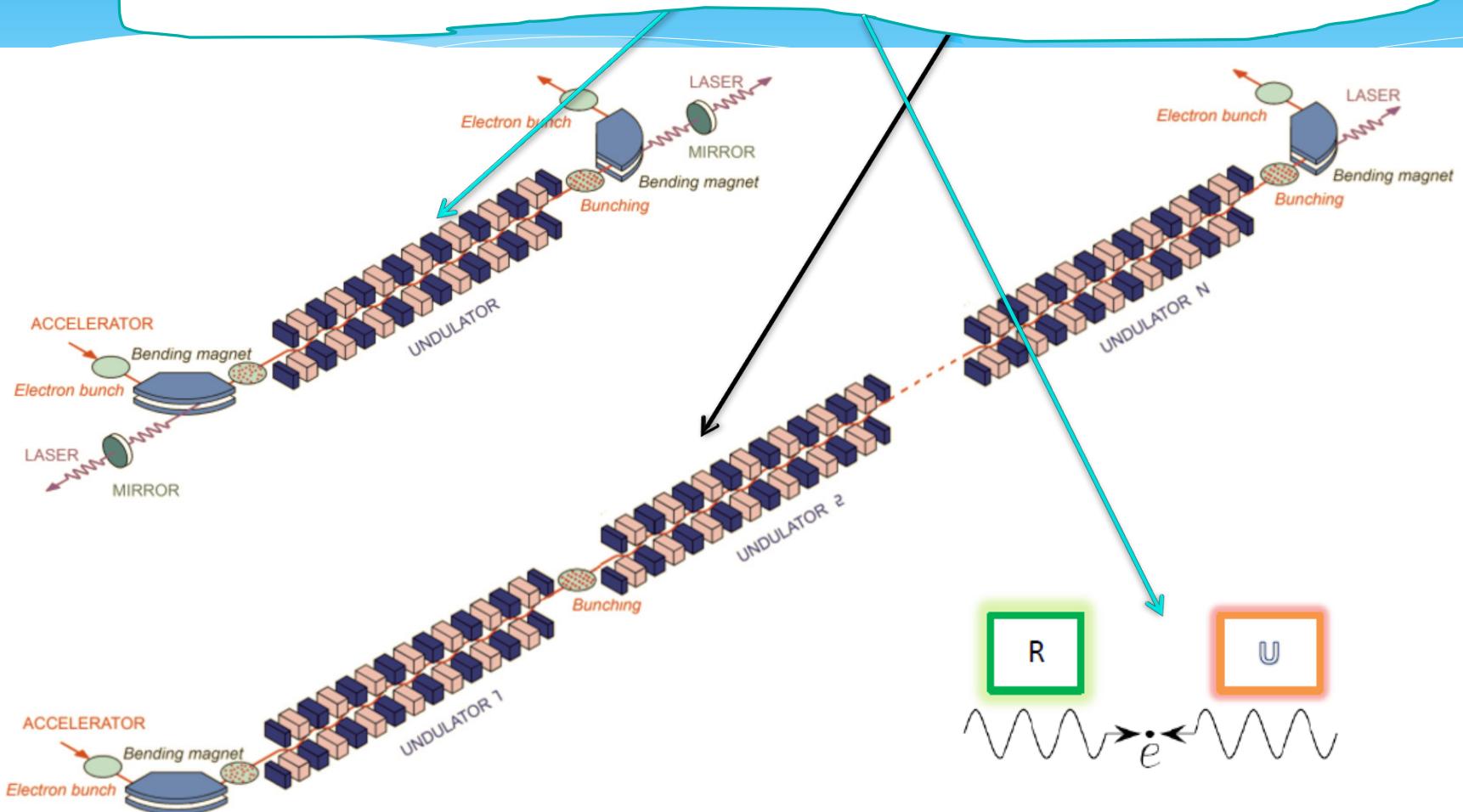


Free Electron Laser: can it become a tool for «fundamental» Physics research?

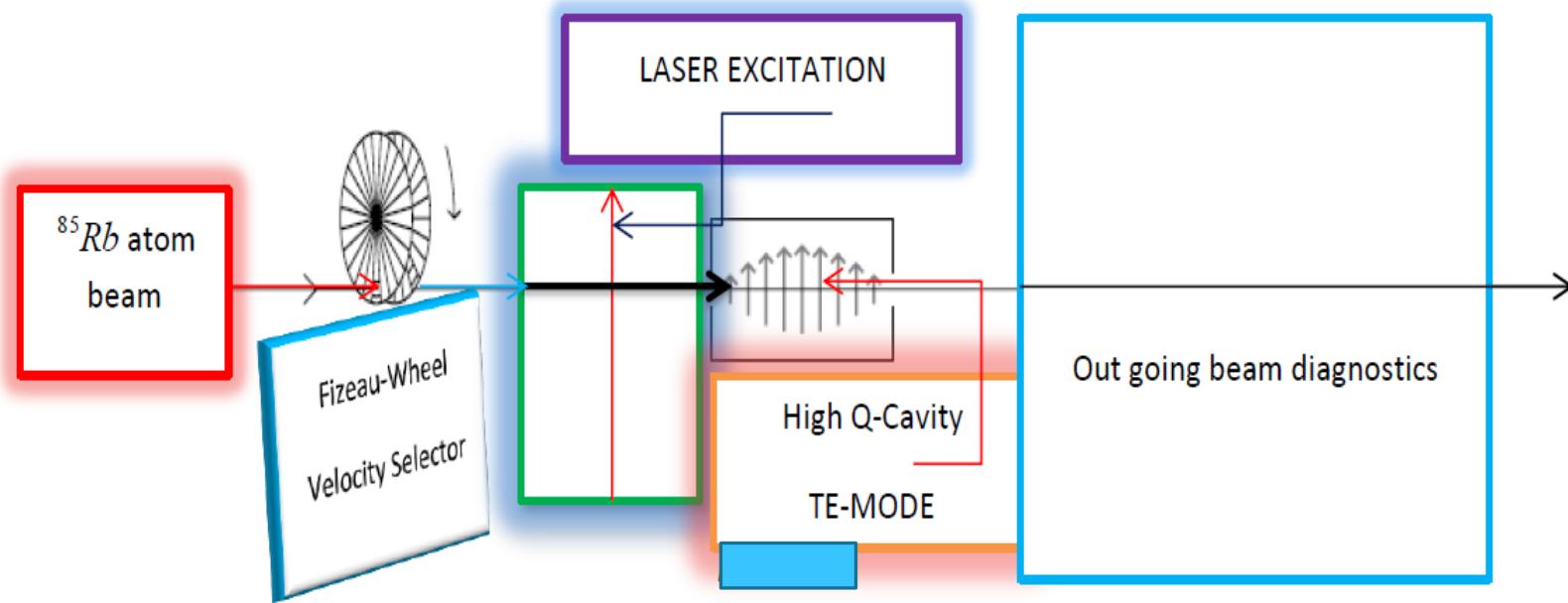
G. Dattoli and F. Nguyen
ENEA-TRASCATI

Whatever we do... oscillators, CASE

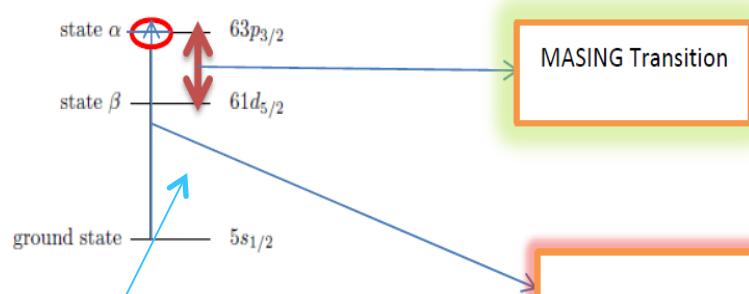
FEL process can be reduced to an Elementary Interaction



