Quantum limits of deep space optical communication

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Republic of Poland
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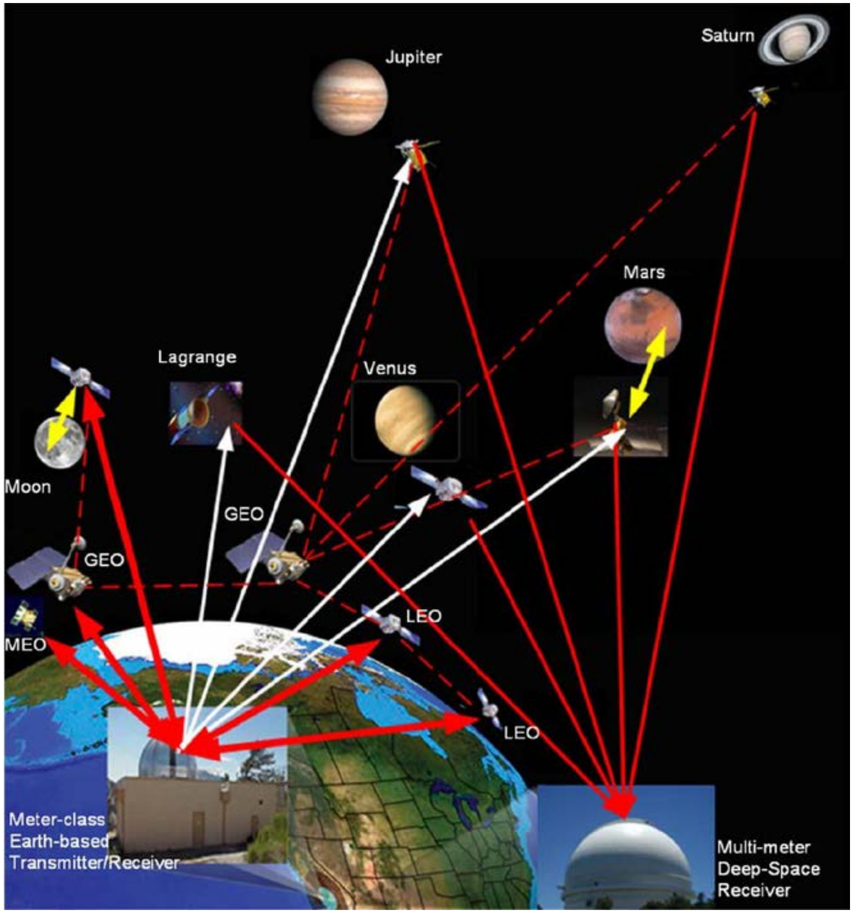
Satellite optical communication



H. Hemmati, A. Biswas, and I. Djordjevic, *Deep-Space Optical Communications: Future Perspectives and Applications*, Proc. IEEE **99**, 2020 (2011)

Optical vs radio frequency communication

Benefits:

- Access to higher bandwidths
- Lower diffraction losses
- Reduced regulatory requirements

Challenges:

- Robustness against atmospheric conditions
- Wall-plug efficiency of onboard transceivers
- Pointing and tracking
- Antenna surface quality

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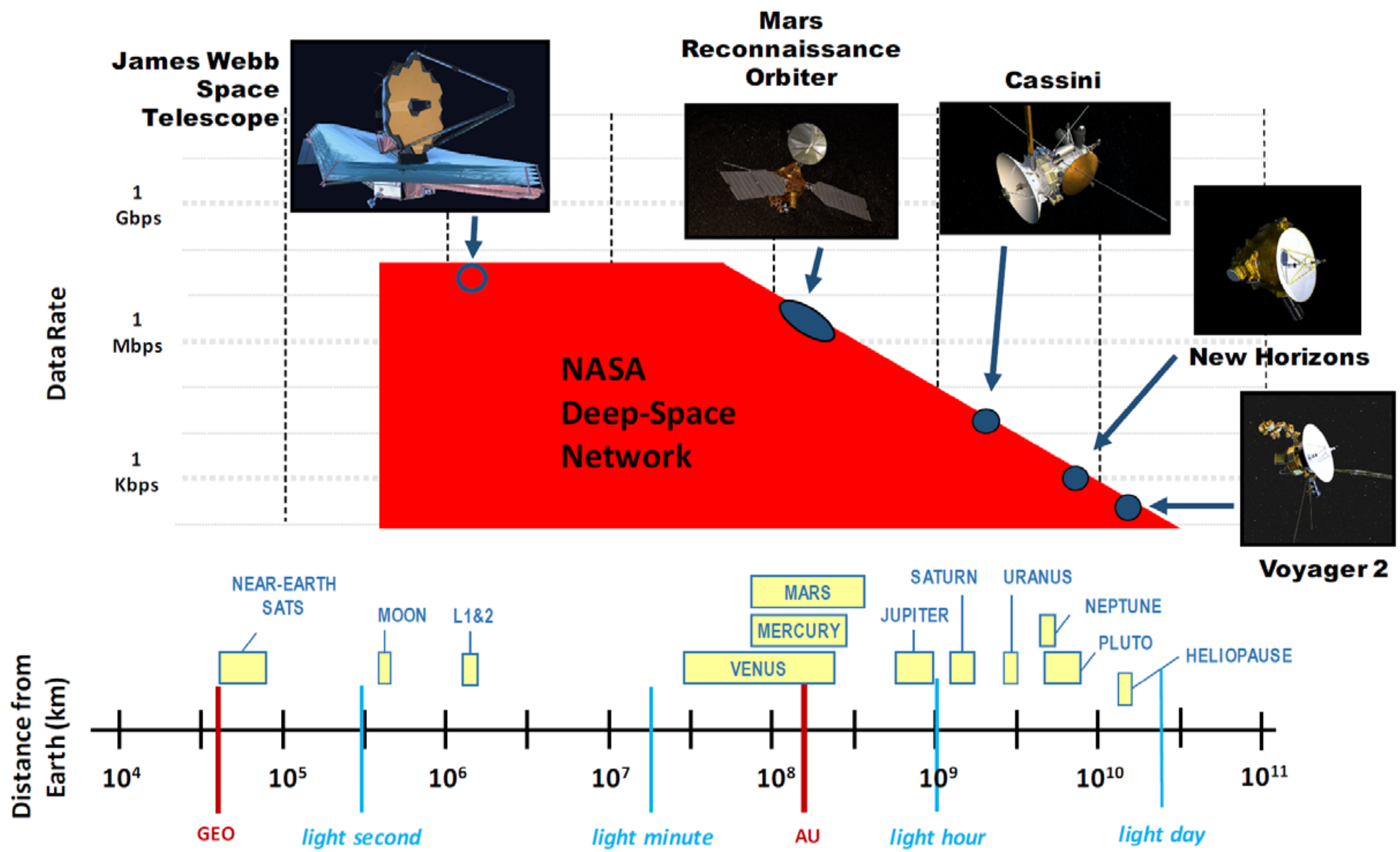
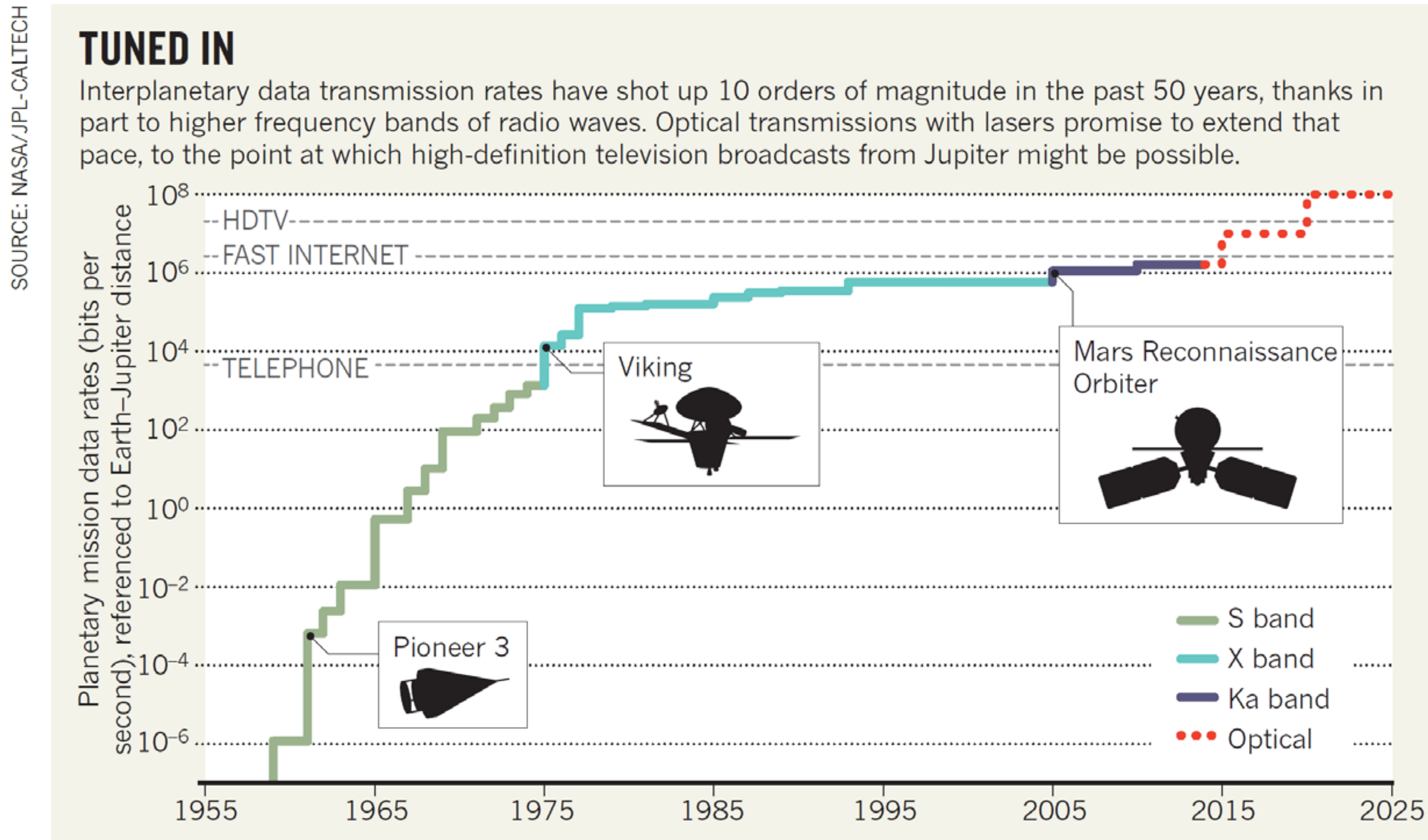
Deep-space rf communication links



