Why did we elaborate an entangled photons experiment in our engineering school?

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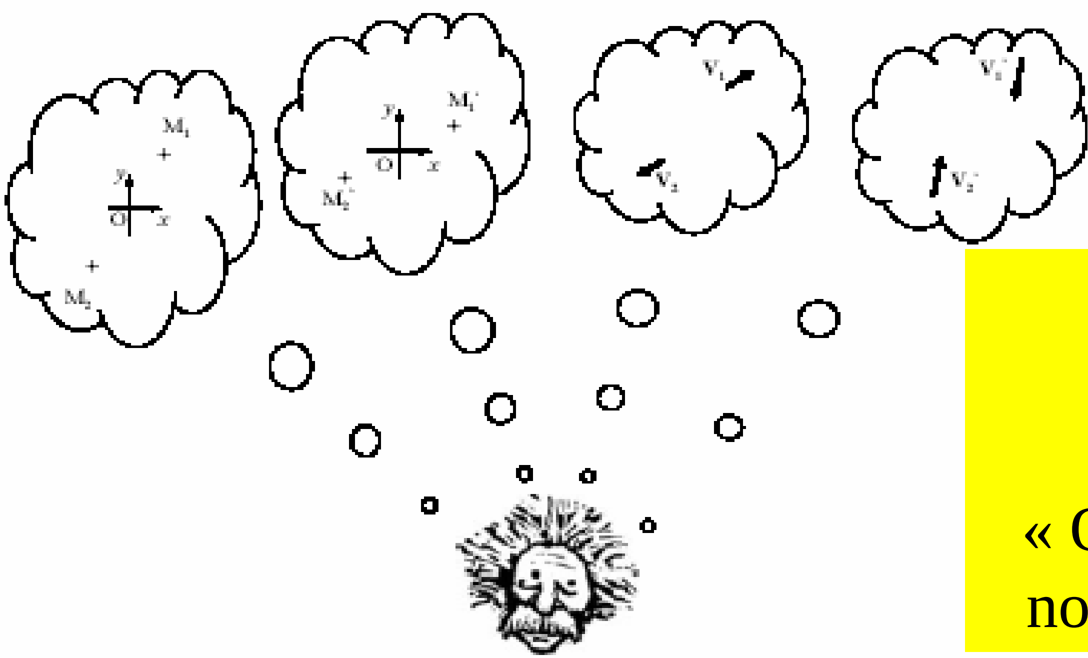
Source of polarization-entangled photons

1935 : Quantum Mechanic allows strange entangled states



EPR Paradox

« Quantum Mechanic is not a ***complete*** theory »

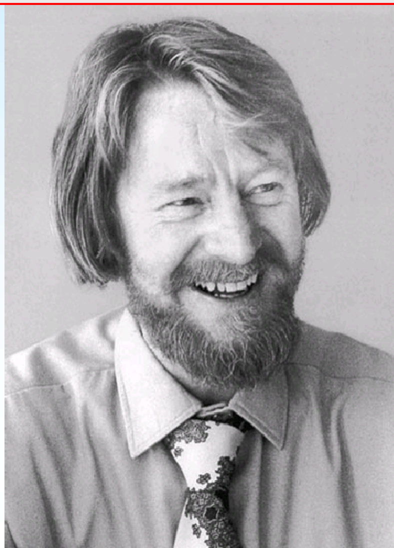
Gedankenexperiment on entanged states

Einstein, Podolsky, et Rosen (1935)

1935 : Quantum Mechanic allows strange entangled states

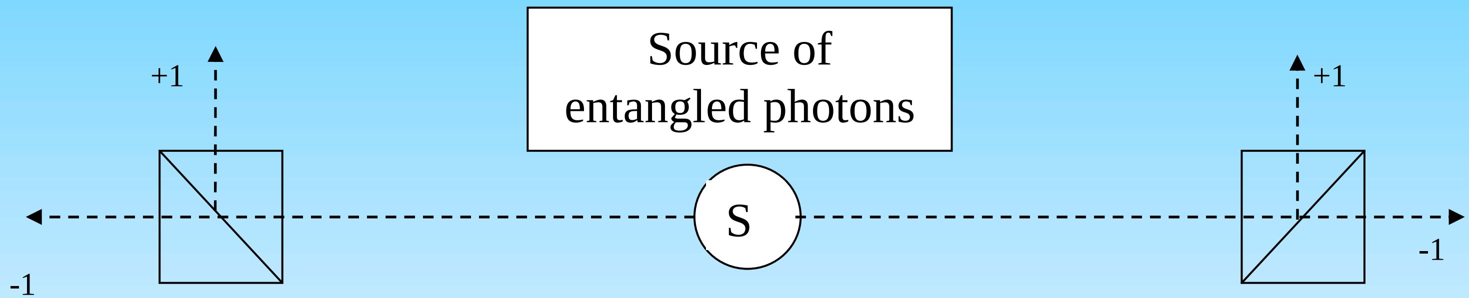
1964 : Bell Theorem

« It is impossible to reproduce all Quantum Mechanics predictions with any Hidden Variable Local Theory. »



What is a test of Bell’s inequalities?

You need a Source of Polarisation-Entangled Photons



Analyzer I oriented in direction **a**

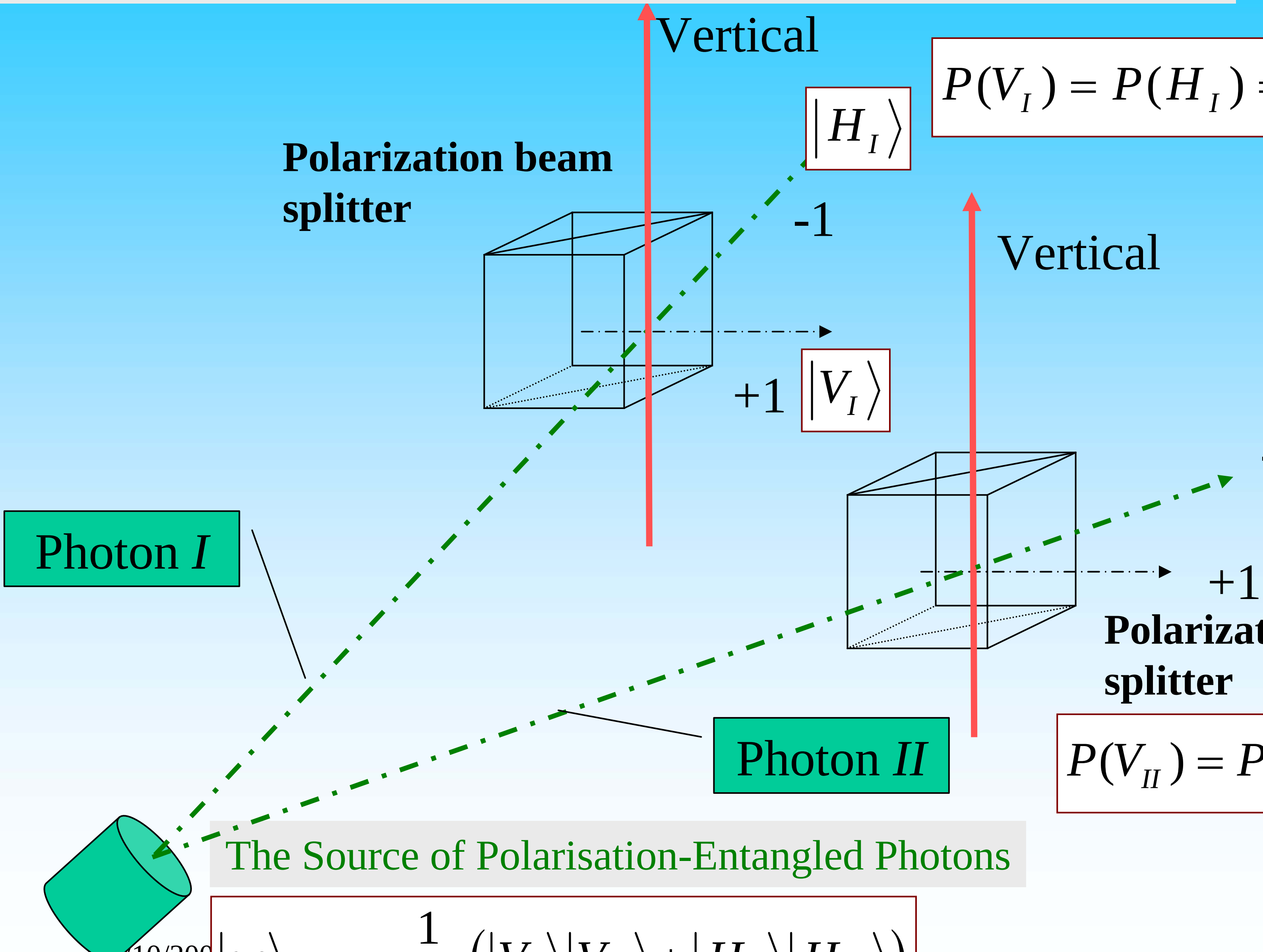
Analyzer II oriented in direction **b**

Polarisation pair state

$$\left|\psi\right\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(\left|V_I\right\rangle\left|V_{II}\right\rangle + \left|H_I\right\rangle\left|H_{II}\right\rangle\right)$$

Creation of polarization-entangled photons in an EPR state and measurement of joint probabilities of detection for different directions of the 2 analyzers.

Individual probabilities



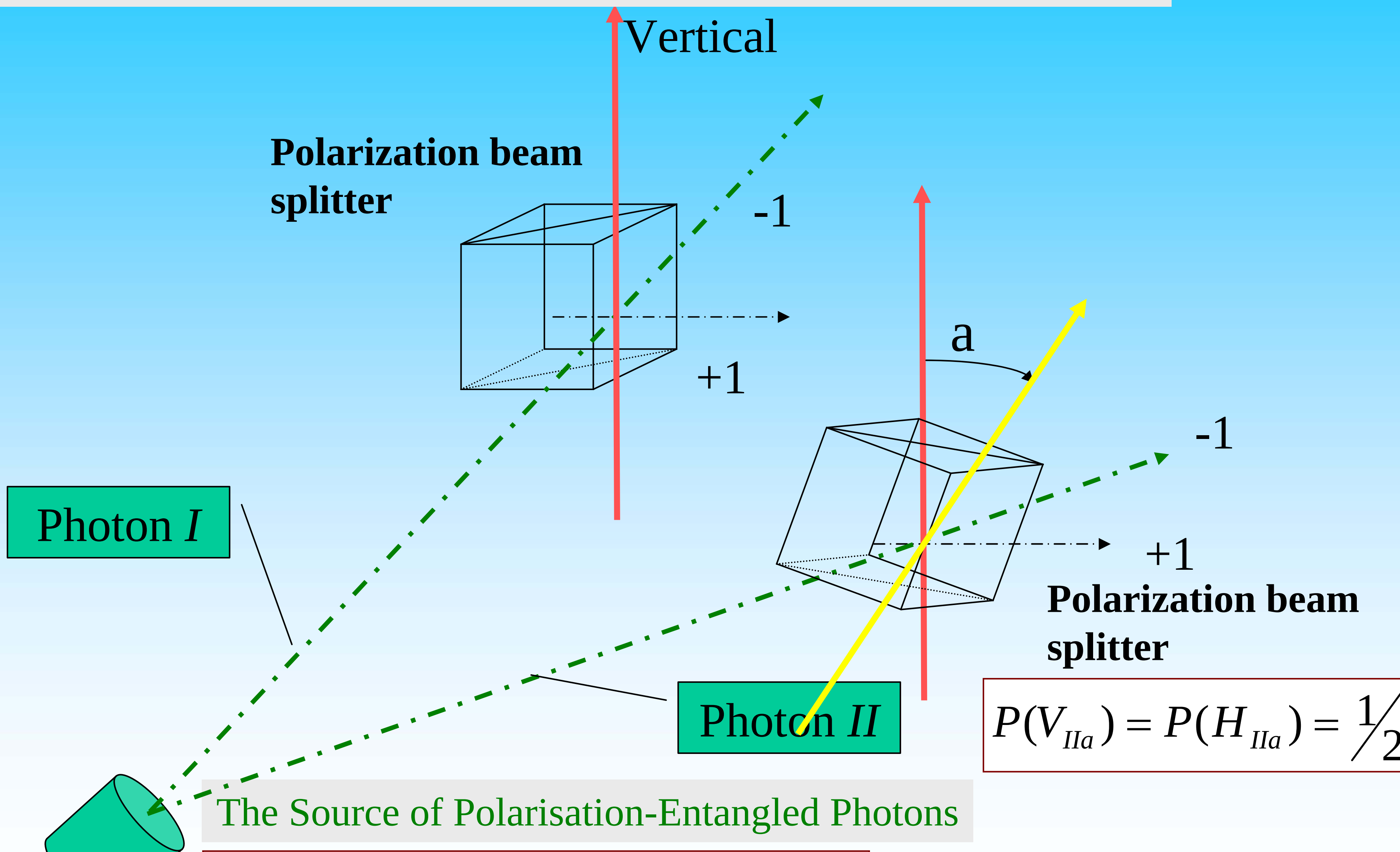
$$|H_I\rangle \quad |V_I\rangle \quad |H_{II}\rangle \quad |V_{II}\rangle$$