One Atom maser

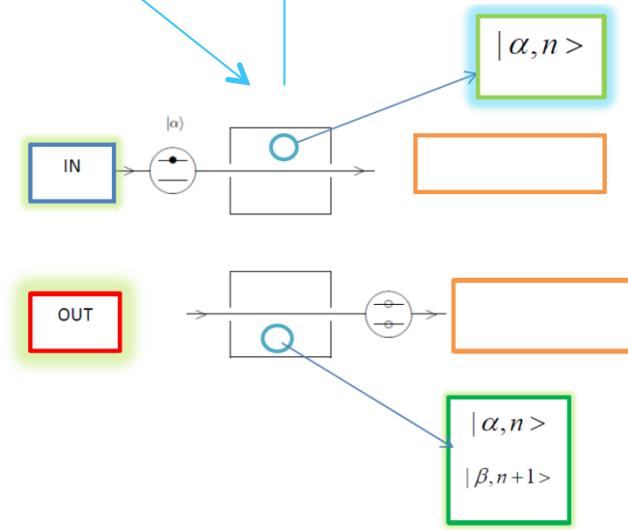
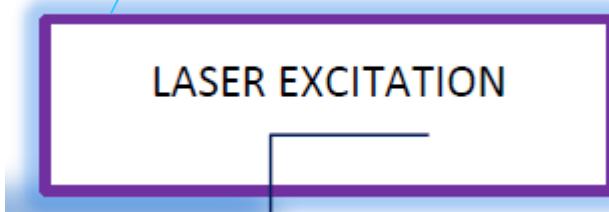


Two Level masing

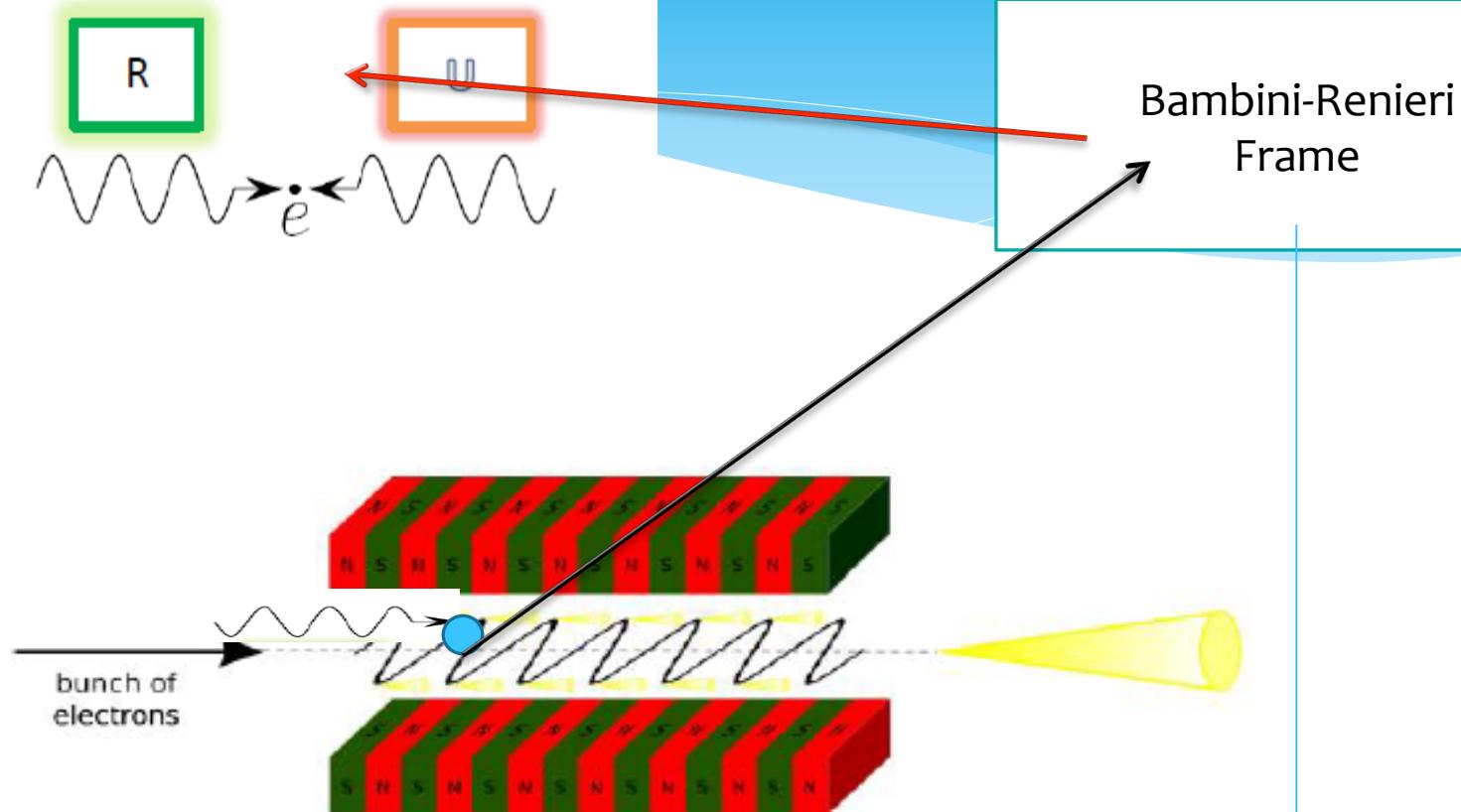


$$\hat{H} = \hbar \Delta_c \hat{a}^\dagger \hat{a} + \hbar \frac{\Delta_a}{2} \hat{\sigma}_3 + \hbar g [\hat{a}^\dagger \hat{\sigma}_- + \hat{a} \hat{\sigma}_+]$$

$$\Delta_c = \omega - \omega_c, \Delta_a = \omega - \Omega$$

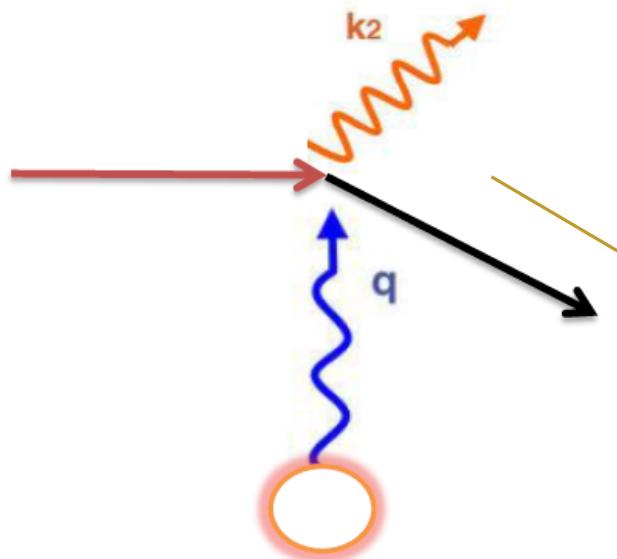


What about FEL?



$$H = \frac{p_z^2}{2m_e} + \hbar\omega(\hat{a}_u^\dagger \hat{a}_u + \hat{a}_r^\dagger \hat{a}_r) + \hbar\Omega(\hat{a}_r^\dagger \hat{a}_u e^{-2ikz} + \hat{a}_u^\dagger \hat{a}_r e^{2ikz})$$

Elementary....



$$q = 2 \hbar k$$

Momentum Recoil

Momentum conservation

$$|n\rangle \equiv |p^{(0)} - n2\hbar k\rangle |n_L^{(0)} + n\rangle |n_W^{(0)} - n\rangle$$

↑ ↑ ↑
electron laser wiggler

Elementary....

Going beyond the Bloch Nordsieck theorem

$$|\Psi(t)\rangle = \sum_n c_n(t) |n\rangle$$

↑

$$|p^{(0)} - n 2\hbar k\rangle |n_L^{(0)} + n\rangle |n_W^{(0)} - n\rangle$$

$$\begin{aligned} i\dot{c}_n = & (-\delta n + \epsilon n^2) c_n + g \left(\sqrt{(n_W^{(0)} - n)(n_L^{(0)} + n + 1)} c_{n+1} \right. \\ & \left. + \sqrt{(n_W^{(0)} - n + a)(n_L^{(0)} + n)} c_{n-1} \right) \end{aligned}$$

