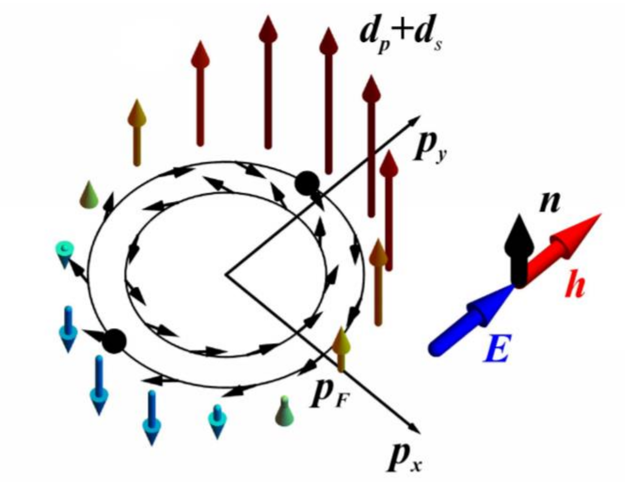

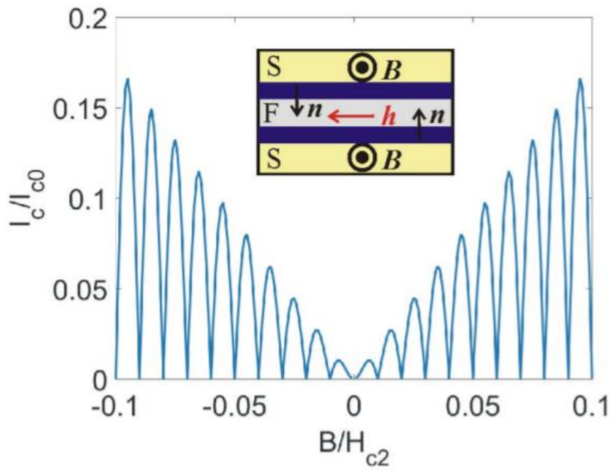

Odd triplet superconductivity induced by the moving condensate

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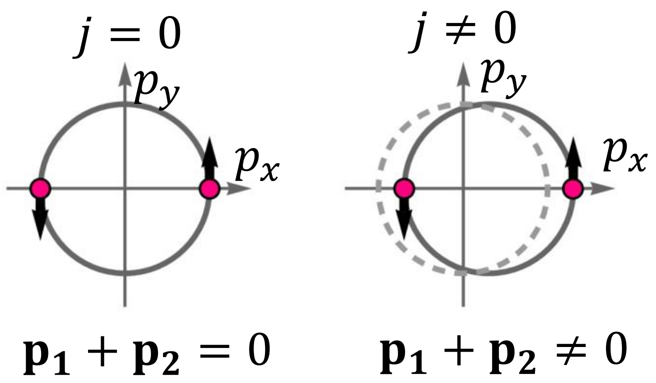
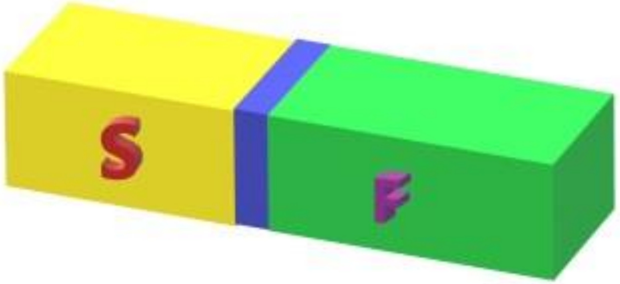
Main idea:

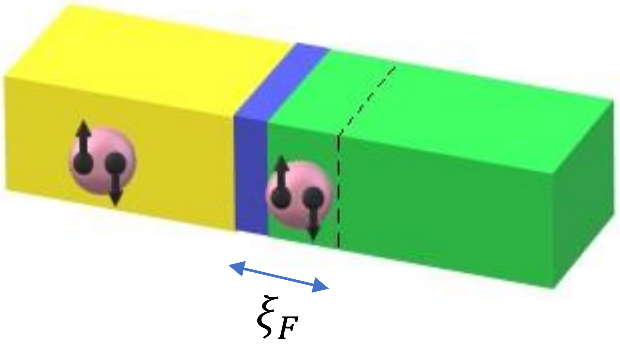


Condensate motion tends to break Cooper pairs by inducing their center-of mass motion, which makes the momenta of two paired electrons to be not exactly opposite