D. Boroson, *On achieving high performance optical communications from very deep space*, Proc. SPIE **10524**, 105240B (2018)

Deep-space optical communication

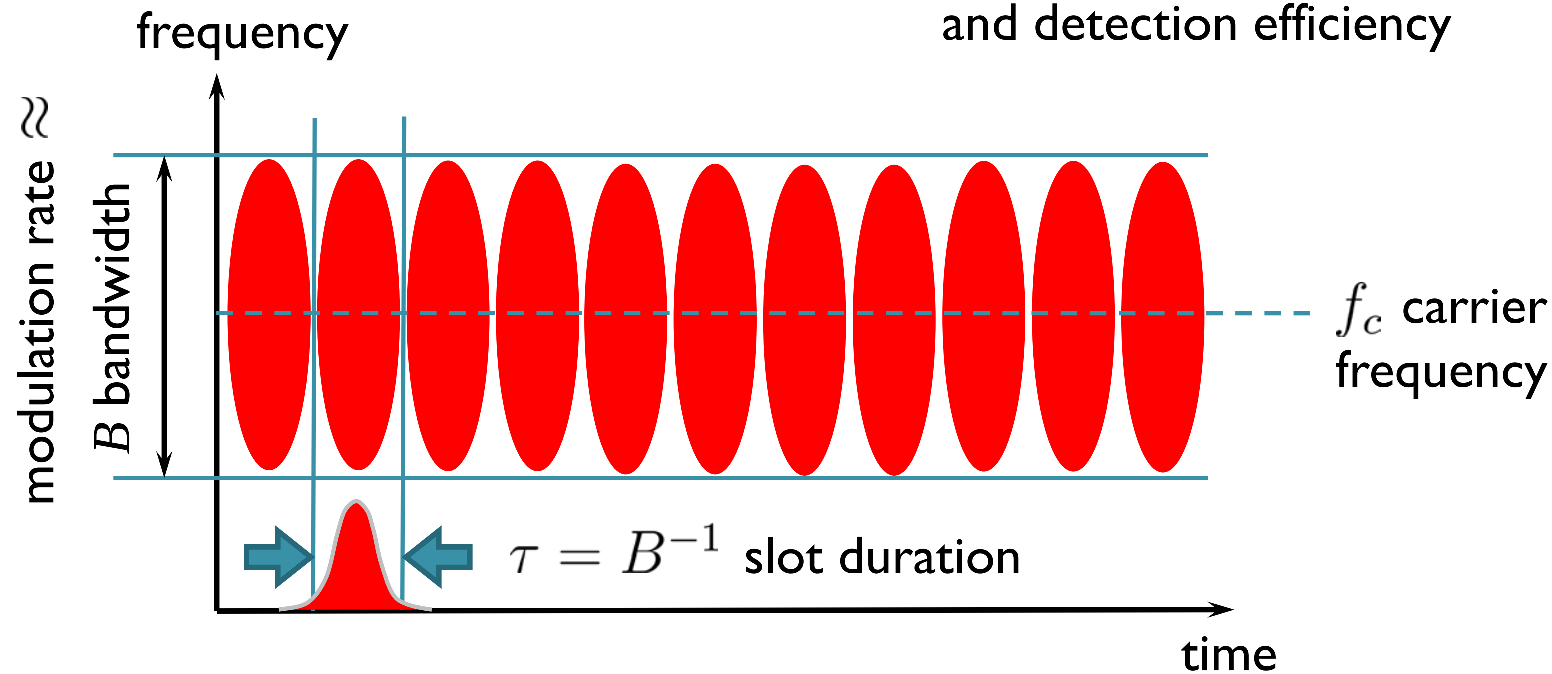


D. Powell, *Lasers boost space communications*, Nature **499**, 266 (2013)

Signal strength

P_{tx} transmitter power

η channel transmission and detection efficiency



Average detected number of photons per slot:

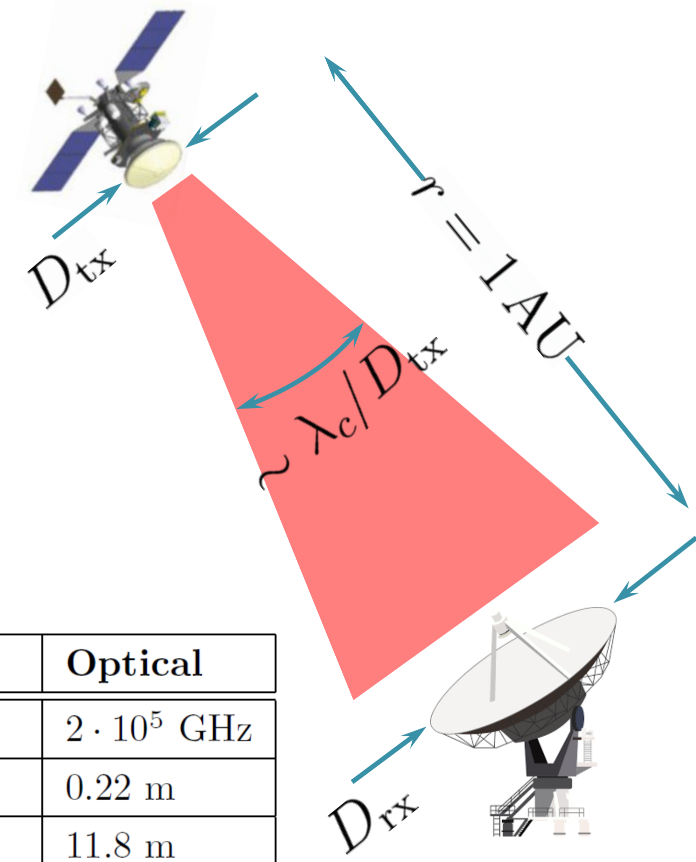
$$n_a = \frac{\eta P_{\text{tx}} \tau}{h f_c} = \frac{1}{h f_c} \cdot \frac{\eta P_{\text{tx}}}{B}$$

Planck's constant $h = 6.626 \times 10^{-34}\ \text{J} \cdot \text{s}$

System characteristics

Channel transmission:

$$\eta_{\mathrm{ch}} = \frac{1}{r^2} \cdot \left(\frac{\pi D_{\mathrm{tx}} D_{\mathrm{rx}}}{4\lambda_c} \right)^2$$



Signal central wavelength $\lambda_c = c/f_c$

Operating regime	RF	Optical
Carrier frequency f_c	32 GHz	$2 \cdot 10^5$ GHz
Transmit antenna diameter D_t	3 m	0.22 m
Receiver antenna diameter D_r	34 m	11.8 m
Channel transmission η_{ch}	$3.29 \cdot 10^{-15}$	$8.32 \cdot 10^{-11}$
Detector efficiency η_{det}	0.1	0.025
Bandwidth B	0.5 GHz	2 GHz
Transmit power P	35 W	4 W
Average output photon number n_a	1.08	0.03
Average noise photon number n_b	66.68	0.03

B. Moision and W. Farr, IPN Prog. Rep. 42-199, 1-10 (2014)

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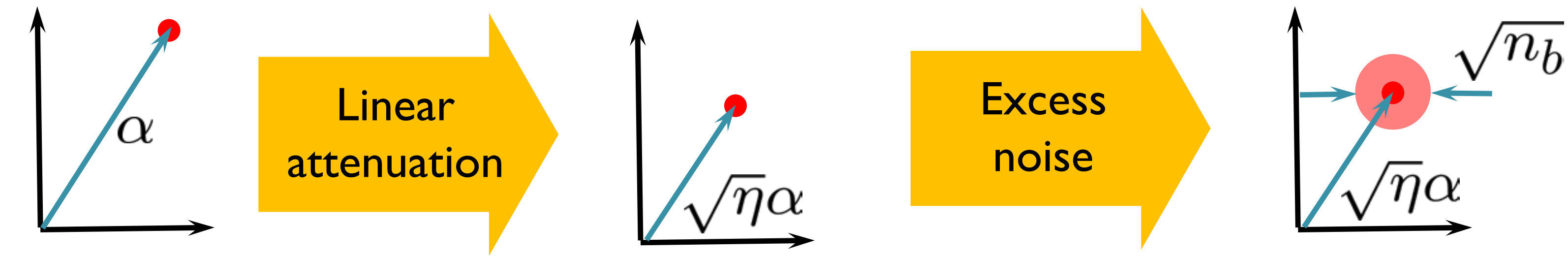
Phase-insensitive Gaussian channel

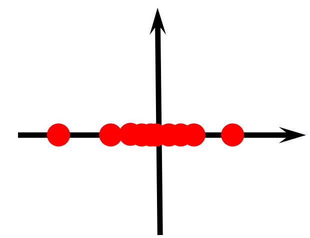


$\bar{n} = \langle |\alpha|^2 \rangle$ $\quad$ $n_a = \eta \bar{n}$ $\quad$ Total: $n_a + n_b$

