# Sensitive optical receivers for space communication

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## The idea

- ✓ To increase capacity and reach in free-space optical transmission links
- ✓ Applications in very long-reach systems (satellite – satellite/earth, and beyond)

# Background

- Currently, RF transmission dominates in space communication.

- Lightwave-based transmission is however, emerging. A key benefit is much smaller diffraction-induced losses due to the much shorter wavelength.

- Loss in free space is quadratic with reach:

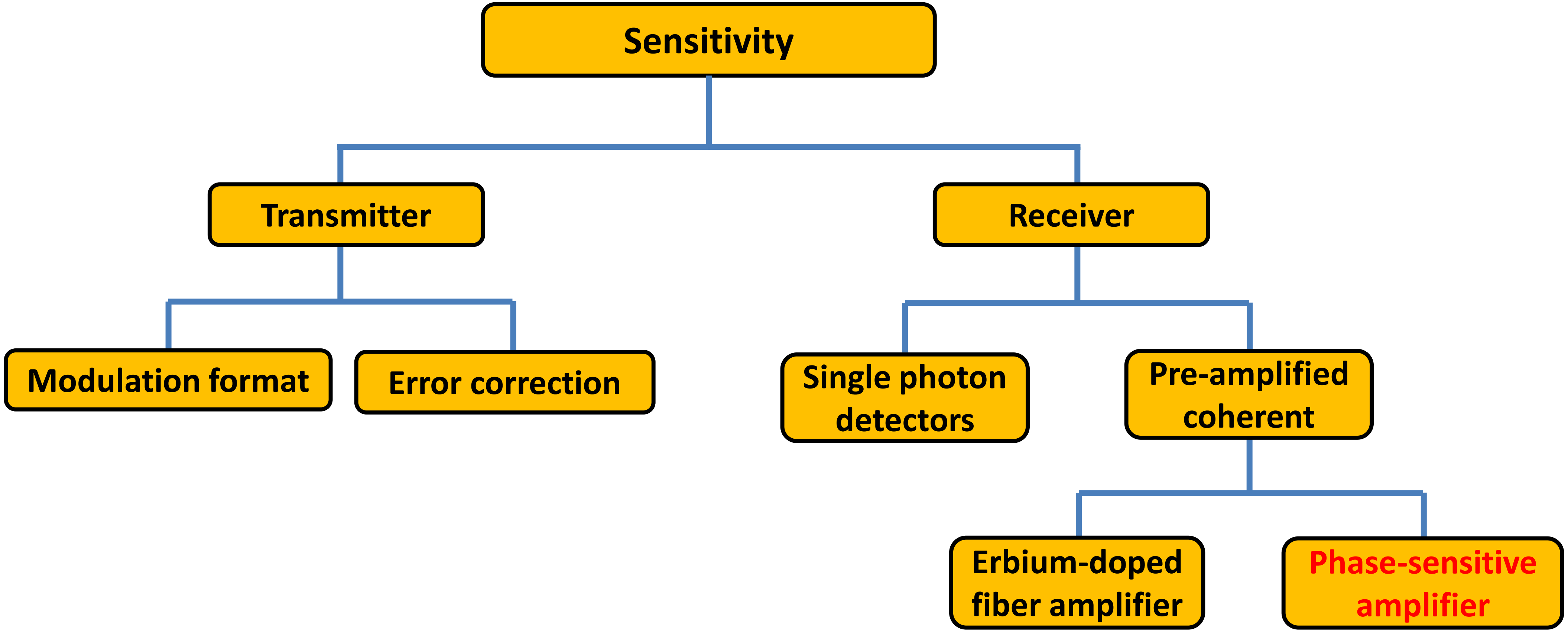
$$\frac{P(r,z)}{P_0} = 1 - exp\left(-\frac{2r^2}{\omega(z)^2}\right) \cong \frac{2r^2}{\omega(z)^2} \; with \quad (z) \cong \frac{\lambda z}{\pi\omega_0} \; and\; r\; is\; aperture\; radius$$

- Diffraction loss (at 1550 nm) over 0.4 million km (to the moon) with 10 cm aperture is about 80 dB.