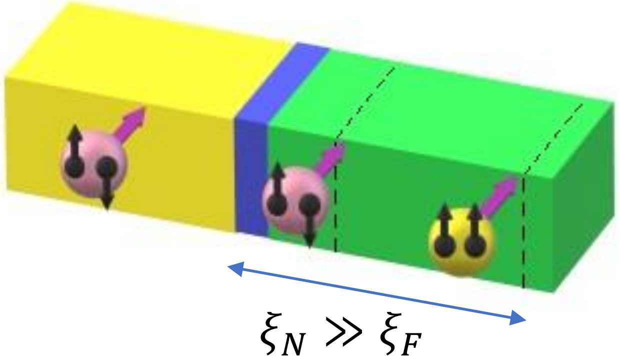
In this talk an S/F hybrid is discussed:



where there are **no superconducting correlations** deep in the ferromagnet **when the condensate is at rest**



But **triplet correlations** appear deep in the ferromagnet **if the condensate motion is induced**



Outline

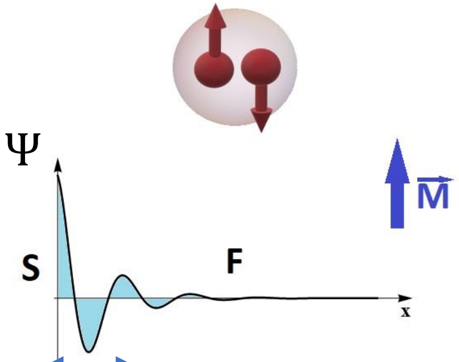
Introduction: mechanisms of LRT generation in S/F hybrids with the
focus on spin-orbit-assisted LRT generation

LRT generation by the moving condensate

- basic mechanism
- LRTs generated by Meissner currents and their manifestations in the DOS and Josephson current
- dynamical LRTs: photo-induced Josephson currents and Josephson photo-magnetic devices

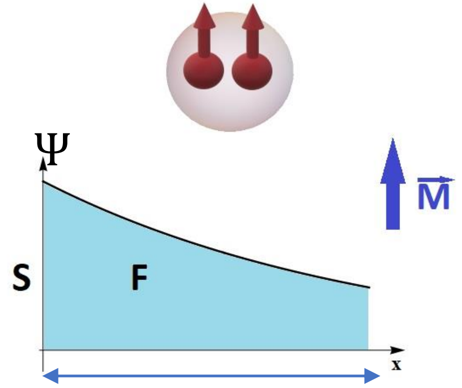
LRT generation mechanisms

opposite-spin pair is short-range (SRT)



$$\xi_F = \sqrt{D/h}$$

equal-spin pair is long-range (LRT)

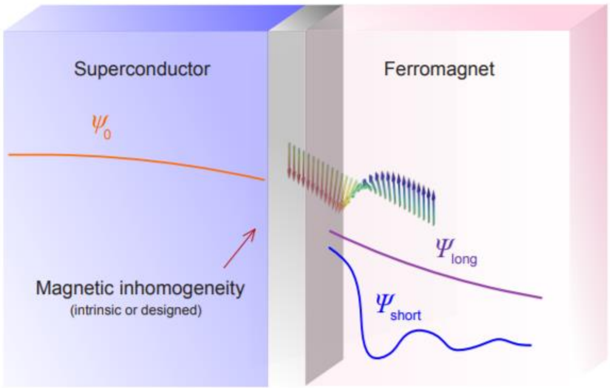


$$\xi_N = \sqrt{D/2\pi T}$$

$$f_t = (d_x - id_y)|\uparrow\uparrow\rangle + (d_x + id_y)|\downarrow\downarrow\rangle + d_z(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

