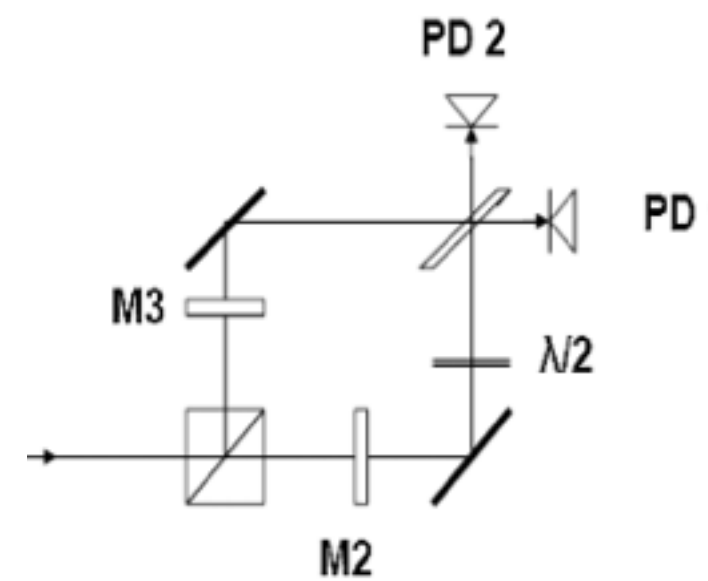
Spin precession



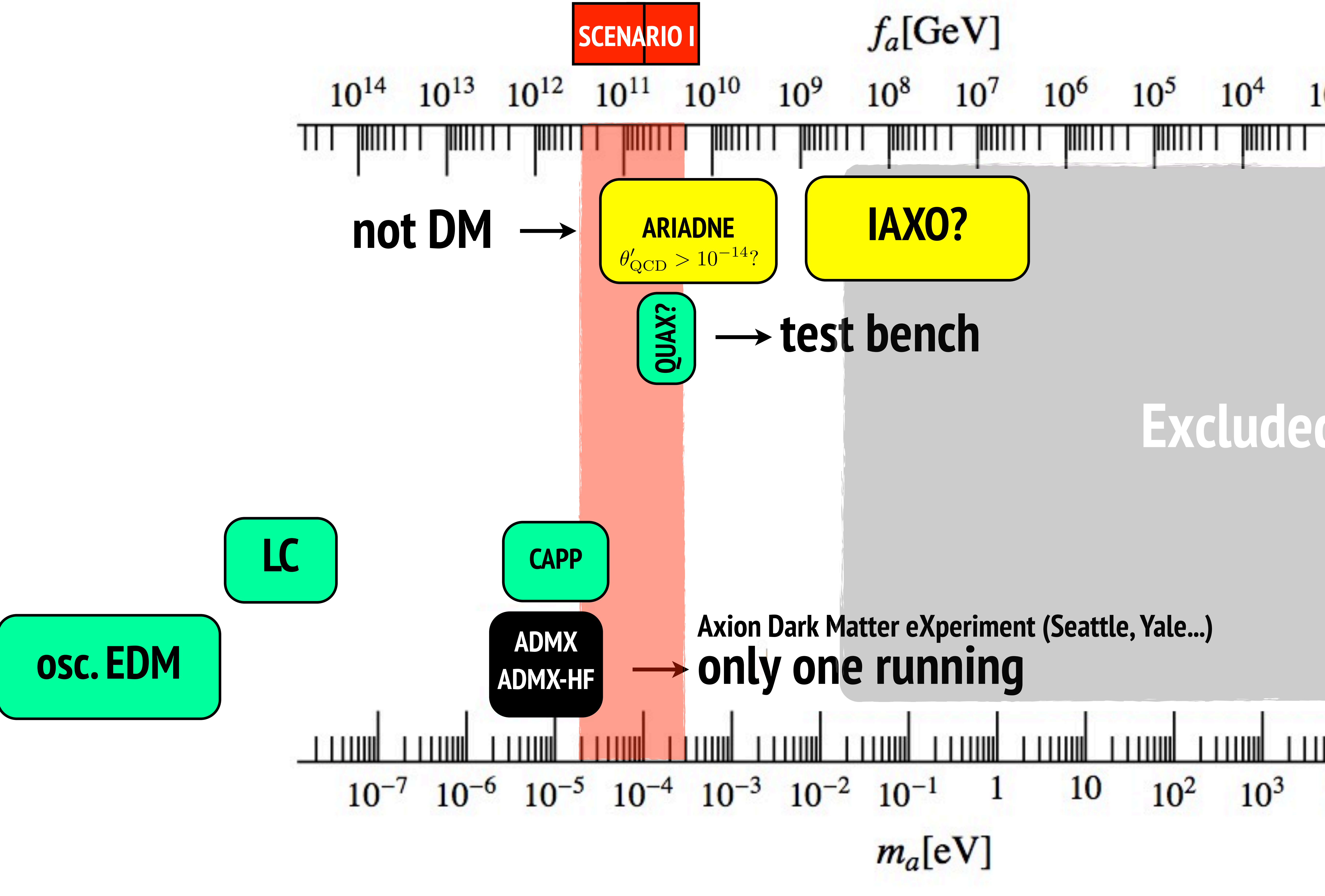
Atomic transitions



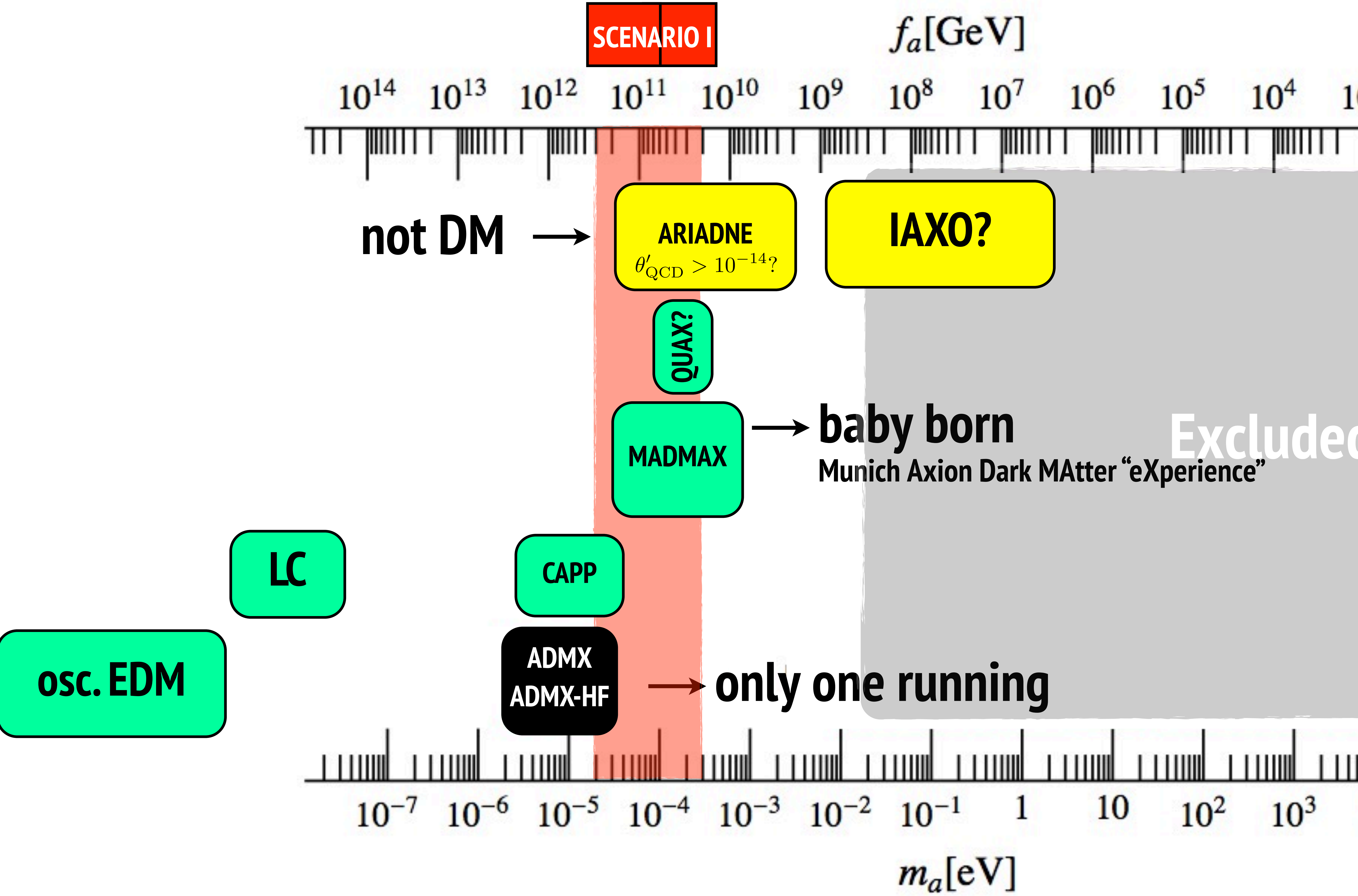
Optical



Axion experiments (target areas)



Axion experiments (target areas)



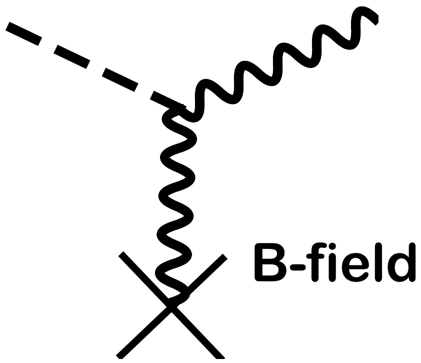
Axion DM in a B-field

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

- 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

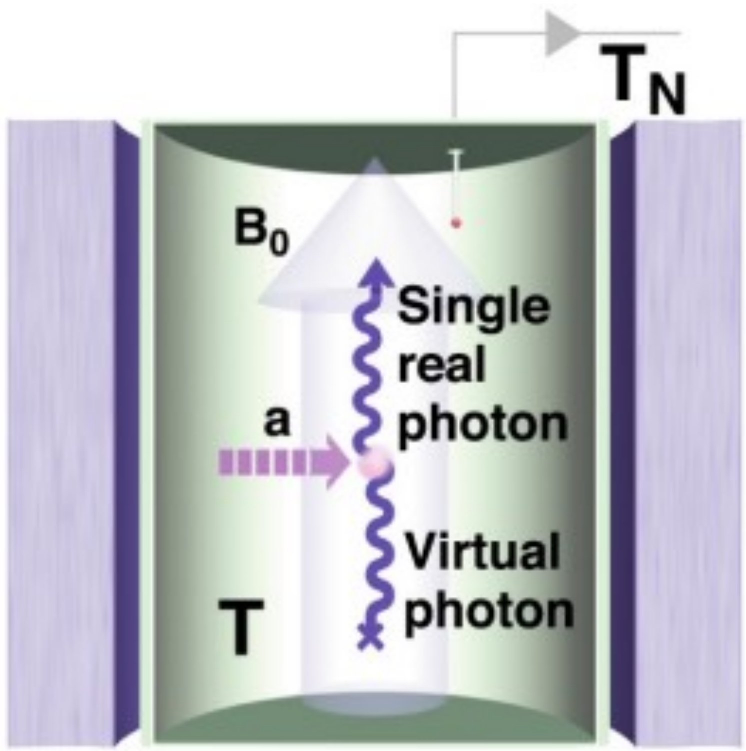