Shannon-Hartley theorem

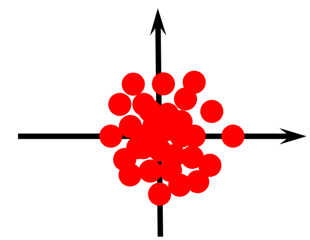
Homodyne capacity per slot

$$C_{\mathrm{hom}} = \frac{1}{2}\log_2\left(1 + \frac{4n_a}{1 + 2n_b}\right)$$



Heterodyne capacity per slot

$$C_{\mathrm{het}} = \log_2\left(1 + \frac{n_a}{1 + n_b}\right)$$



shot-noise limited detection

channel excess noise

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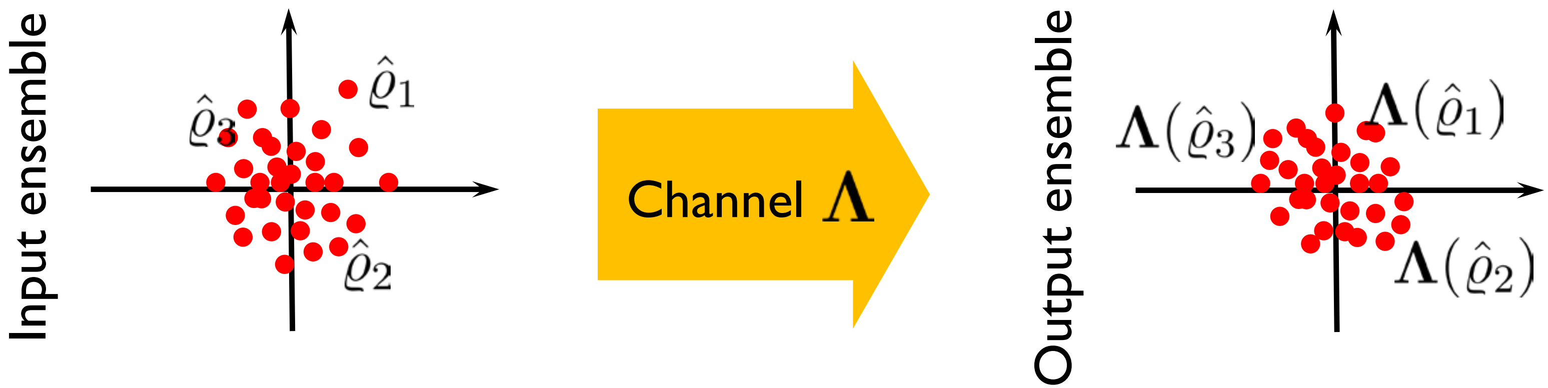
Quantum Shannon theory



Holevo quantity χ**:** for *any* measurement on the output ensemble

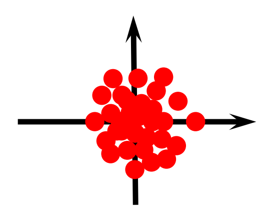
$$\mathsf{I} \leq \chi = \mathsf{S}\left(\sum_i p_i \mathbf{\Lambda}(\hat{\varrho}_i)\right) - \sum_i p_i \mathsf{S}(\mathbf{\Lambda}(\hat{\varrho}_i))$$

where $\mathsf{S}(\hat{\varrho}) = -\mathrm{Tr}(\hat{\varrho}\log_2\hat{\varrho})$ is the von Neumann entropy.

For a phase-insensitive Gaussian channel under average power constraint:

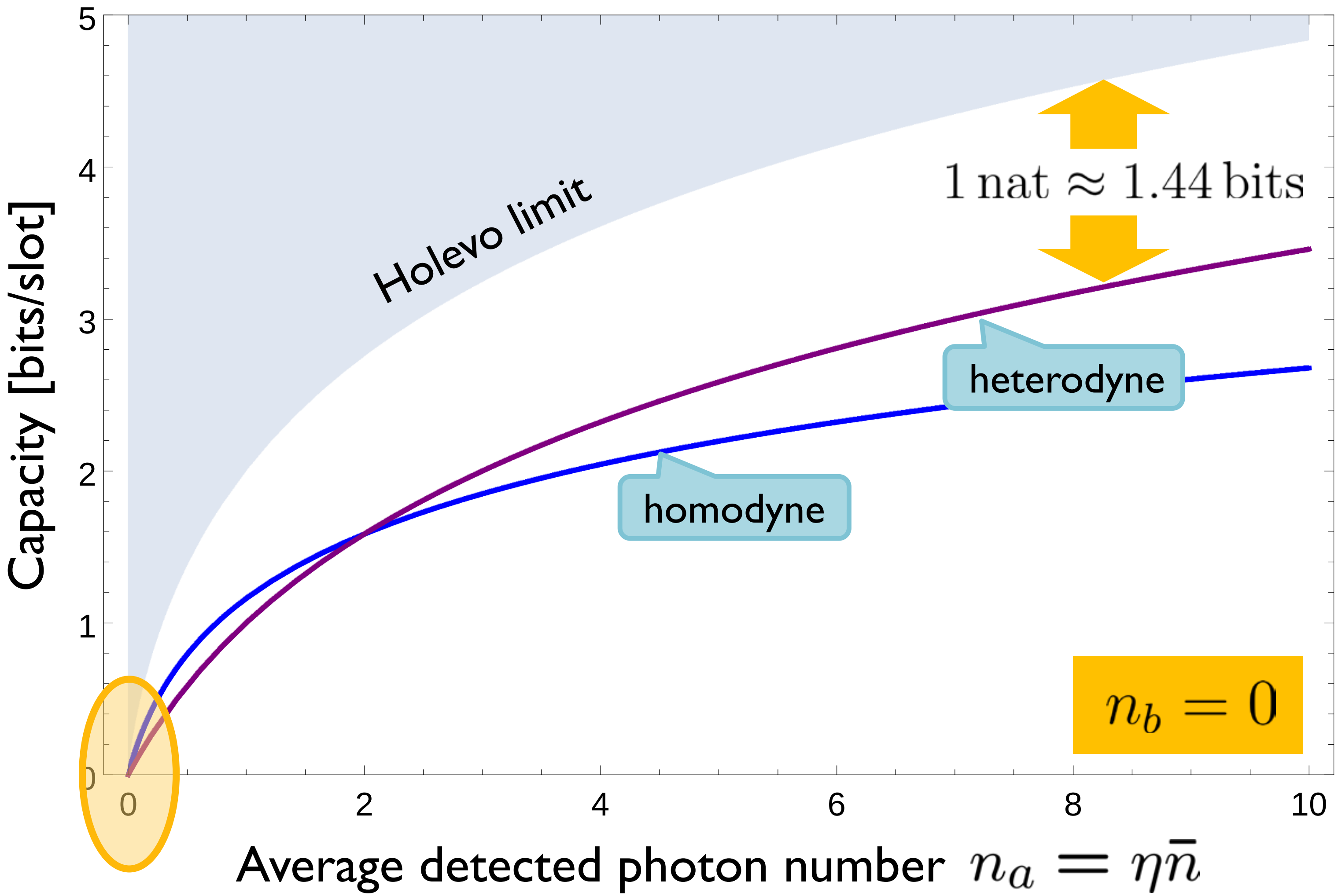
$$\mathsf{C}_{\mathrm{Hol}} = g(n_a + n_b) - g(n_b)$$

where $g(x) = (x+1)\log_2(x+1) - x\log_2 x$



V. Giovannetti, R. García-Patrón, N. J. Cerf, A. S. Holevo, Nature Photon. **8**, 796 (2014)

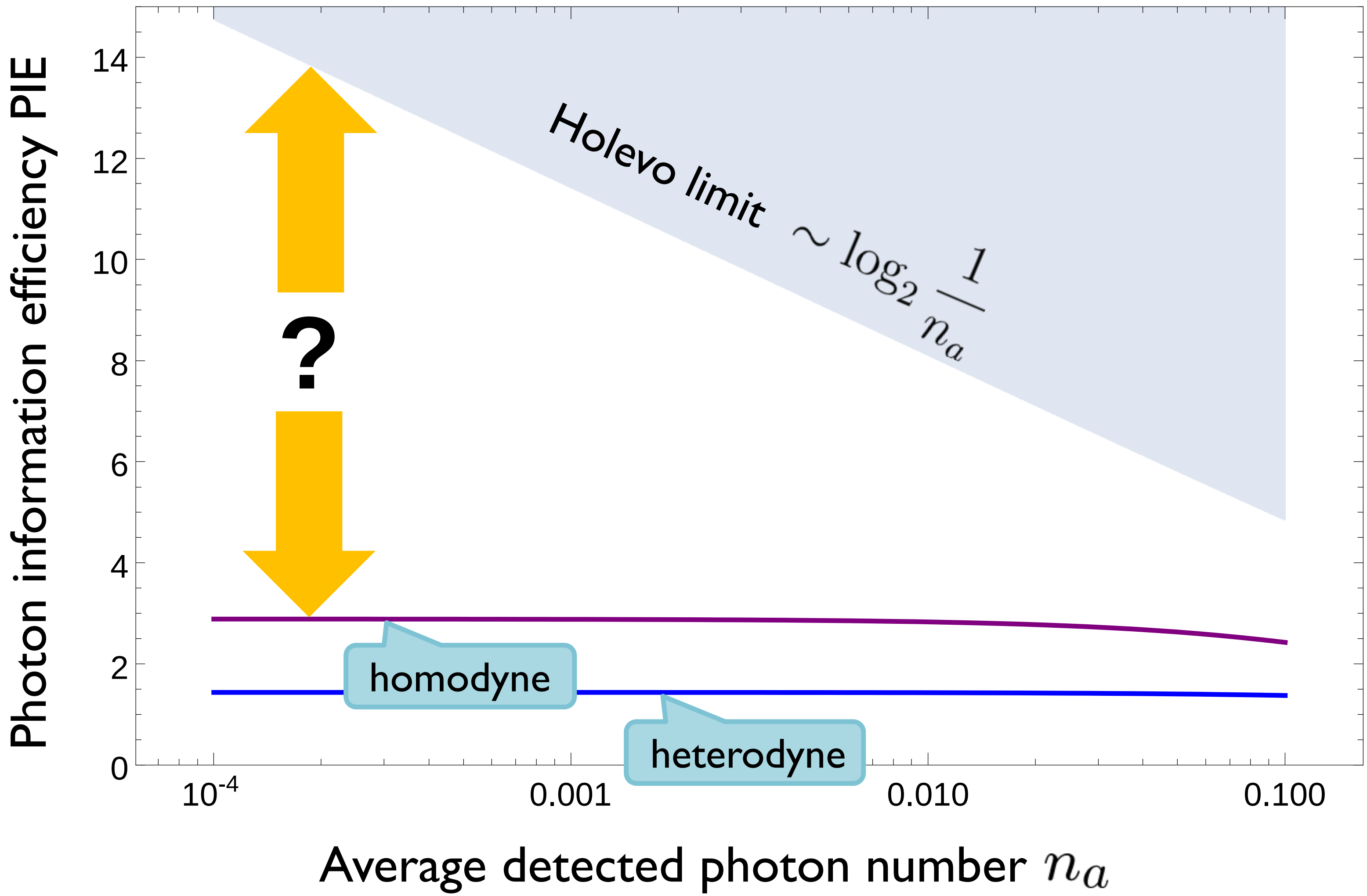
Pure loss channel



$$\mathrm{C}_{\mathrm{Hol}} - \mathrm{C}_{\mathrm{het}} = n_a \log_2\left(1 + \frac{1}{n_a}\right) \xrightarrow[n_a \gg 0]{} \log_2 e$$

