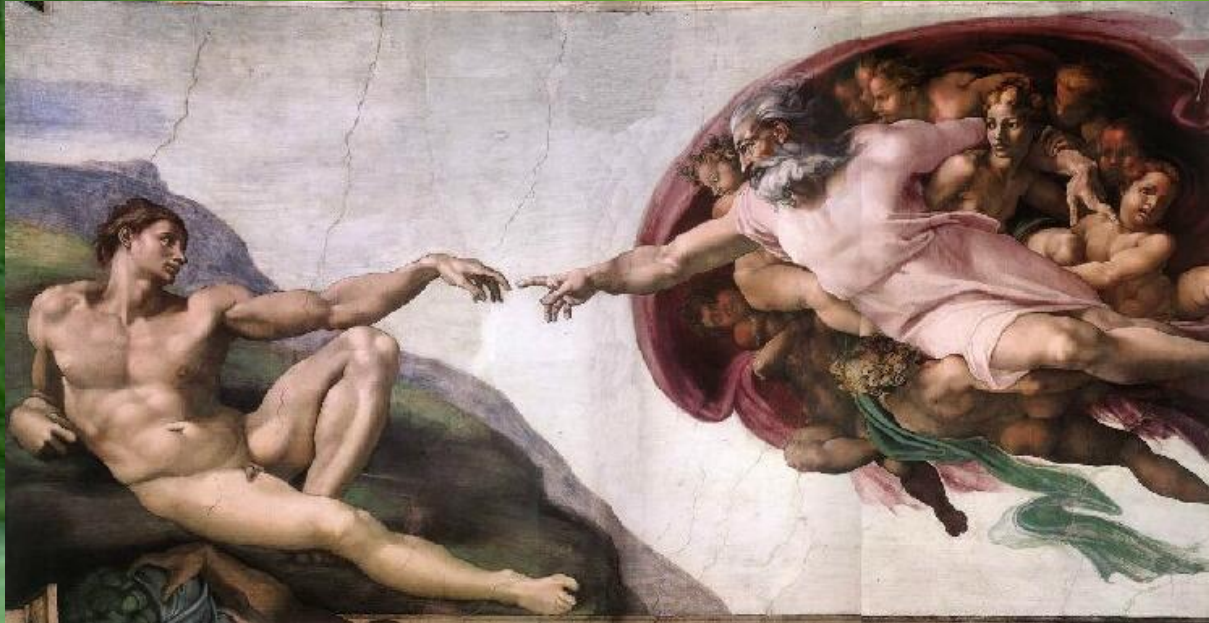


# Kwazicząstki– model standardowy kwaziwszechświata



Wydział Fizyki Uniwersytetu Warszawskiego

Jacek.Szczytko@fuw.edu.pl


Andrzej Gołębiewski, Anita Gardias, Jarosław Rybusiński

# Google: Jacek Szczytko

**Jacek Szczytko** Faculty of Physics, University of Warsaw

home research publications teaching students career

## about me



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Head of the project: *Nowe wyzwania - nowe kierunki* <http://www.nowekierunki.fuw.edu.pl/>  
Representative of the Dean of *Nanostructures Engineering* <http://nano.fuw.edu.pl/>

## about my work

2015, Radio TokFM 9 września. Audycja Karoliny Głowackiej [Radiowa Akademia Nauk](#) *Co to jest nanotechnologia i jakie perspektywy nam daje?*

magnetic nanoparticles and apparatus for determining the


[CK](#), [English version](#)

(rsaw)


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### Projects



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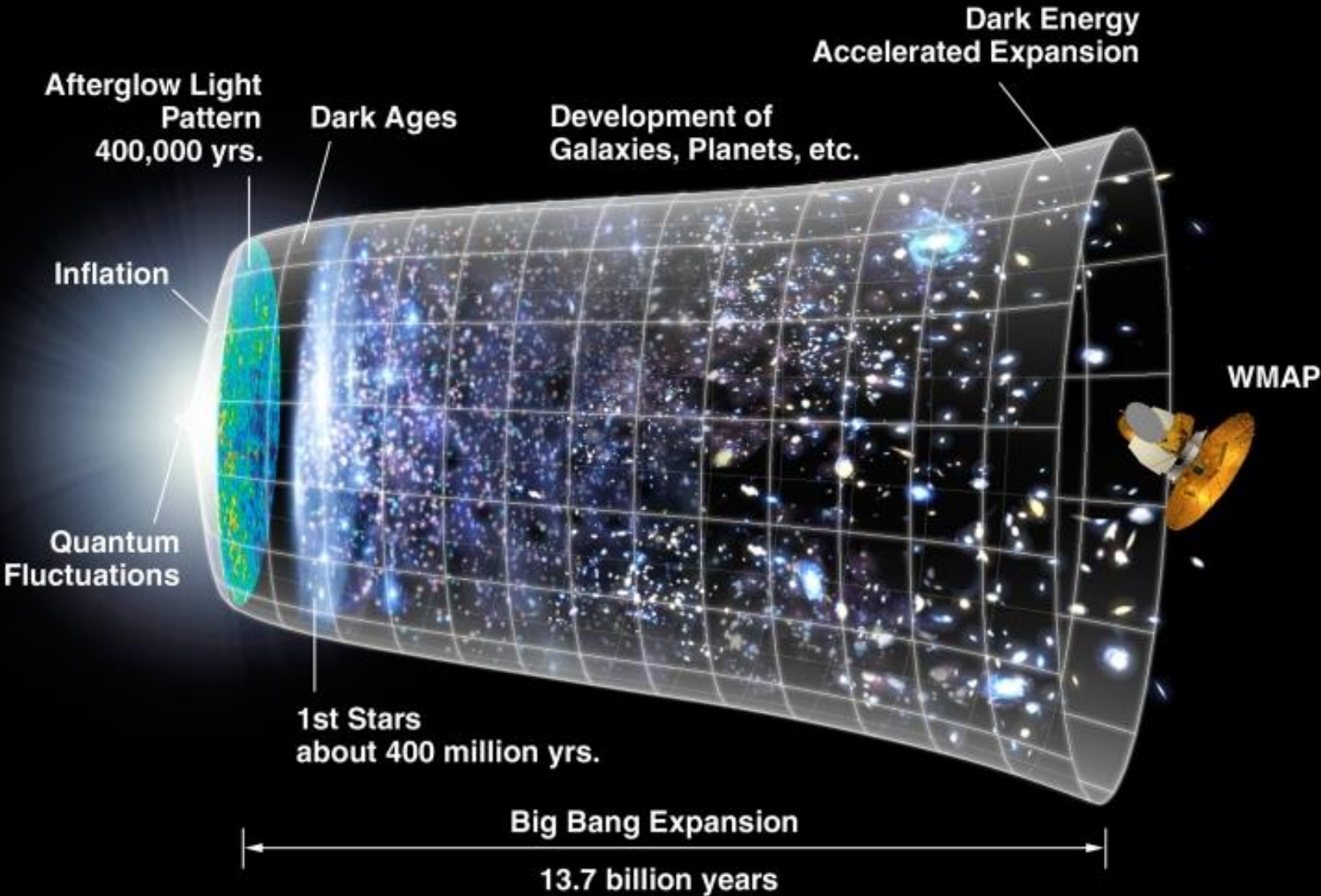


# Matematyka i przyroda

The background of the slide is a vast field of galaxies, known as the Hubble Ultra Deep Field 2014. It features a dense collection of galaxies in various colors, including blue, yellow, and red, set against a dark cosmic background. The galaxies are of different shapes and sizes, some appearing as bright points of light and others as more complex structures.

*Dialog z przyrodą musi być  
prowadzony w języku matematyki,  
w przeciwnym razie przyroda nie  
odpowiada na nasze pytania.*

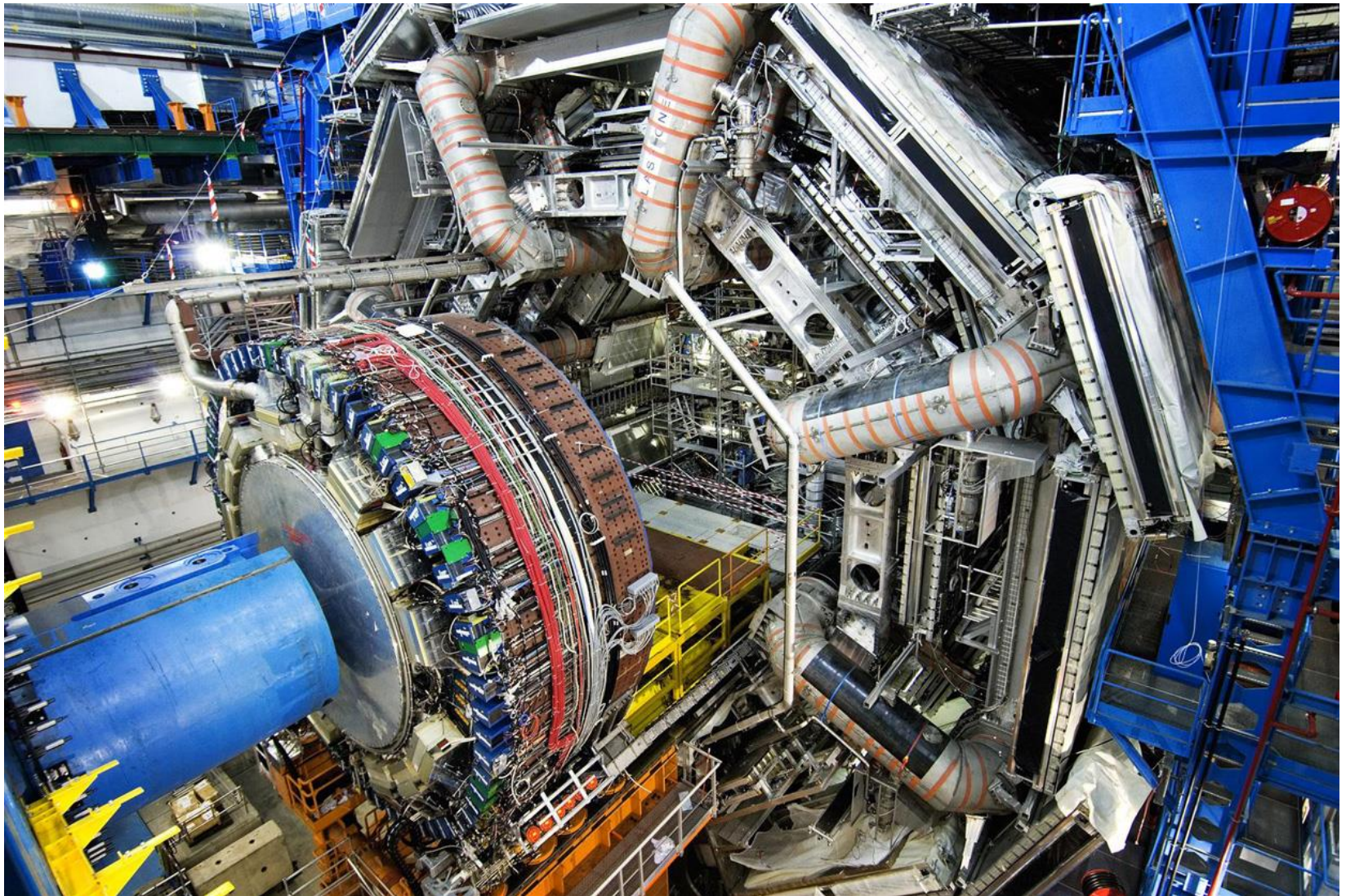
**prof. Michał Heller**



# Pierwiastki

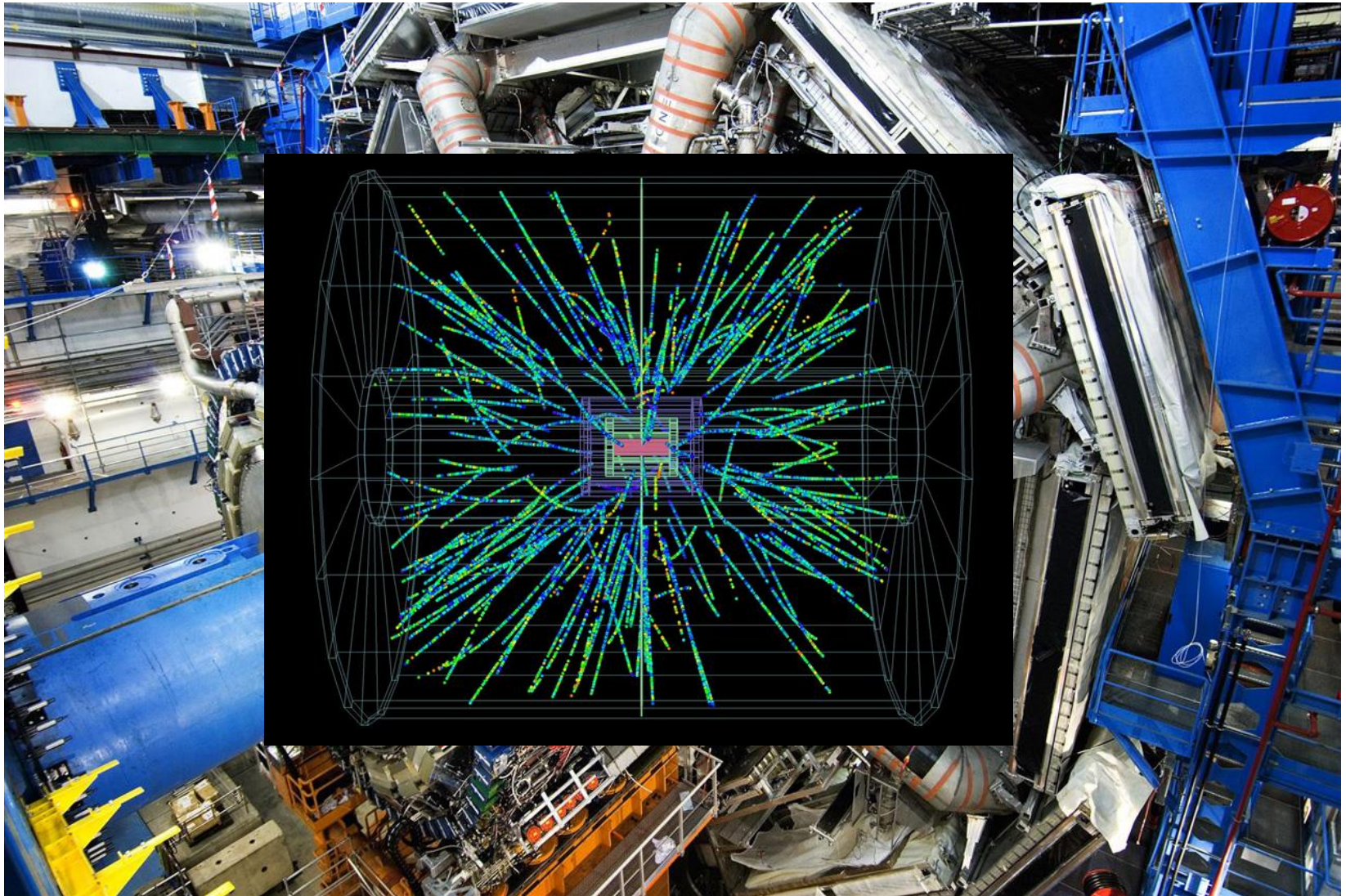
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Period																			
1	1 H																		2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	* 71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
7	87 Fr	88 Ra	** 103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo	
*Lanthanoids			* 57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb			
**Actinoids			** 89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No			

# Cząstki elementarne



LHC  
CERN

# Cząstki elementarne



LHC  
CERN

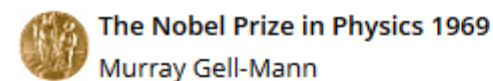
Category	Particle Name	Symbol	Anti-particle	Mass (MeV/c <sup>2</sup> )	B	L <sub>e</sub>	L <sub>μ</sub>	L <sub>τ</sub>	S	Lifetime(s)	Principal Decay Modes <sup>a</sup>	
<b>Leptons</b>	Electron	e <sup>-</sup>	e <sup>+</sup>	0.511	0	+1	0	0	0	Stable		
	Electron-neutrino	ν <sub>e</sub>	$\bar{\nu}_e$	< 7 eV/c <sup>2</sup>	0	+1	0	0	0	Stable		
	Muon	μ <sup>-</sup>	μ <sup>+</sup>	105.7	0	0	+1	0	0	2.20 × 10 <sup>-6</sup>	e <sup>-</sup> ν <sub>e</sub> ν <sub>μ</sub>	
	Muon-neutrino	ν <sub>μ</sub>	$\bar{\nu}_\mu$	< 0.3	0	0	+1	0	0	Stable		
	Tau	τ <sup>-</sup>	τ <sup>+</sup>	1.784	0	0	0	+1	0	< 4 × 10 <sup>-13</sup>	μ <sup>-</sup> $\bar{\nu}_\mu$ ν <sub>τ</sub> , e <sup>-</sup> $\bar{\nu}_e$ ν <sub>τ</sub>	
	Tau-neutrino	ν <sub>τ</sub>	$\bar{\nu}_\tau$	< 30	0	0	0	+1	0	Stable		
<b>Hadrons</b>	<b>Mesons</b>	Pion	π <sup>+</sup>	π <sup>-</sup>	139.6	0	0	0	0	2.60 × 10 <sup>-8</sup>	μ <sup>+</sup> ν <sub>μ</sub>	
			π <sup>0</sup>	Self	135.0	0	0	0	0	0.83 × 10 <sup>-16</sup>	2γ	
		Kaon	K <sup>+</sup>	K <sup>-</sup>	493.7	0	0	0	0	+1	1.24 × 10 <sup>-8</sup>	μ <sup>+</sup> ν <sub>μ</sub> , π <sup>+</sup> π <sup>0</sup>
			K <sub>s</sub> <sup>0</sup>	$\bar{K}_s^0$	497.7	0	0	0	0	+1	0.89 × 10 <sup>-10</sup>	π <sup>+</sup> π <sup>-</sup> , 2π <sup>0</sup>
		K <sub>L</sub> <sup>0</sup>	$\bar{K}_L^0$	497.7	0	0	0	0	+1	5.2 × 10 <sup>-8</sup>	π <sup>±</sup> e <sup>∓</sup> $\bar{\nu}_e$ , 3π <sup>0</sup>	
											π <sup>±</sup> μ <sup>∓</sup> $\bar{\nu}_\mu$	
	Eta	η	Self	548.8	0	0	0	0	0	< 10 <sup>-18</sup>	2γ, 3π <sup>0</sup>	
		η'	Self	958	0	0	0	0	0	2.2 × 10 <sup>-21</sup>	ηπ <sup>+</sup> π <sup>-</sup>	
	<b>Baryons</b>	Proton	p	$\bar{p}$	938.3	+1	0	0	0	0	Stable	
		Neutron	n	$\bar{n}$	939.6	+1	0	0	0	0	614	pe <sup>-</sup> $\bar{\nu}_e$
Lambda		Λ <sup>0</sup>	$\bar{\Lambda}^0$	1115.6	+1	0	0	0	-1	2.6 × 10 <sup>-10</sup>	pπ <sup>-</sup> , nπ <sup>0</sup>	
		Sigma	Σ <sup>+</sup>	$\bar{\Sigma}^-$	1189.4	+1	0	0	0	-1	0.80 × 10 <sup>-10</sup>	pπ <sup>0</sup> , nπ <sup>+</sup>
		Σ <sup>0</sup>	$\bar{\Sigma}^0$	1192.5	+1	0	0	0	-1	6 × 10 <sup>-20</sup>	Λ <sup>0</sup> γ	
		Σ <sup>-</sup>	$\bar{\Sigma}^+$	1197.3	+1	0	0	0	-1	1.5 × 10 <sup>-10</sup>	nπ <sup>-</sup>	
Delta		Δ <sup>++</sup>	$\bar{\Delta}^{--}$	1230	+1	0	0	0	0	6 × 10 <sup>-24</sup>	pπ <sup>+</sup>	
		Δ <sup>+</sup>	$\bar{\Delta}^-$	1231	+1	0	0	0	0	6 × 10 <sup>-24</sup>	pπ <sup>0</sup> , nπ <sup>+</sup>	
		Δ <sup>0</sup>	$\bar{\Delta}^0$	1232	+1	0	0	0	0	6 × 10 <sup>-24</sup>	nπ <sup>0</sup> , pπ <sup>-</sup>	
		Δ <sup>-</sup>	$\bar{\Delta}^+$	1234	+1	0	0	0	0	6 × 10 <sup>-24</sup>	nπ <sup>-</sup>	
Xi	Ξ <sup>0</sup>	$\bar{\Xi}^0$	1315	+1	0	0	0	-2	2.9 × 10 <sup>-10</sup>	Λ <sup>0</sup> π <sup>0</sup>		
	Ξ <sup>-</sup>	$\bar{\Xi}^+$	1321	+1	0	0	0	-2	1.64 × 10 <sup>-10</sup>	Λ <sup>0</sup> π <sup>-</sup>		
Omega	Ω <sup>-</sup>	Ω <sup>+</sup>	1672	+1	0	0	0	-3	0.82 × 10 <sup>-10</sup>	Ξ <sup>-</sup> π <sup>0</sup> , Ξ <sup>0</sup> π <sup>-</sup> , Λ <sup>0</sup> K <sup>-</sup>		

Particles zoo

<sup>a</sup> Notations in this column such as pπ<sup>-</sup>, nπ<sup>0</sup> mean two possible decay modes. In this case, the two possible decays are Λ<sup>0</sup> → p + π<sup>-</sup> and Λ<sup>0</sup> → n + π<sup>0</sup>.



# Cząstki elementarne - kwarki



## The Nobel Prize in Physics 1969



Murray Gell-Mann

The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann "for his contributions and discoveries concerning the classification of elementary particles and their interactions".

### Zweig, George



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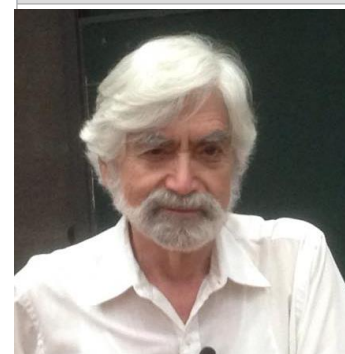
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### George Zweig [\[edytuj\]](#)

**George Zweig** (ur. w roku 1937 w Moskwie, w rodzinie żydowskiej) - fizyk, był początkowo uczniem Richarda Feynmana, lecz z czasem poświęcił się neurobiologii. W roku 1959 ukończył Uniwersytet Michigan, a w roku 1964 Politechnikę Kalifornijską. Wiele lat spędził jako pracownik naukowej prowadząc badania naukowe w amerykańskim Narodowym Laboratorium Los Alamos i Politechnice w Massachusetts. Od roku 2004 zajął się pracą w przemyśle finansowym.

W roku 1964 Zweig, będąc studentem ostatniego roku Politechniki Kalifornijskiej, (niezależnie od M. Gell-Manna) wysunął hipotezę istnienia kwarków. Zweig początkowo nazywał je "asami", posługując się analogią do czterech asów w tali kart, gdyż podejrzewał on, iż kwarków jest cztery.

George Zweig

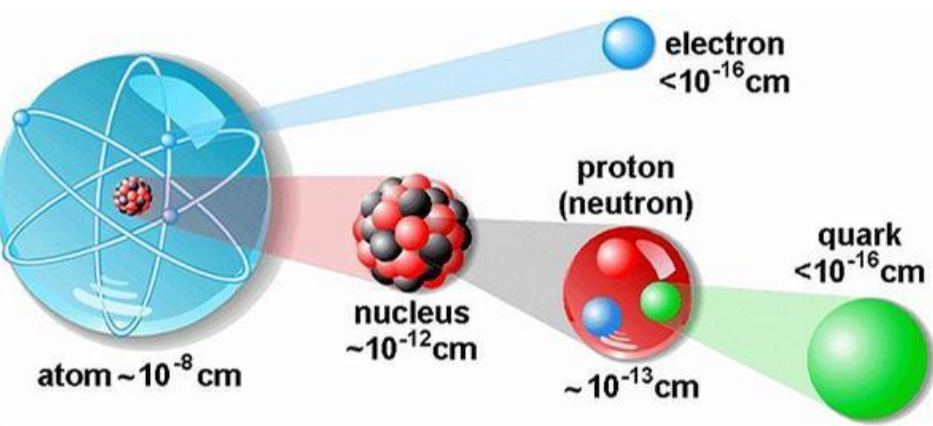


# Cząstki elementarne

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Period																			
1	H																	He	
2	Li	Be											B	C	N	O	F	Ne	
3	Na	Mg											Al	Si	P	S	Cl	Ar	
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
6	Cs	Ba	* Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
7	Fr	Ra	** Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo	
			* 57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb			
			** 89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No			

## Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force



Bosons (Forces)

# Cząstki elementarne

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																		
1	1																	2
	H																	He
2	3	4											5	6	7	8	9	10
	Li	Be											B	C	N	O	F	Ne
3	11	12											13	14	15	16	17	18
	Na	Mg											Al	Si	P	S	Cl	Ar
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	55	56	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
	Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	87	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
	Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo
			* 57 58 59 60 61 62 63 64 65 66 67 68 69 70 La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb															
			** 89 90 91 92 93 94 95 96 97 98 99 100 101 102 Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No															

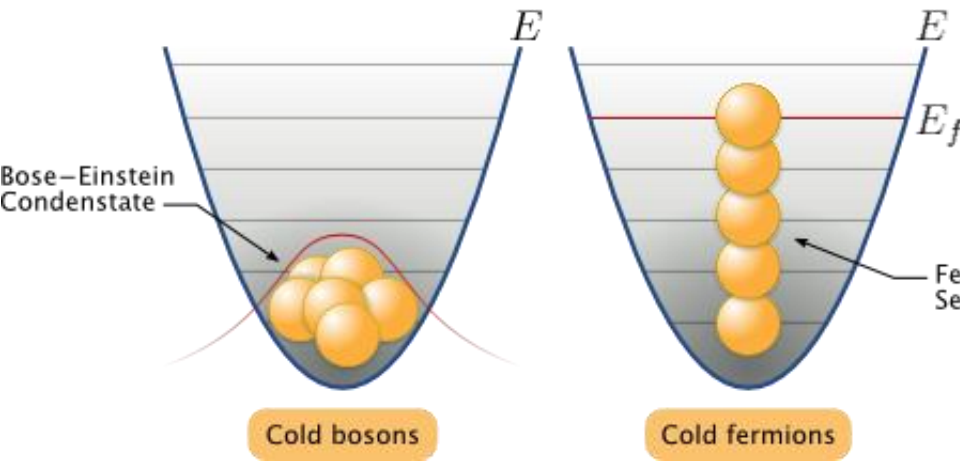
## Three Generations of Matter (Fermions)

	I	II	III	
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spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	up	charm	top	photon
	<b>u</b>	<b>c</b>	<b>t</b>	<b>γ</b>
	up	charm	top	photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	down	strange	bottom	gluon
	<b>d</b>	<b>s</b>	<b>b</b>	<b>g</b>
	down	strange	bottom	gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	electron neutrino	muon neutrino	tau neutrino	weak force
	<b>ν<sub>e</sub></b>	<b>ν<sub>μ</sub></b>	<b>ν<sub>τ</sub></b>	<b>Z<sup>0</sup></b>
	electron neutrino	muon neutrino	tau neutrino	weak force
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	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	electron	muon	tau	weak force
	<b>e</b>	<b>μ</b>	<b>τ</b>	<b>W<sup>±</sup></b>
	electron	muon	tau	weak force

Quarks

Leptons

Bosons (Forces)



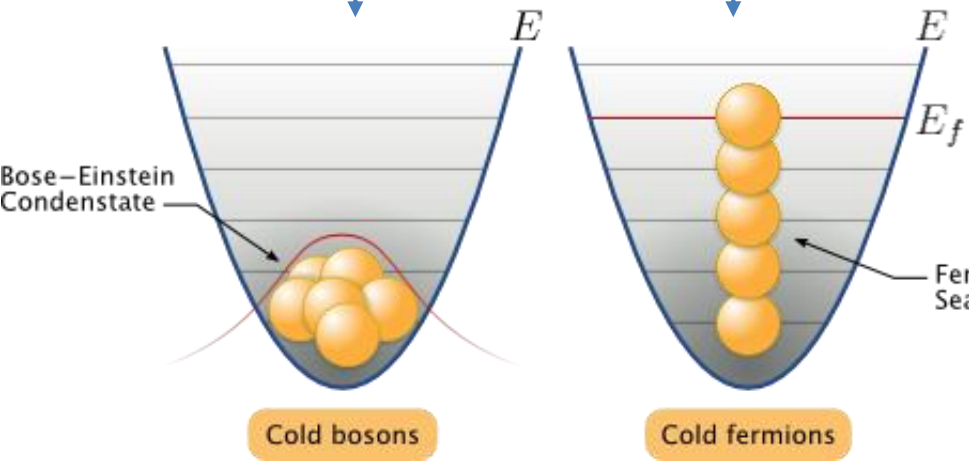
# Cząstki elementarne

## SPIN CAŁKOWITY

$J = 0$  (Higgs)  
 $J = 1$  ( $\gamma, g, Z^0, W^{+/-}$ )

## SPIN POŁÓWKOWY

$J = 1/2$



## Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
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	Quarks			
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	Leptons			
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b><math>Z^0</math></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>W^\pm</math></b> weak force
	Bosons (Forces)			

