WISPy cold dark matter with mirrors

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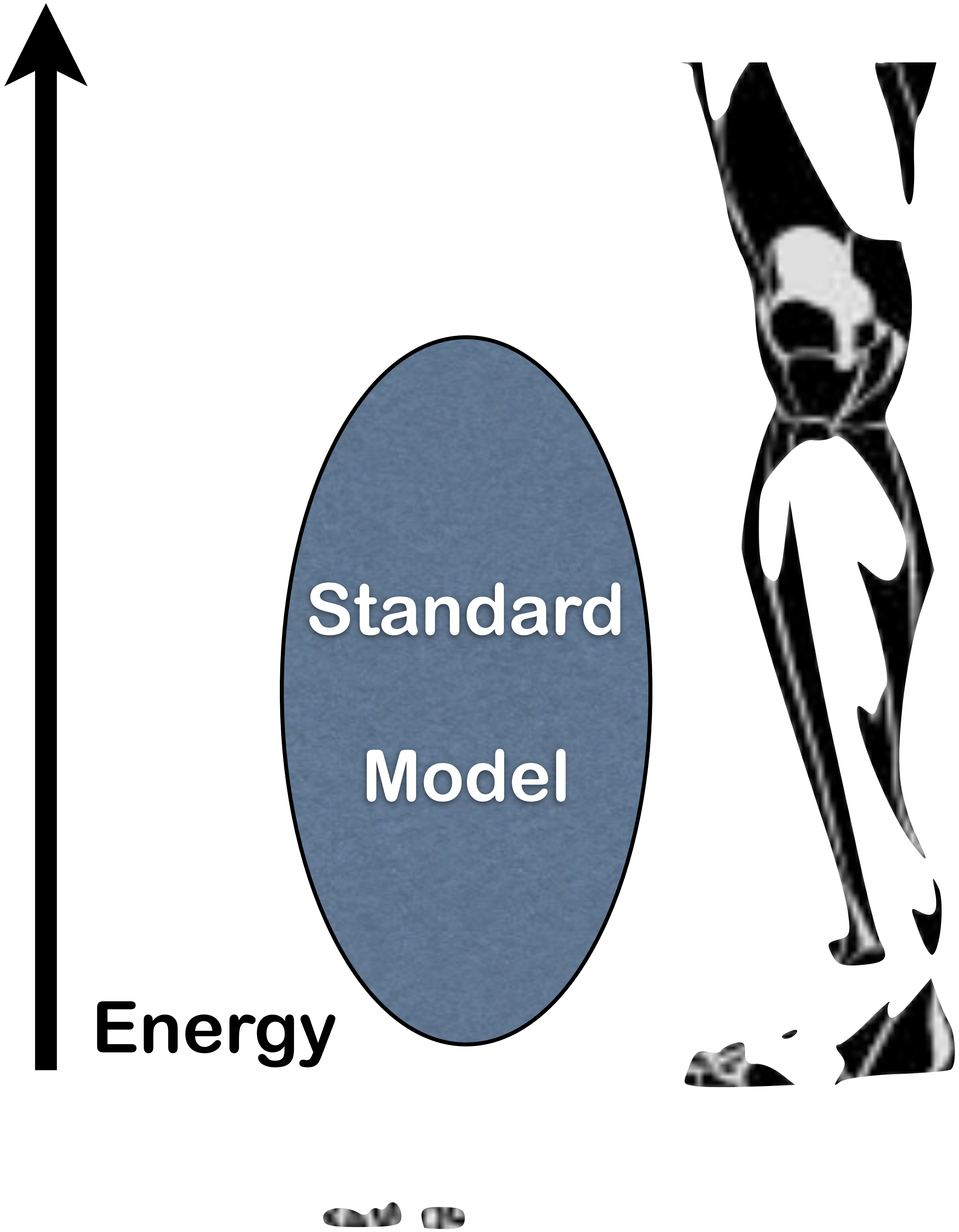
- Invitation
- Axion (and WISPy) dark matter
- Parameter space
- Detecting WISPy DM with photons
- Dish antenna
- Cavities
- Prospects

Beyond the SM ... at low energies

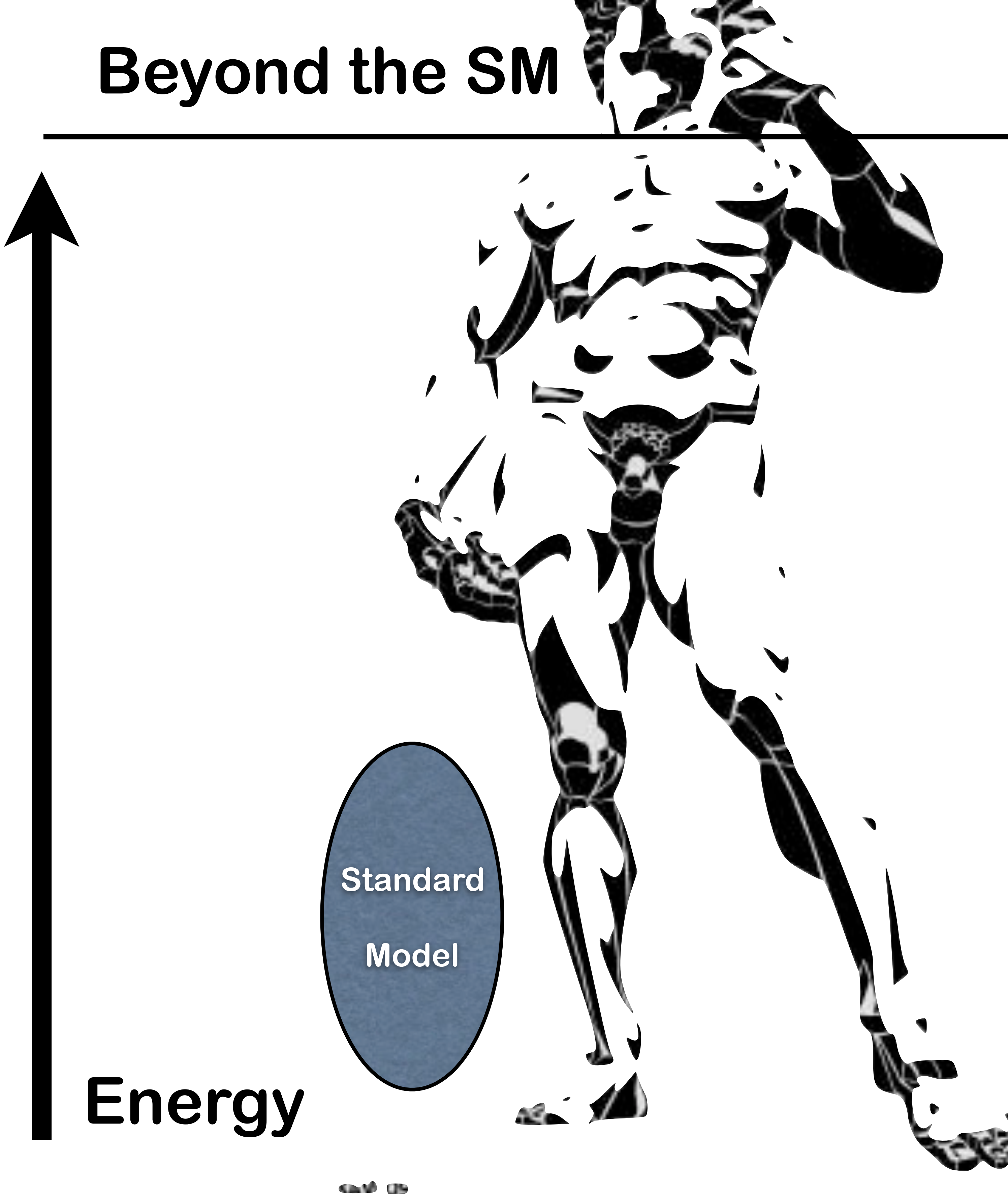


Describes
extremely well
fundamental physics
(at low energies)

but feels certainly

INCOMPLETE

Beyond the SM ... at low energies



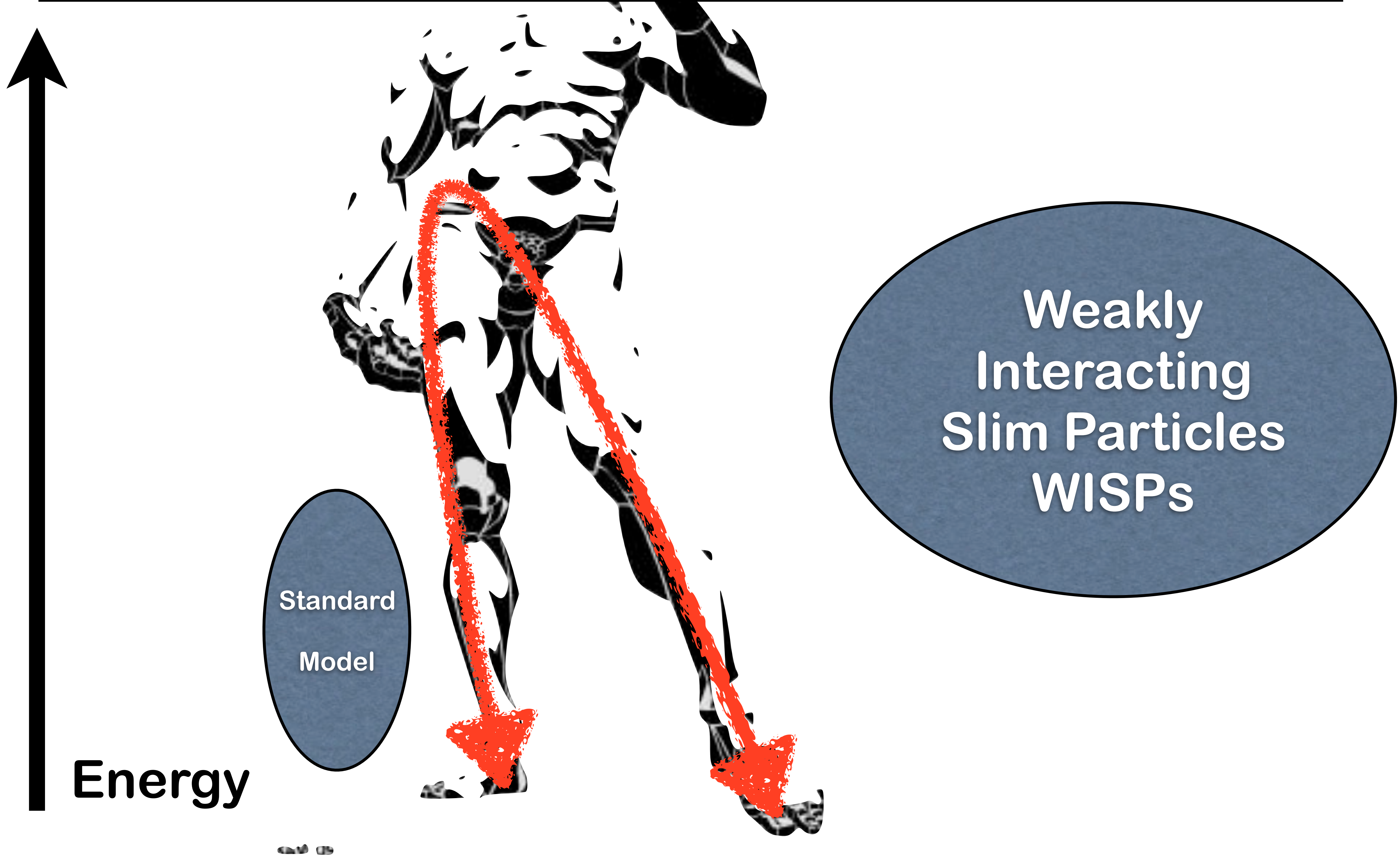
Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

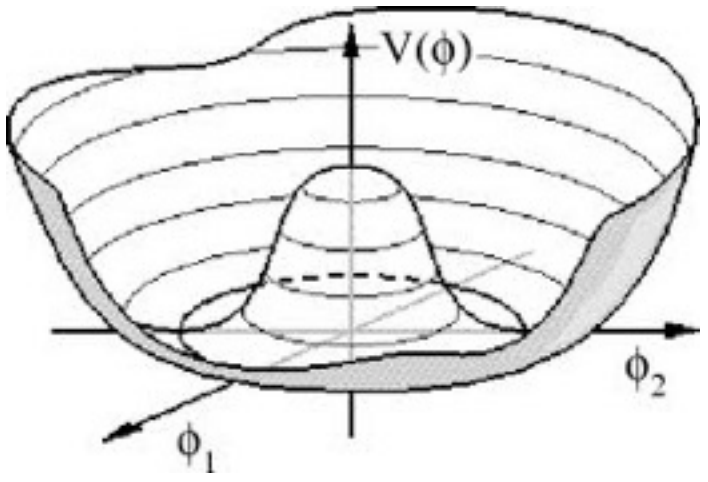
... and can imply physics at low energies

Beyond the SM ... at low energies



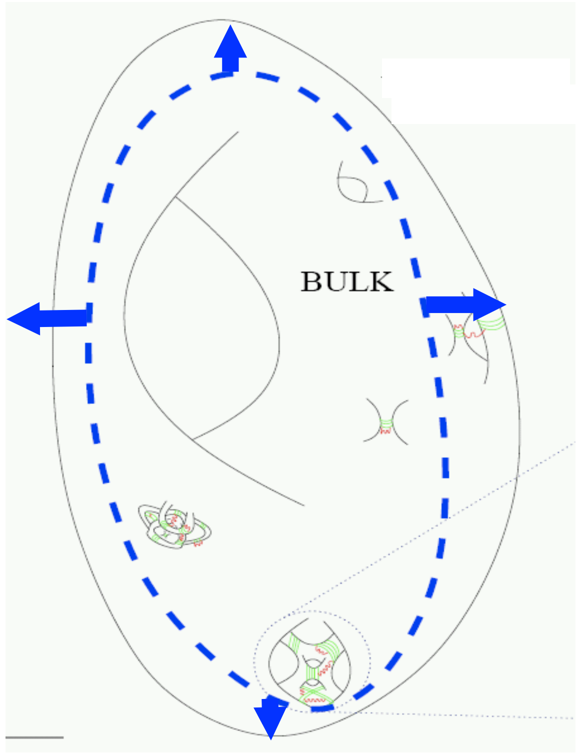
Low mass bosons (technically natural)

- Pseudo-Goldstone bosons
  Very generic BSM
  Axions motivated by the strong CP problem
  Majorons, familons, etc...

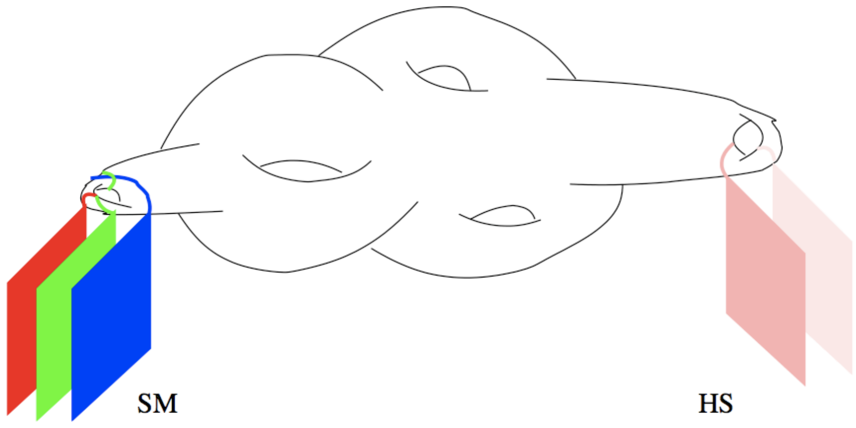


- Axion-like particles in string theories
  Non-perturbative masses

  O(100) ALPs in compactifications ... an Axiverse!



- Gauge U(1) vector bosons
  Stuckelberg mass
  Hidden sectors of string theory?



Axions and strong CP (bottom up)

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

$$\theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

↓

P, T (CP) violating

Axions and strong CP (bottom up)

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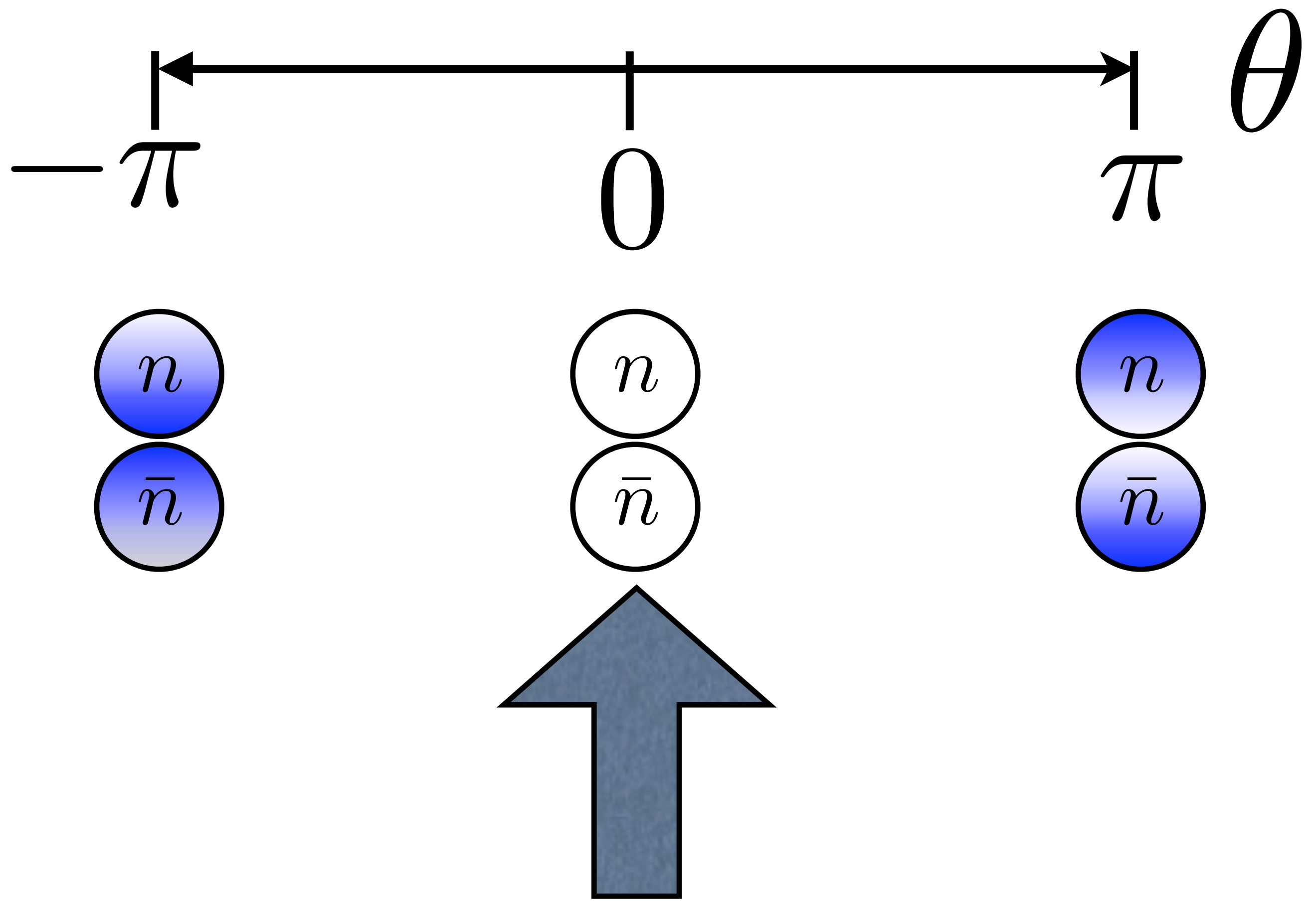
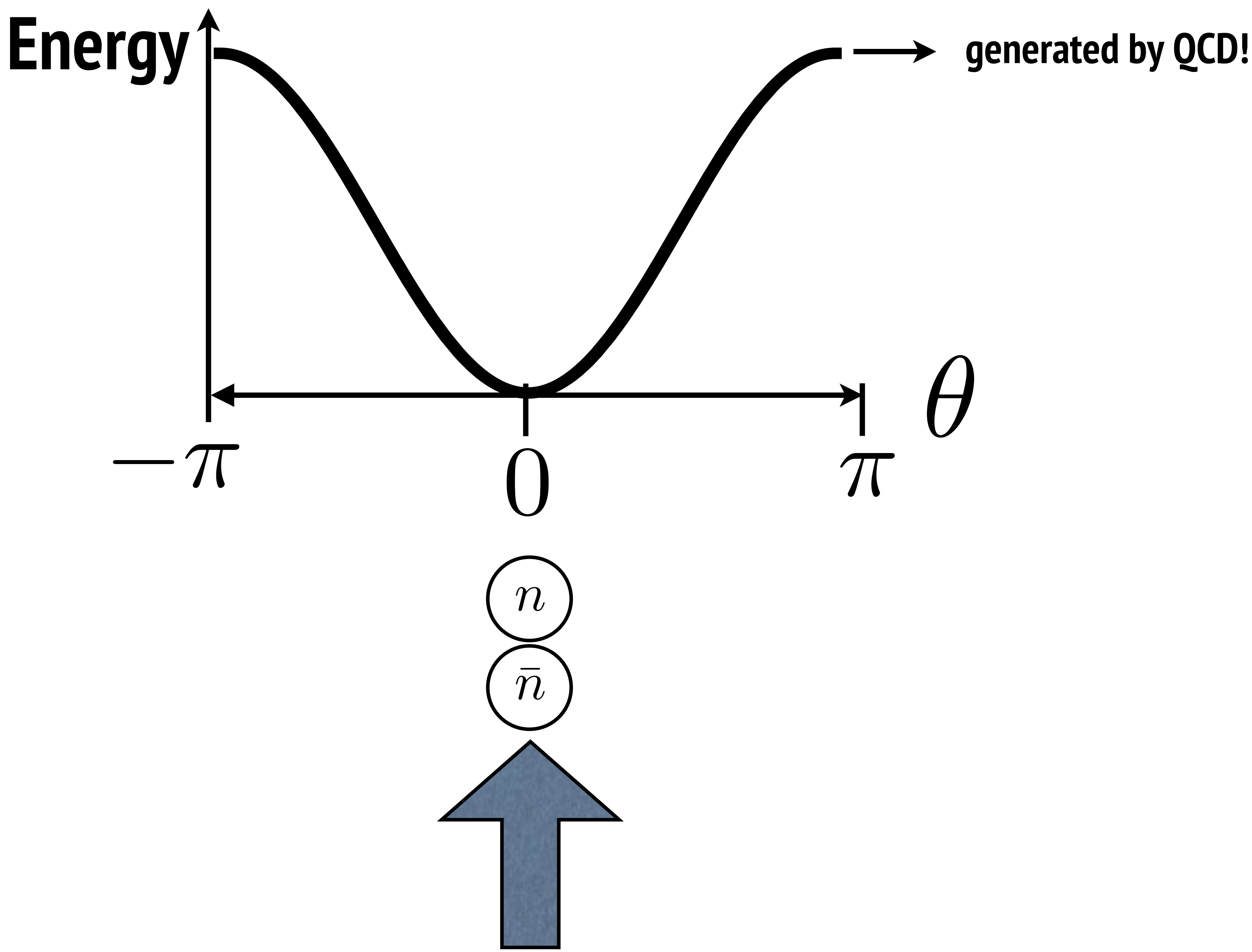


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Axions and strong CP (bottom up)

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



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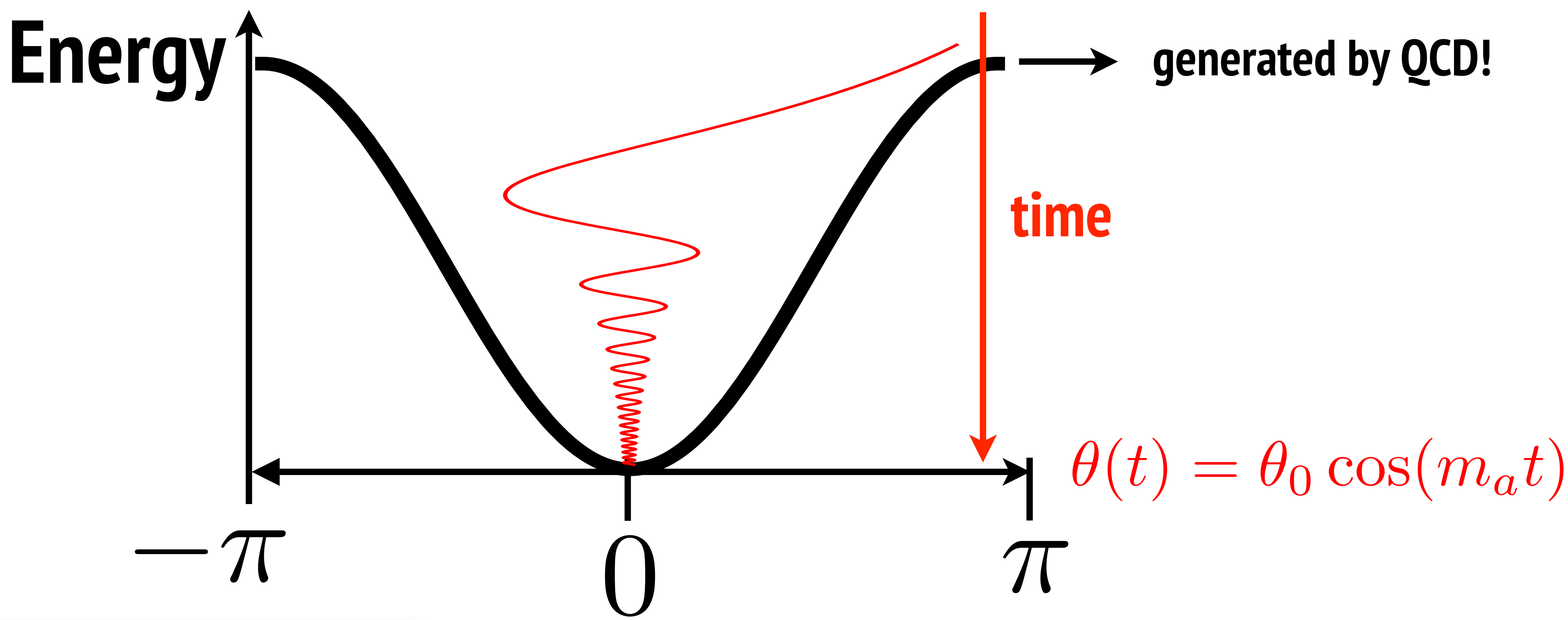
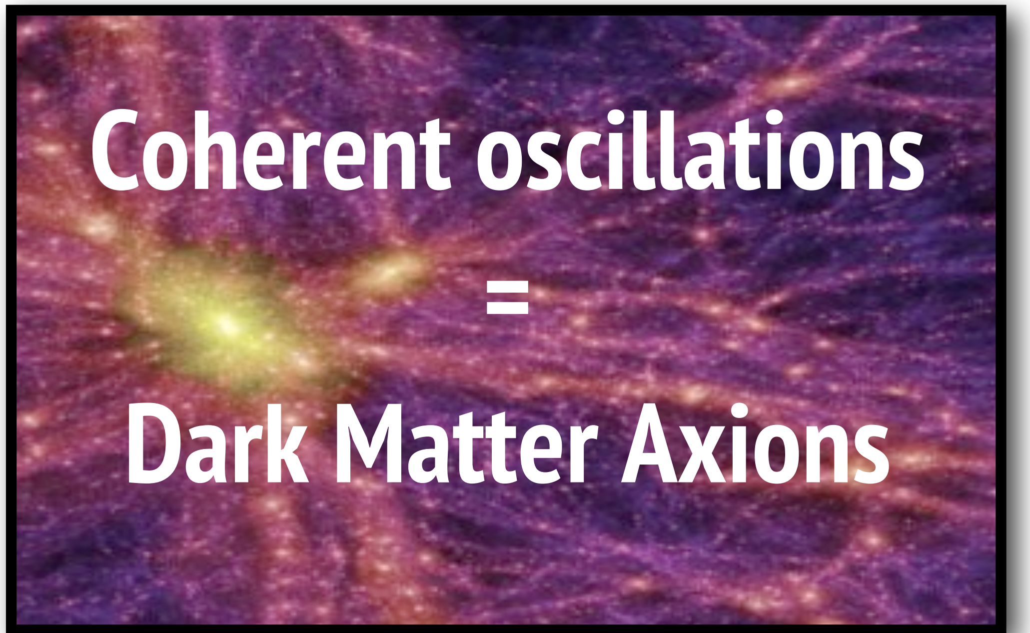
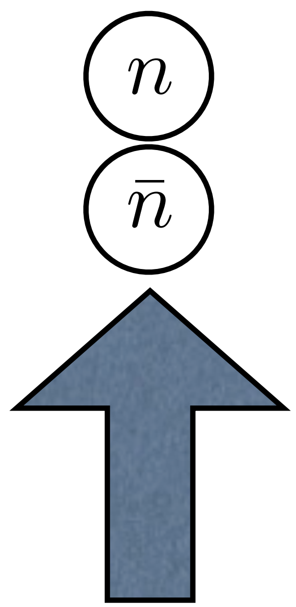