- As long-range systems are diffraction-limited, the SNR, i.e. **capacity and reach, will be fundamentally limited by the noise in the receiver, as well as by the available transmit power and the channel loss.**

# What determines the receiver sensitivity?

(input power needed for error-free operation)

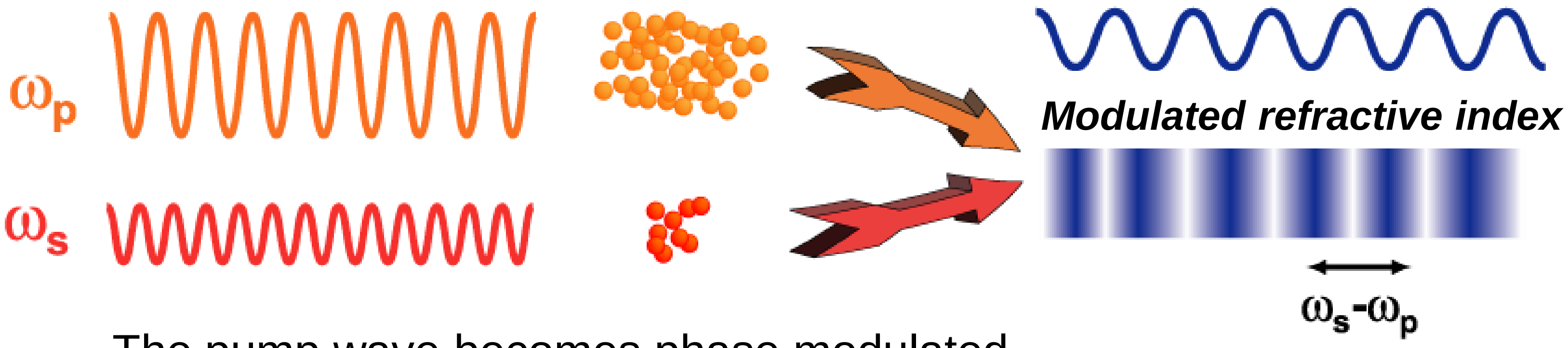


# Phase-sensitive optical amplifiers (PSAs)

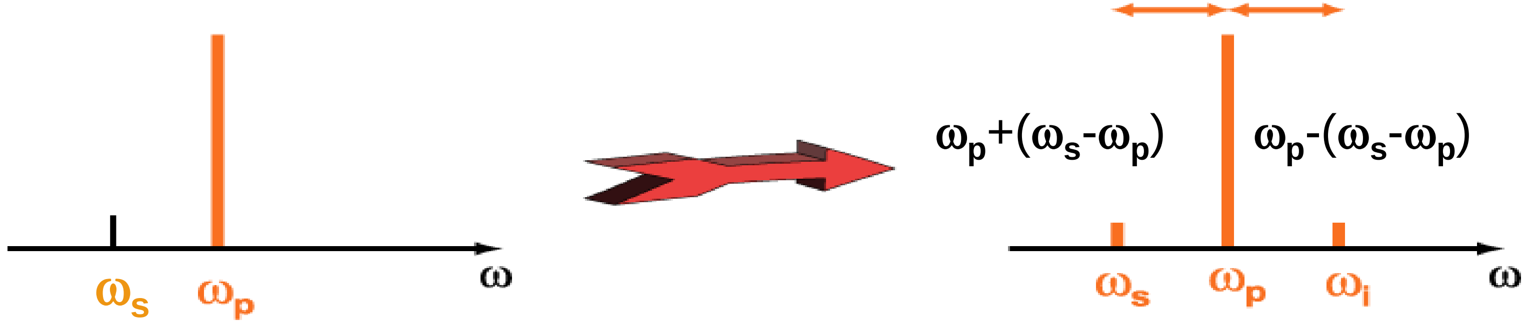
- In contrast to conventional optical amps (EDFAs), PSAs can reach a noise figure of 0 dB (1 dB measured): [Z. Tong, et. al, Nature Photonics 5, 430-436 (2011)]
- Involves three waves: signal, idler and pump, which need to be phase controlled
- Transmission reach extension of 5x demonstrated in fiber systems
- Key challenges include management of chromatic dispersion, polarization, and nonlinearities
- **These challenges are essentially non-existing in free space, leading to much simpler implementation!**
- PSAs provide the lowest possible amplification noise, making them **the ultimate solution to provide the best possible receiver sensitivity!**