$$P(V_I) = P(H_I) = \tfrac{1}{2}$$

$$P(V_{II}) = P(H_{II}) = \tfrac{1}{2}$$

$$|\psi\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$

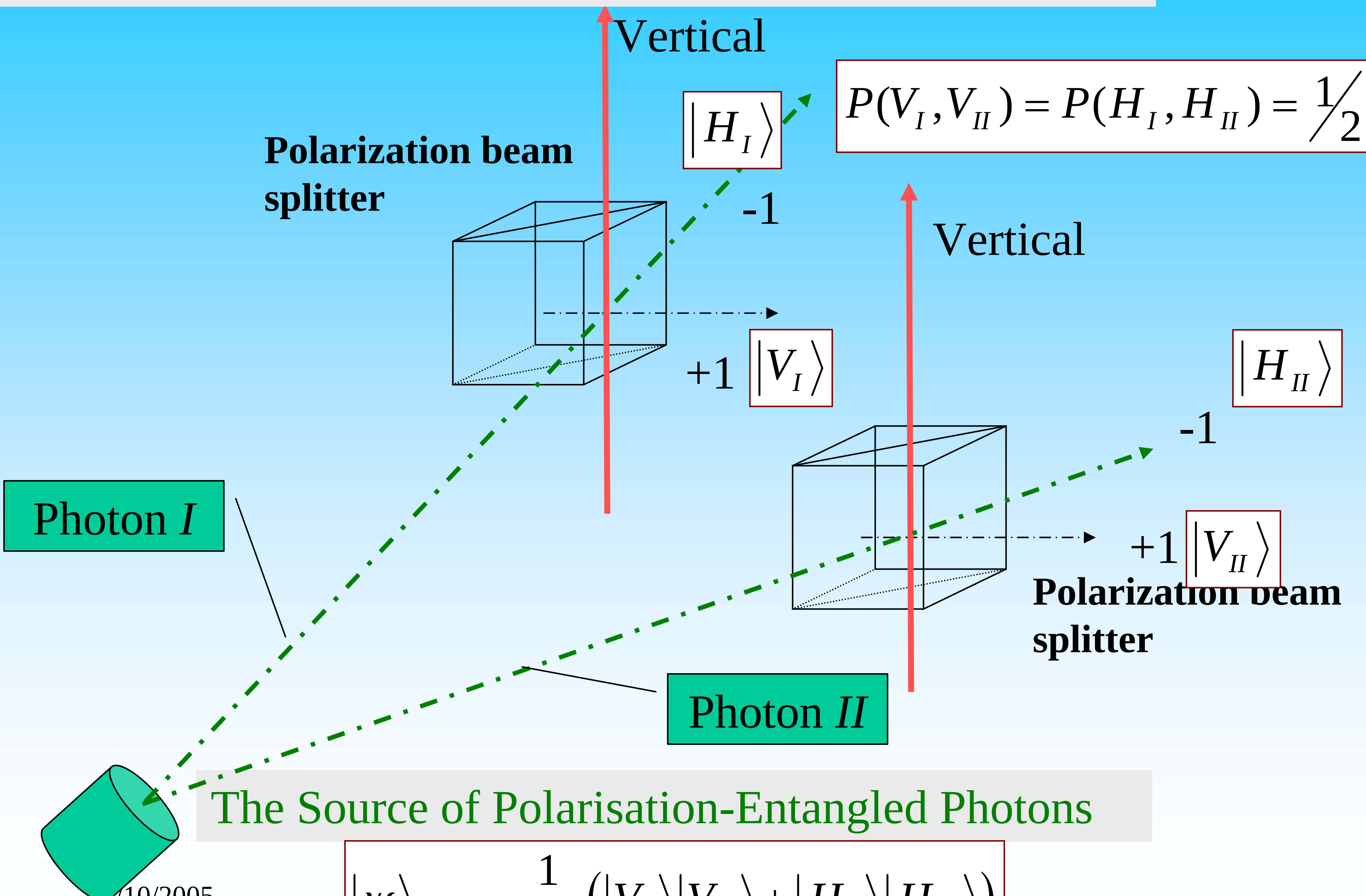
Individual probabilities for any direction a



$$P(V_{IIa}) = P(H_{IIa}) = \frac{1}{2}$$

$$|\psi\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$

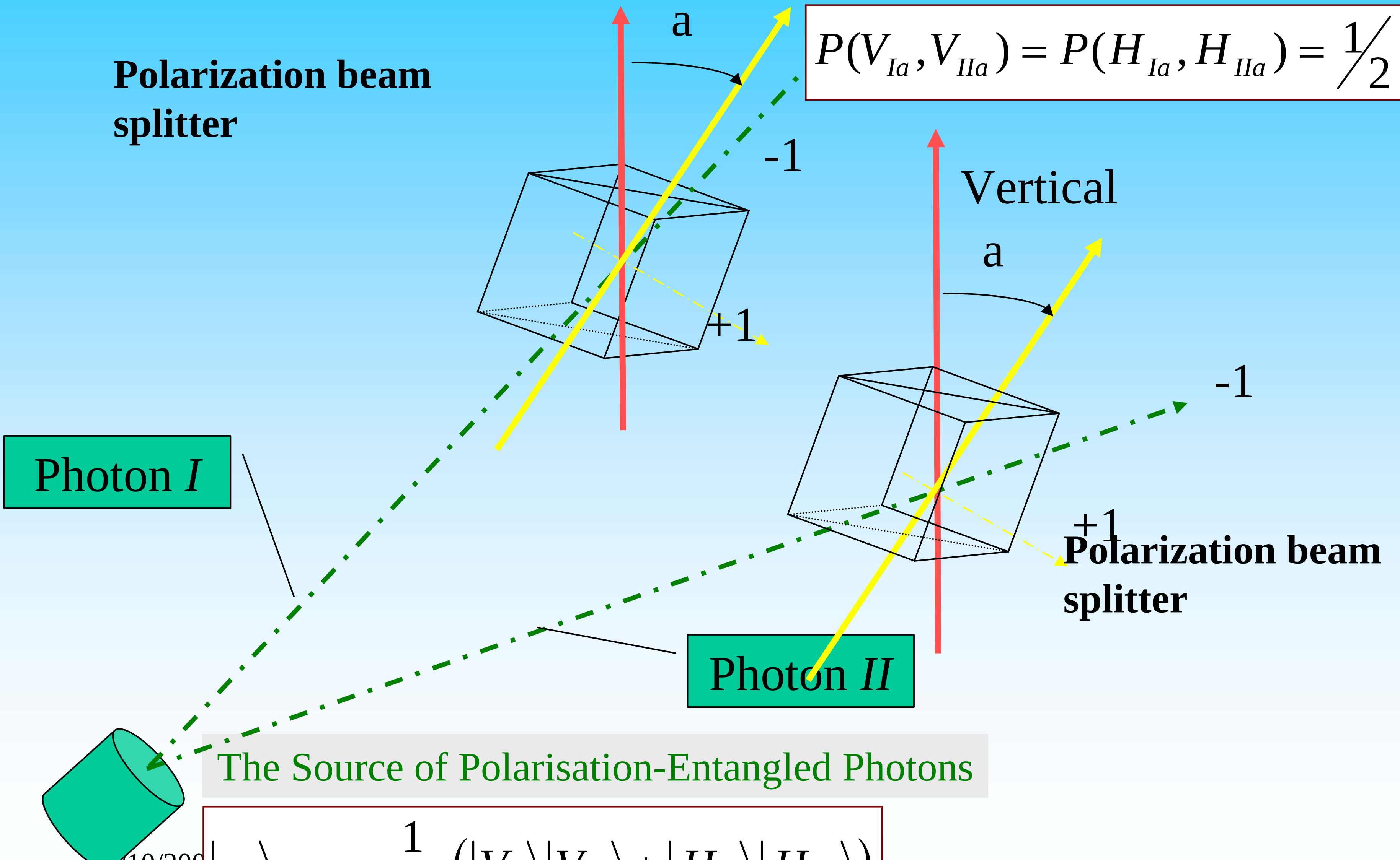
Joint probabilities?



$$|\psi\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$

Joint probabilities for any direction a : $P(V_{Ia},V_{IIa})$ or $P(H_{Ia},H_{IIa})$?

$$P(V_{Ia},V_{IIa}) = P(H_{Ia},H_{IIa}) = 1/2$$



The Source of Polarisation-Entangled Photons

$$|\psi\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$

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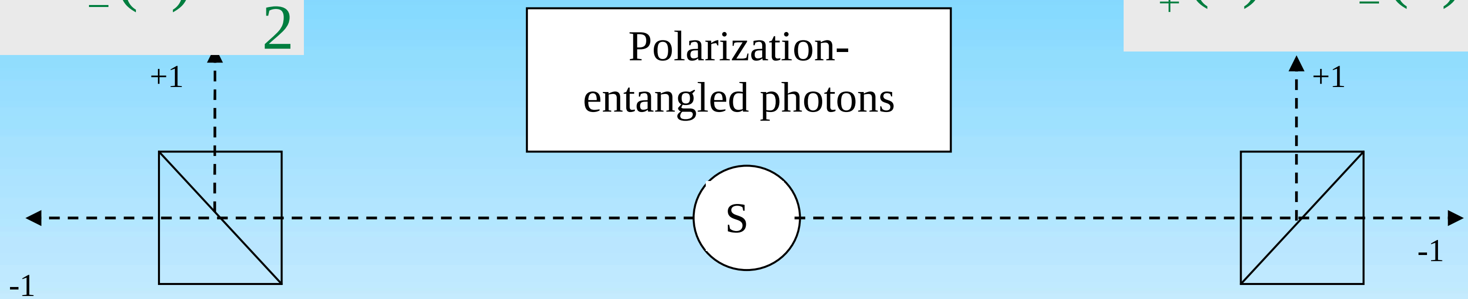
$$|\psi\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$

The outstanding properties of this state !

$$P_+(\mathbf{a}) = P_-(\mathbf{a}) = \frac{1}{2}$$

$$P_+(b) = P_-(b) = \frac{1}{2}$$



Analyzer I oriented in direction **a**

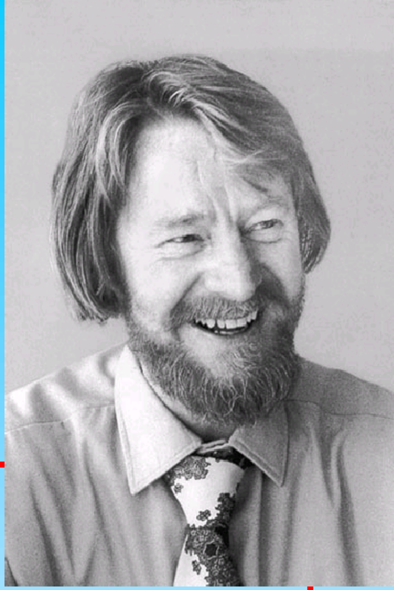
Analyzer II oriented in direction **b**

$$if\ (\mathbf{a},\mathbf{b}) = 0 \quad \Rightarrow \quad P_{++} = P_{--} = \frac{1}{2}$$

$$P_{+-} = P_{-+} = 0$$

EPR state is characterized by a perfect correlation and a circular symmetry : the joint detection probabilities is always be 0.5 if the analyzers are parallel.

What is a test of Bell's inequalities?