~ One parameter theory

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

axion mass

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

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

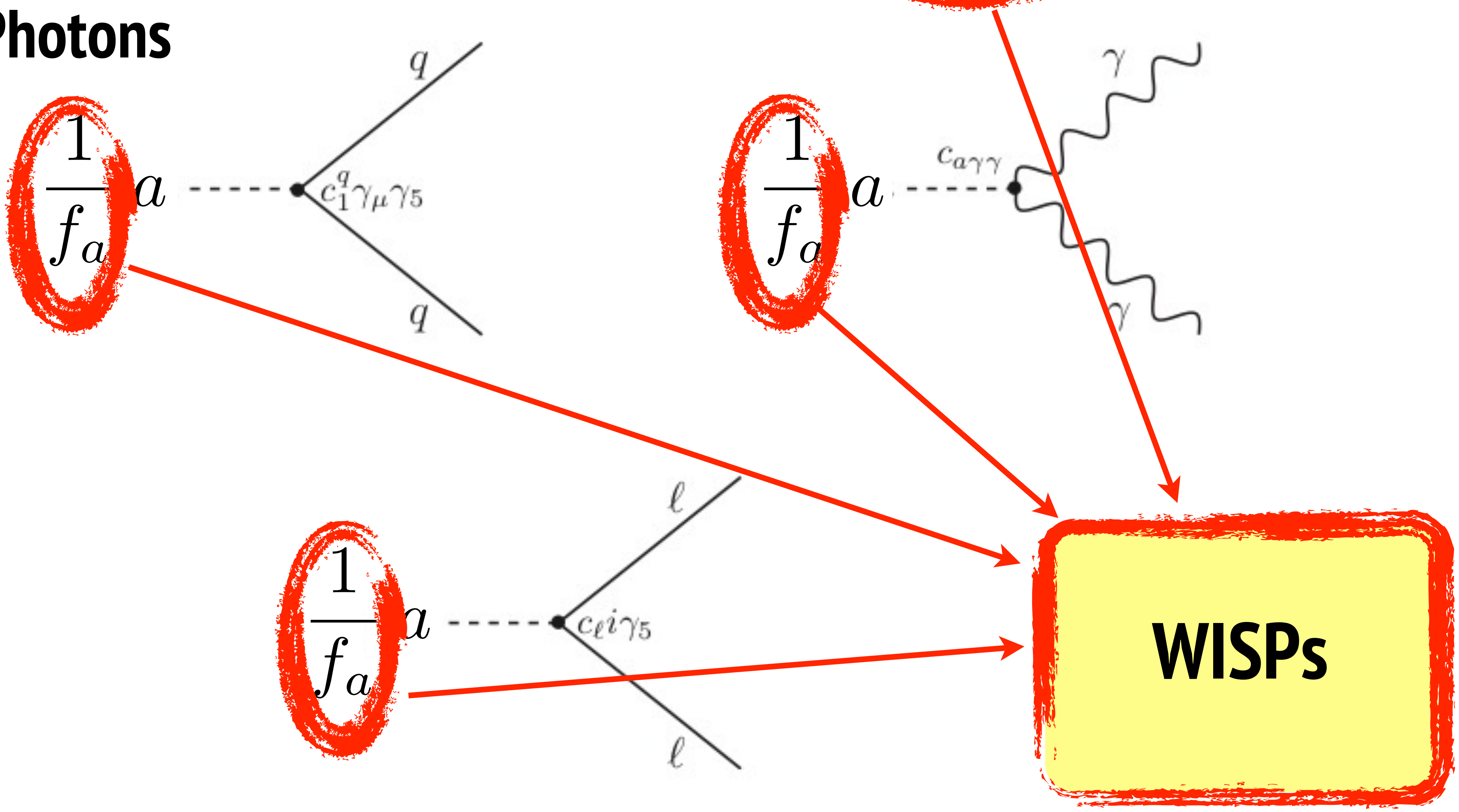
Axion Mass/couplings

Mass

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

Quarks, Photons

Leptons

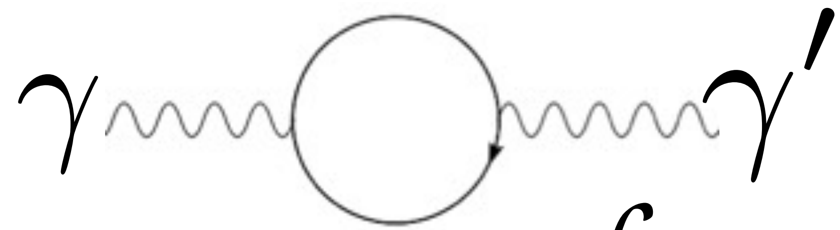


- Generic interactions for Pseudo-Goldstone bosons
- Stringy ALPs, f scale ~ string scale, mass unrelated

New gauge forces : light hidden photons

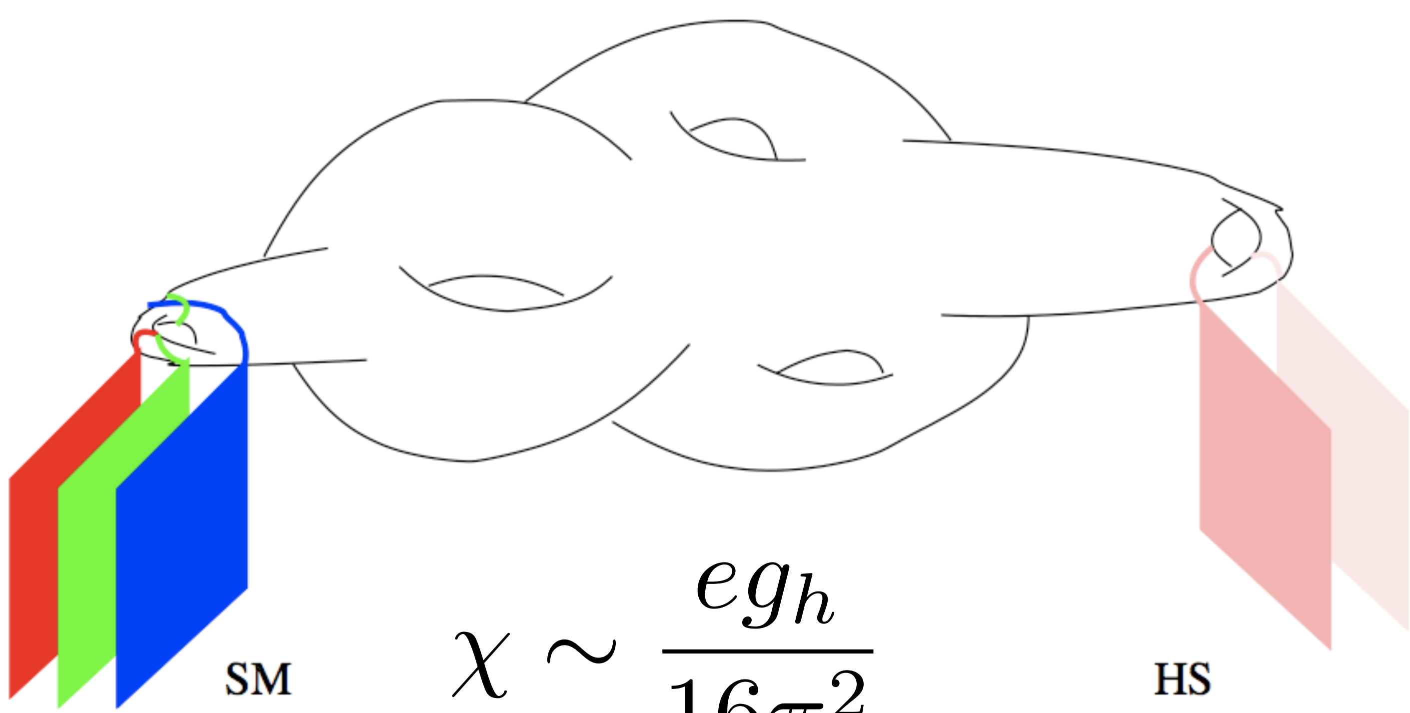
- **Extra hidden U(1)'s (Stückelberg mass)**

- **Kinetic mixing with photon**



$$\mathcal{L}_I = -\frac{1}{2}\chi F_{\mu\nu}B^{\mu\nu}$$

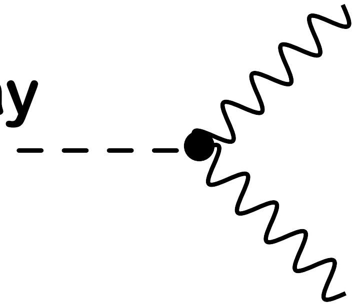
- **Building blocks in type IIb string theory**



$$\chi \sim \frac{e g_h}{16\pi^2}$$

Axion cold dark matter

- Axions decay



$$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$

only low mass axions can be DM!

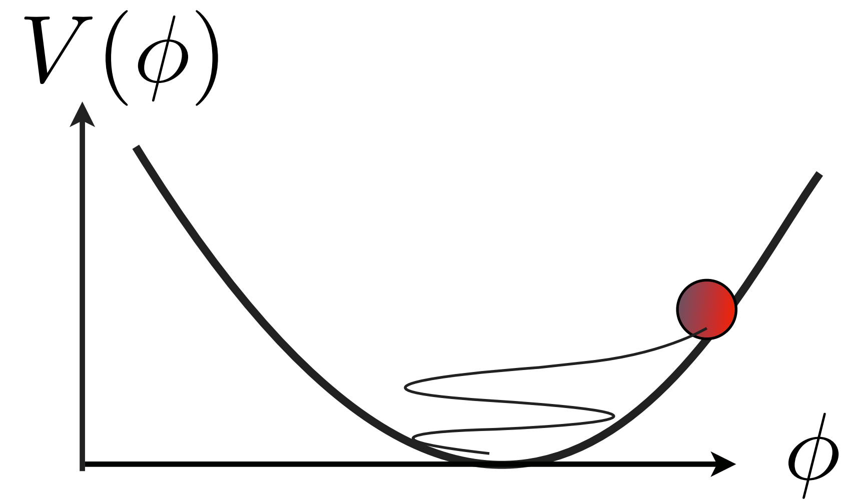
- THERMAL PRODUCTION $\quad p_{\mathrm{today}} \sim T_{\mathrm{today}} \sim \mathrm{meV}$

~~$m_a \sim \mathrm{eV}$???~~

- NON-THERMAL → $p \sim H \lll T$

  - initial conditions
  - decay of cosmic strings, domain walls

Relic abundance of WISPy Dark matter (realignment)

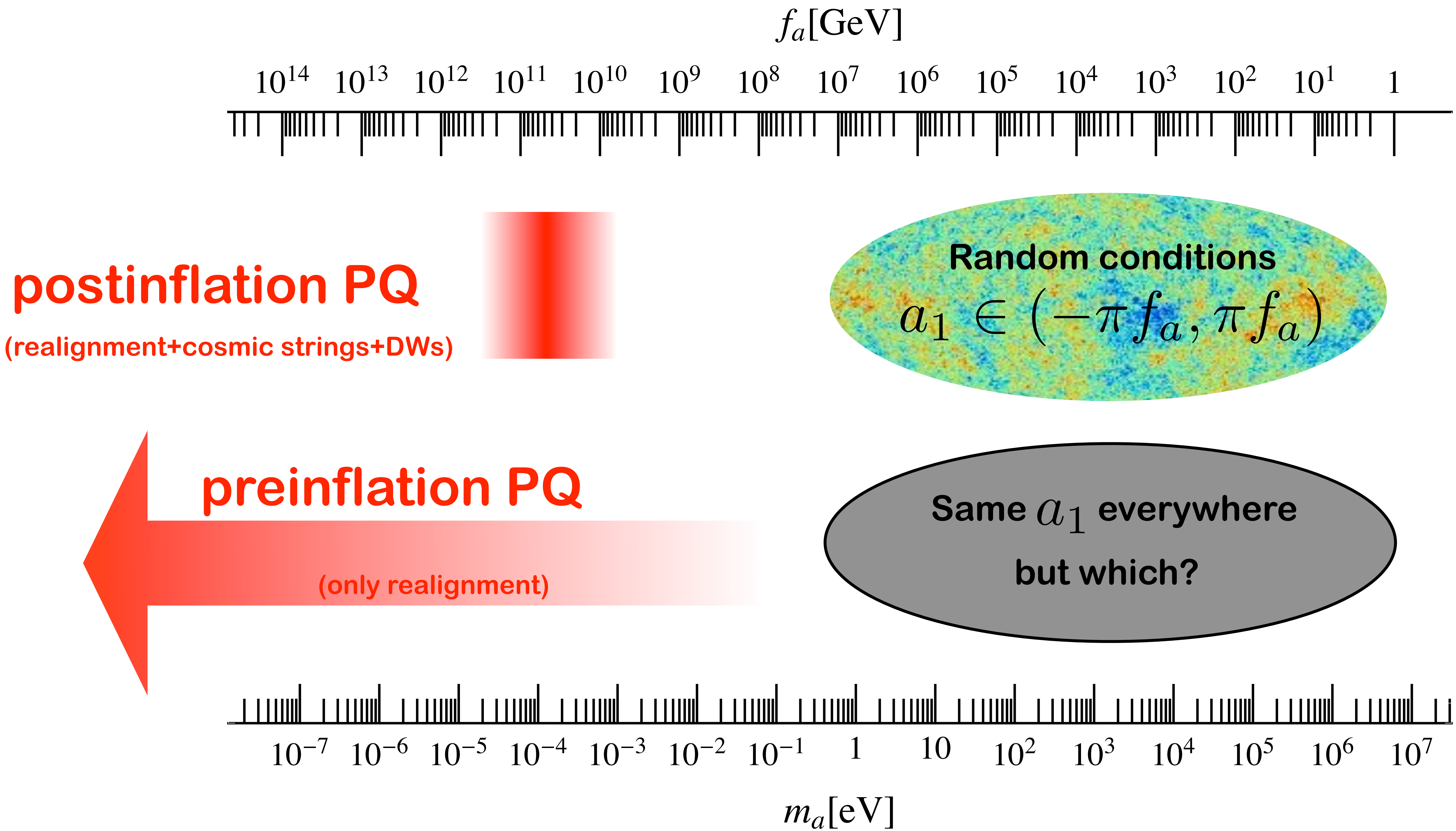


$$\rho_{a,0} \simeq 1.2\,\frac{\mathrm{keV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_\phi}{\mathrm{eV}}}\left(\frac{\phi_{\mathrm{initial}}}{4.8\times 10^{11}\,\mathrm{GeV}}\right)^2 \mathcal{F},$$

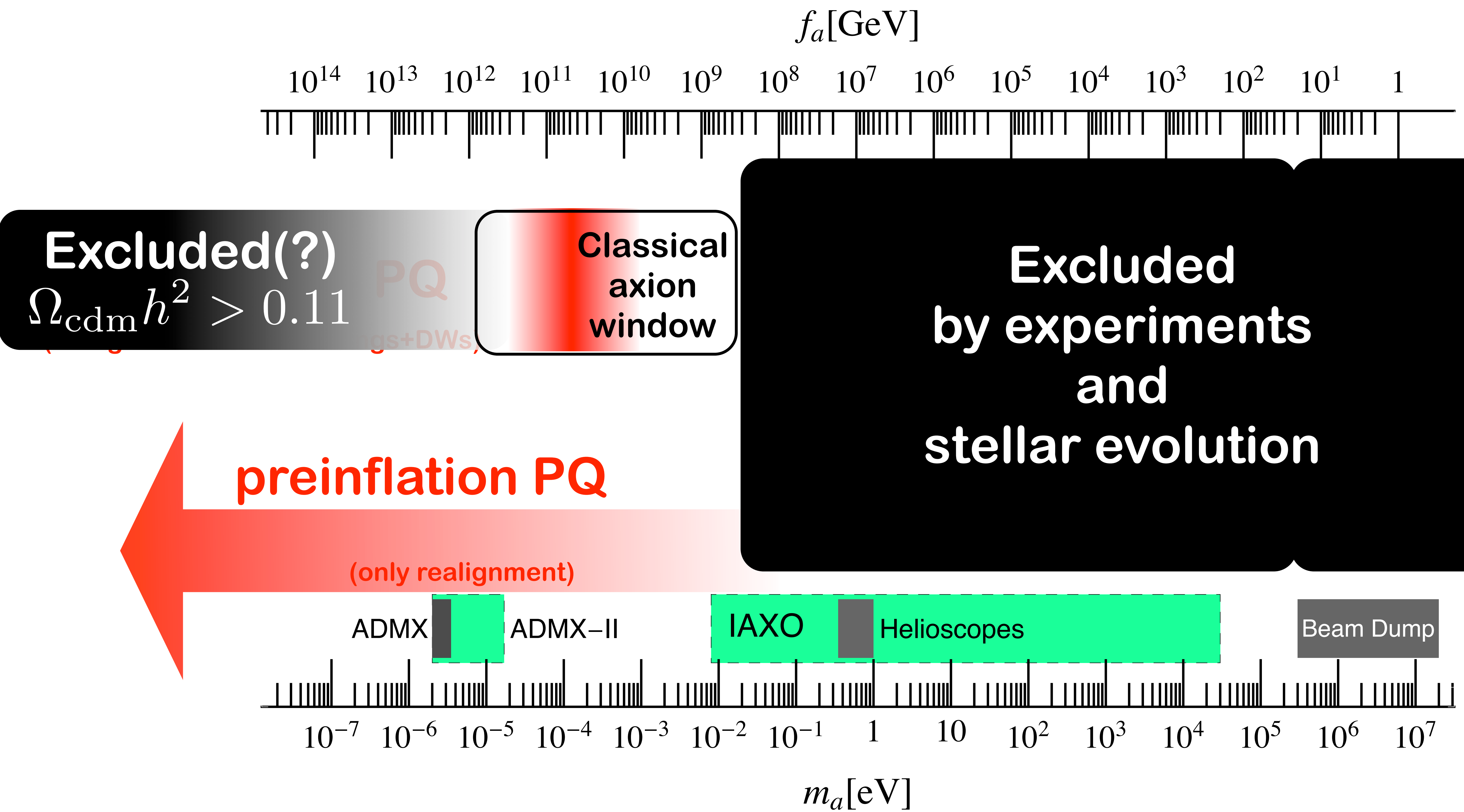
recall $\rho_{\mathrm{CDM}} = 1.2\frac{\mathrm{keV}}{\mathrm{cm}^3}$

- **Initial amplitude, physics at <u>very high energies</u>**
- **WISPy DM opens a window to HEP**

QCD axion cold dark matter (two scenarios)



bounds and prospects



bounds and prospects

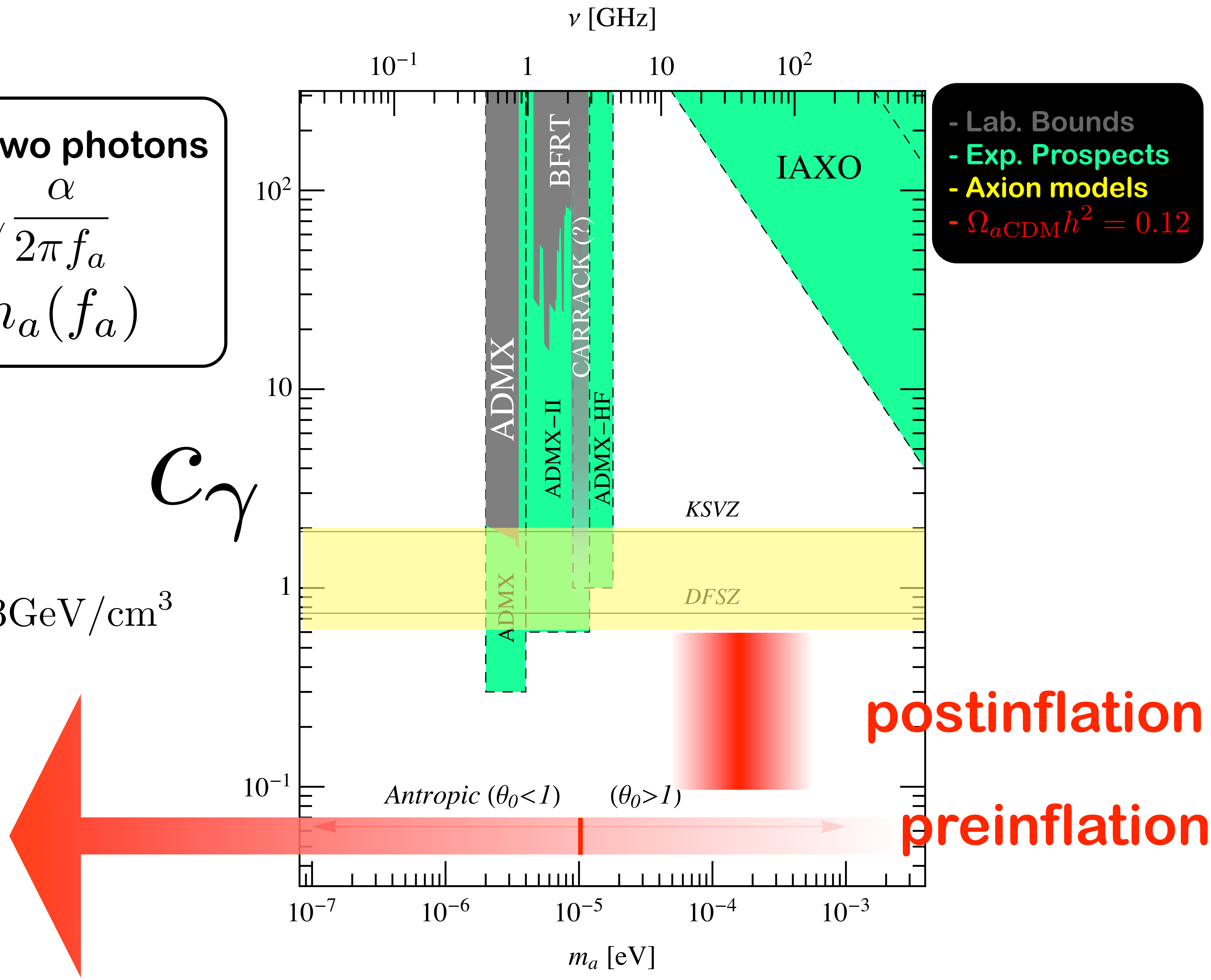
coupling to two photons

$$g_{a\gamma} = c_\gamma \frac{\alpha}{2\pi f_a}$$

$$m_a = m_a(f_a)$$

$$\rho_{\rm CDM} = 0.3{\rm GeV/cm^3}$$

c_γ



postinflation PQ

preinflation PQ

General Axion-like particles (ALPs)

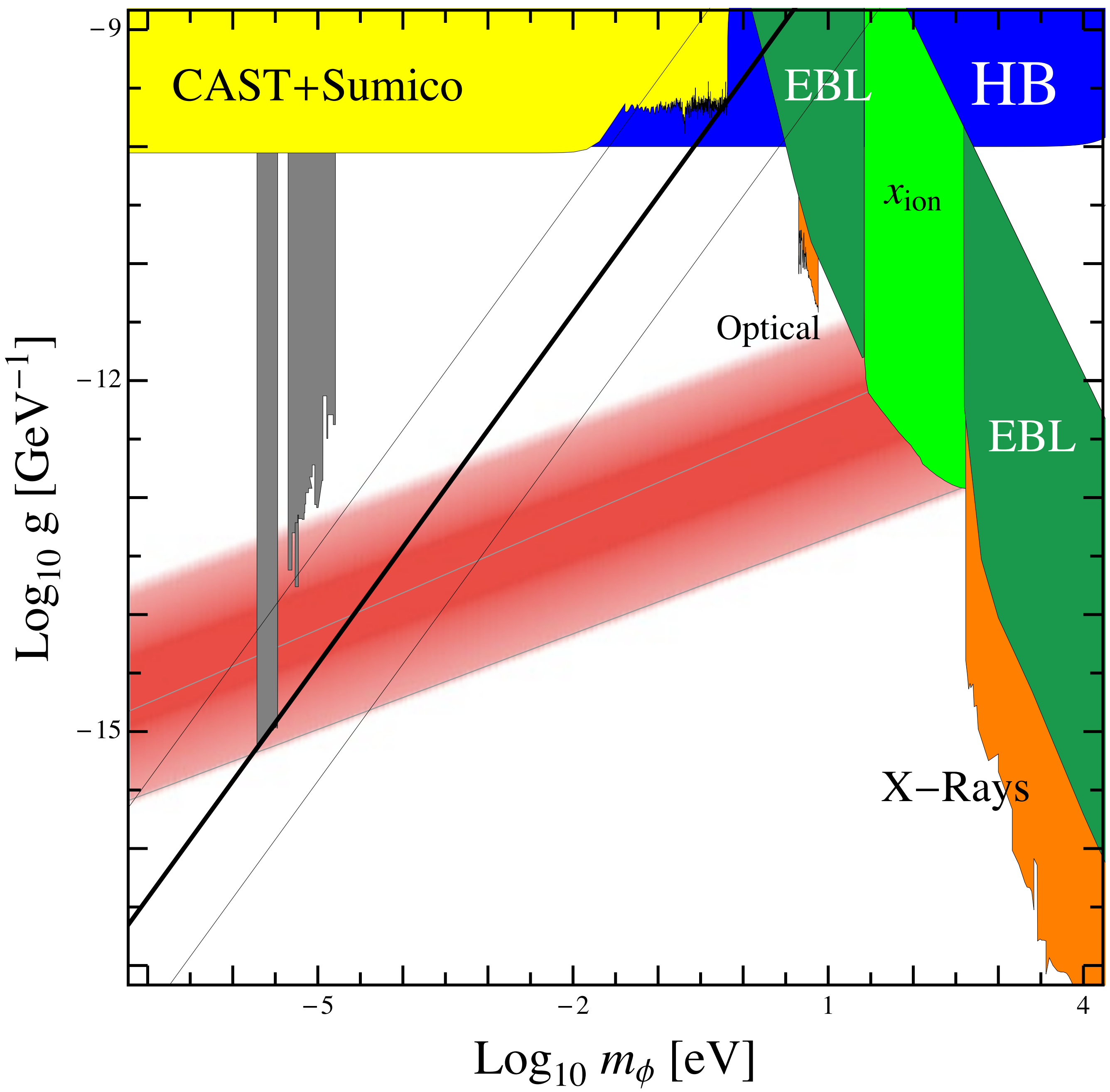
- Mass and coupling unrelated

$$g = \frac{\alpha}{2\pi f_a} \times O(1)$$

- Scenario 1

$$f_a < H_I$$

(realignment+cosmic strings, DWs..)



General Axion-like particles (ALPs)

- Mass and coupling unrelated

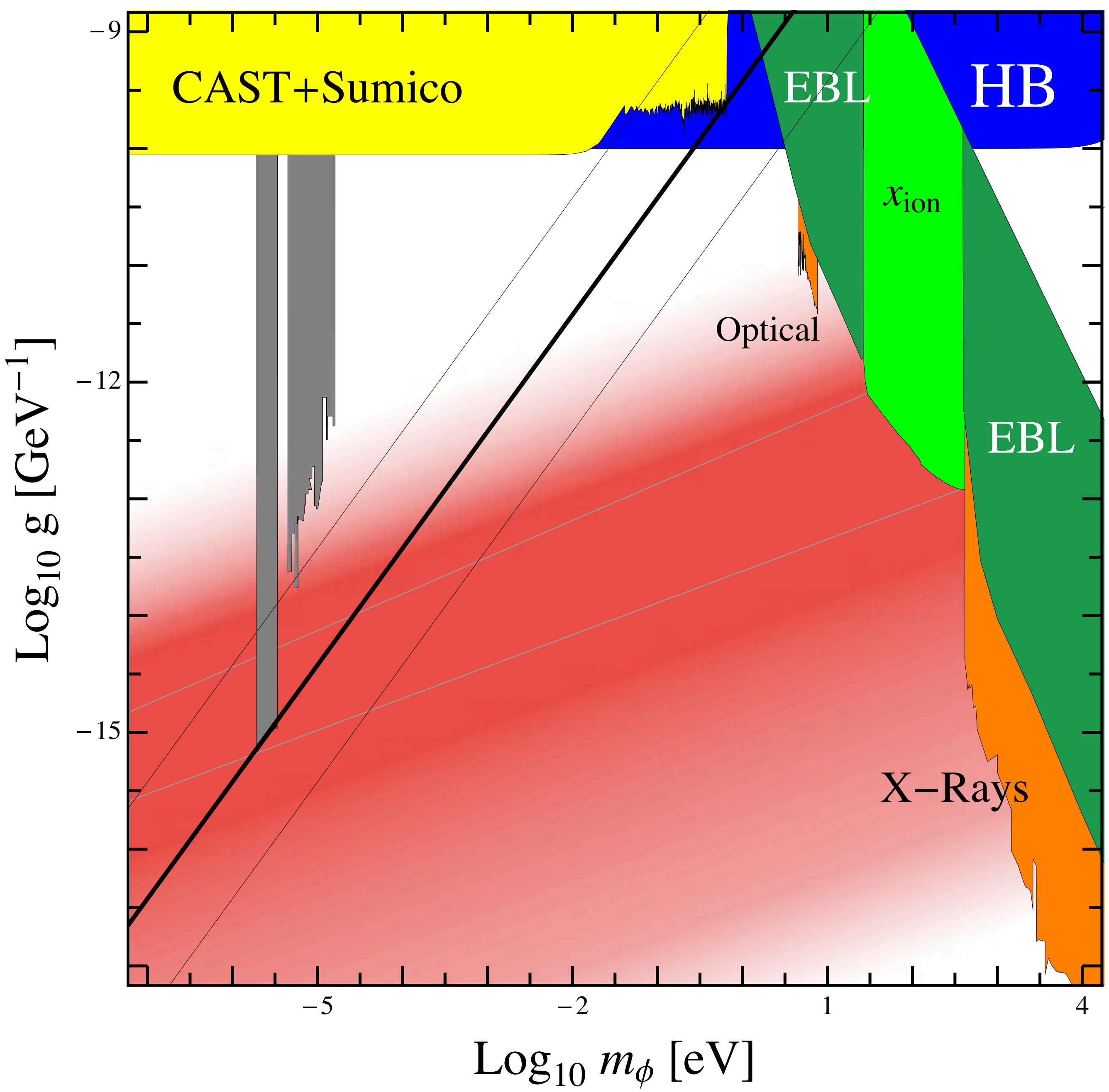
$$g = \frac{\alpha}{2\pi f_a} \times O(1)$$

- Scenario 2

$$f_a > H_I$$

(realignment mechanism)

- Isocurvature constraints!!