# Fiber-Optic Parametric Amplifiers

Nonlinear index of refraction; *n = n(I)*
Pump and signal waves mix in a nonlinear media creating a dynamic grating

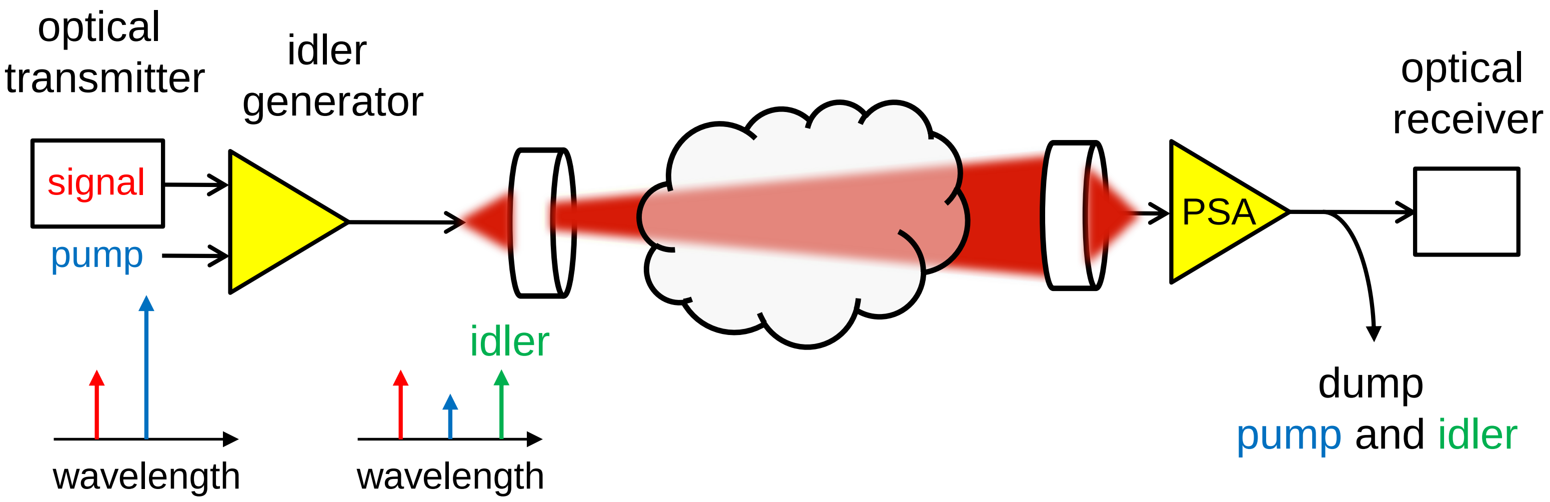


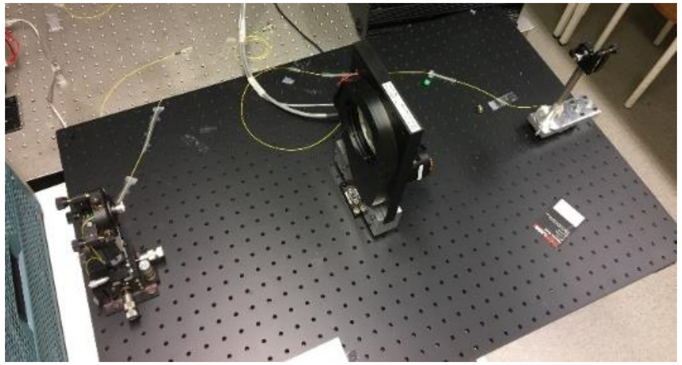

The pump wave becomes phase modulated




Power is transferred from pump to signal (at $\omega_s$) and to $\omega_i$ (the "idler")