You can measure the degree of correlation :

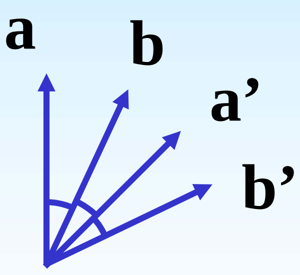
$$E(a,b) = P(a,b) + P(a_\perp, b_\perp) - P(a, b_\perp) - P(a_\perp, b)$$

Classical theory :

$-2 \le S \le 2$ avec $S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$

Quantum Mechanics $E_{\mathrm{MQ}}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b})$

For these directions $(\mathbf{a},\mathbf{b}) = (\mathbf{b},\mathbf{a}') = (\mathbf{a}',\mathbf{b}) = \frac{\pi}{8}$

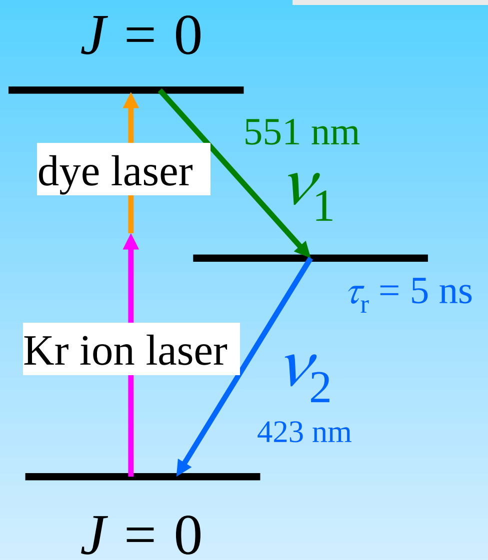


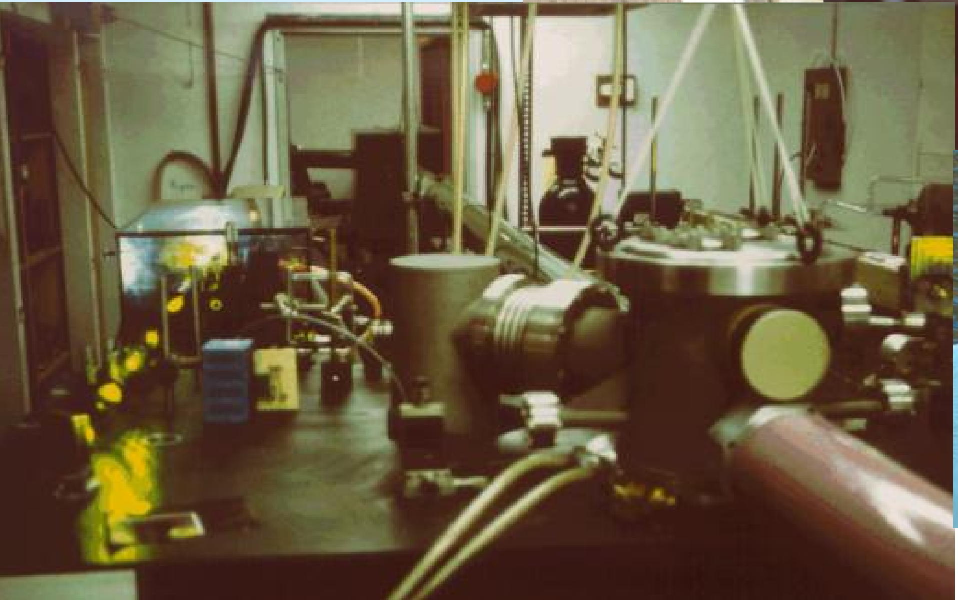
$$S_{\mathrm{QM}} = 2\sqrt{2} = 2.828... > 2$$

Excel Simulation : Alain Vivier

Expérience Alain Aspect 2

The Orsay source of entangled photons

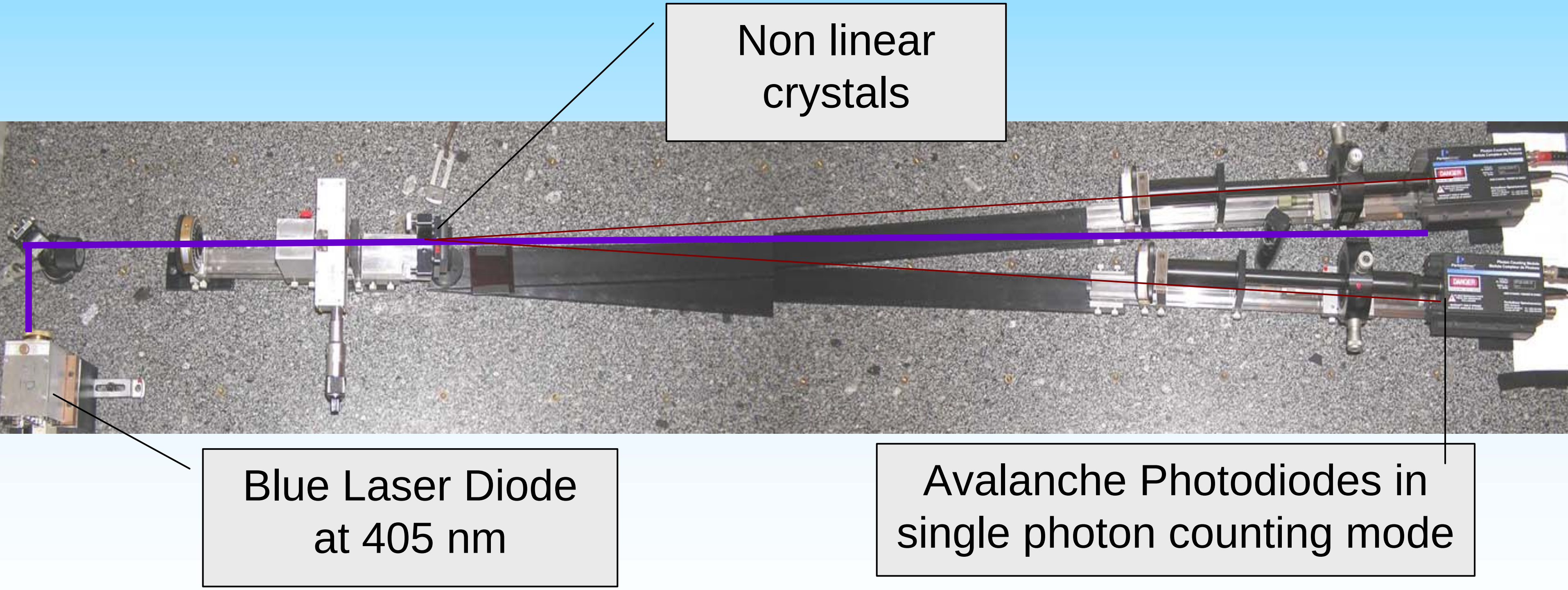




Alain Aspect, Philippe Grangier in Institut d'Optique

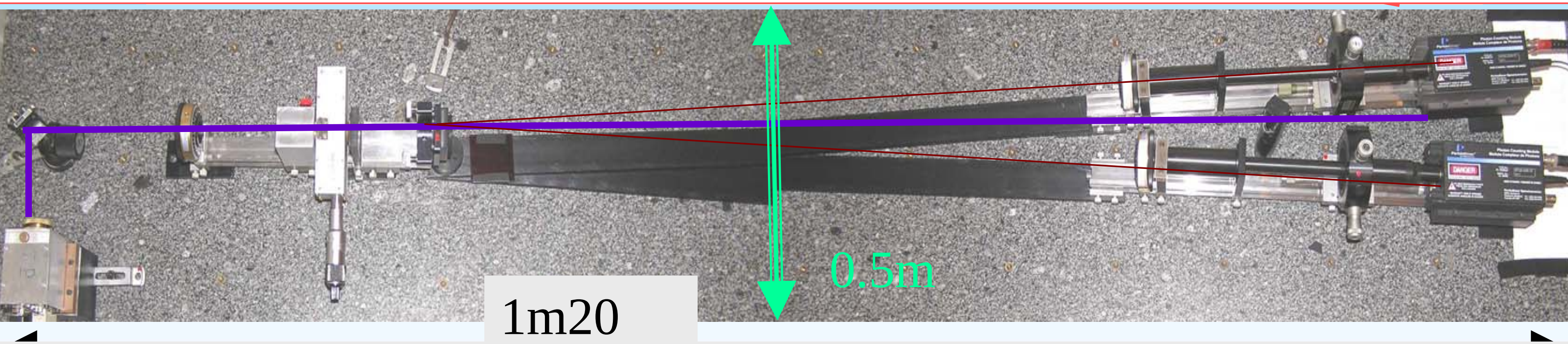
First convincing violations of Bell inequalities

Twenty five years later, due to recent advances in laser diode technology, new techniques for generation of photon pairs and avalanche photodiodes, this experience is now part of the experimental lab course for our students.



Why did we build an entangled photons experiment in our engineering school?

A unique opportunity to deal with entanglement concept and experimental techniques on polarization, non linear effects, photon counting avalanche photodiodes, counting statistics!



Entangled photons, nonlocality and Bell inequalities in the undergraduate laboratory (Dietrich Dehlinger, M. W. Mitchell)
Physics Department, Portland, Oregon
Quantum Physic (27 May 2002)

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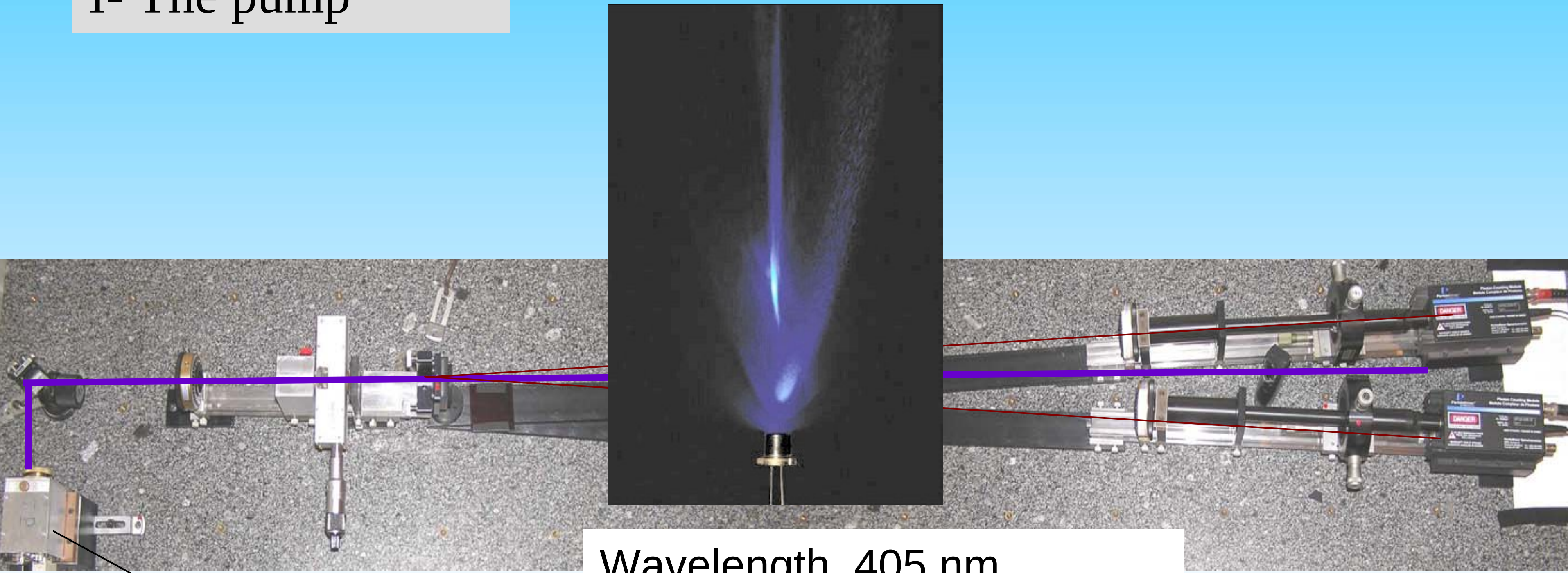
The source of polarization-entangled photon pairs

I- The pump



Blue Laser diode at 405 nm

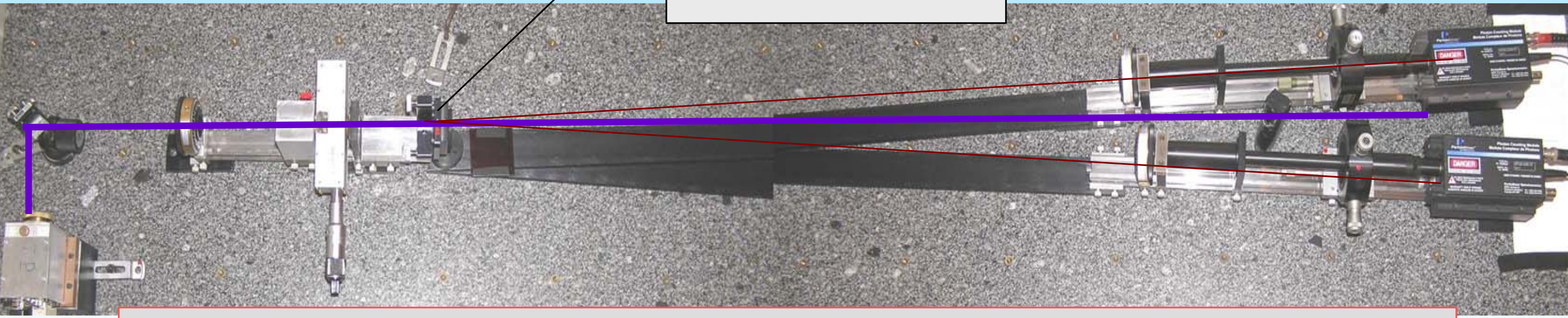
Wavelength 405 nm

Power : 5 mW to 60 mW

$$N_{pump\ photons} = P/h\nu \approx 10^{17} \text{ photons/second}$$

The source of polarization-entangled photon pairs

II- The crystals



Creation of photon pairs : non linear optics

Non linear effect : Spontaneous Parametric Downconversion

Spontaneous Parametric Downconversion
in crystals of β-BBO
Type I Phase Matching

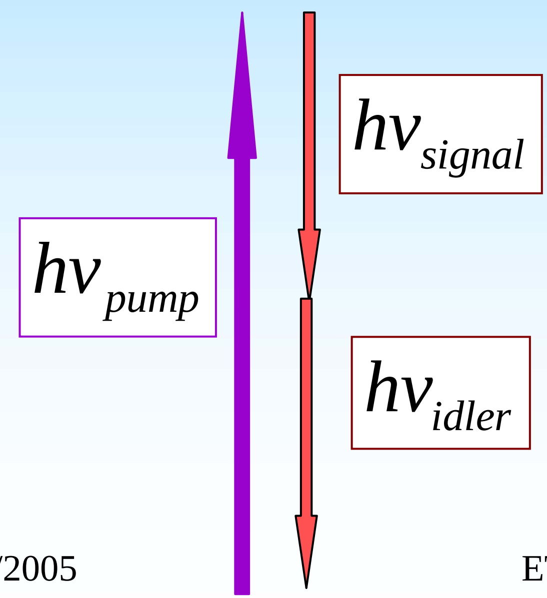
- Energy Conservation :