- Electric fields $\mathbf{E}_a = C_{a\gamma}\frac{\alpha\mathbf{B}_{\rm ext}}{2\pi}\theta_0\cos(m_a t)$ (amp independent of mass!)

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

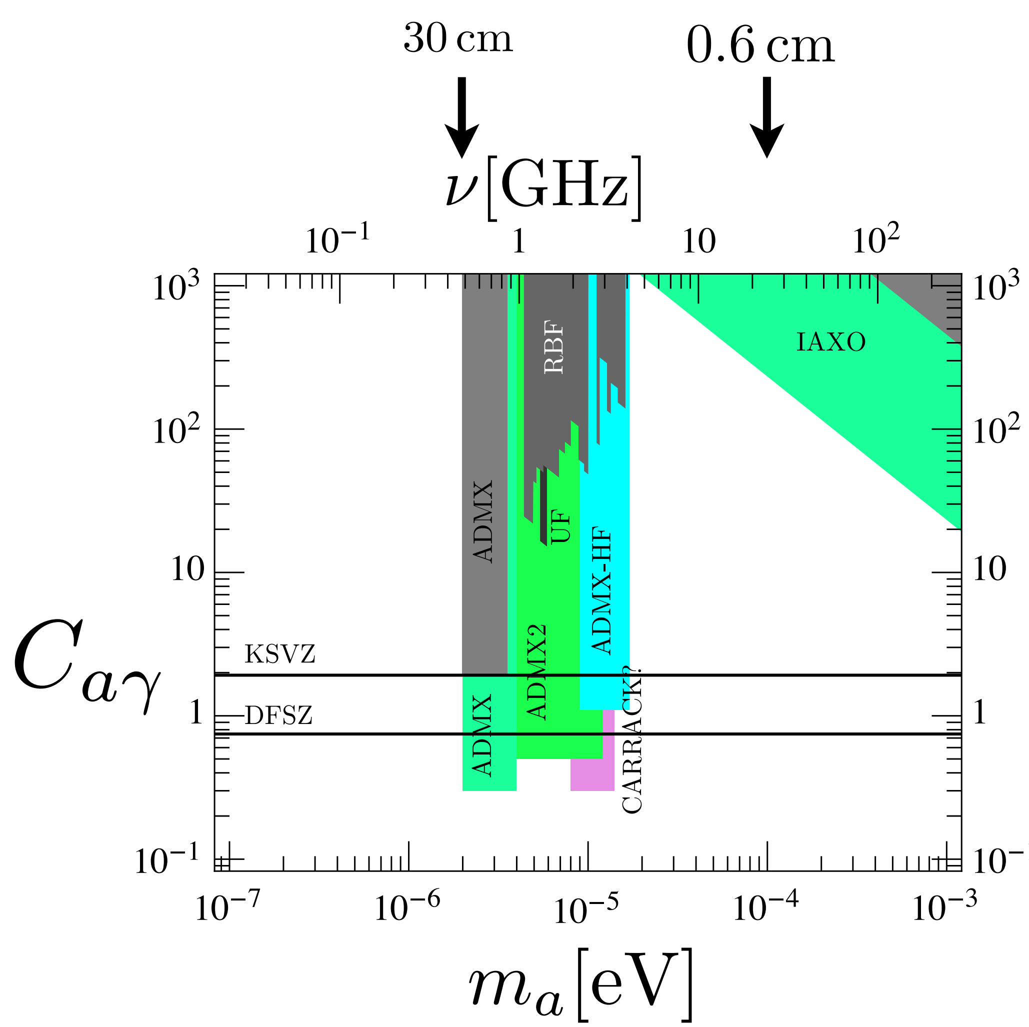
Resonant cavity experiments

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



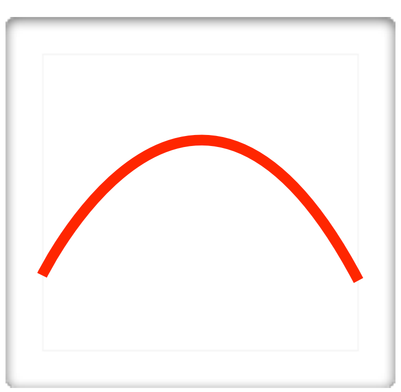
Output EM power $P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$