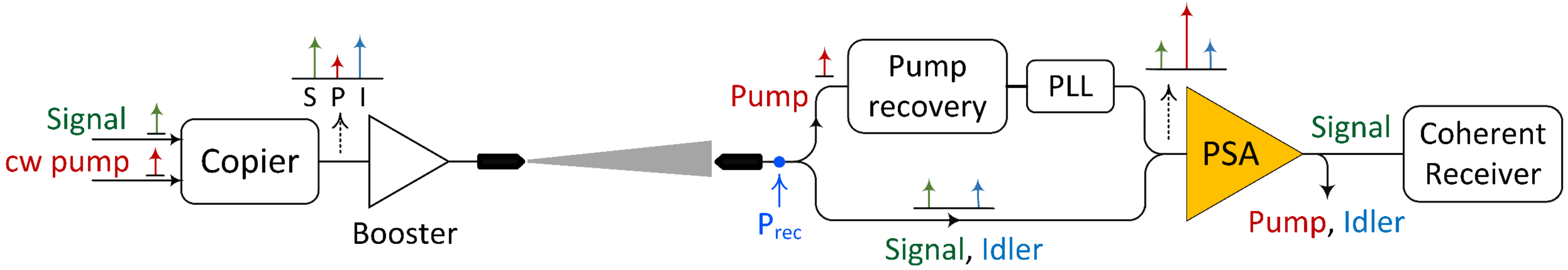
# Free space optical link using optical pre-amplification with PSA



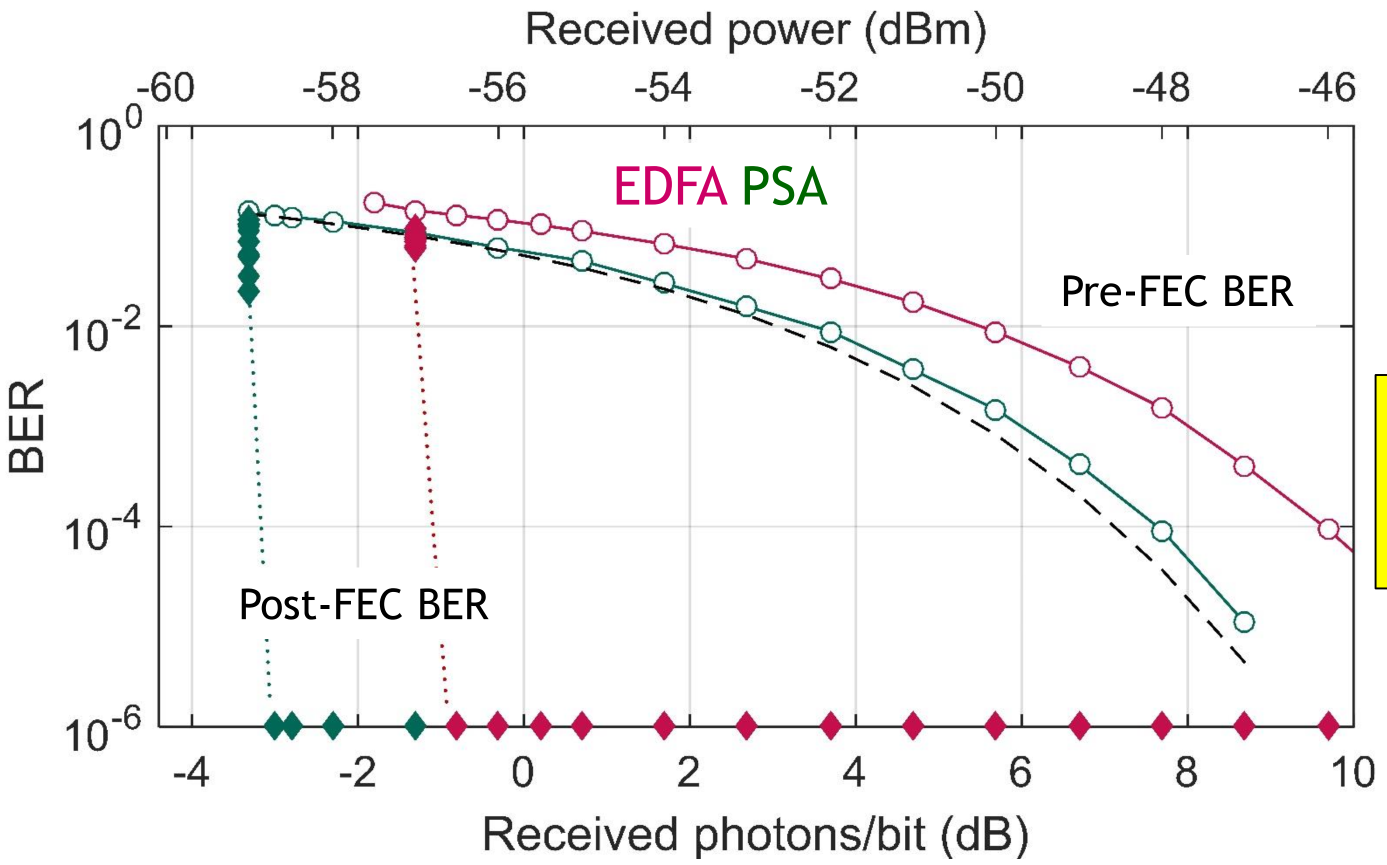
- Only signal is used in the receiver (no need for particular, high BW receiver)
- Sensitivity improvement can be used for higher throughput/reach and traded for smaller aperture
- Can be combined with all other approaches for sensitivity improvement; coherent detection, sensitive modulation formats, coding, and parallel links (WDM, SDM).
- Challenges (aside from the already existing ones in FSO links) include:
  - PSA pump recovery – can impact power budget – we use optical injection locking
  - Optical phase-locked loop