$$\frac{hc}{\lambda_{pump}} = \frac{hc}{\lambda_{signal}} + \frac{hc}{\lambda_{idler}}$$

$$\lambda_{pump} = 405\ nm$$

$$\lambda_{signal} = 810\ nm$$

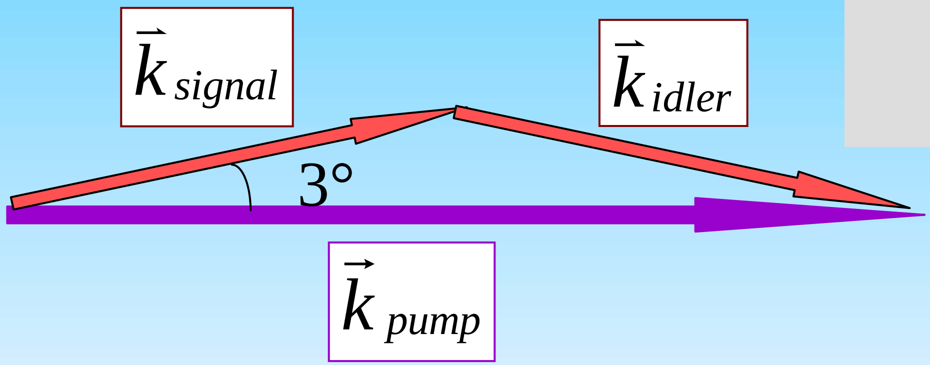
$$\lambda_{iddler} = 810\ nm$$



Degenerate case :
idler and signal have the same wavelength

- Photon momentum conservation :

$$\frac{2\pi n_e}{\lambda_{pump}}\vec{u}_{iddler} = \frac{2\pi n_o}{\lambda_{signal}}\vec{u}_{signal} + \frac{2\pi n_o}{\lambda_{iddler}}\vec{u}_{iddler}$$



β-BBO is birefringent crystal negative uniaxe ($n_e<n_o$)

The crystal is cut with the axis at 30° from pump beam

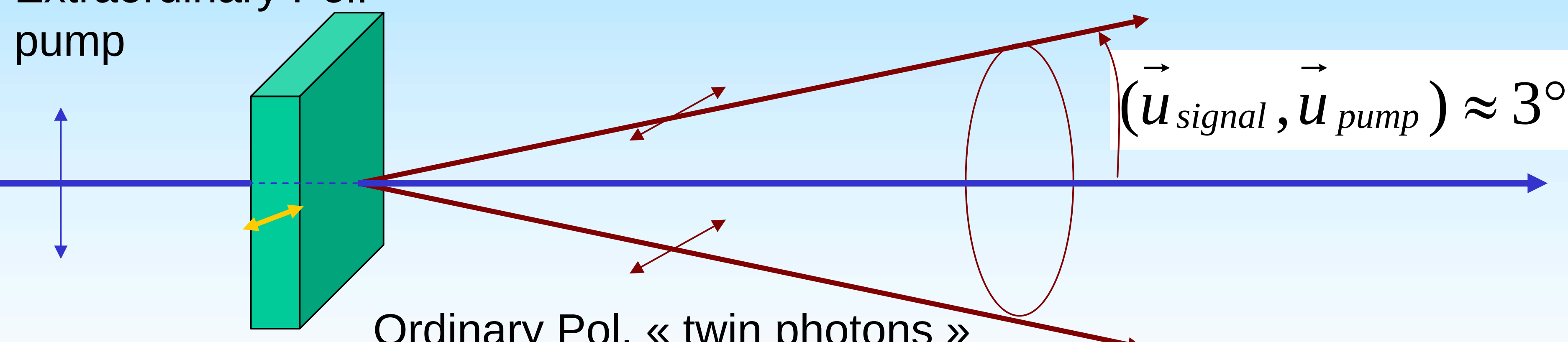
- Type I phase matching : « twin » photons are in the same state of polarization.

β-BBO : type I phase matching

$$\frac{n_e}{\lambda_{405nm}} = 2\frac{n_0}{\lambda_{810nm}}\cos(\vec{u}_{signal}, \vec{u}_{pump})$$

β-BBO is birefringent crystal
negative uniaxe (n_e<n_o)

The crystal is cut with the axis at 30° from pump beam



You get same polarization photon pairs

The source of polarization-entangled photon pairs

2 identical BBO crystals : *the second one is rotated by 90°*

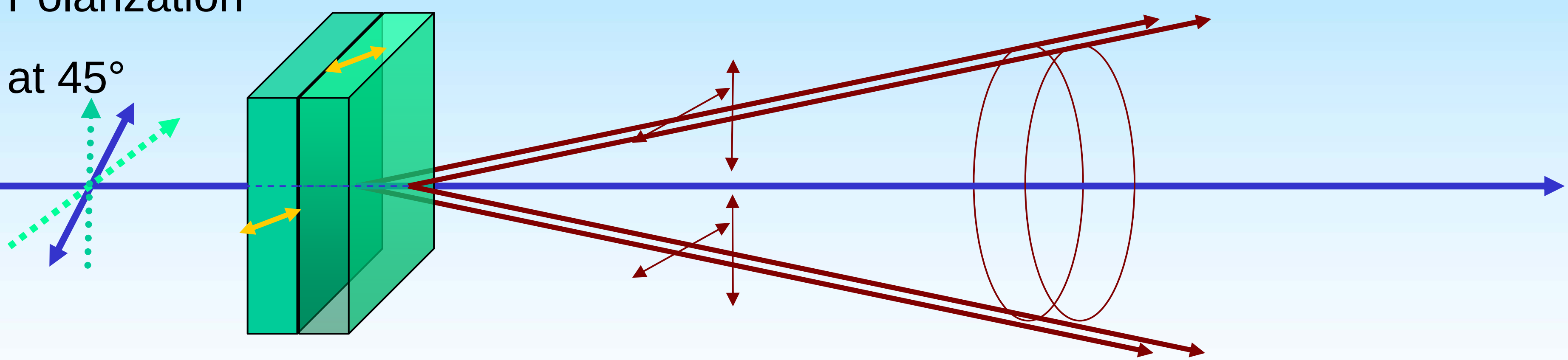
Ultra-bright source of polarization-entangled photons

(Paul G. Kwiat and al., may 1999)