# Cząstki elementarne

## Three Generations of Matter (Fermions)

SPIN POŁÓWKOWY

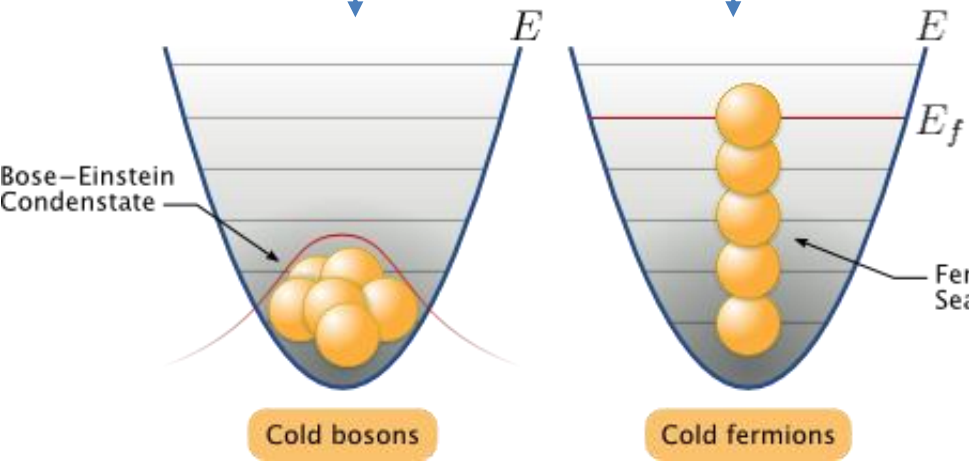
$$J = 1/2$$

SPIN CAŁKOWITY

$$J = 0 \text{ (Higgs)}$$

$$J = 1 (\gamma, g, Z^0, W^{+/-})$$

**ELEKTRON**



Quarks

Leptons

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
me →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\gamma</math></b> photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b><math>Z^0</math></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>W^\pm</math></b> weak force

Bosons (Forces)

# Energia kinetyczna $E(\vec{p})$

$$E(\vec{v}) = \frac{mv^2}{2}$$



# Energia kinetyczna $E(\vec{p})$

$$E(\vec{p}) = \frac{p^2}{2m}$$

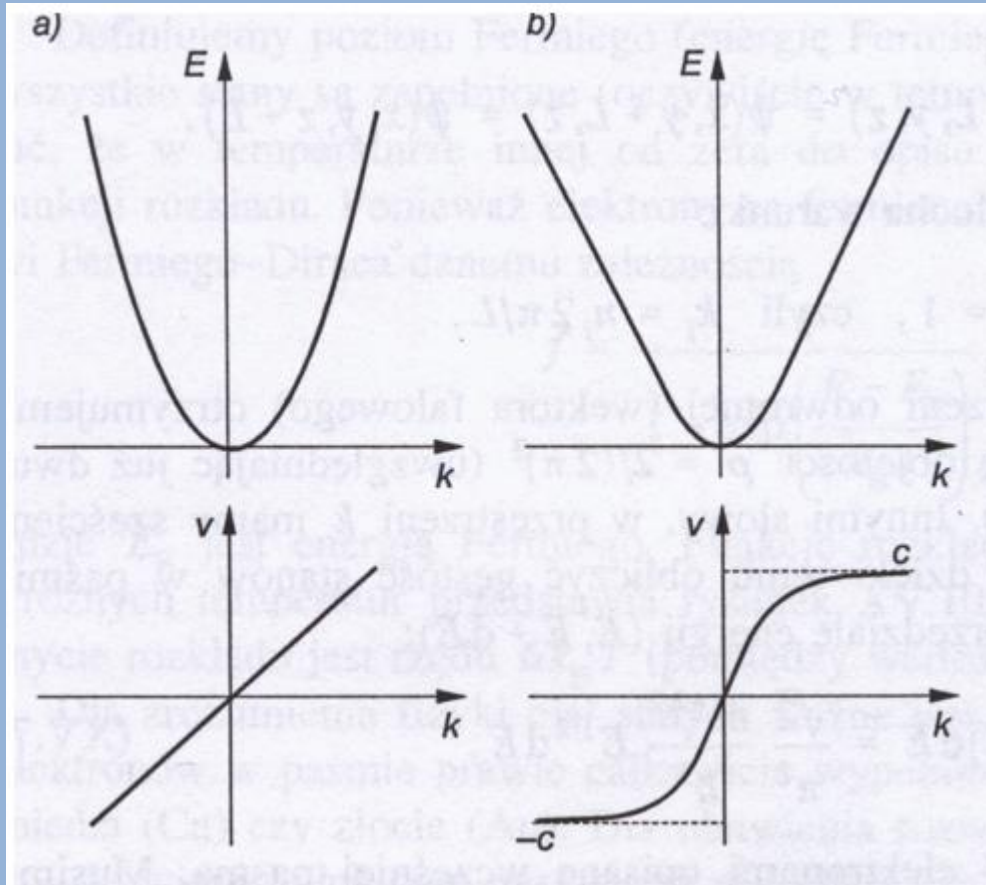


# Energia kinetyczna $E(\vec{p})$

$m \neq 0$

$$E(\vec{p}) = \frac{mv^2}{2} = \frac{\vec{p}^2}{2m}$$

$$E(\vec{p}) = \sqrt{m^2c^4 + p^2c^2}$$



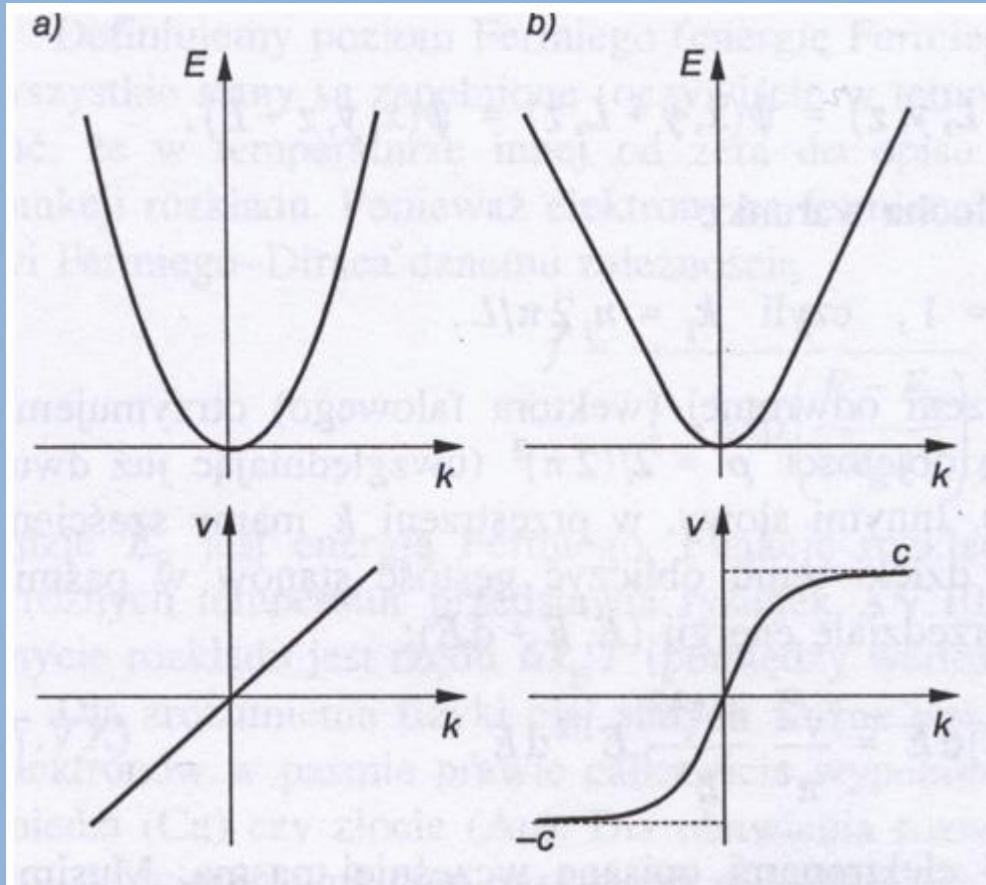


# Energia kinetyczna $E(\vec{p})$

$$m \neq 0$$

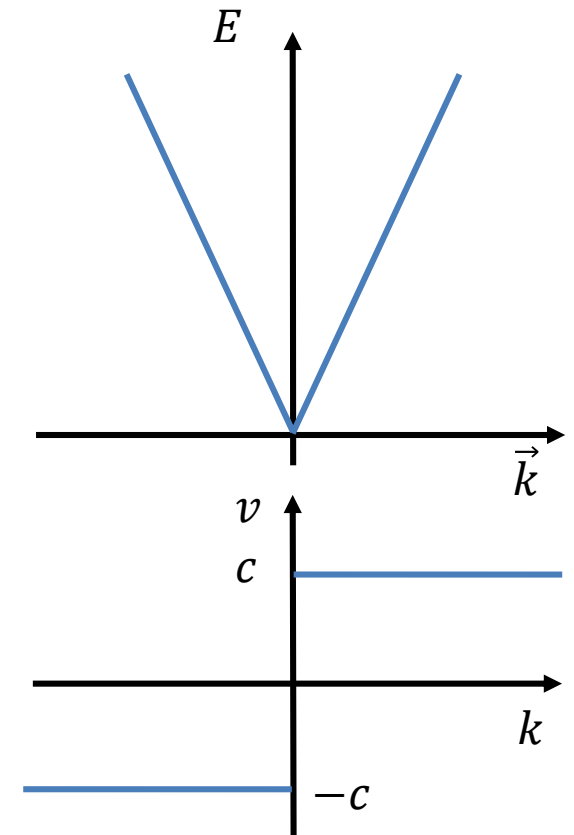
$$E(\vec{p}) = \frac{mv^2}{2} = \frac{\vec{p}^2}{2m}$$

$$E(\vec{p}) = \sqrt{m^2c^4 + p^2c^2}$$



$$m = 0$$

$$E(\vec{p}) = c|\vec{p}|$$



# Trochę historii

## XX w: materia ma (również) charakter falowy

Fale materii – De Broglie 1924 (Nobel 1929), doświadczenia G.P. Thomsona L.H. Germera i C.J. Davissona (Nobel 1937)

$$\lambda = h / p$$

$$p = h / \lambda$$

klasycznie



kwantowo

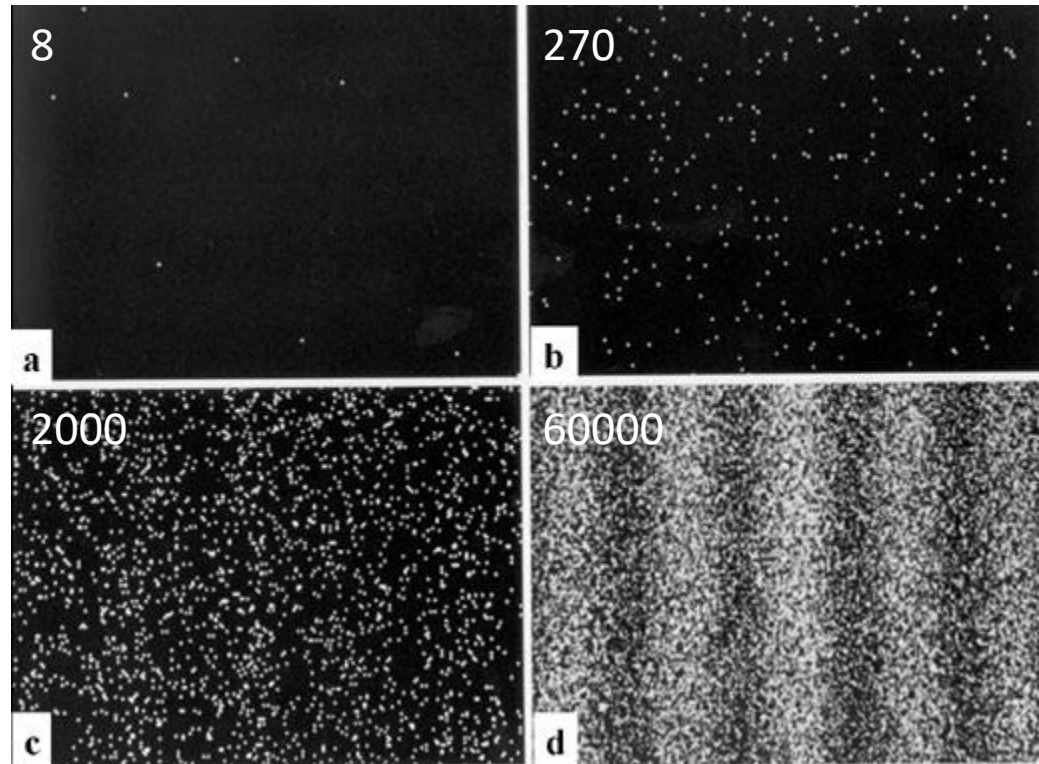


# Trochę historii

## XX w: materia ma (również) charakter falowy

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$$\lambda = h / p$$

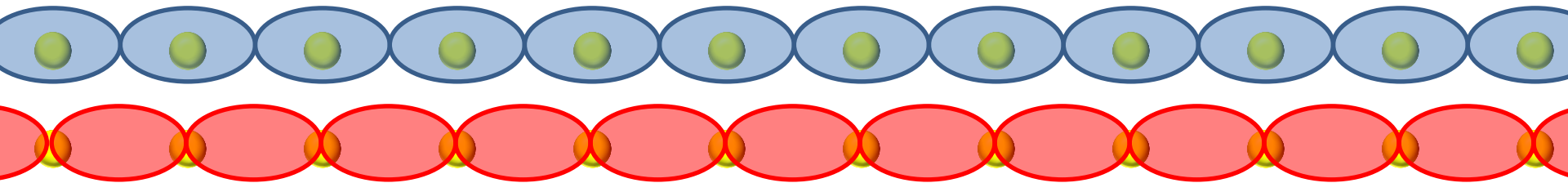


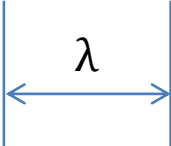
Single-electron events build up over a 20 minute exposure to form an interference pattern in this double-slit experiment by Akira Tonomura and co-workers. (a) 8 electrons; (b) 270 electrons; (c) 2000 electrons; (d) 60,000. A video of this experiment will soon be available on the web

[www.hqrd.hitachi.co.jp/em/doubleslit.html](http://www.hqrd.hitachi.co.jp/em/doubleslit.html).

# Fala materii (de Broigle'a) $\vec{p} = \hbar \vec{k}$

$$\vec{p} = m\vec{v} = \hbar \vec{k}$$



$$|\vec{k}| = \frac{2\pi}{\lambda}$$
A diagram showing a horizontal double-headed arrow labeled with the Greek letter lambda (λ), representing the wavelength of the wave.

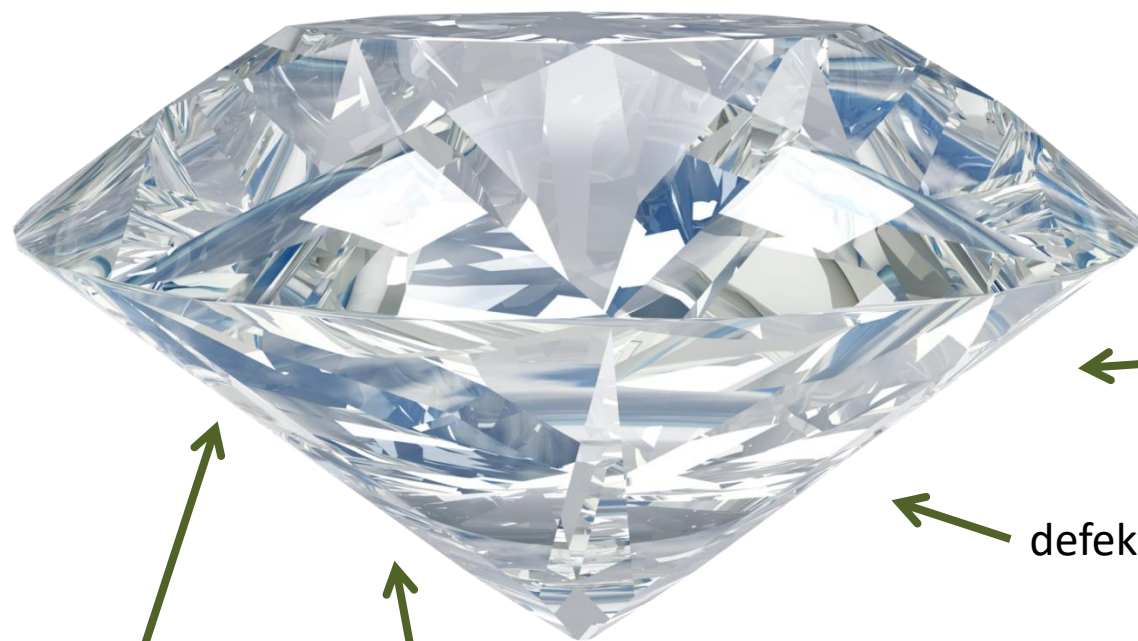


# Oddziaływania wielociałowe

Many-body interactions



# Oddziaływania wielociałowe



← atomy..

← wiązania chemiczne...

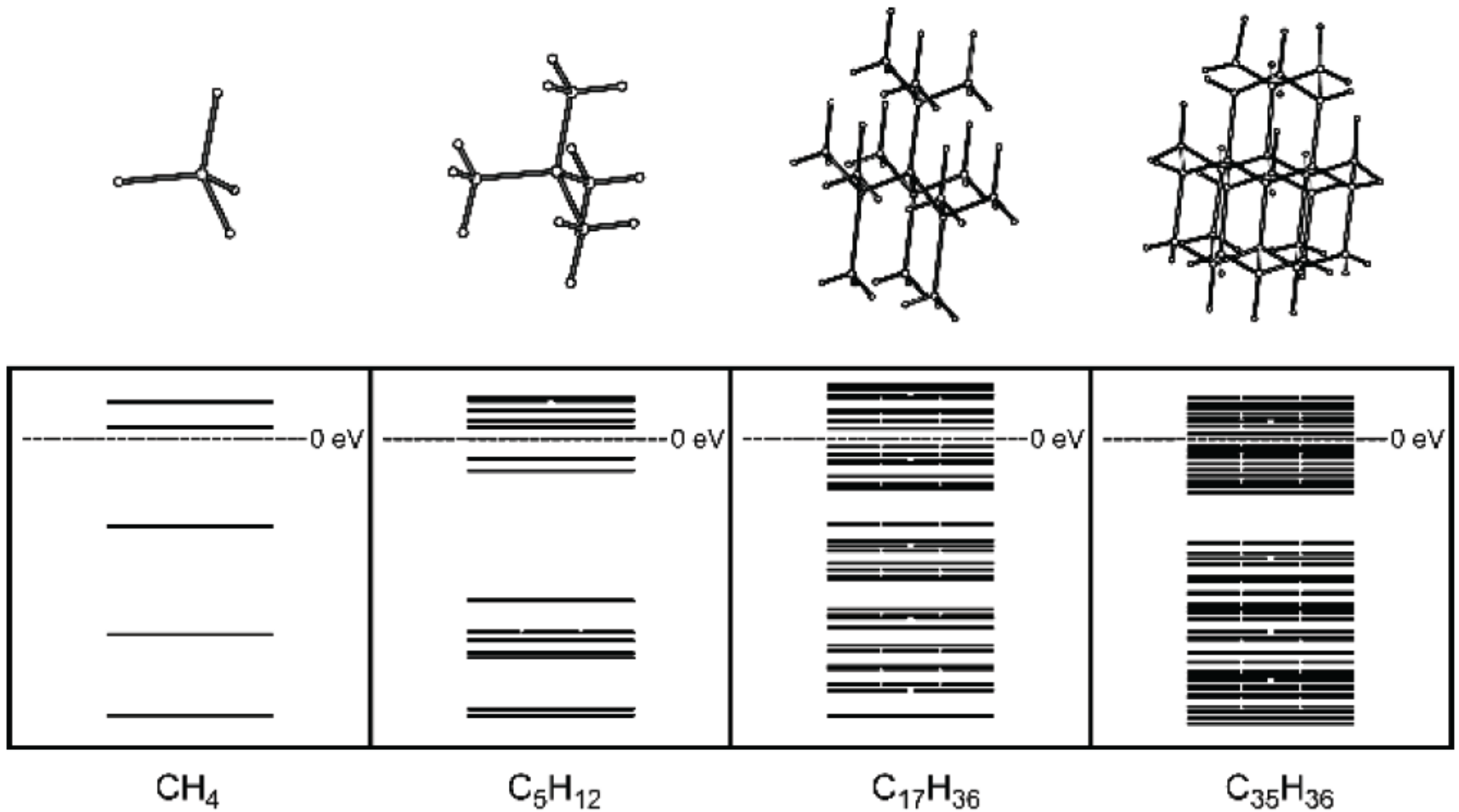
← symetria, struktura...

← defekty, domieszki...

złącza, technologia, 2D, 1D, 0D...

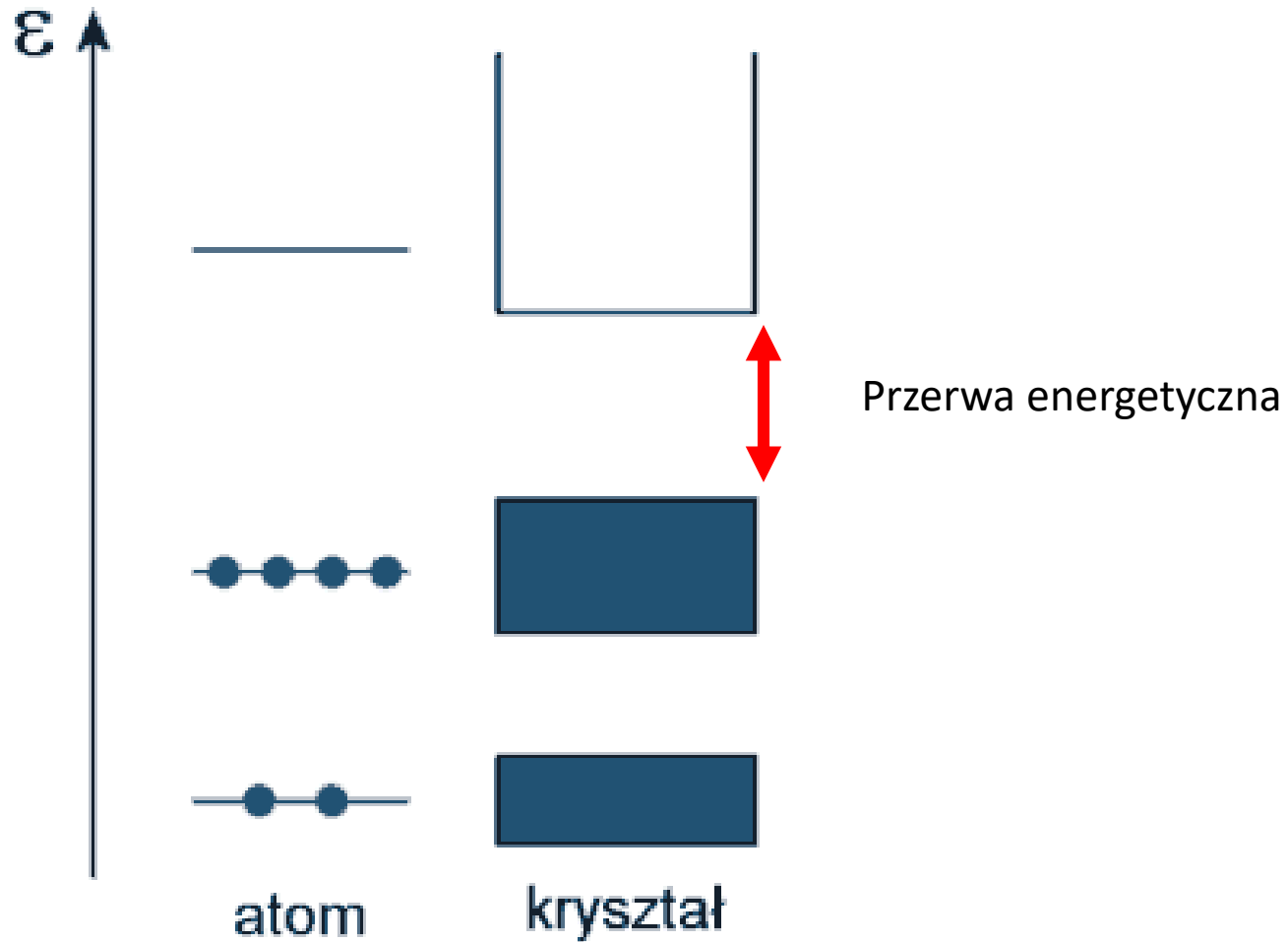
pola zewnętrzne  $\vec{E}$ ,  $\vec{B}$ , światło  $h\nu$ , naprężenie, ciepło...

# Struktura elektronowa ciała stałego



**Fig. 2.3** Development of the diamond band gap

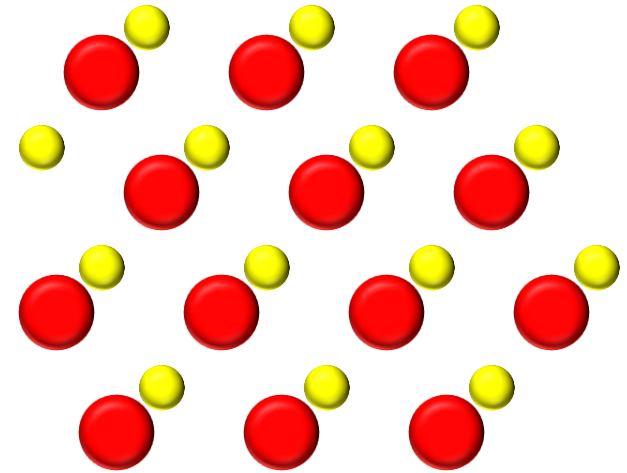
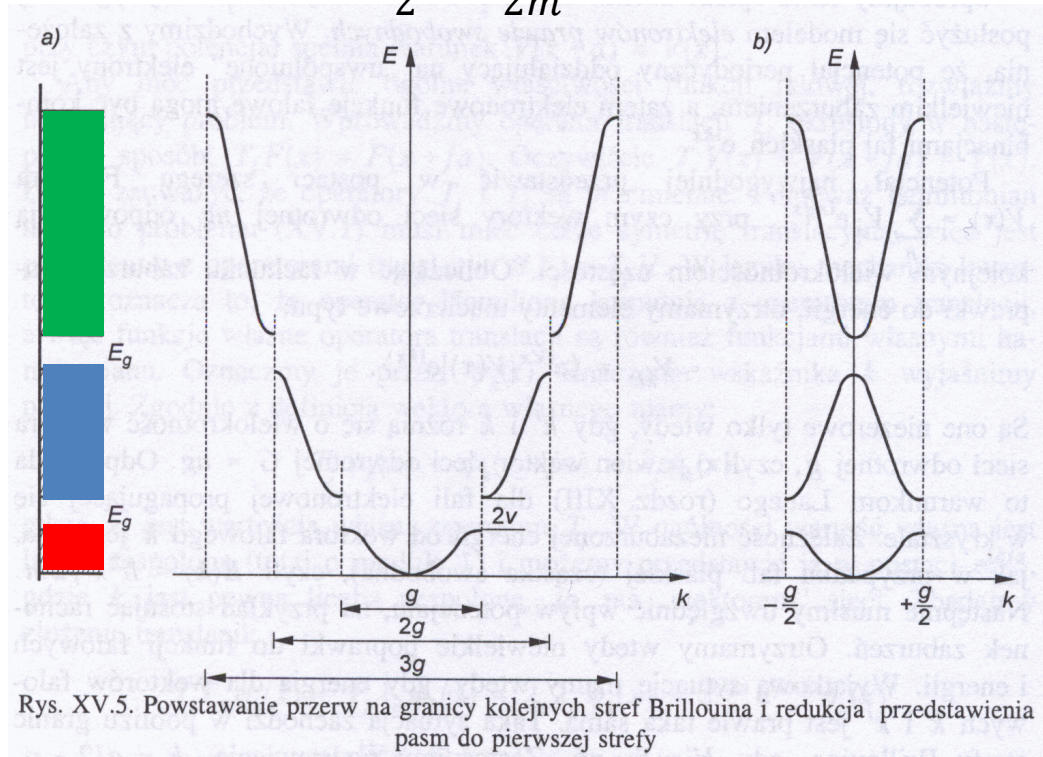
# Teoria pasmowa ciał stałych.