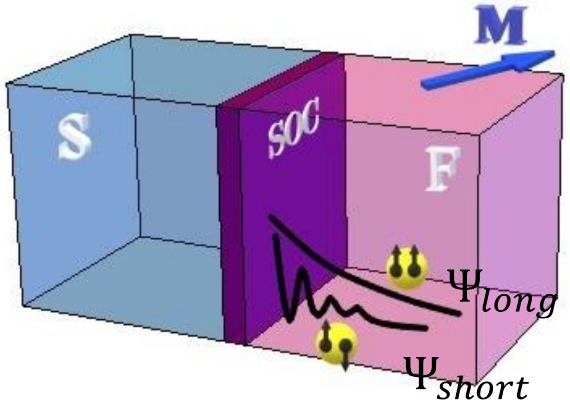
Buzdin, A. I. RMP **77**, 935 (2005);
Bergeret, F.S., Volkov, A. F. Efetov & K. B. RMP **77**, 1321 (2005)

LRT generation by a magnetic inhomogeneity



From J. Linder, J. W. A. Robinson, Nat. Phys. **11**, 307 (2015)

LRT generation by a spin-orbit coupling



LRT generation by spin-orbit coupling

F. S. Bergeret and I. V. Tokatly, PRL **110**, 117003 (2013); PRB **89**, 134517 (2014)

$$H_0 = \frac{\mathbf{p}^2}{2m} - \frac{1}{2}\Omega^a(\mathbf{p})\sigma^a + V_{\mathrm{imp}} \qquad \text{with} \qquad \Omega^a(\mathbf{p}) = \mathcal{A}_k^a \frac{p_k}{m}$$

SRT

LRT $\boldsymbol{f}_t^{\perp} = (f_t^x, f_t^y, 0)$

Triplet correlations $\boldsymbol{f}_t$ can be divided into SRTs and LRTs: $\boldsymbol{f}_t = f_t^{\parallel}\hat{\mathbf{z}} + \boldsymbol{f}_t^{\perp}$

Superconducting singlet f_s and triplet f_t condensate wave functions obey the following equations:

$$D\nabla^2 f_s - 2|\omega| f_s - 2i\,\mathrm{sgn}(\omega) h^a f_t^a = 0,$$

$$D\nabla^2 f_t^a + 2C_k^{ab}\partial_k f_t^b - \Gamma^{ab} f_t^b - 2|\omega| f_t^a - 2i\,\mathrm{sgn}(\omega) h^a f_s = 0$$

the precession of the spin of diffusively moving particles in the presence of a spatially inhomogeneous spin distribution

$$C_k^{ab} = D\varepsilon^{acb}\mathcal{A}_k^c$$

anisotropic Dyakonov-Perel spin relaxation

$$\Gamma^{ab} = D\left(\mathcal{A}_k^c\mathcal{A}_k^c\delta^{ab} - \mathcal{A}_k^a\mathcal{A}_k^b\right)$$

LRT generation by spin-orbit coupling

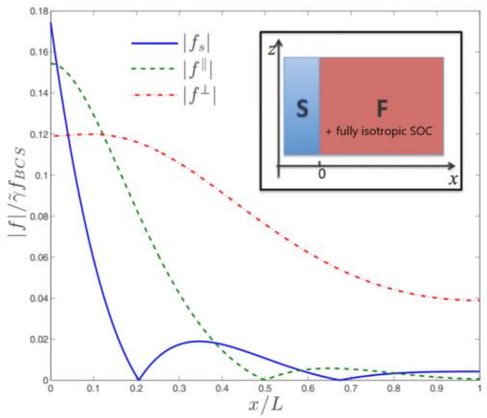
the both mechanisms can generate LRTs

"precession"