Pump

Polarization

at 45°

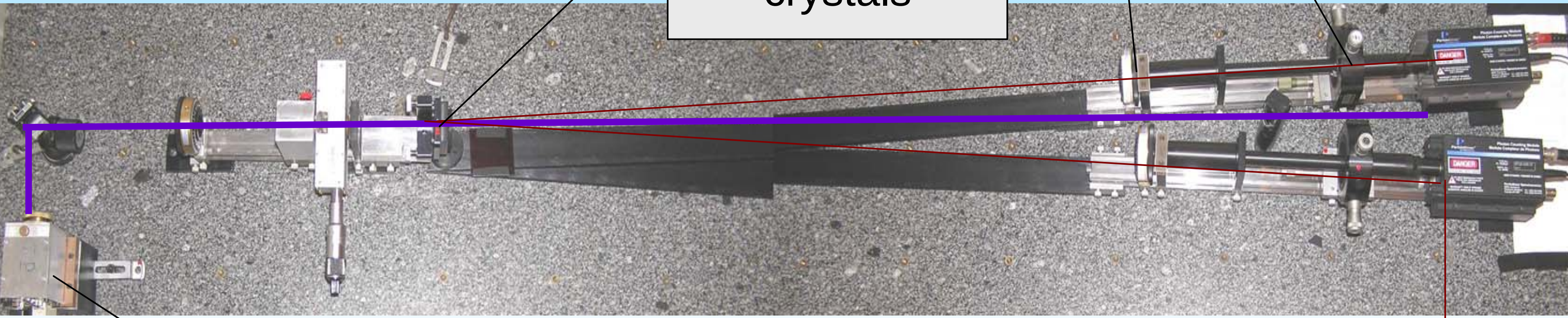


With 2 identical BBO crystals

Axis at 30° from pump beam

5 mm x 5 mm and 0,5 mm thick

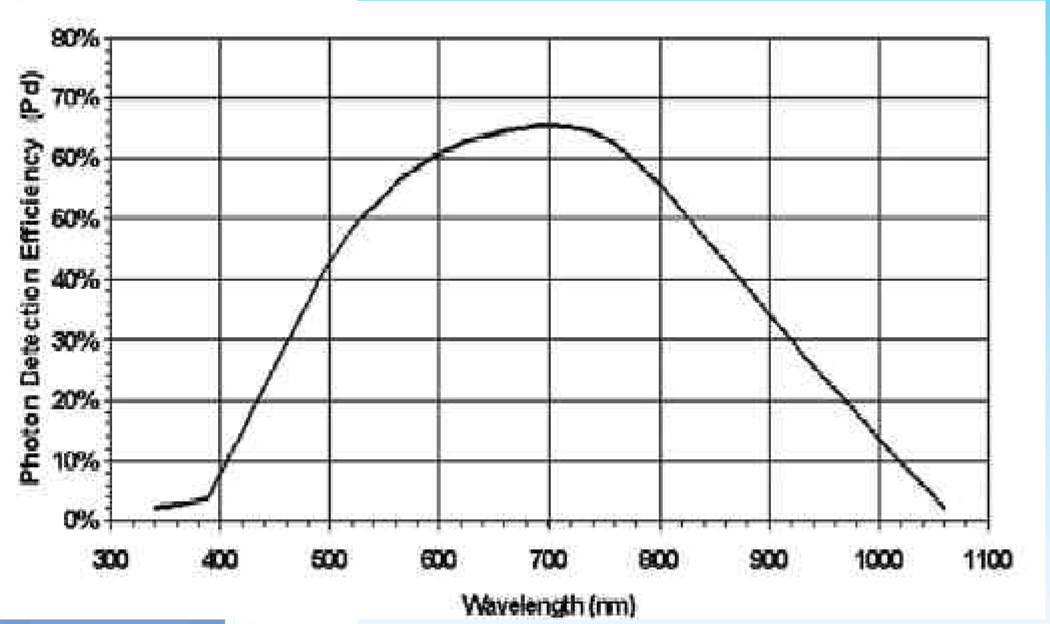
III- The detectors



SPCM avalanche photodiode

Single Photon Counting Module

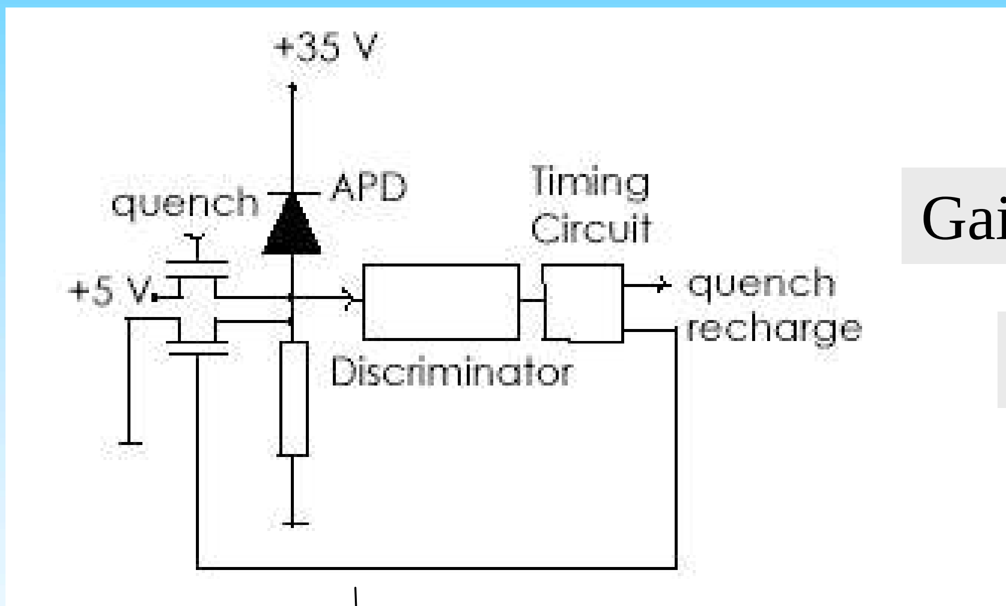
SPCM-AQR Series



Dark counts < 500 cps/s

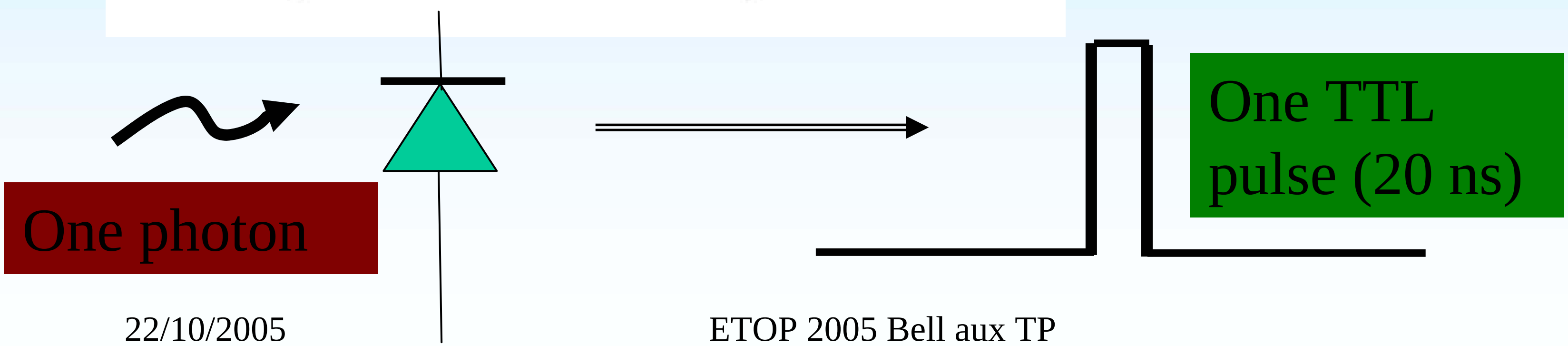
Saturation : $5\ 10^{6}$ cps/s

Active quenching

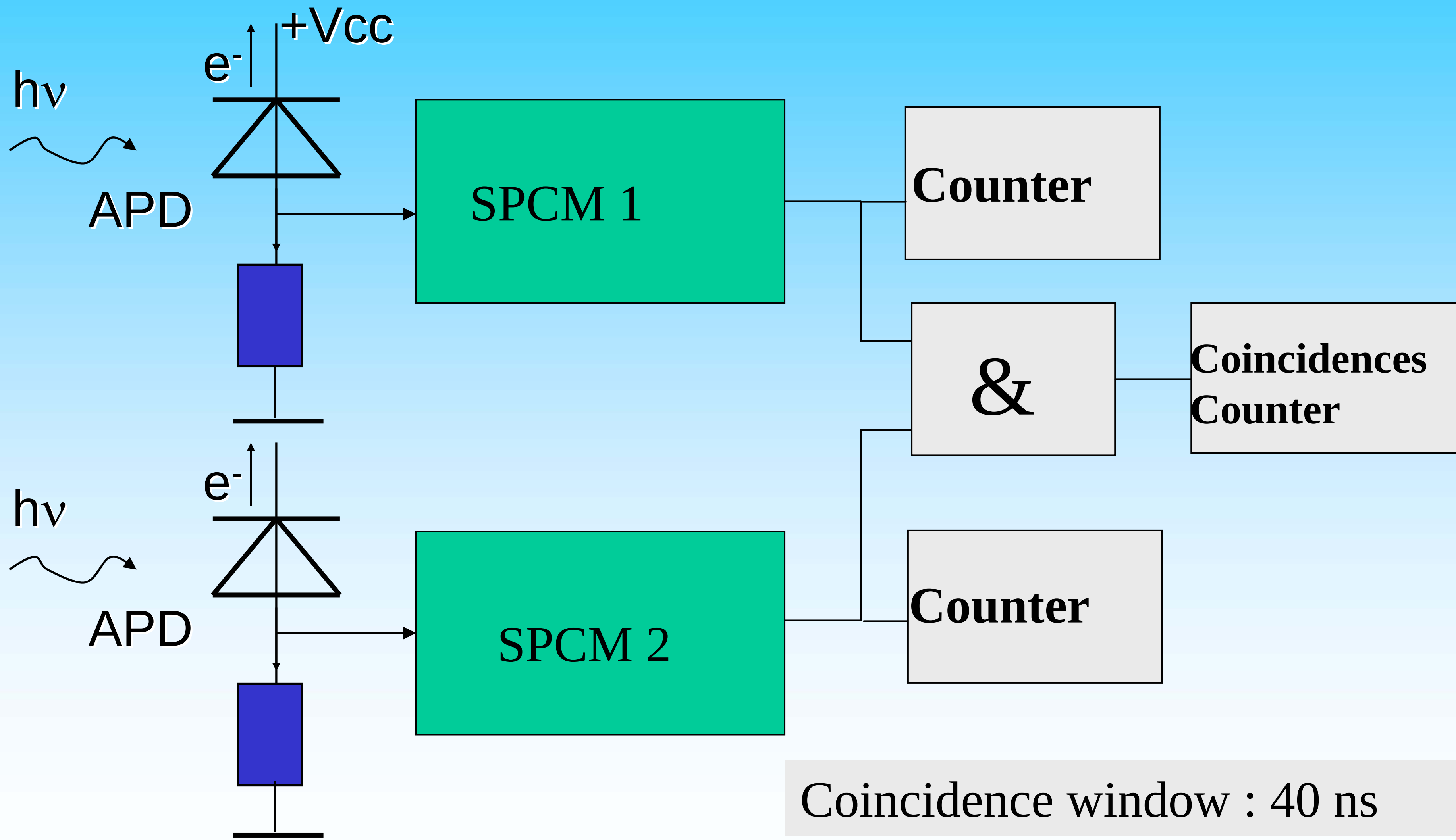


Gain : 10^8 - 10^9

Reset : 75 ns

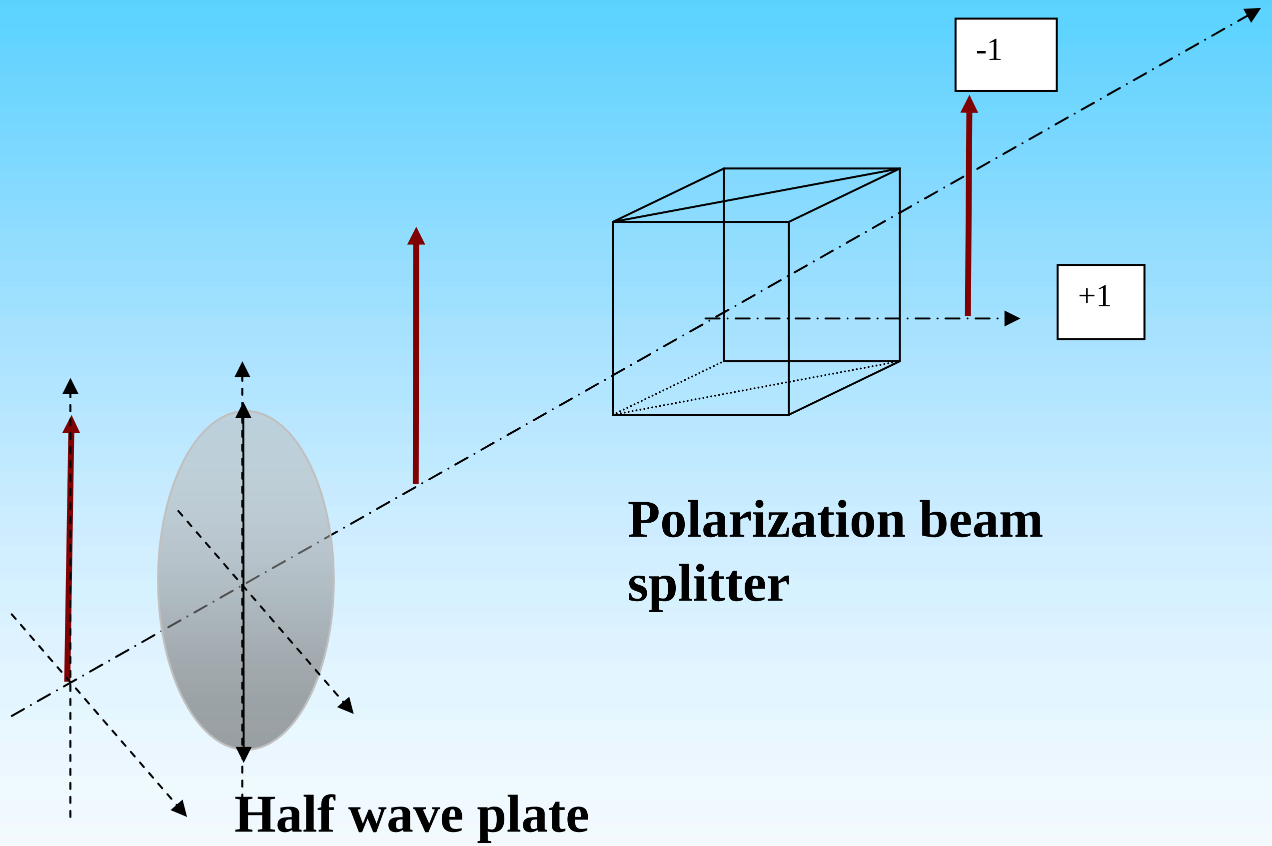


Coincidences Detection

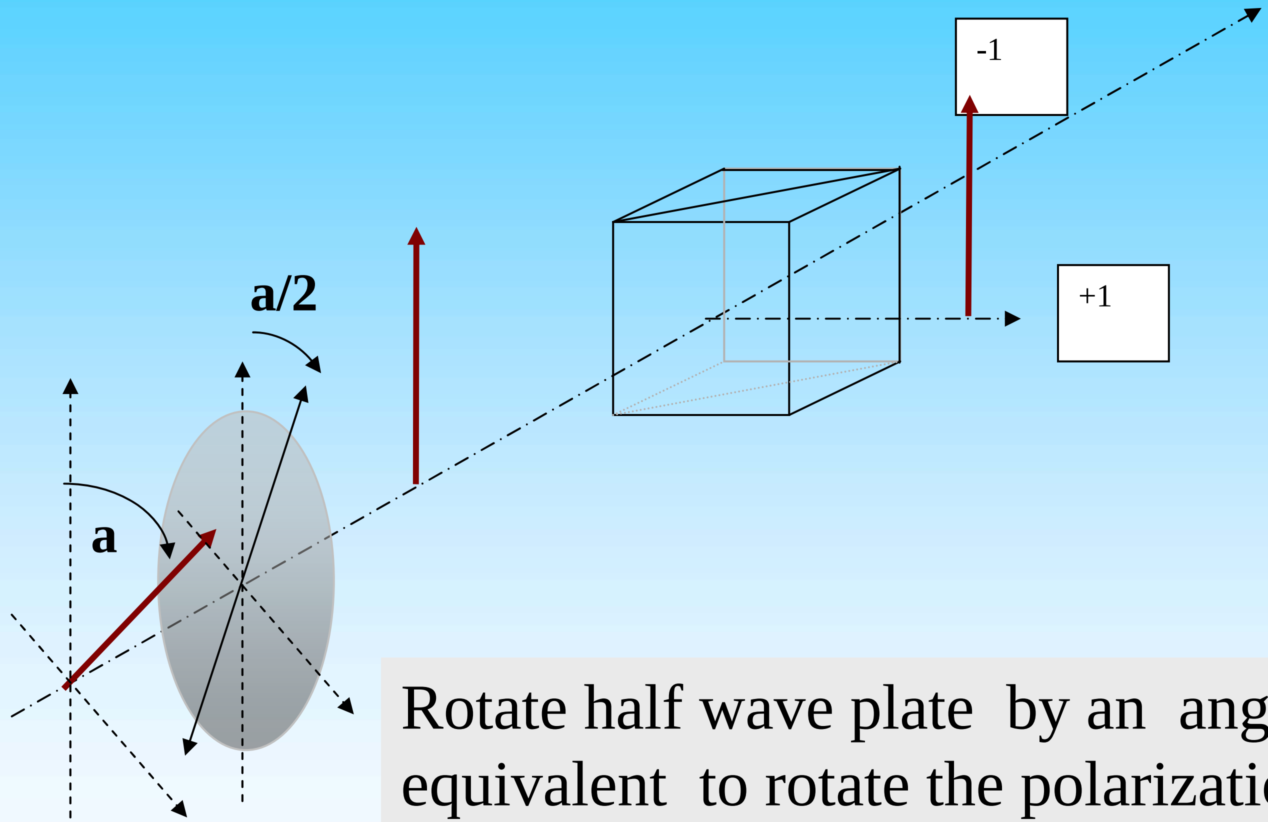


Coincidence window : 40 ns

Polarization analyzers



Polarization analyzers

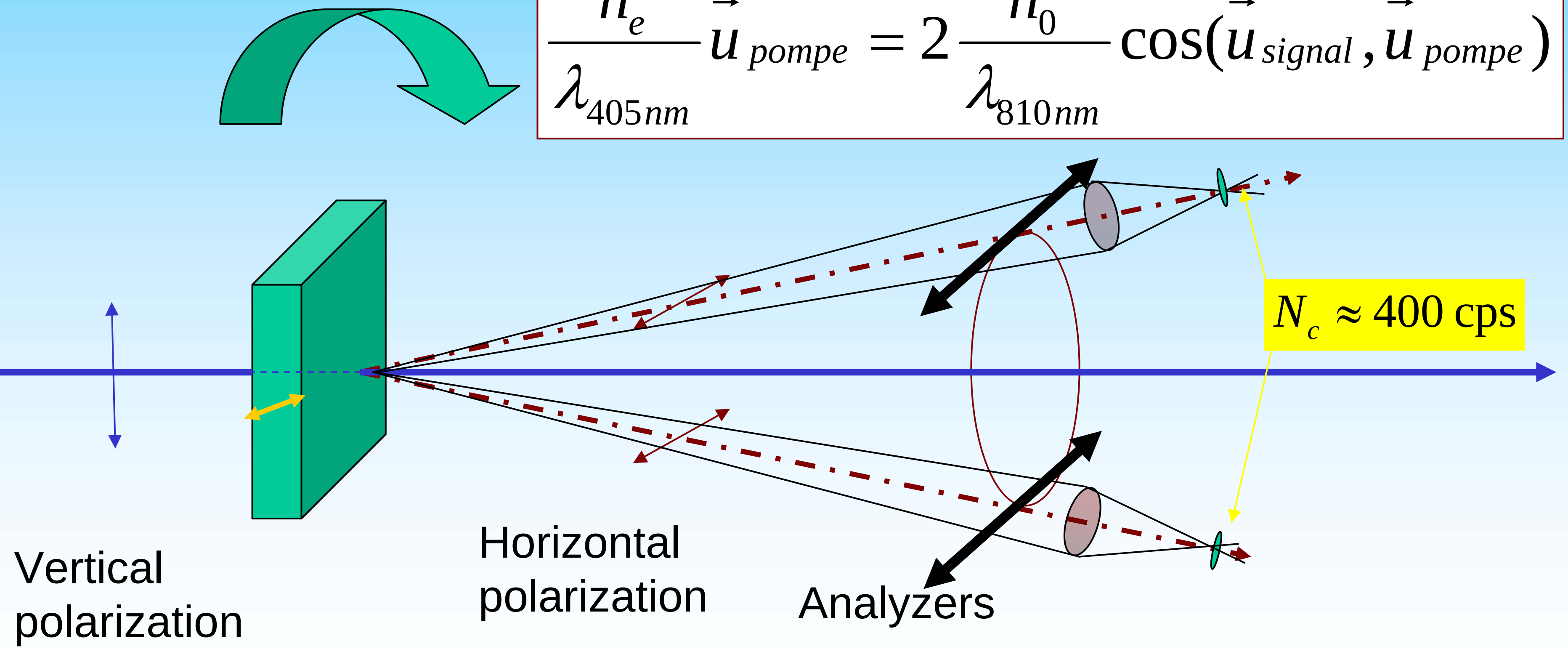


Rotate half wave plate by an angle **a/2** is equivalent to rotate the polarization beam splitter by an angle **a**.

IV- Adjustments of the polarization-entangled photon pair source

Phase matching in the vertical crystal