on resonance $\nu_{\rm res} = \frac{m_a}{2\pi}$



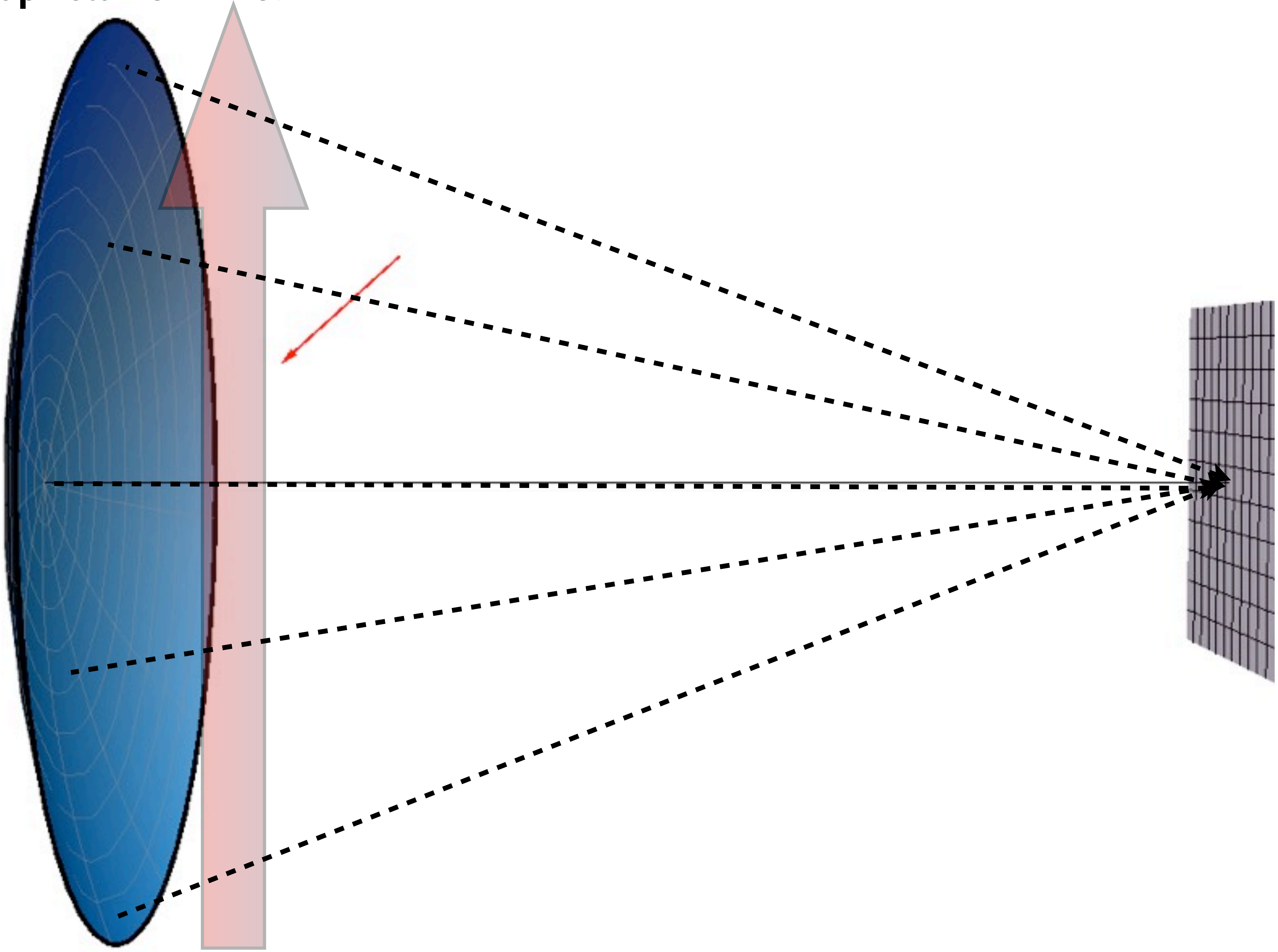
- Noise $\quad P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$

- Signal $\quad (V \propto m_a^{-3}) \quad P_{\rm out} \propto V m_a \sim \frac{1}{m_a^2}$



pre MADMAX (dish antenna)

- Do not give up volume -> Area



$$D \gg \frac{1}{m_a}$$

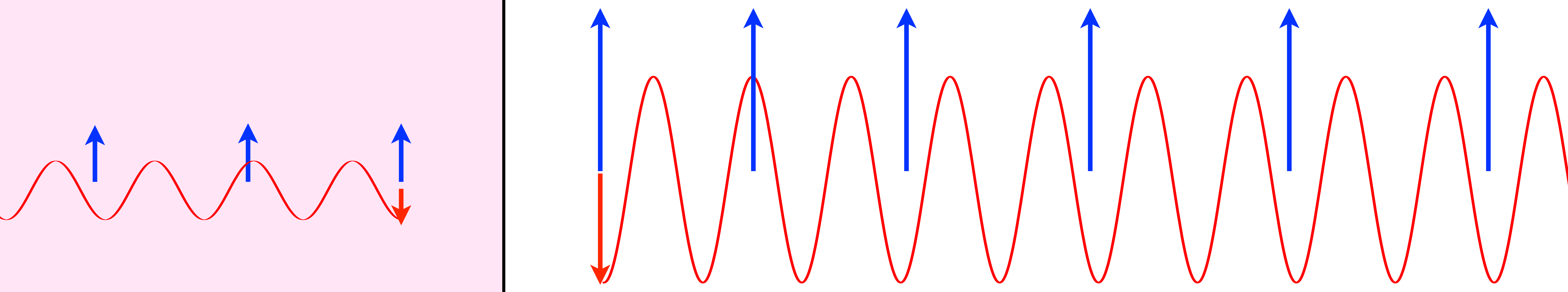
spherical reflecting dish

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

Radiation from a dielectric interface ...