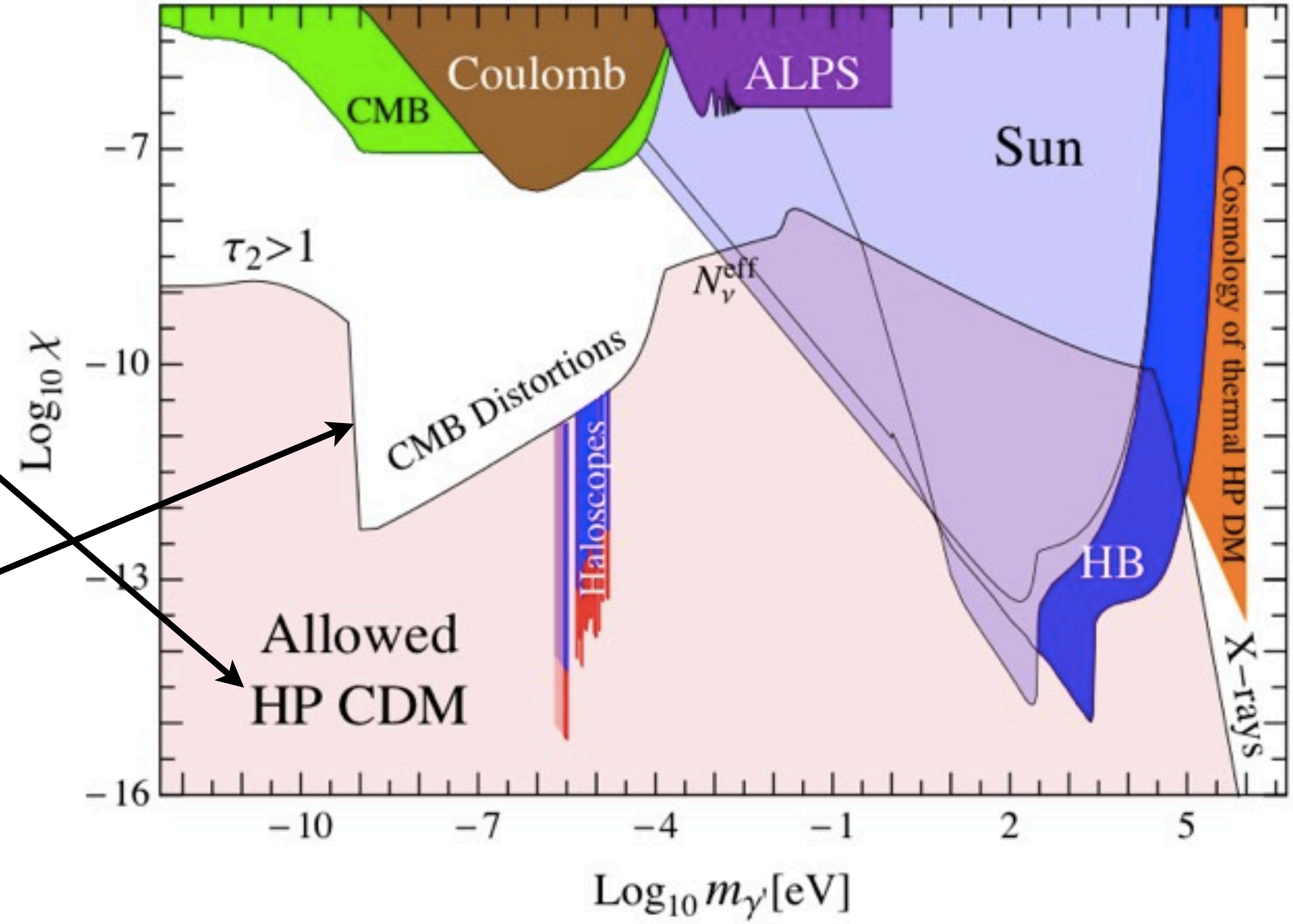


hidden photon parameter space

- initial condition not related with mixing

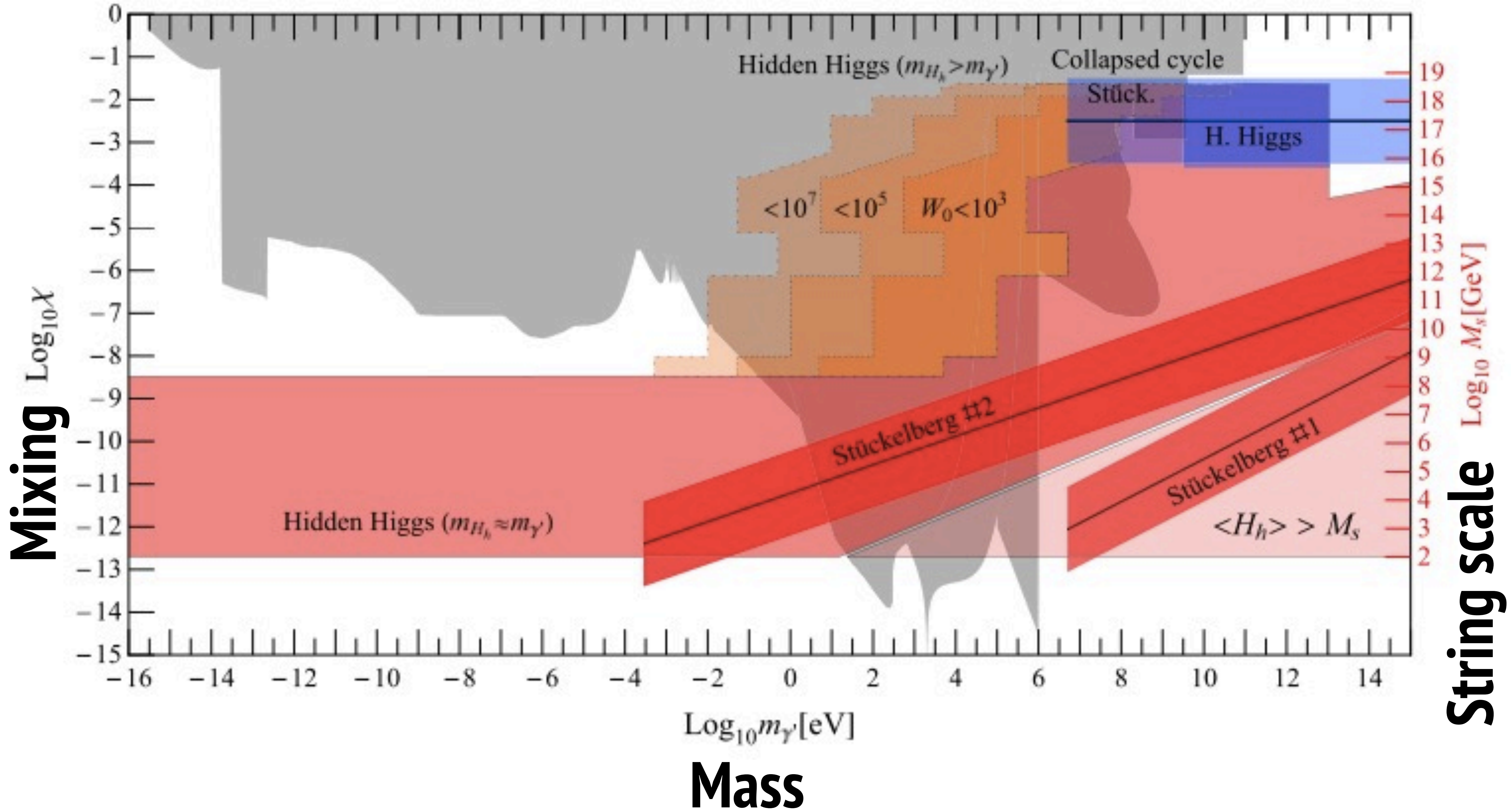
- broader parameter space

- constraints from DM oscillations into photons



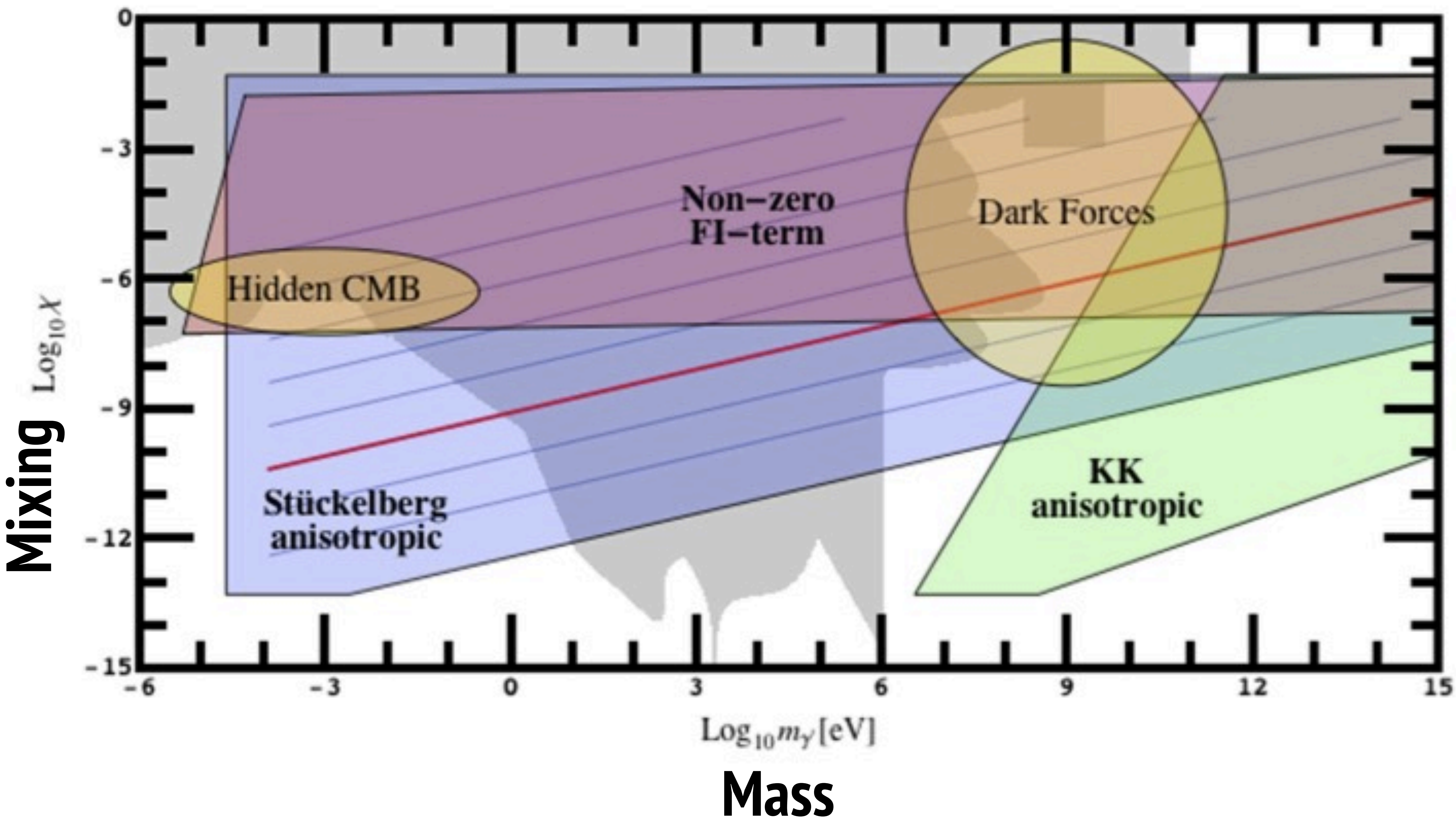
Predictions ...

Goodsell 2011



Anisotropic predictions ...

Cicoli 2011



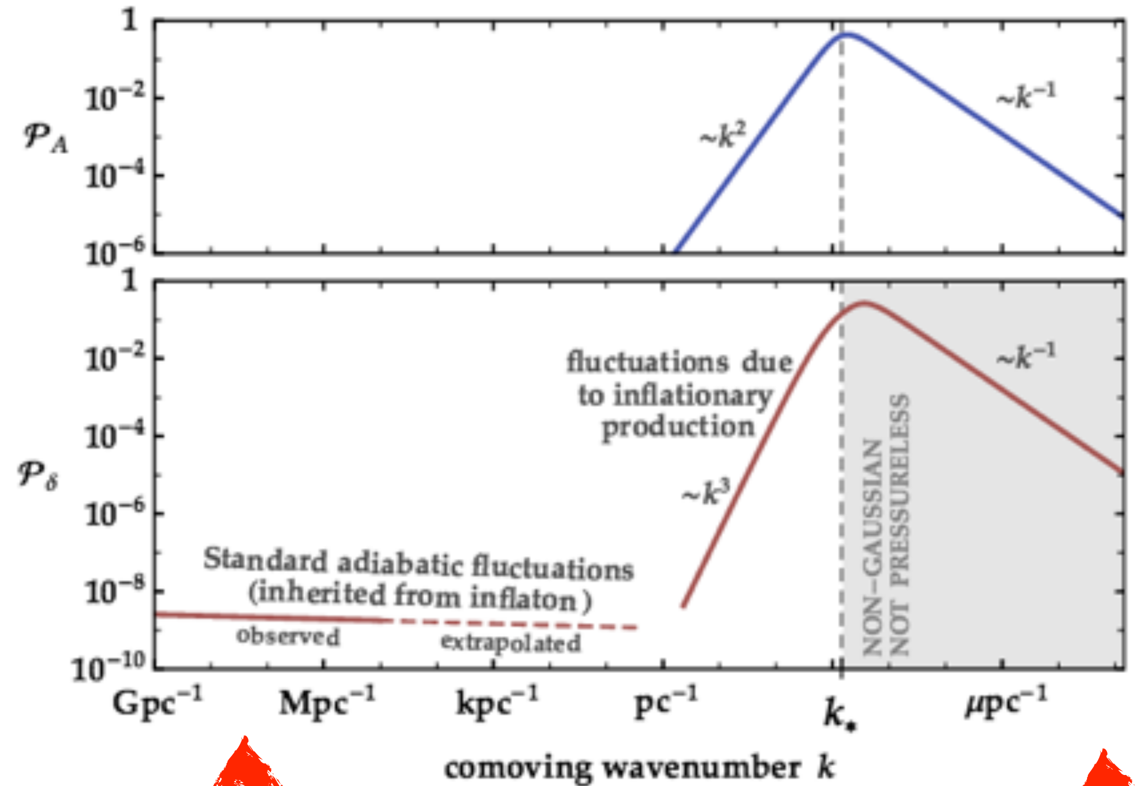
Hidden photons : isocurvature dark matter

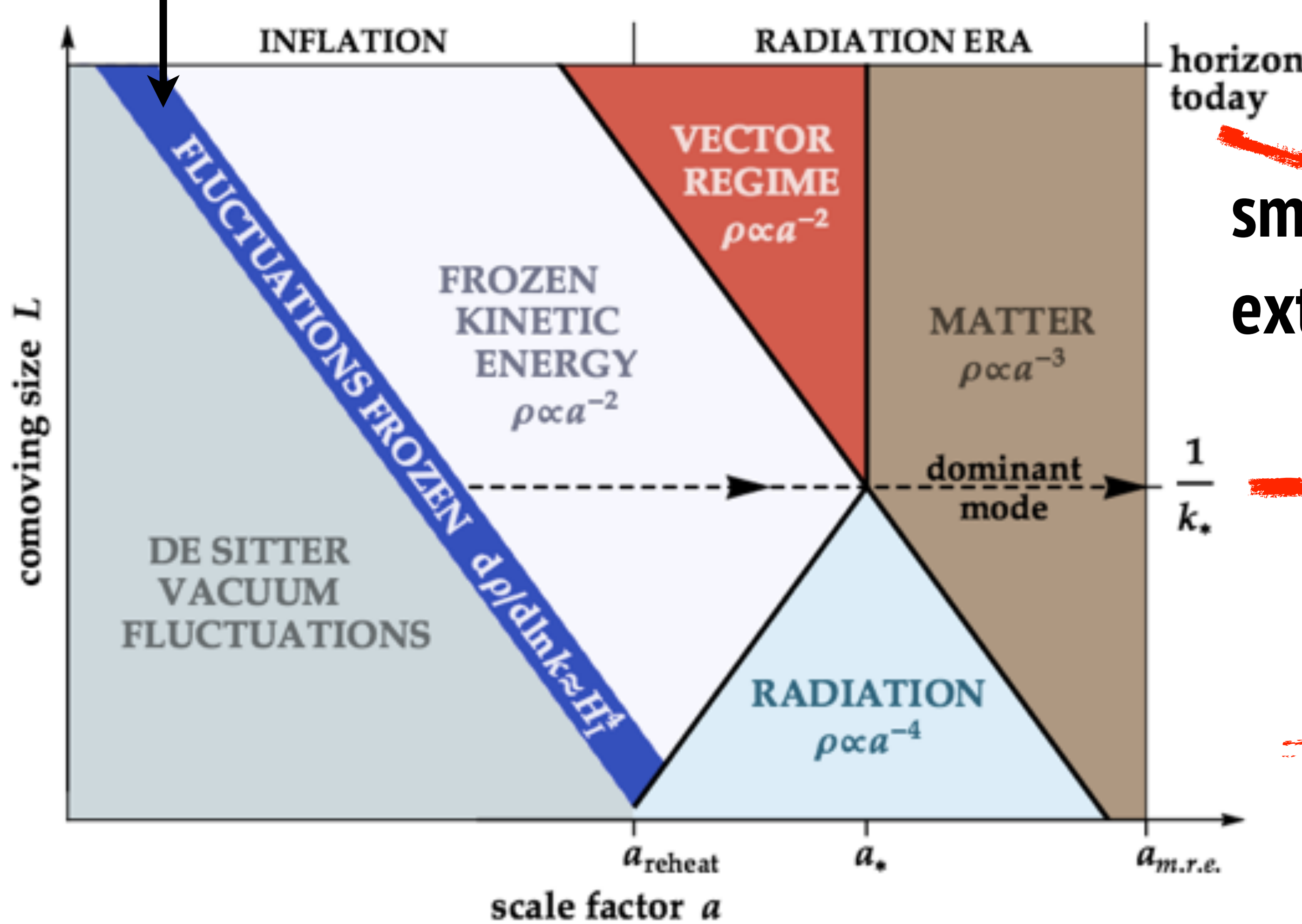
Graham 2015

- Misalignment sourced by Inflation itself

$$\langle |A_l| \rangle \sim \frac{H_I}{2\pi}$$

- Longitudinal mode ~ scalar
- Except for extra suppression low modes
- Compatible with CMB isocurvature constraints
- Not possible for axions & ALPs



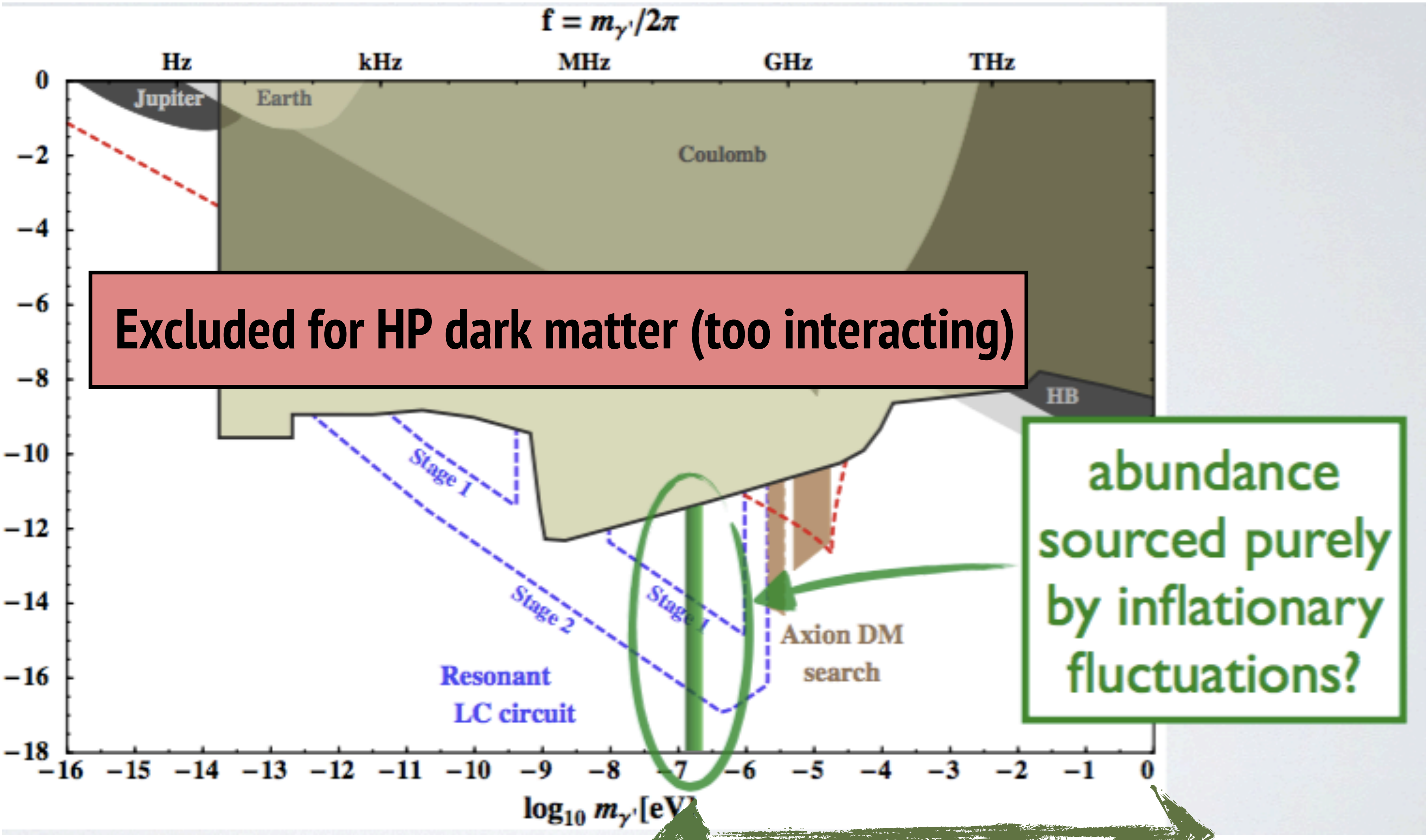


small scale
extra suppression

Hidden photons : isocurvature dark matter

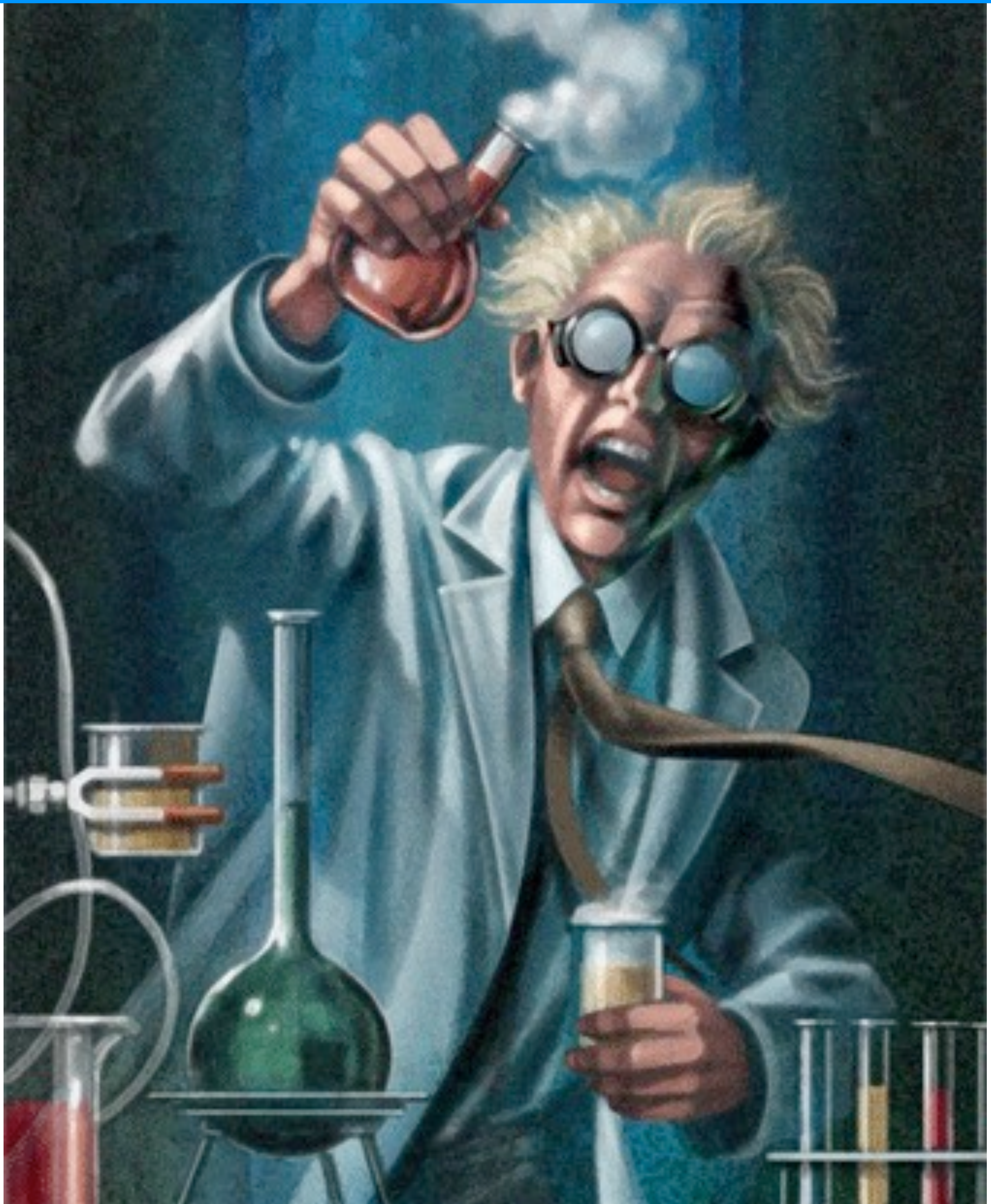
Graham 2015

- Prediction?, connection of DM abundance with H-Inflation (measurable from B-modes)

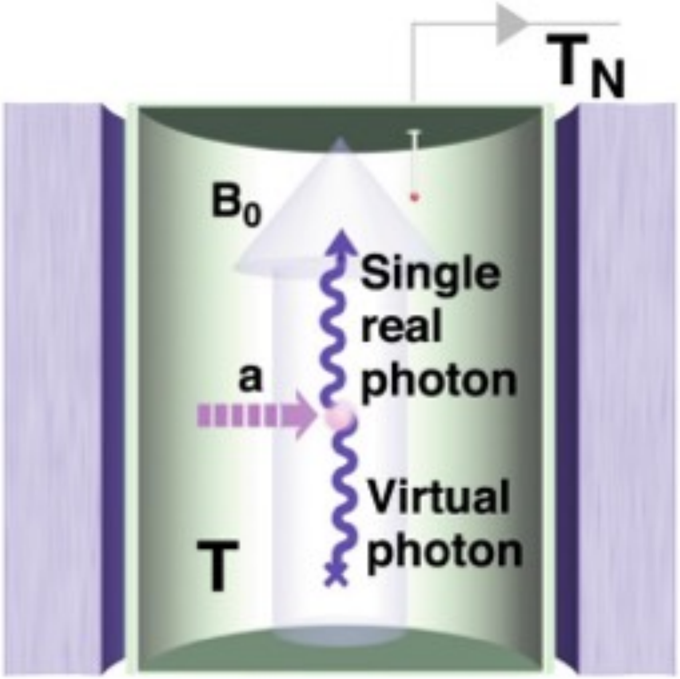


$H_I \sim 10^{14}\text{GeV}$ $H_I < 10^{14}\text{GeV}$

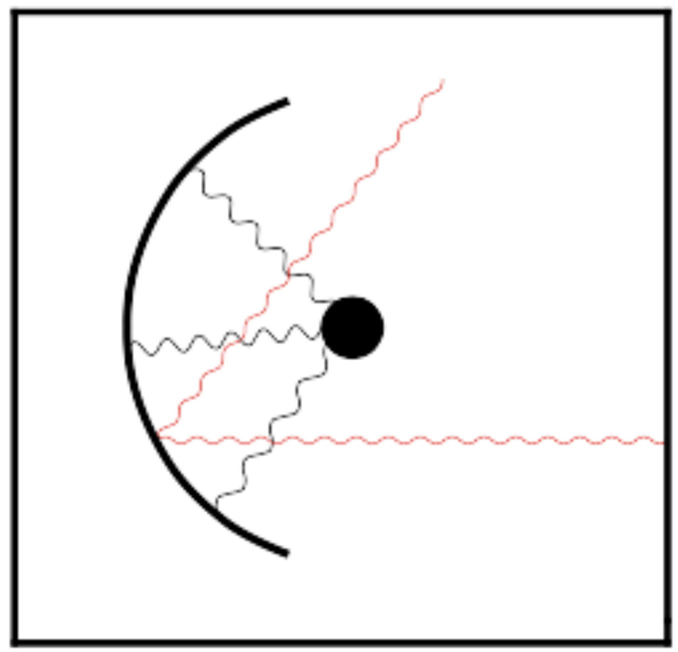
DM Direct detection of axions and the like