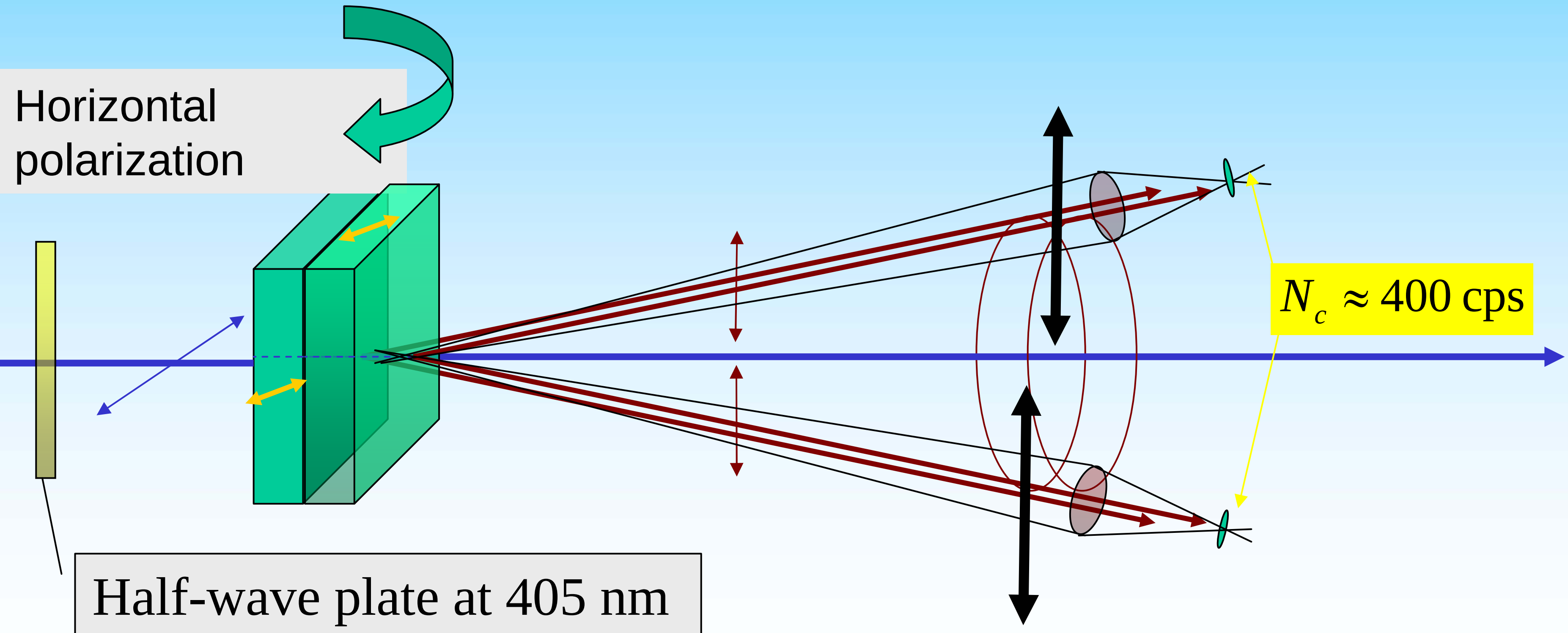
$$\frac{n_e}{\lambda_{405nm}}\vec{u}_{pompe} = 2\frac{n_0}{\lambda_{810nm}}\cos(\vec{u}_{signal}, \vec{u}_{pompe})$$



IV- Adjustments of the polarization-entangled photon pair source

Phase matching in the horizontal crystal

Horizontal polarization

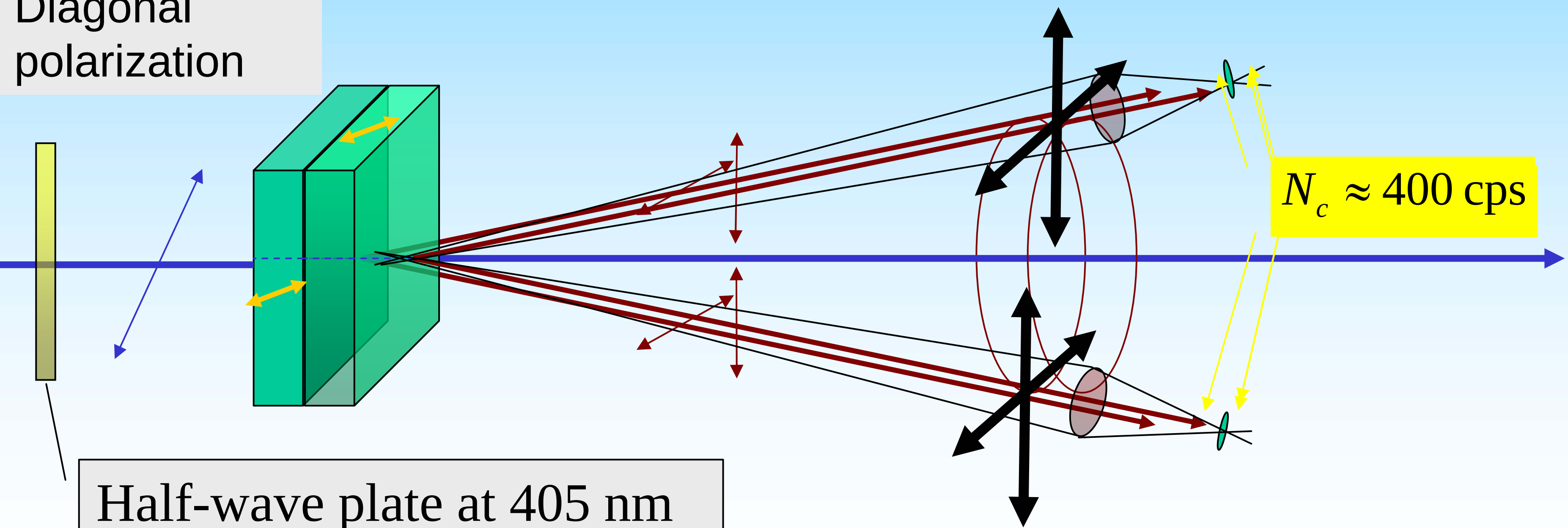


Half-wave plate at 405 nm rotated by 45°

IV- Adjustments of the polarization-entangled photon pair source

We try to count as many vertical pairs as horizontal pairs of entangled photons : *same coincidences rate*

Diagonal polarization



Half-wave plate at 405 nm rotated by 22.5° to get a diagonal pump

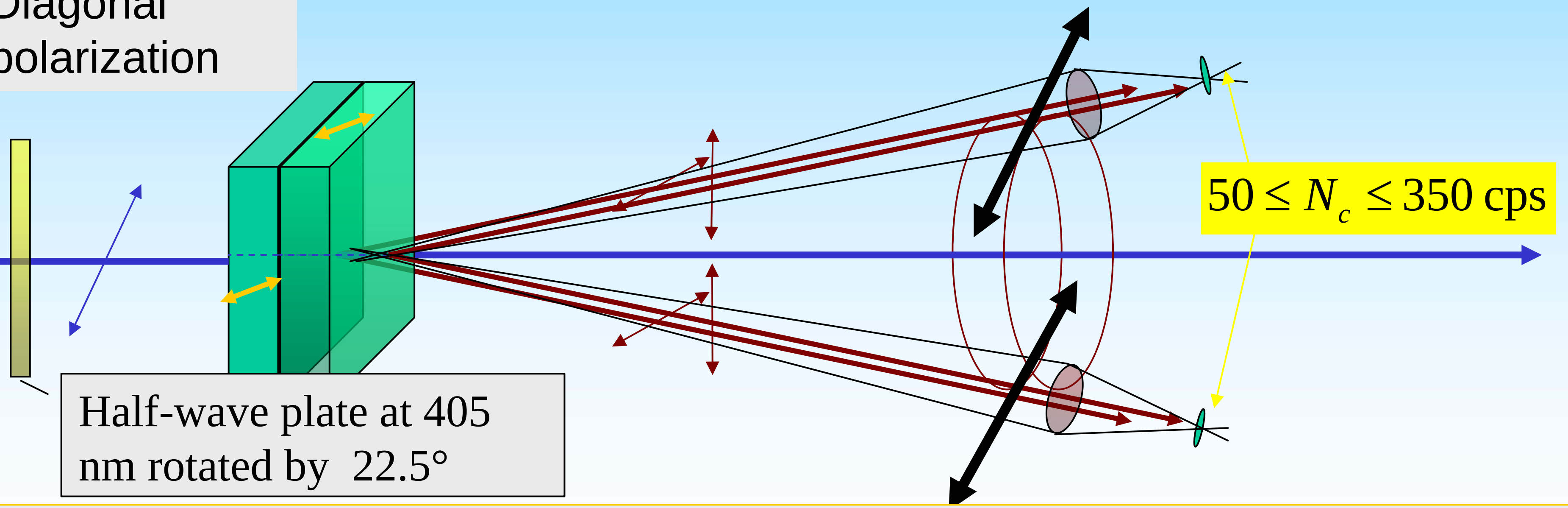
IV- Adjustments of the polarization-entangled photon pair source

But,

when the analyzers are in the diagonal base :

We don't get the same number of photon pairs !

Diagonal polarization



Remember ! EPR state is characterized by a circular symmetry : the joint detections probabilities should always be 0.5 if the analyzers are parallel.