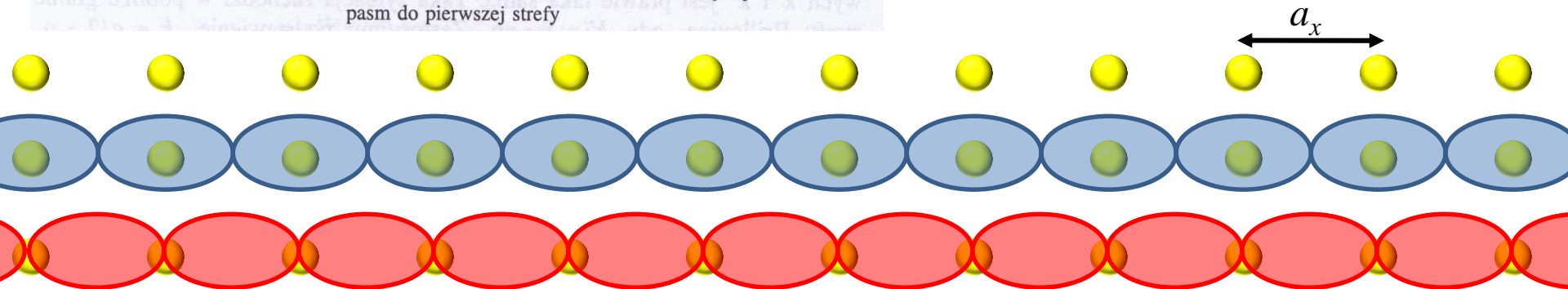


# Przybliżenie masy efektywnej

$$E(\vec{p}) = \frac{mv^2}{2} = \frac{\vec{p}^2}{2m}$$

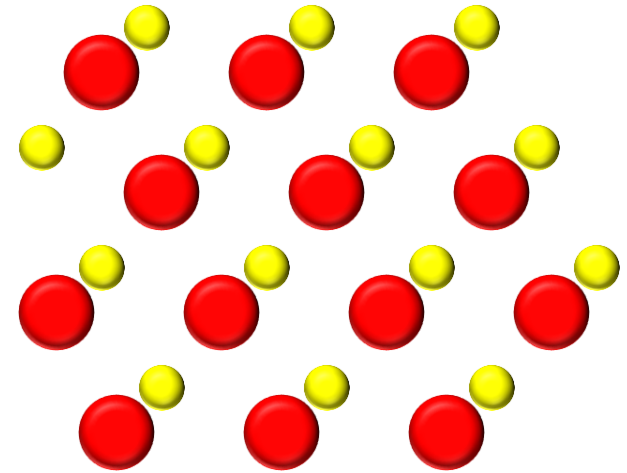
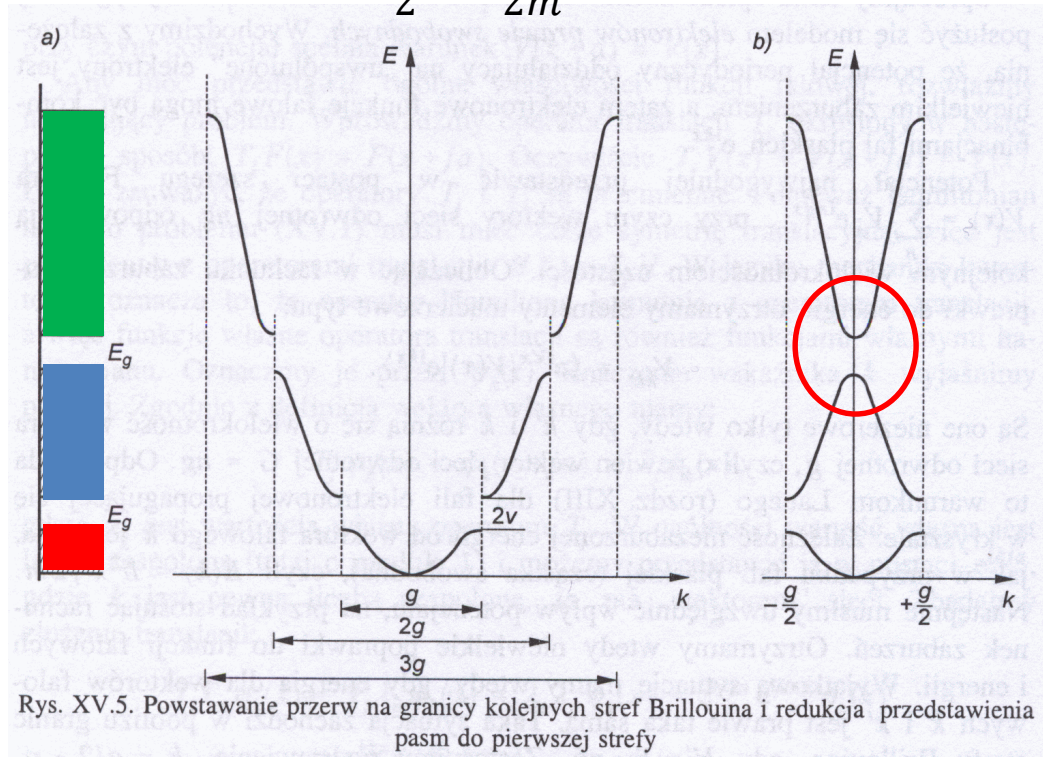


Kryształ = potencjał periodyczny

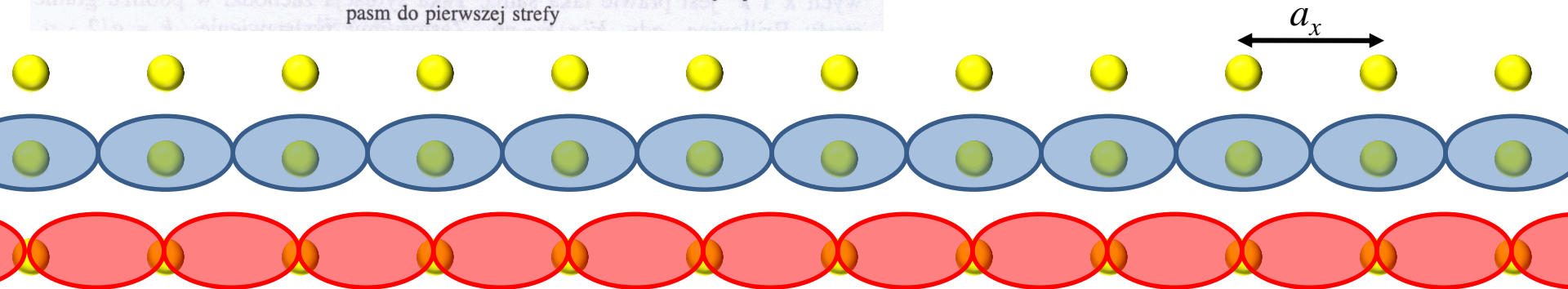


# Przybliżenie masy efektywnej

$$E(\vec{p}) = \frac{mv^2}{2} = \frac{\vec{p}^2}{2m}$$



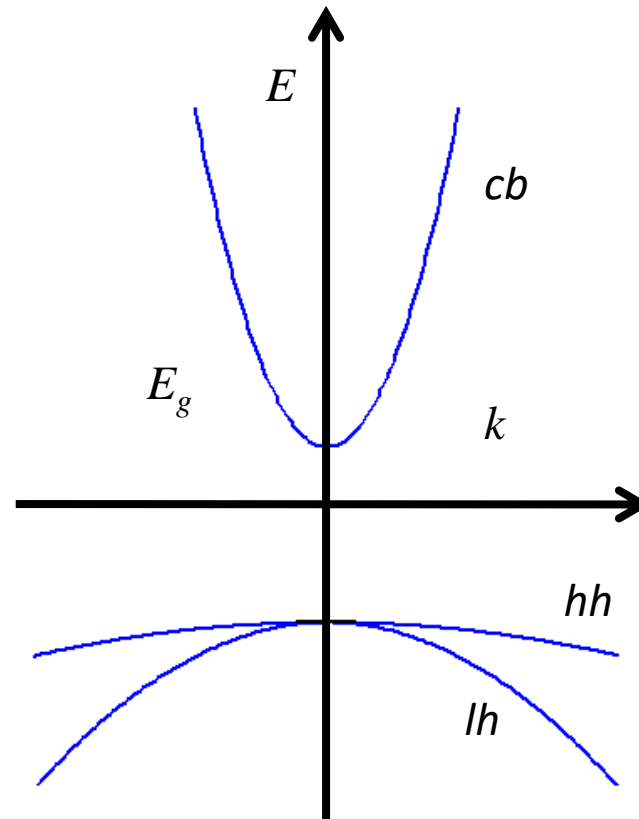
Kryształ = potencjał periodyczny



# Przybliżenie masy efektywnej

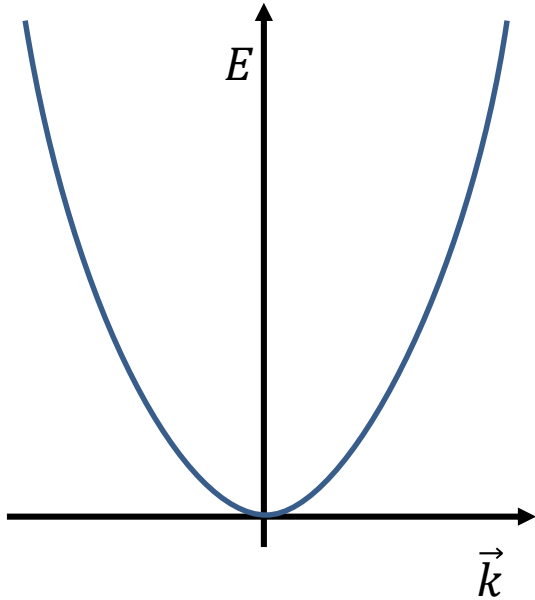
$$E(\vec{v}) = \frac{m^* v^2}{2}$$

$$m^* = 0.0 - 1000m_0$$



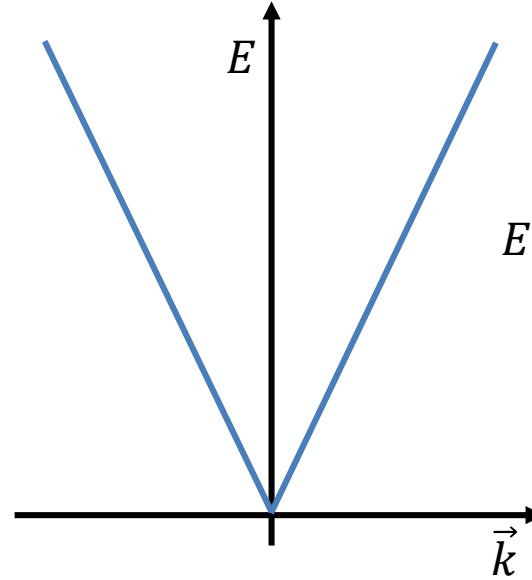
# Przybliżenie masy efektywnej

$m^* > 0$



$$E(\vec{k}) = \frac{\hbar^2 \vec{k}^2}{2m^*}$$

$m^* = 0$

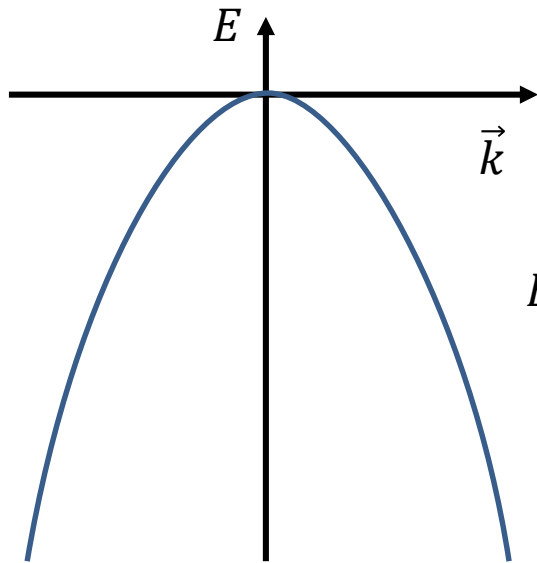


$$E(\vec{k}) = \hbar \tilde{c} |\vec{k}|$$

$$E(\vec{p}) = \frac{mv^2}{2} = \frac{\vec{p}^2}{2m} = \frac{\hbar^2 \vec{k}^2}{2m^*}$$

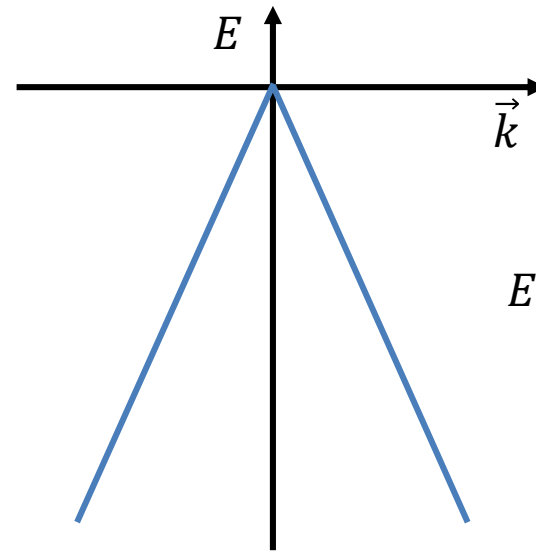
# Przybliżenie masy efektywnej

$$m^* < 0$$



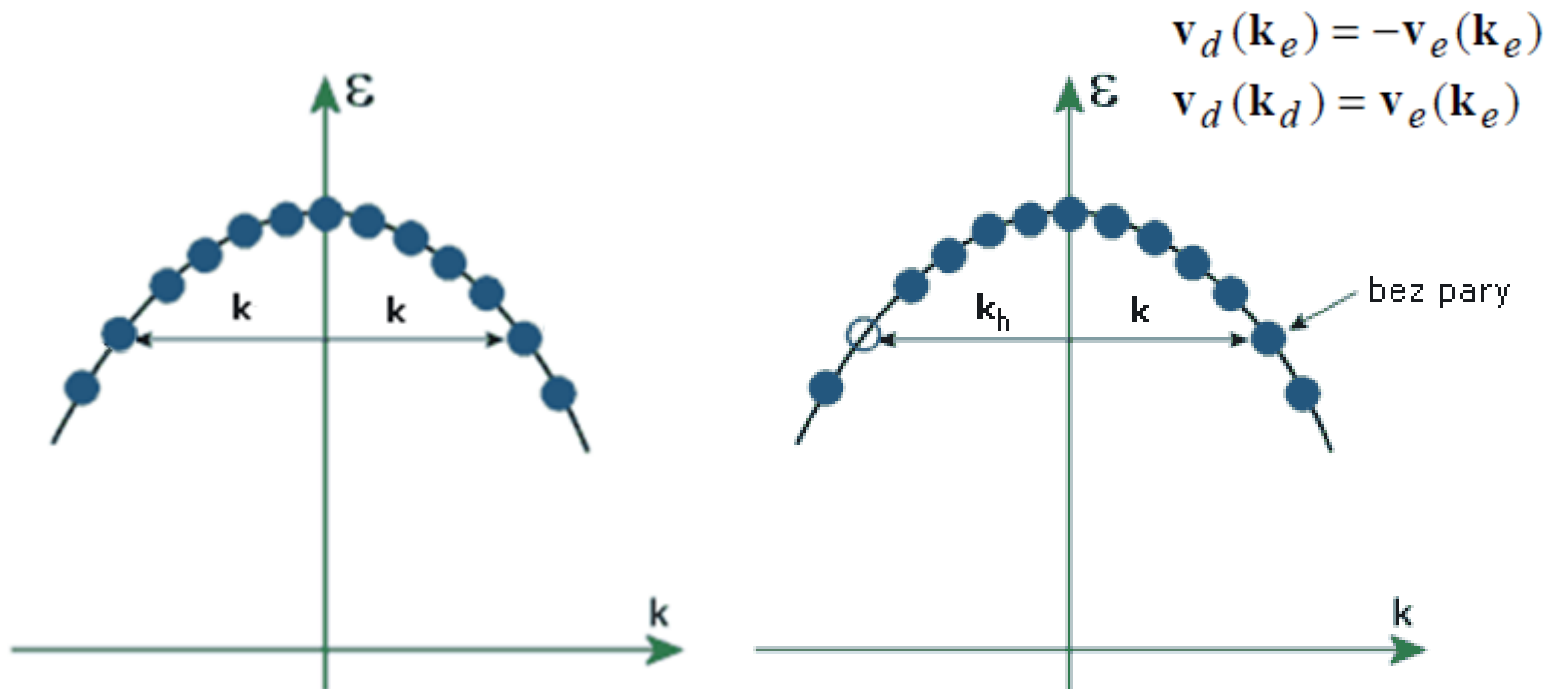
$$E(\vec{k}) = \frac{\hbar^2 \vec{k}^2}{2m^*}$$

$$m^* = 0 \text{ (i } m^* < 0)$$



$$E(\vec{k}) = \hbar c |\vec{k}|$$

# Przybliżenie masy efektywnej

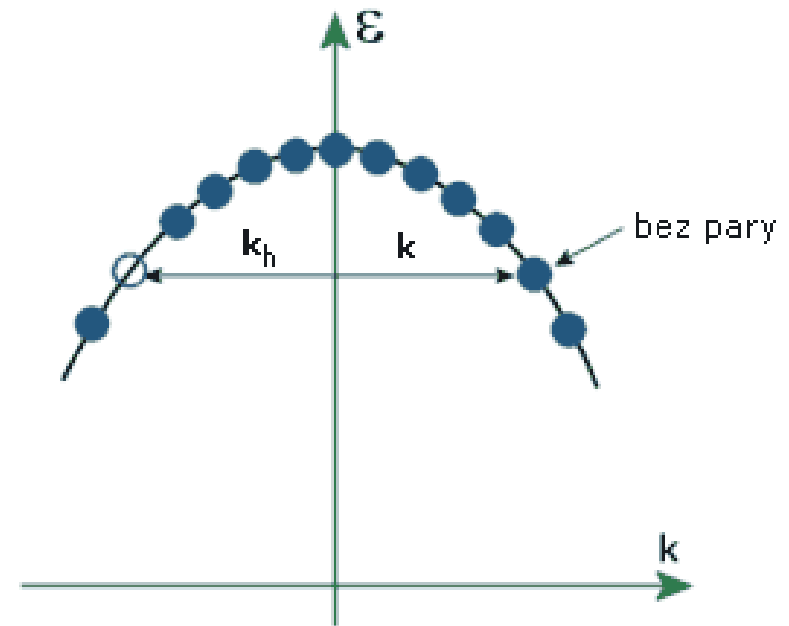
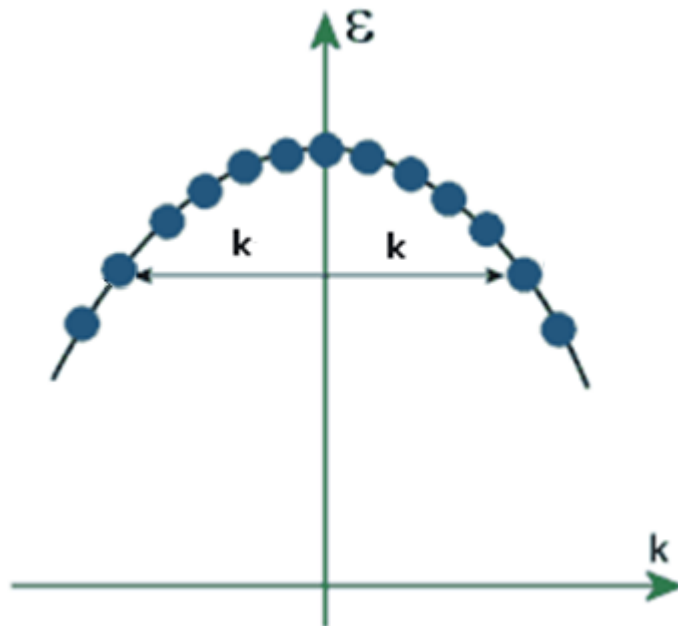
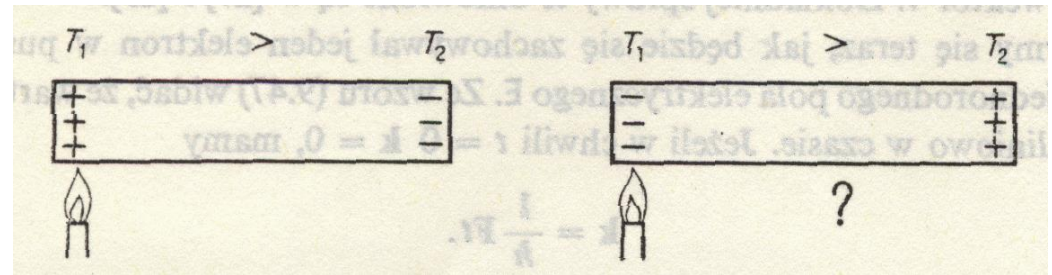


# Przybliżenie masy efektywnej

Na, K, Co, Al – elektrony

Zn, Cu, Au - ???

Pasma prawie całkowicie wypełnione  
elektronami.

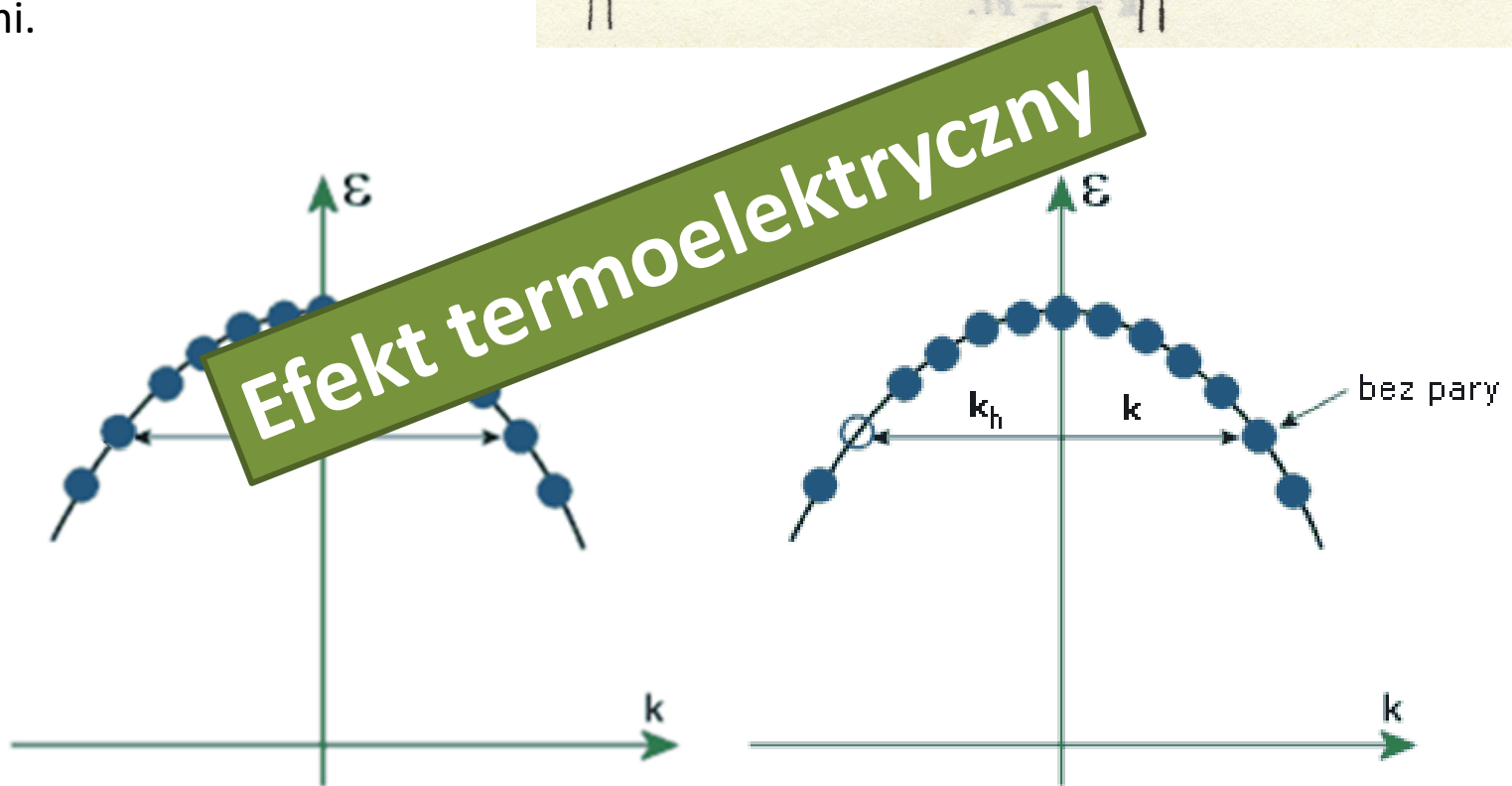
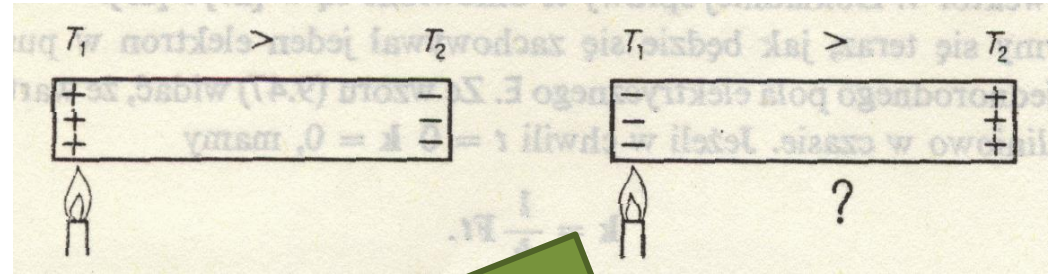


# Przybliżenie masy efektywnej

Na, K, Co, Al – elektrony

Zn, Cu, Au - ???

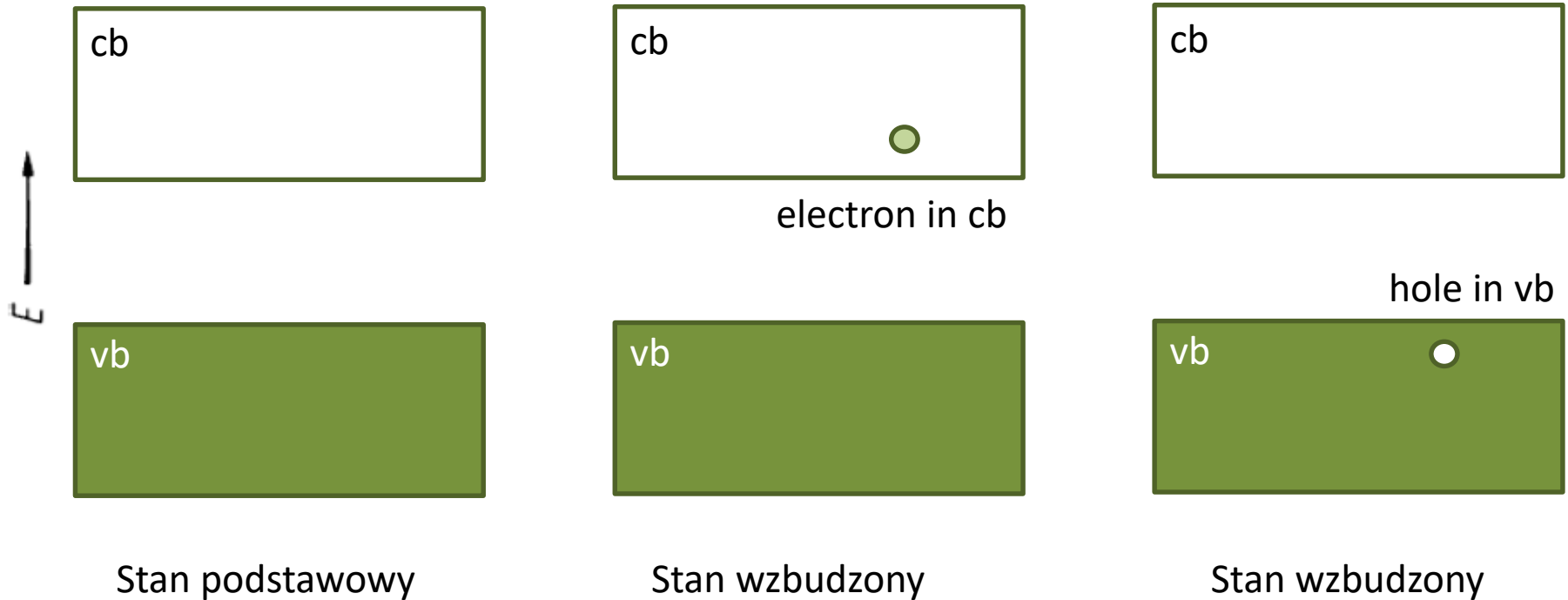
Pasmo prawie całkowicie wypełnione elektronami.





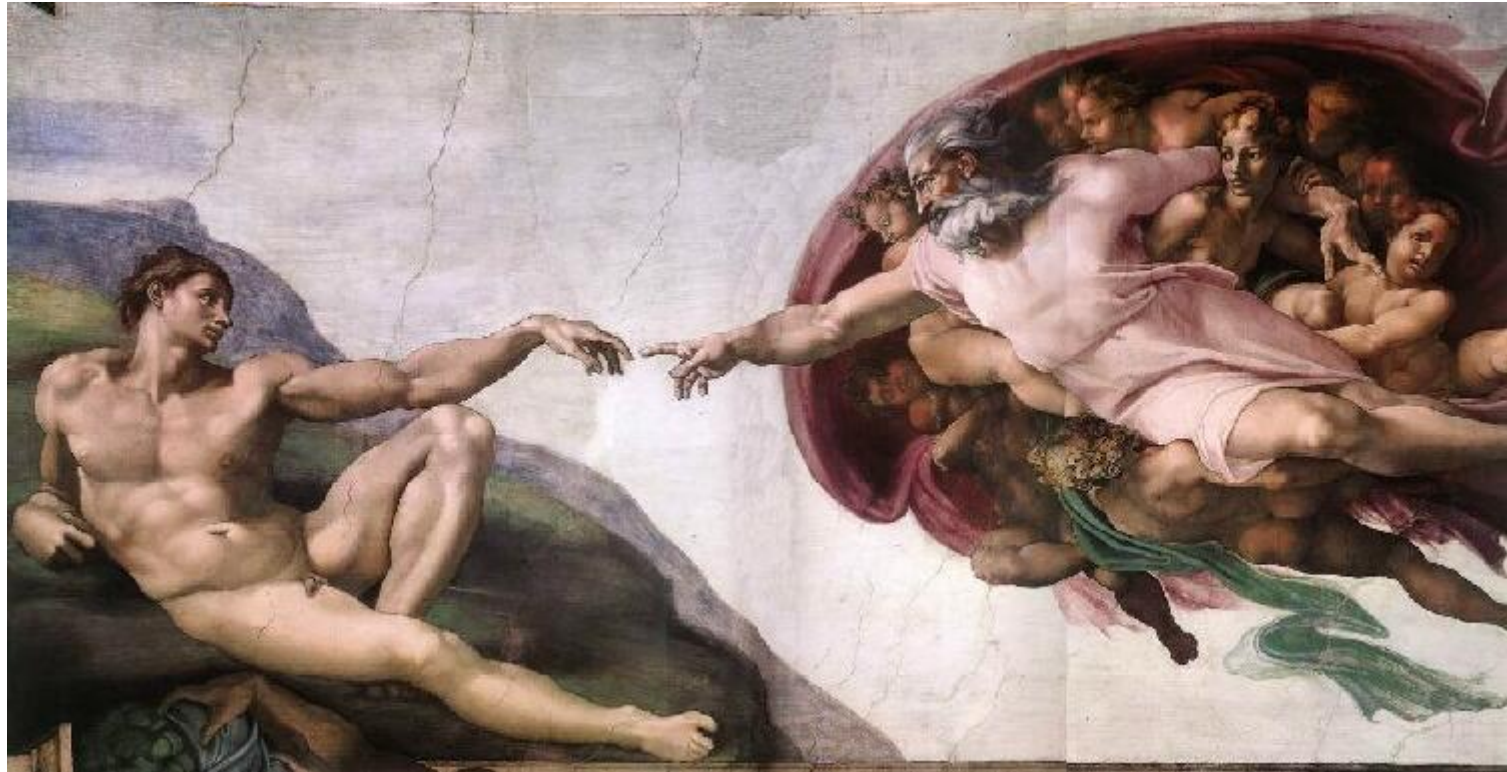
# Przybliżenie masy efektywnej

Układ wielociałowy:



Tworzymy kwazi-cząstki, które nie oddziałują (albo przynajmniej niezbyt silnie), np. „swobodne elektrony” – to samo dla fononów, polaronów, plazmonów, ekscytonów, trionów, bi-ekscytonów....