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

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



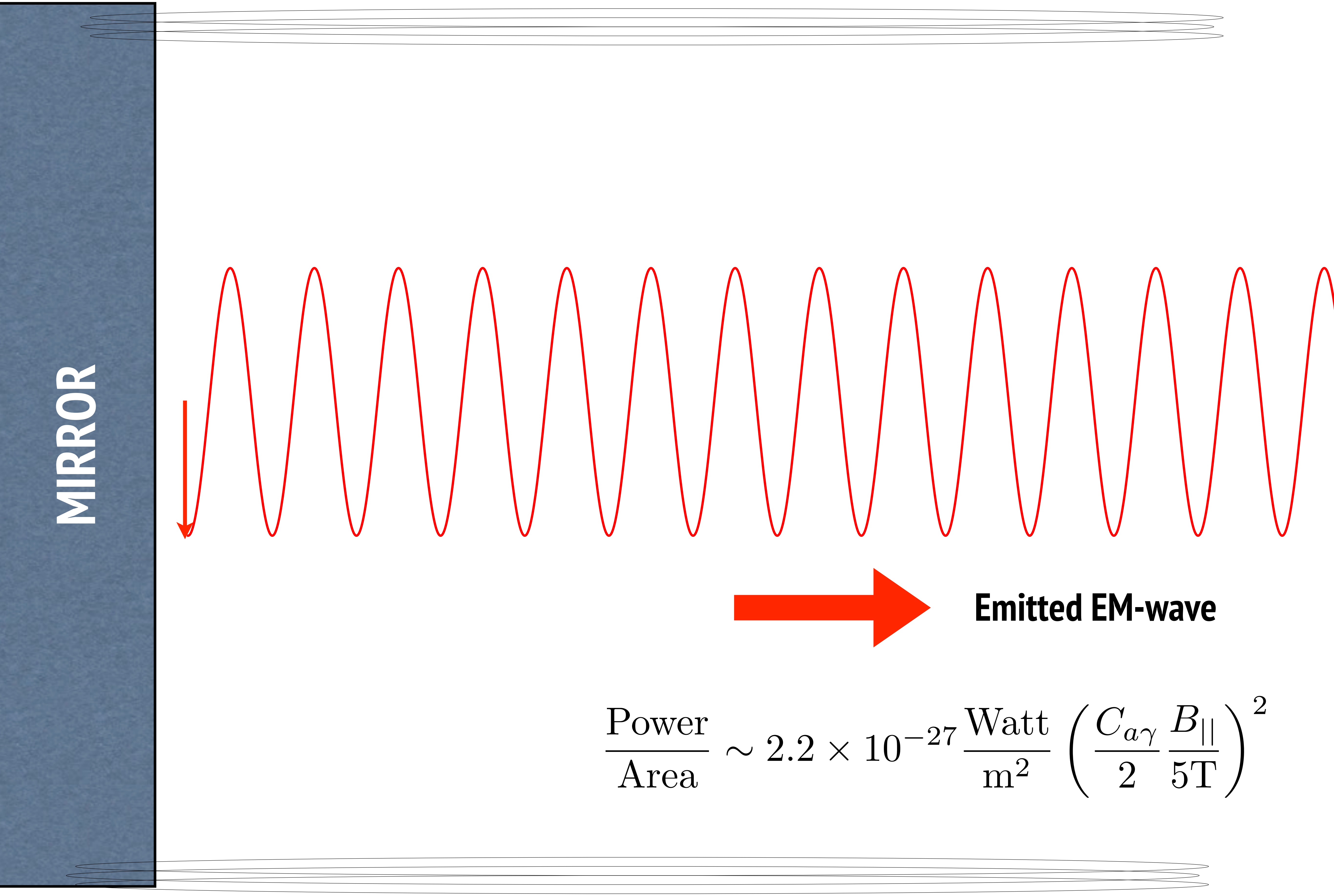
← Boundary conditions!