# Experimental FSO link setup




- 10.5 Gbd QPSK signal
- PSA amplification: 21 dB, NF = 1.2 dB
- Half-rate standard FEC code (DVB-S2), i.e. 100% overhead or net information rate 10.5 Gb/s
- Injection locked pump wave at -71 dBm (80 pW) or 0.06 photons per symbol (<< $P_s$)
- Penalty due to presence of pump (received signal + idler power is > -59 dBm): 0.26 dB, additional 0.3 dB penalty due to OIL in PSA
- Comparison with EDFA preamplifier also made (NF = 3.7 dB)

# Experimental results at information rate 10.5 Gb/s

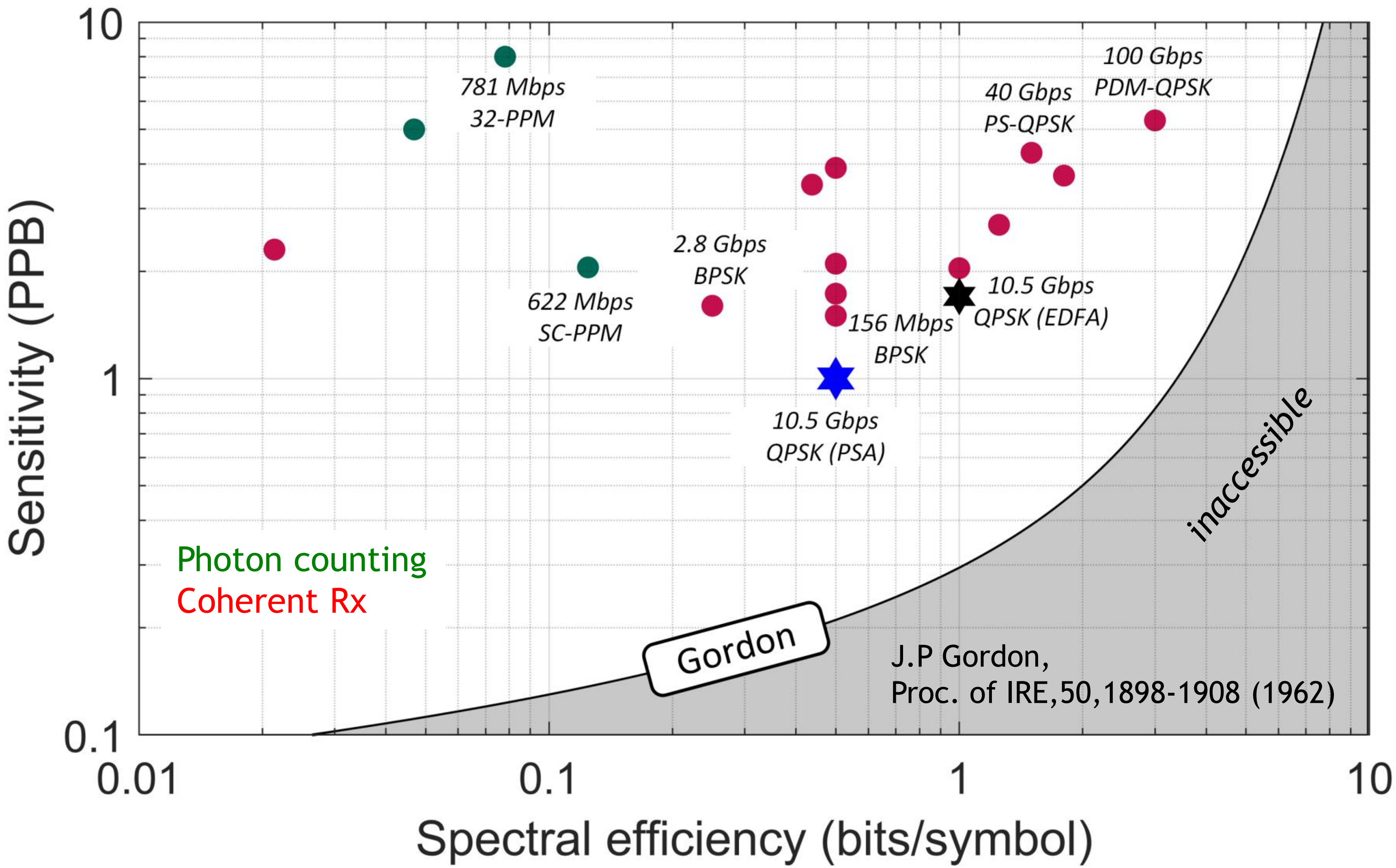



All photons (signal, idler, pump in the case of PSA)

PSA receiver sensitivity: 0.5 PPB @ BER = $10^{-6}$
i.e. 1 photon per information bit.
(PPB in signal is only 0.47 PPB)