# Stwórca kwazicząstek (Ty!)



# Kwazi-cząstki (model standardowy)

cb



elektron w paśmie przewodnictwa

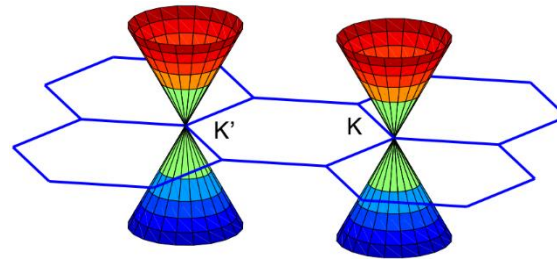
$$E = \frac{\hbar^2 k^2}{2m^*}$$

Fermiony

$$m^* \neq 0$$

dziura w paśmie walencyjnym

vb



$$E = \tilde{c}\vec{k}$$

$$m^* = 0$$

# Kwazi-cząstki (model standardowy)

cb



elektron w paśmie przewodnictwa

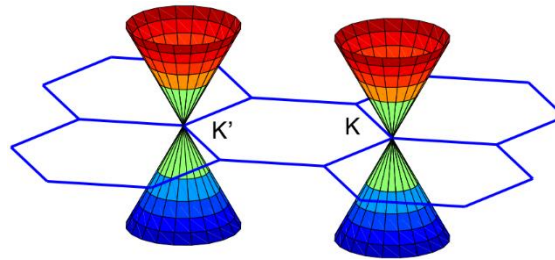
$$E = \frac{\hbar^2 k^2}{2m^*}$$

Fermiony

$$m^* \neq 0$$

dziura w paśmie walencyjnym

vb

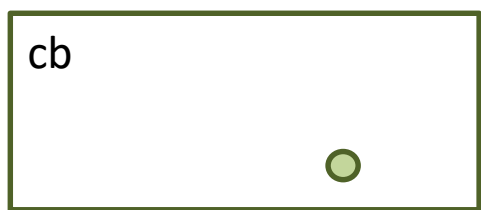


$$E = \tilde{c}\vec{k}$$

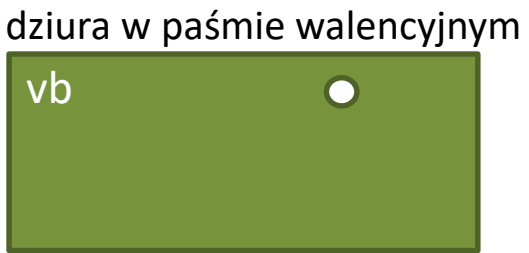
$$m^* = 0$$

grafen

# Kwazi-cząstki (model standardowy)

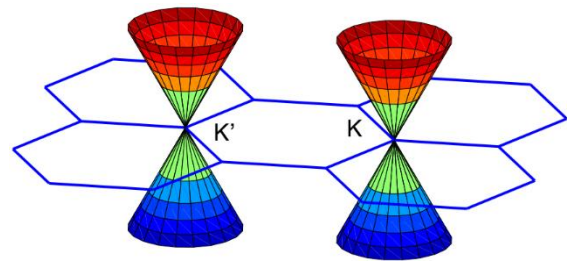


elektron w paśmie przewodnictwa

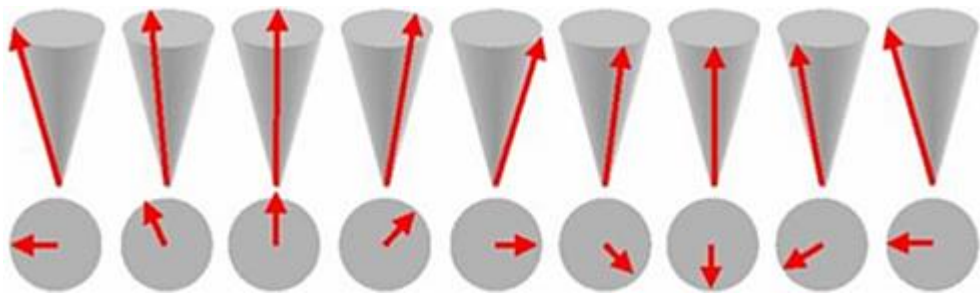
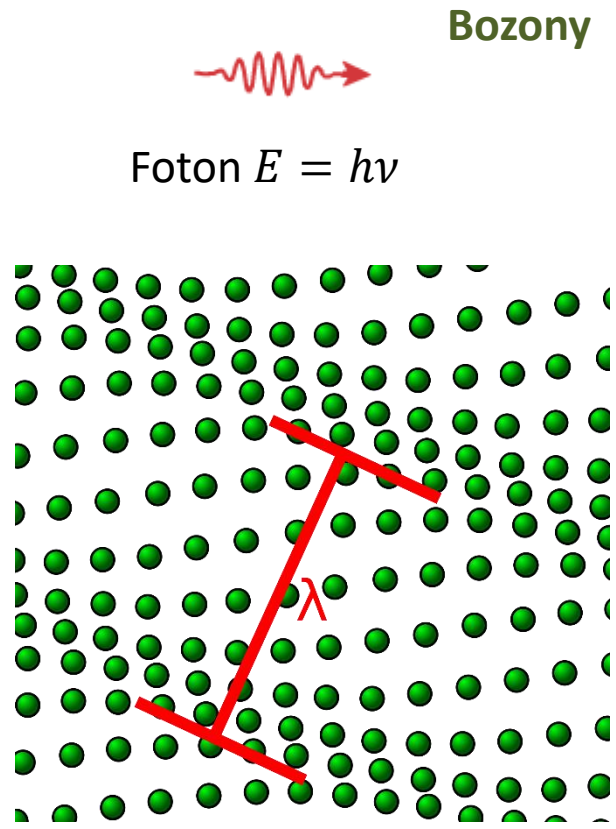


dziura w paśmie walencyjnym

**Fermiony**  
 $E = \frac{\hbar^2 k^2}{2m^*}$   
 $m^* \neq 0$

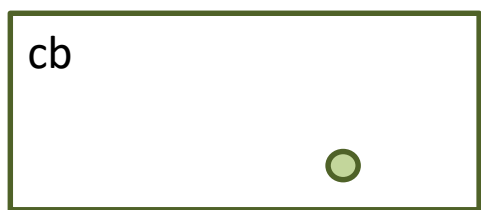


$E = \tilde{c}\vec{k}$        $m^* = 0$

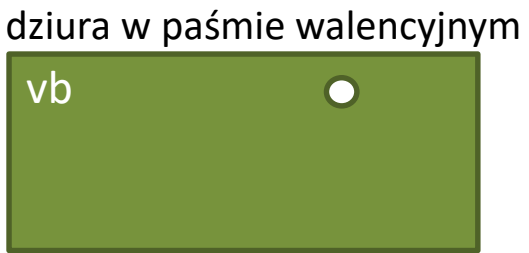


Magnon  $E = \hbar\omega$

# Kwazi-cząstki (model standardowy)

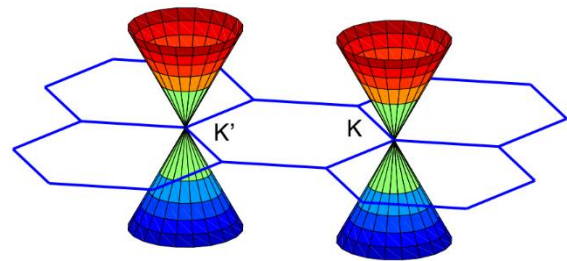


elektron w paśmie przewodnictwa

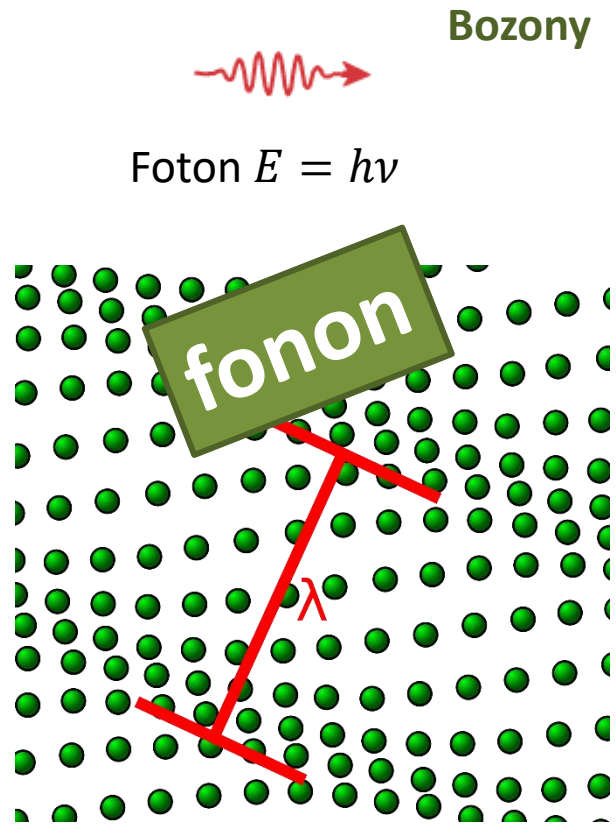


dziura w paśmie walencyjnym

$E = \frac{\hbar^2 k^2}{2m^*}$  **Fermiony**  
 $m^* \neq 0$



$E = \tilde{c}\vec{k}$   $m^* = 0$



# Cząstki elementarne

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
<b>Quarks</b>	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
<b>Leptons</b>	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force

Bosons (Forces)

3D

0.0-1000 $m_0$   
-1  
 $\frac{1}{2}$   
**e**  
electron

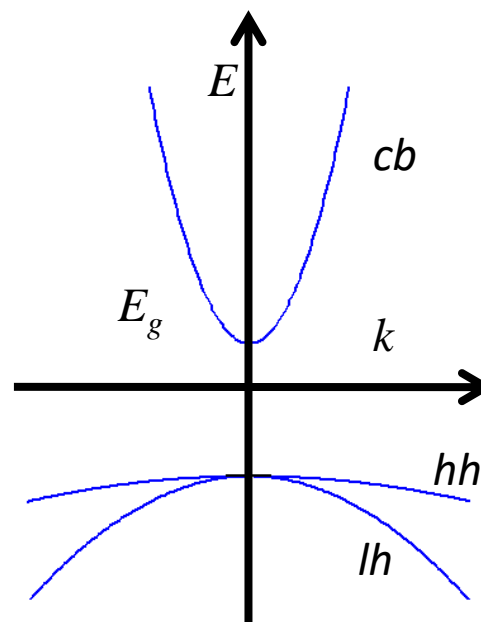
0.0-1 $m_0$   
1  
 $\frac{1}{2}$   
**lh**  
light hole

0.1-1000 $m_0$   
1  
 $\frac{3}{2}$   
**hh**  
heavy hole

0  
0  
1  
**γ**  
photon

0  
0  
1  
**ħω**  
phonon

0  
0  
1  
**ħΩ**  
magnon



# Cząstki elementarne

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
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	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
<b>Quarks</b>	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
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<b>Leptons</b>	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force

Bosons (Forces)

3D

0.0-1000 $m_0$   
-1  
 $\frac{1}{2}$   
**e**  
electron

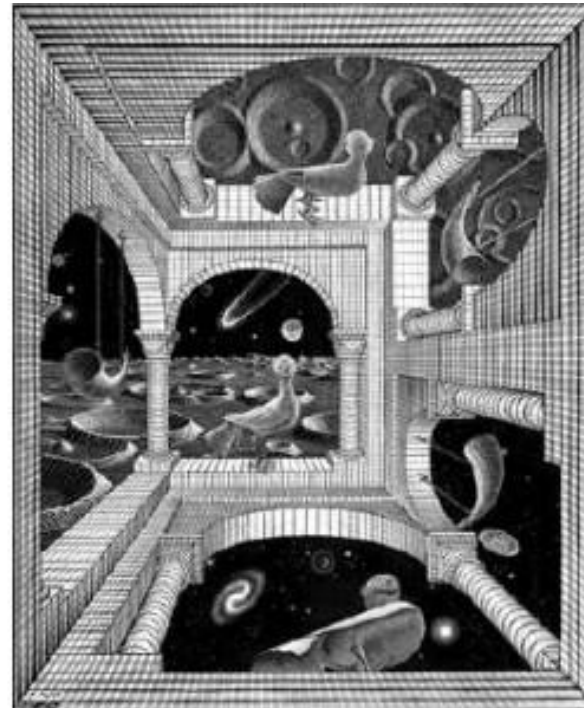
0.0-1 $m_0$   
1  
 $\frac{1}{2}$   
**lh**  
light hole

0.1-1000 $m_0$   
1  
 $\frac{3}{2}$   
**hh**  
heavy hole

0  
0  
1  
**γ**  
photon

0  
0  
1  
**ħω**  
phonon

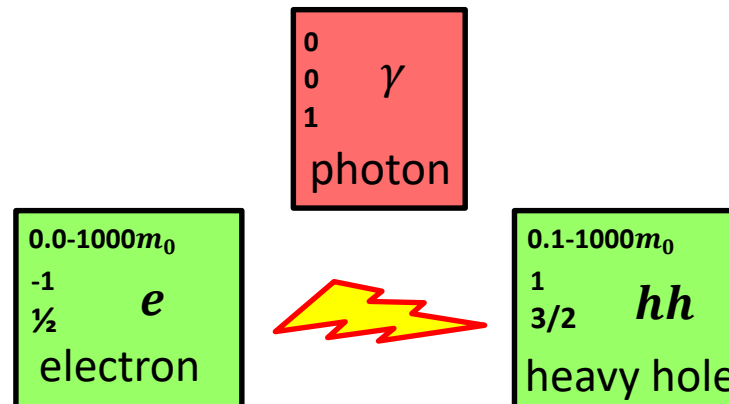
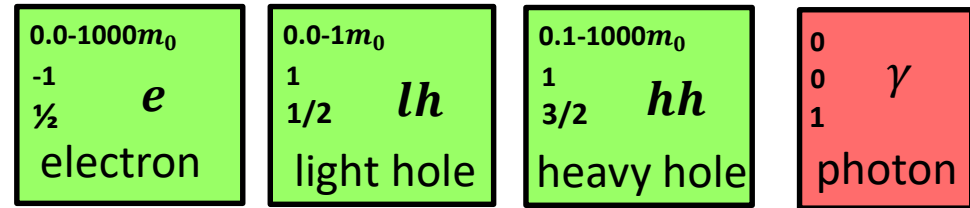
0  
0  
1  
**ħΩ**  
magnon





# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :



# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :

0.0-1000 $m_0$ -1 $\frac{1}{2}$ <i>e</i> electron	0.0-1 $m_0$ 1 $\frac{1}{2}$ <i>lh</i> light hole	0.1-1000 $m_0$ 1 $\frac{3}{2}$ <i>hh</i> heavy hole	0 0 $\gamma$ 1 photon
--	---	--	--------------------------------



# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :

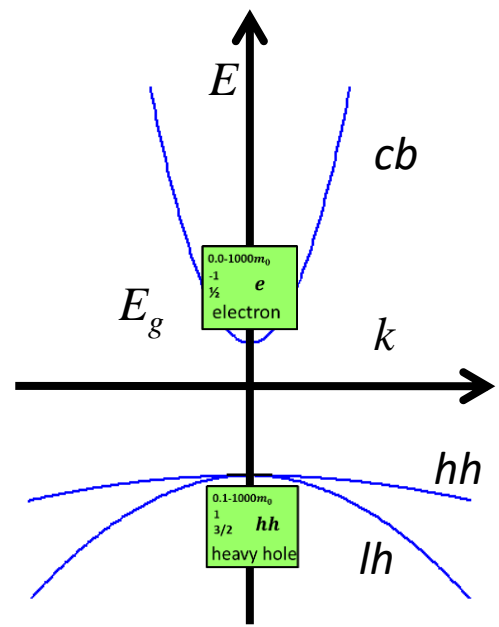


0.0-1000 $m_0$   
-1  
 $\frac{1}{2}$  *e*  
electron

0.0-1 $m_0$   
1  
 $\frac{1}{2}$  *lh*  
light hole

0.1-1000 $m_0$   
1  
 $\frac{3}{2}$  *hh*  
heavy hole

0  
0  $\gamma$   
1  
photon



# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :

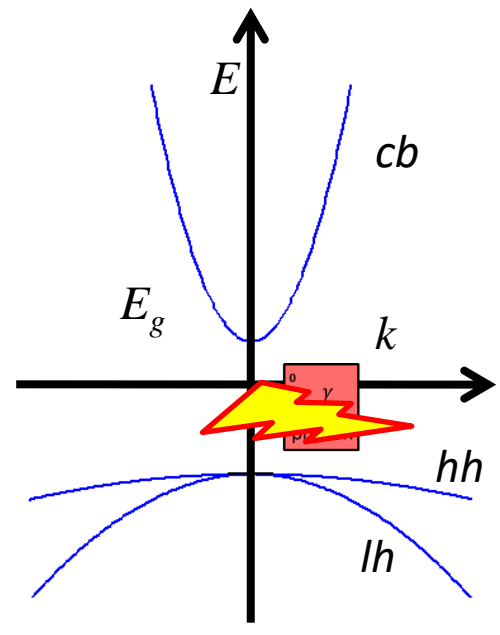
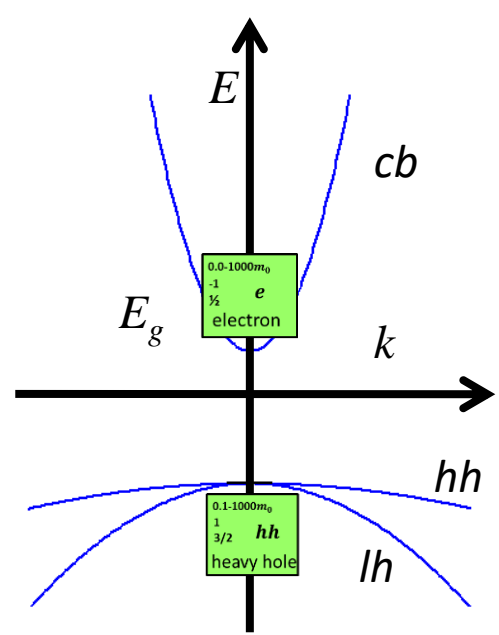


0.0-1000 $m_0$
-1
1/2
<i>e</i>
electron

0.0-1 $m_0$
1
1/2
<i>lh</i>
light hole

0.1-1000 $m_0$
1
3/2
<i>hh</i>
heavy hole

0
0
1
$\gamma$
photon



# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :

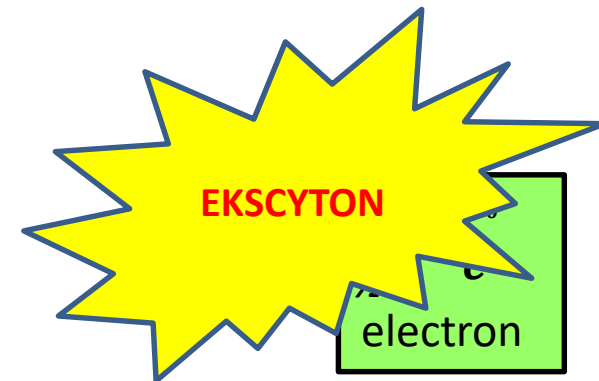


$0.0-1000m_0$
$-1$
$\frac{1}{2}$
$e$
electron

$0.0-1m_0$
$1$
$\frac{1}{2}$
$lh$
light hole

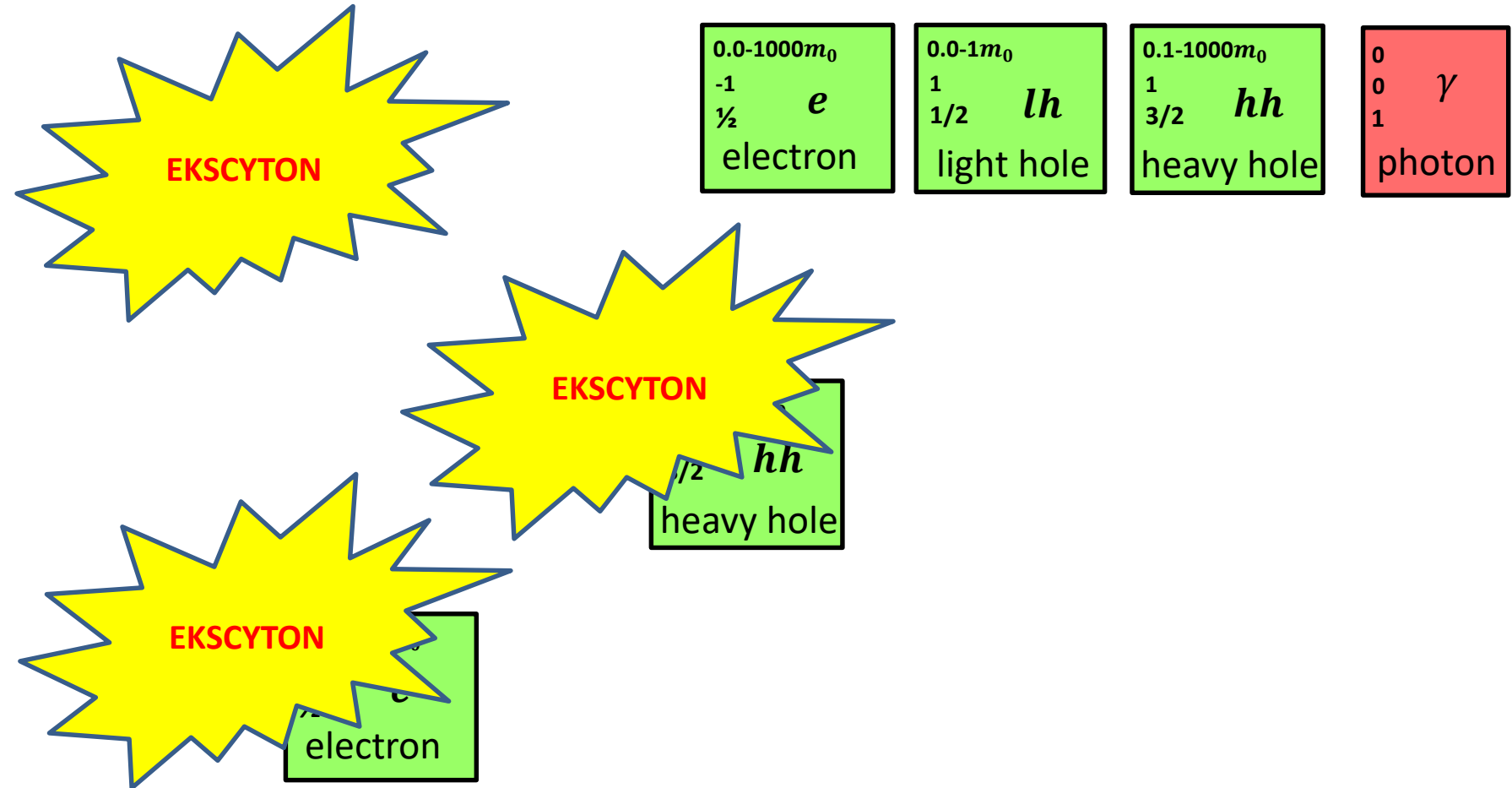
$0.1-1000m_0$
$1$
$\frac{3}{2}$
$hh$
heavy hole

$0$
$0$
$1$
$\gamma$
photon



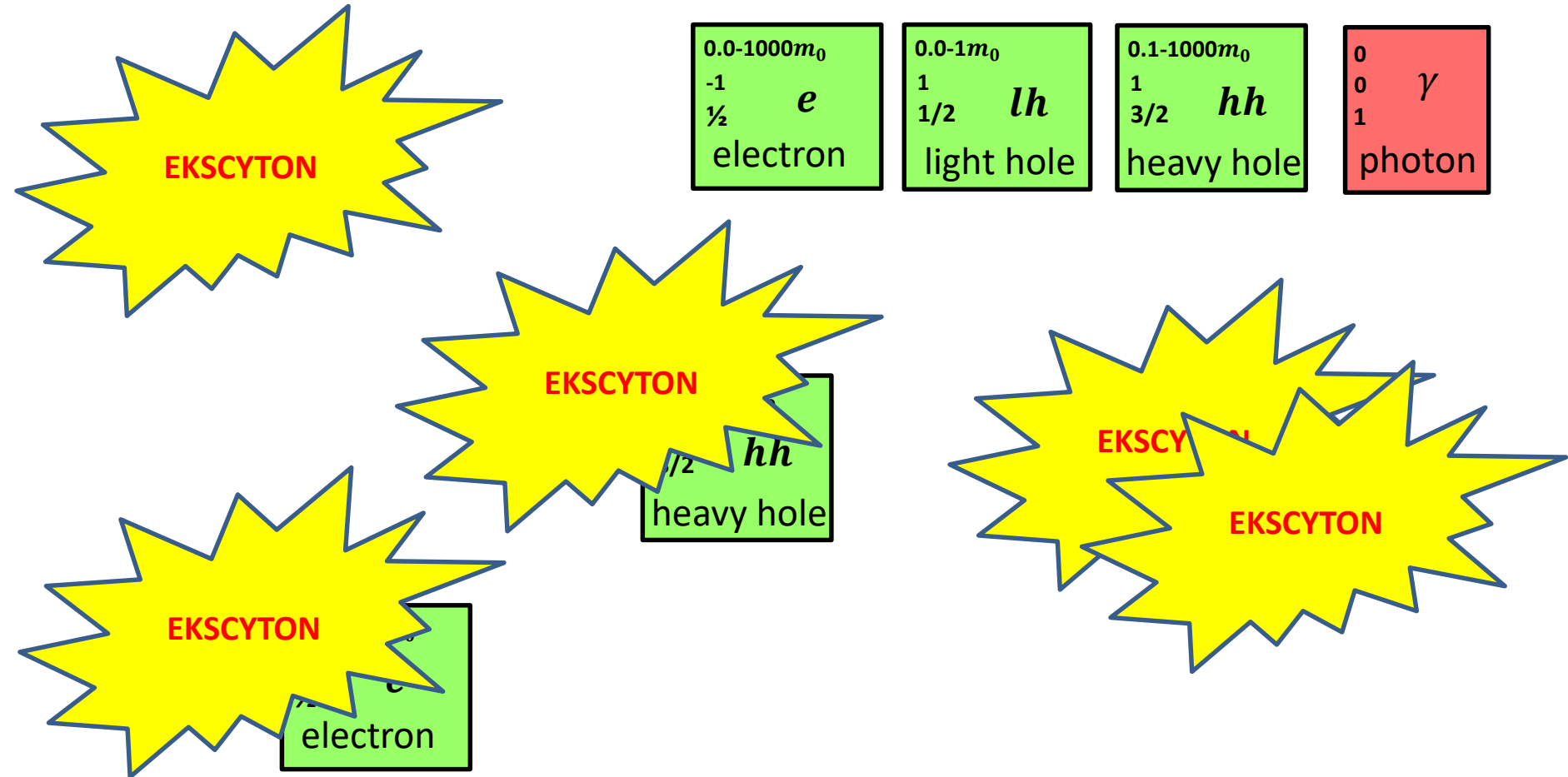
# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :



# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :



# Cząstki złożone

FIRST:

Coulomb potential in 3D in the semiconductor of dielectric constant  $\epsilon_r$ , effective mass  $m^*$ :

0.0-1000 $m_0$
-1
$\frac{1}{2}$ <i>e</i>
electron

0.0-1 $m_0$
1
$\frac{1}{2}$ <i>lh</i>
light hole

0.1-1000 $m_0$
1
$\frac{3}{2}$ <i>hh</i>
heavy hole

0
0 $\gamma$
1
photon

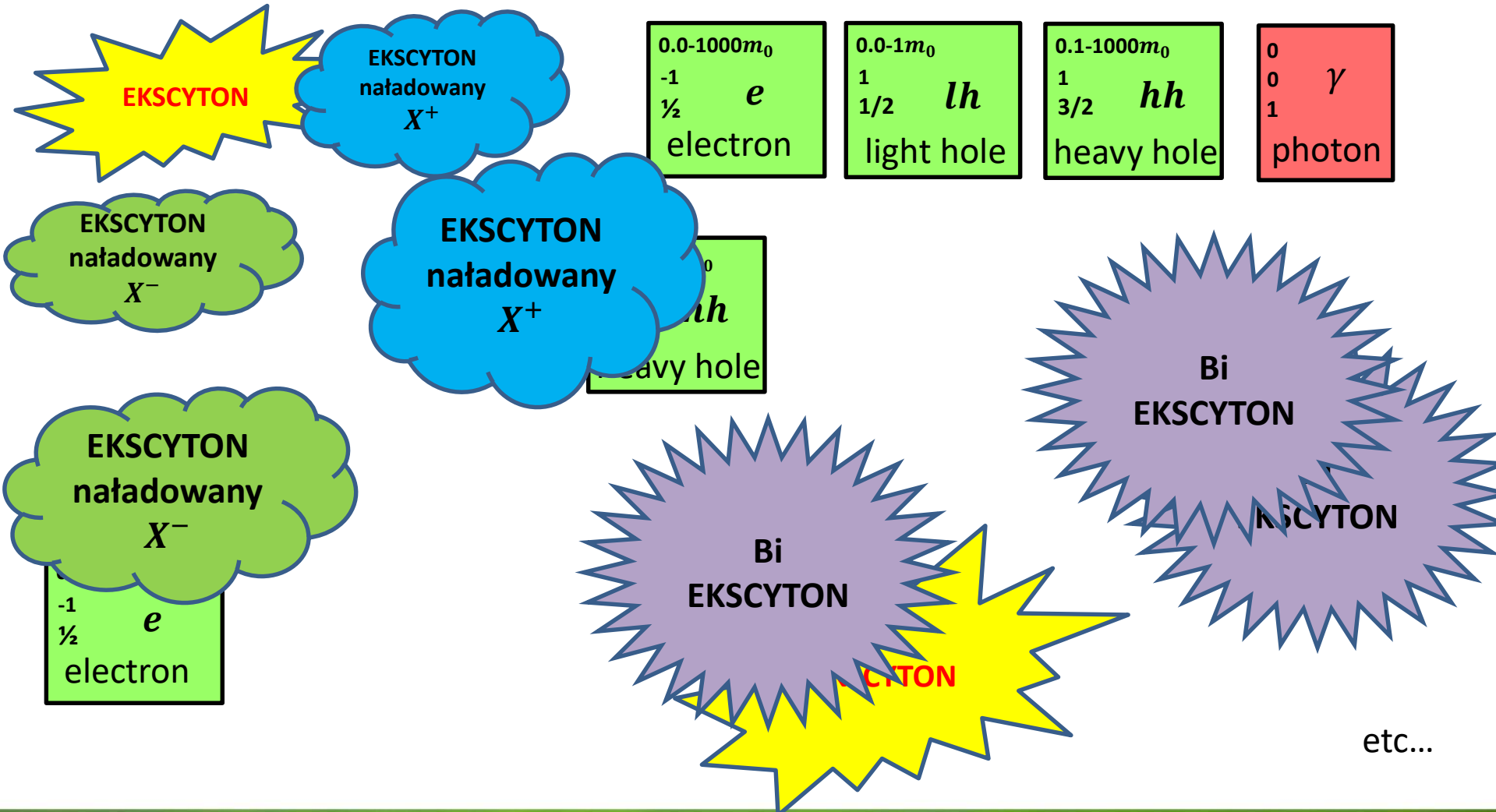


etc...