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

Emitted EM-wave

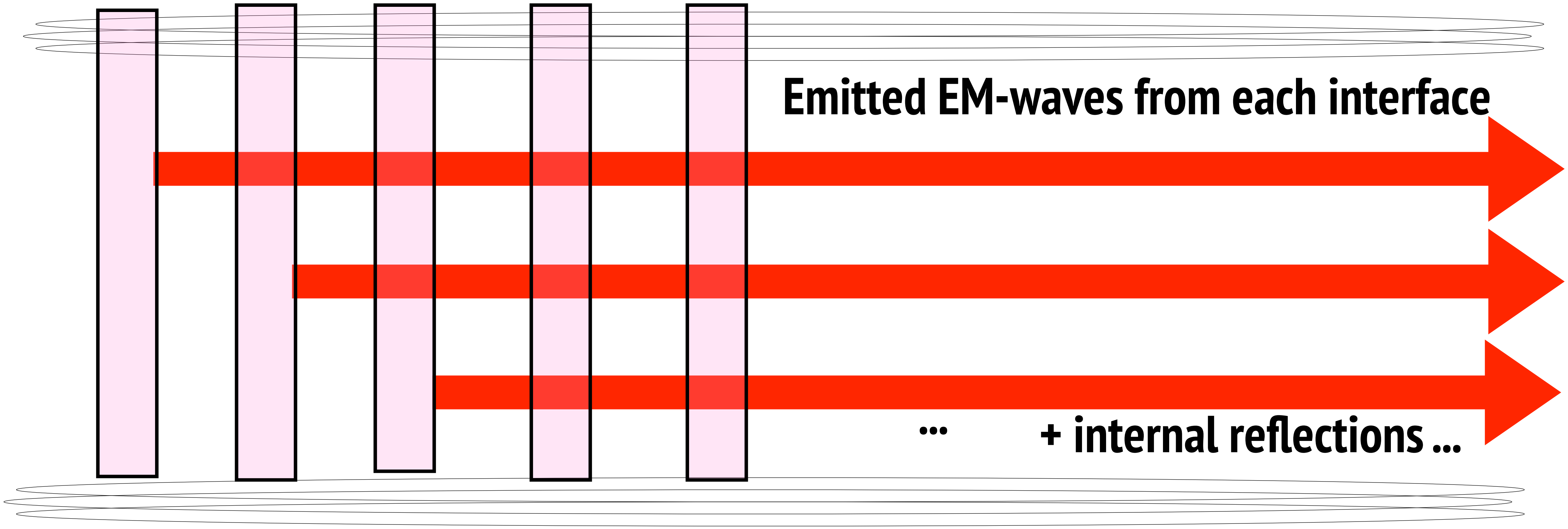
Emitted EM-wave

Radiation from a magnetised mirror : Power



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

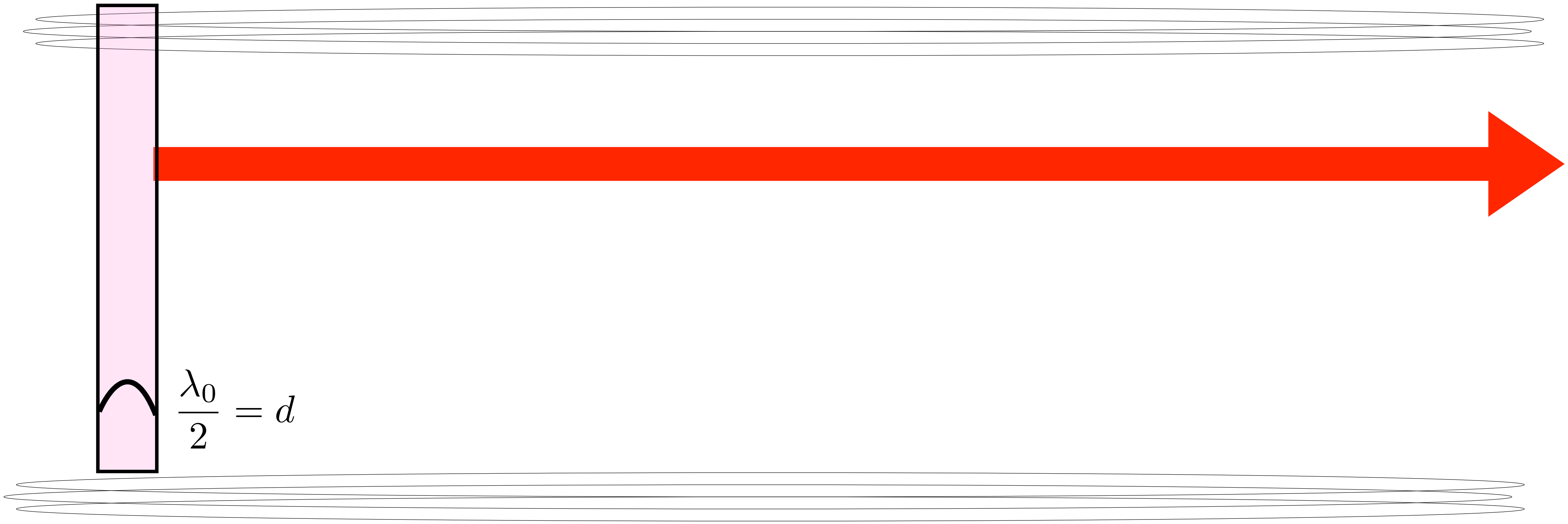
Many dielectrics : MADMAX at MPP Munich



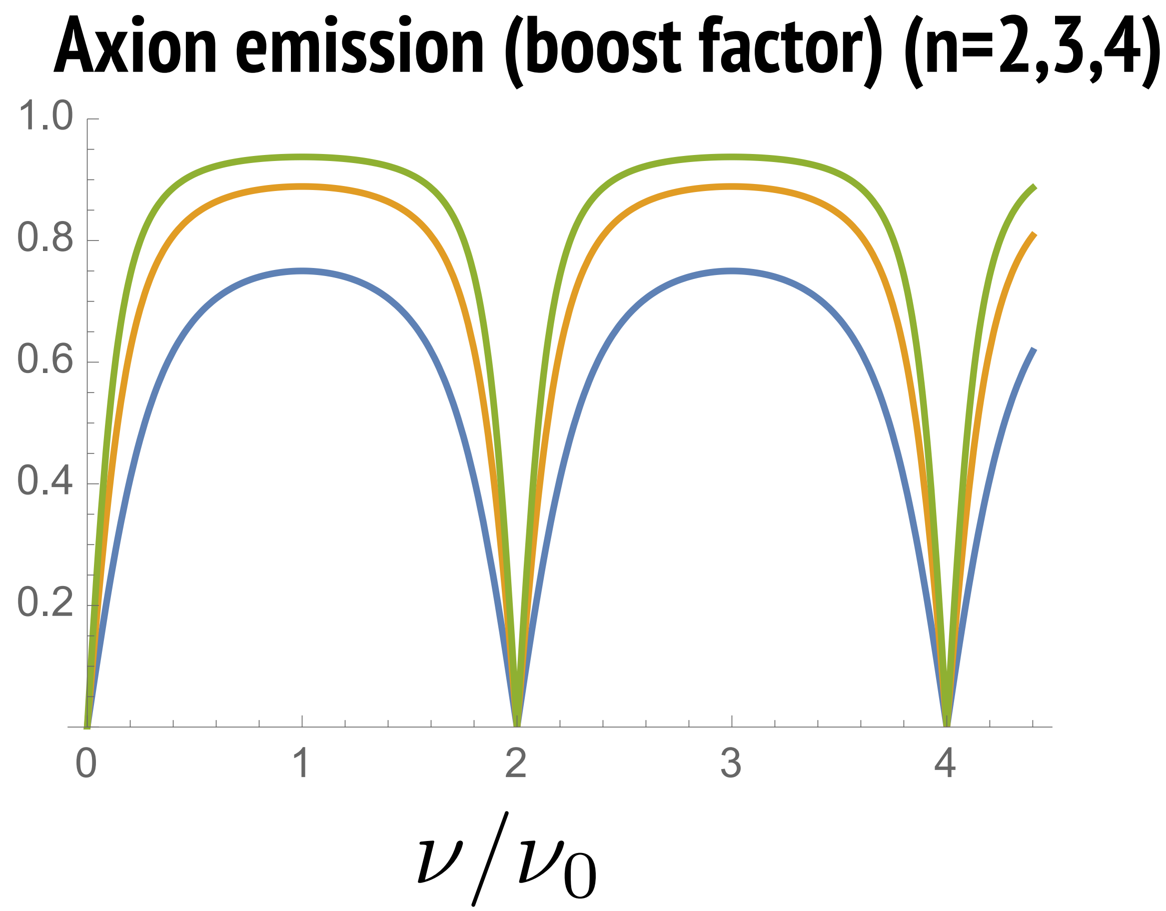
- Emission has large spatial coherence; adjusting plate separation -> coherence

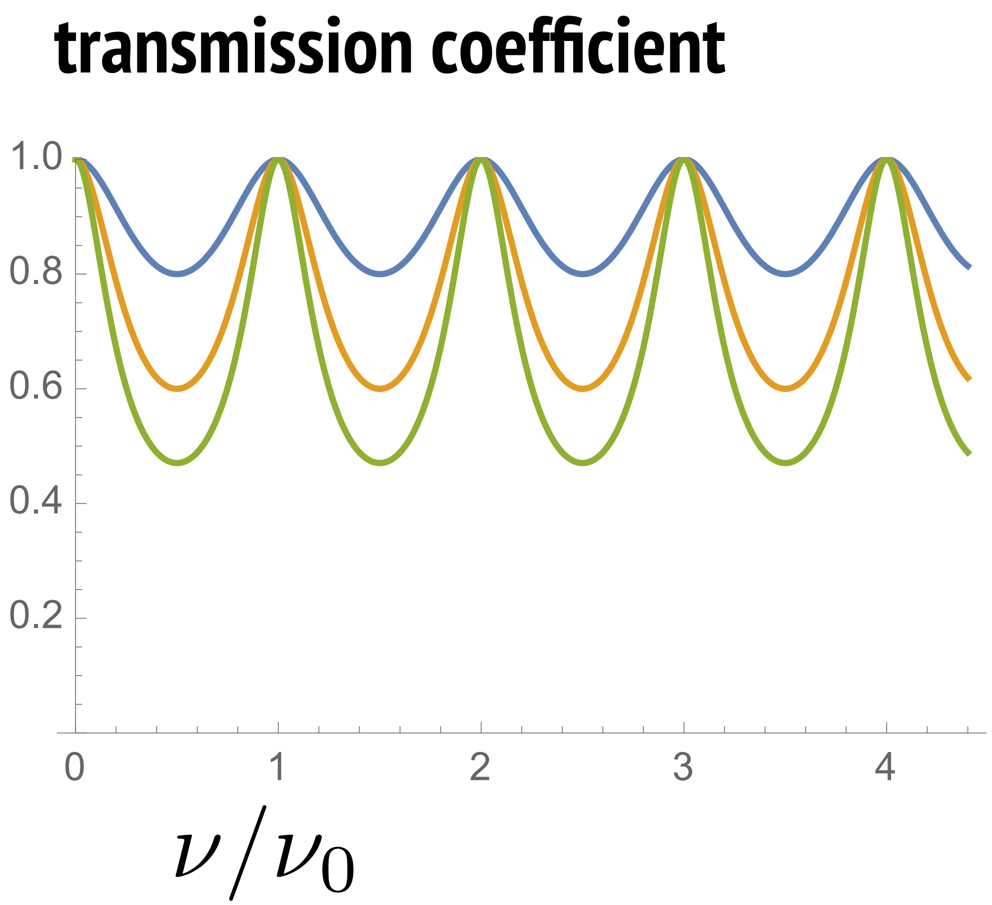
$$\frac{P}{Area} \sim 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(C_{a\gamma} \frac{B_{||}}{10\mathrm{T}} \right)^2 \boxed{\times \beta^2(\omega) \quad \textbf{boost factor}}$$