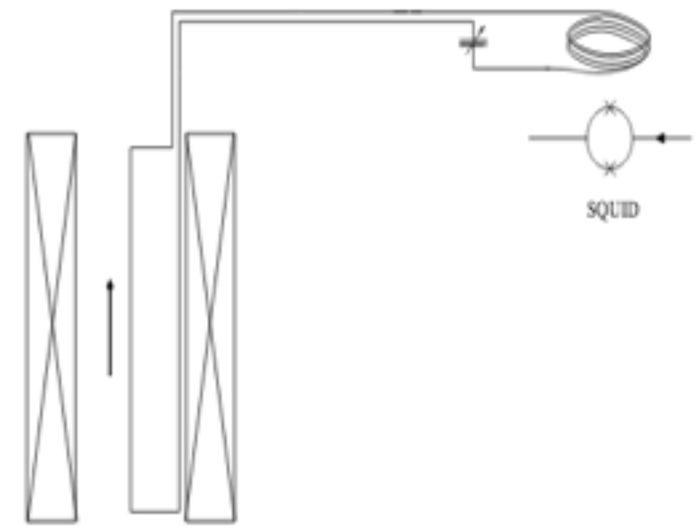
Cavities



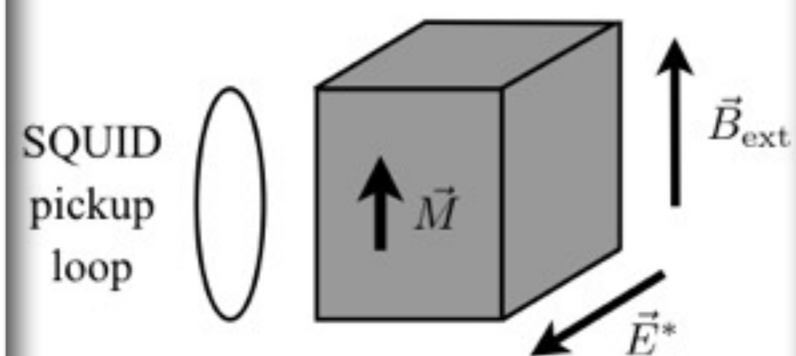
Mirrors



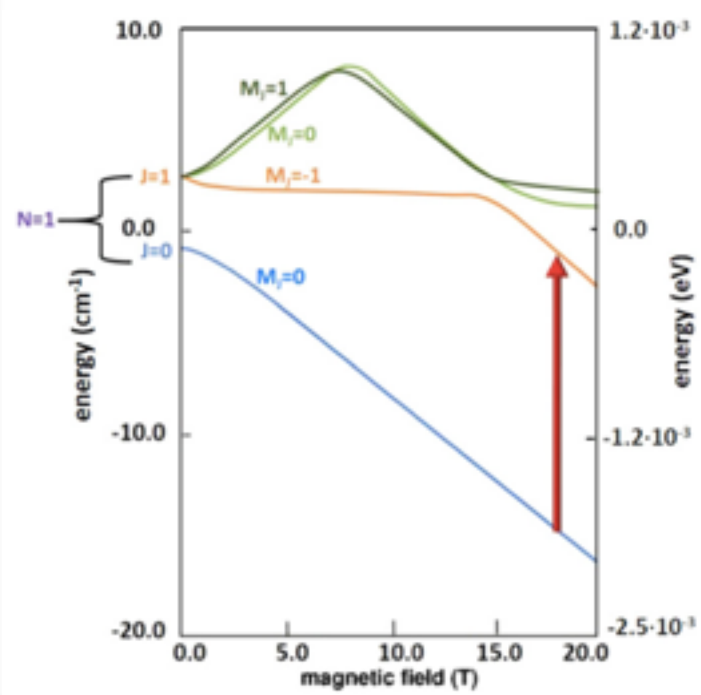
LC-circuit



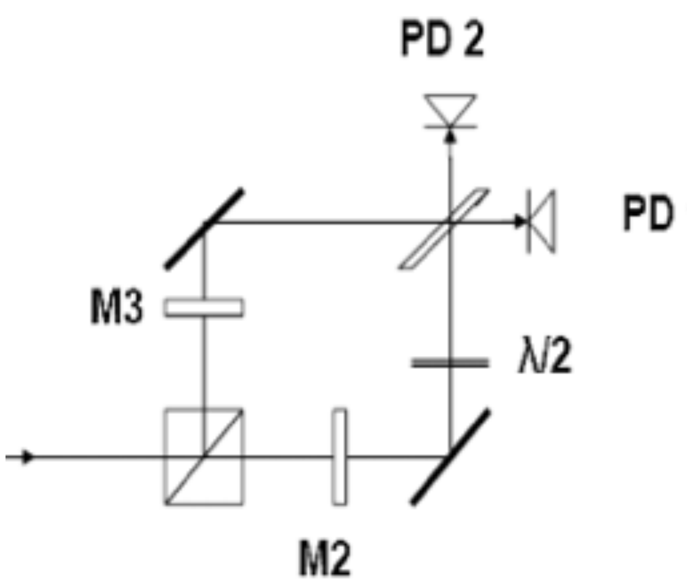
Spin precession



Atomic transitions



Optical



Wispy dark matter around

density

$$\rho_{\rm CDM} \simeq 0.3 \frac{\rm GeV}{\rm cm^3} = m_a n_a$$

velocities in the galaxy

$$v \lesssim 300~{\rm km/s} \sim 10^{-3} c$$

phase space density

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

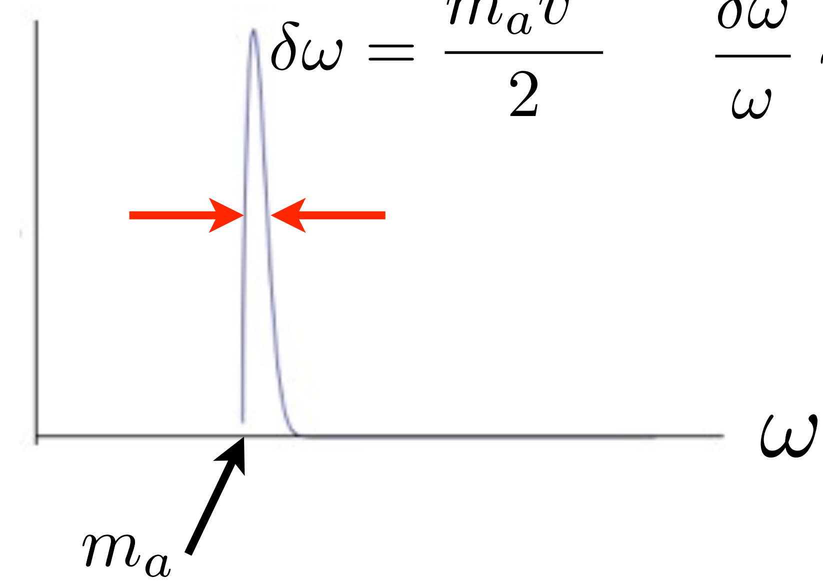
occupation number is HUGE!

⟶ **behaves classically**

Fourier-transform $a(x)$

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

$$\delta\omega = \frac{m_a v^2}{2} \qquad \frac{\delta\omega}{\omega} \sim 10^{-6}$$



Axion - photon mixing in a magnetic field

Raffelt, PRD'88

- In a magnetic field one photon polarization Q-mixes with the axion

$$\mathcal{L}_I = \frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a = -g_{a\gamma} \mathbf{B} \cdot \mathbf{E}\, a$$

Not axions, nor photons are propagation eigenstates!

Axion - photon mixing in a magnetic field

Raffelt, PRD'88

- **Equations of motion for a plane wave** $\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} \exp(-i(\omega t - kz)).$

$$\left[(\omega^2 - k^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g_{a\gamma}|\mathbf{B}|\omega \\ -g_{a\gamma}|\mathbf{B}|\omega & m_a^2 \end{pmatrix}\right]\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

axion mixes with A-component PARALLEL to the external B-field

- **"Dark matter" solution** $v = \frac{k}{\omega} \quad ; \quad \omega \simeq m_a(1 + v^2/2 + ...)$

$$\left.\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\right|_{\rm DM} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

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It has a small E field!

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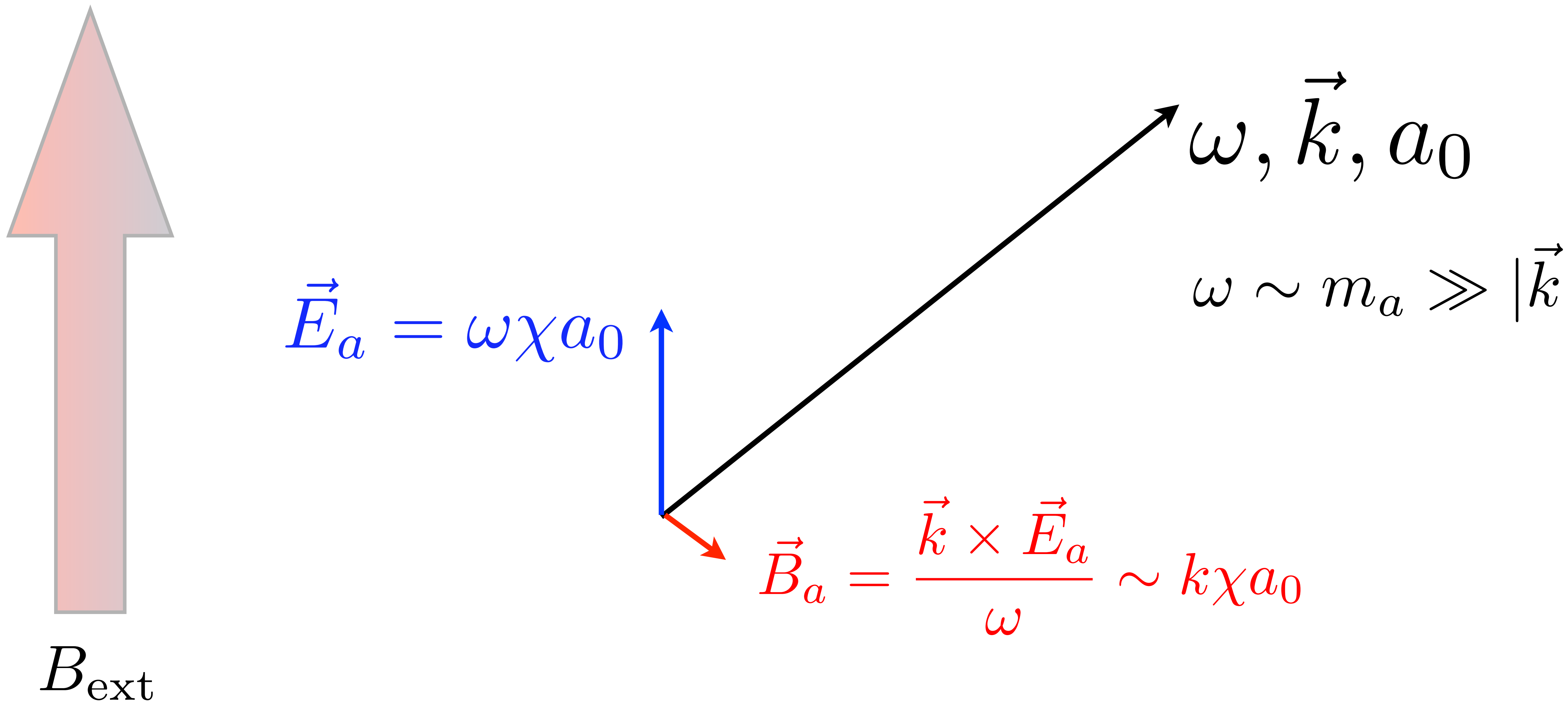
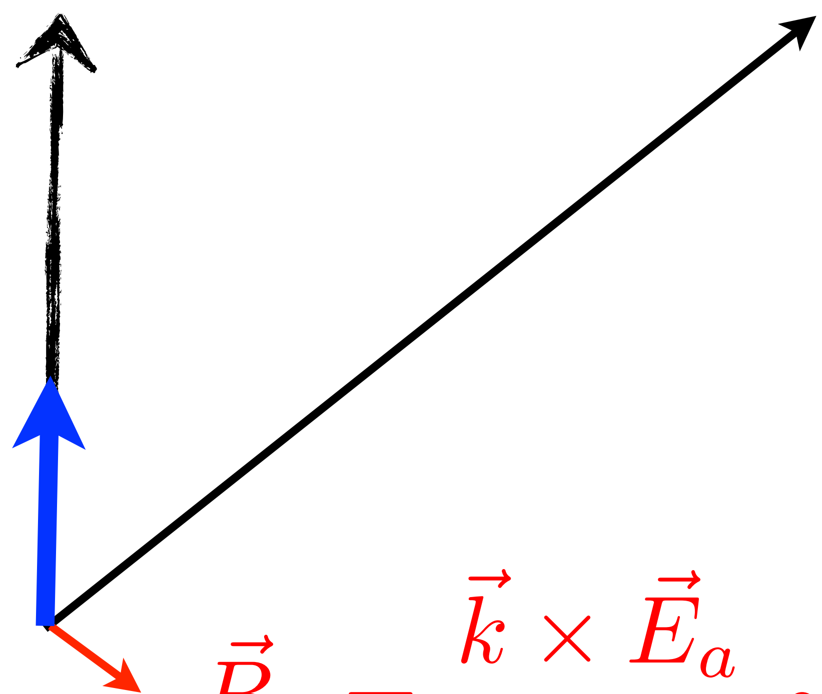
$$\chi_a \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$$

DM axions in a magnetic field



hidden photons ~~in a magnetic field~~

kinetic mixing γ  γ' $\mathcal{L} \in \frac{1}{2}\chi F^{\mu\nu}F'_{\mu\nu}$



$\vec{E}' = \omega \vec{A}'$

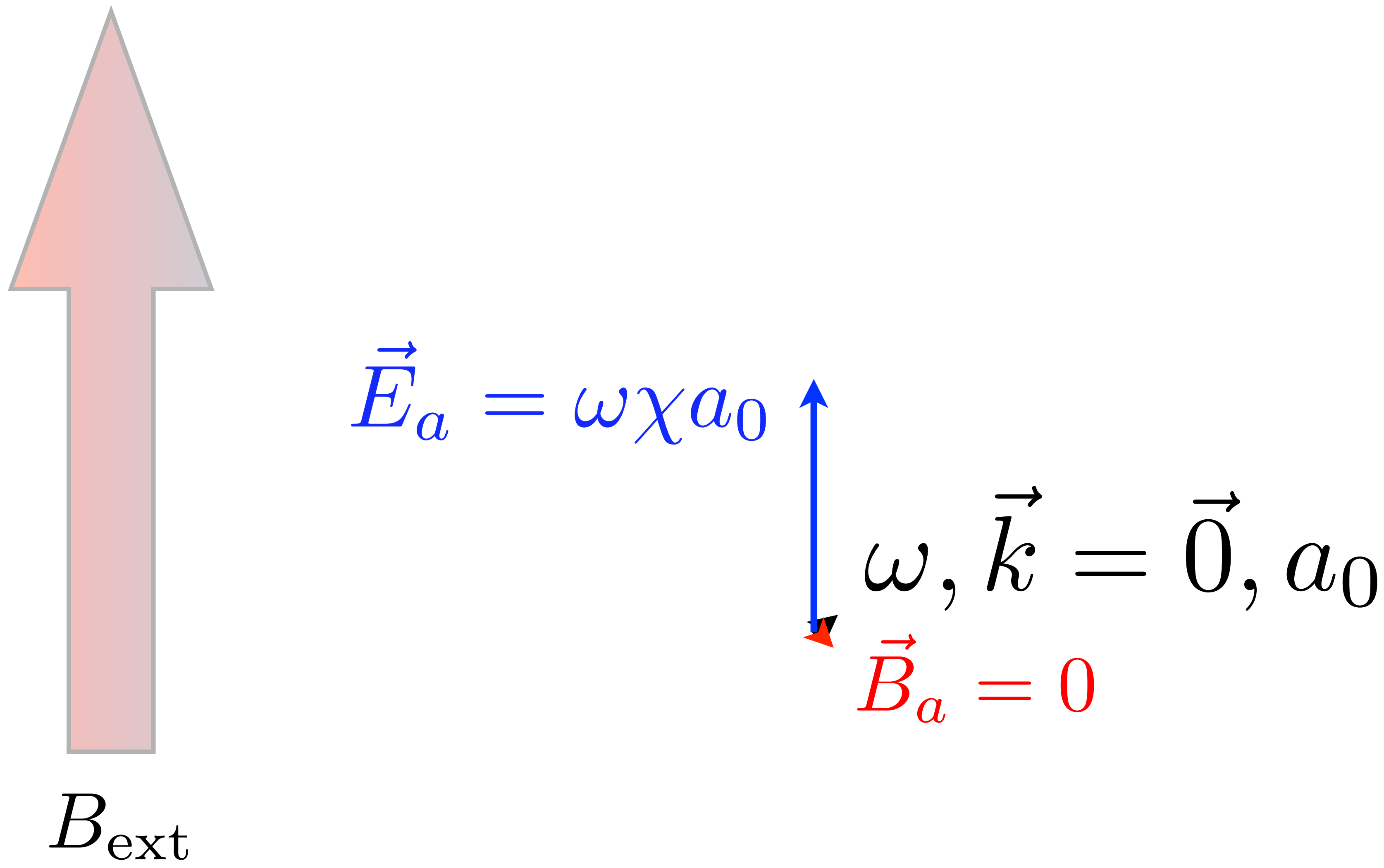
$\omega, \vec{k}, \vec{A}'$

$\omega \sim m_a \gg |\vec{k}|$

$\vec{E}_a = \omega\chi\vec{A}'$

$\vec{B}_a = \frac{\vec{k} \times \vec{E}_a}{\omega} \sim \mathcal{O}(k\chi A')$

DM axions in a magnetic field



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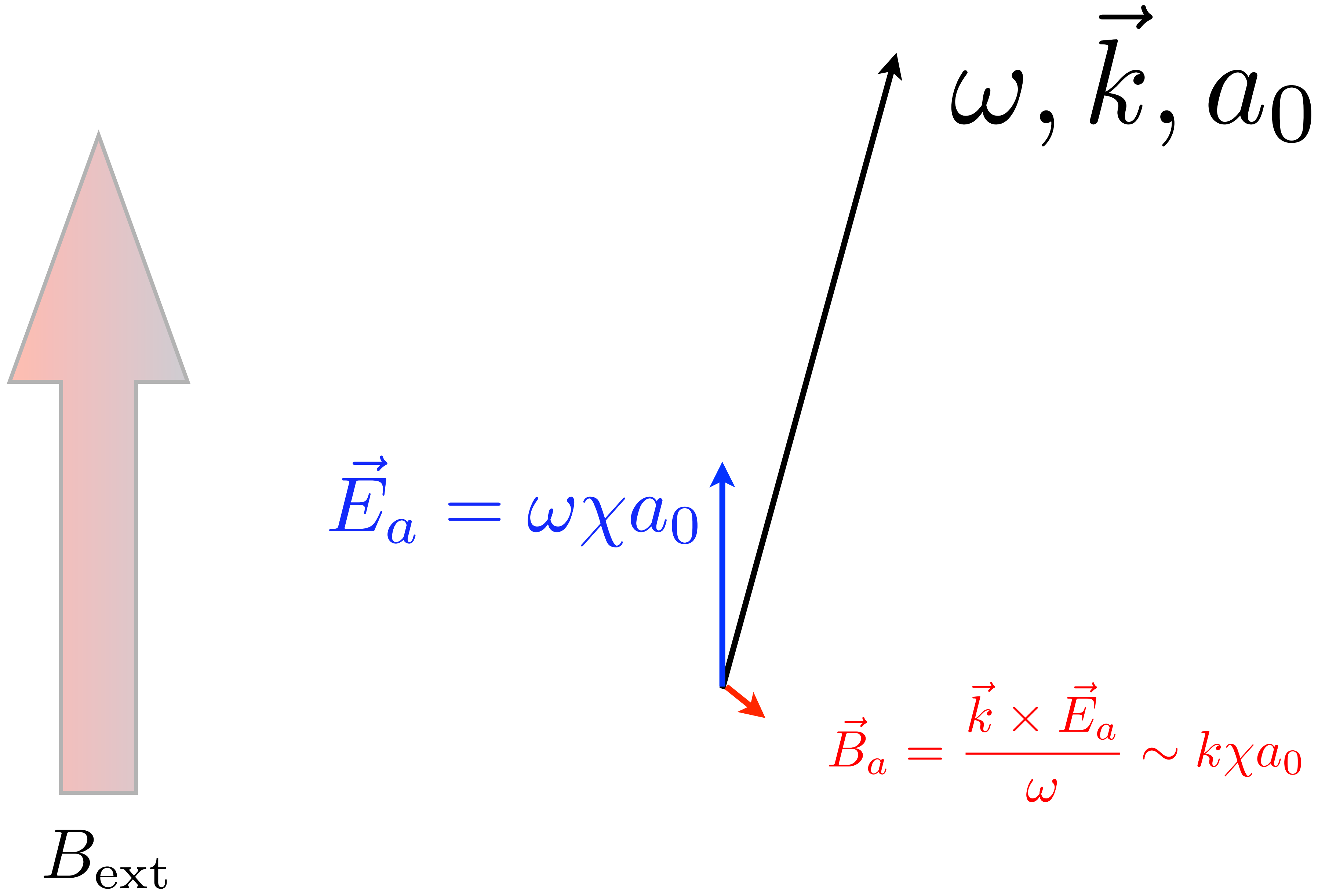
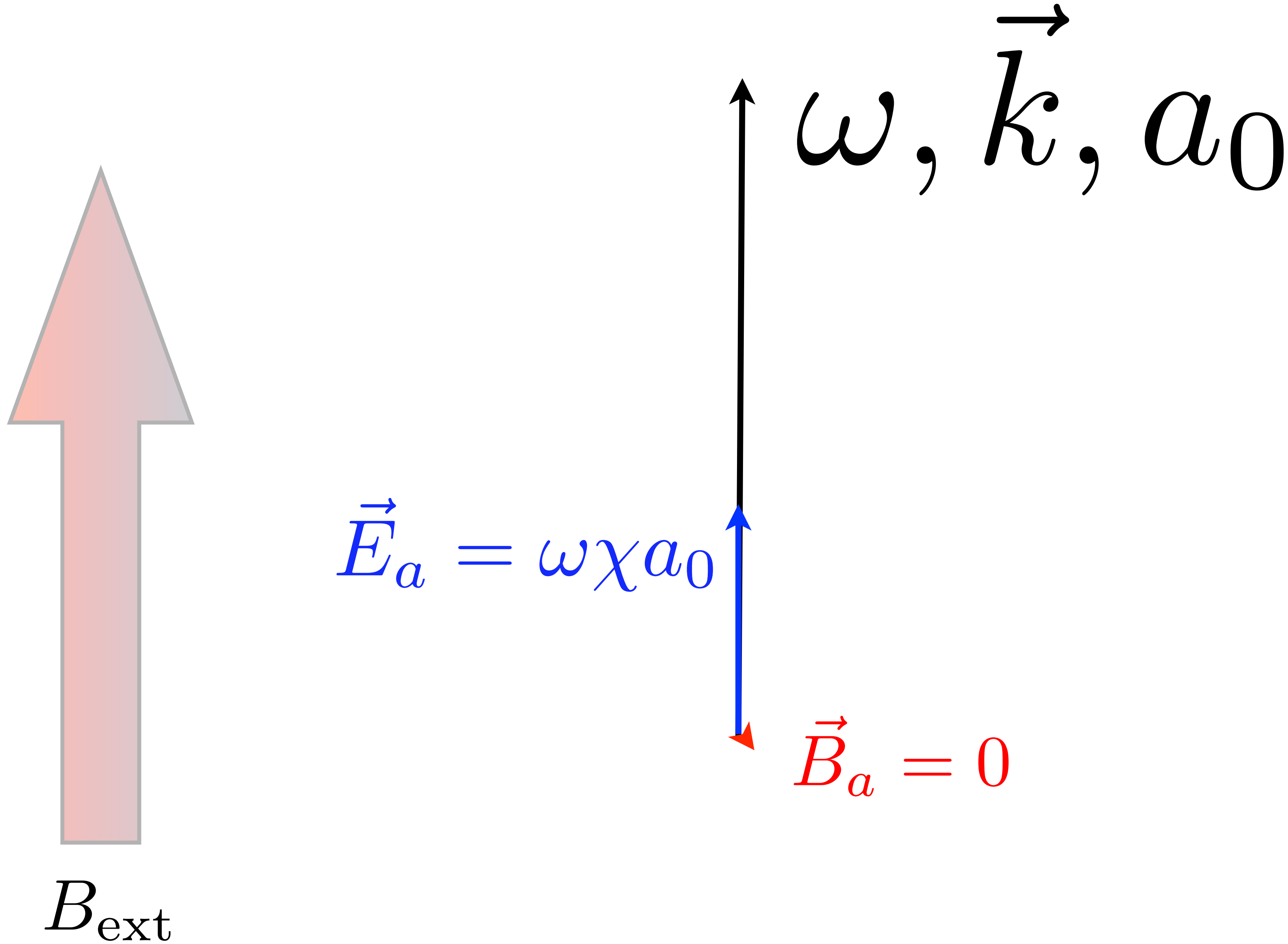
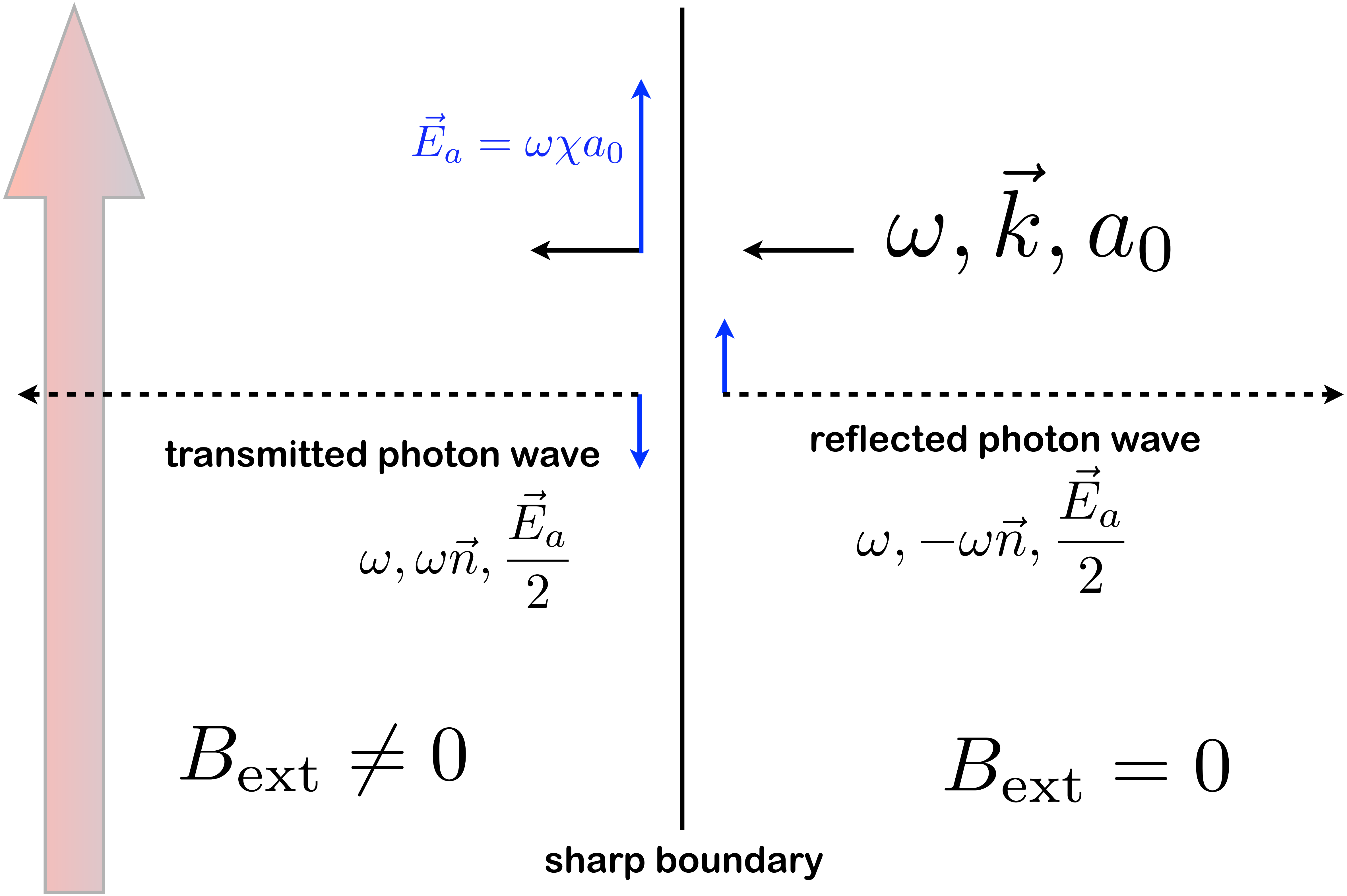