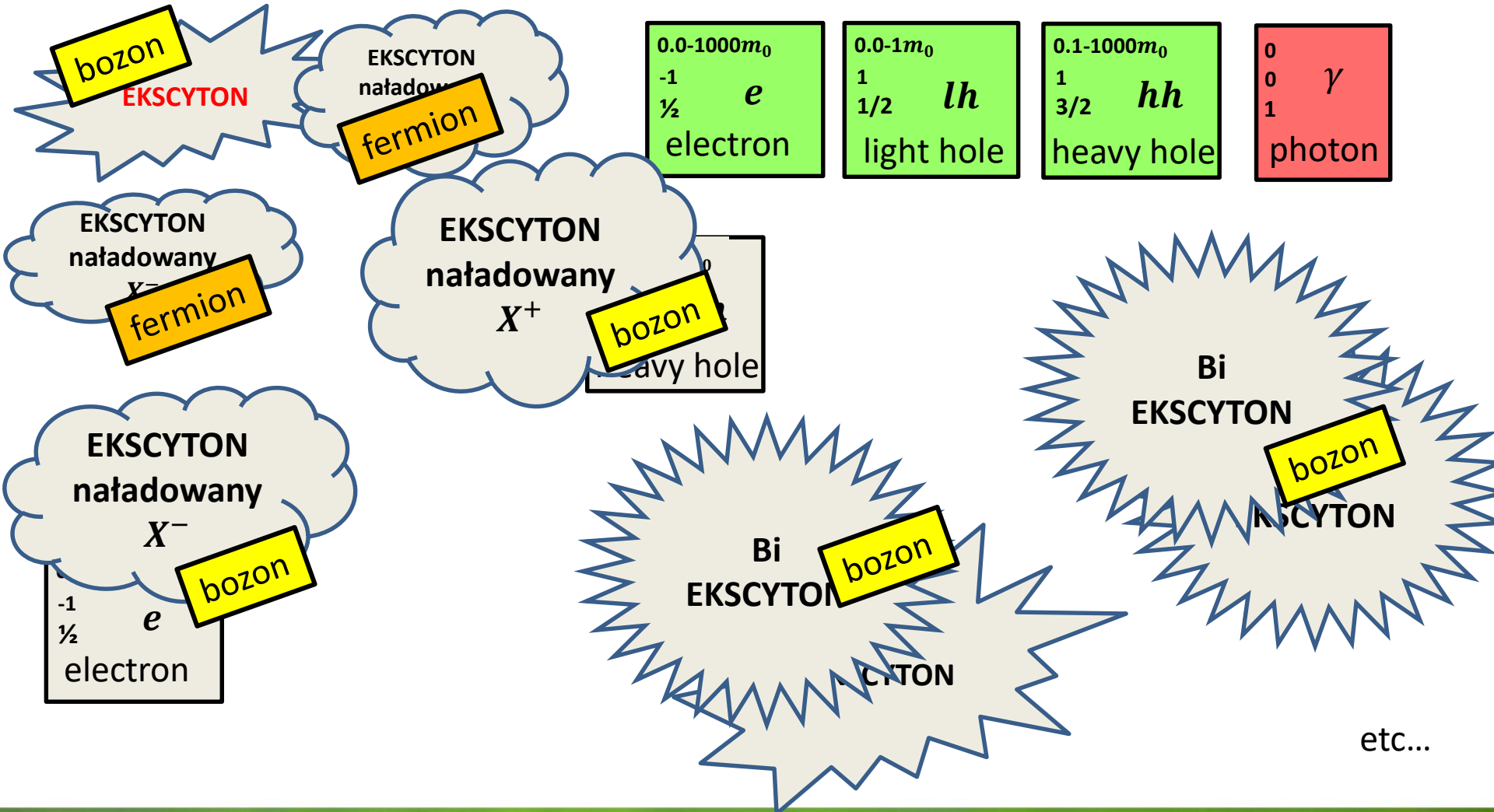
# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :



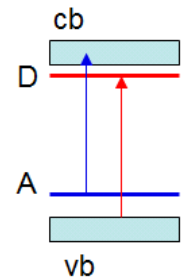
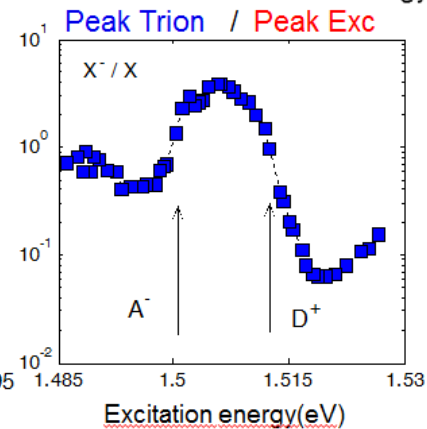
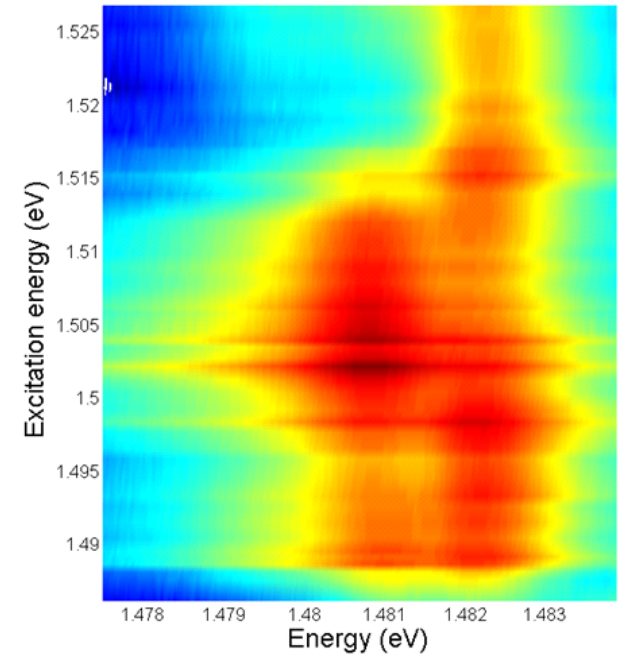
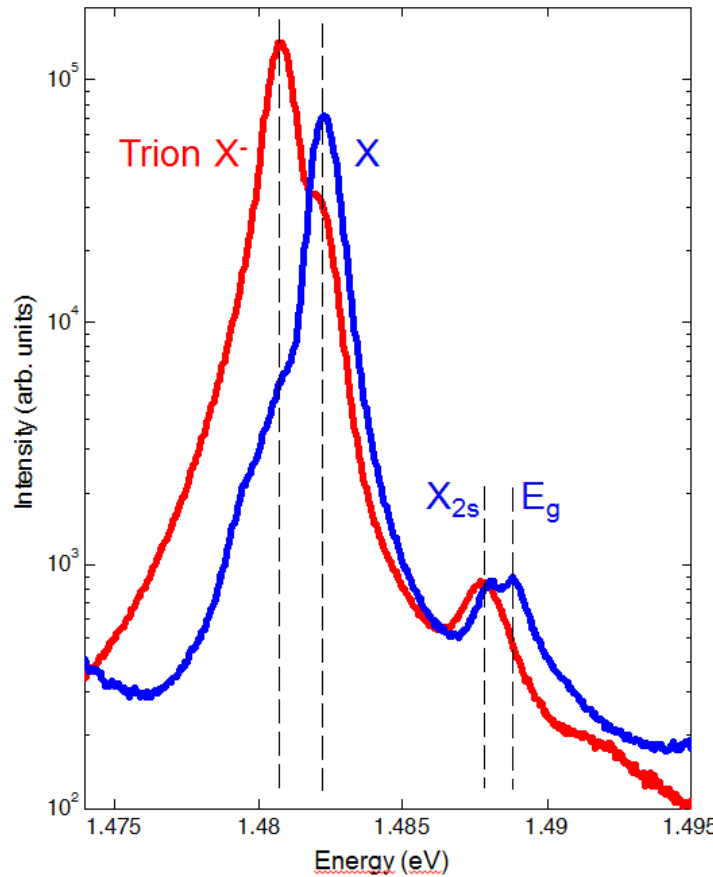
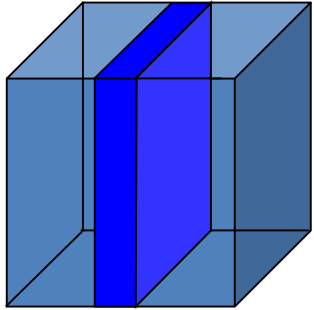
# Cząstki złożone

Potencjał kulombowski w 3D półprzewodniku o stałej dielektrycznej  $\epsilon_r$ , masie efektywnej  $m^*$ :



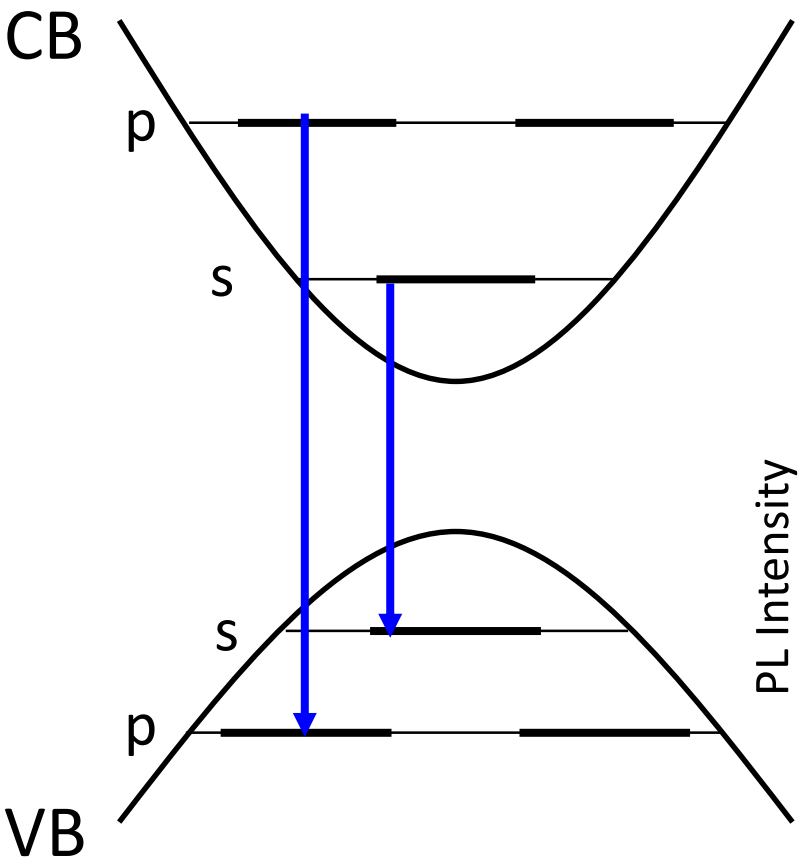
# Cząstki złożone

## Studnia kwantowa

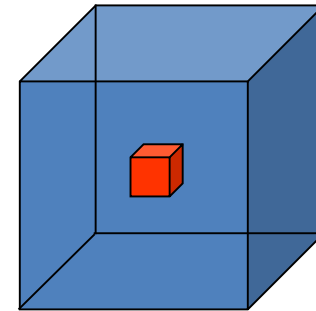


J. Szczytko et al.

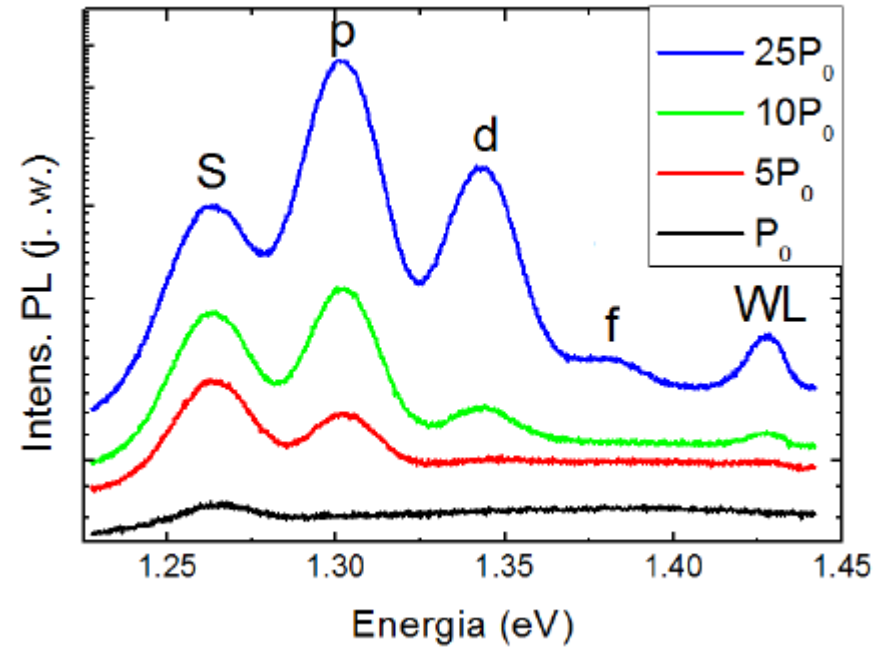
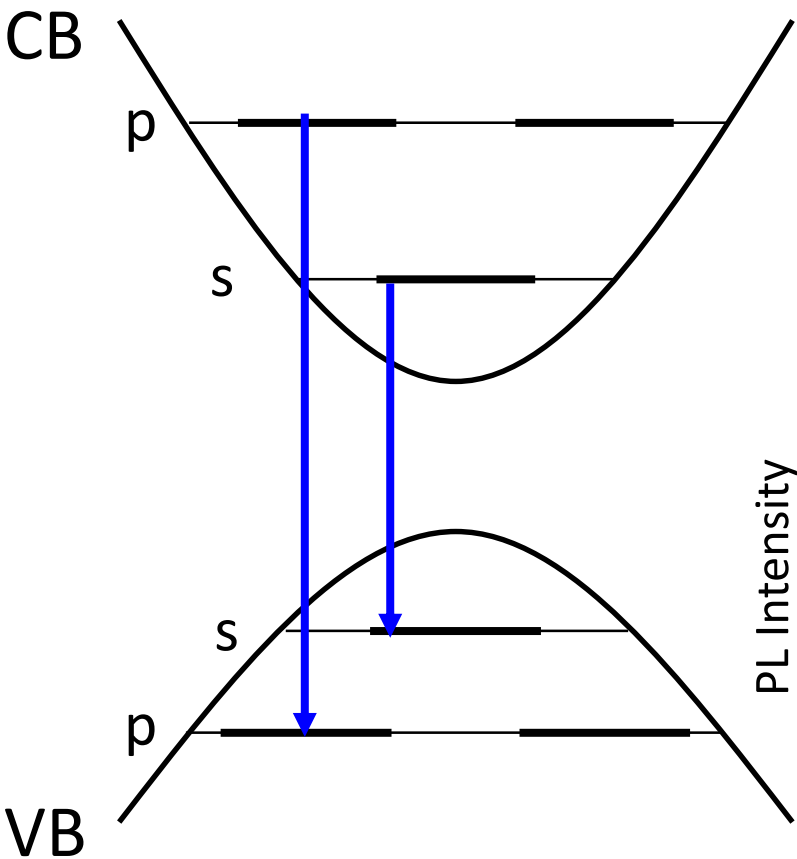
# Cząstki złożone



quantum dot

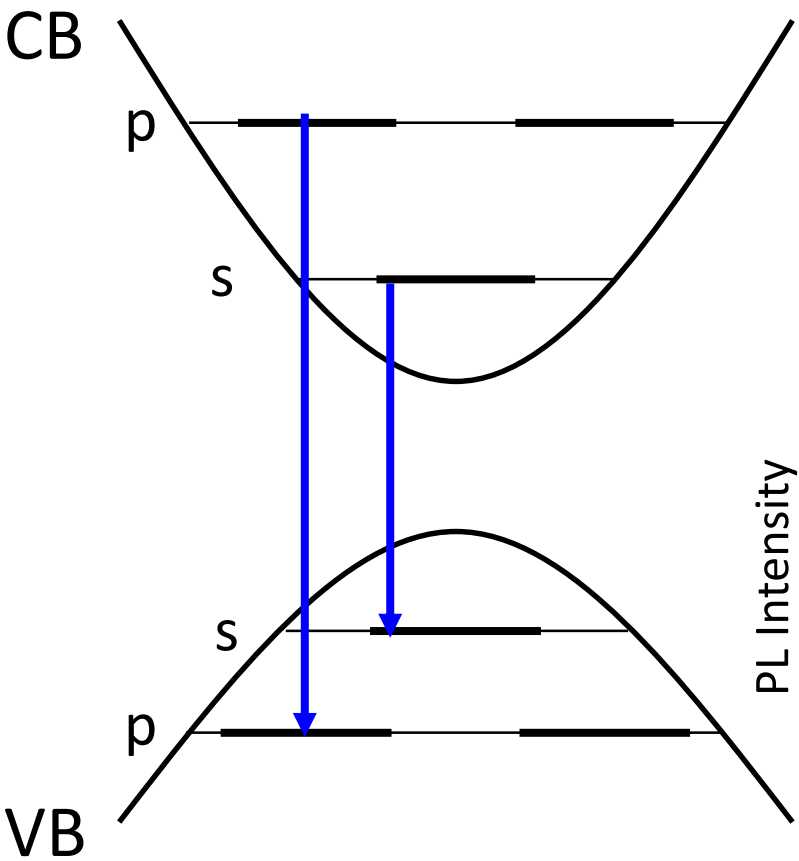


# Potencjał harmoniczny 2D

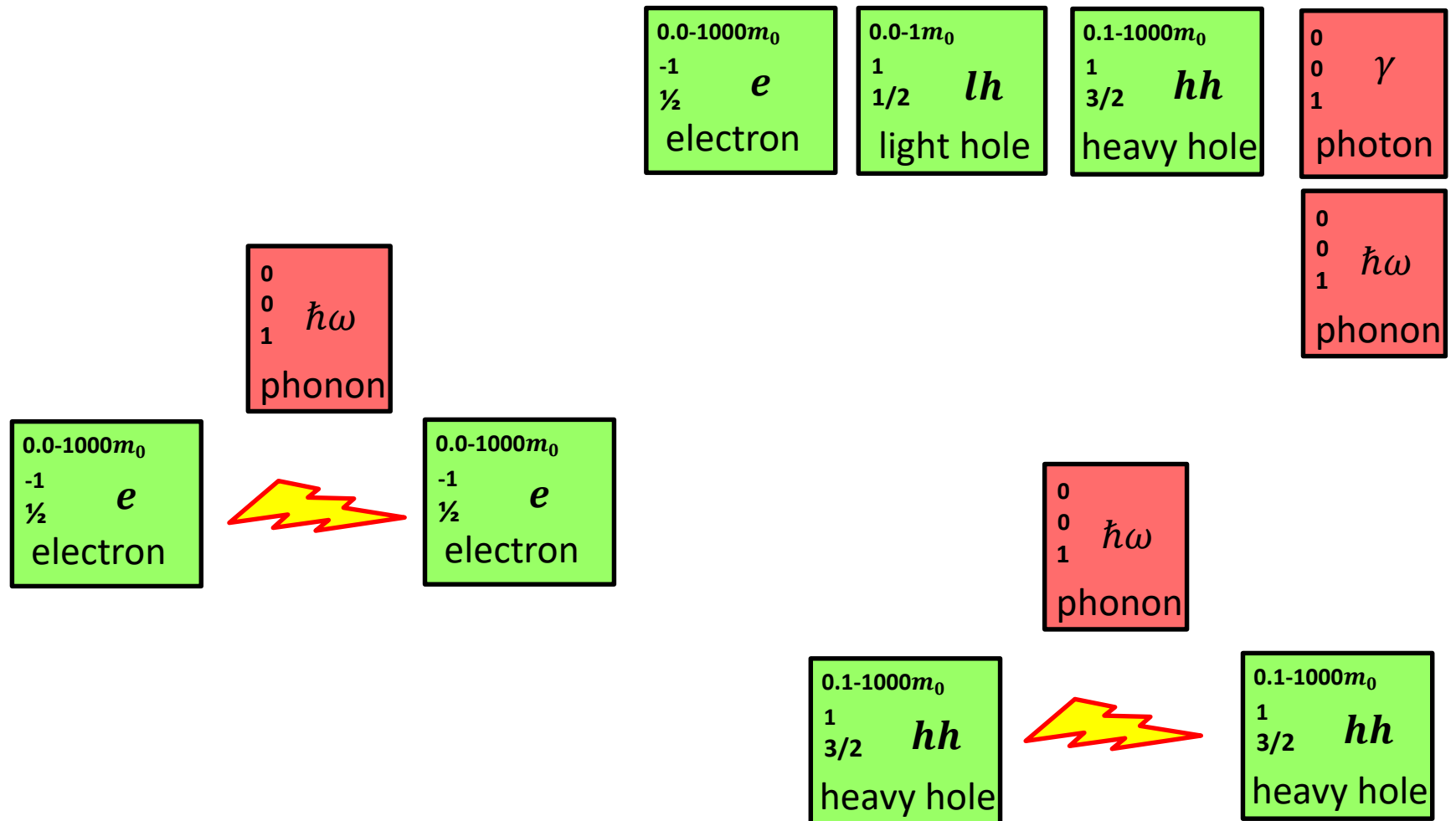


Zależność od mocy pobudzenia widm fotoluminescencji otrzymanych w temperaturze bliskiej temperatury ciekłego helu (ok. 5 K) dla licznego (wielomilionowego) zbioru kropek kwantowych InAs/GaAs.

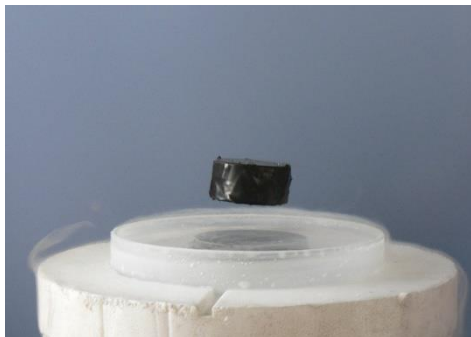
# Potencjał harmoniczny 2D



# Bozony złożone



# Bozony złożone



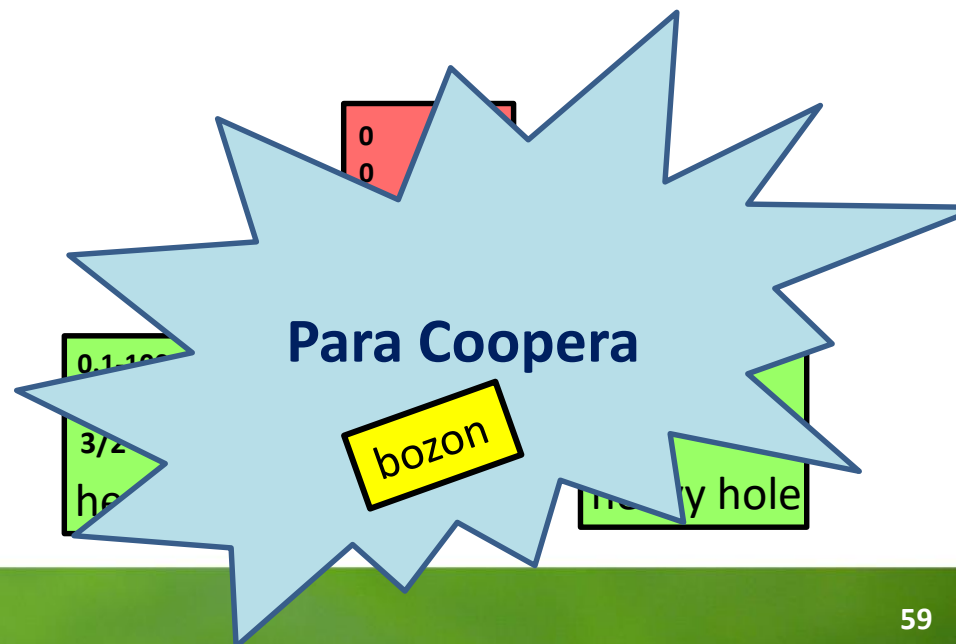
0.0-1000 $m_0$   
-1  
 $\frac{1}{2}$   $e$   
electron

0.0-1 $m_0$   
1  
 $\frac{1}{2}$   $lh$   
light hole

0.1-1000 $m_0$   
1  
 $\frac{3}{2}$   $hh$   
heavy hole

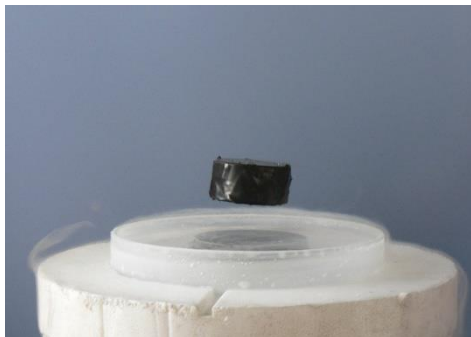
0  
0  $\gamma$   
1  
photon

0  
0  $\hbar\omega$   
1  
phonon





# Bozony złożone



0.0-1000 $m_0$
-1
$\frac{1}{2}$ <i>e</i>
electron

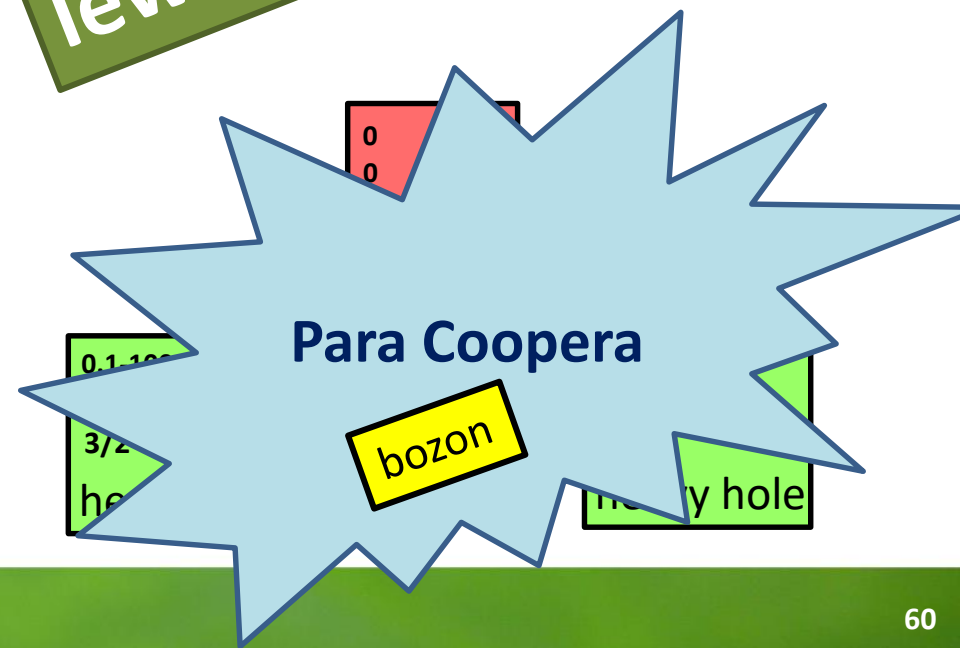
0.0-1 $m_0$
1
$\frac{1}{2}$ <i>lh</i>
light hole