$$\delta \equiv 2 \frac{kp_0}{m}$$

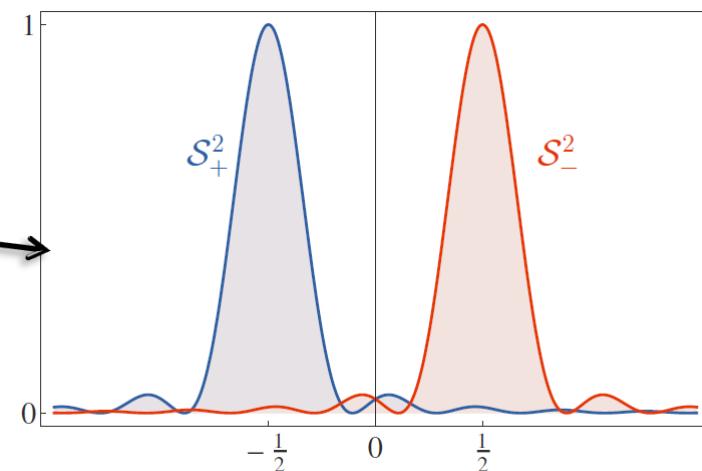
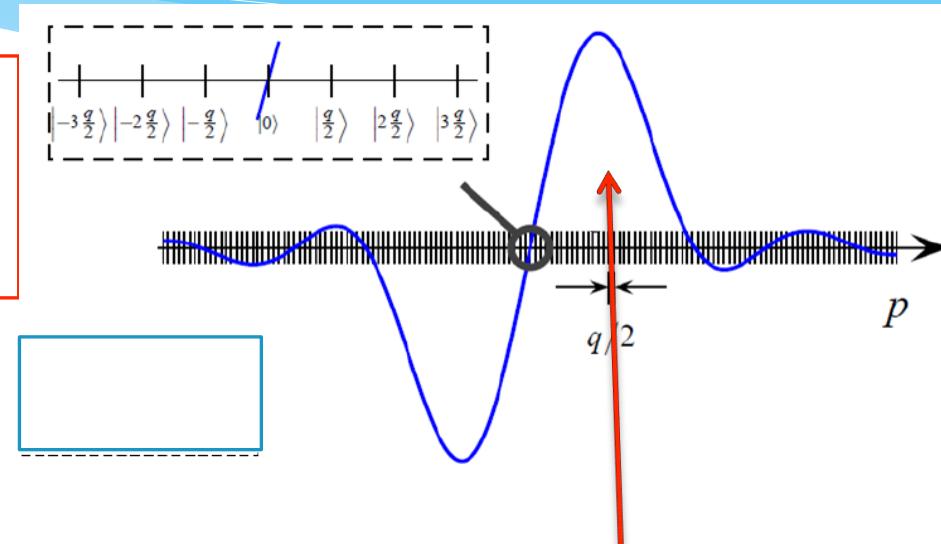
$$\varepsilon \equiv \frac{2\hbar k^2}{m}$$

Recoil Kinetic energy

Momentum recoil and Gain

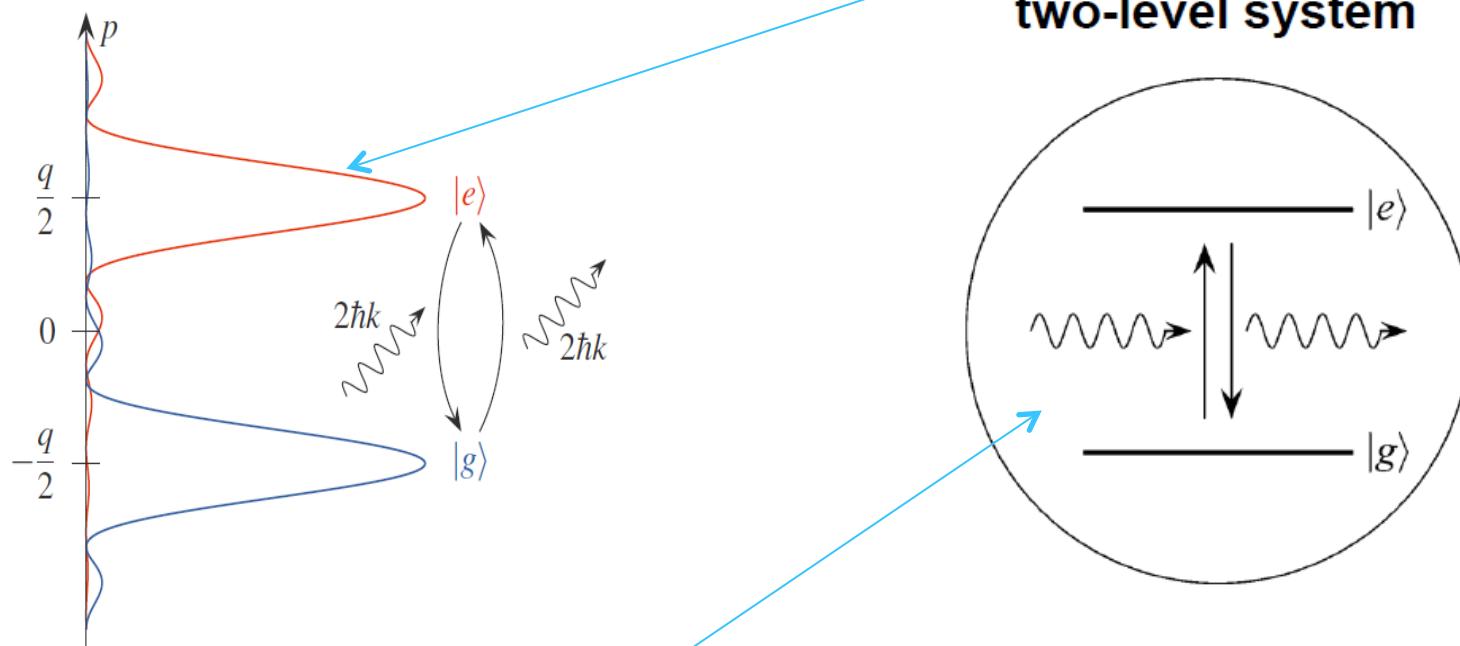
$$q = 2\hbar k$$

$$G \propto |c_{-1}|^2 - |c_{+1}|^2$$



Jaynes - Cummings FEL

$$H = \frac{p_z^2}{2m_e} + \hbar\omega(\hat{a}_u^\dagger\hat{a}_u + \hat{a}_r^\dagger\hat{a}_r) + \hbar\Omega(\hat{a}_r^\dagger\hat{a}_u e^{-2ikz} + \hat{a}_u^\dagger\hat{a}_r e^{2ikz})$$



$$\hat{H} = \hbar\Delta_c\hat{a}^\dagger\hat{a} + \hbar\frac{\Delta_a}{2}\hat{\sigma}_3 + \hbar g[\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+],$$

$$\Delta_c = \omega - \omega_c, \Delta_a = \omega - \Omega$$

Why such a detour?

Just to remind that FEL is not just a technological device.....

FLASH tunnel: cryo module

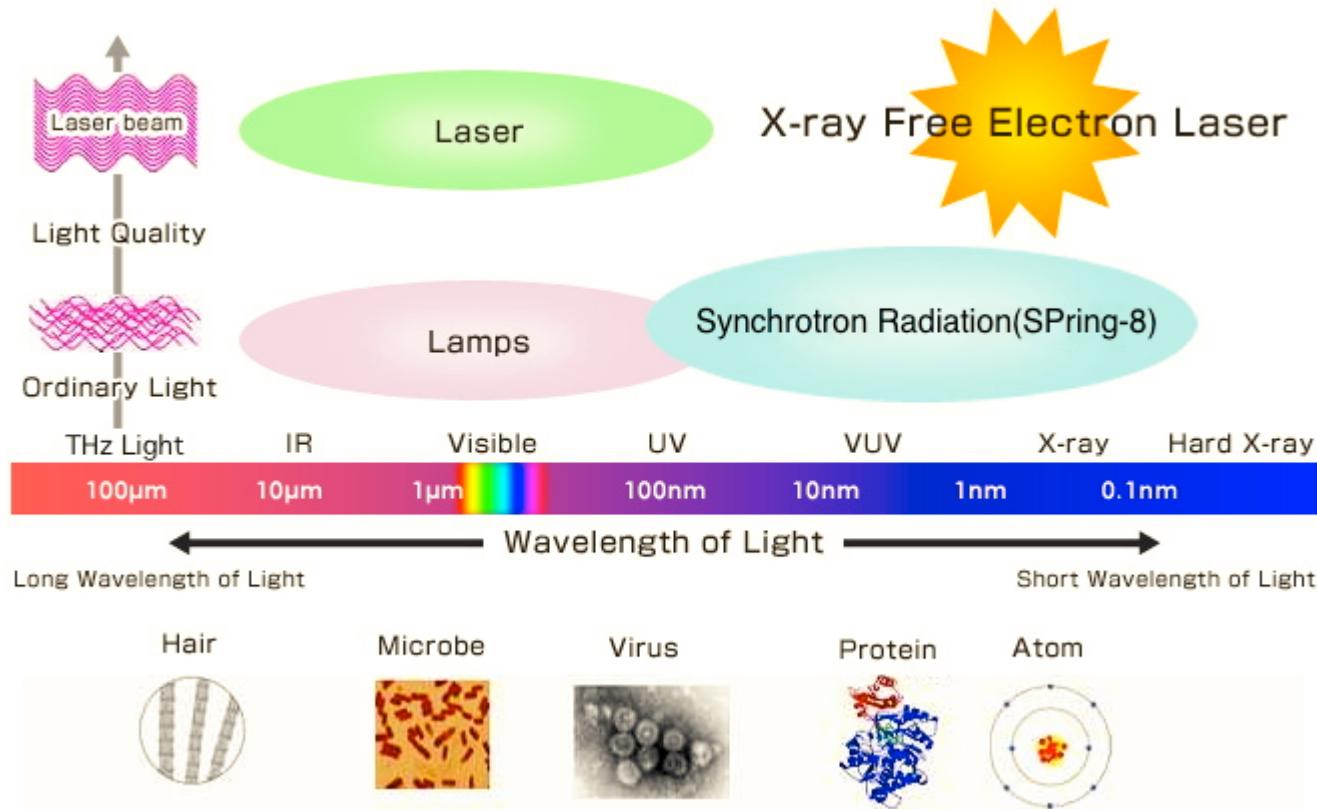


undulator



...That it can be exploited as an experimental tool covering realmof research not strictly associated with the main stream...