DM axions in a magnetic field

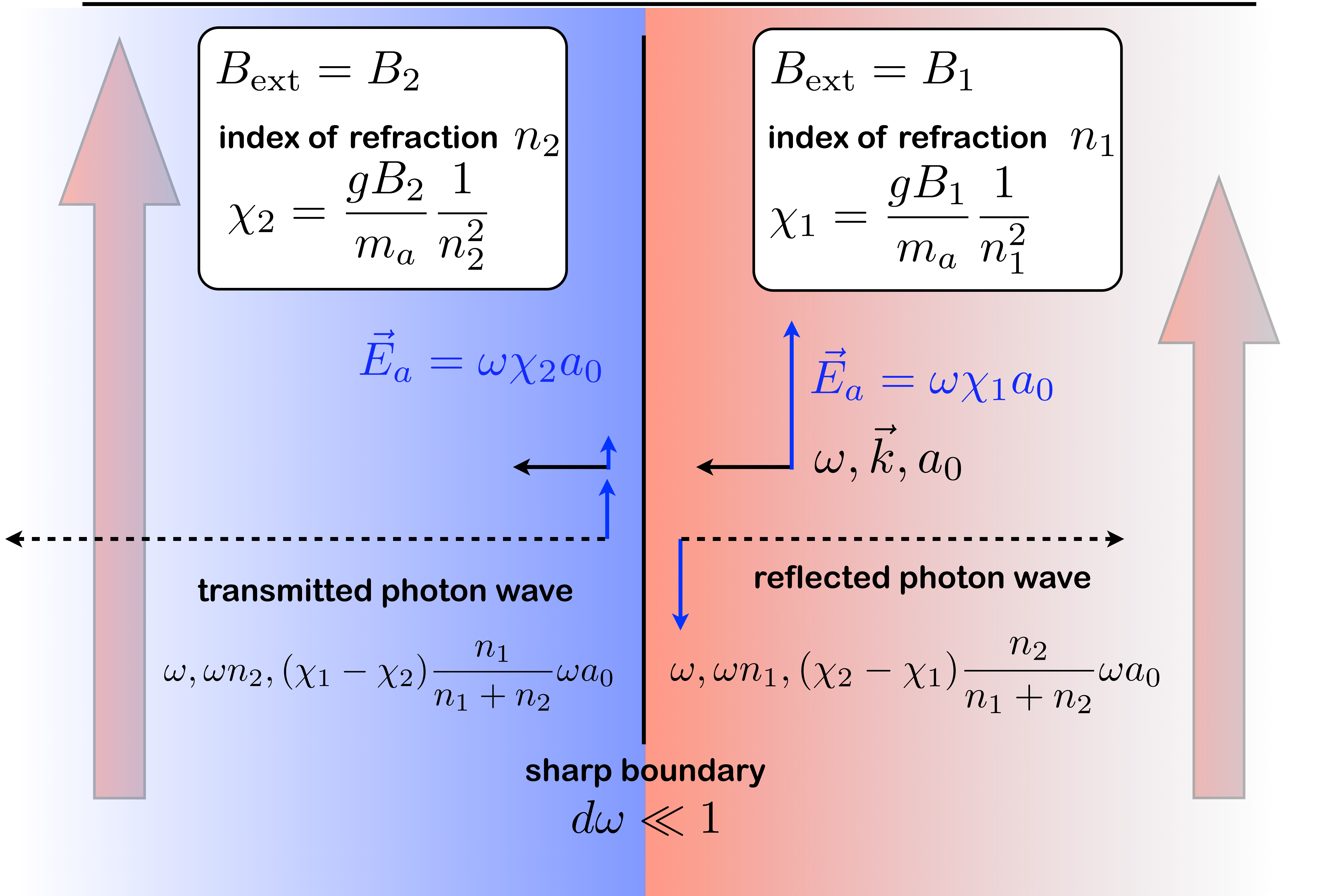


DM axions entering a magnetic field



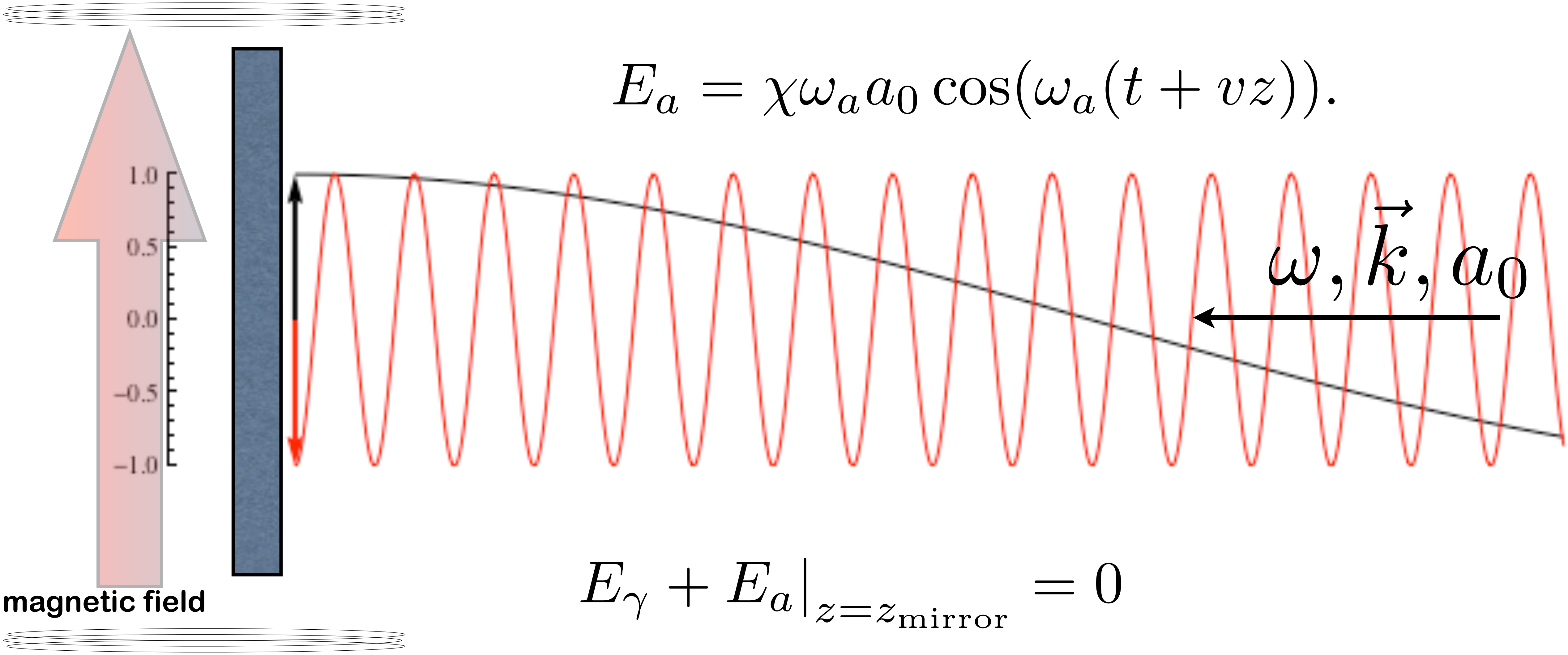
DM axions changing medium

Jaeckel and JR arXiv:1308.1103



Radiation from a magnetised mirror

Horns at al JCAP04(2013)016



$$E_a = \chi \omega_a a_0 \cos(\omega_a (t + vz)).$$

$$E_\gamma + E_a|_{z=z_{\text{mirror}}} = 0$$

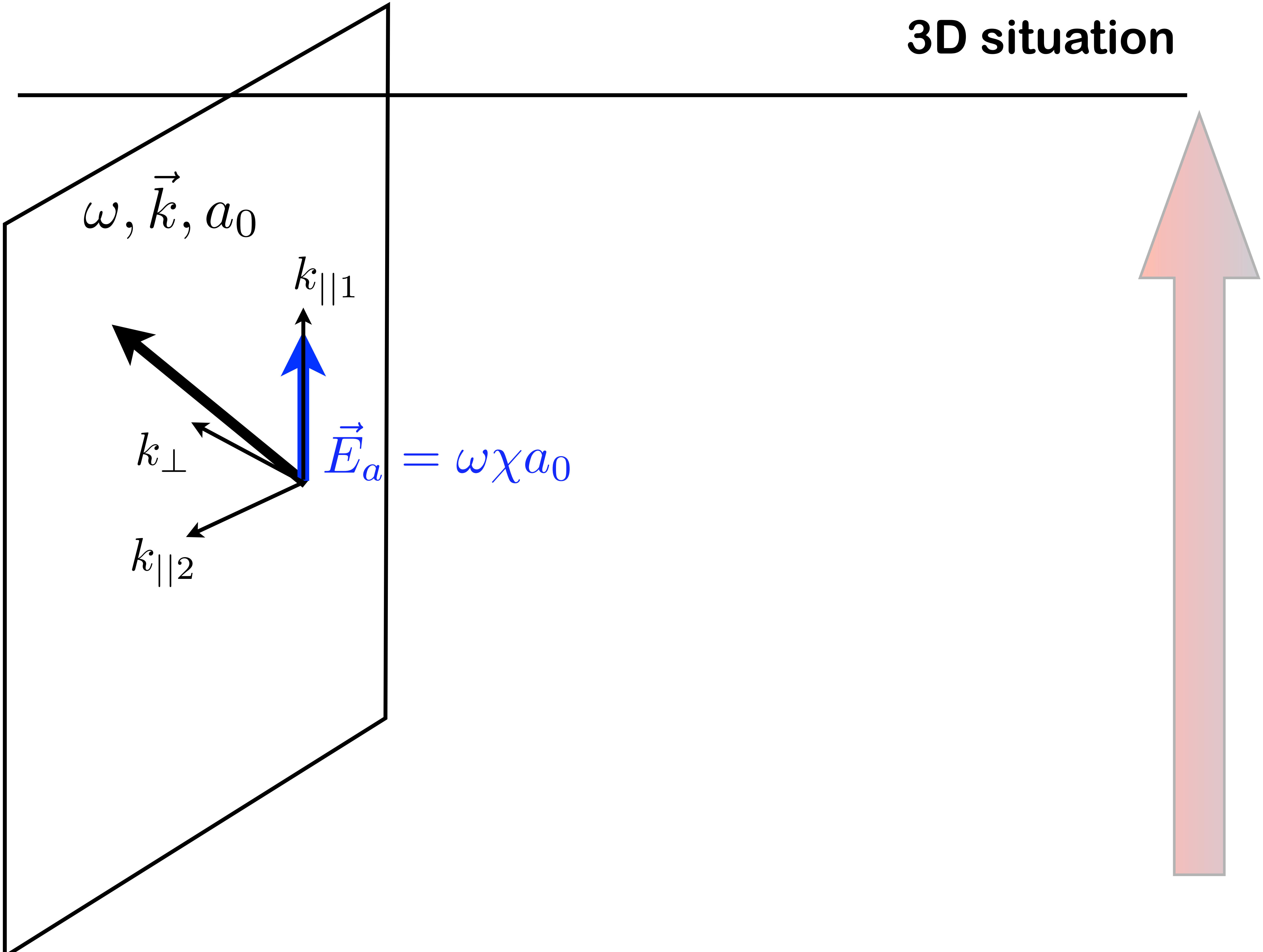
Radiated photon wave

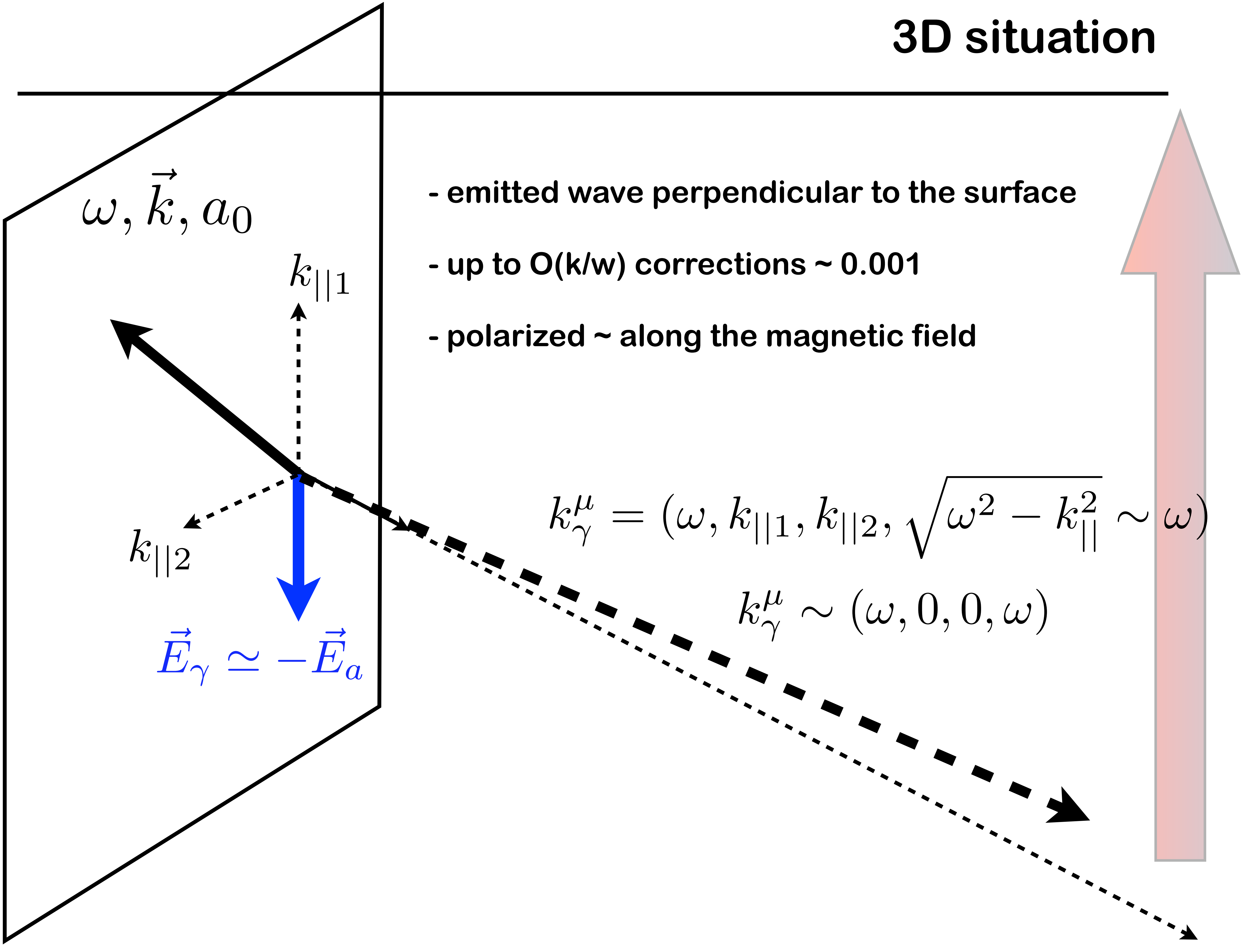
$$E_\gamma = -\chi \omega_a a_0 \cos(\omega_\gamma (t - z)).$$

whose frequency is

$$\omega_\gamma = \omega_a = m_a(1 + v^2/2)$$

3D situation



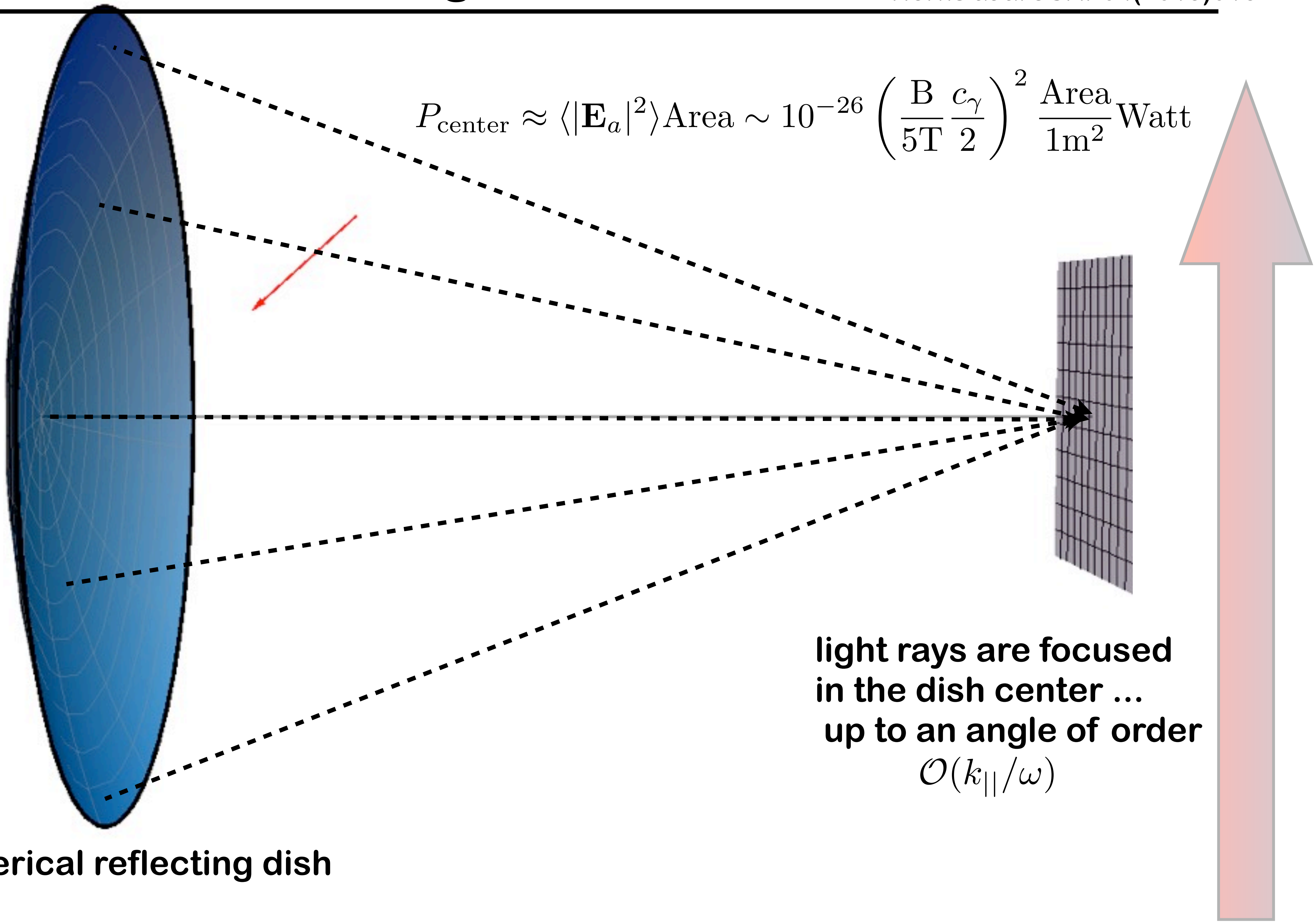


3D situation
- emitted wave perpendicular to the surface
- up to O(k/w) corrections ~ 0.001
- polarized ~ along the magnetic field
$\omega, \vec{k}, a_0$
$k_{||1}$
$k_{||2}$
$\vec{E}_\gamma \simeq -\vec{E}_a$
$k^\mu_\gamma = (\omega, k_{||1}, k_{||2}, \sqrt{\omega^2 - k^2_{||}} \sim \omega)$
$k^\mu_\gamma \sim (\omega, 0, 0, \omega)$

Radiation from a magnetised mirror

Horns at al JCAP04(2013)016

$$P_{\text{center}} \approx \langle|\mathbf{E}_a|^2\rangle \text{Area} \sim 10^{-26} \left(\frac{\text{B}}{5\text{T}}\frac{c_\gamma}{2}\right)^2 \frac{\text{Area}}{1\text{m}^2}\text{Watt}$$



light rays are focused
in the dish center ...
up to an angle of order
$\mathcal{O}(k_{||}/\omega)$

spherical reflecting dish

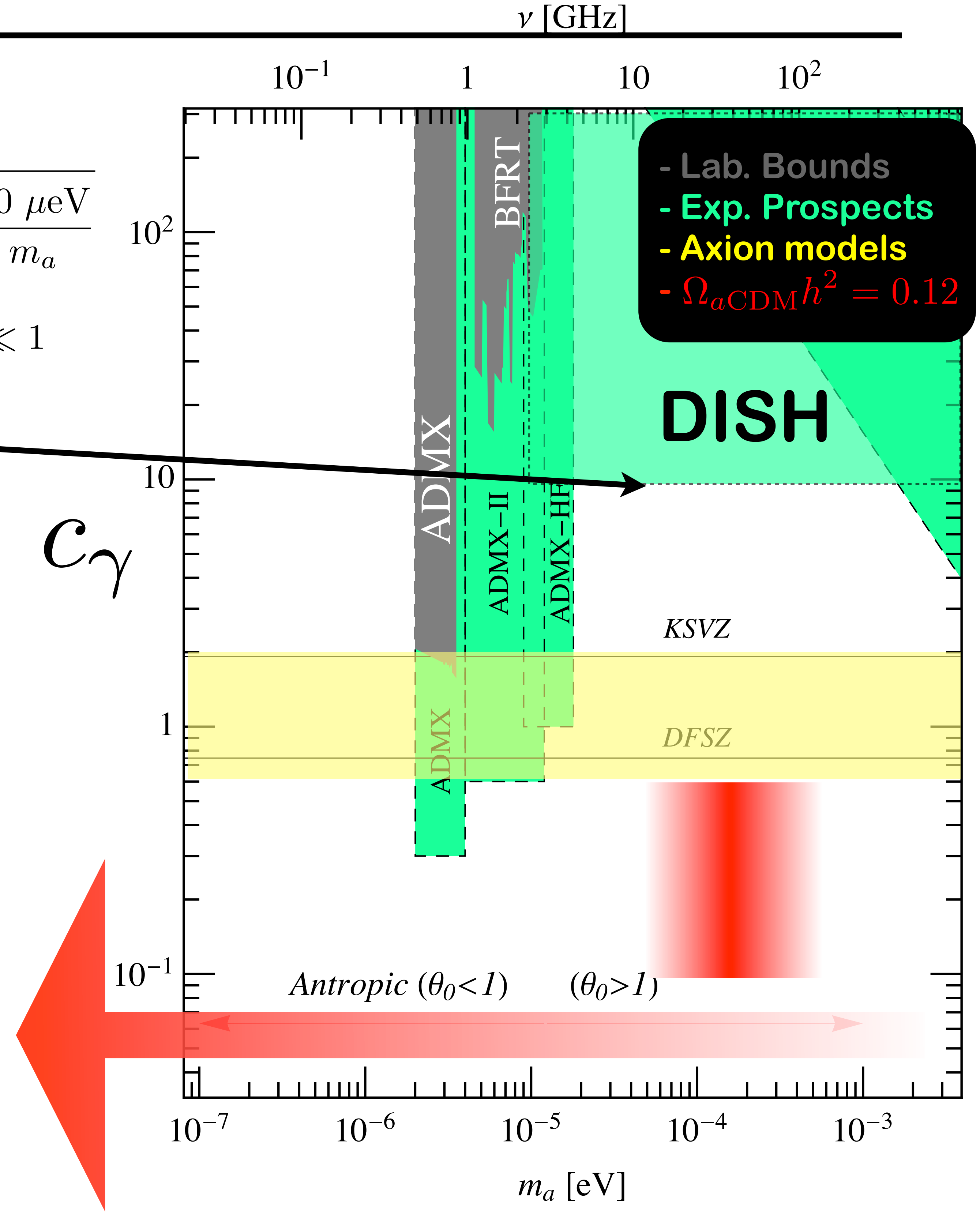
Reach

Signal to noise

$$\frac{S}{N}=3\times10^{-2}\frac{5\text{K}}{T_S}\frac{\text{Area}}{10\ \text{m}^2}\left(\frac{B}{5\ \text{T}}\frac{c_\gamma}{2}\right)^2\sqrt{\frac{\text{time}}{1\ \text{year}}\frac{10^{-6}}{\Delta\omega/\omega}\frac{10\ \mu\text{eV}}{m_a}}$$

diffraction $m_a R \ll 1$

- **A=10 m2**
- **B=5 T**
- **T_{noise}=5K**
- **Detectors every 1/8 in frequency**

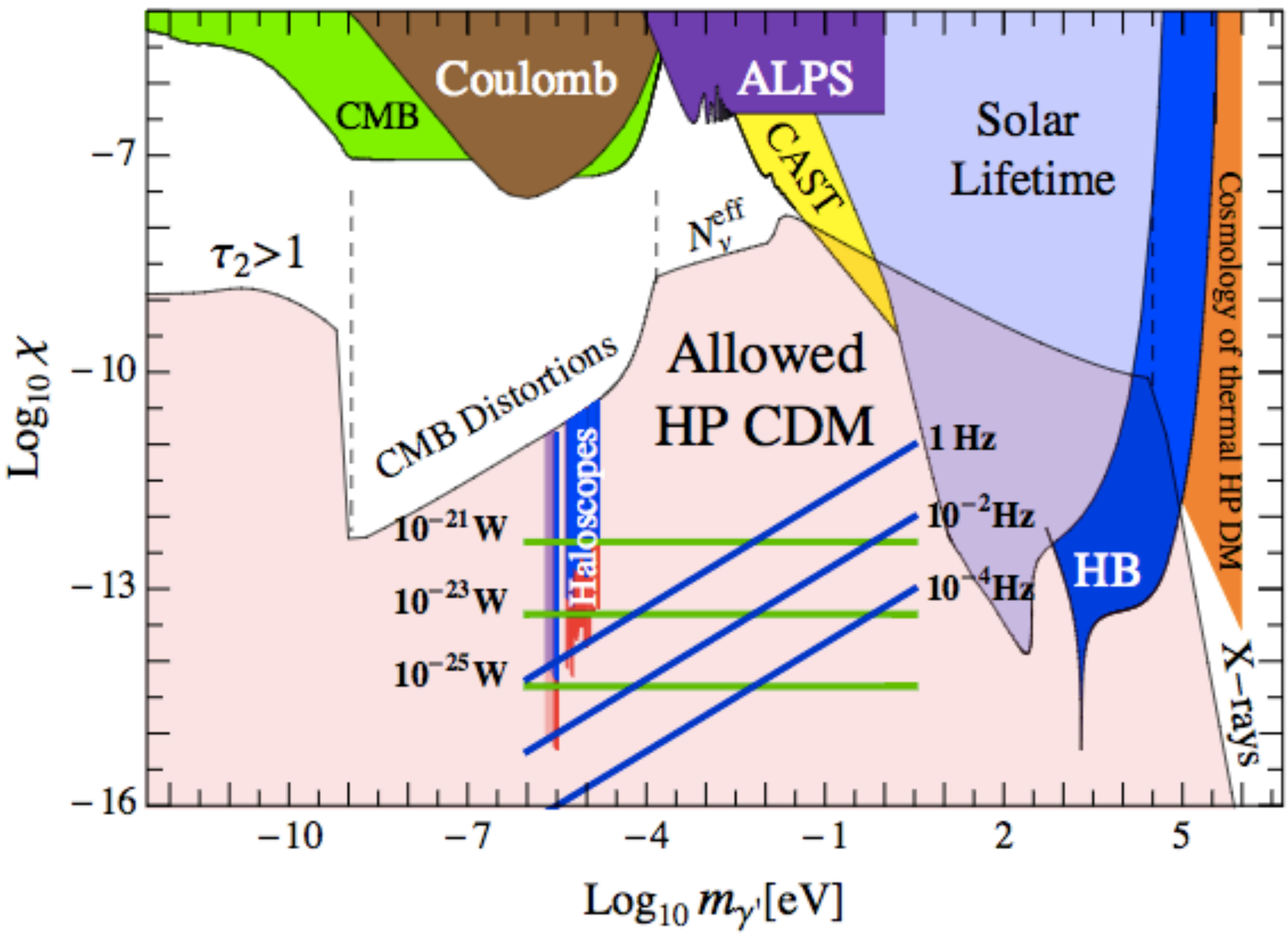


-need more area?
-more B?
-less noise?
-more time?
-up-fluctuation in the DM density?