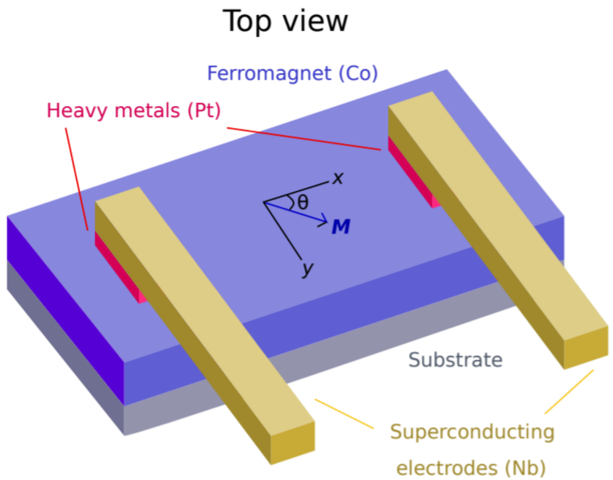
$$2C_k^{ab}\partial_k f_t^b$$

"anisotropic Dyakonov-Perel spin relaxation"

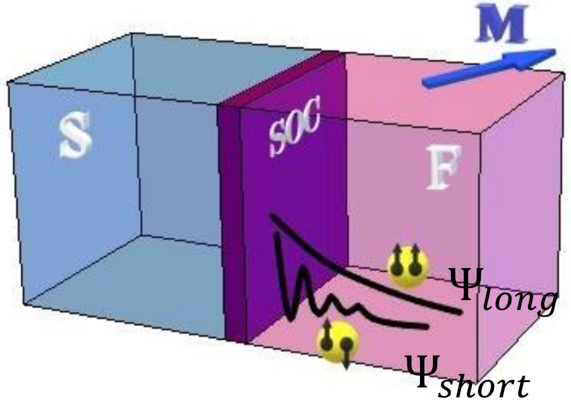
$$\Gamma^{ab} f_t^b$$



F. S. Bergeret and I. V. Tokatly, PRB **89**, 134517 (2014)



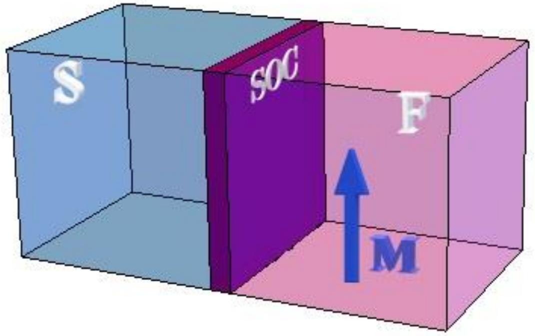
J. R. Eskilt, *et. al,* PRB **100**, 224519 (2019)

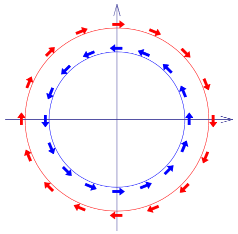


All the discussed examples of LRTs generation exploit **intrinsic material features, geometric inhomogeneities** engineered in the particular setup or **manipulation by the magnetization**

The inhomogeneity of the superconducting condensate phase can be easily driven externally