Dr. Madey's terrific beam enlightens the darkness and solves any mystery...



...And, may be, other...

FEL for q - q collider

Double FEL scheme

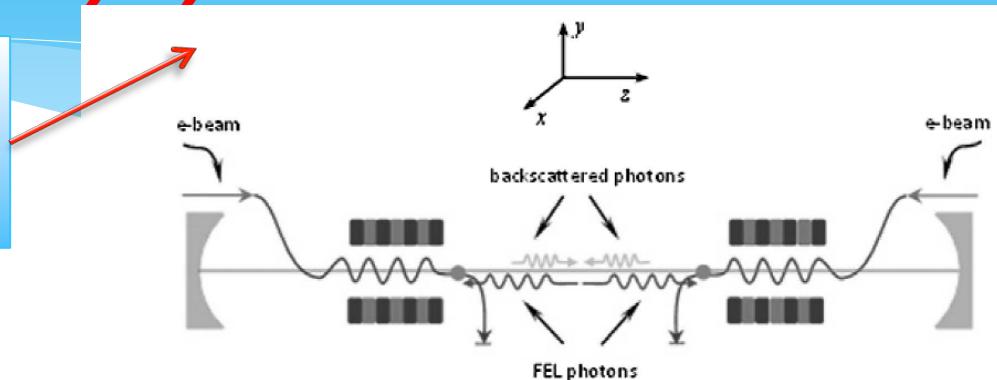


Fig. 2. "Double" FEL oscillator as a possible device for head-on γ -photon collisions.

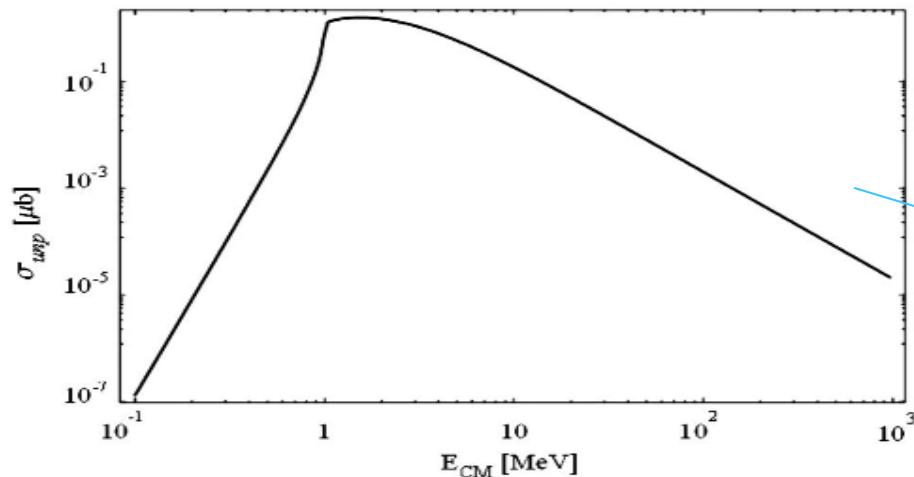


Fig. 1. Total cross section σ_{unp} for unpolarized initial photons versus CM energy $E_{\text{CM}} = 2E_{\text{ph}}$. The scale for both axes is logarithmic. We recall that $1 \mu\text{b} = 10^{-30} \text{ cm}^2$.

Cross section

g-g-FEL number of counts

$$\dot{\mathcal{N}}[\text{s}^{-1}] = \sigma \frac{N_e^2}{4\Sigma_{\text{ph}}} f = \frac{1.43 \cdot 10^{58}}{\omega_{\text{FEL}}^2} \cdot \frac{\sigma}{\Sigma_{\text{ph}}} \cdot \mathcal{F}^2 J_e^2 \Sigma_e^2 I_{\text{FEL}}^2 T_e^4 F^2 (K_{\text{FEL}}) f.$$

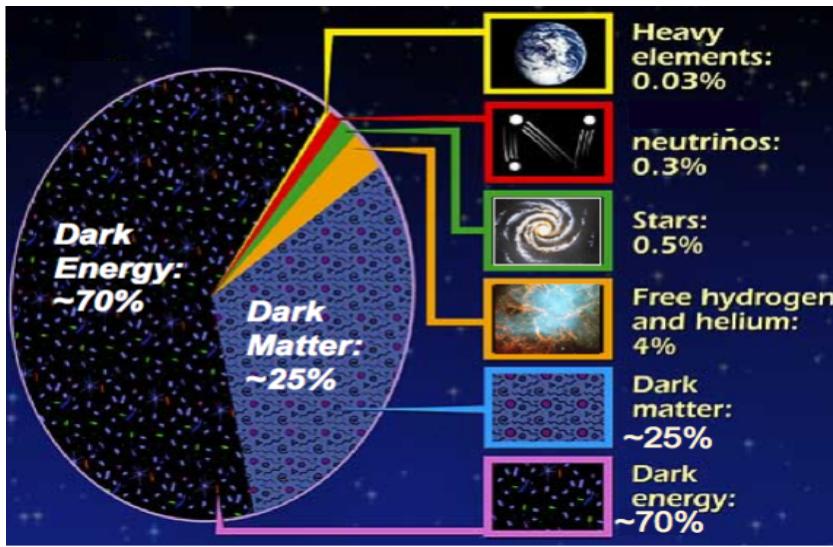
Table 1. Collision Rate for Some Device Configurations Having $K_U = 40$ and $N_U = 20$

$\lambda_U [\text{cm}]$	25	20	15
$\gamma_e^{(\text{max})}$	1983	1876	1745
$\lambda_{\text{FEL}} _{\gamma_e^{(\text{max})}} [\mu\text{m}]$	25	23	20
$L_C [\text{m}]$	13	11	9
$f [\text{MHz}]$	23	27	33
$\tau_R [\mu\text{s}]$	$\begin{cases} \eta - 0.01 \\ \eta - 0.02 \end{cases}$	$\begin{cases} 0.15 \\ 0.151 \end{cases}$	$\begin{cases} 0.145 \\ 0.144 \end{cases}$
$\dot{\mathcal{N}} [\text{s}^{-1}]$	$\begin{cases} \eta - 0.01 \\ \eta - 0.02 \end{cases}$	$\begin{cases} 6.22 \cdot 10^{-6} \\ 3.04 \cdot 10^{-6} \end{cases}$	$\begin{cases} 6.57 \cdot 10^{-6} \\ 3.19 \cdot 10^{-6} \end{cases}$
$\mathcal{N}_{\text{year}}$	$\begin{cases} \eta - 0.01 \\ \eta - 0.02 \end{cases}$	$\begin{cases} 196 \\ 95 \end{cases}$	$\begin{cases} 207 \\ 100 \end{cases}$
			222
			107

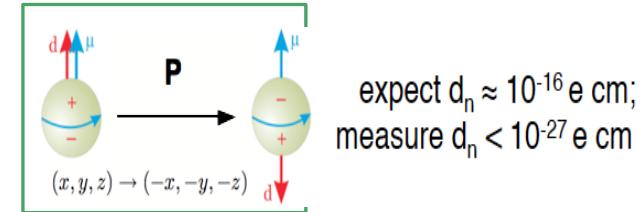
Table 2. Collision Rate for Some Device Configurations Having $K_U = 45$ and $N_U = 15$

$\lambda_U [\text{cm}]$	40	30	20
$\gamma_e^{(\text{max})}$	2366	2201	1989
$\lambda_{\text{FEL}} _{\gamma_e^{(\text{max})}} [\mu\text{m}]$	36	31	26
$L_C [\text{m}]$	15	12	9
$f [\text{MHz}]$	20	25	33
$\tau_R [\mu\text{s}]$	$\begin{cases} \eta - 0.01 \\ \eta - 0.02 \end{cases}$	$\begin{cases} 0.204 \\ 0.202 \end{cases}$	$\begin{cases} 0.191 \\ 0.189 \end{cases}$
$\dot{\mathcal{N}} [\text{s}^{-1}]$	$\begin{cases} \eta - 0.01 \\ \eta - 0.02 \end{cases}$	$\begin{cases} 3.85 \cdot 10^{-5} \\ 1.89 \cdot 10^{-5} \end{cases}$	$\begin{cases} 4.25 \cdot 10^{-5} \\ 2.06 \cdot 10^{-5} \end{cases}$
$\mathcal{N}_{\text{year}}$	$\begin{cases} \eta - 0.01 \\ \eta - 0.02 \end{cases}$	$\begin{cases} 1215 \\ 592 \end{cases}$	$\begin{cases} 1342 \\ 649 \end{cases}$
			1535
			731

A detour from universe energy budget to strong CP problem



For instance, why doesn't the neutron have an electric dipole moment?