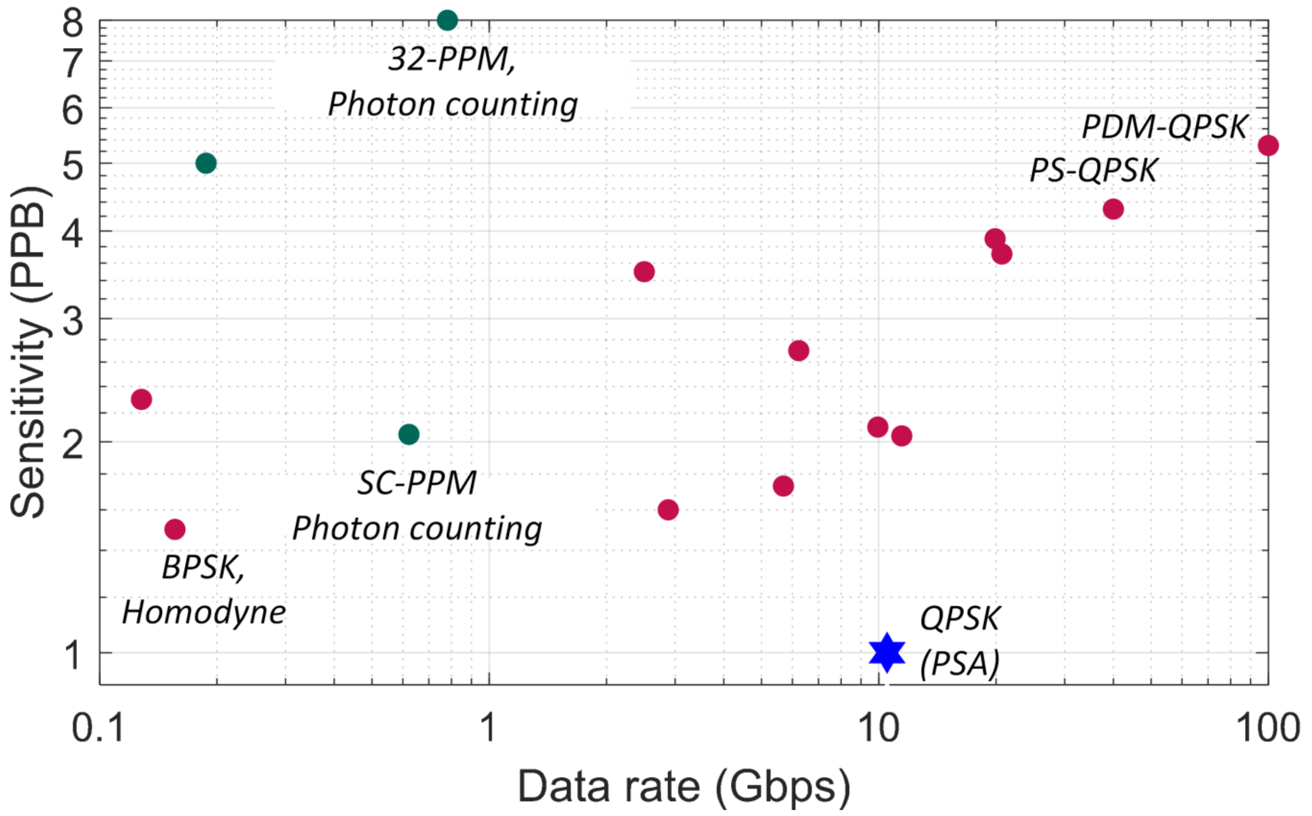
R. Kakarla et al., CLEO 2019, JTh5B.1(post-deadline paper) USA, May 2019

# A comparison with previous experimental results ("black-box" sensitivity)

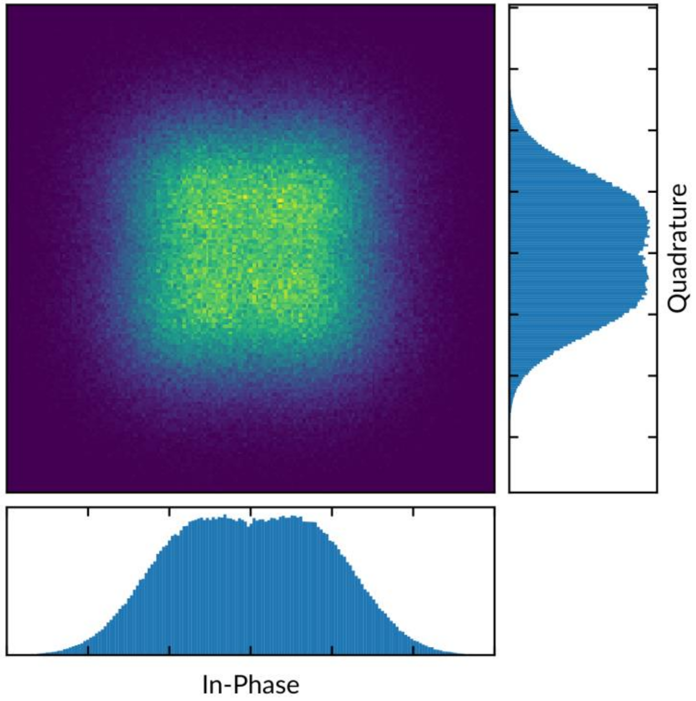


# Summary:

1 PPB (BER < $10^{-6}$) “black-box” sensitivity at 10.5 Gb/s (0.8 PPB based on GMI)
Novel approach and best sensitivity reported to date




Constellation diagram at 1 PPB (error-free)



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