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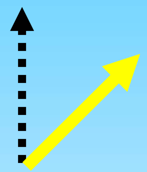
State of the photon pairs !

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + e^{i\phi}\,|H_I\rangle|H_{II}\rangle\right)$$

Phase between the 2 processes of pair creation

Analyzer 1

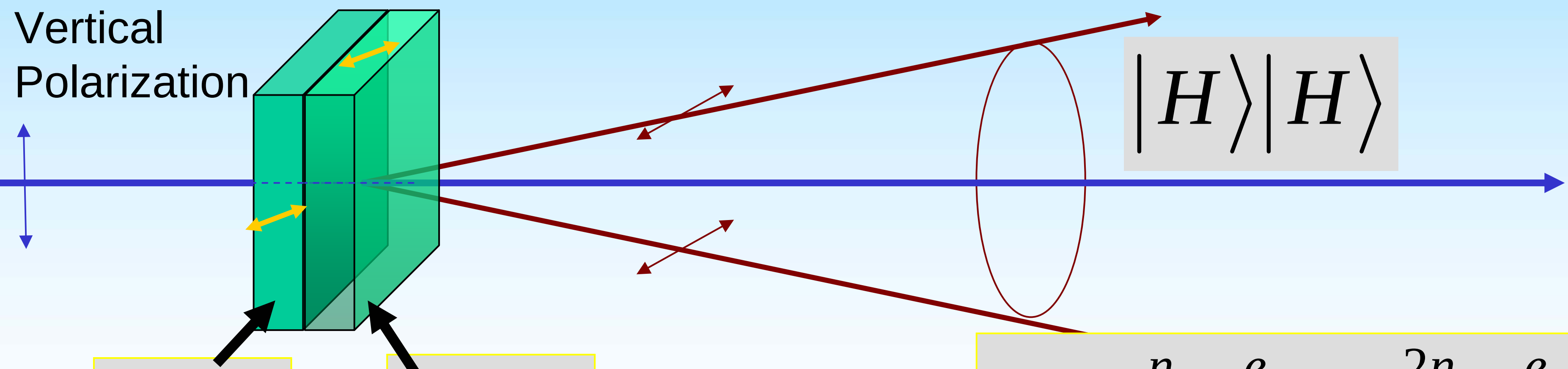


Analyzer 2

$$P(V_{I\,45°}, V_{II\,45°}) = \frac{1}{4}\left(1+\cos\phi\right)$$

Where does this phase between the 2 processes come from ?

Phase between the 2 processes

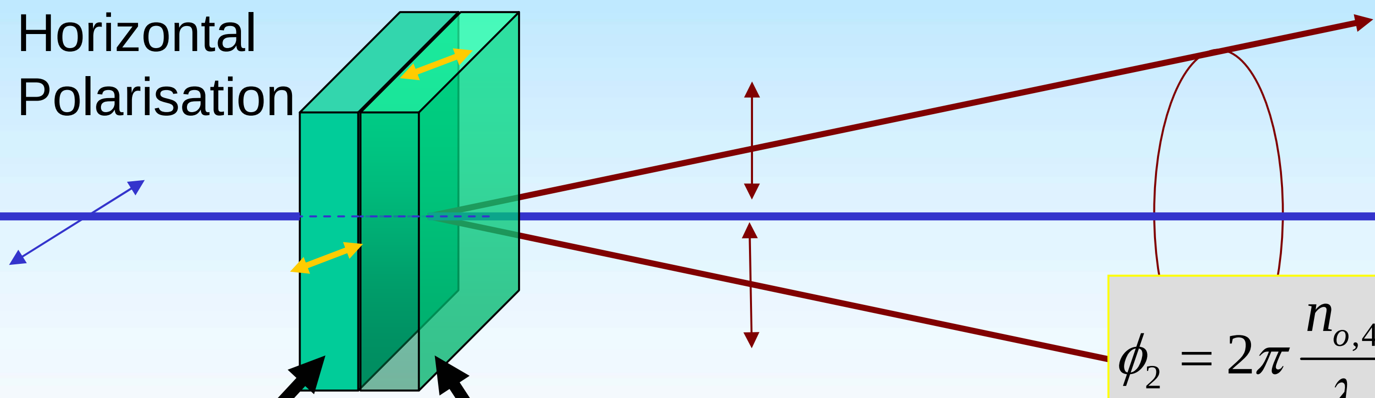


$2\pi \frac{n_{e,405} e_1}{\lambda_{pump}}$ + $2\pi \frac{n_{e,810} e_2}{\lambda_{pair}}$ × 2

$$\phi_1 = 2\pi \frac{n_{e,405} e_1}{\lambda_{pump}} + 2\pi \frac{2 n_{e,810} e_2}{\lambda_{pair}}$$

Phase between the 2 processes

$$\begin{cases} \text{Creation process in the vertical crystal : } \left|V\right\rangle_{pompe} \rightarrow e^{i\phi_1}\left|H_I\right\rangle\left|H_{II}\right\rangle \\ \text{Creation process in the horizontal crystal : } \left|H\right\rangle_{pompe} \rightarrow e^{i\phi_2}\left|V_I\right\rangle\left|V_{II}\right\rangle \end{cases}$$



$$\left|V\right\rangle\left|V\right\rangle$$

$$\phi_2 = 2\pi\frac{n_{o,405}e_1}{\lambda_{pump}} + 2\pi\frac{n_{e,405}e_2}{\lambda_{pump}}$$

$$2\pi\frac{n_{o,405}e_1}{\lambda_{pump}} \quad + \quad 2\pi\frac{n_{e,405}e_2}{\lambda_{pump}}$$

$$\phi_1 = 2\pi\frac{n_{e,405}e_1}{\lambda_{pompe}} + 2\pi\frac{2n_{e,810}e_2}{\lambda_{paires}} \qquad \left|H\right\rangle\left|H\right\rangle$$

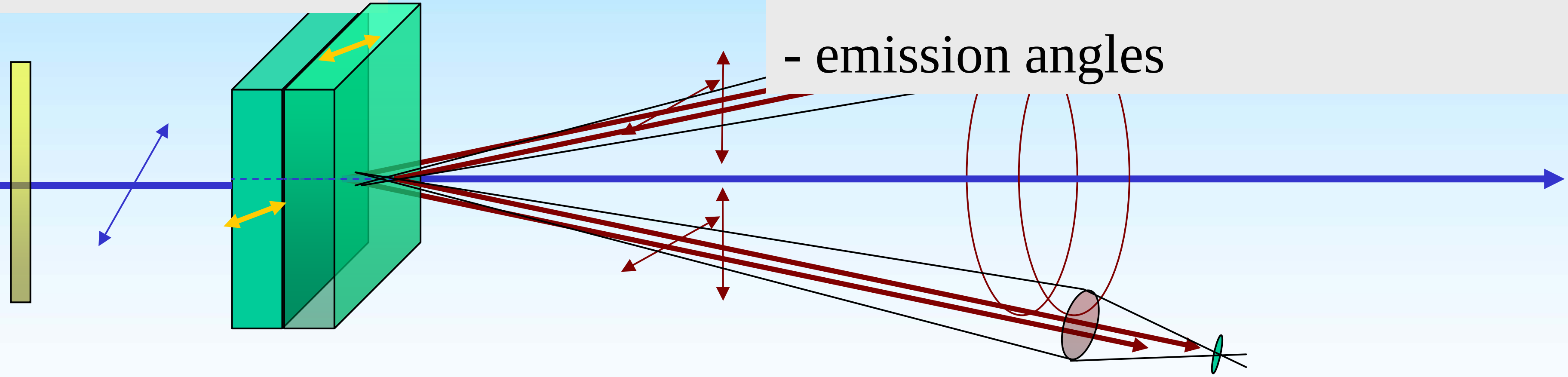
Phase between the 2 processes

$$\phi = \phi_2 - \phi_1 = 2\pi \frac{n_{o,405} e_1}{\lambda_{pump}} + 2\pi \frac{n_{e,405} e_2}{\lambda_{pump}} - 2\pi \frac{n_{e,405} e_1}{\lambda_{pump}} - 2\pi \frac{2 n_{e,810} e_2}{\lambda_{pair}}$$

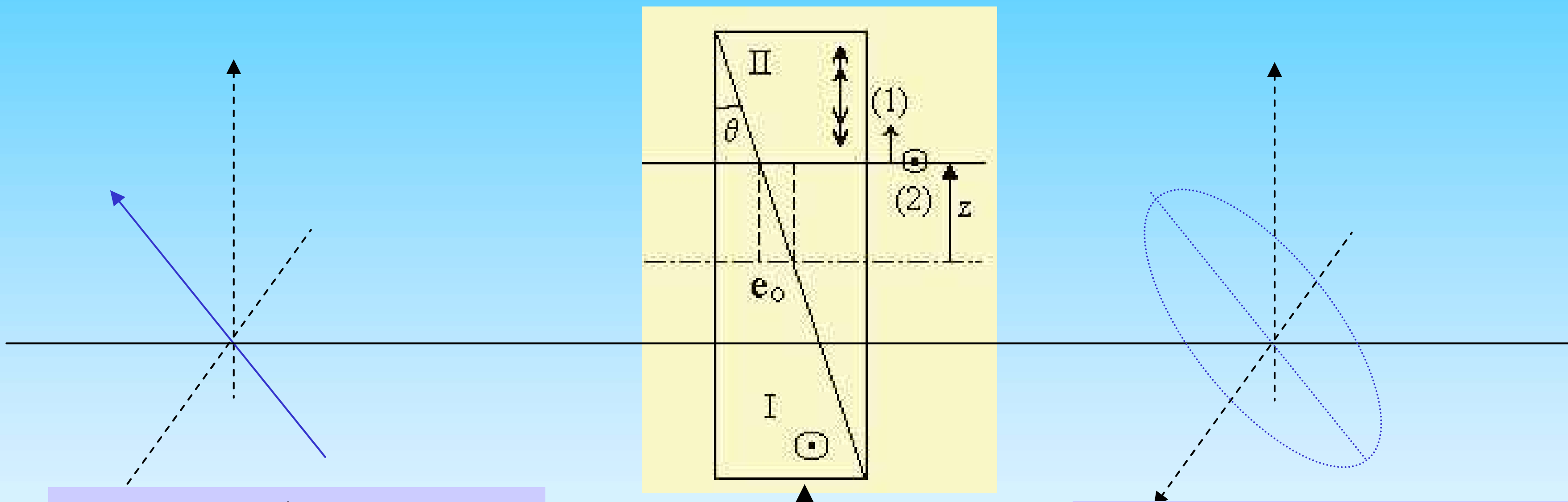
Depends on : - pump wavelength

- photon pairs wavelength
- crystal thicknesses
- emission angles

Diagonal Polarization



Babinet Compensator



$$\left|\psi_{pompe}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|V\right\rangle + \left|H\right\rangle\right)$$

Rectilinear Polarization

$$\left|\psi\right\rangle_{pompe} = \frac{1}{\sqrt{2}}\left(\left|V\right\rangle + \exp(i\phi_{Babinet(z)})\left|H\right\rangle\right)$$

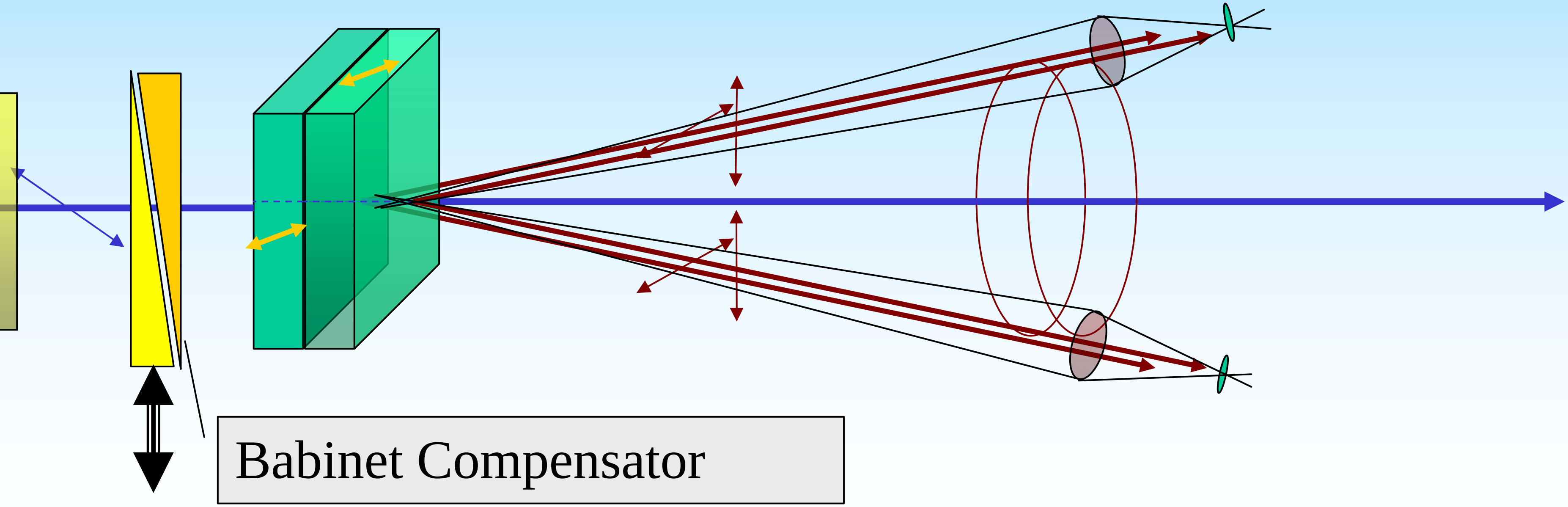
Elliptical Polarization

$$\phi_{pompe} = 2\pi\frac{\delta}{\lambda_{pump}} = 2\pi\frac{2(n_e - n_o)\theta z}{\lambda_{pump}} = 2\pi\frac{z}{z_0}$$