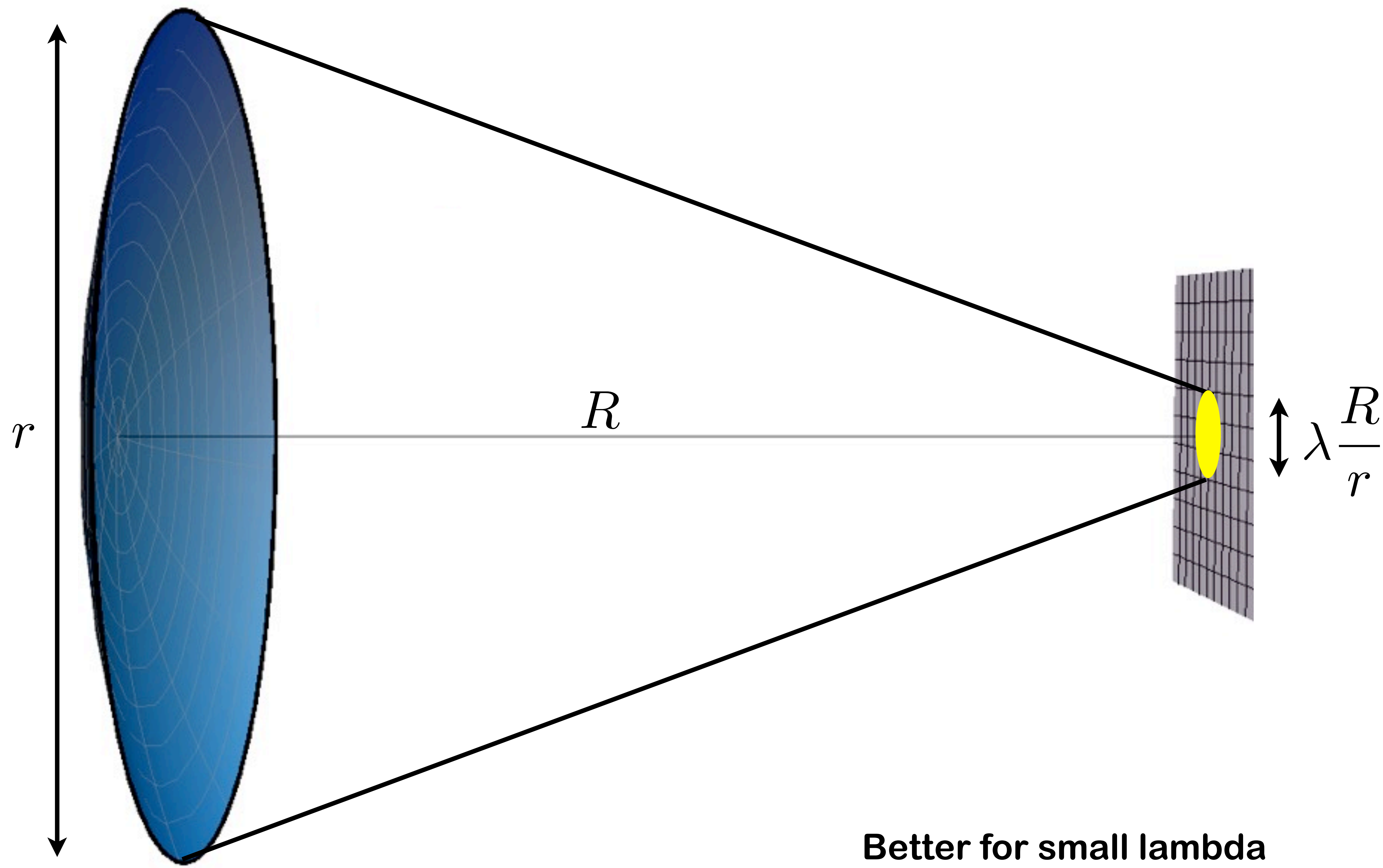
Sensitivity for HPs

Horns at al JCAP04(2013)016

different background levels

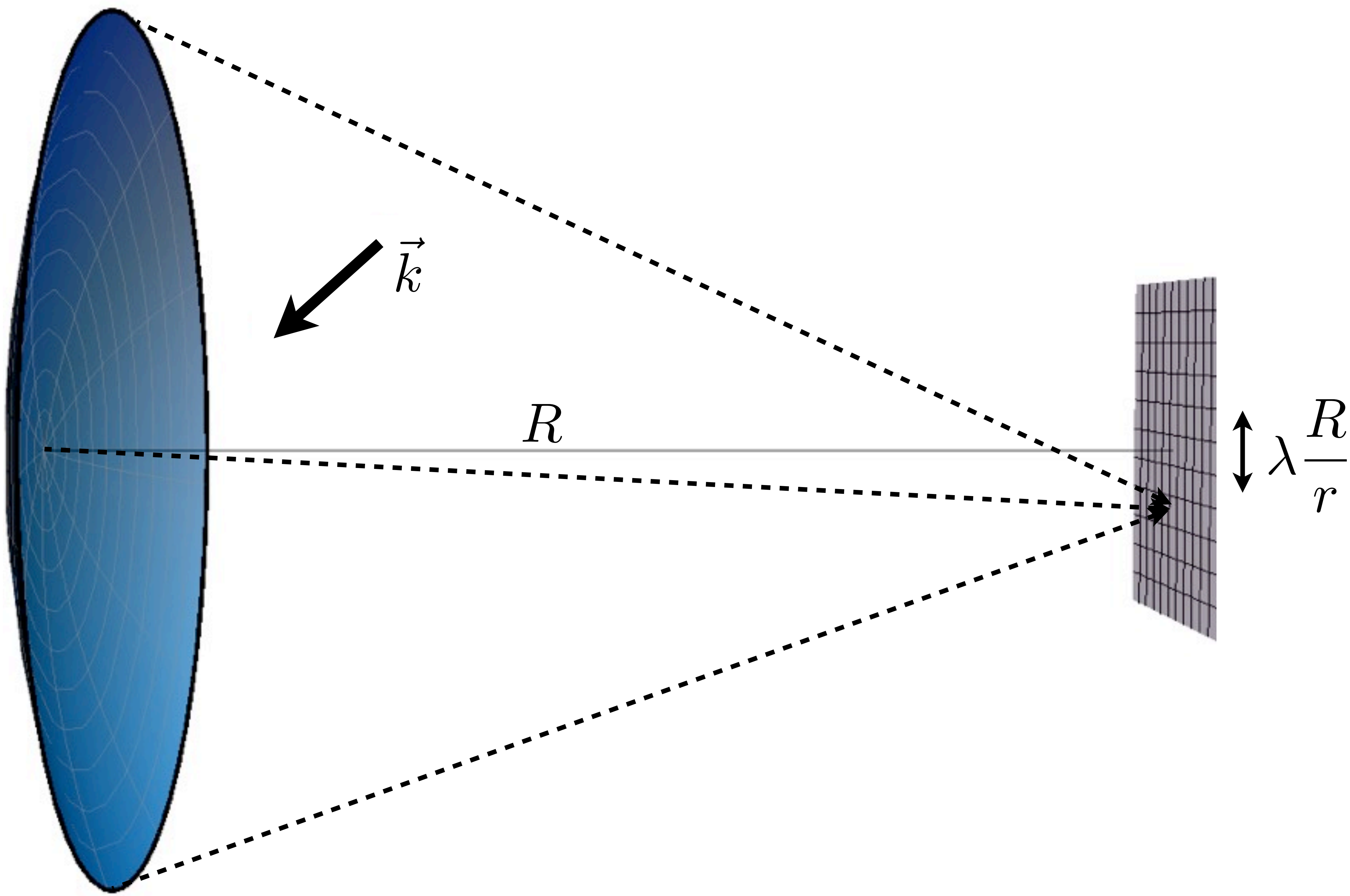


Limitations: Diffraction

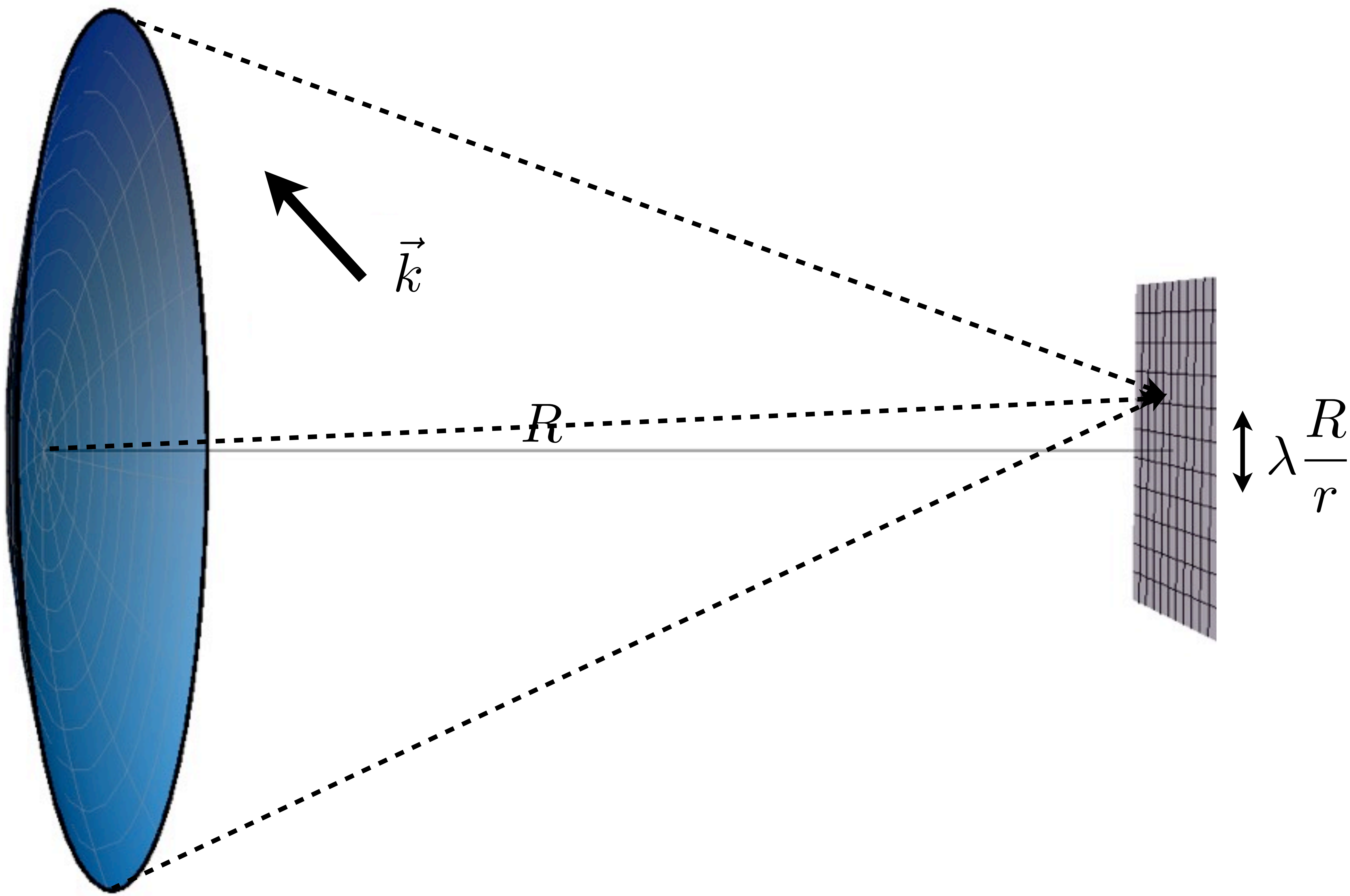


Better for small lambda

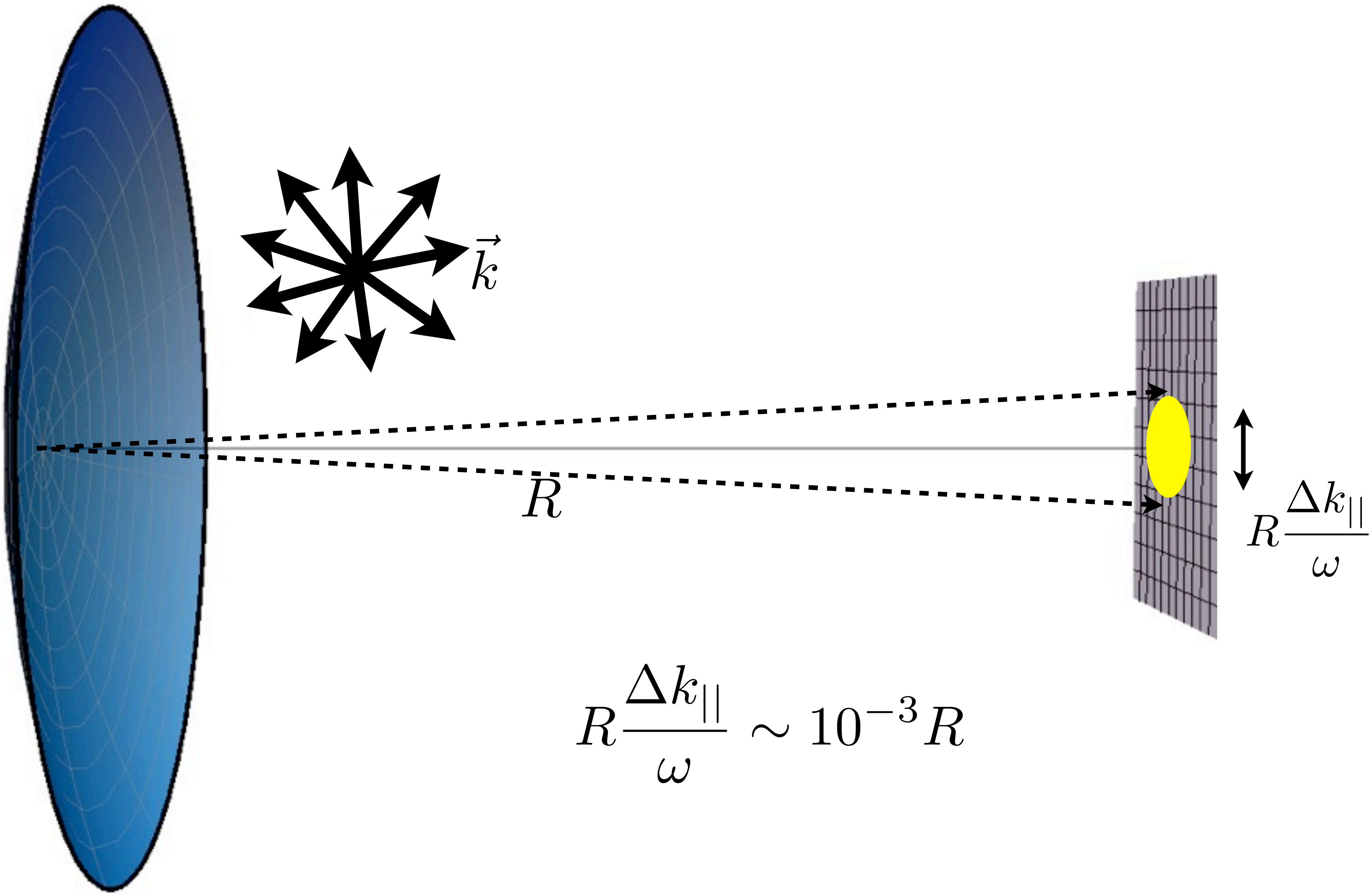
Limitations: momentum distribution



Limitations: momentum distribution

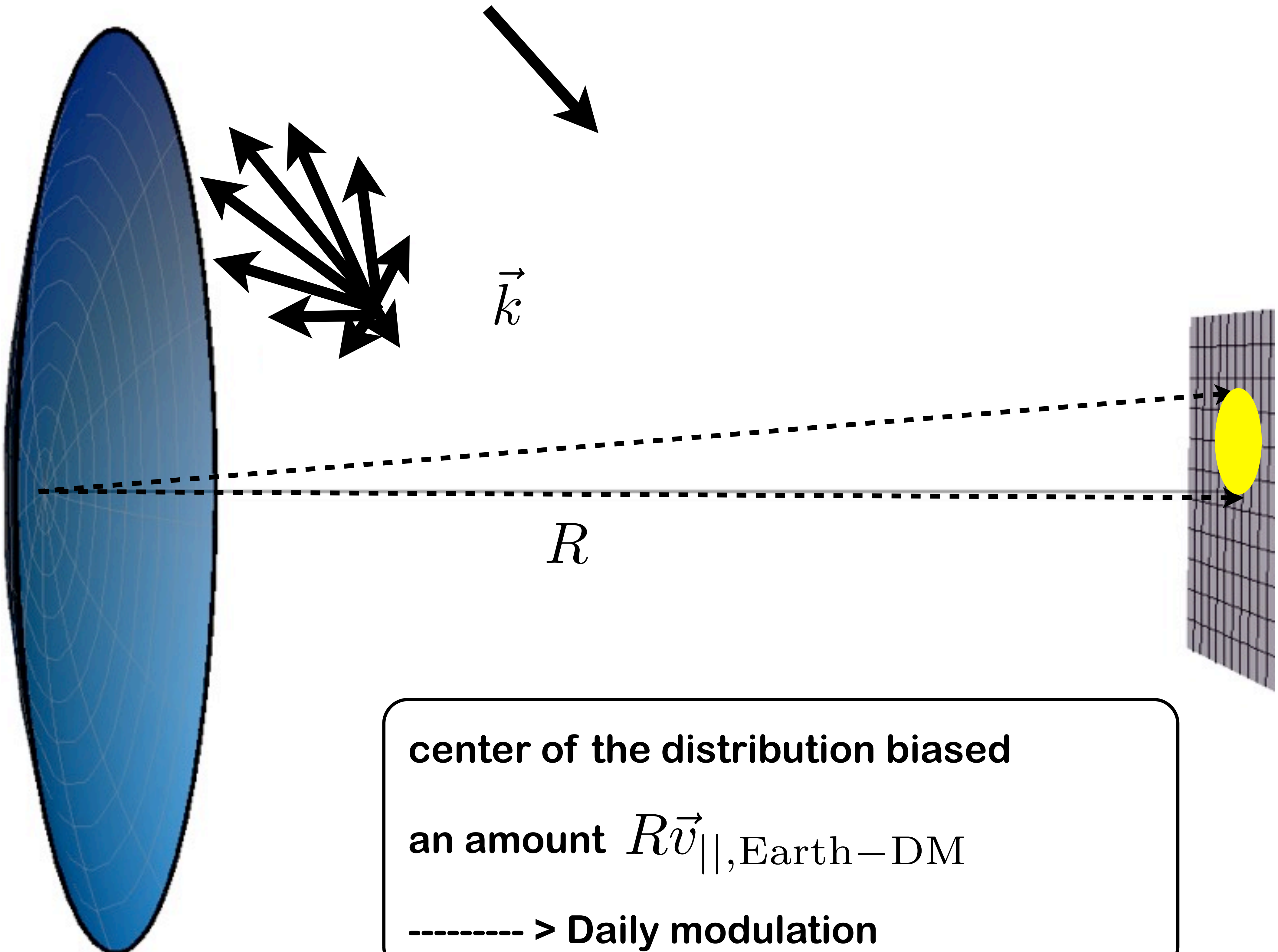


Limitations: momentum distribution



$$R\frac{\Delta k_{||}}{\omega} \sim 10^{-3} R$$

Limitations: momentum distribution and Earth's motion with respect to DM

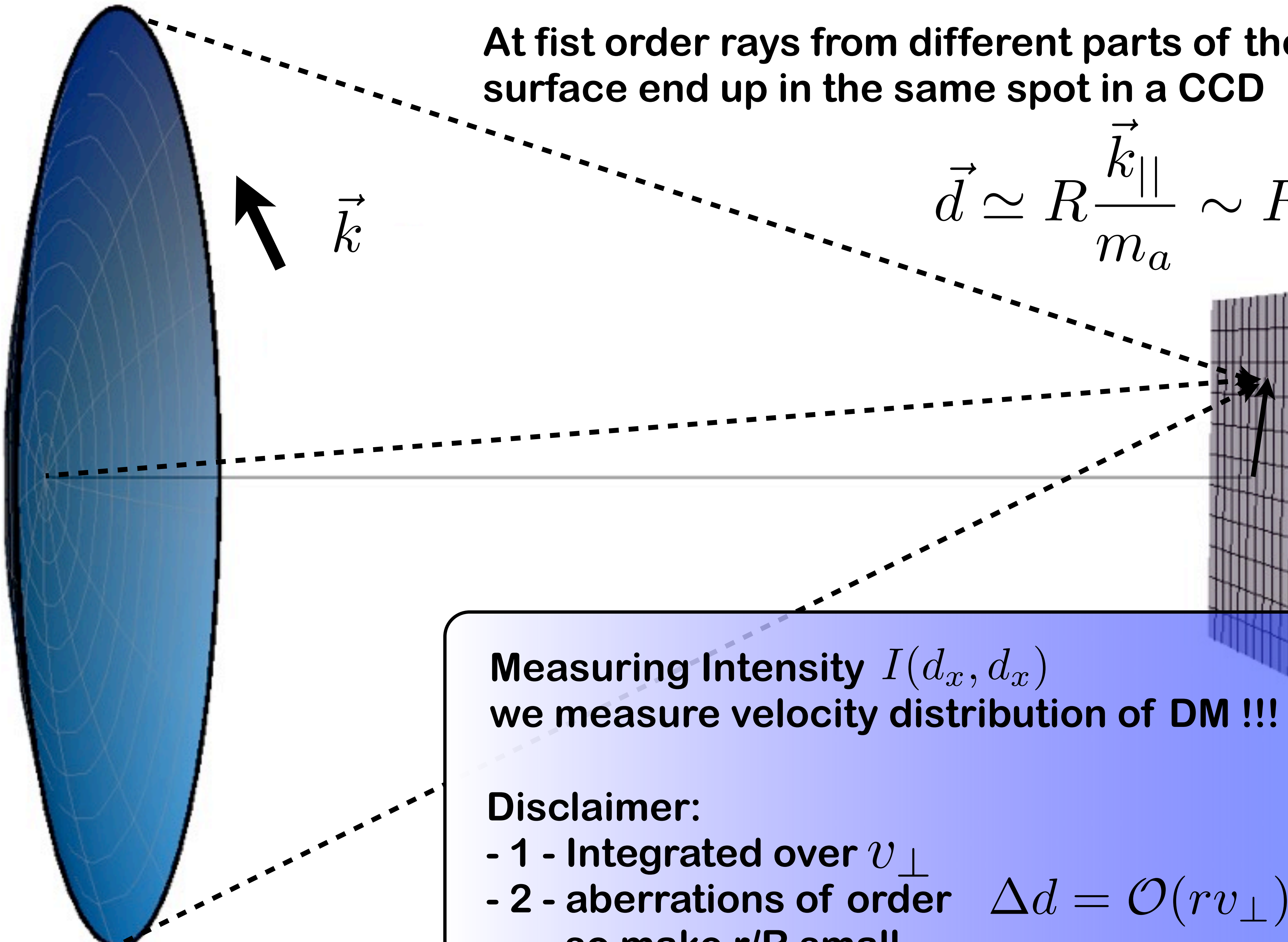


center of the distribution biased

an amount $R\vec{v}_{||,\mathrm{Earth-DM}}$

---------> Daily modulation

Detecting the velocity distribution of DM!



At fist order rays from different parts of the surface end up in the same spot in a CCD

$$\vec{d} \simeq R\frac{\vec{k}_{||}}{m_a} \sim R\vec{v}_{||}$$

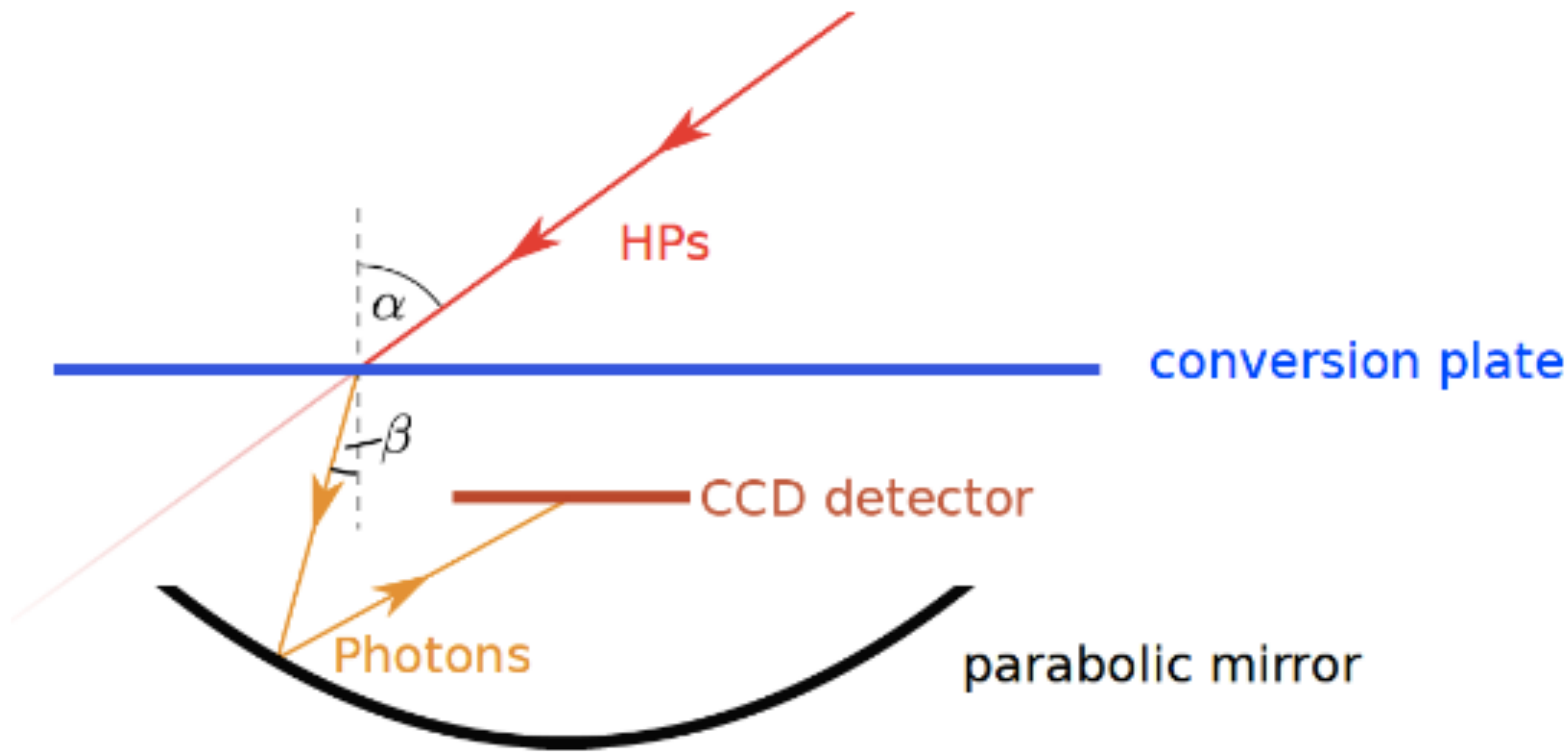
Measuring Intensity $I(d_x, d_x)$
we measure velocity distribution of DM !!!

Disclaimer:
- 1 - Integrated over $v_\perp$
- 2 - aberrations of order $\Delta d = \mathcal{O}(r v_\perp)$
  so make r/R small

Recent revisit

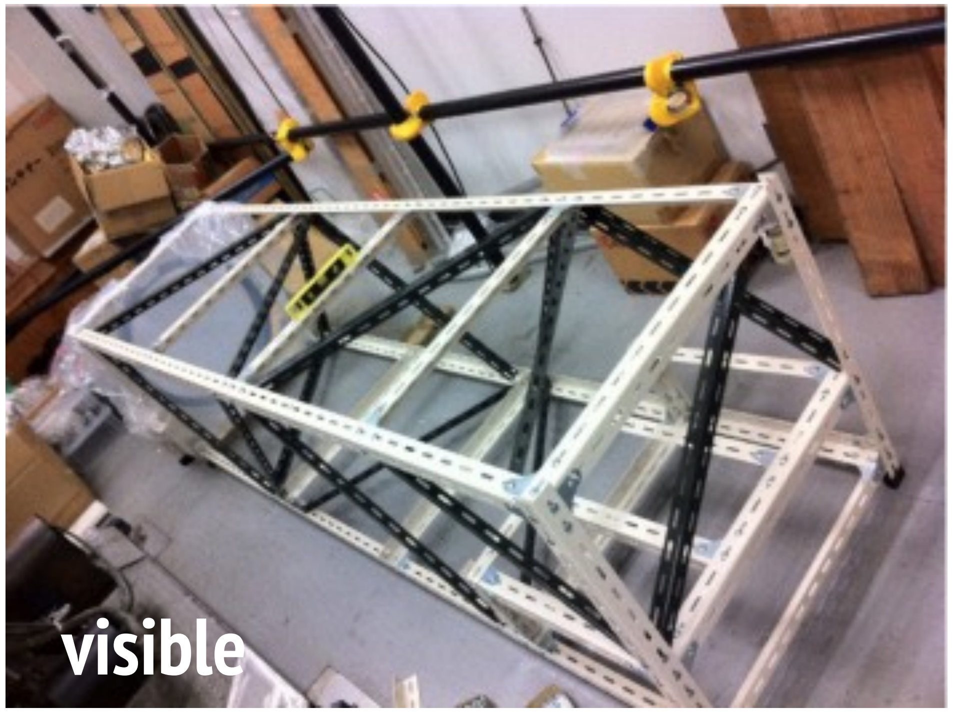
http://arxiv.org/pdf/1509.00371.pdf

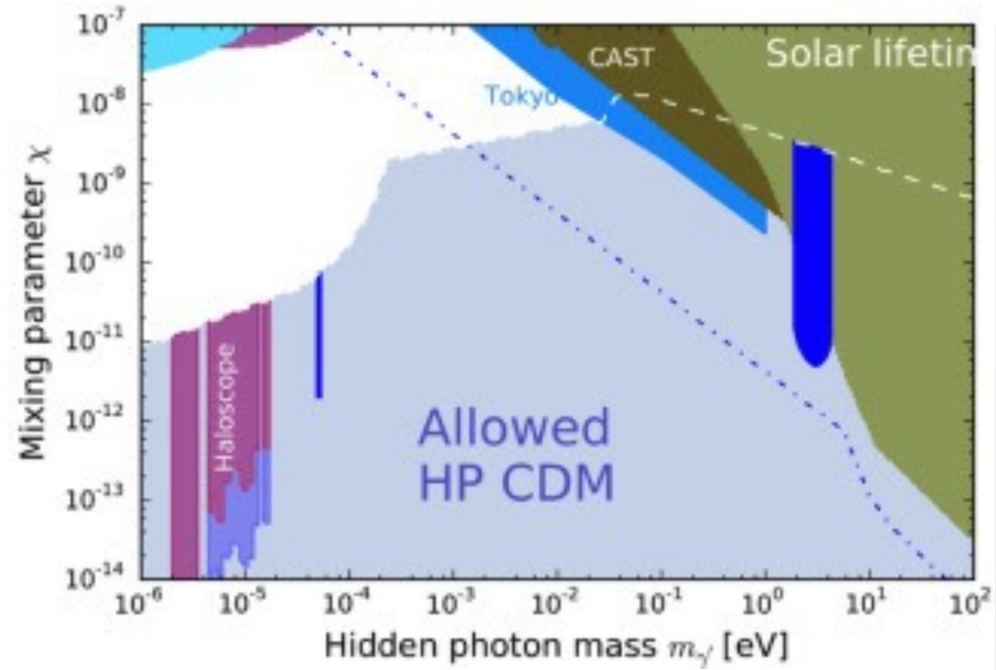
- Large aspect ratio requires higher orders in r/R
- Plane-parabolic geometry