One dielectric

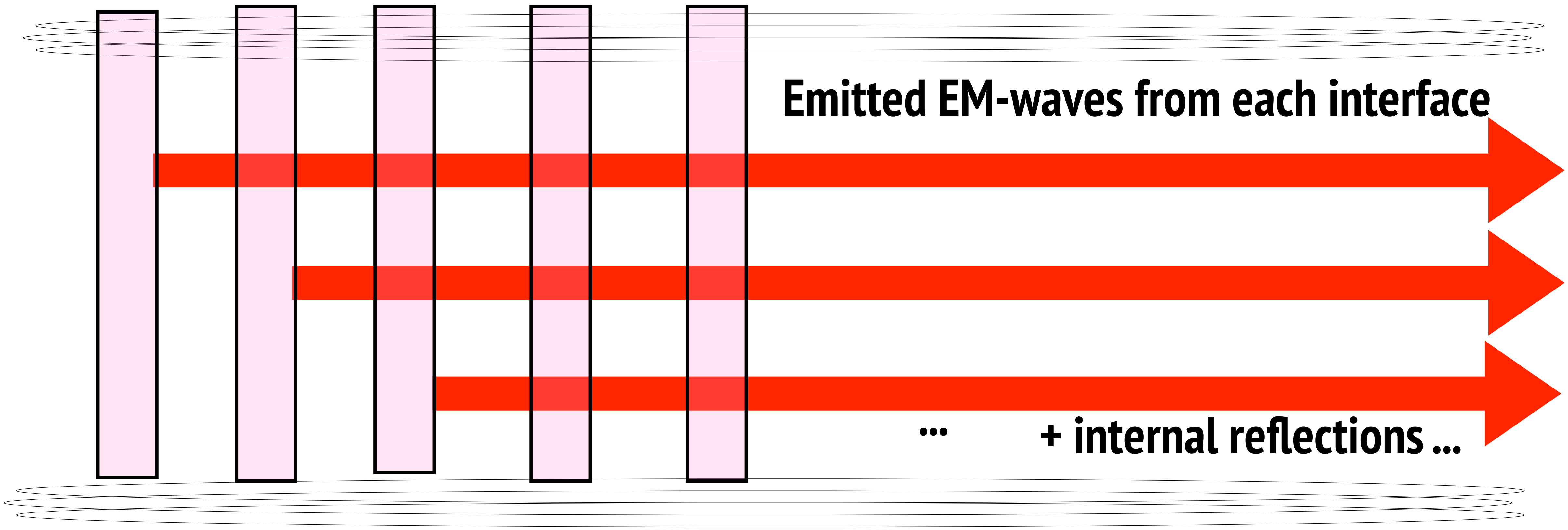


- **Frequency response**

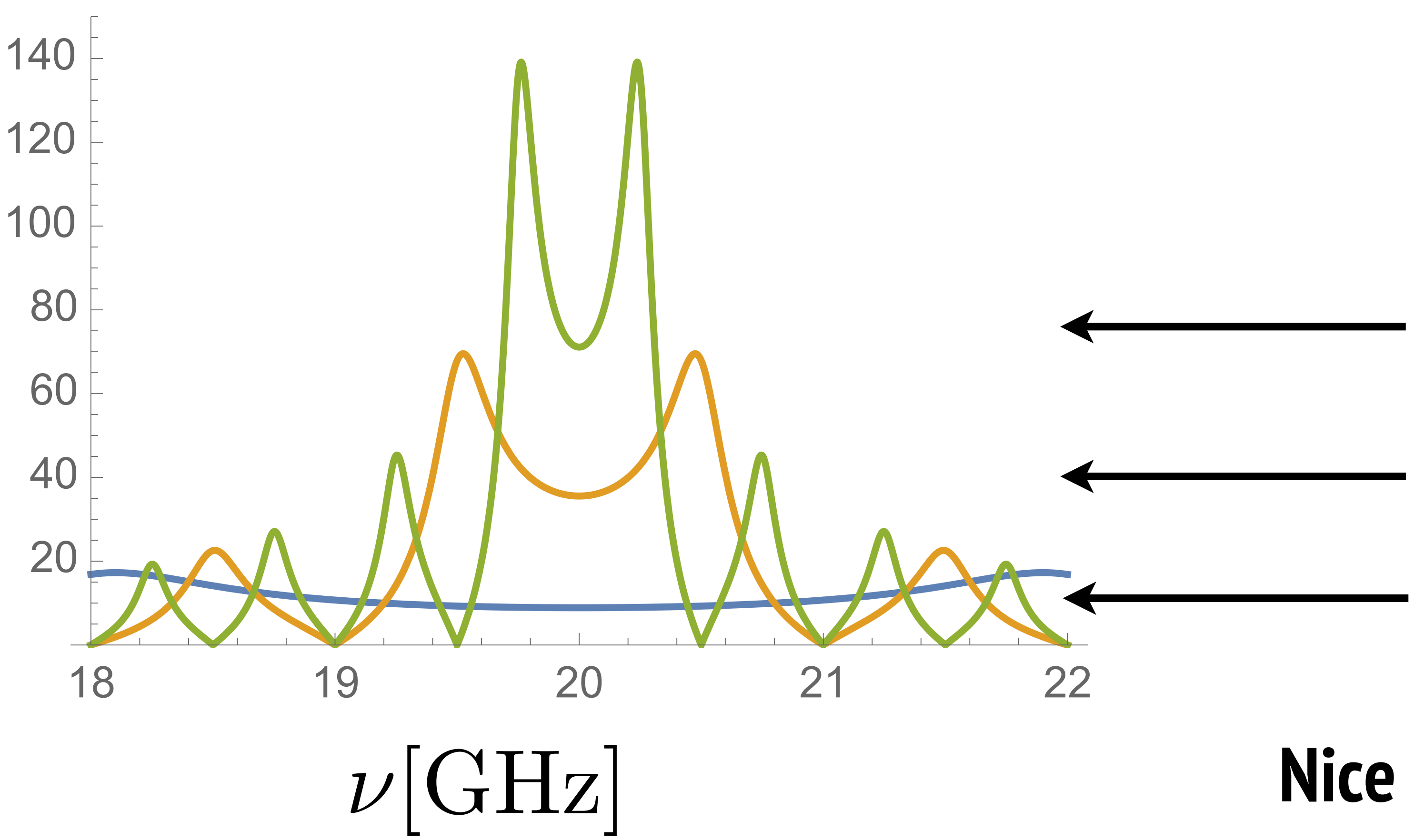




Close to nu0, many layers



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

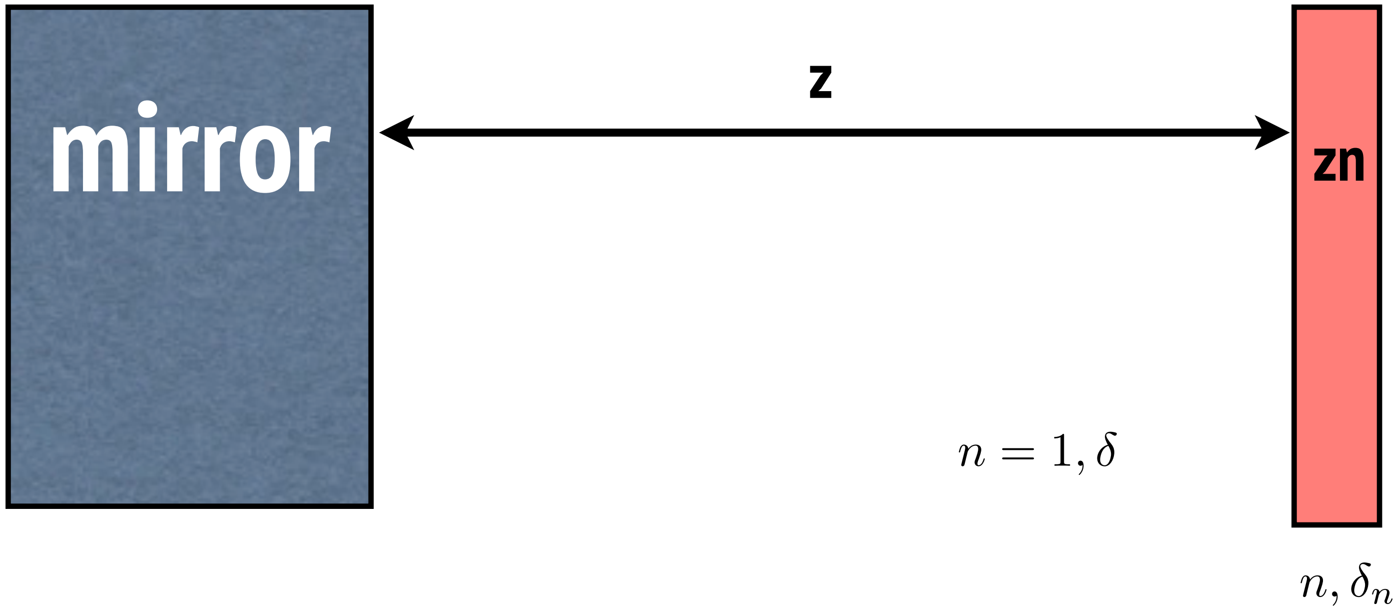


$$\beta_N \sim N \times \beta_1$$

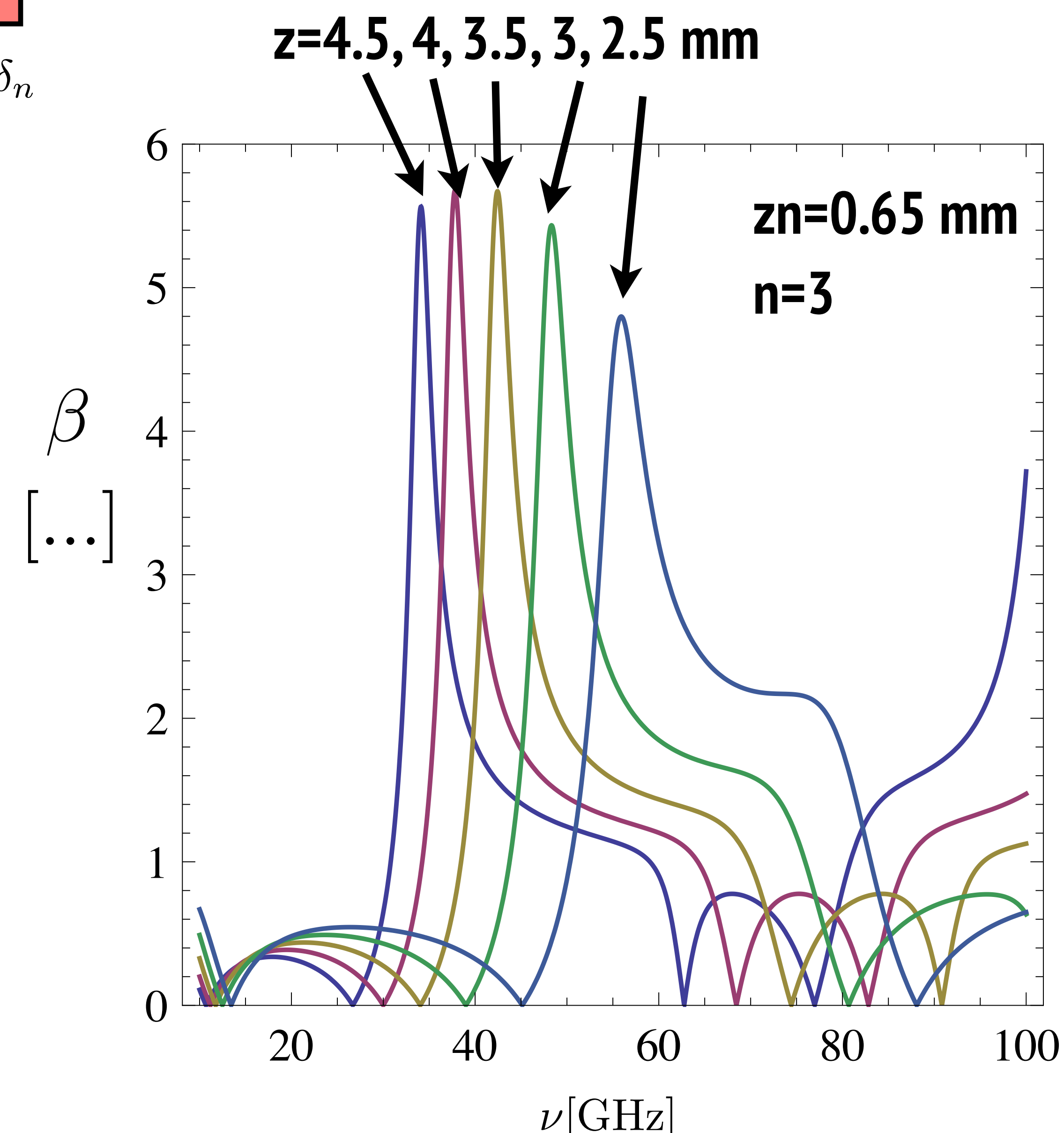