LRT generation by the moving condensate



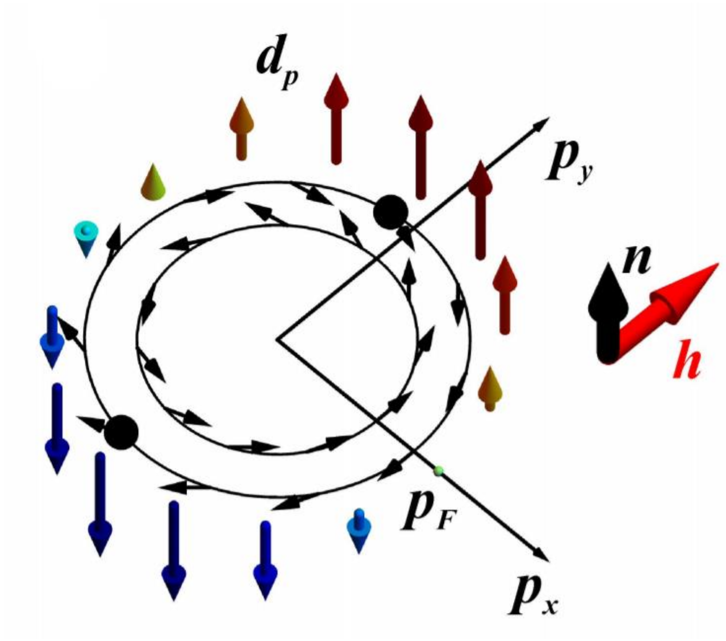


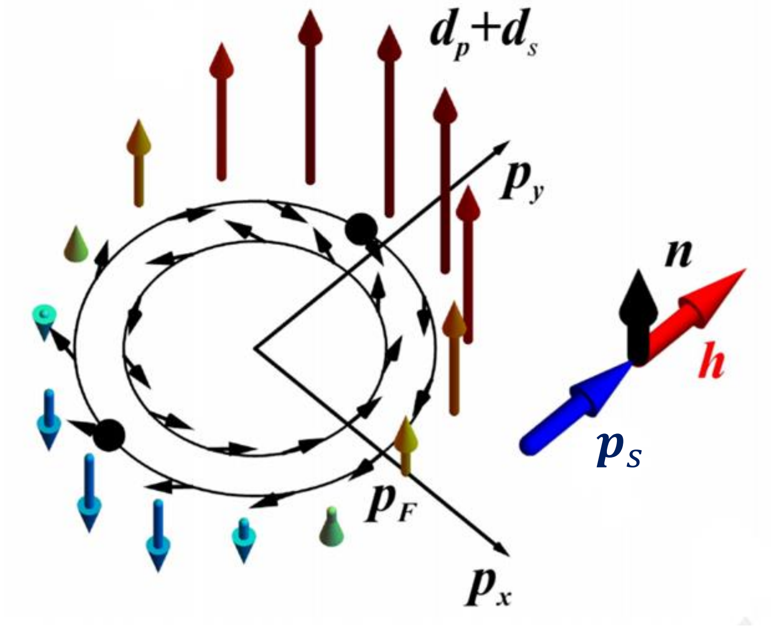
$$\widehat{H} = \xi_p + \alpha(\boldsymbol{p} \times \boldsymbol{n})\boldsymbol{\sigma} \; + \boldsymbol{h}\boldsymbol{\sigma}$$

No intrinsic gradients of the condensate wave function;

No anisotropy of the Dyakonov-Perel Spin relaxation tensor –

No LRTs without a moving condensate





$$\boldsymbol{d}_p(\boldsymbol{p},\omega) = F_{pw}(\omega)\boldsymbol{h} \times (\boldsymbol{n} \times \boldsymbol{p})$$

$$\boldsymbol{d}_p(\boldsymbol{p}) = -\boldsymbol{d}_p(-\boldsymbol{p})$$

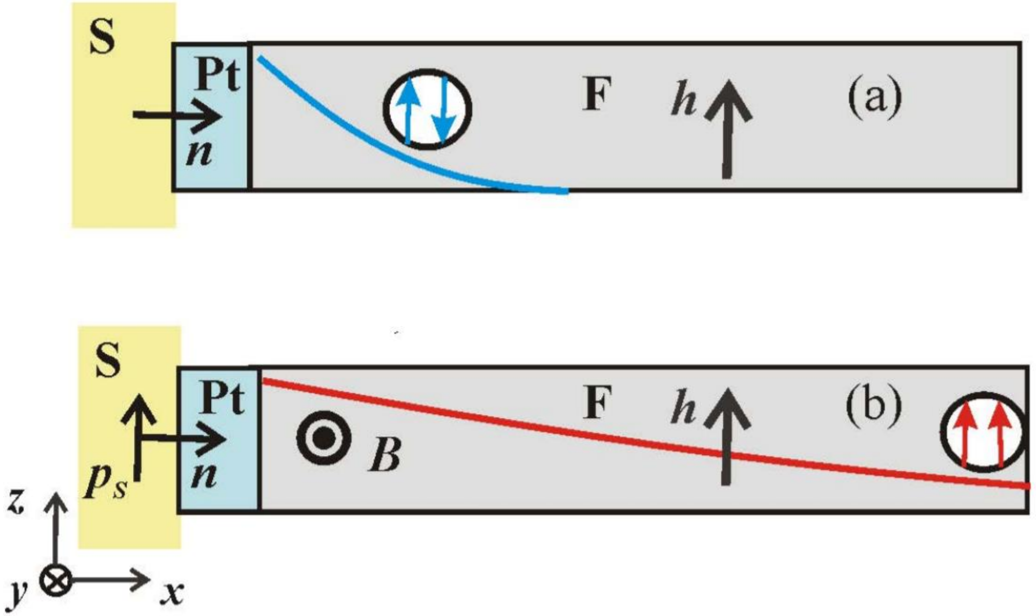
$$F_{pw}(\omega - i\boldsymbol{v}_F \cdot \boldsymbol{p}_s) \approx F_{pw}(\omega) - i(\boldsymbol{v}_F \cdot \boldsymbol{p}_s)\partial_\omega F_{pw}$$