This leads to the “Strong CP Problem”: Where did QCD CP violation go?

1977: Peccei and Quinn: Apply Higgs-like physics to the problem:

Posit a hidden broken U(1) symmetry \Rightarrow

- 1) A new Goldstone boson (the axion);
- 2) Axion VEV & field nulls QCD CP violation.

In 1933, F. Zwicky first discovered Dark Matter in the velocity dispersion of galaxies in the COMA cluster.

The Solution: A new field cancelling this effect

The new field bring a particle the Axion: the
origin of the name



clears the
strong CP problem
like my favorite soap

Frank Wilczek
Nobel Prize in
Physics 2004



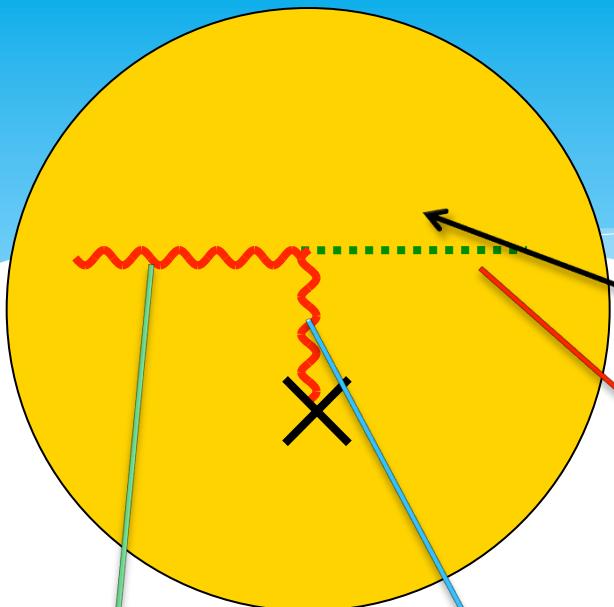
Few more details

- Axion: a neutral pseudoscalar predicted to explain the CP conservation in QCD. Its physics is determined just by a symmetry breaking scale f_a :
 - Mass: $m_a = 0.6\text{eV} \cdot (10^7\text{GeV} / f_a)$
 - Coupling to two photons: $g_{a\gamma\gamma} = \alpha \cdot g_\gamma / (2\pi \cdot f_a)$
- Axion-like particles (ALPs):
Coupling strength and mass are not related by one f_a .
- Hidden photons: neutral vector bosons.
- Mini-charged particles, Chameleons, massive gravity scalars, ...
(some of these might be related to dark energy).

All these are classified as Weakly Interacting Slim Particles:
Hypothetical bosons with mass $m < 1 \text{ eV}/c^2$

Axion interaction with matter?

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



Primakoff- Effect

photon

Virtual-
photon

Axion

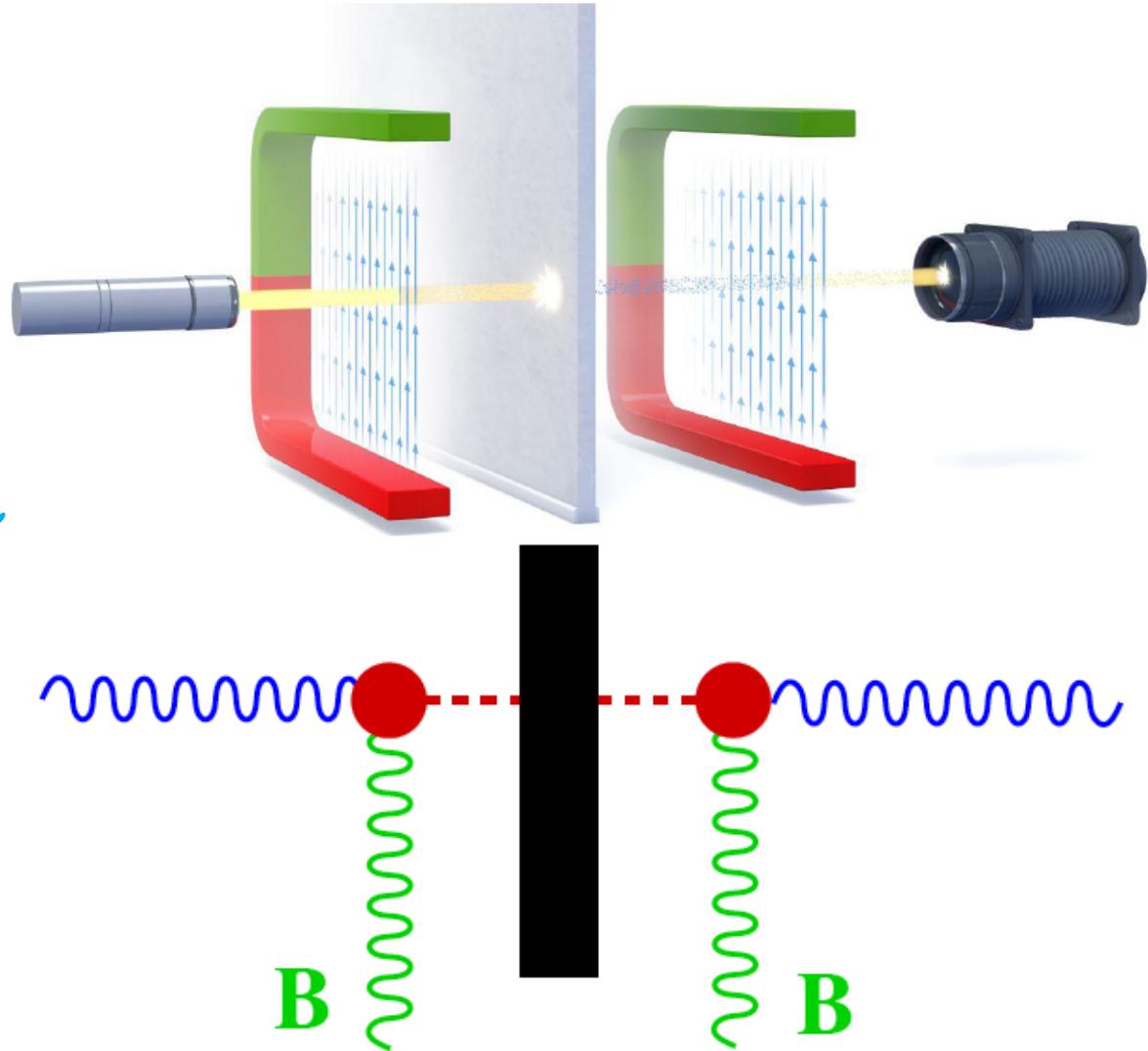
Light Shining through the Wall

Ideal physics case:
reproduce axions in
laboratory!