0.1-1000 $m_0$
1
$\frac{3}{2}$ <i>hh</i>
heavy hole

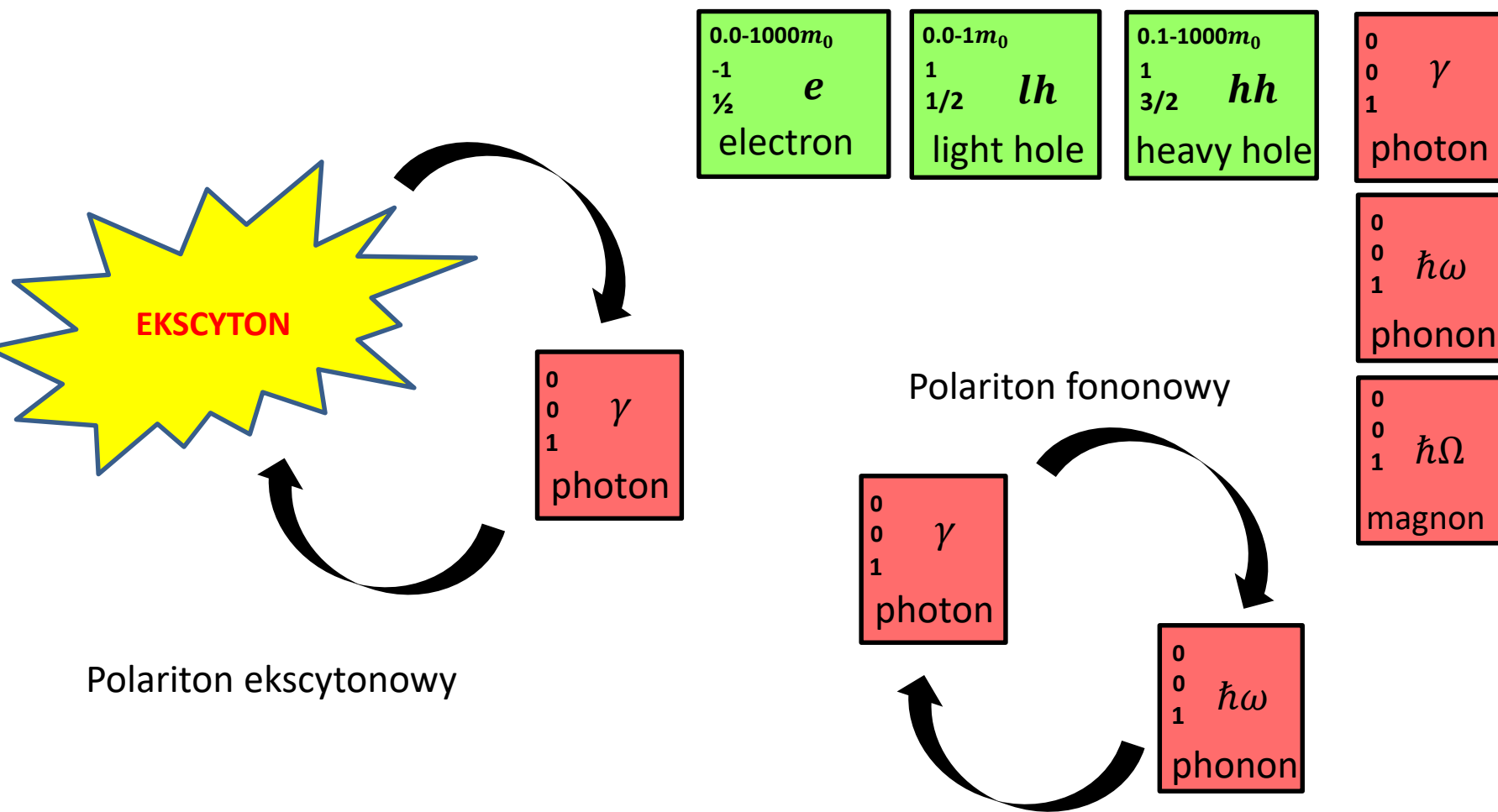
0
0 $\gamma$
1
photon

0
0 $\hbar\omega$
1
phonon

lewitacja



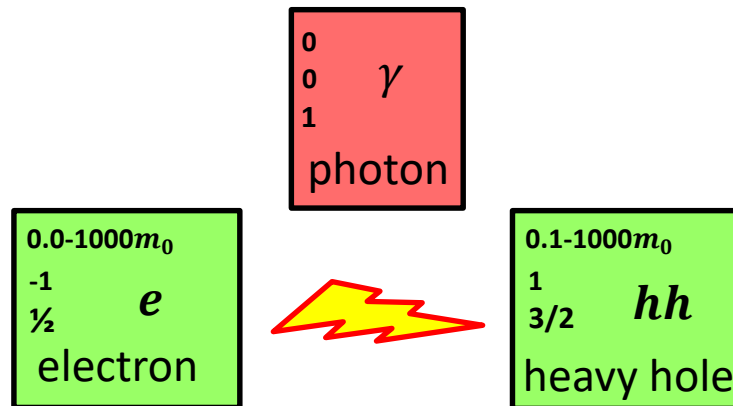
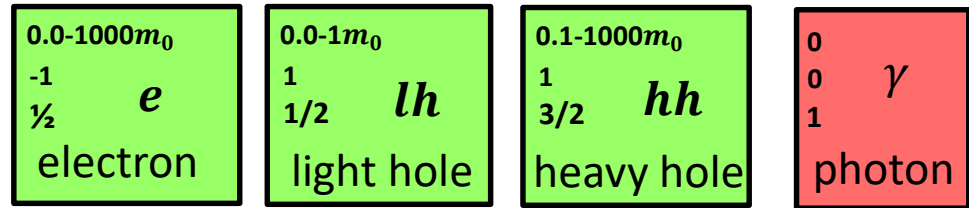
# Bozony złożone



# Stany ubrane (ang. dressed states)



# Cząstki złożone

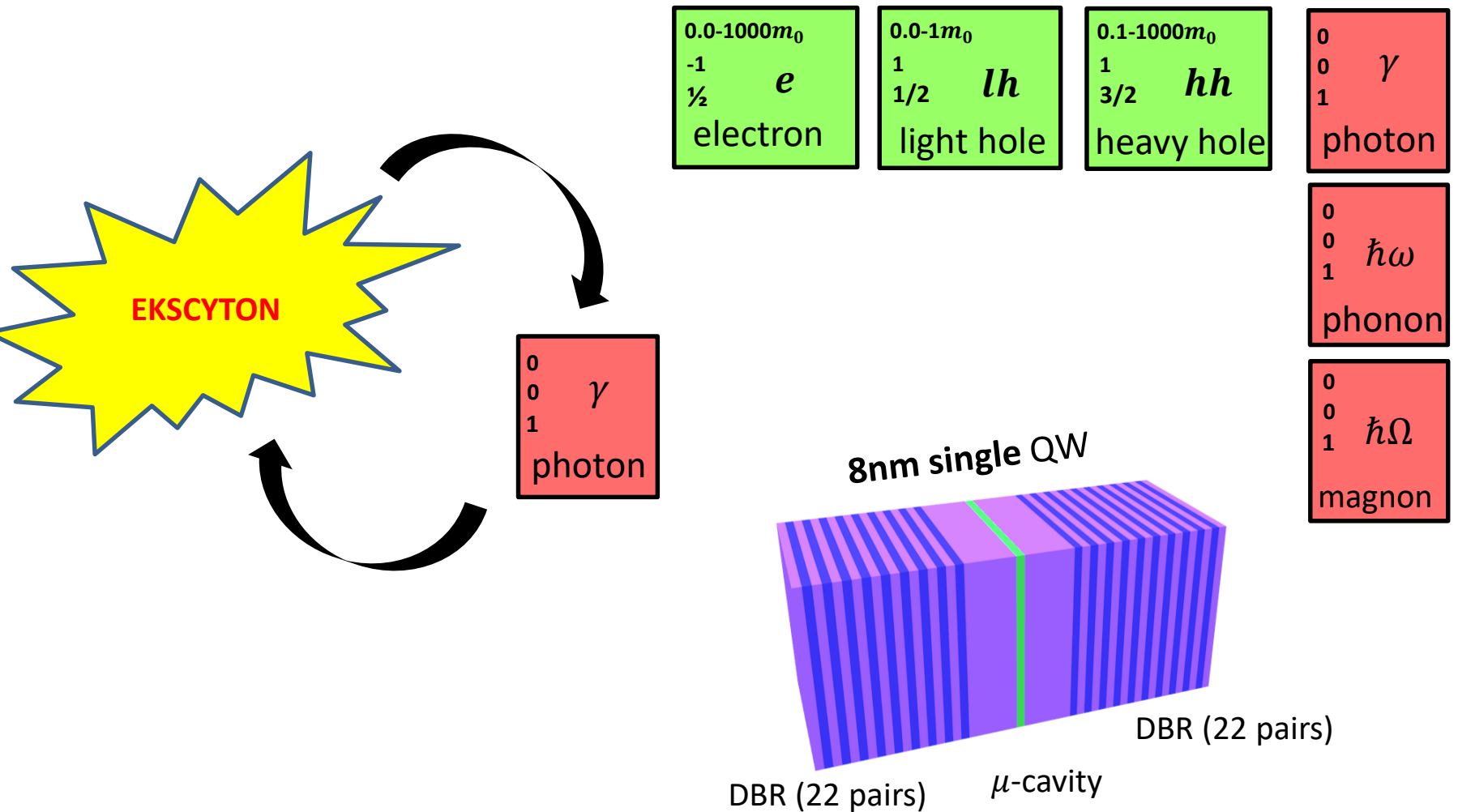


# Cząstki złożone

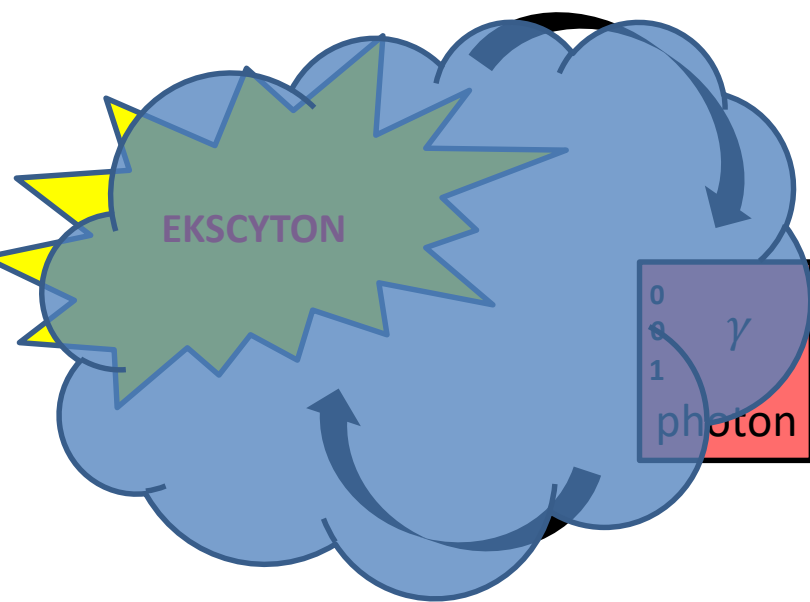
0.0-1000 $m_0$ -1 $\frac{1}{2}$ <i>e</i> electron	0.0-1 $m_0$ 1 $\frac{1}{2}$ <i>lh</i> light hole	0.1-1000 $m_0$ 1 $\frac{3}{2}$ <i>hh</i> heavy hole	0 0 $\gamma$ 1 photon
--	---	--	--------------------------------



# Cząstki złożone



# Bozony złożone



0.0-1000 $m_0$	-1	$e$
	1/2	electron

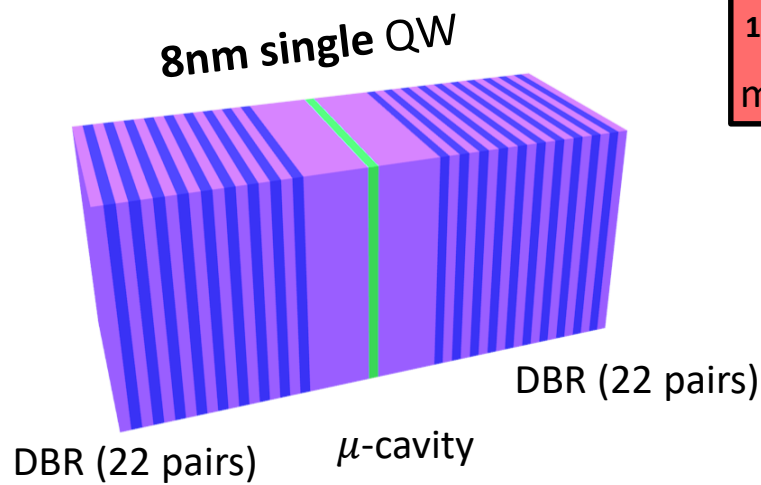
0.0-1 $m_0$	1	$lh$
	1/2	light hole

0.1-1000 $m_0$	1	$hh$
	3/2	heavy hole

0	$\gamma$
0	
1	photon

0	$\hbar\omega$
0	
1	phonon

0	$\hbar\Omega$
0	
1	magnon



Exciton polariton

# Cząstki elementarne

**SPIN CAŁKOWITY**

$J = 0$  (Higgs)  
 $J = 1(\gamma, g, Z^0, W^{+/-})$

**SPIN POŁÓWKOWY**

$J = 1/2$

**Three Generations of Matter (Fermions)**

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\gamma</math></b> photon
	<b>Quarks</b>			
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<b>Leptons</b>			
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b><math>Z^0</math></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>W^\pm</math></b> weak force

**Bosons (Forces)**



# The polariton laboratory

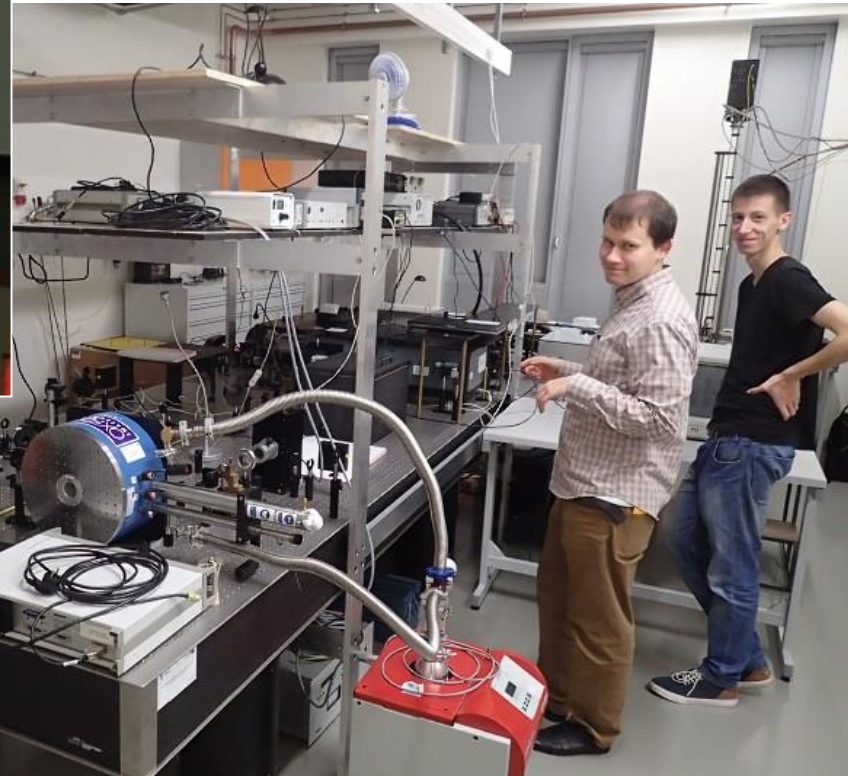
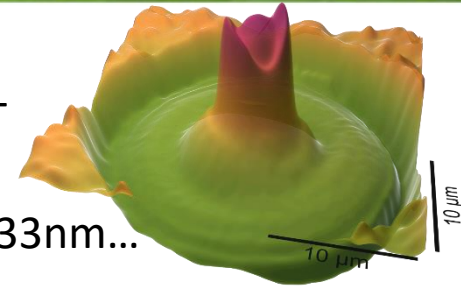


Kasia Lekenta



Dr Barbara Piętka

attocube CFM  
1.5-320K, 0.0-9.0T  
700-1000nm  
420nm, 532nm, 633nm...

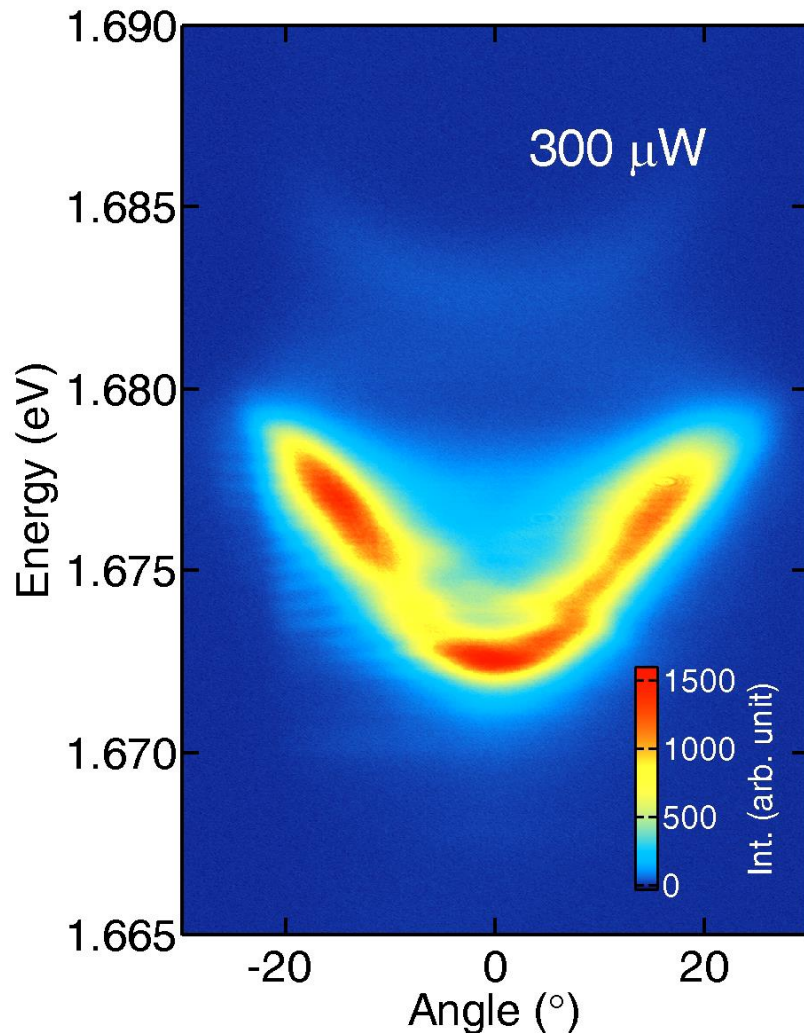


Mateusz Król

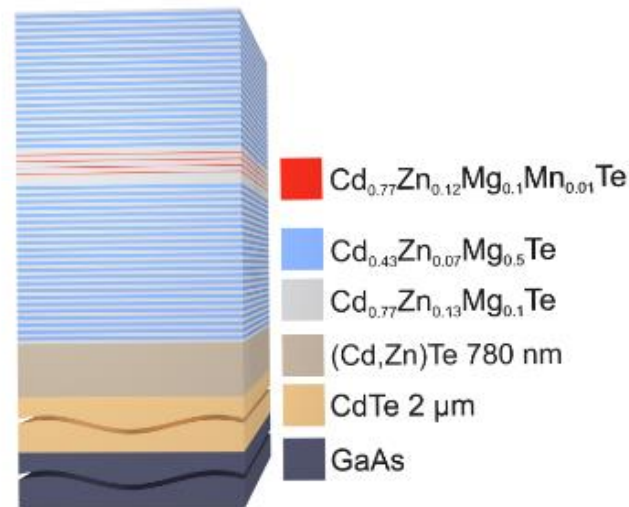
Rafał Mirek

# Bozony złożone

## Fotoluminescencja polaritonów ekscytonowych

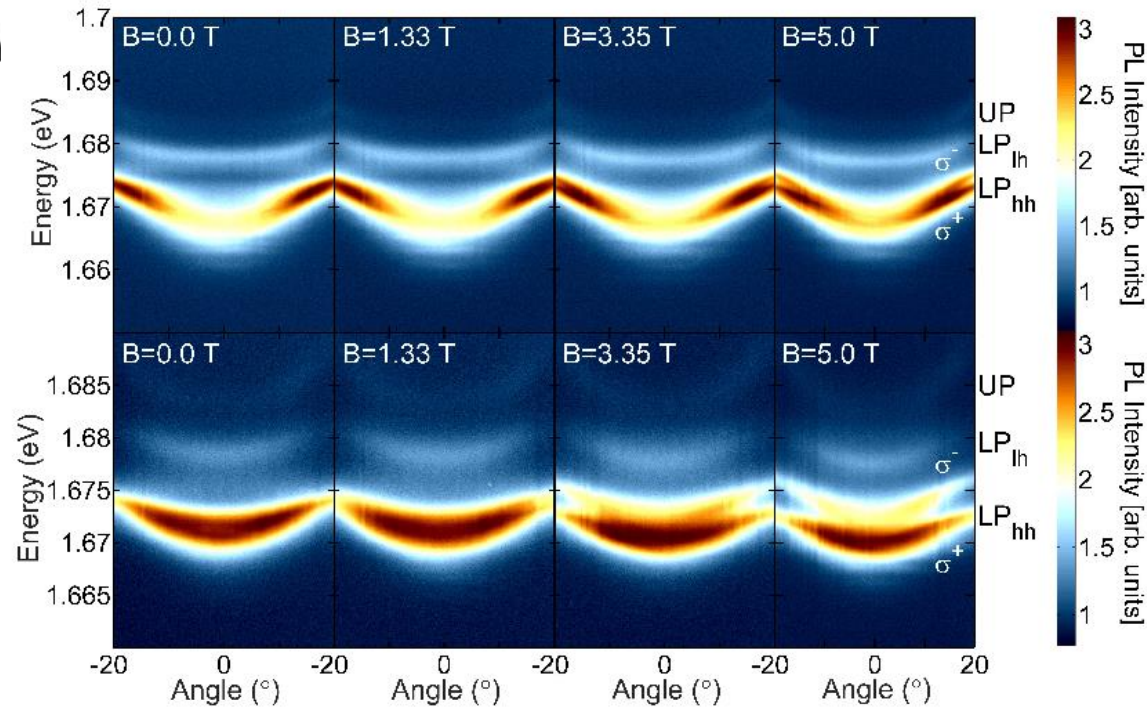
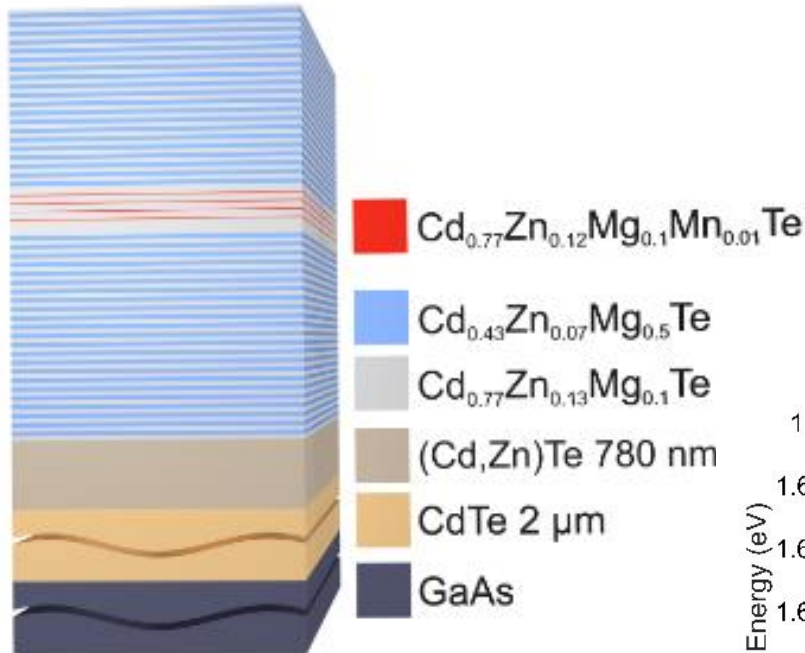


	atoms	polaritons
<b>m</b>	Rb: $10^4 m_e$	$10^{-4} m_e$
<b>T</b>	$10^{-7} K$	$>100 K$
<b>N</b>	$10^{14}/cm^3$	$<10^{11}/cm^2$
<b>t</b>	$\infty$	1 ps



M. Król, R. Mirek, K. Lekenta, **W. Pacuski**, J-G. Rousset, **B. Piętko**

# Ekscytony polaritonowe

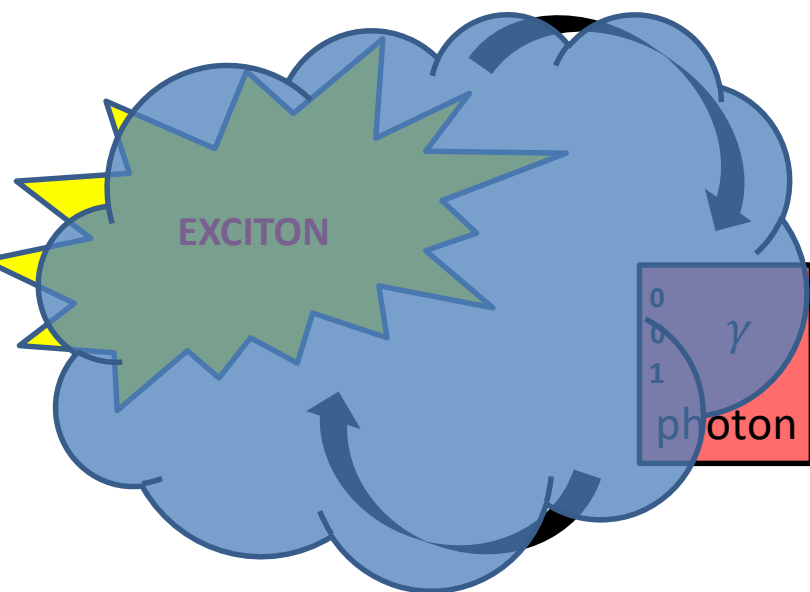


W. Pacuski, R. Mirek et al.

# Stany podwójnie ubrane (doubly dressed states)



# Bozony złożone



0.0-1000 $m_0$	-1	$e$
	$\frac{1}{2}$	electron

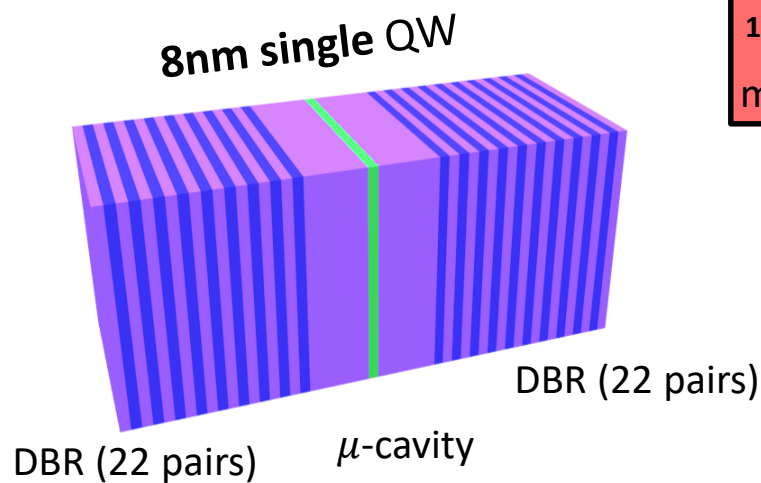
0.0-1 $m_0$	1	$lh$
	$\frac{1}{2}$	light hole