Photon information efficiency

Information rate [bits/s]: $R = B \cdot \mathsf{C} = B \cdot n_a \cdot \mathsf{PIE}$



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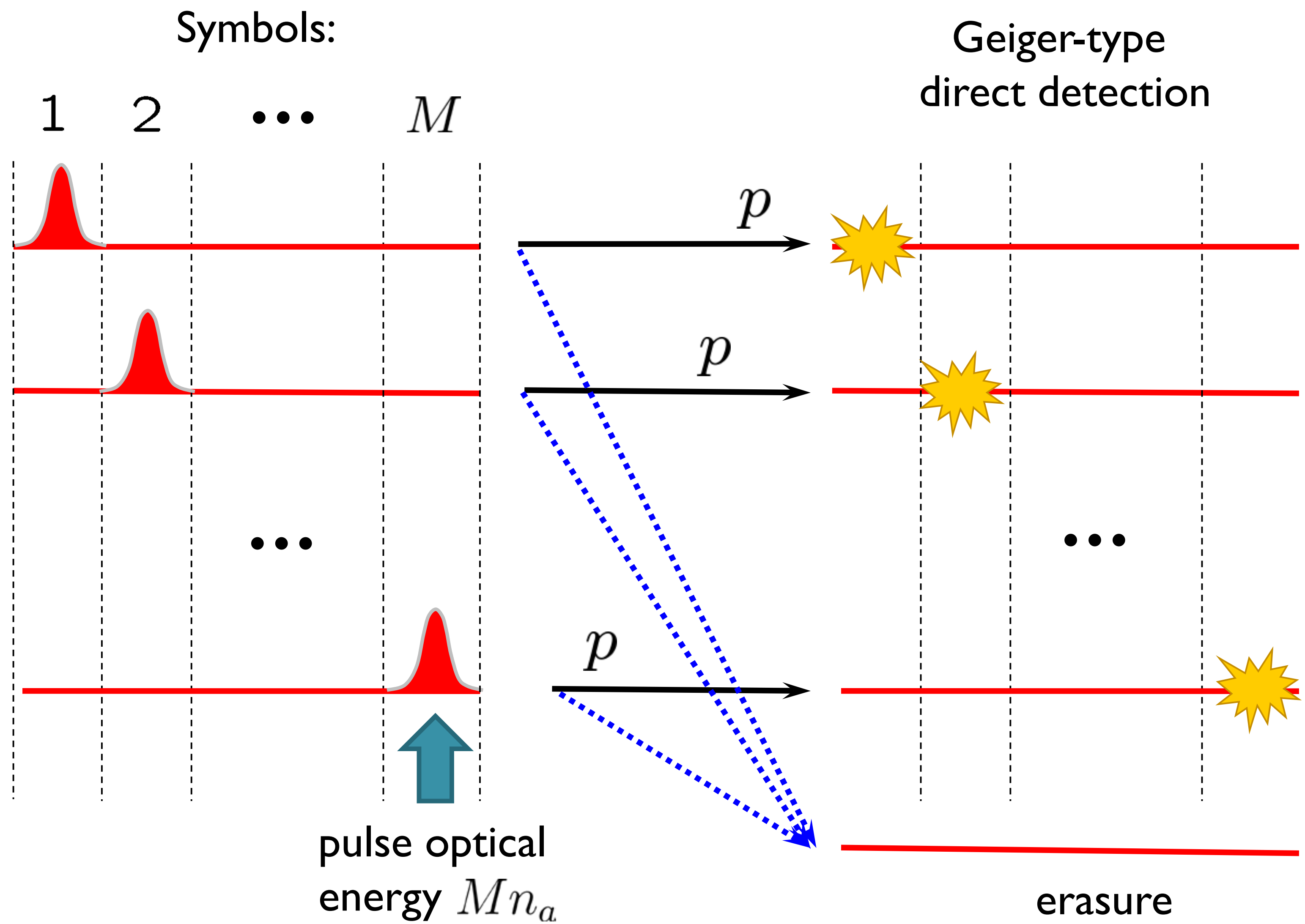
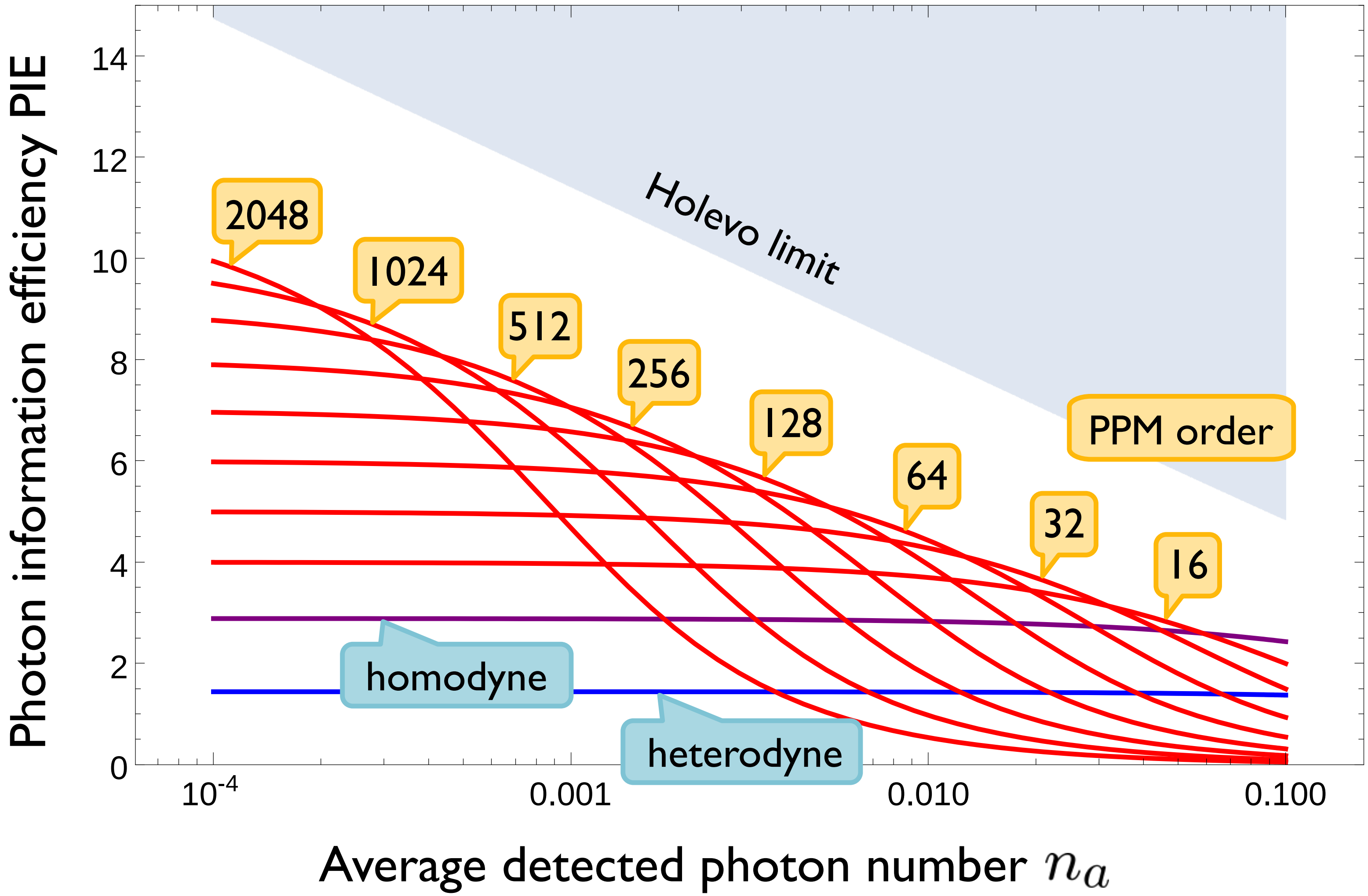
PPM – Pulse Position Modulation



Photocount probability (symbol recovery): $p = 1 - \mathrm{e}^{-Mn_a}$

PPM photon information efficiency

$$\text{PIE} = \frac{1 - e^{-Mn_a}}{Mn_a} \log_2 M \xrightarrow[n_a \to 0]{} \log_2 M$$