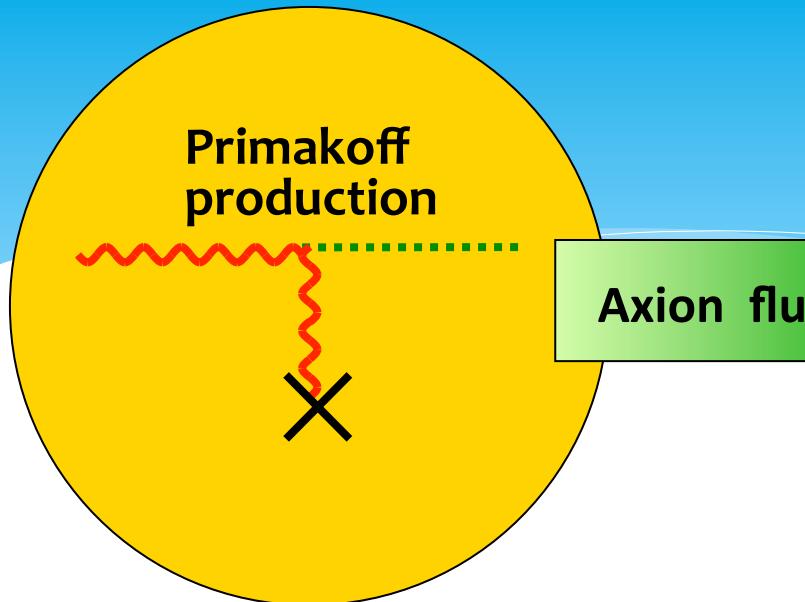
EM radiation free to
propagate in a B field region,
in vacuum

Photon detectors properly
shielded

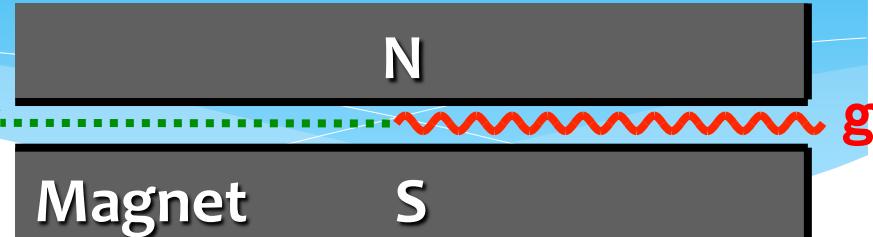
Any signal is related to
something non-standard



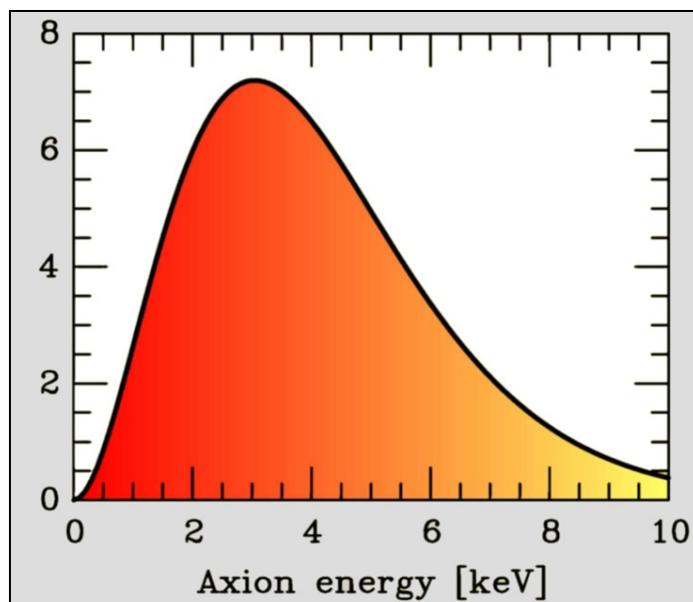
Search for Solar Axions



Axion Helioscope
(Sikivie 1983)



Axion-Photon-Oscillation



- Tokyo Axion Helioscope ("Sumico")
(Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST)
(Data since 2003)

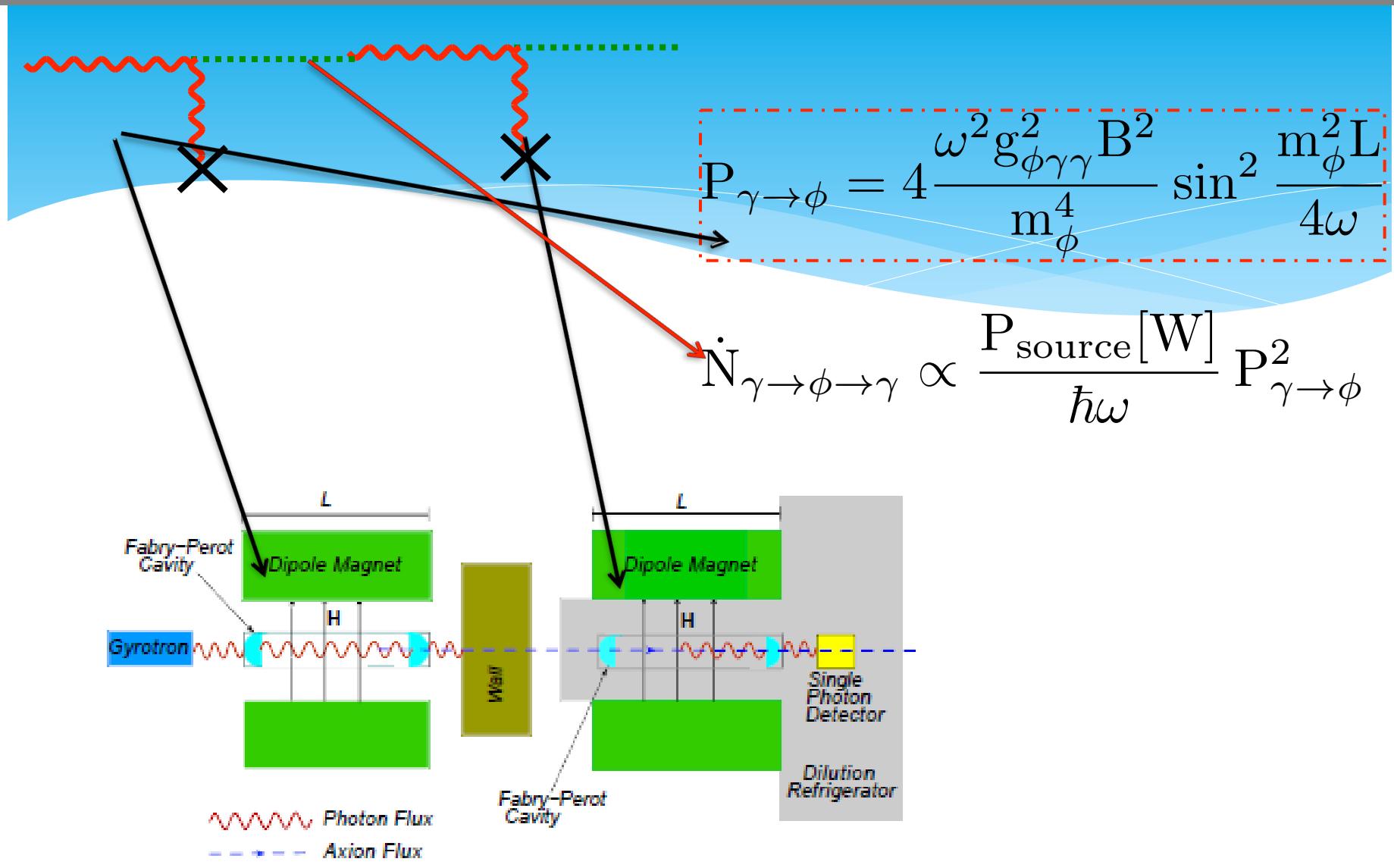
Alternative technique:

Bragg conversion in crystal

*Experimental limits on solar axion flux
from dark-matter experiments*

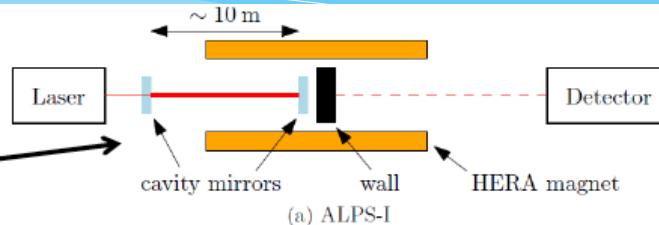
(SOLAX, COSME, DAMA, CDMS ...)

SLW Experiment

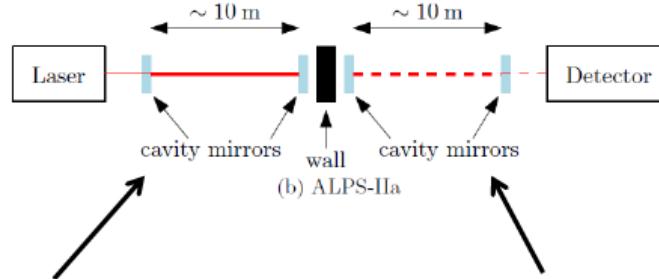


Intracavity photon axion interaction

ALPS I:
basis of success was
the optical resonator
in front of the wall.