0.1-1000 $m_0$	1	$hh$
	$\frac{3}{2}$	heavy hole

0	$\gamma$
0	
1	photon

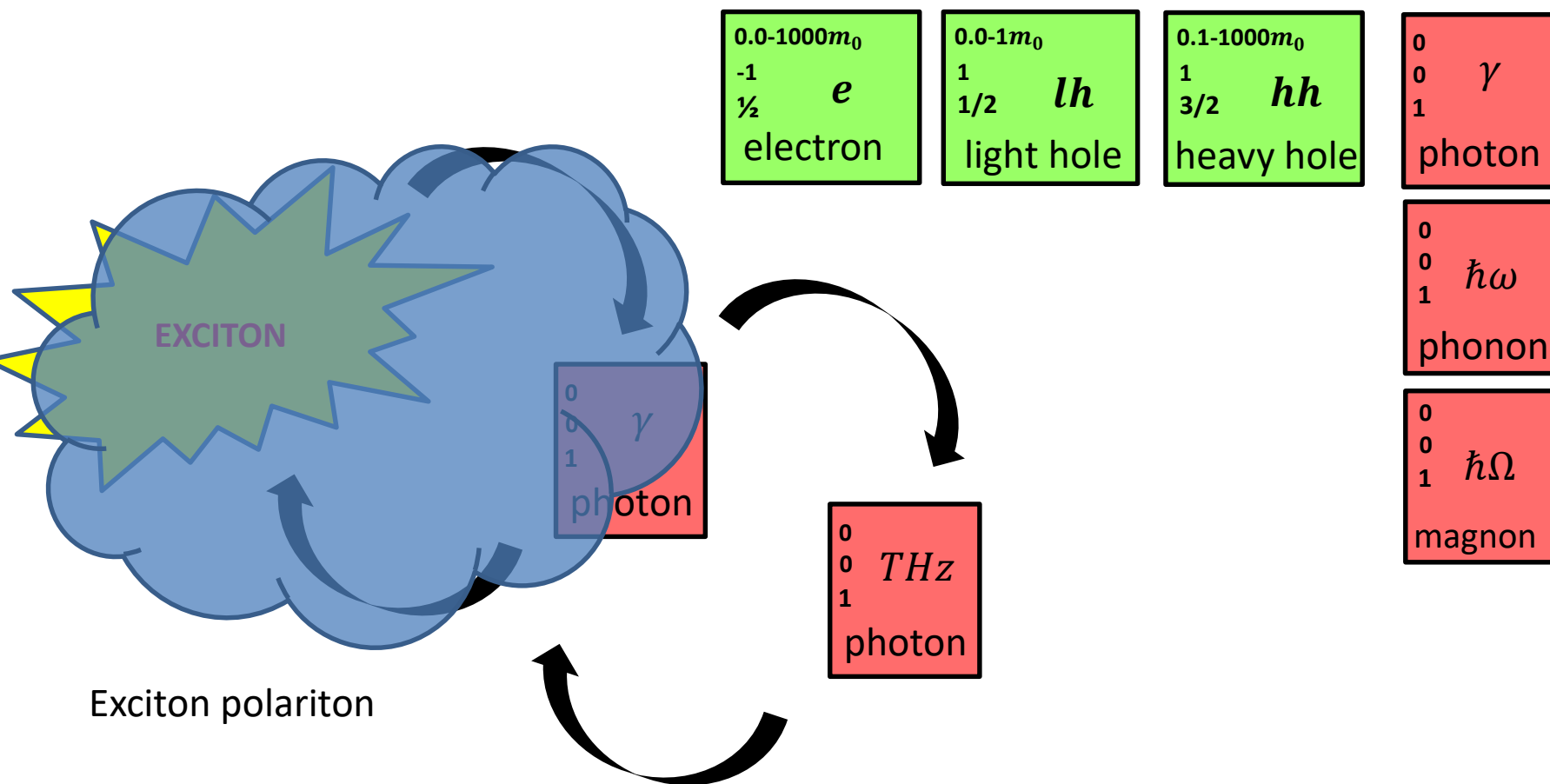
0	$\hbar\omega$
0	
1	phonon

0	$\hbar\Omega$
0	
1	magnon



Exciton polariton

# Bozony złożone



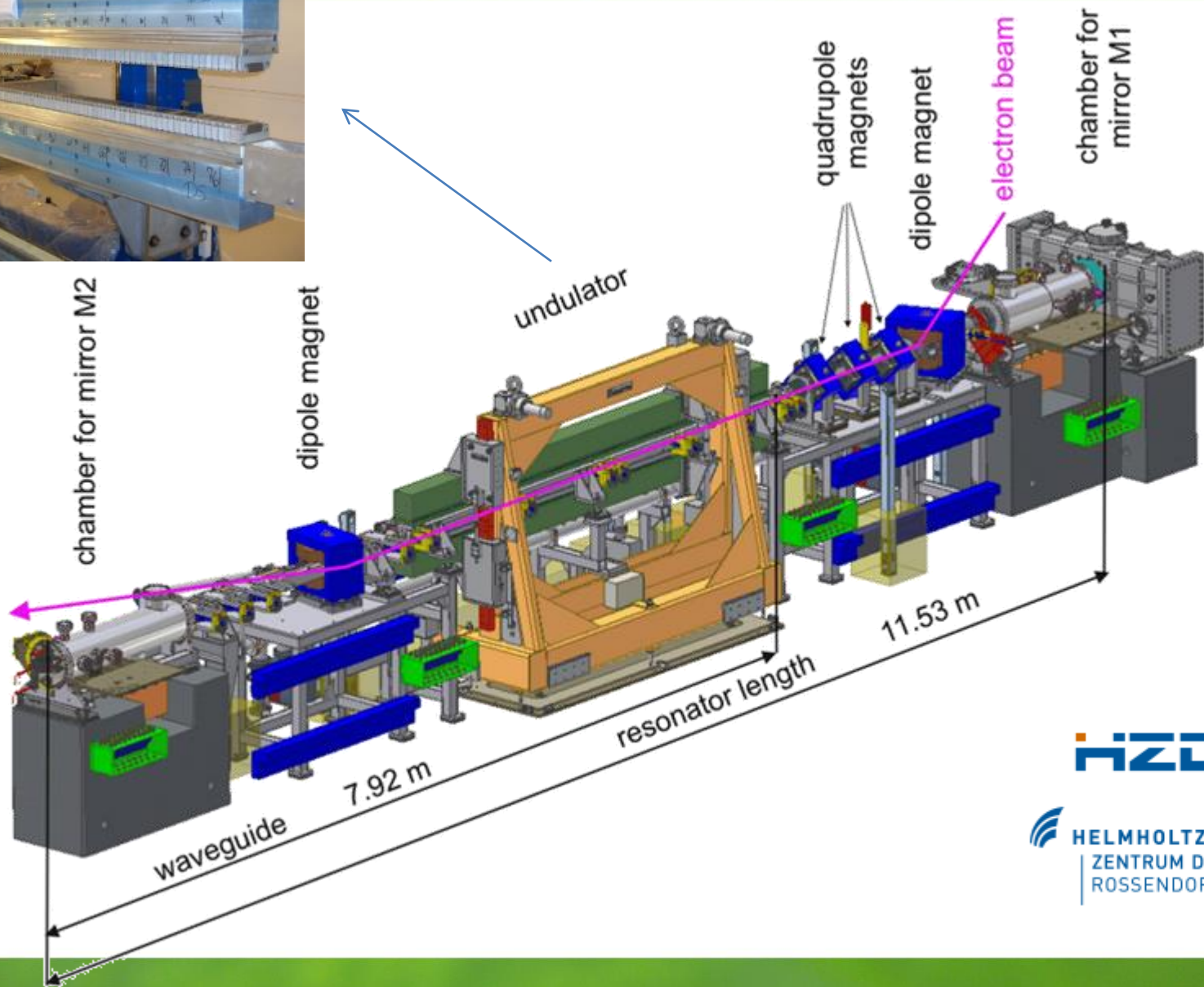
ELBE 



**HZDR**

 **HELMHOLTZ  
ZENTRUM DRESDEN  
ROSSENDORF**

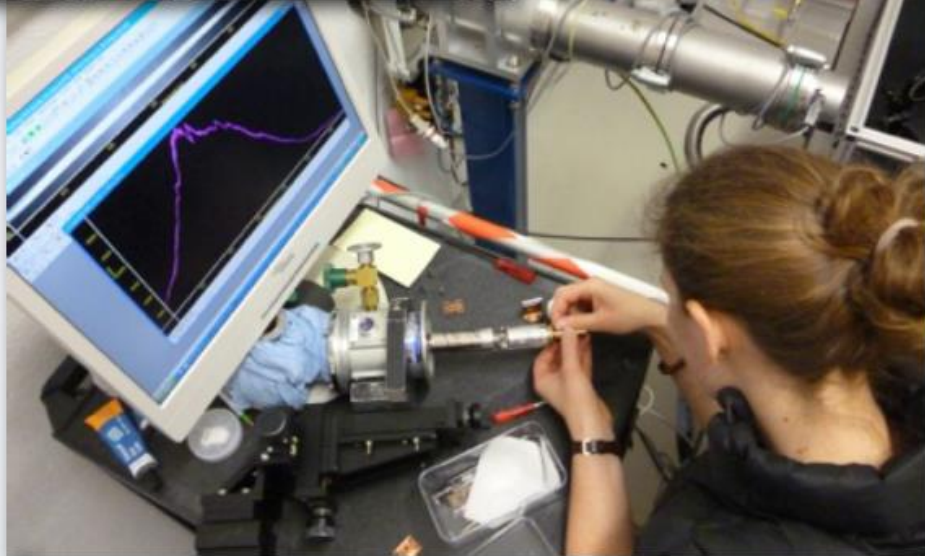
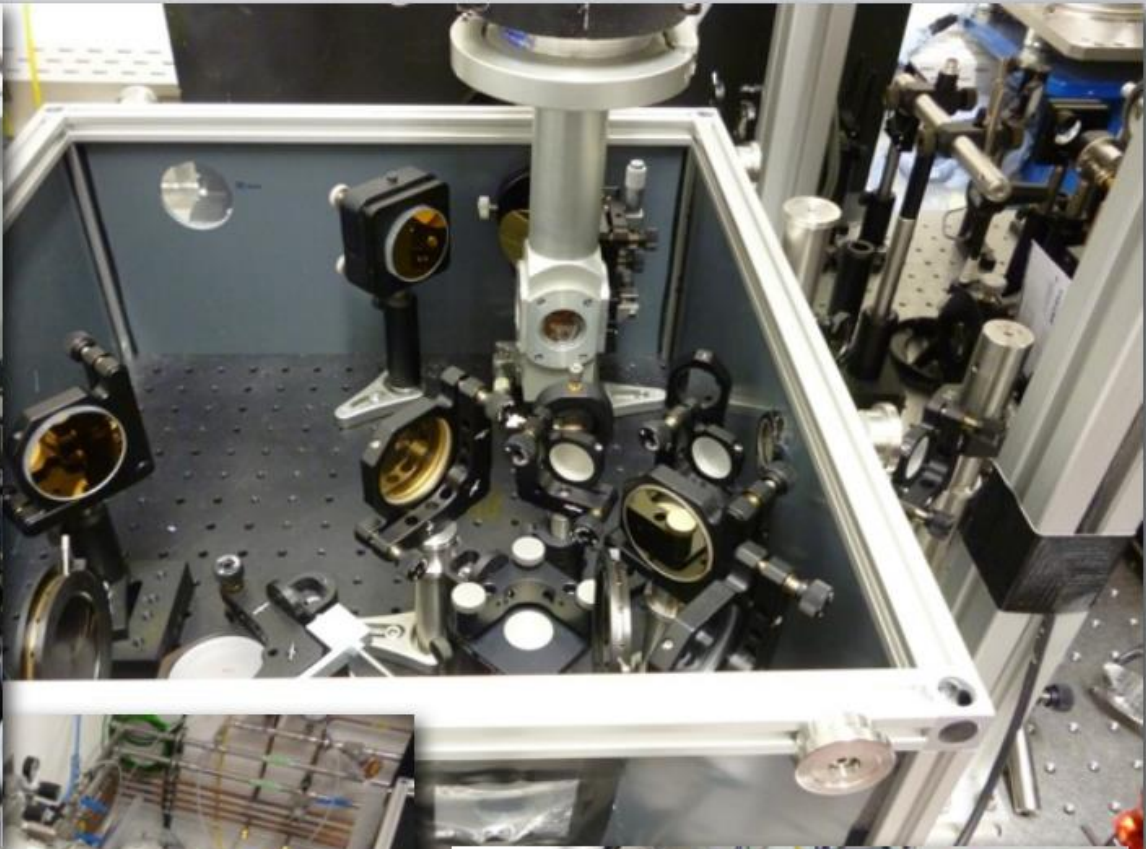
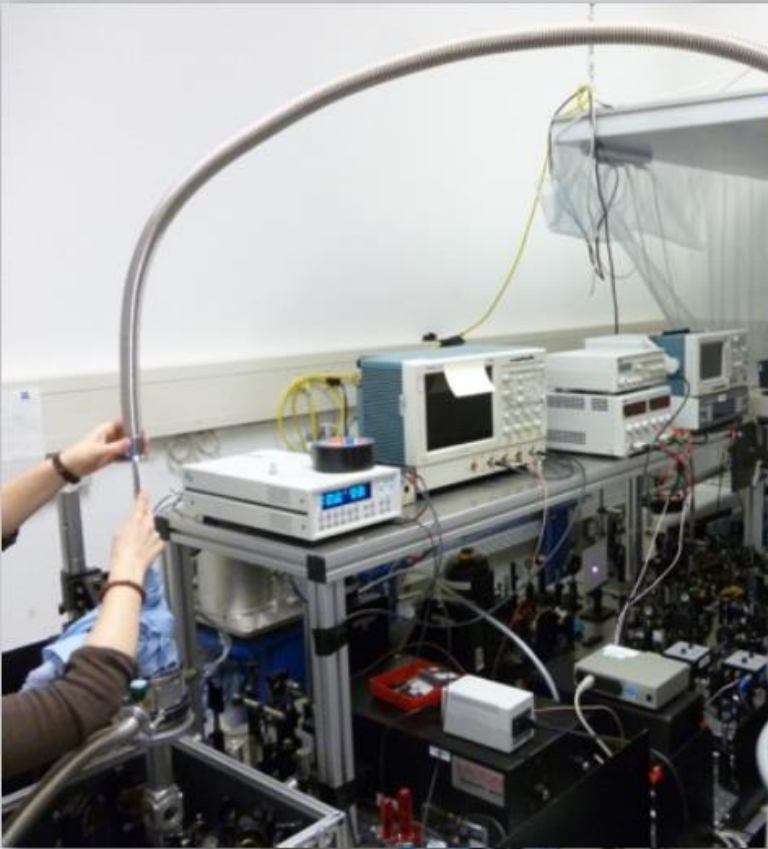




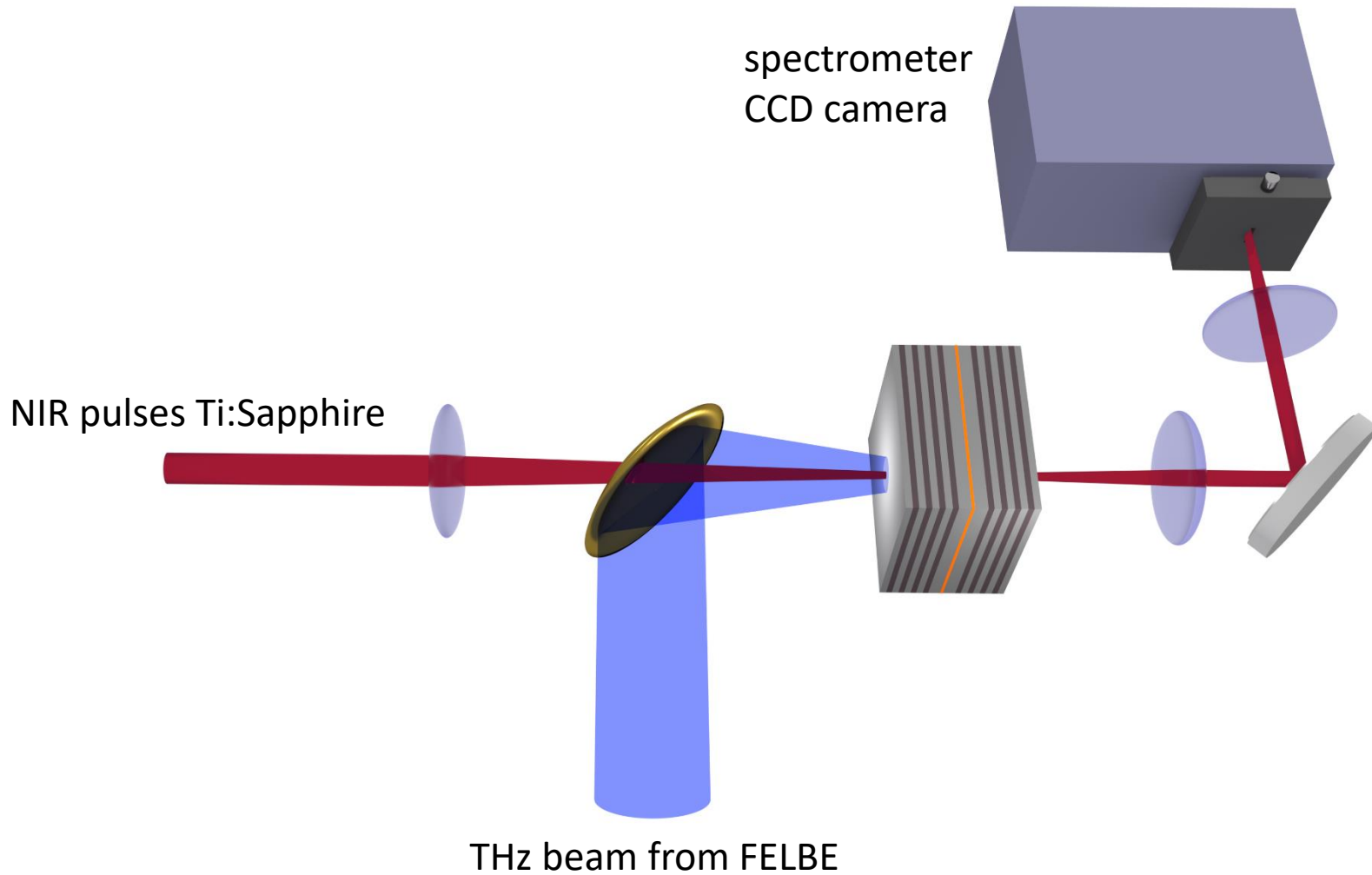
**HZDR**

HELMHOLTZ  
ZENTRUM DRESDEN  
ROSSENDORF

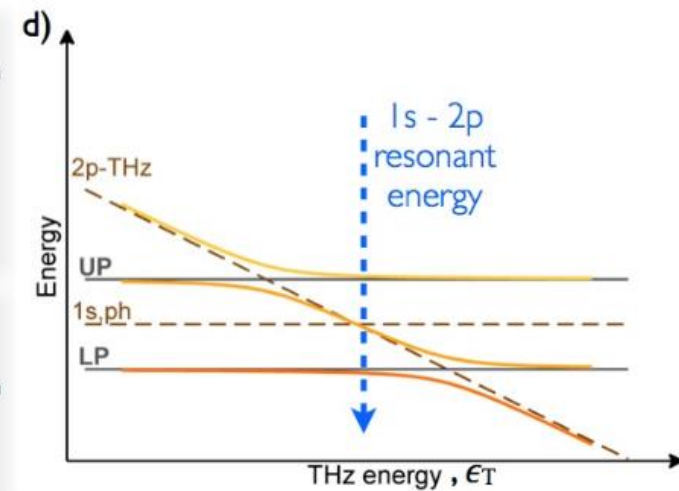
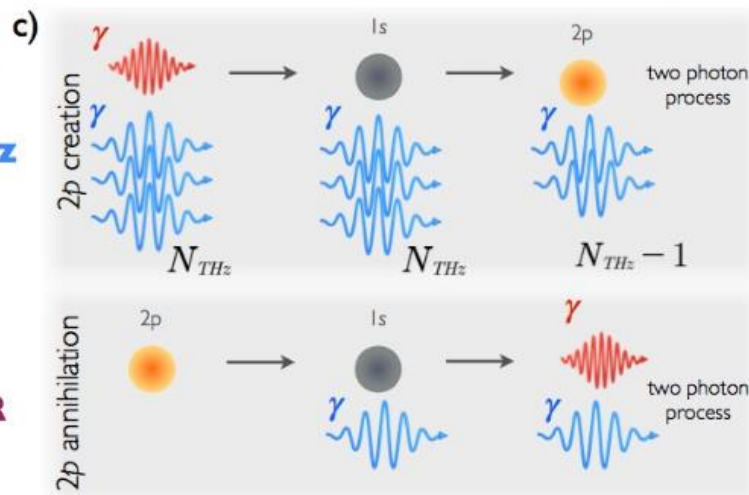
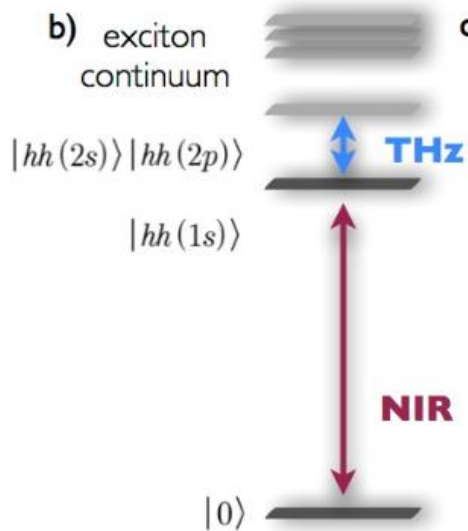
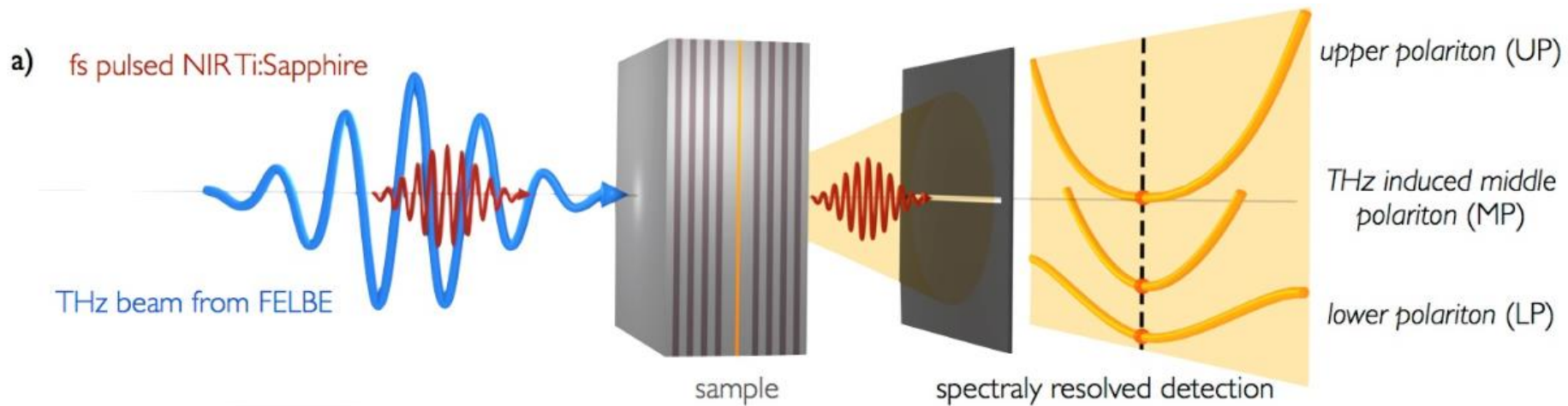




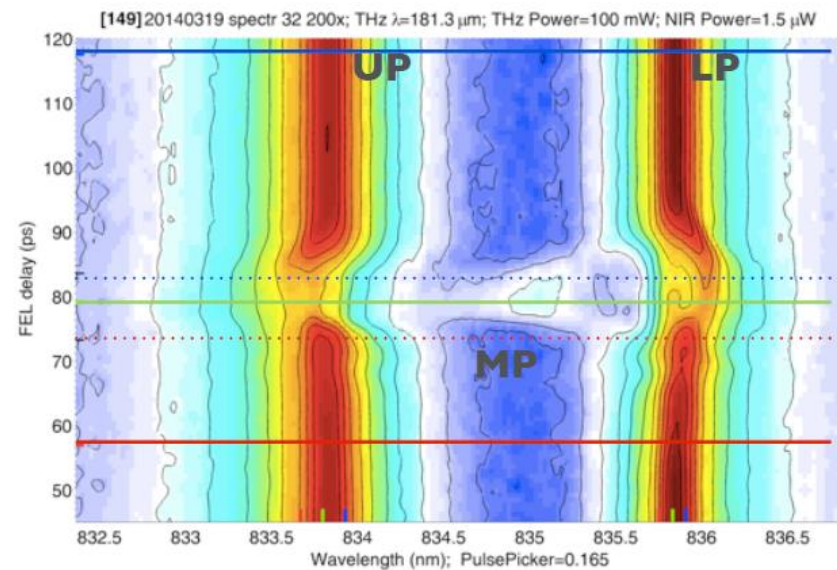
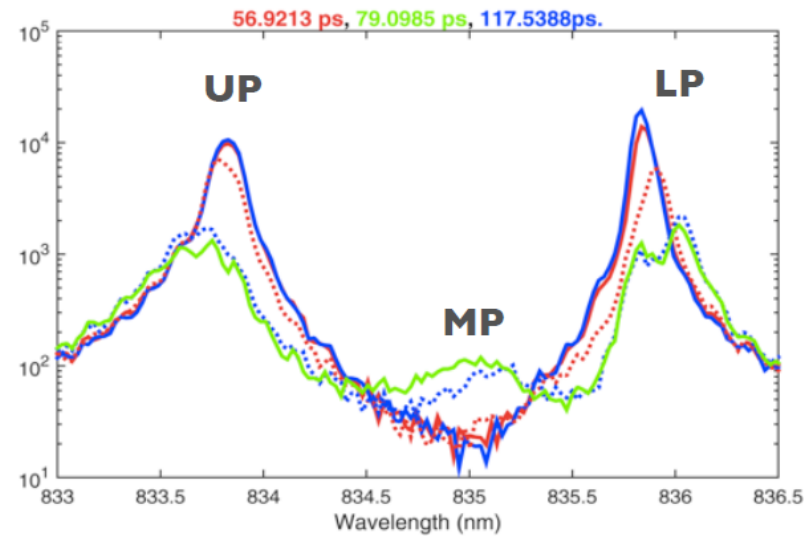
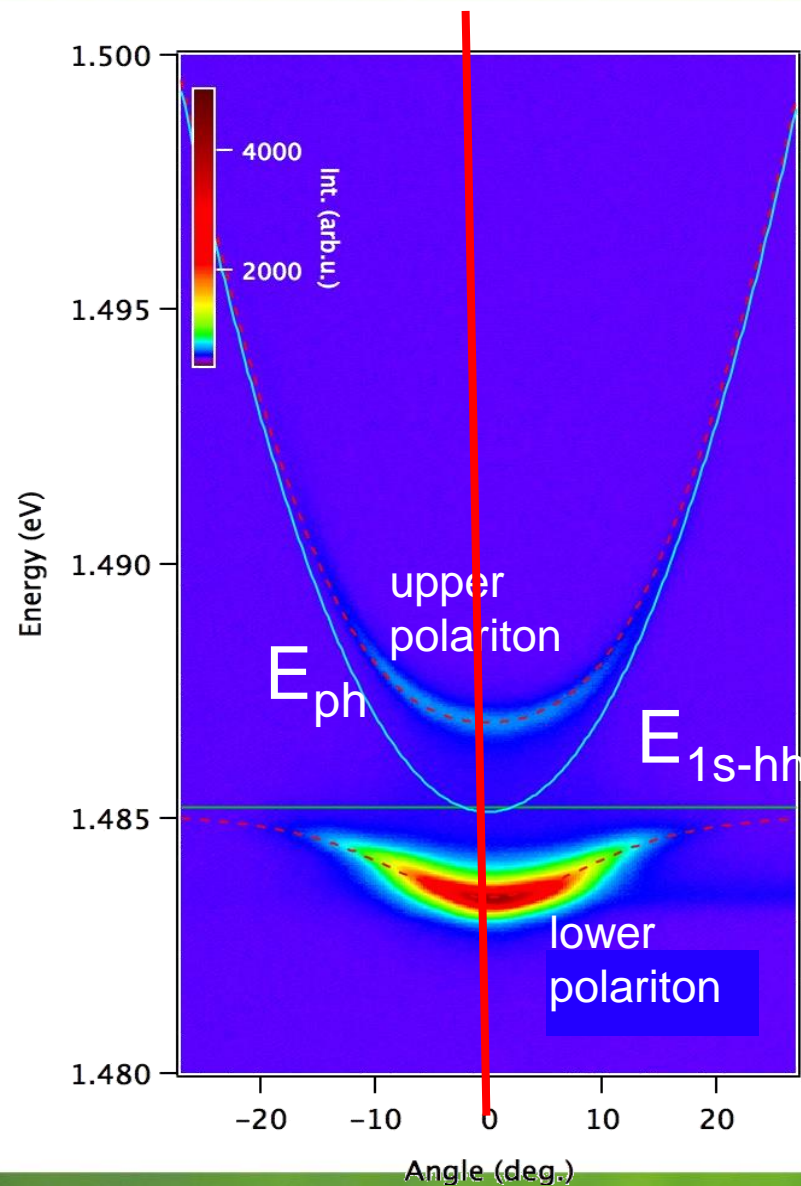
# Podwójnie ubrane bozony



# Podwójnie ubrane bozony



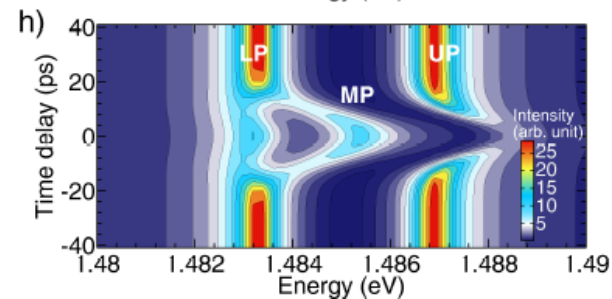
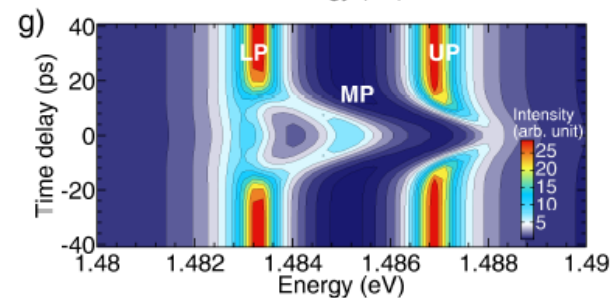
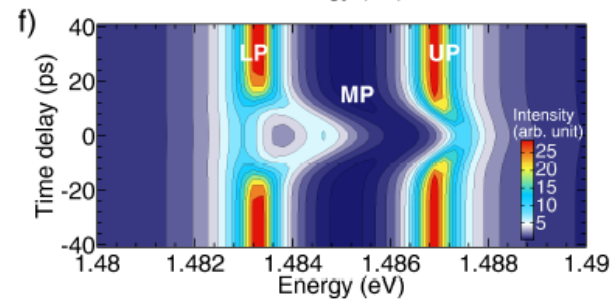
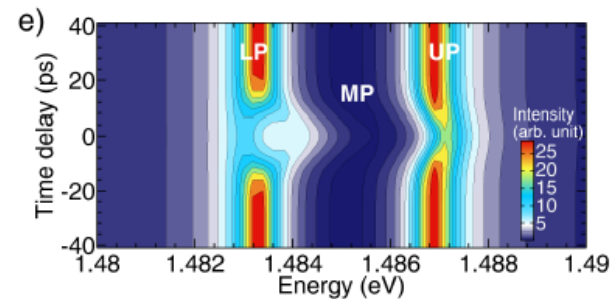
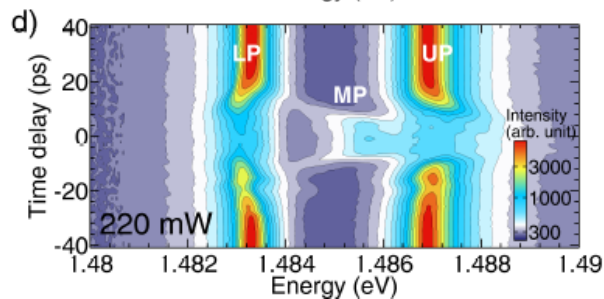
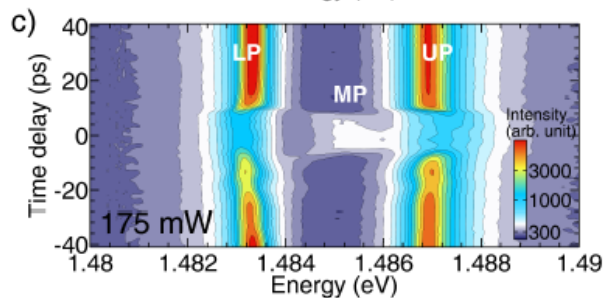
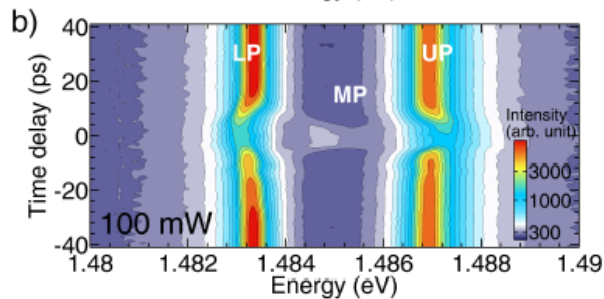
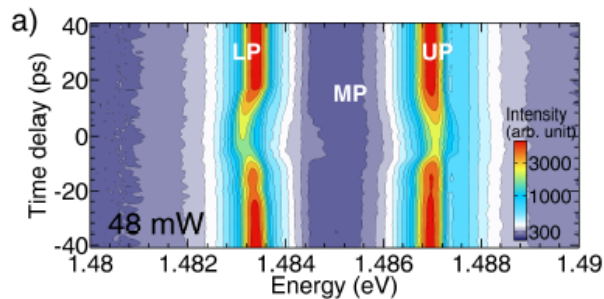
# Podwójnie ubrane bozony