$$\boldsymbol{d}_s \propto (\boldsymbol{n} \times \boldsymbol{p}_s) \times \boldsymbol{h}$$

$$\boldsymbol{d}_s \; - even\ spin, even\ momentum \; \Rightarrow odd\ frequency$$

LRT generation by the Meissner currents

M. A. Silaev, I. V. Bobkova, A. M. Bobkov, PRB **102**, 100507 (2020)



$$p_s(d_F/2) = -p_s(-d_F/2) = B\lambda_L/\Phi_0$$

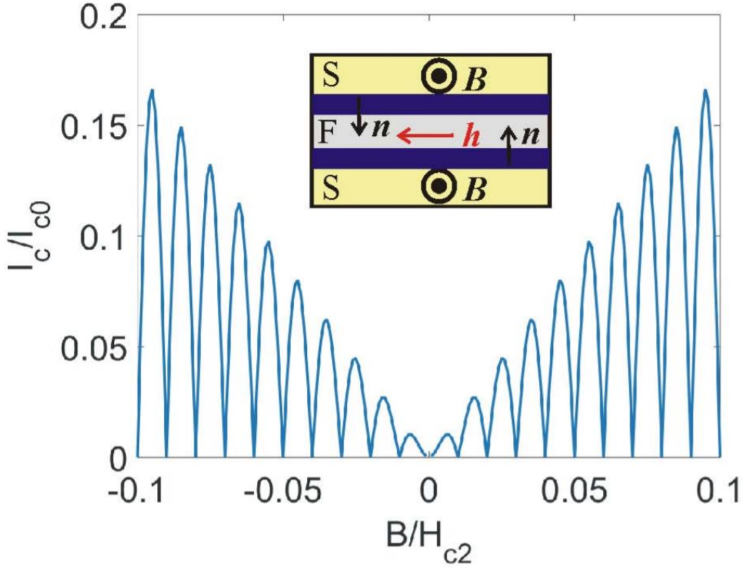
$$I_c \propto B^2 \quad at\ \Phi \ll \Phi_0$$

at larger fields $I_c \propto B^2 \frac{\sin[2\pi\Phi/\Phi_0]}{2\pi\Phi/\Phi_0}$

DOS:

$$\delta N(\varepsilon) = \frac{1}{2}|\hat{f}_t^2|(\omega = i\varepsilon + \delta) \propto B^2$$

Josephson effect:

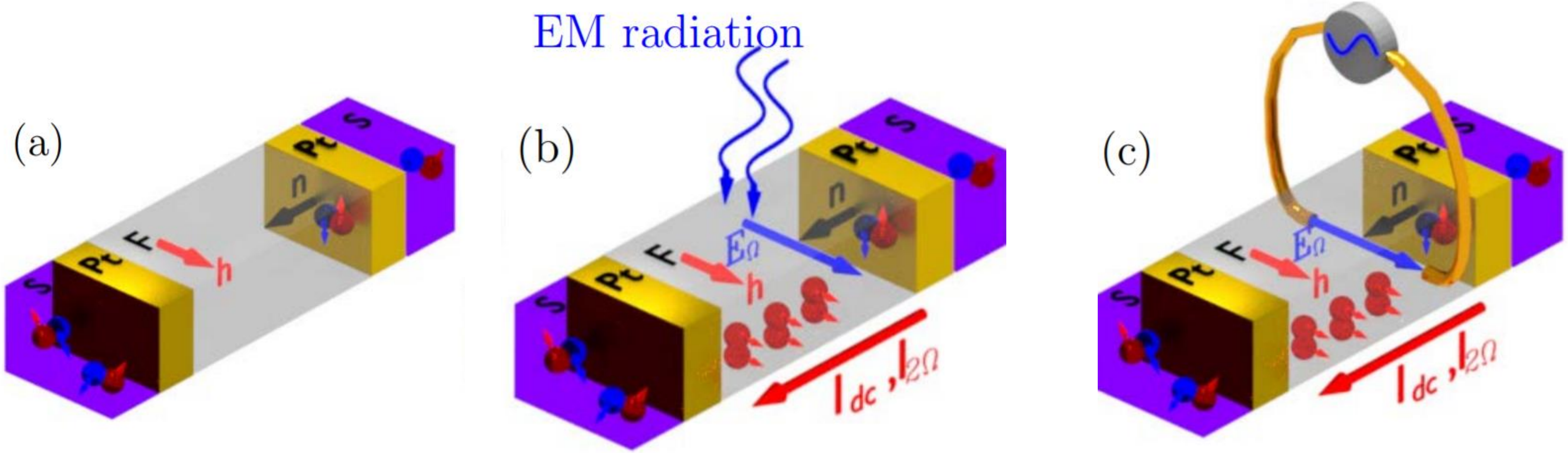


$$I_c \sim 10^{-4} - 10^{-2}\text{A}$$

at $\frac{B}{H_{c2}} \sim 0.03$ *and* $S_{junction} \sim 50 \times 50 \mu m^2$

Dynamical LRTs generated by microwaves

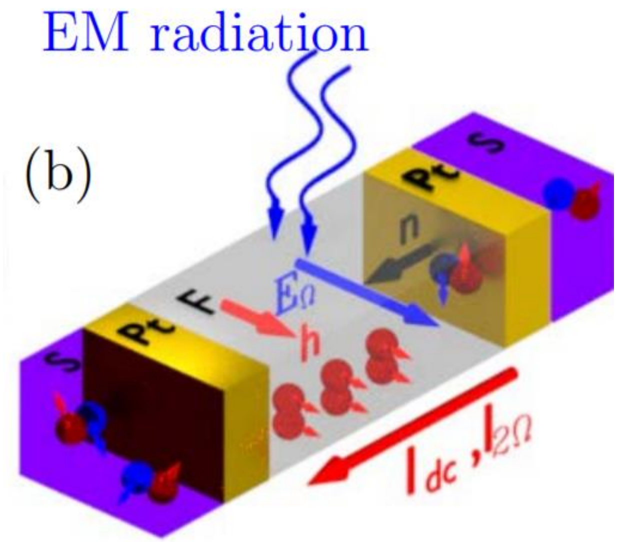
I.V. Bobkova, A.M. Bobkov, M.A. Silaev, arxiv:2007.01805



$$\boldsymbol{E}(t) = \boldsymbol{E}_\Omega e^{i\Omega t} \longrightarrow \boldsymbol{p}_s = -2ie\boldsymbol{E}_\Omega/\Omega$$

$$\boldsymbol{d}(\varepsilon, t) = \int dt' K_d(\varepsilon, t-t')(\boldsymbol{E}(t') \times \boldsymbol{n}) \times \boldsymbol{h}$$

Dynamical LRTs generated by microwaves



$$I(\chi,t) = [I^c_{dc} + I^c_{2\Omega}\cos(2\Omega t)]\sin\chi$$

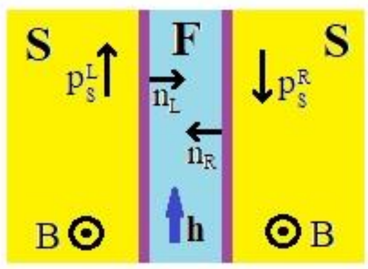
$$I^c_{dc} \propto E_\Omega E_{-\Omega} \text{ and } I^c_{2\Omega} \propto E^2_\Omega$$

$$I^c_{dc},\ I^c_{2\Omega} \sim I_0$$

$I_0 \sim \left(\frac{P}{P_c}\right)(10^{-3} - 10^{-1})\text{A}$ at $S_{junction} \sim 50 \times 50\mu m^2$