PPM PIE asymptotics

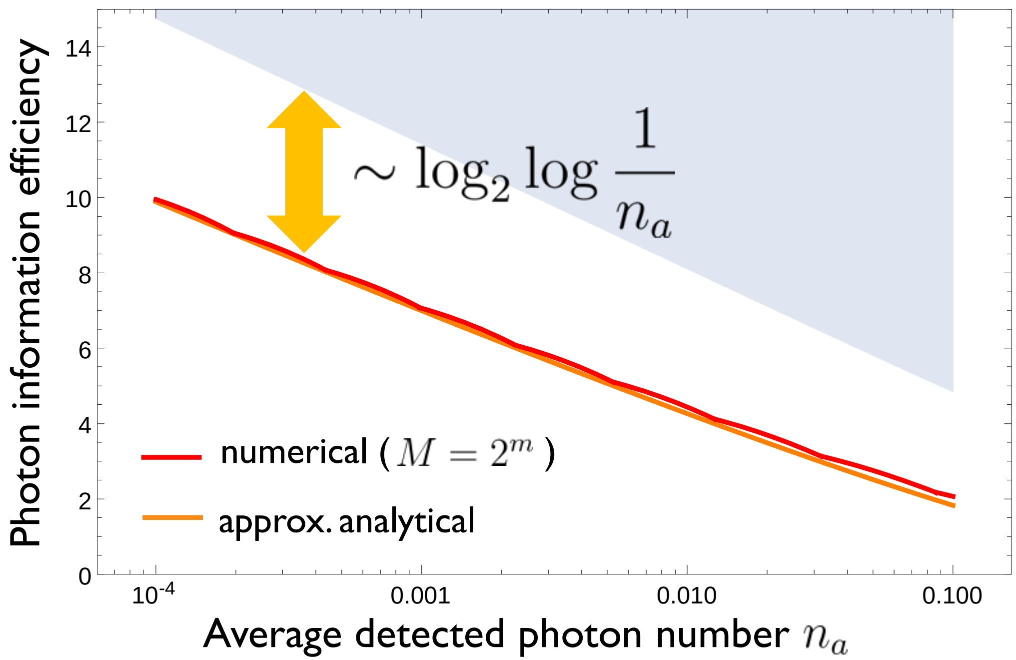
M. Jarzyna, P. Kuszaj, K. Banaszek, Opt. Express **23**, 3170 (2015)

Photocount probability:

$$p = 1 - \exp(-Mn_a) \approx Mn_a - \tfrac{1}{2}(Mn_a)^2$$

Approximate analytical expression:

$$\mathrm{PIE}_{\mathrm{PPM}} \approx \left(W\left(\frac{2\mathrm{e}}{n_a}\right) - 2 + \left[W\left(\frac{2\mathrm{e}}{n_a}\right)\right]^{-1} \right) \log_2 \mathrm{e}$$



Lambert function $W(x)$

$\approx \log x - \log \log x$

for $x \gg 1$

Optimal PPM order

$$M \approx \frac{2}{n_a} \left[W\left(\frac{2\mathrm{e}}{n_a}\right)\right]^{-1}$$

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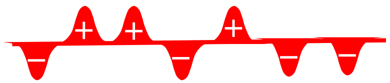
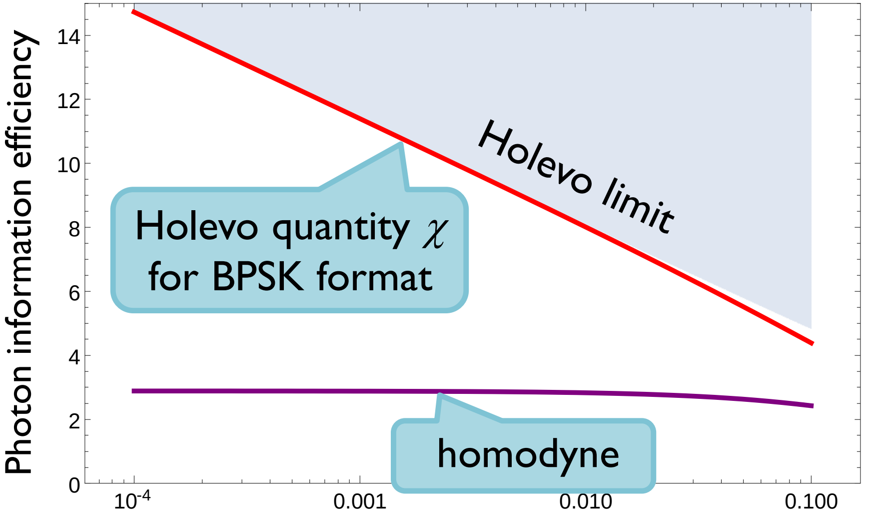
Superadditivity of accessible information

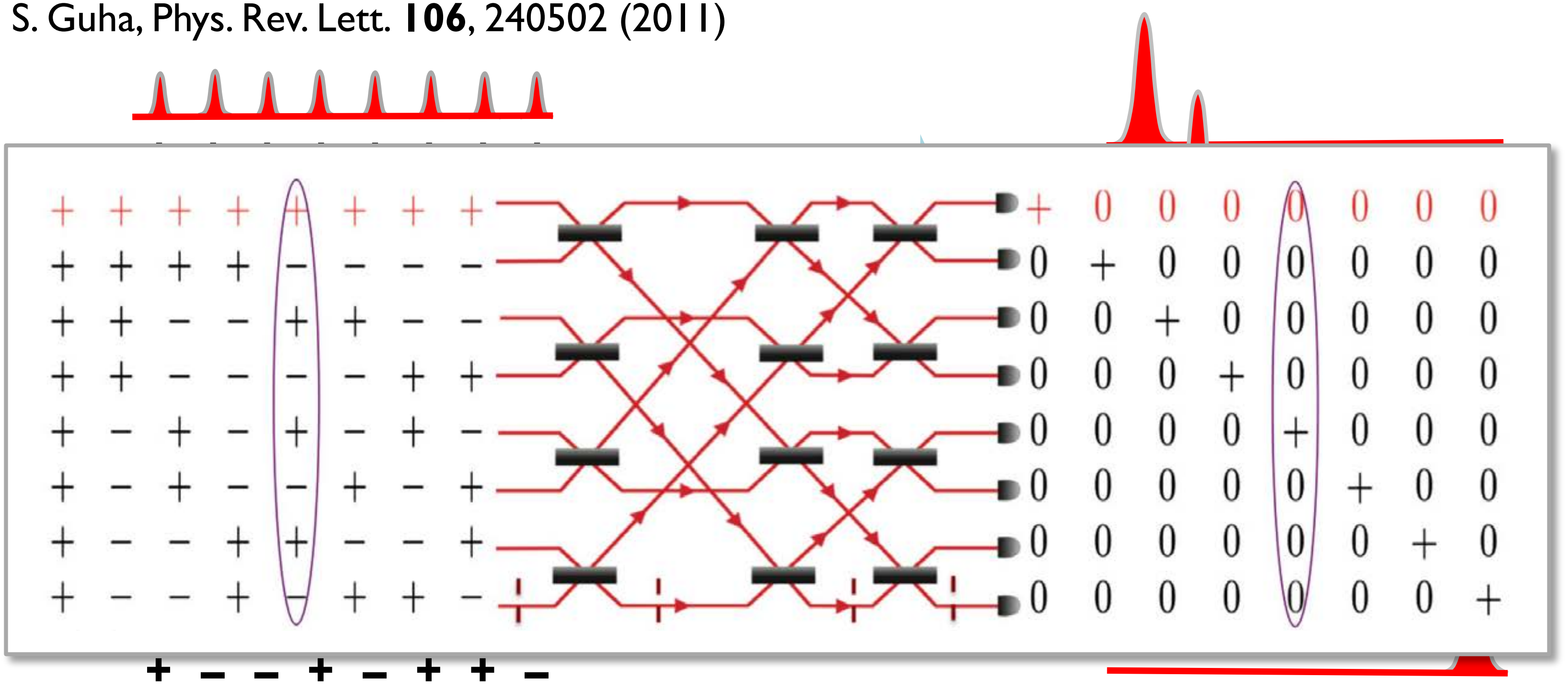
BPSK: 

Holevo quantity assumes:

- preparation of codewords
- collective detection of multiple symbols



S. Guha, Phys. Rev. Lett. **106**, 240502 (2011)



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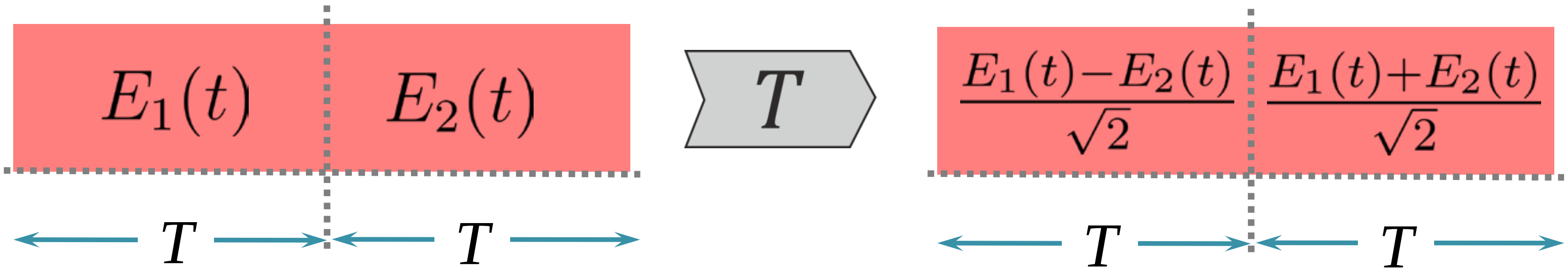
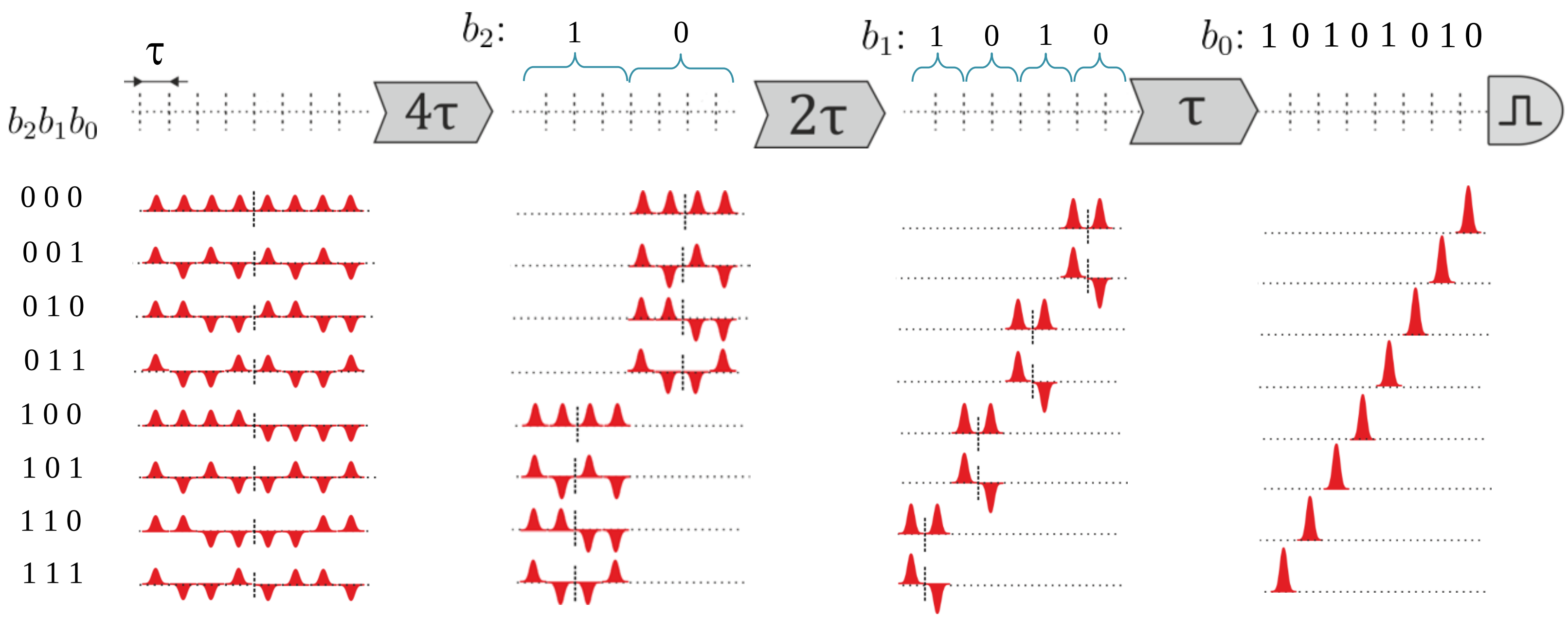
Scalable structured receiver