Nice boost, excellent bandwidth!

Close to 2nu0, cavity effects

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



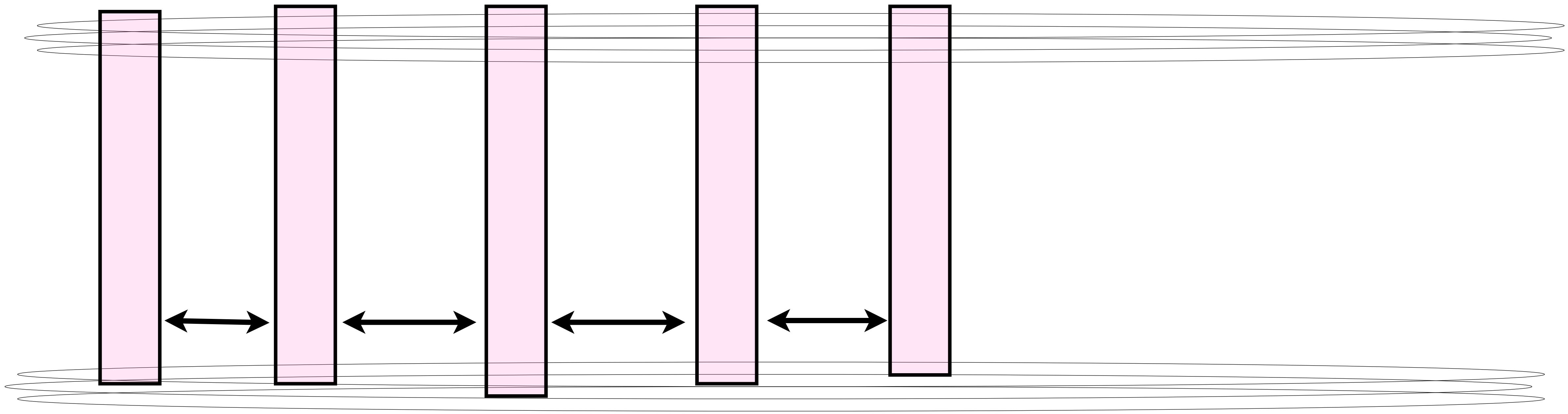
Maximum effect for $z = \frac{\lambda}{2}, z_d = \frac{\lambda'}{4} = \frac{\lambda}{4n}$



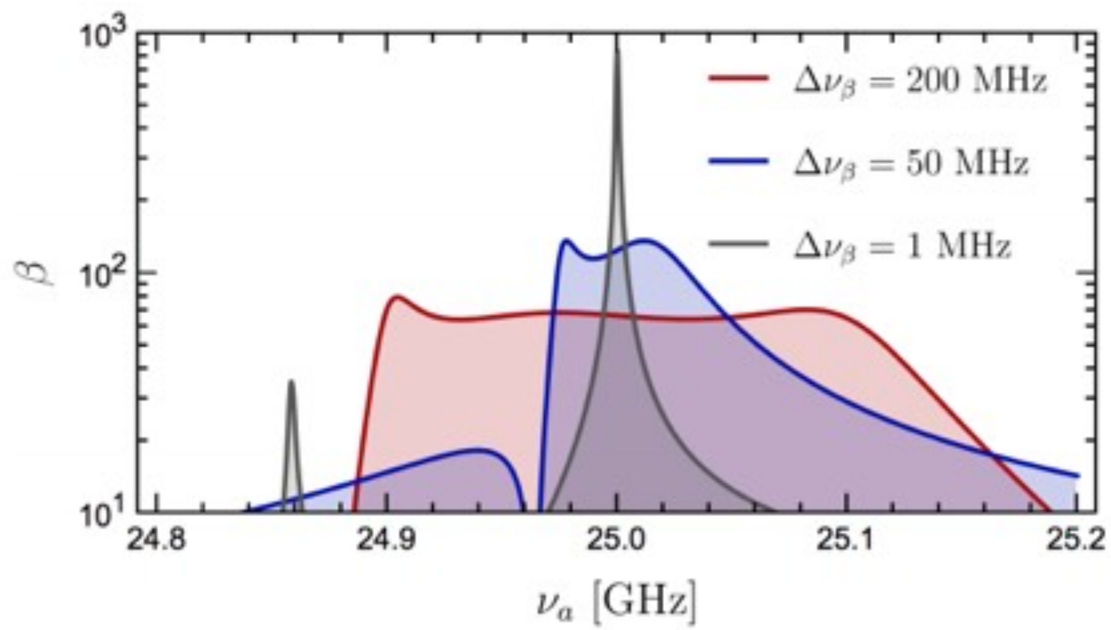
tuning

JCAP 1701 (2017)