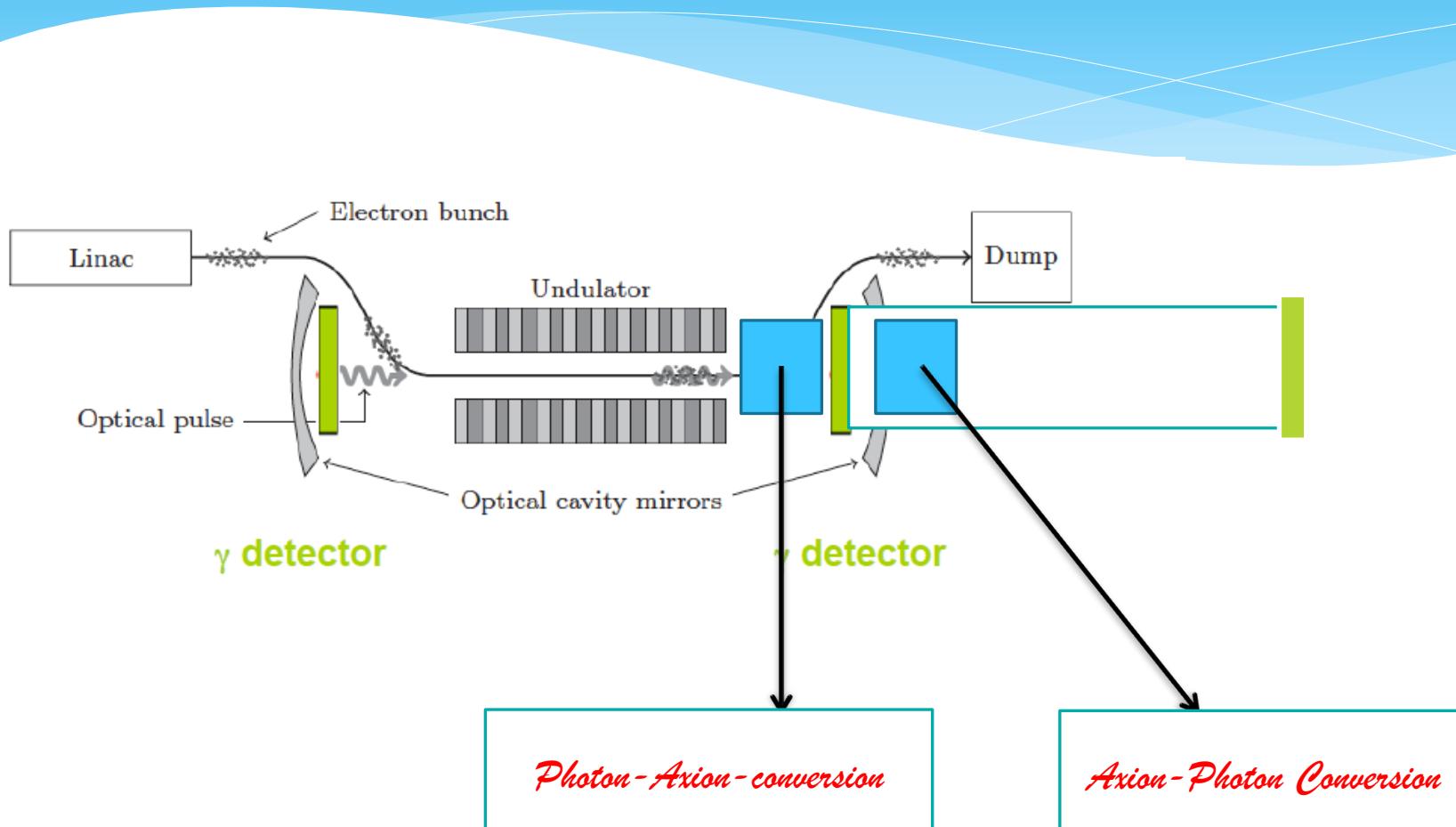
ALPS IIa



Optical resonator to
increase effective
light flux by
recycling the laser
power

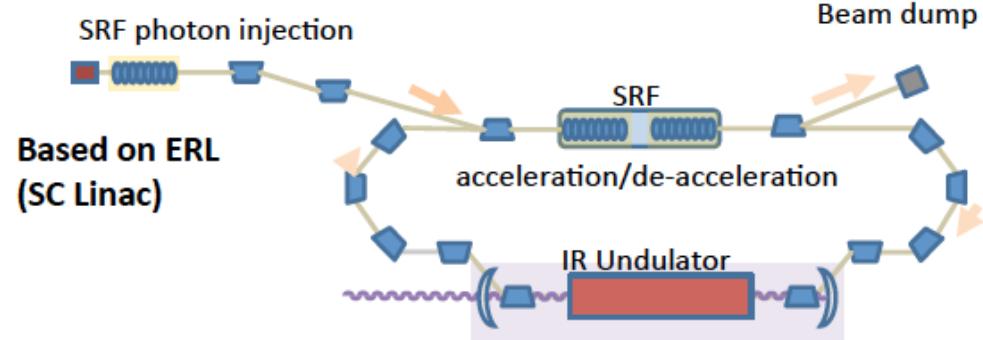
Optical resonator to
increase the conversion
probability
 $\text{WISP} \rightarrow \gamma$

AXION & FEL=AXEL

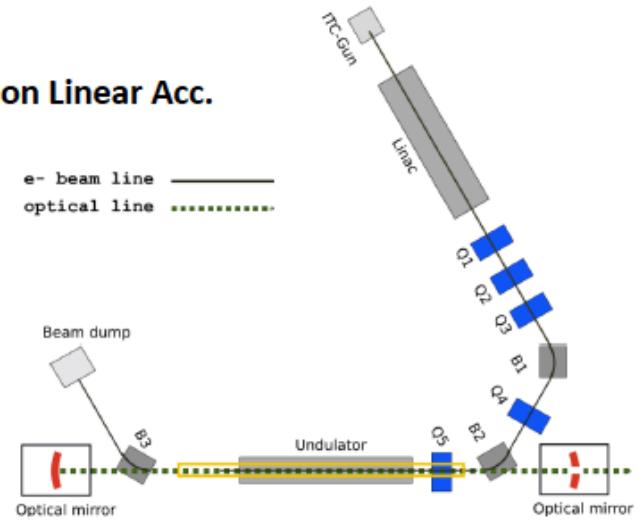


Electron beam parameters	
Energy E	158 MeV
Lorentz factor γ	309
Rel. Energy spread σ_e	0.5 %
Charge Q_e	500 pC
r.m.s. pulse dur. σ_t	2 ps
Peak current	100 A
r.m.s pulse length σ_z	600 μm
RF freq.	1.3 GHz

SC Undulator parameters	
Magn. field	4 T
Undulator par. K	11
Und. Period λ_u	30 mm
# periods N	50
Und. Length L_u	1.5 m
Resonant wl λ_0	10 μm



Based on Linear Acc.



Considerations on the FEL0 cavity

- Resonator cavity design

Stability criterion

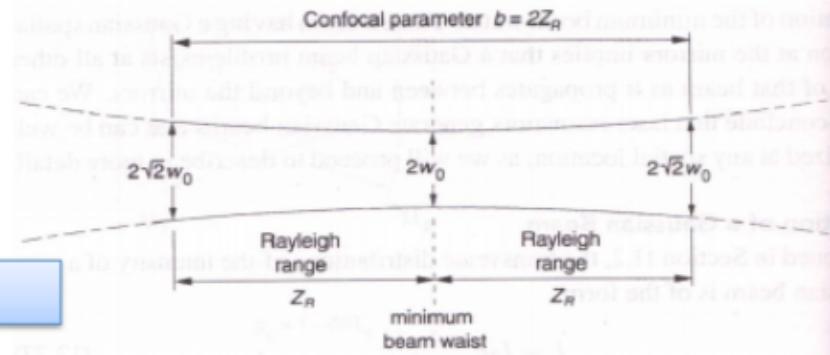
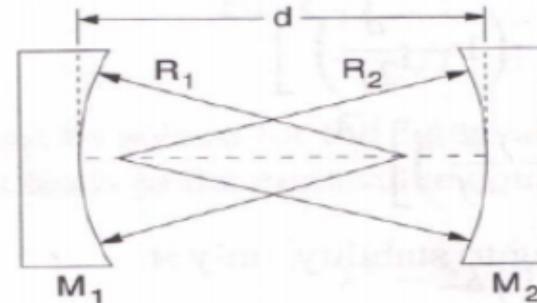
$$0 < \left(1 - \frac{d}{R_1}\right) \left(1 - \frac{d}{R_2}\right) < 1 \quad \text{or} \quad 0 < g_1 g_2 < 1.$$

- Expected beam size

At waist: $w_0^2 = \frac{d\lambda}{\pi} \sqrt{\frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2g_1 g_2)^2}},$