K. Banaszek and M. Jachura, Proc. IEEE ICSOS 2017, pp. 34-37





Pulse position: $\sum_k b_k 2^k$

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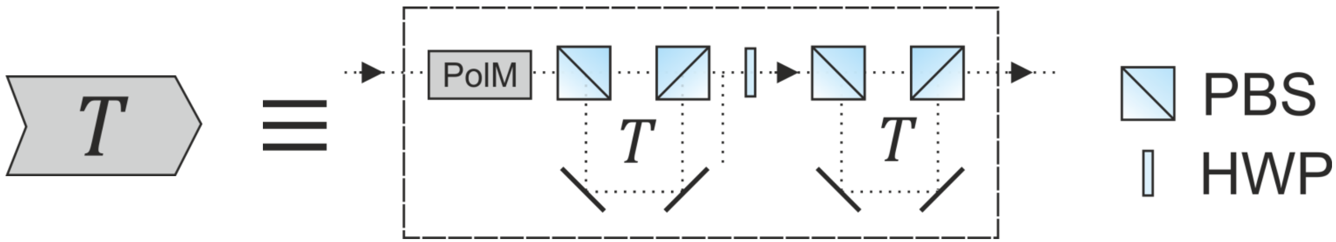
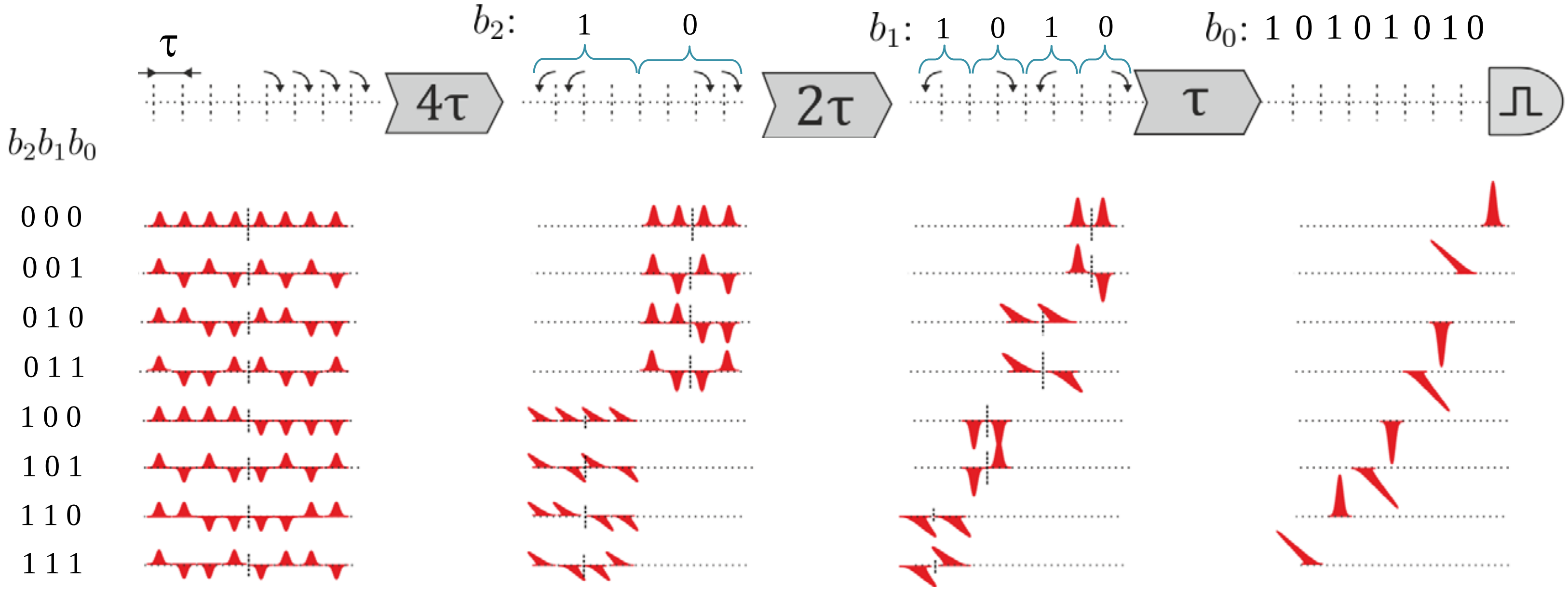
Realization