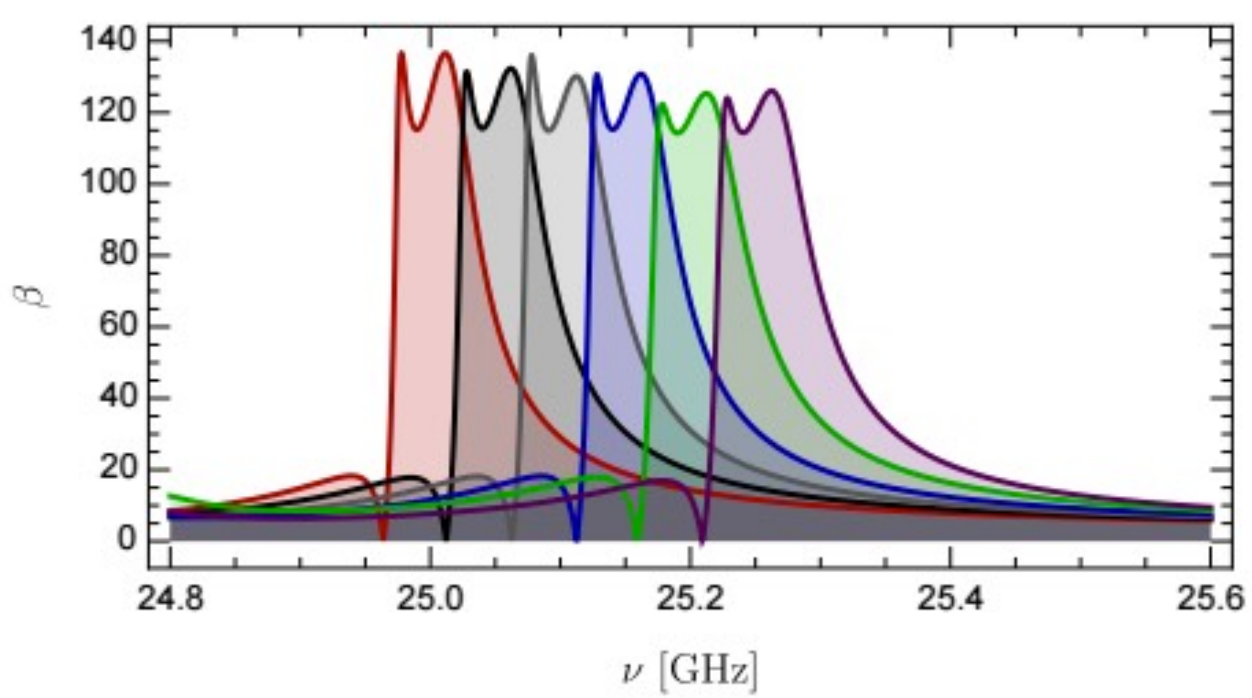
Distances between layers allow tuning (transfer matrix formalism)



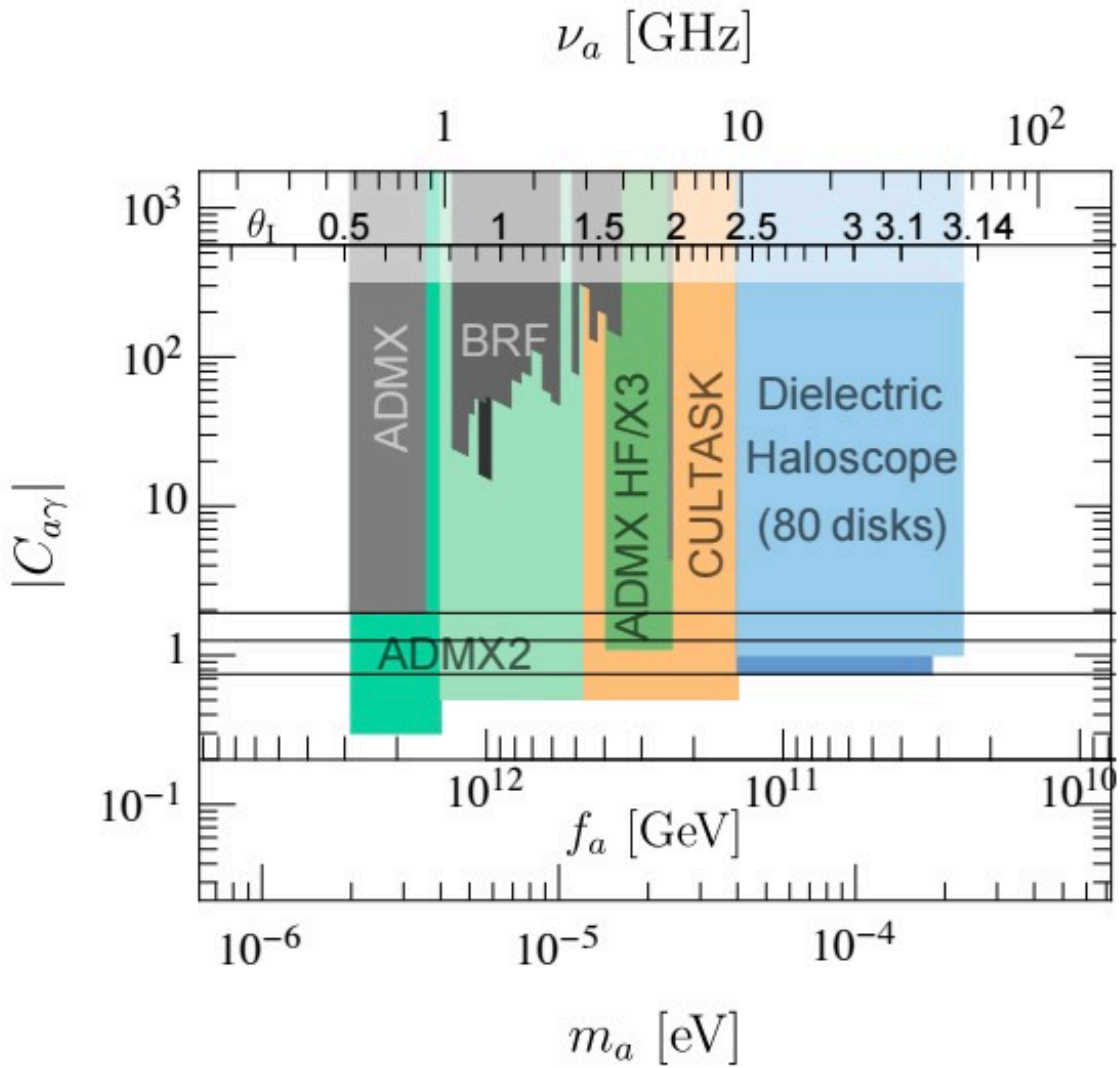
Broadband vs narrowband



central frequency



Potential reach



A = 1 m^2

B-field = 10 T

80disk n=5

whys

- why can it work?

  Large volume + (relatively) simple tuning
  long measurements broadband
  short measurements narrowband

- What can go wrong?

  - 10T dipole-like Magnet, 1 m^2 aperture !
  - 1 m^2 dielectrics (tiling smaller pieces)
  - Tolerances (several micron distances)
  - difraction

Conclusions

- Strong CP problem and dark matter motivate Axions

- 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