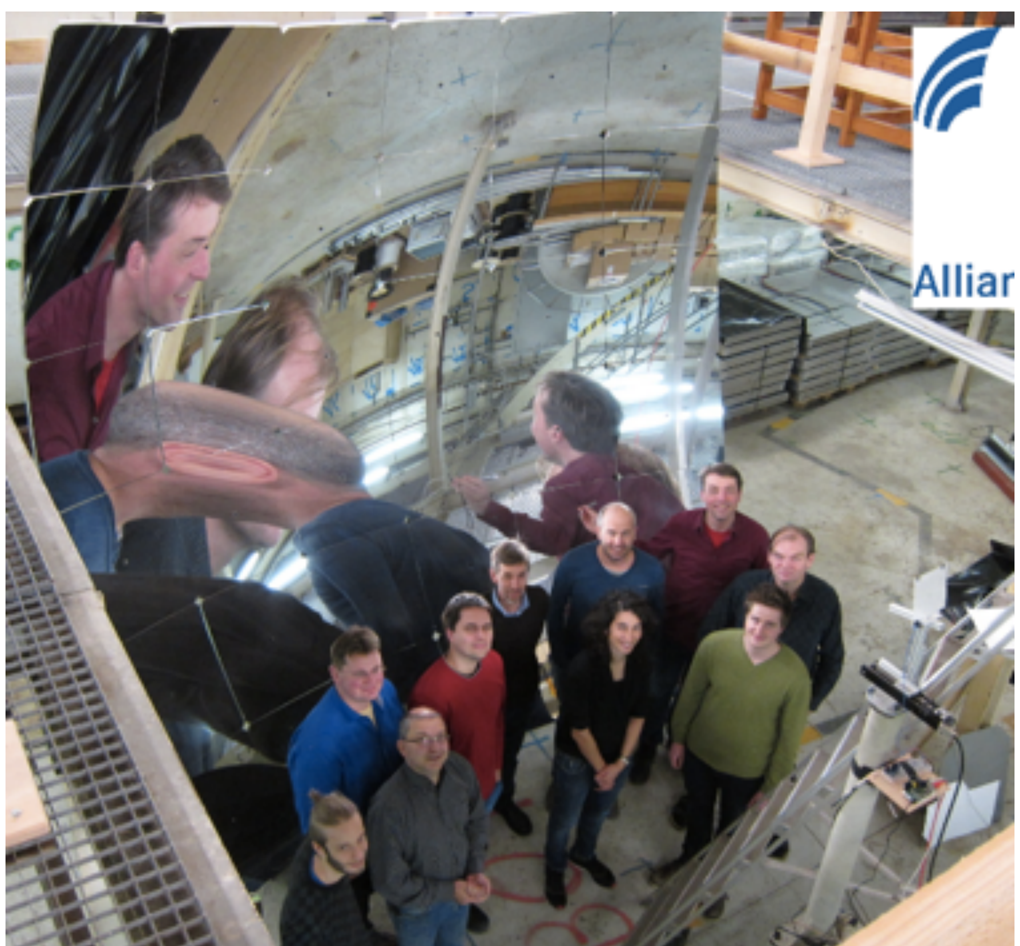
Dish antenna for Hidden Photons

Tokyo Experiments

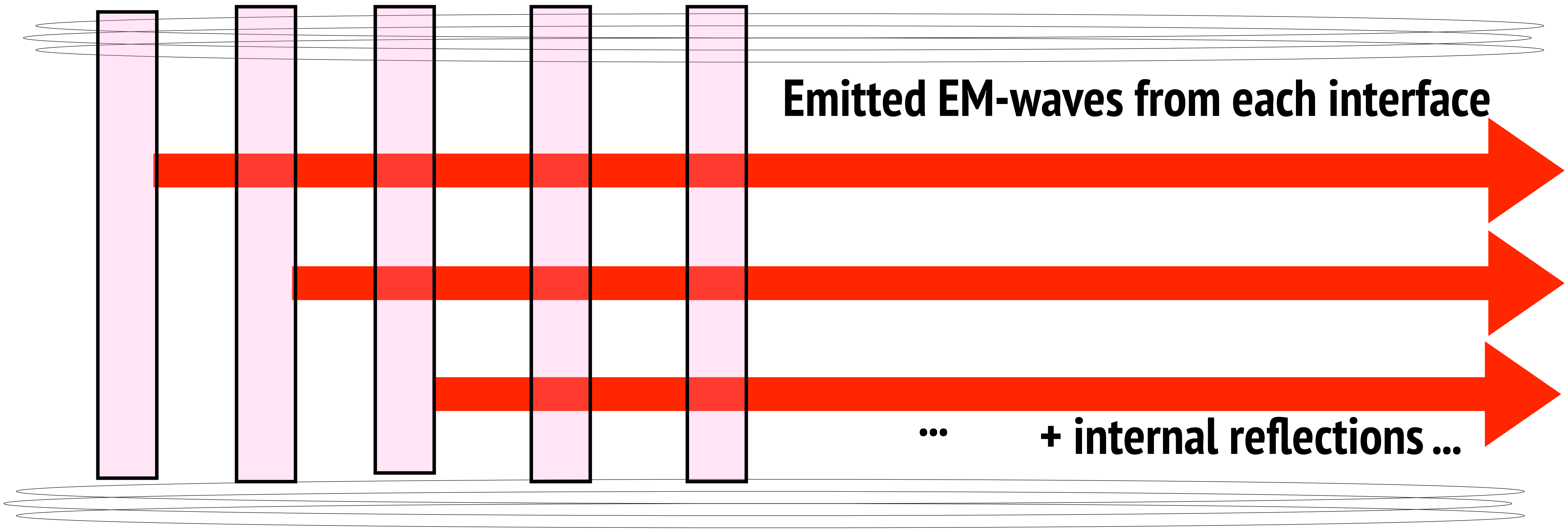




Karsruhe FUNK



Many dielectrics : MADMAX at MPP Munich



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

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

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

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

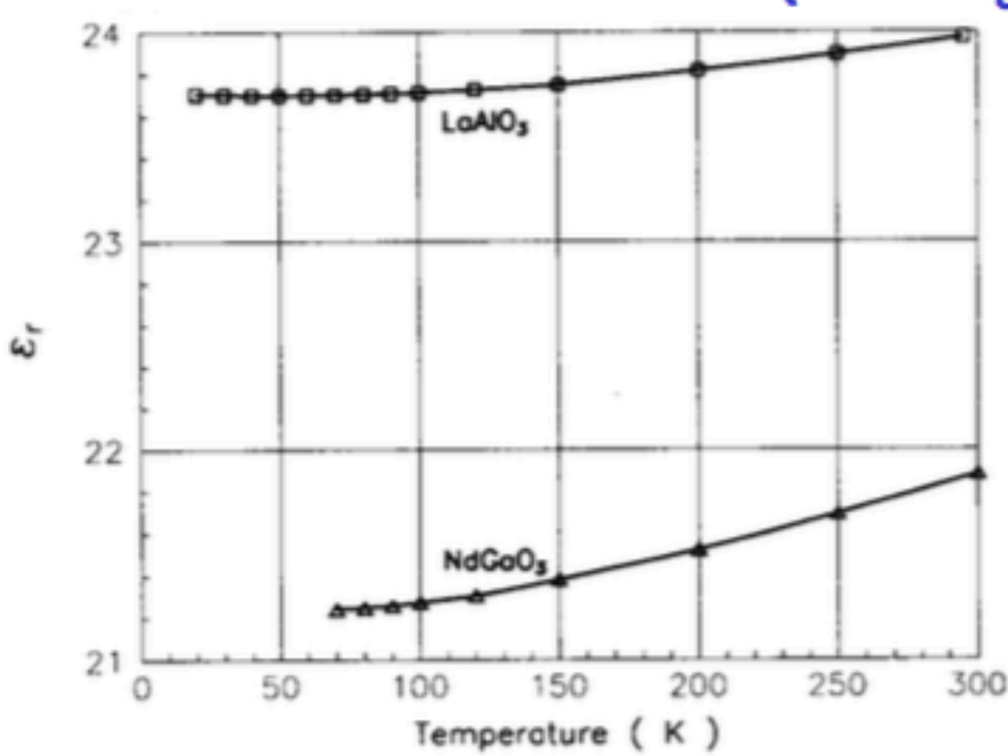
Experimental idea

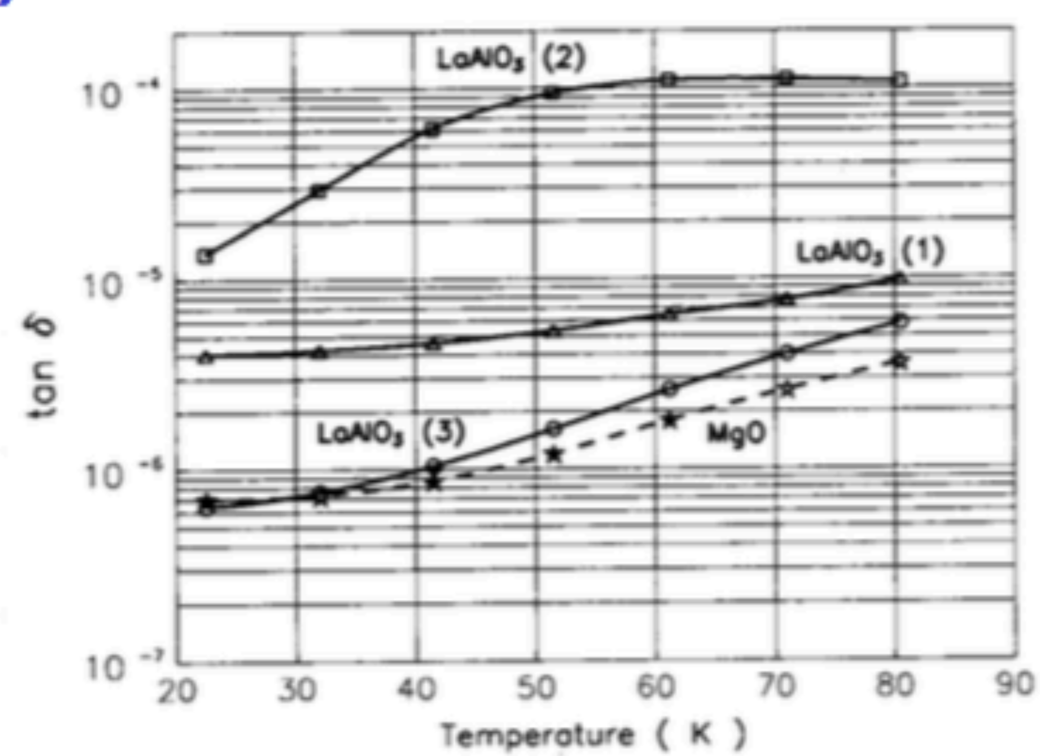
Chose dielectric material:

- 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: $\varepsilon_\perp = 9.35; \tan\delta_\perp = 3\cdot10^{-5}$
$\varepsilon_= = 11.53; \tan\delta_= = 8.6\cdot10^{-5}$

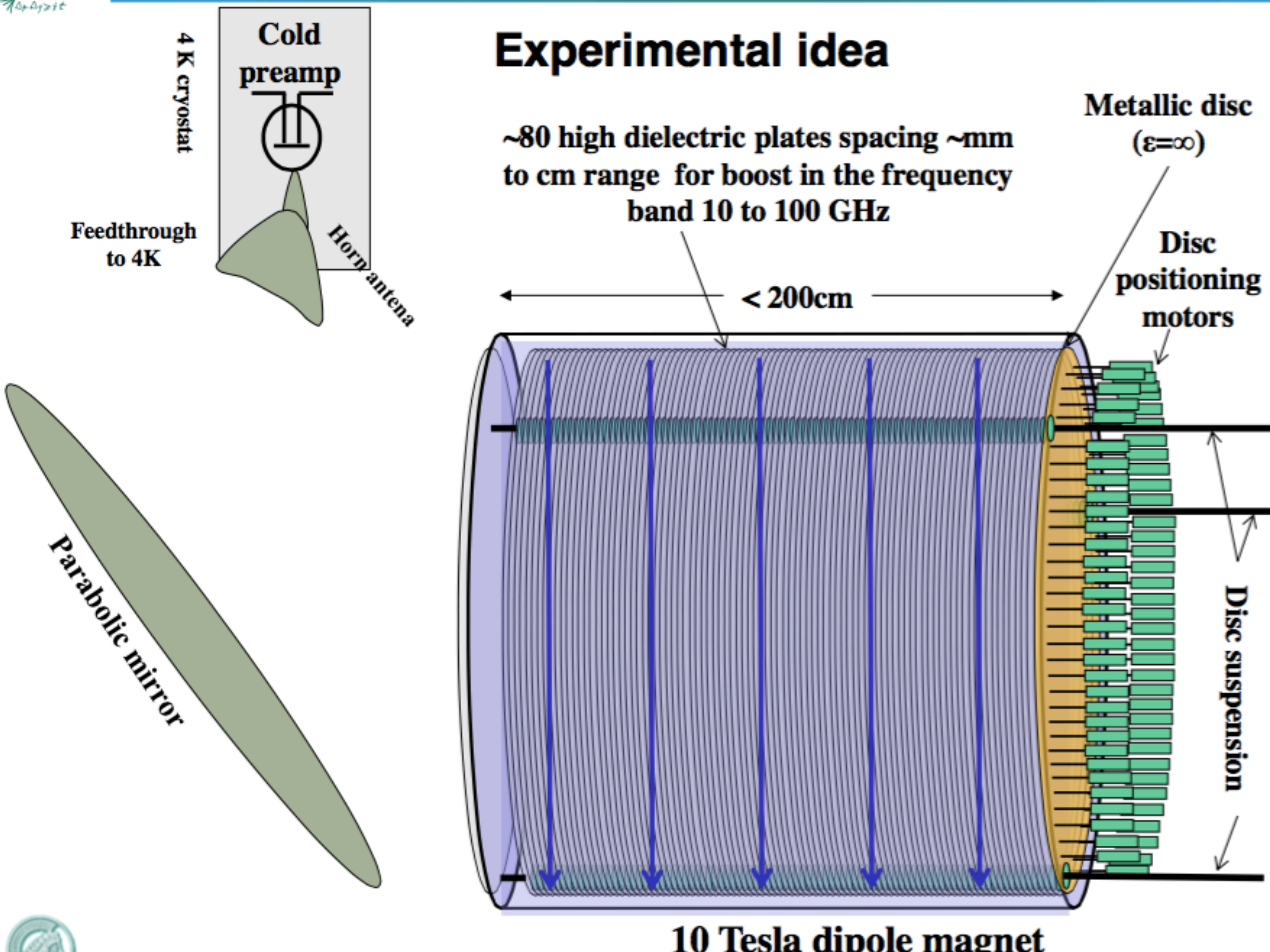
→ Lanthanide Aluminate ($LaAlO_3$)



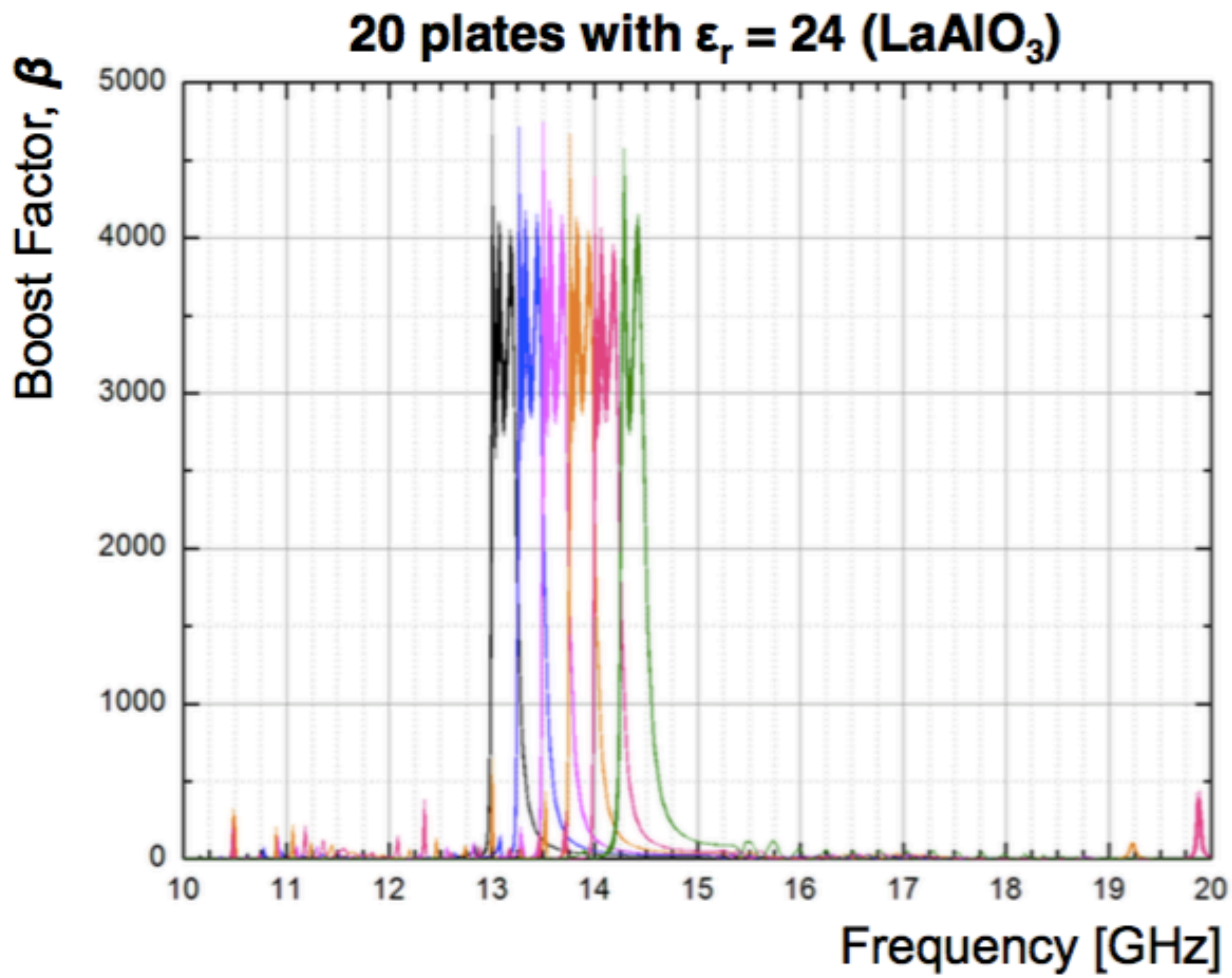


→ Titanium dioxide – Rutil (TiO_2) $\varepsilon \sim 100; \tan\delta = ?$
being investigated

Experimental idea



First simulations: the boost factor

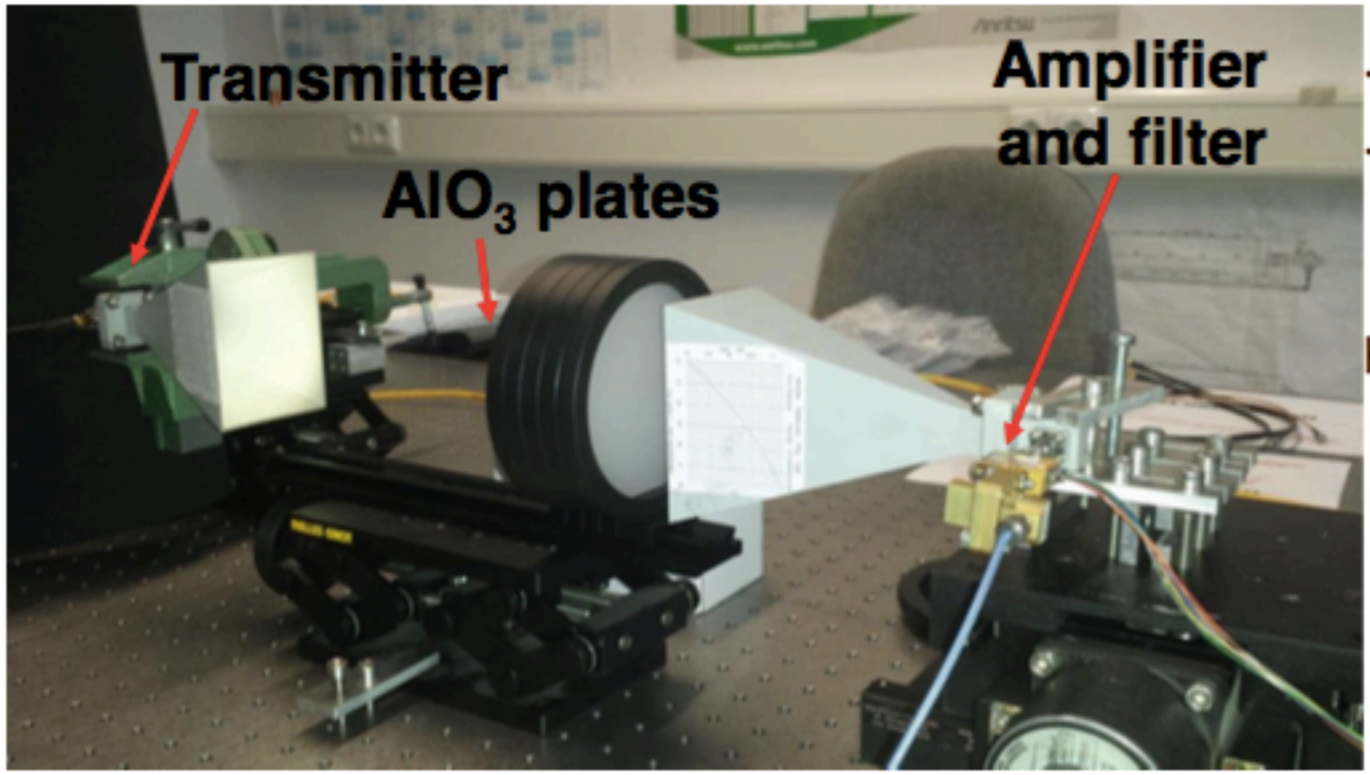


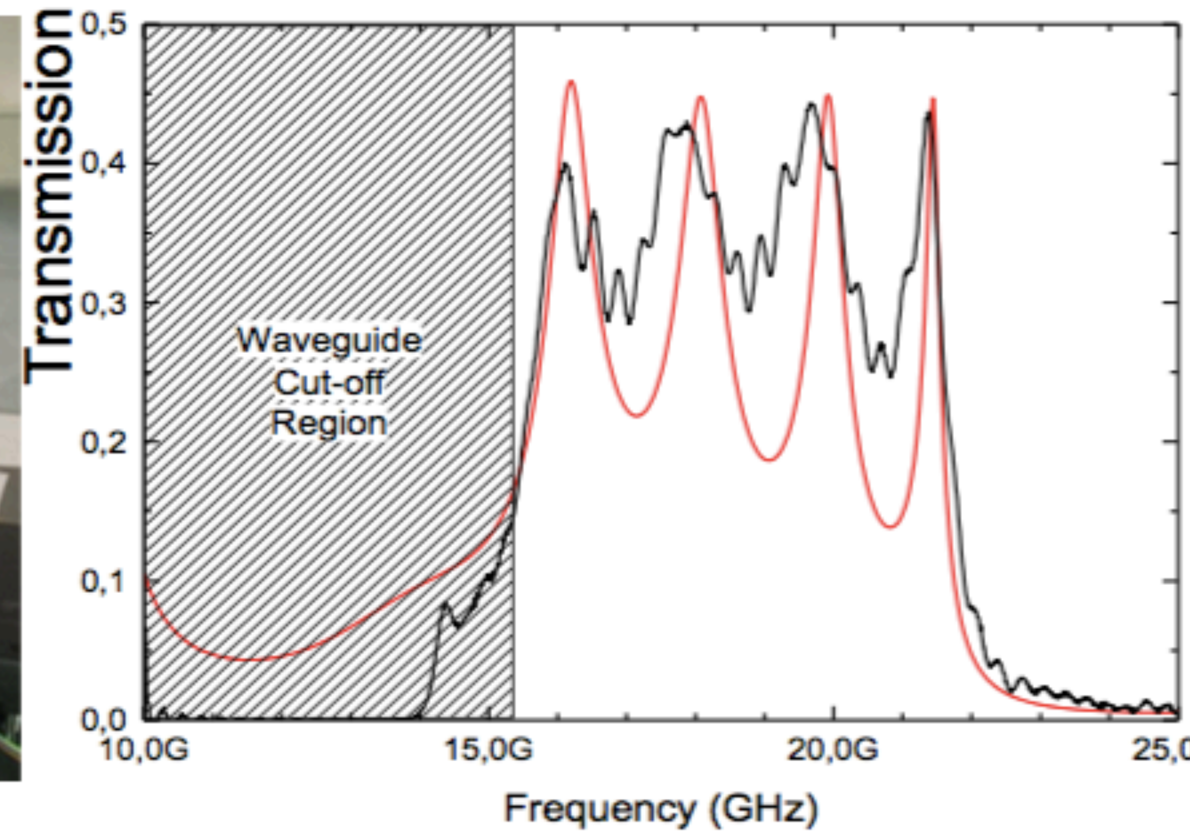
It is possible to adjust disc setting to reach sizeable β over broad bandwidth

Bandwidth per setting: ~250MHz
Precision of placement of high ε plates needed: ~few μm

First measurements: transmission

Boost factor is coupled to transmission behavior

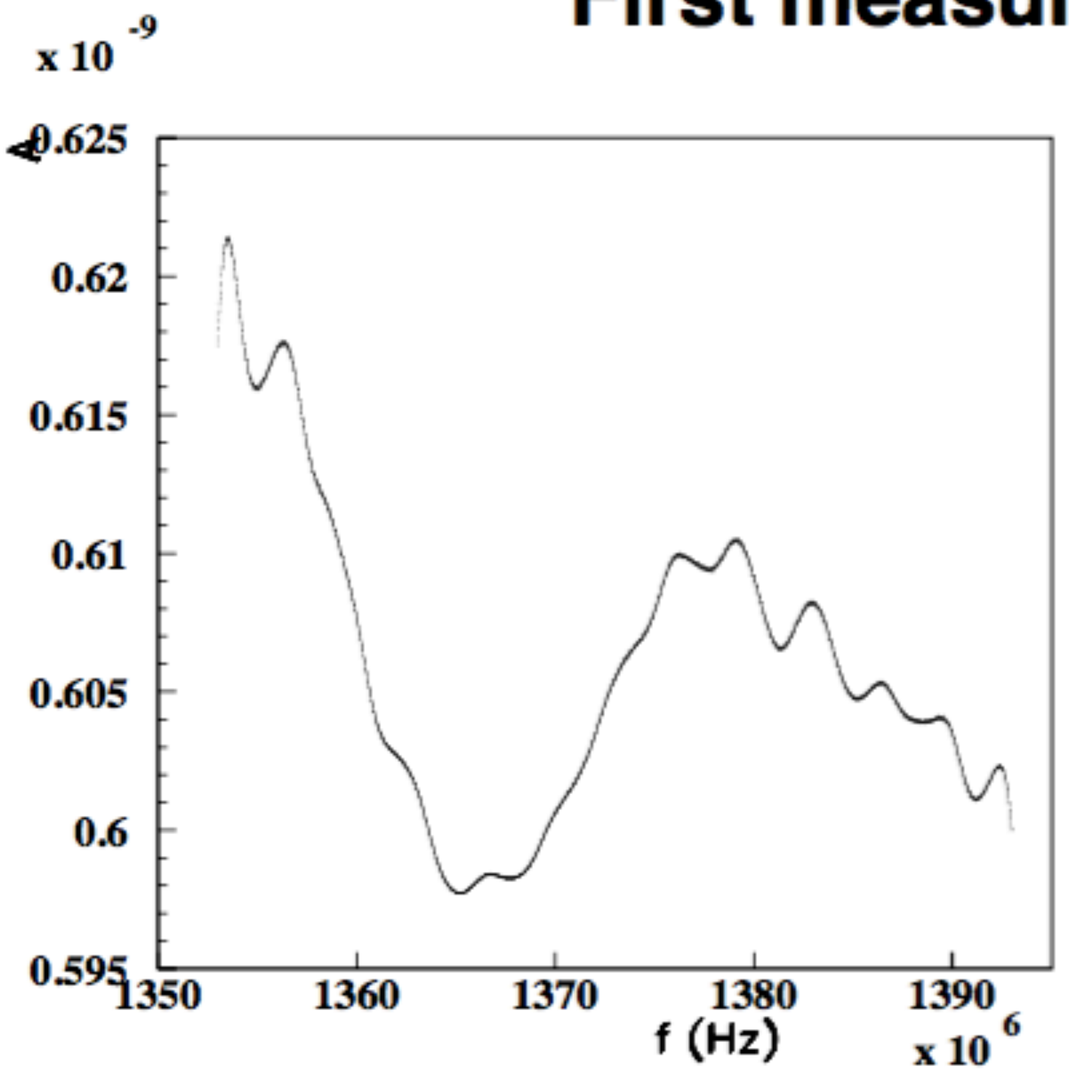


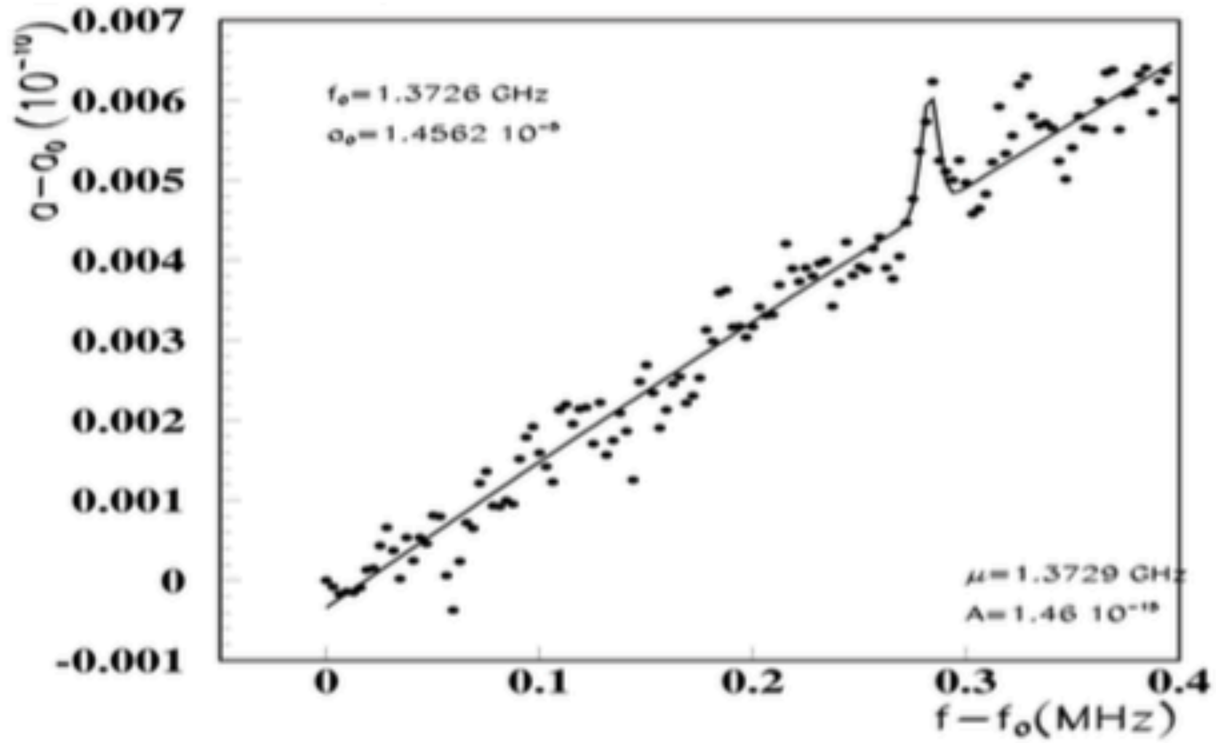


- 5 AlO_3 discs with diameter 100mm positioned within uncertaintiy ~ 1mm
  - Disc positions determine **transmission, reflection** and **boost factor** (***β***) curves
  - Prediction (red) fits measurement (black) well.

→ Verification of boost by transmission measurement!

First measurements: sensitivity



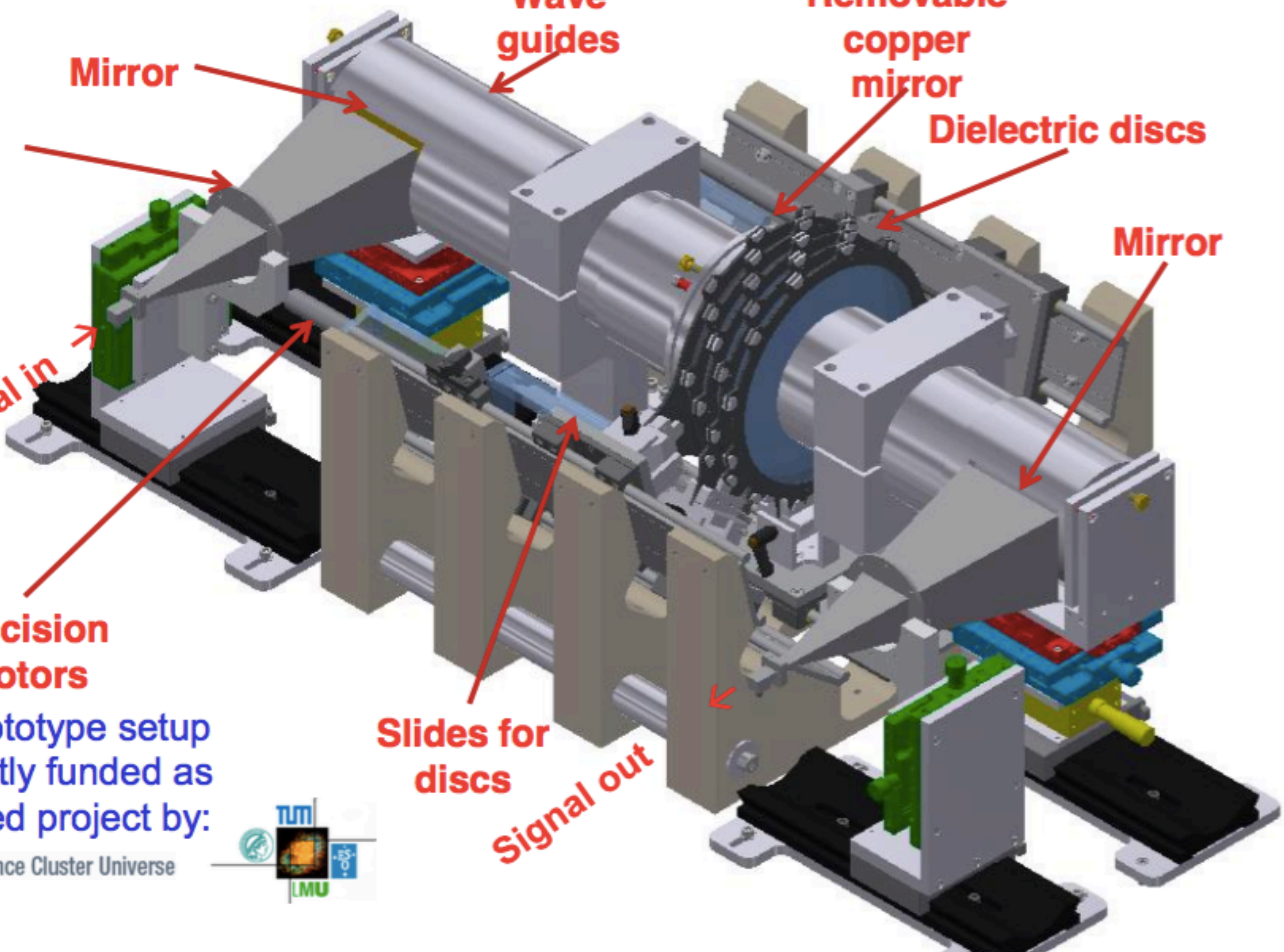


- Inject fake axion signal with **3·10^{-21}** W power
- Mesurement for one week (integrate signal): Receiver at Room Temp.