K. Banaszek and M. Jachura, Proc. IEEE ICSOS 2017, pp. 34-37



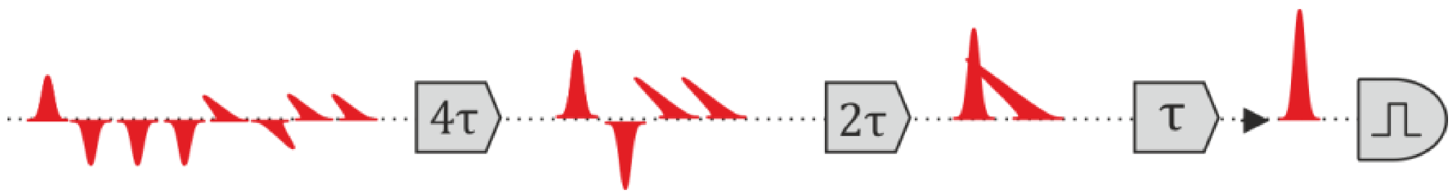
polarization switching



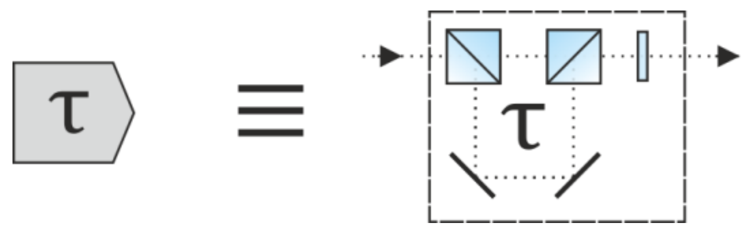
Pulse position: $\sum_k b_k 2^k$

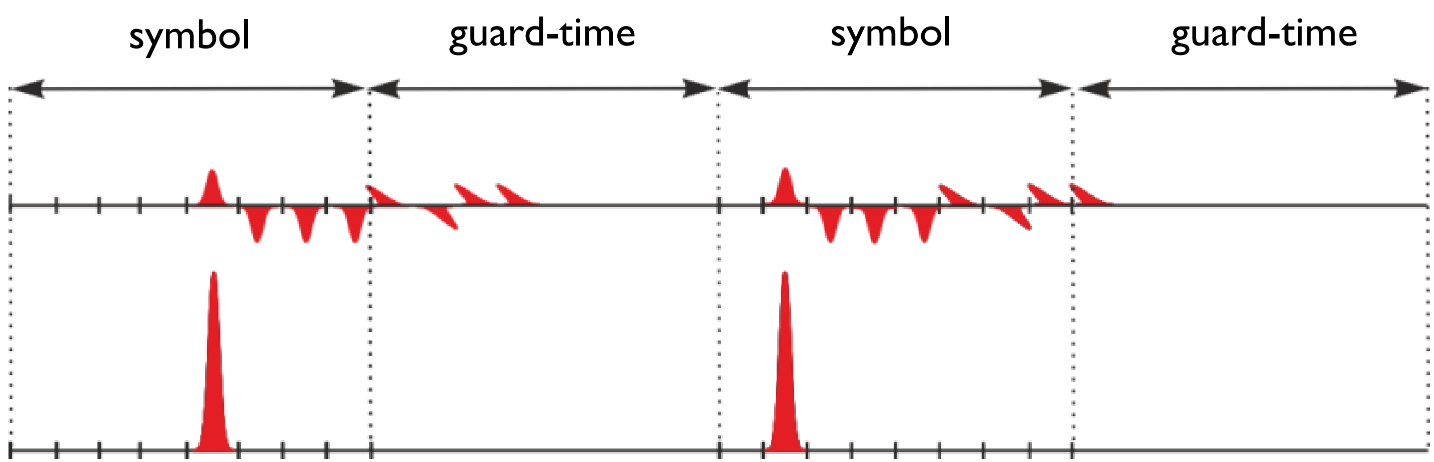
Phase-polarization patterns

K. Banaszek and M. Jachura, Proc. IEEE ICSOS 2017, pp. 34-37



Polarization-dependent delay + rotation by 45°





PPM encoding achieved by shifting the entire pattern in time

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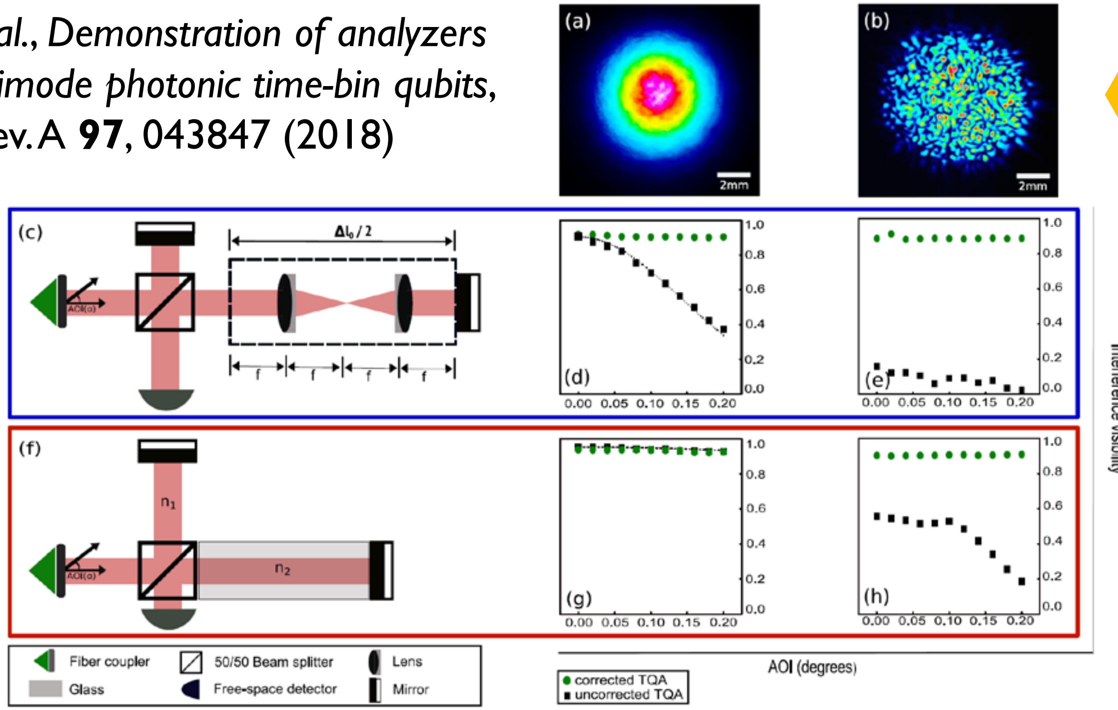
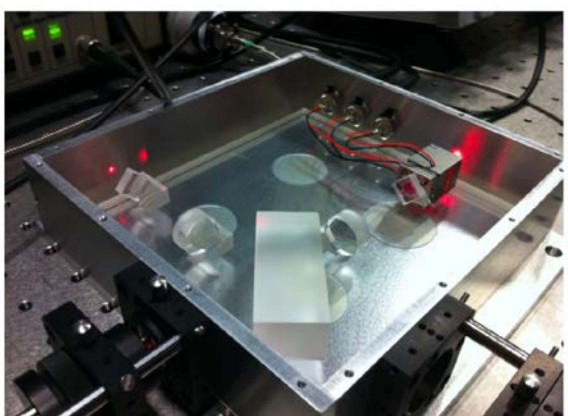
Atmospheric turbulence

J. Jin *et al.*, *Demonstration of analyzers for multimode photonic time-bin qubits*, Phys. Rev. A **97**, 043847 (2018)

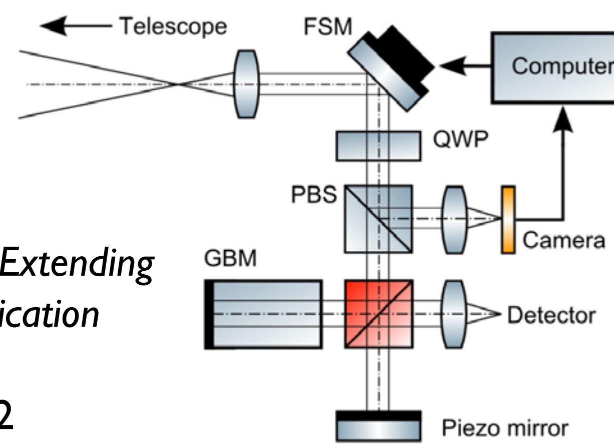


wavefront distorted signal



Multimode DPSK receiver

Z. Sodnik and M. Sans, *Extending EDRS to Laser Communication from Space to Ground*, Proc. ICSOS 2012, 13-2



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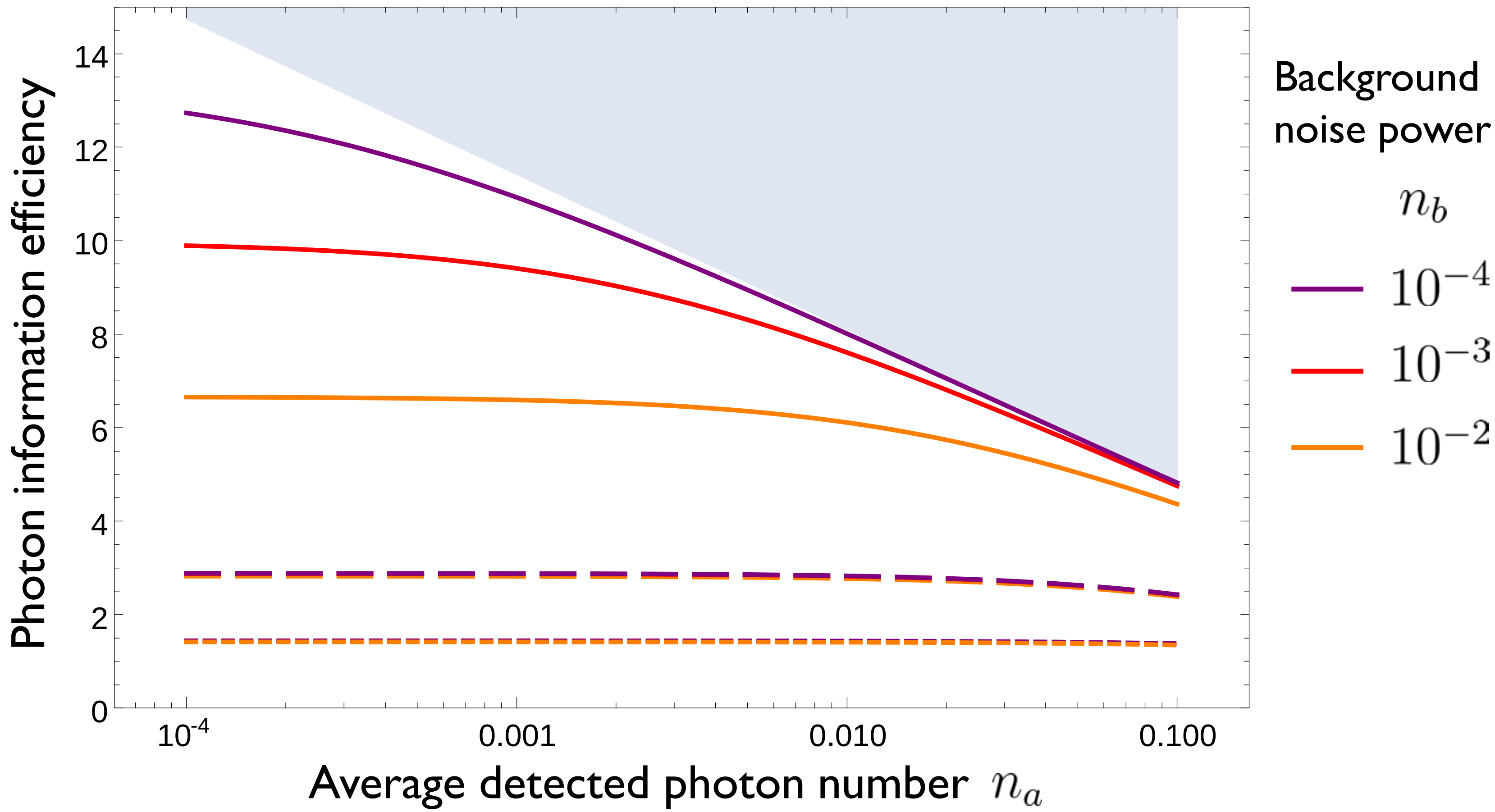
Noisy channel asymptotics