At mirror: $w_1^2 = \frac{d\lambda}{\pi} \sqrt{\frac{g_2}{g_1 (1 - g_1 g_2)}},$

Determines minimum gap of undulator



Cavity Parameters			
Cavity loss η	0.5 %	Beam waist w_0	1.7 mm
Cavity length d	3 m	Beam size @ mirror w_1	3.3 mm
Mirror curvature R	2 m	Rayleigh length Z_R	87 cm
Rep. rate	50 MHz	Quality factor Q	10000

Number of Counts vs. FEL-O Parameters

$$\dot{N}_e [s^{-1}] = 6.25 \cdot (2Q) \cdot 10^{18} \frac{P[W]}{\varepsilon_\gamma [eV]} \left(\frac{3 \cdot G \cdot B[T] \cdot L[m]}{2} \right)^4$$

$$P[W] \equiv \frac{3.2 \cdot 10^{-20}}{(2Q)} \frac{\varepsilon_\gamma [eV]}{(G \cdot B[T] \cdot L[m])^4} \dot{N}_e [s^{-1}]$$

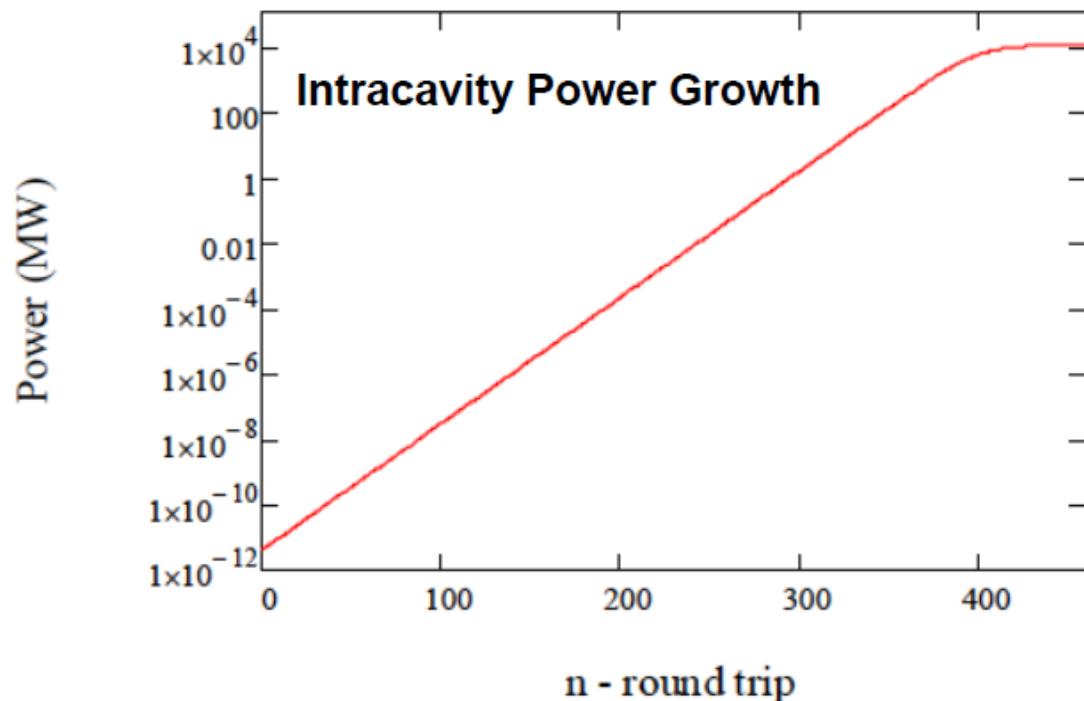
$$\dot{N}_e [s^{-1}] \equiv 3 \cdot 10^{-7}$$

$$B[T]L[m] = 20, \varepsilon_\gamma [eV] \equiv 0.1, Q \equiv 10^3$$

$$m_a [eV] \equiv 1.575 \cdot 10^{-3} \sqrt{\frac{\varepsilon_\gamma [eV]}{\lambda_u [m]}}$$

Expected ALP counts in 1 year

FEL osc. parameters	
FEL low gain par. g_0	0.13
Pierce par. ρ	1.2×10^{-3}
Cavity Gain G	0.1
Sat. Power	1.3 GW
Equil. Power	10.5 GW
# round trip	400
Avg. Power	1 MW
N_{fot}/s	5.3×10^{25}



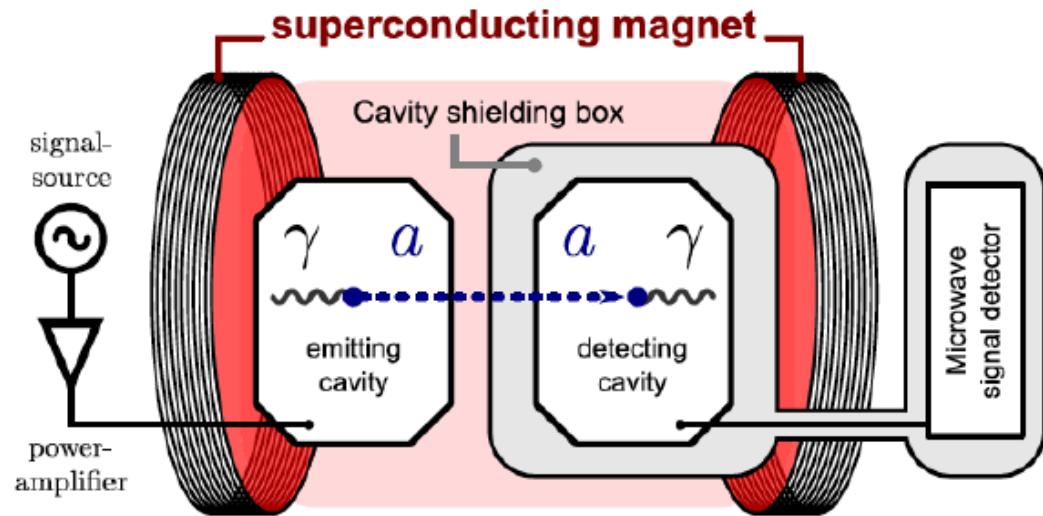
$$\dot{N}_\gamma \times P_{\gamma \rightarrow \phi}^2 \times Q_{\text{FEL0}} \times 3 \times 10^7 \text{ s} \simeq 12 \text{ counts}$$

Promising but preliminary result we wish to optimize

Enhancing the γ flux: sub-THz sources

$$P_{\text{ALP}} = \left(\frac{gB_0}{f_{\text{sys}}} \right)^4 |G_{\text{ALP}}|^2 Q_{\text{em}} Q_{\text{det}} P_{\text{em}}$$

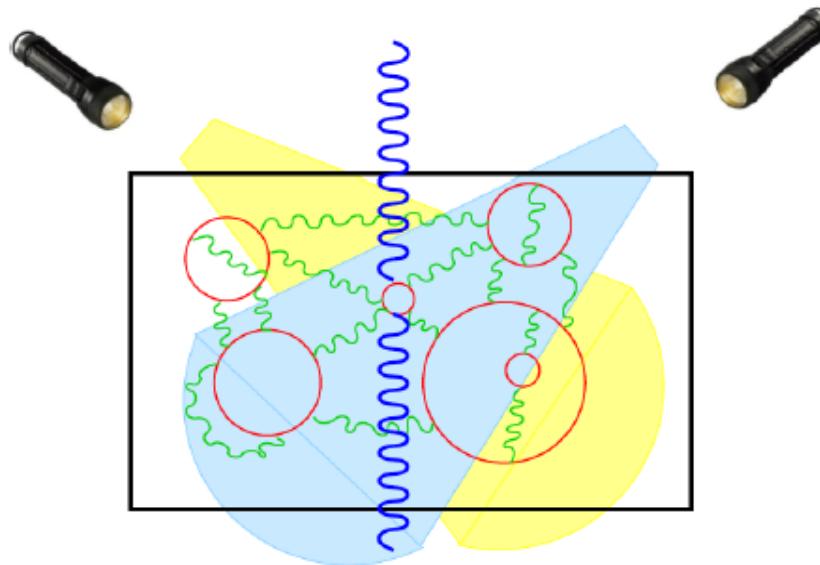
CROWS Experiment



Together with I. Spassovsky, S. Ceccuzzi & G. Ravera, we are discussing the feasibility of a possible test experiment with klystron, gyrotron, CARM (to probe higher frequency)

Conclusions

- ✓ ALPs & Axions Physics case has been set
- ✓ A no-lose enterprise: even if no ALP does exist, diverse high intensity tests on QED vacuum have been carried on



- ✓ We addressed a couple of ideas and we wish to bring them to a mature stage for experiment proposal