# Podwójnie ubrane bozony

## Experiment

B. Piętko  
J. Szczytko  
(WF UW)  
D. Stephan  
M. Teich et al.  
(HZDR)



## Theory

M. Matuszewski,  
N. Bobrovska  
(IF PAN)

# Cząstki złożone

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force

Bosons (Forces)

3D

0.0-1000 $m_0$   
-1  
 $\frac{1}{2}$   
**e**  
electron

0.0-1 $m_0$   
1  
 $\frac{1}{2}$   
**lh**  
light hole

0.1-1000 $m_0$   
1  
 $\frac{3}{2}$   
**hh**  
heavy hole

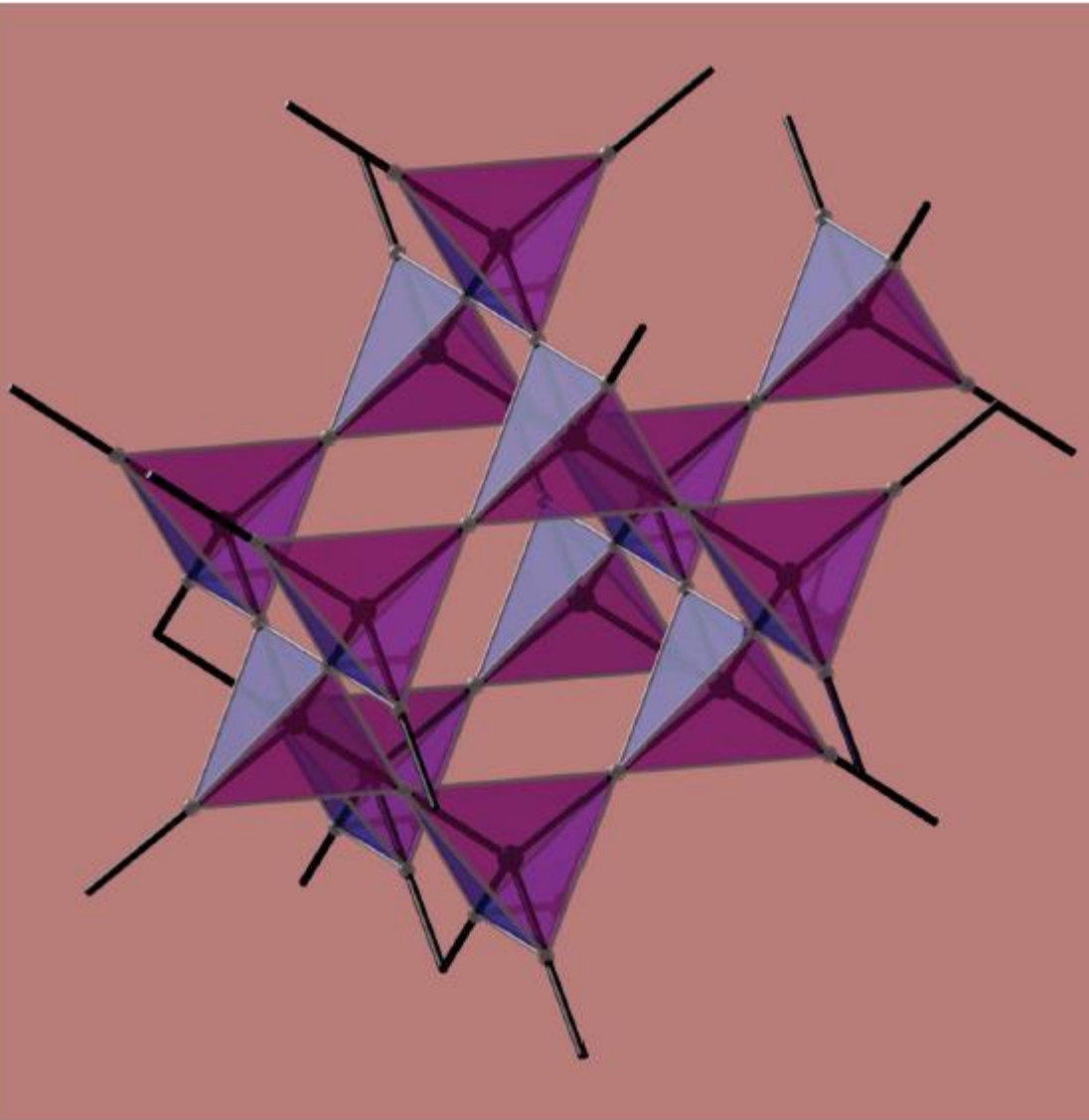
0  
0  
1  
**γ**  
photon

0  
0  
1  
**ħω**  
phonon

0  
0  
1  
**ħΩ**  
magnon

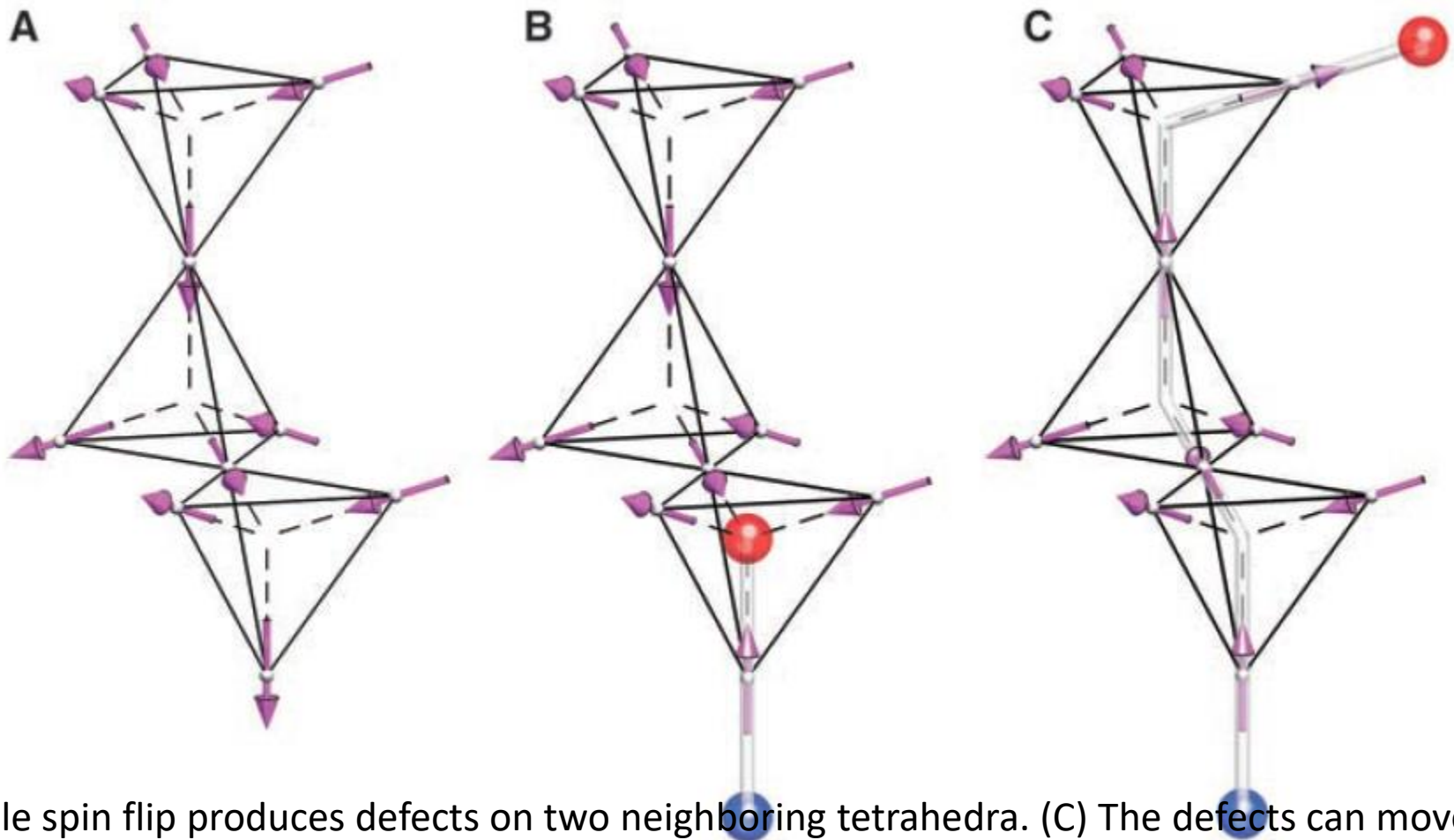
- Monopole magnetyczne
- spinon, orbiton, holon
- skyrmiony
- majorana fermions
- ...

# Monopola magnetyczne w lodzie spinowym



The pyrochlore and diamond lattices. The magnetic moments in spin ice reside on the sites of the pyrochlore lattice, which consists of cornersharing tetrahedra. These are at the same time the midpoints of the bonds of the diamond lattice (black) formed by the centres of the tetrahedra. The ratio of the lattice constant of the diamond and pyrochlore lattices is  $a_d/a = \sqrt{3/2}$ . The Ising axes are the local [111] directions, which point along the respective diamond lattice bonds.

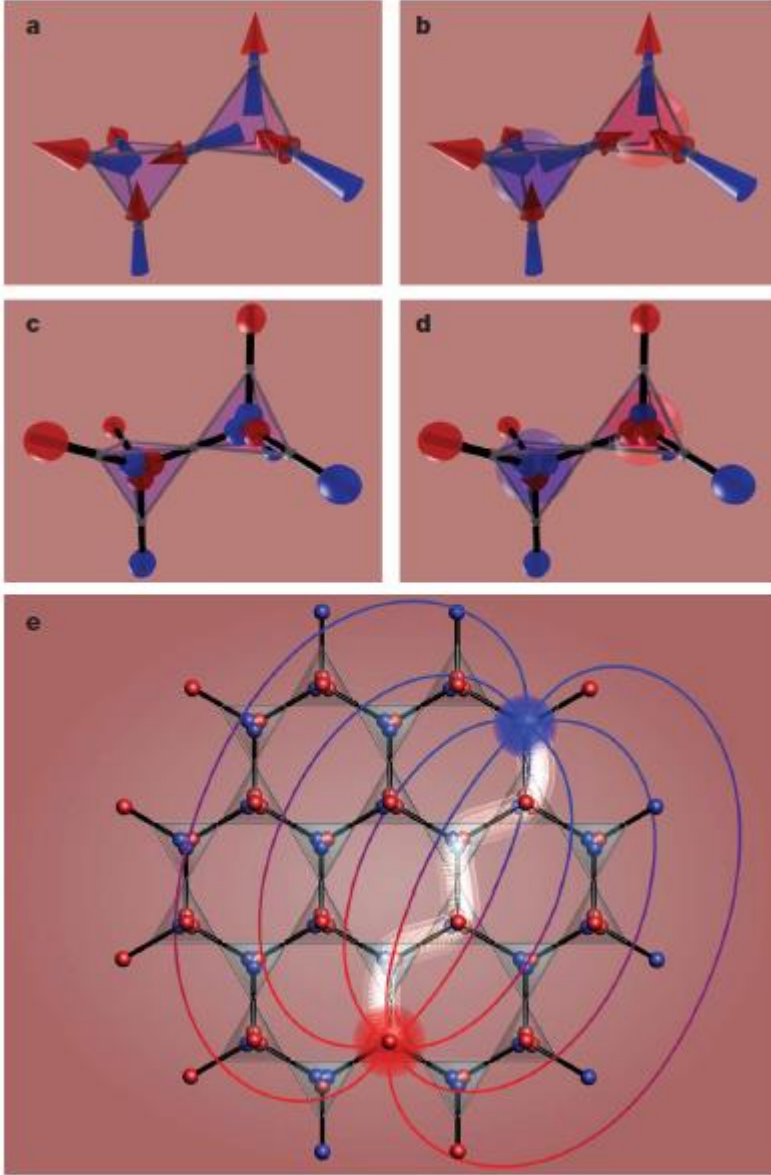
# Monopola magnetyczne w lodzie spinowym



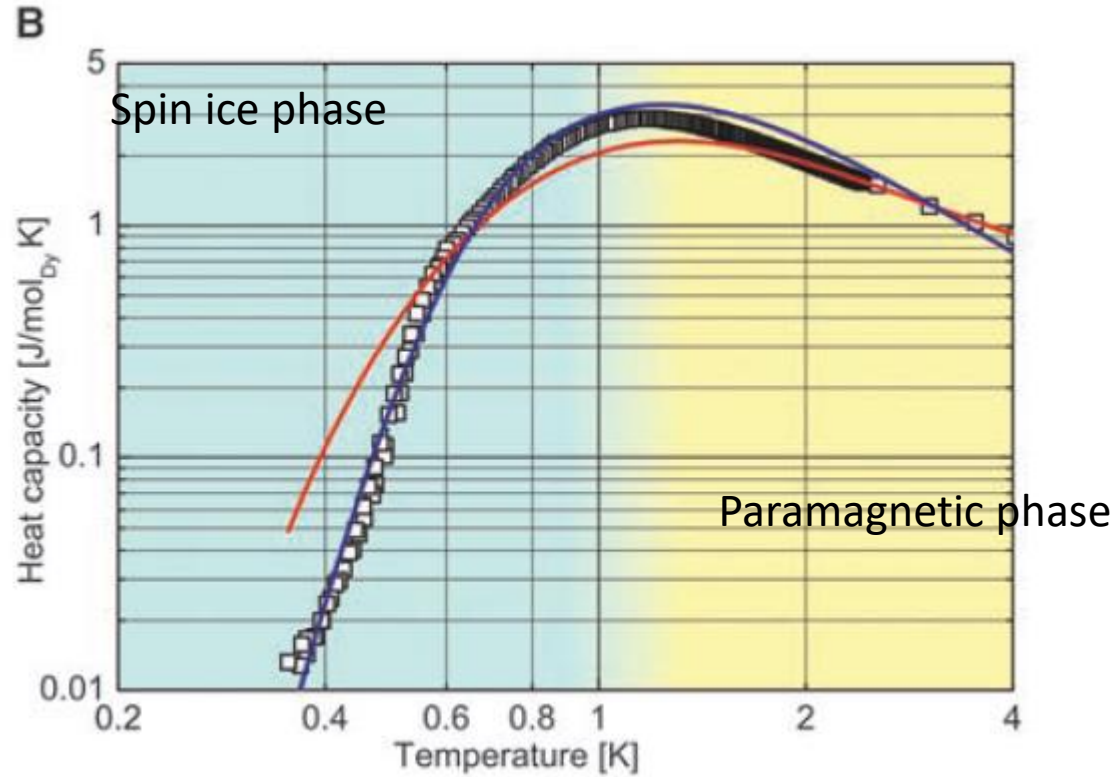
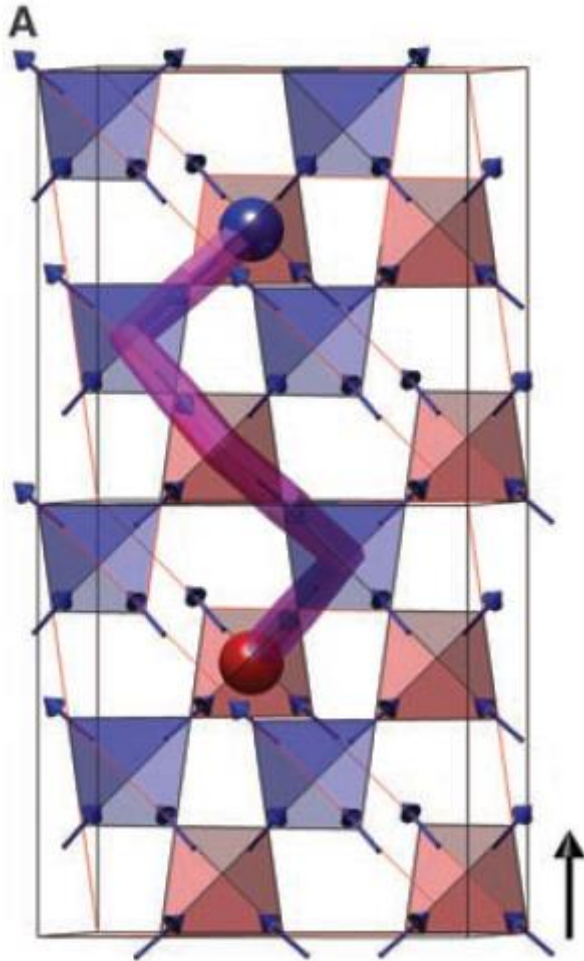
A single spin flip produces defects on two neighboring tetrahedra. (C) The defects can move apart. They interact like oppositely charged magnetic monopoles connected by a trail of flipped spins (a Dirac string). The pink arrows indicate spins, the blue spheres indicate monopoles, and the red spheres indicate antimonopoles.



# Magnetic monopoles in spin ice



# Monopola magnetyczne w lodzie spinowym

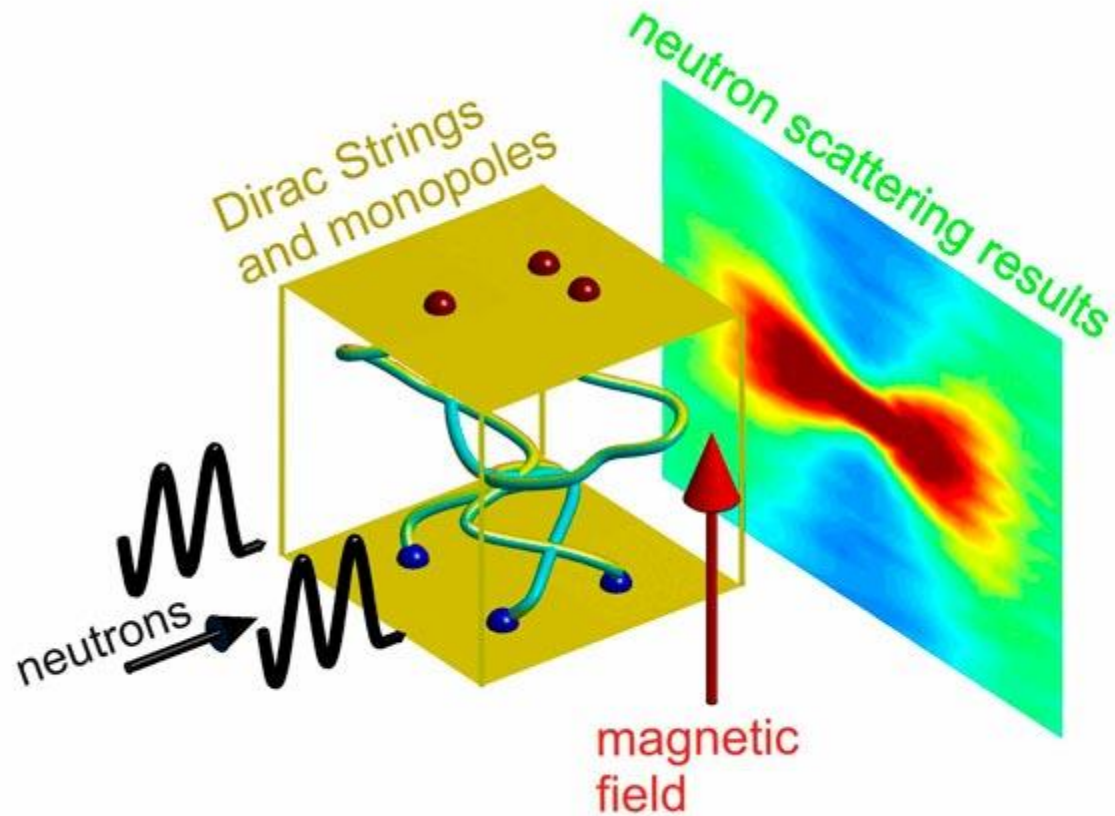


The measured heat capacity per mole of  $\text{Dy}_2\text{Ti}_2\text{O}_7$  at zero field (open squares) is compared with a Debye-Hückel theory for the monopoles (blue line) and the best fit to a single-tetrahedron (Bethe lattice) approximation (red line).

D. J. P. Morris et al. SCIENCE VOL 326, 411 (2009)

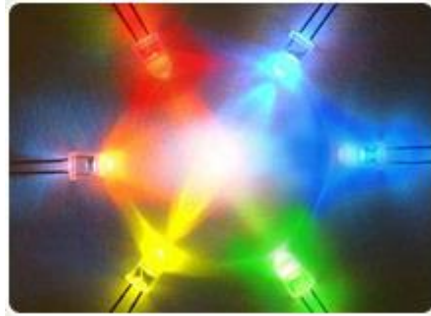
# Monopola magnetyczne w lodzie spinowym

Dirac string

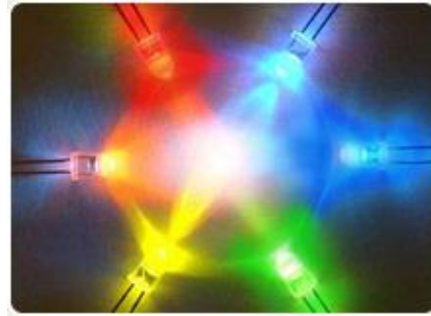


<http://physicsworld.com/cws/article/news/2009/sep/03/magnetic-monopoles-spotted-in-spin-ices>

# Zastosowania kwazicząstek



# Zastosowania kwazicząstek



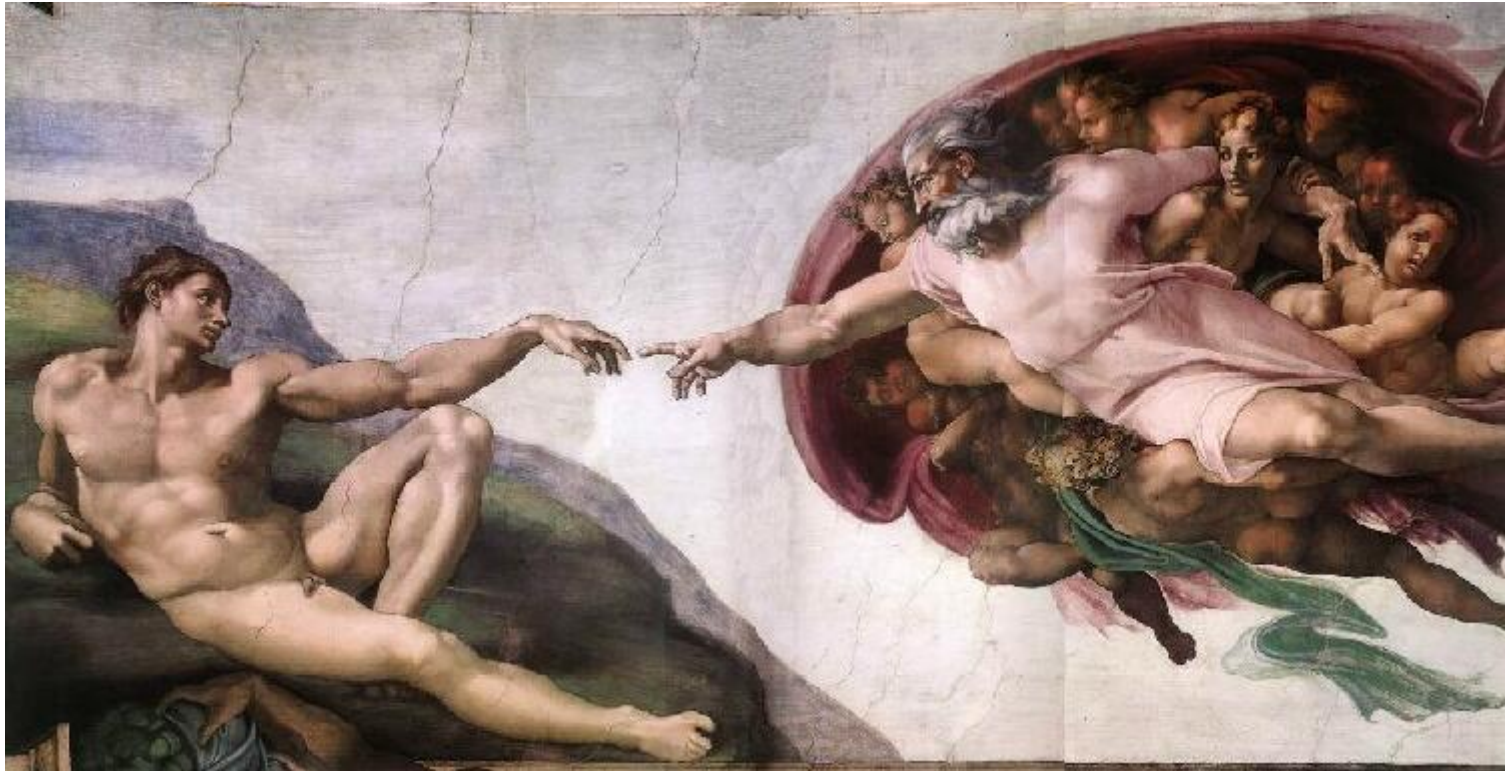
**“Physics is like sex: sure, it may give some practical results, but that's not why we do it.”**

**Richard Feynman**



# Zamiast podsumowania

Stwórz sobie kwazi-cząstkę!



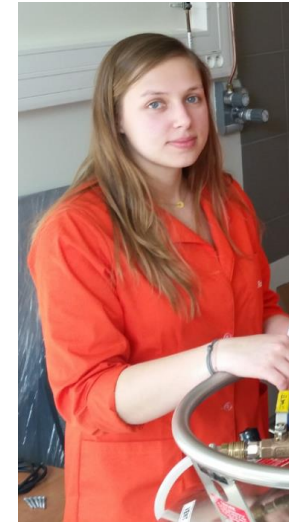
**PODZIĘKOWANIA:**

**Andrzej Gołębiewski, Anita Gardias, Jarosław Rybusiński**

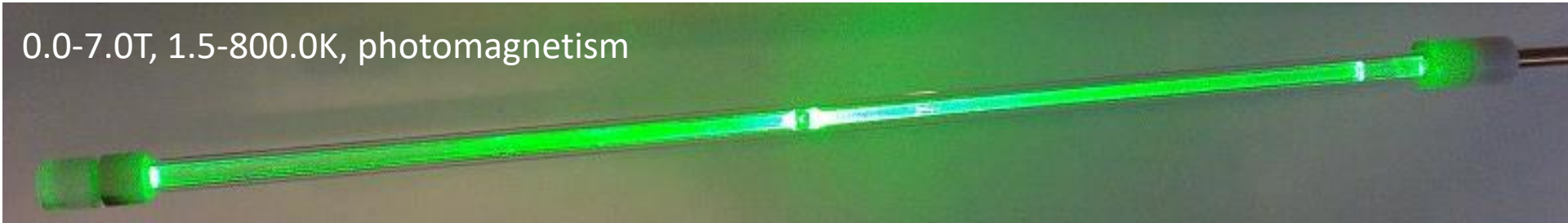
# Laboratorium magnetometrii SQUID



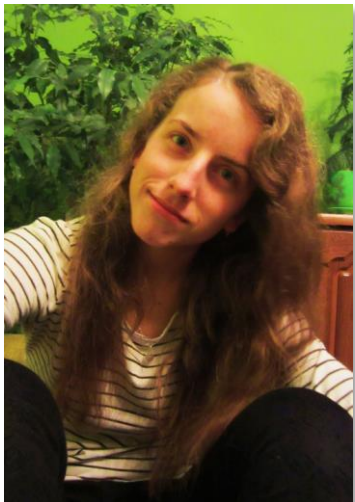
Andrzej Twardowski  
Andrzej Majhofer  
Anita Gardias  
Jarosław Rybusiński  
Maciej Marchwiany (Monte Carlo)



0.0-7.0T, 1.5-800.0K, photomagnetism



# Studenci!



Karolina Łempicka



Marcin Witkowski



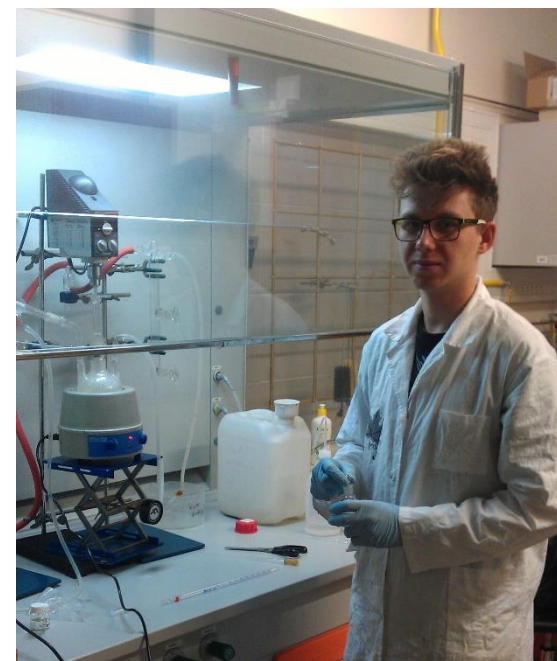
Piotr Łaski



Marcin Bartmański



Konrad Norowski



Arek Gempka



# Dziękuję za uwagę