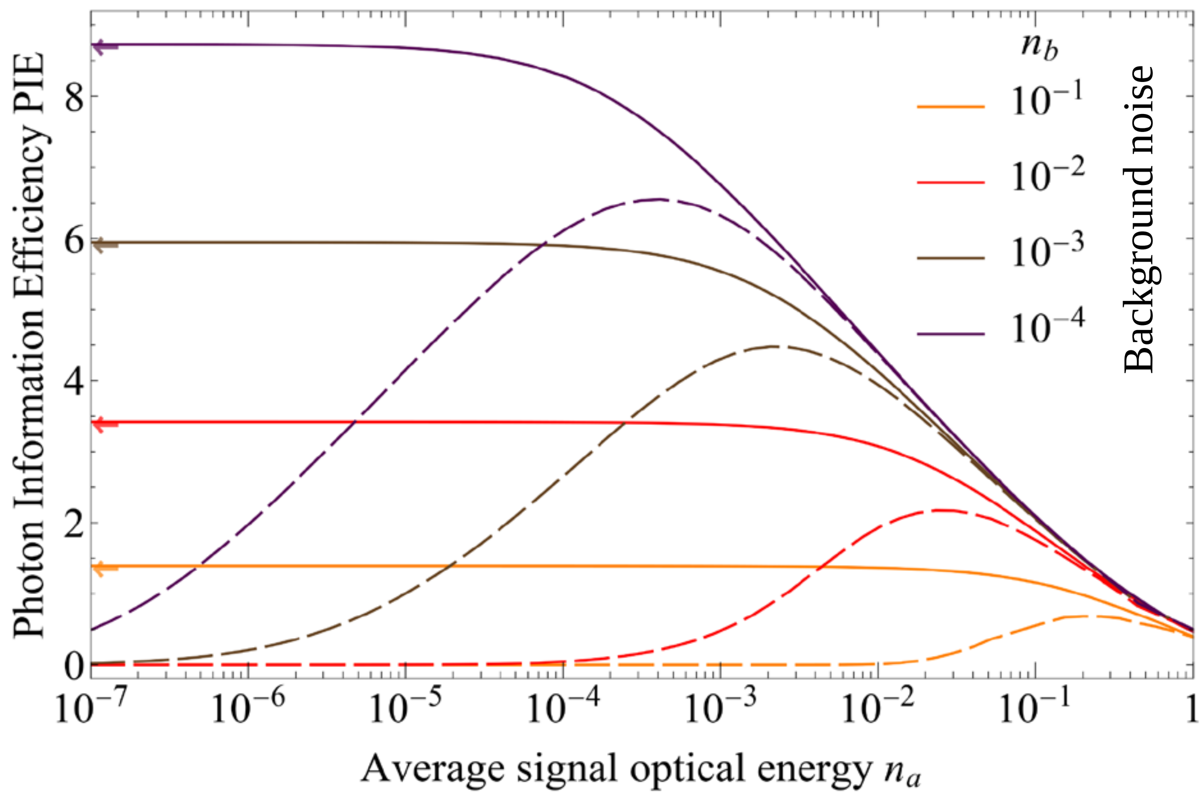


heterodyne — homodyne — Holevo

$$\mathrm{PIE} \xrightarrow[n_a \to 0]{} \quad \frac{\log_2 e}{1+n_b} \qquad 2\frac{\log_2 e}{1+n_b} \qquad \log_2\left(1+\frac{1}{n_b}\right)$$

Optimized PPM with background noise

W. Zwoliński, M. Jarzyna, and K. Banaszek, Opt. Express **26**, 25827 (2018)



complete decoding

$M \sim 1/n_a$

simple decoding

$M \sim \text{const}$

- multimode background noise yielding Poissonian count statistics
- Geiger-type direct detection
- unconstrained peak-to-average power ratio (PPM order)

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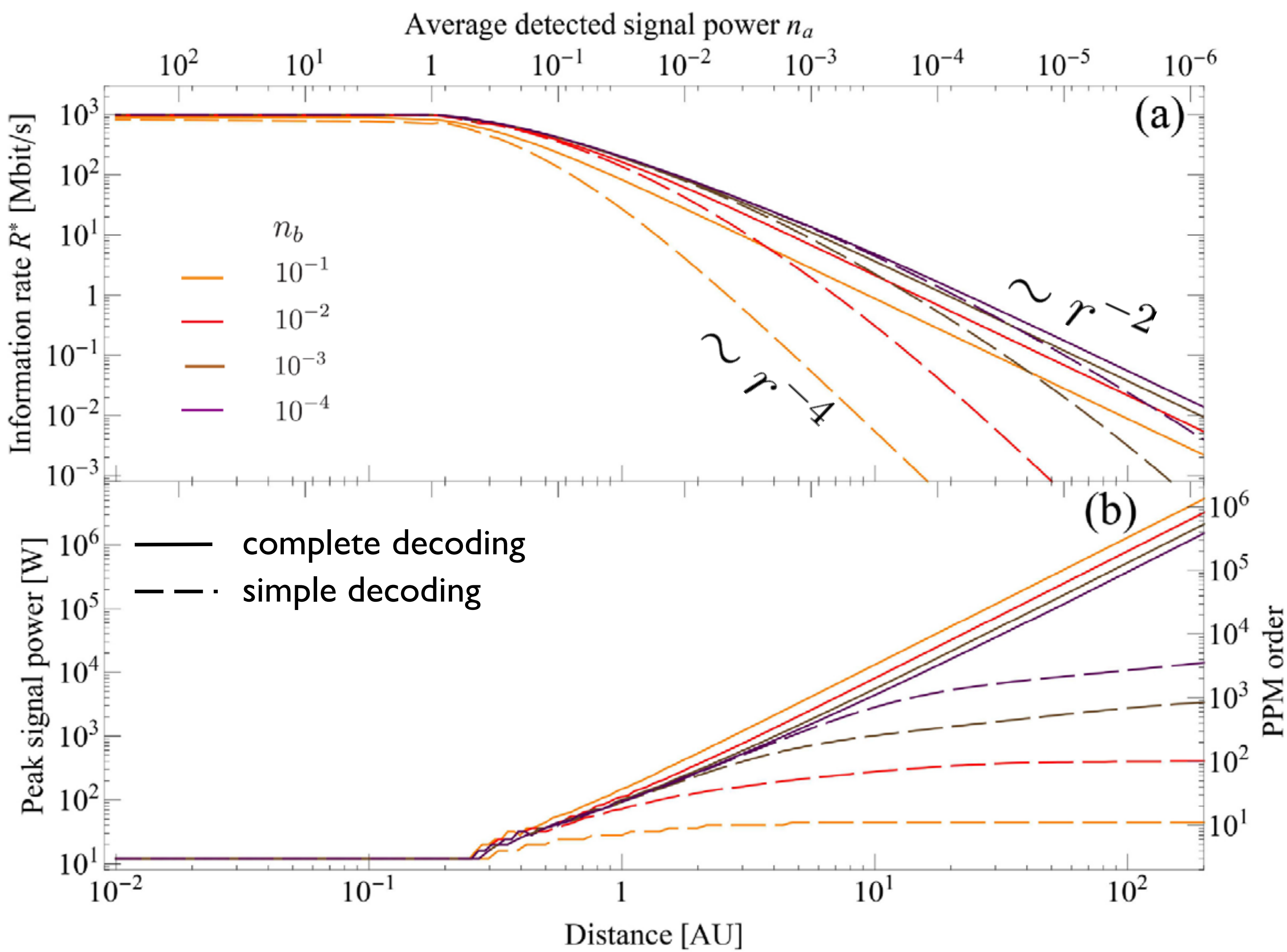
Range dependence

W. Zwoliński, M. Jarzyna, and K. Banaszek, Opt. Express **26**, 25827 (2018)



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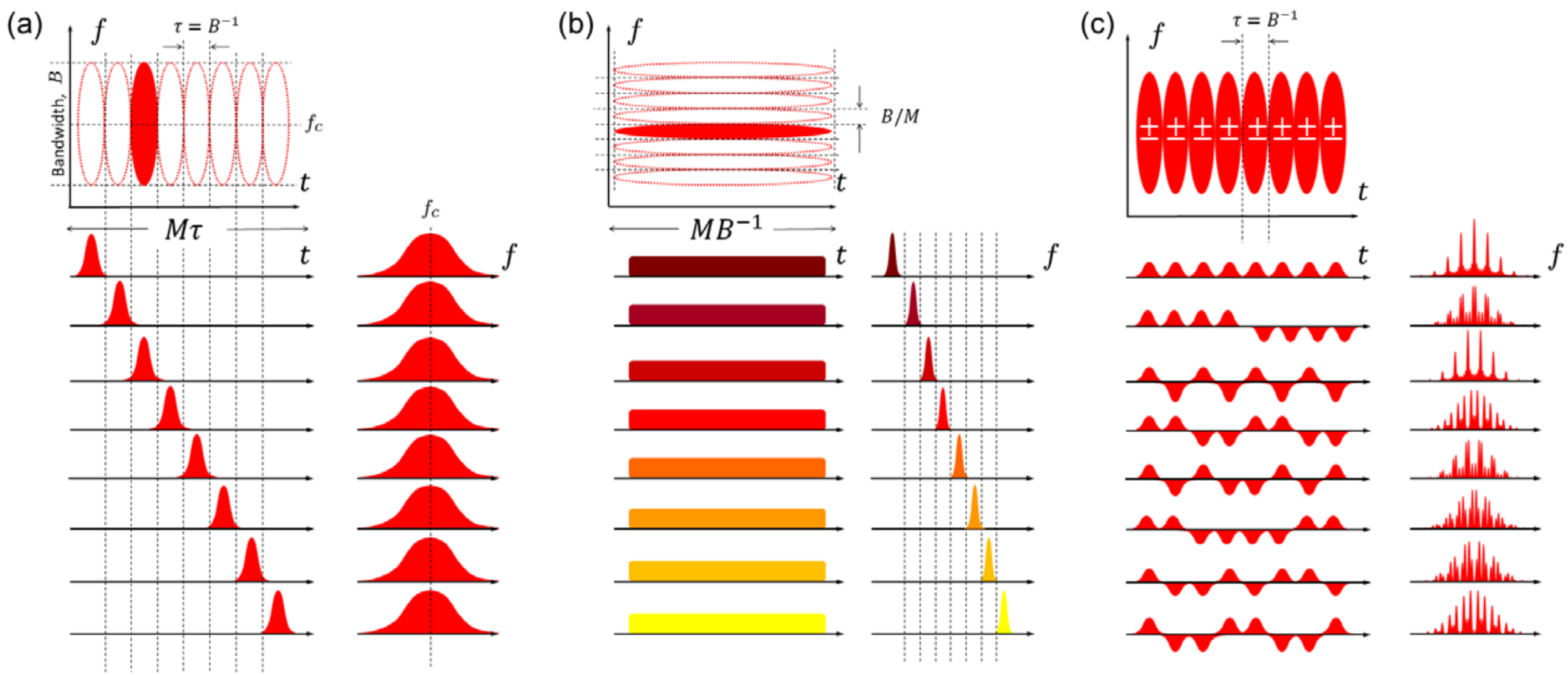
High-order modulation formats

pulse position modulation

frequency shift keying

BPSK Hadamard codewords



K. Banaszek, M. Jachura, W. Wasilewski, *Utilizing time-bandwidth space for efficient deep-space communication*, Proc. International Conference on Space Optics 2018, paper P22

Thank you!

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