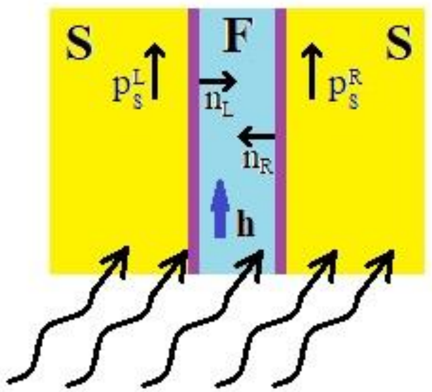
$P_c = (c\hbar/e^2)\hbar\Omega^2/\xi^2$ and at $\xi = 30nm$ $P_c \approx 10(\Omega/GHz)^2$ W /m^2

Compare:



$f_{t,L} \propto (n_L \times p_S^L) \times h = f_{t,R}$

0-junction



$f_{t,L} \propto (n_L \times p_S^L) \times h = -f_{t,R}$

π-junction

<u>cell phones</u>: $\Omega \approx 3-4$ GHz and $P \sim P_c$ ➡ $I_0 \sim 10^{-1} - 10^{-3}$ A

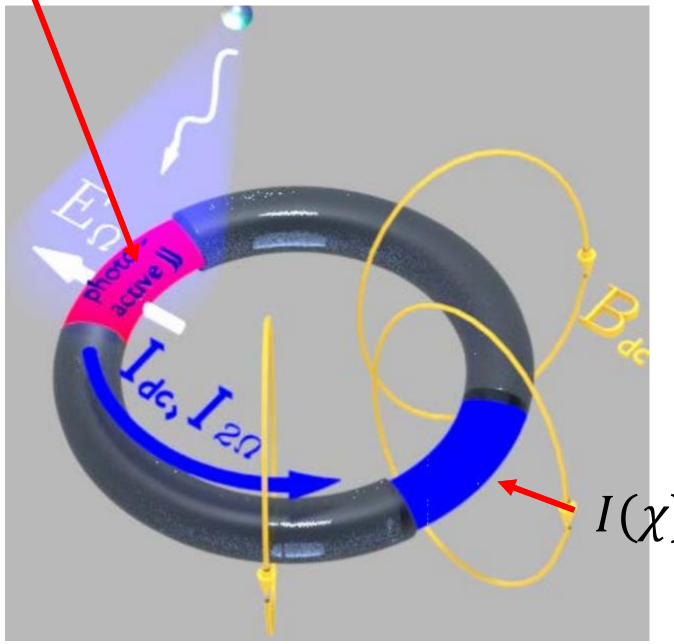
<u>cosmic background radiation:</u> $P_c \approx 10^6$ W /m^2 and $P = 10^{-5}$ W /m^2

⬇

$$I_0 \sim 10^{-12} - 10^{-15}\text{ A}$$

Josephson photo-magnetic device

$I(\chi) = [I_{dc}^{c} + I_{2\Omega}^{c}\cos(2\Omega t)]\,sin\chi$



$I(\chi) = I_{o}^{c}\,sin\chi$

$\Omega \ll \omega_0 = 1/\sqrt{LC}$

<u>no external radiation</u>: **no spontaneous current** in the ground state

<u>under external radiation</u>: **the zero-current state is unstable** at

$$I_{dc}^{c} > \frac{\Phi_0}{2\pi}\frac{\omega_0\omega_p}{\sqrt{\omega_0^2+\omega_p^2}}$$

$$\omega_p = \sqrt{2\pi I_o^c / C\Phi_0}$$

Conclusions

- Moving superconducting condensate allows for externally controllable generation of LRTs in S/F hybrid structures with spin-orbit interfaces

- The LRTs manifest itself in unusual dependencies of the DOS on the applied magnetic field $\propto B^2$ in S/F hybrids and interference patterns of the Josephson current with the envelope $\propto B$ in S/F/S junctions

- The mechanism allows for a generation of dynamical LRTs by alternating electric fields, what results in photo-assisted Josephson effect and photo-magnetic devices

Thank you for your attention!