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

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

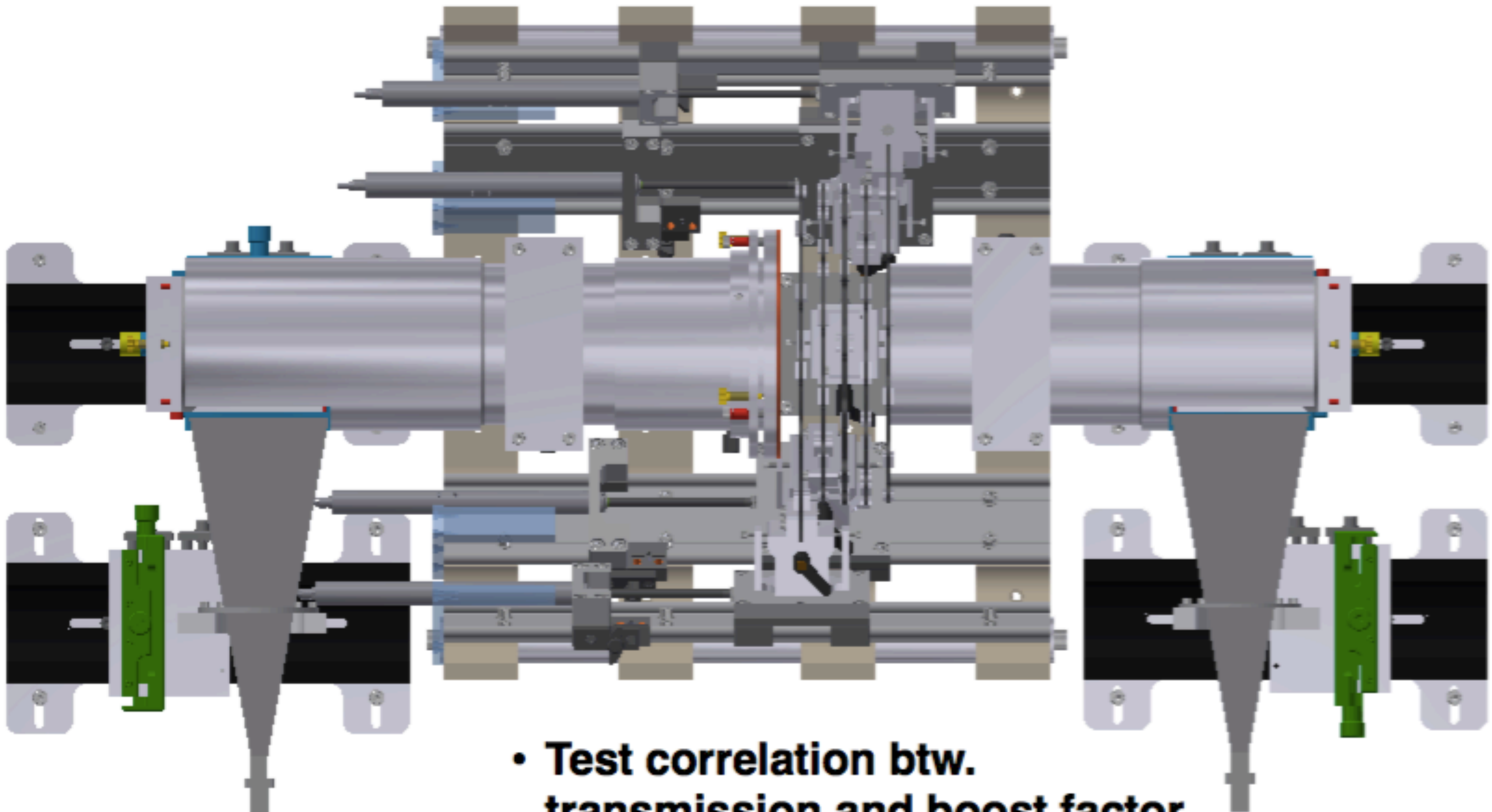
First prototype setup at MPI



Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First prototype setup at MPI

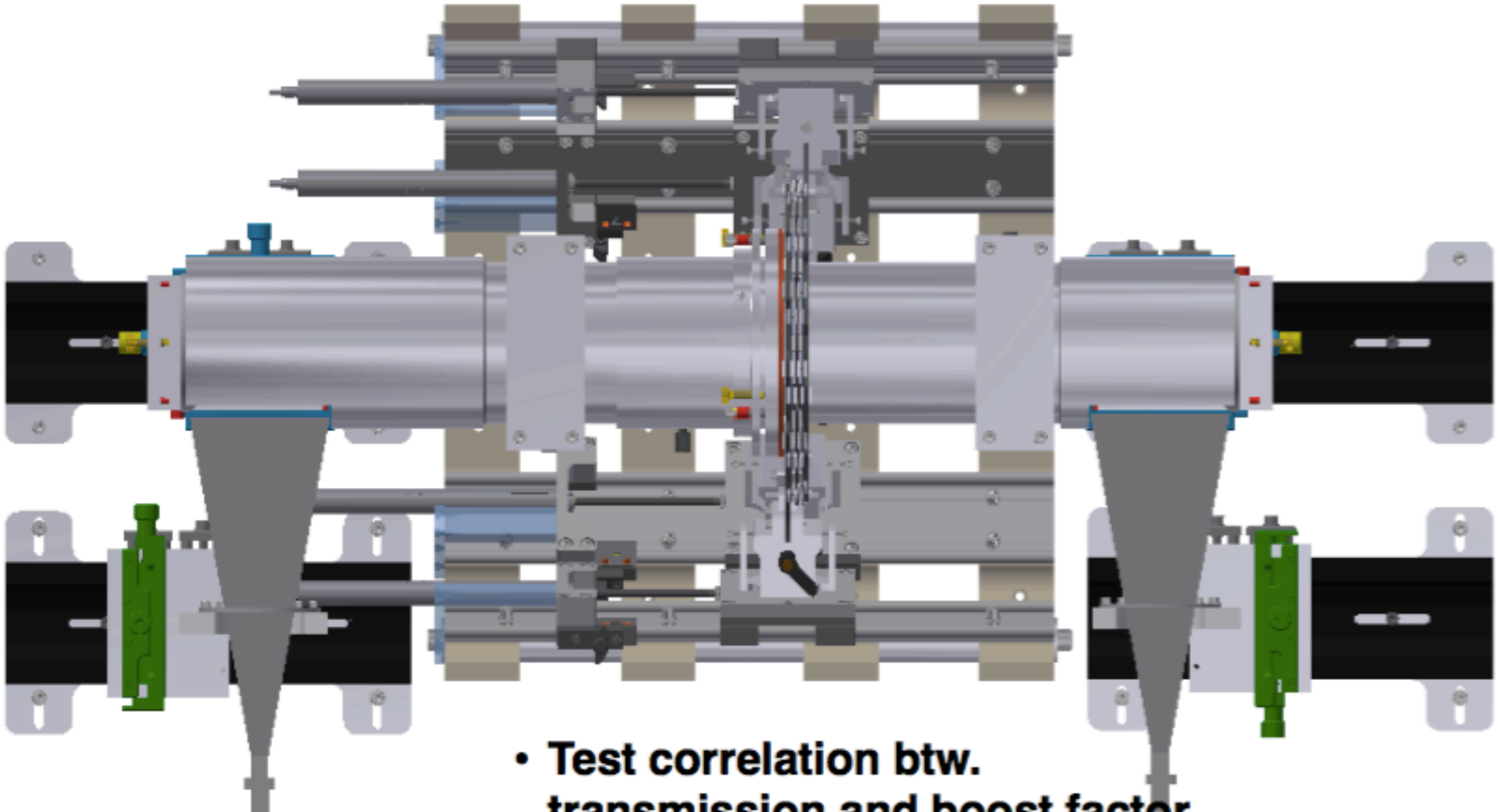


- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
- R&D on tiling

Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First prototype setup at MPI



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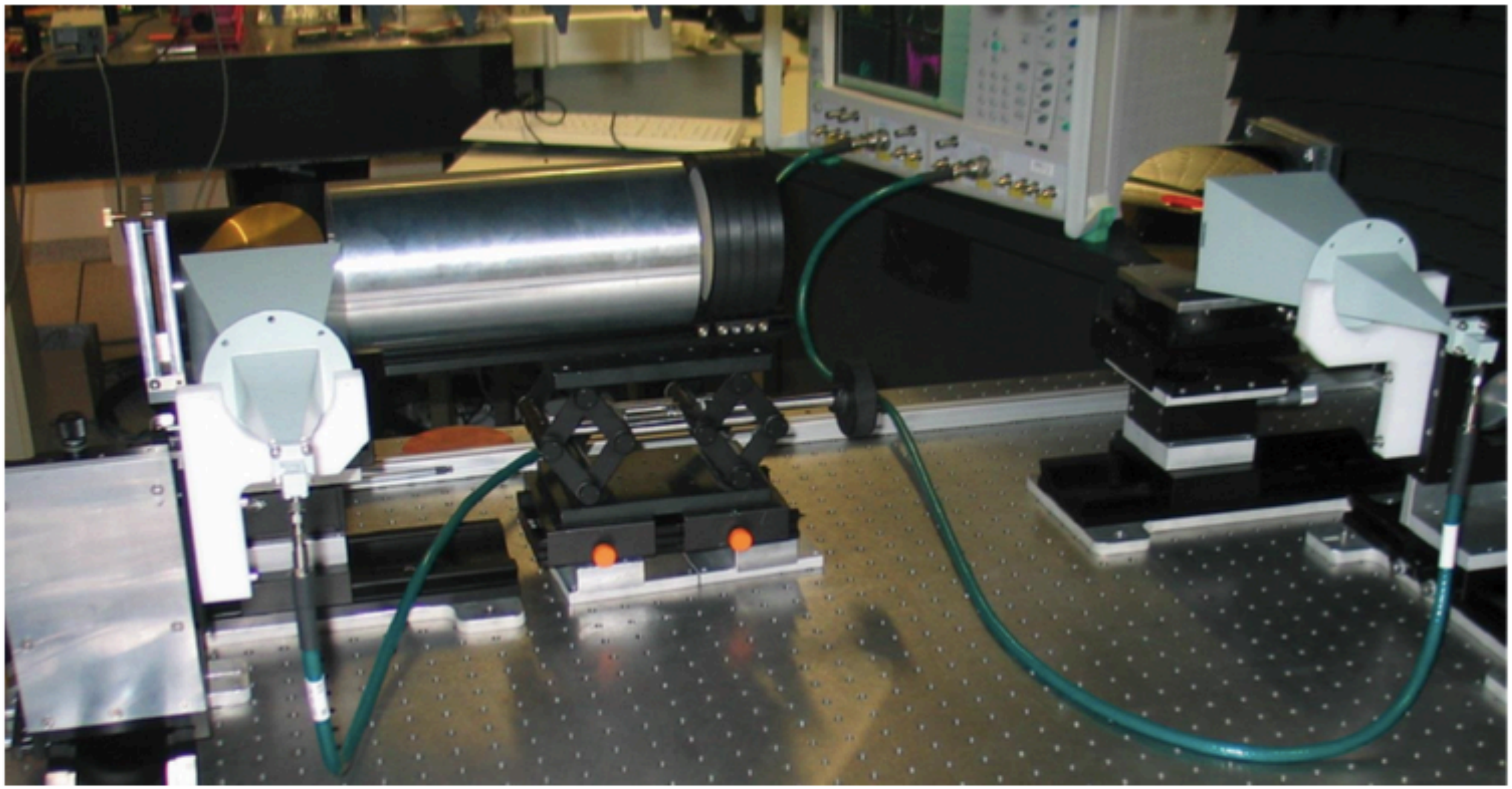
- R&D on tiling

Prototype setup partly funded as seed project by:

Excellence Cluster Universe

TUM LMU

First prototype setup at MPI



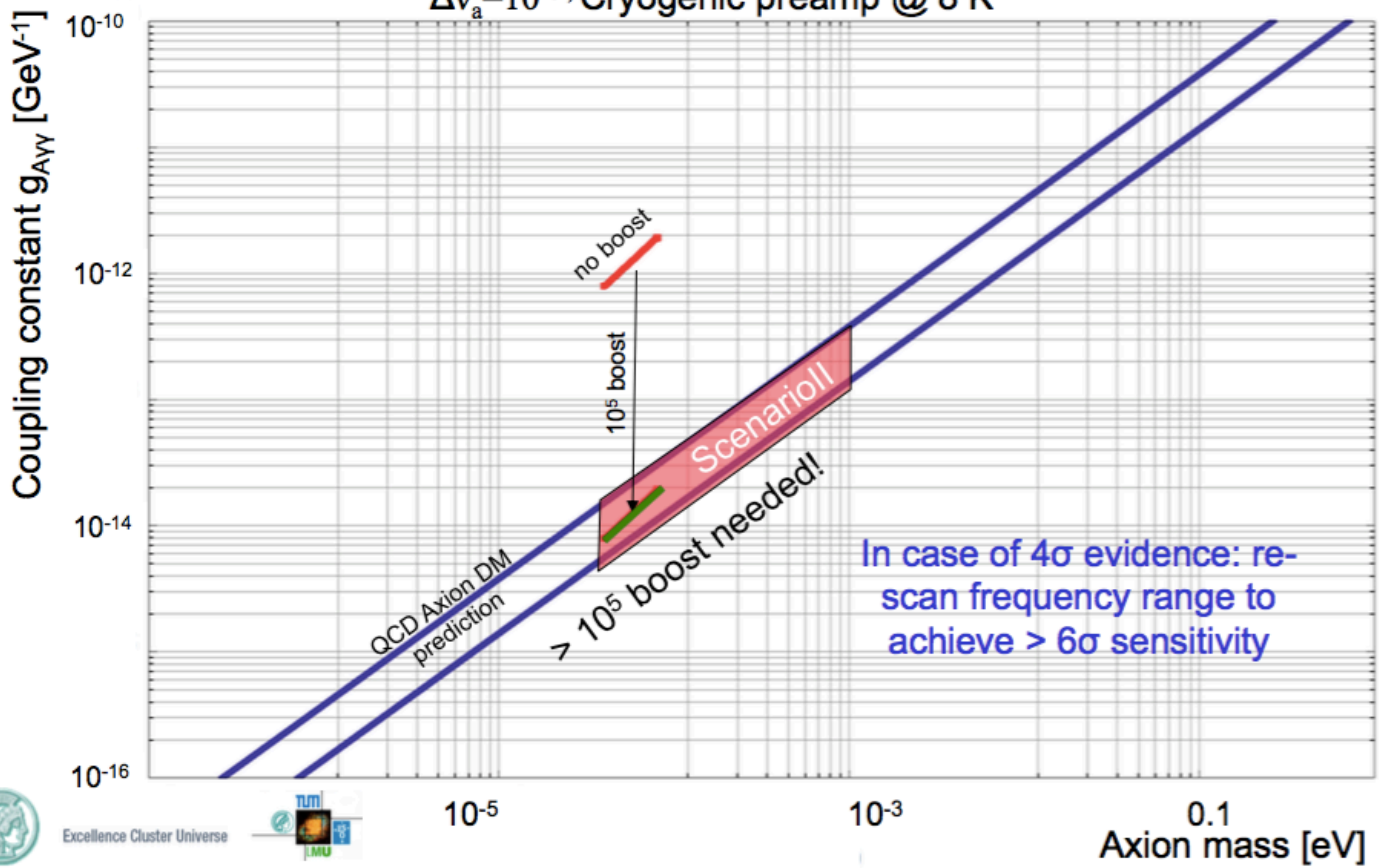
- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
- R&D on tiling

Prototype setup partly funded as seed project by:

Excellence Cluster Universe

First measurements: sensitivity

Expected 4σ detection sensitivity with and without boost
for 80 discs, 1m² 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 :

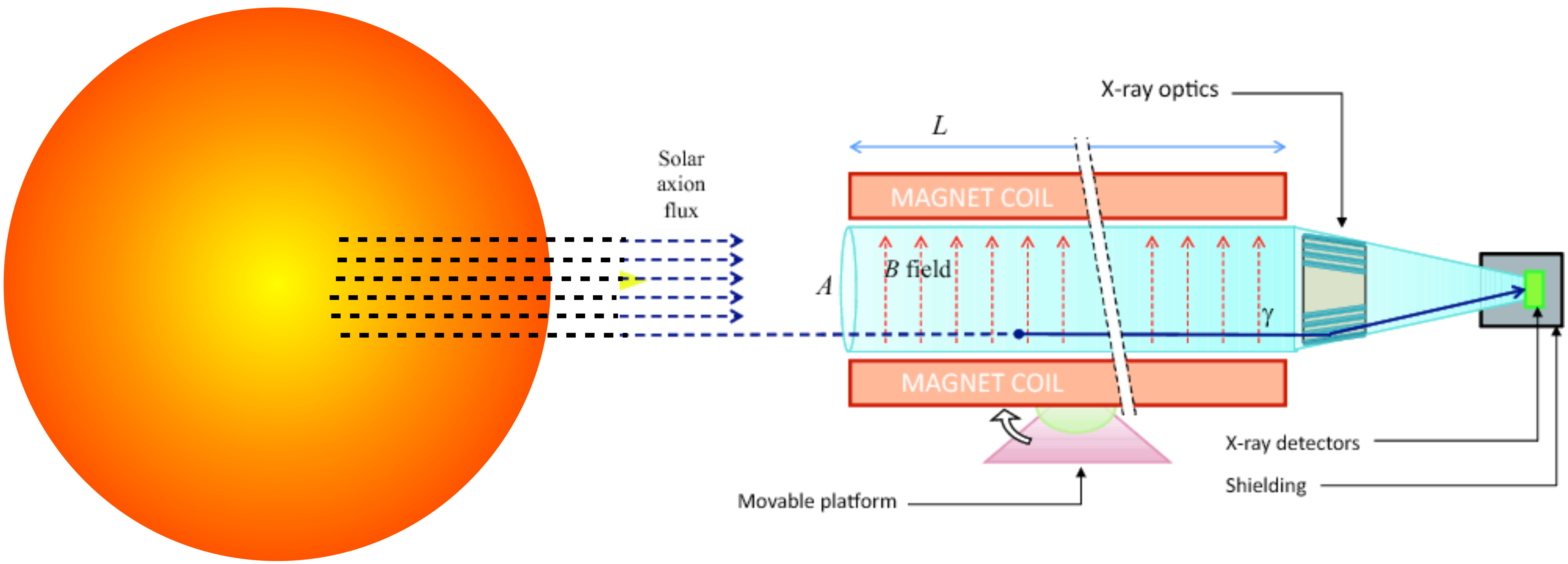
- Start building full scale experiment

IAXO: The international axion observatory

Helioscopes

The Sun is a copious emitter of axions!

convert into X-rays focus detect



Next generation (proposed) IAXO

Boost parameters to the maximum

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

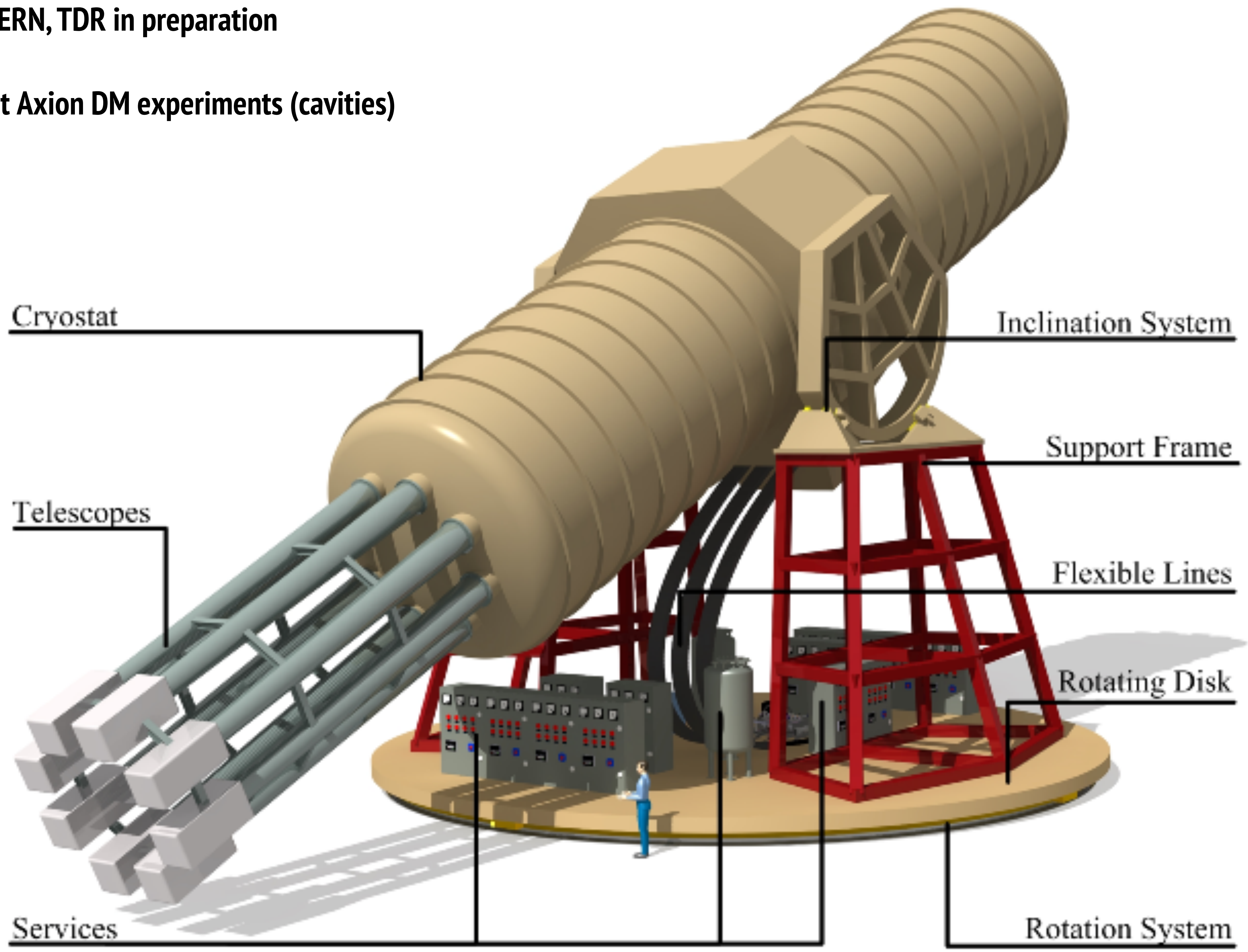
- -Possibility of Direct Axion DM experiments (cavities)

Large toroidal 8-coil magnet L = ~20 m

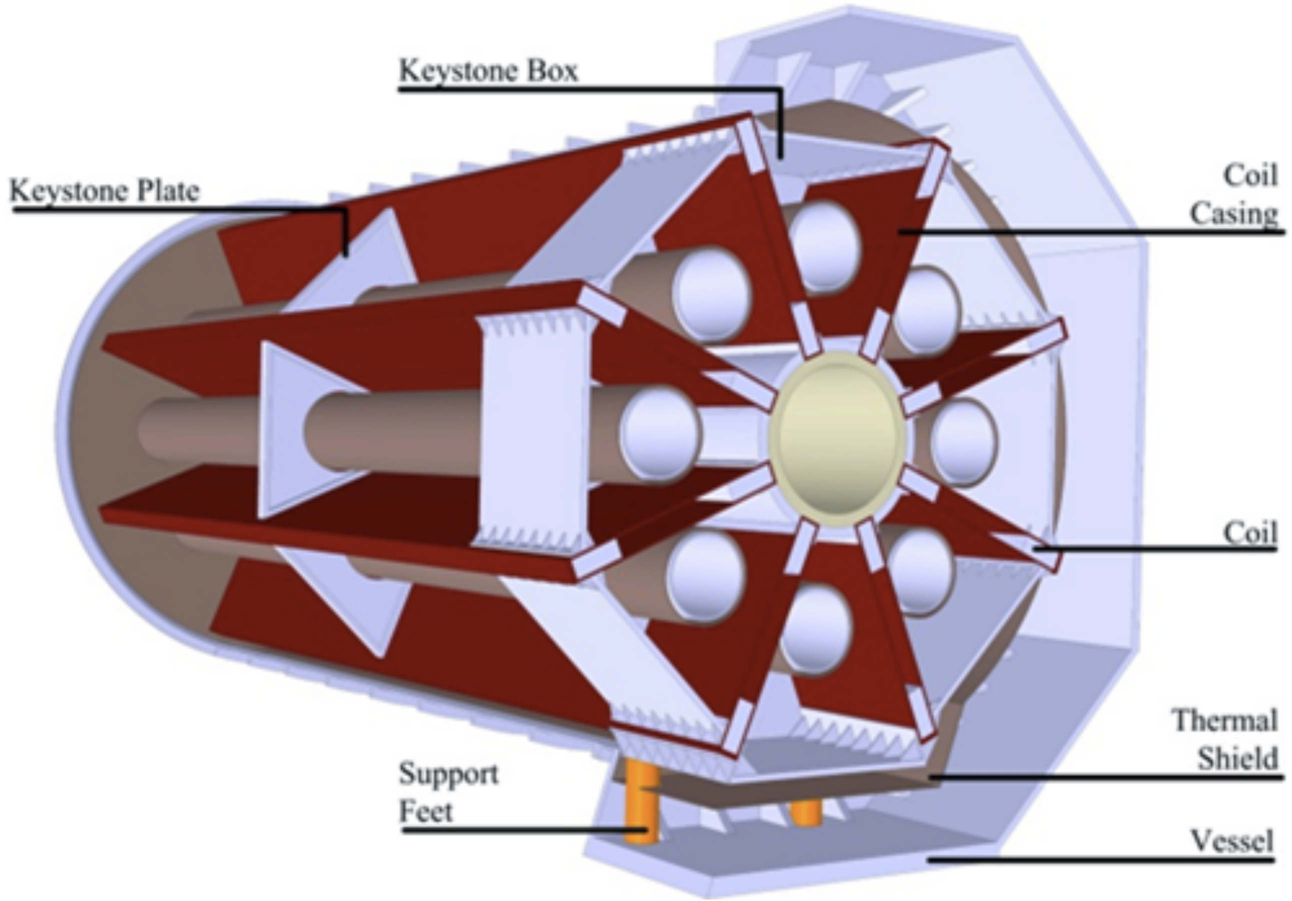
8 bores: 600 mm diameter each

8 x-ray optics + 8 detection systems

Rotating platform with services

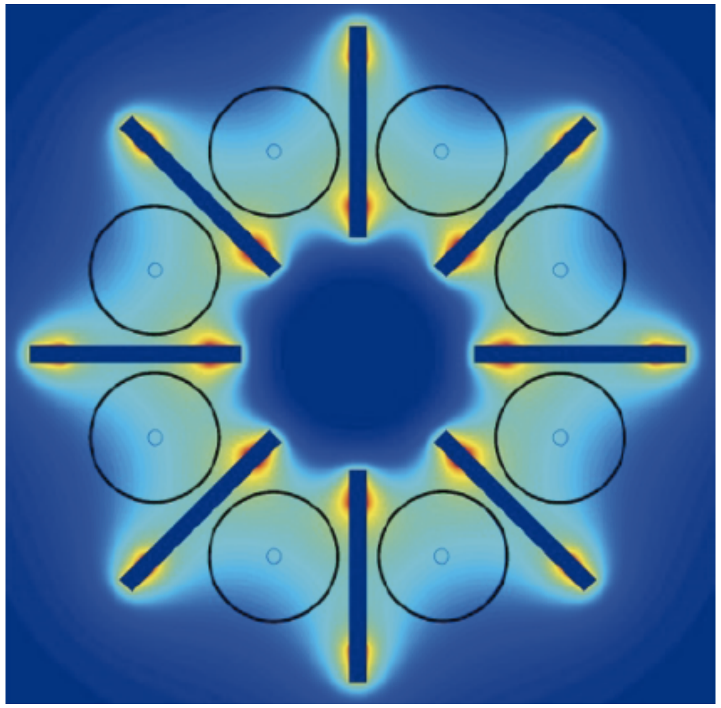


IAXO magnet (under development)



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 $\times$ 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

Conclusions

- Axion DM
  - well motivated
  - underrepresented (getting better)
  - testable
  - key targets not covered
  - experiments are sensitive to ALPs and HPs

- New experiment: dish antenna
  - a little short for axions (ALPs,WISPs!)
  - directional detection
  - dielectric mirrors
  - IAXO magnet?

- More experiments needed!, some on the go!
  - ADMX-II, HF, CAPP, MADMAX?
  - New efforts in EU, stay in tune!