Adjustment of this phase by a Babinet compensator on pump beam

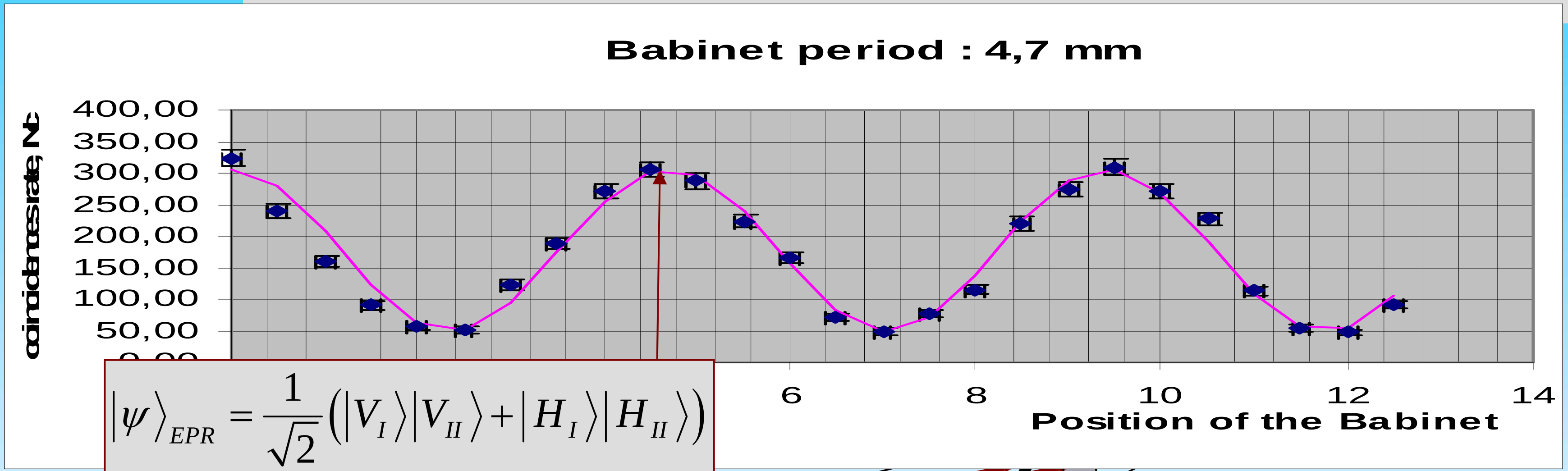
$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|V_I\right\rangle\left|V_{II}\right\rangle + e^{i(\phi+\phi_{Babinet}(z))}\left|H_I\right\rangle\left|H_{II}\right\rangle\right)$$

$$\left|\psi\right\rangle = \left|\psi_{EPR}\right\rangle \; if \;\; \phi + \phi_{Babinet} = 2k\pi$$

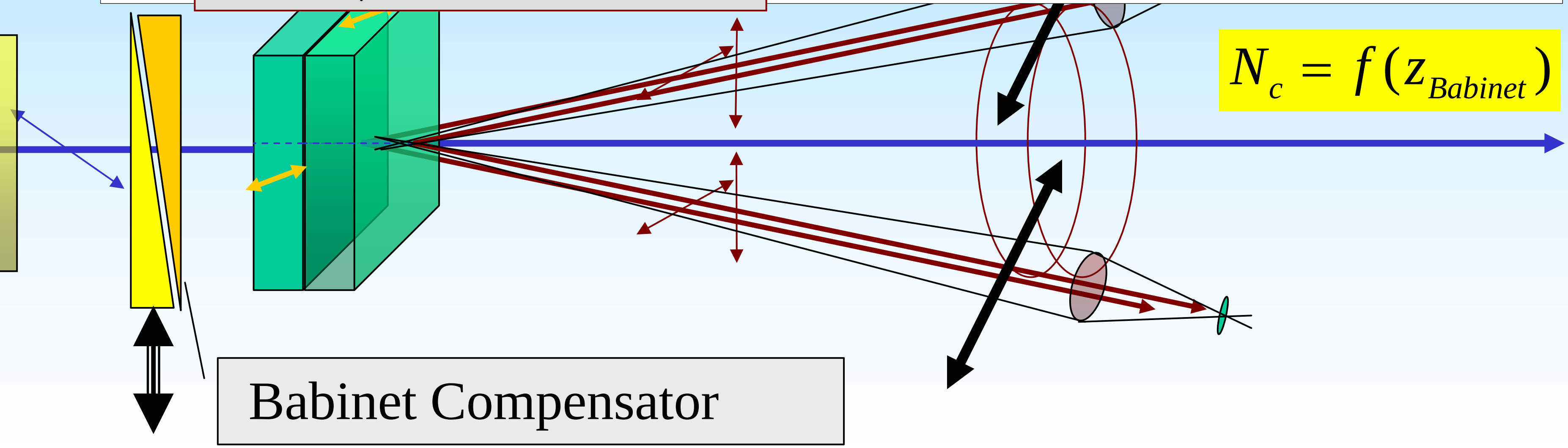


Babinet Compensator

Adjustment of this phase by a Babinet compensator on pump beam



$$|\psi\rangle_{EPR} = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$



$$N_c = f(z_{Babinet})$$

V- A test of Bell inequalities

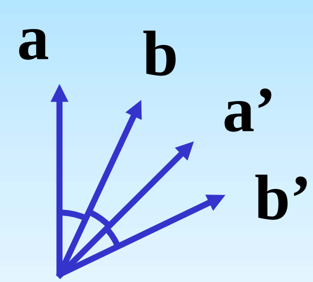
Bell inequalities :

$-2 \le S \le 2$ avec $S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$

Quantum Mechanics $E_{\mathrm{MQ}}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b})$

For the directions $(\mathbf{a},\mathbf{b}) = (\mathbf{b},\mathbf{a}') = (\mathbf{a}',\mathbf{b}) = \frac{\pi}{8}$

$S_{\mathrm{QM}} = 2\sqrt{2} = 2.828... > 2$



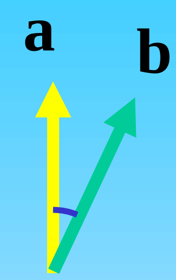
$$E(a,b) = P(a,b) + P(a_\perp,b_\perp) - P(a,b_\perp) - P(a_\perp,b)$$

$$E(a,b) = \frac{N(a,b) + N(a+90,b+90) - N(a,b+90) - N(a+90,b)}{N(a,b) + N(a+90,b+90) + N(a,b+90) + N(a+90,b)}$$

We need 16 coincidences rate measurements to determine S.

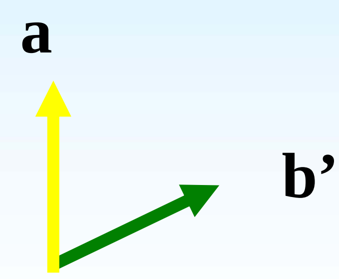
An example of measurements

$$S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$$



T (s)	10

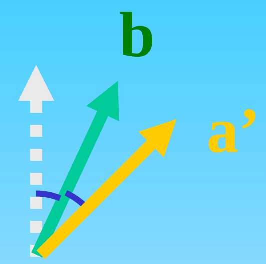
		nc	sigma(nc)	P(a,b)
aV =0°	bV =22,5°	258	5,08	0,390
aH =0°+90°	bH =22,5°+90°	299	5,47	0,452
aH =0°+90°	bV =22,5°	52	2,28	0,079
aV =0°	bH =22,5°+90°	52	2,28	0,079
		661		**0,685**
		nt		E(a,b)



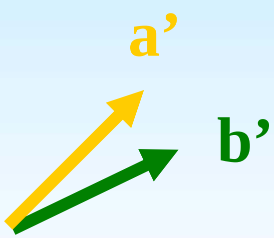
		nc	sigma(nc)	P(a,b')
aV =0°	bV'=67,5°	61	2,47	0,083
aH =0°+90°	bH'=67,5°+90°	57	2,39	0,078
aH =0°+90°	bV'=67,5°	293	5,41	0,401
aV =0°	bH'=67,5°+90°	320	5,66	0,438
		731		**-0,677**
		nt		E(a,b')

$$S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$$

		nc	sigma(nc)	P(a',b)
aV'=45°	bV =22,5°	282	5,31	0,392
aH'=45°+90°	bH =22,5°+90°	270	5,20	0,376
aH'=45°+90°	bV =22,5°	83	2,88	0,115
aV'=45°	bH =22,5°+90°	84	2,90	0,117
		719		**0,535**
		nt		E(a',b)



		nc	sigma(nc)	P(a',b')
aV'=45°	bV'=67,5°	292	5,40	0,401
aH'=45°+90°	bH'=67,5°+90°	280	5,29	0,384
aH'=45°+90°	bV'=67,5°	78	2,79	0,107
aV'=45°	bH'=67,5°+90°	79	2,81	0,108
		729		**0,569**
		nt		E(a',b')



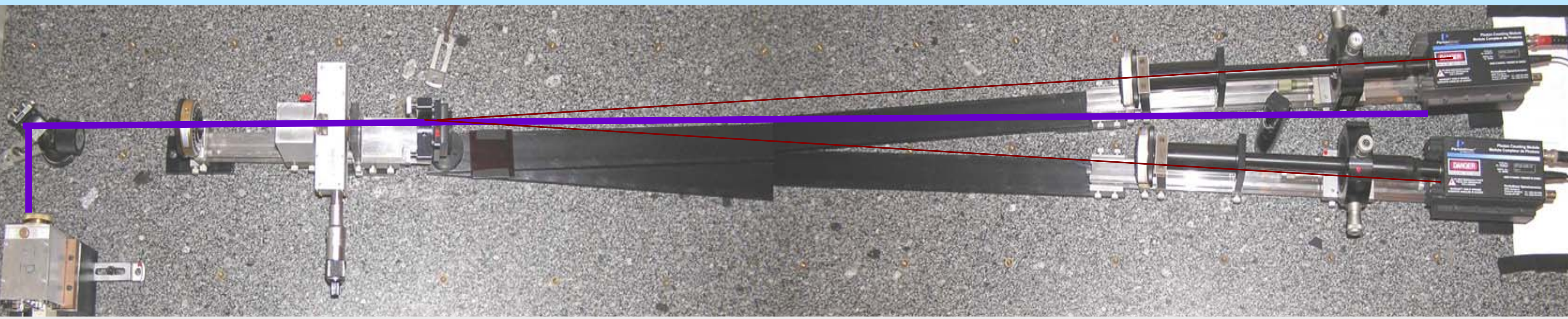
S	**2,467**

S M.Q.	**2,828**

SupOptique

Bohr - Einstein

From gedankenexperiment (1935)



Now a Lab work for students

and a Violation of Bell Inequalities twice a week by them !

http://www.institutoptique.fr/affiche.jsp?folder=ecole_moyens_pedagogiques

Thanks to :

- Alain Aspect
- Philippe Grangier
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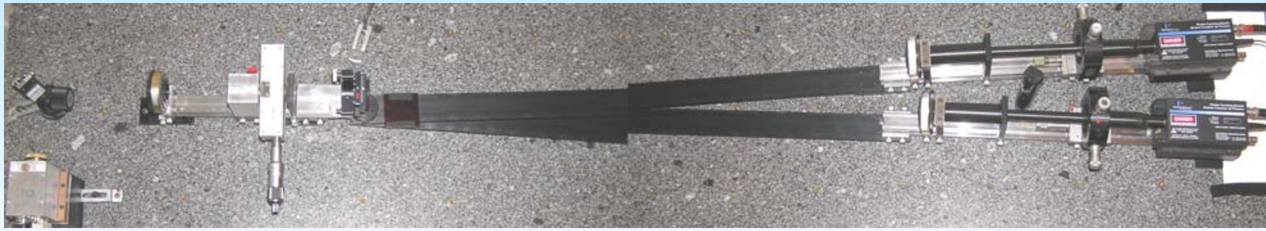
- Thierry Avignon
- Gaetan Messin
- ….



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