MAX PLANCK INSTITUTE for the science of light

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

Chekhova Research Group

M. V. Lomonosov Moscow State University

Palacký University Olomouc

# Extreme events and enhanced nonlinear effects due to ultrafast photon-number fluctuations

Kirill Spasibko, Mathieu Manceau, Denis Kopylov, Victor Krutyanskiy, Tatiana Murzina, Radim Filip, Gerd Leuchs, and Maria Chekhova

Photons Beyond Qubits

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DFG Deutsche Forschungsgemeinschaft

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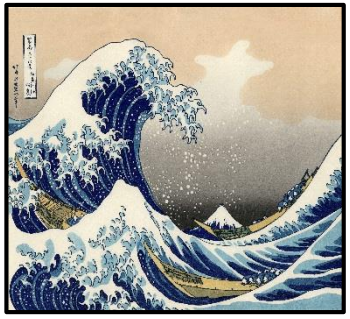
# Outline

- Ultrafast fluctuations via bright squeezed vacuum
- Efficiency enhancement
  - SH, TH and FH generation
- Enhancement of rogue-wave behavior
  - Harmonics generation
  - Supercontinuum generation
- Summary

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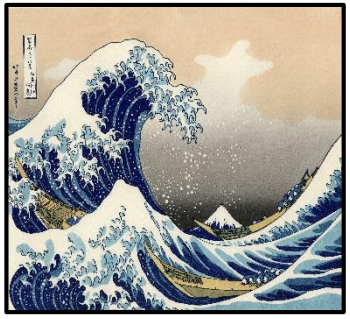
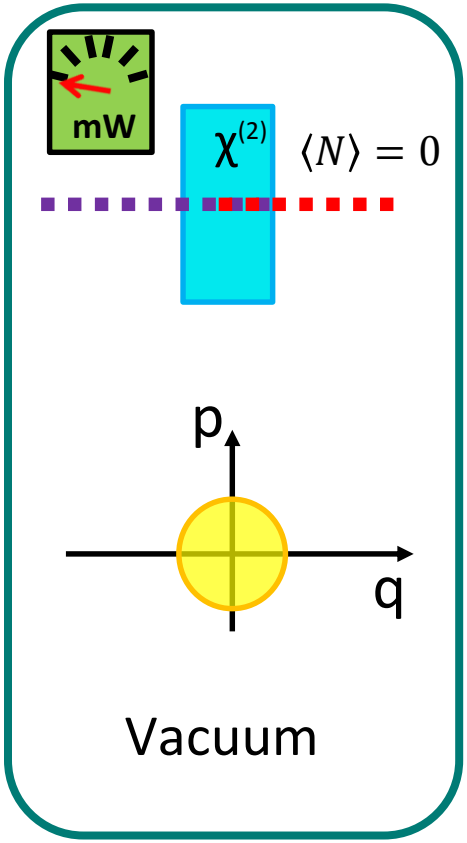


# Bright Squeezed Vacuum via PDC




Jedrkiewicz, O. et al. PRL. 93, 243601 (2004).
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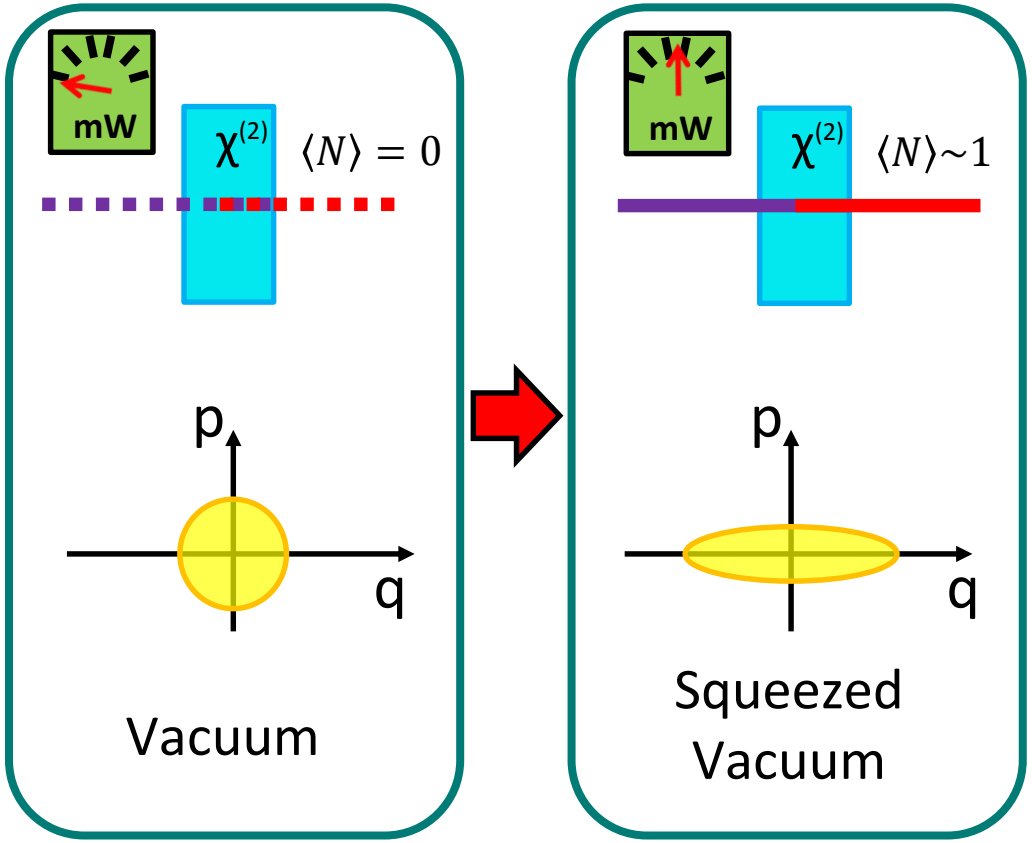


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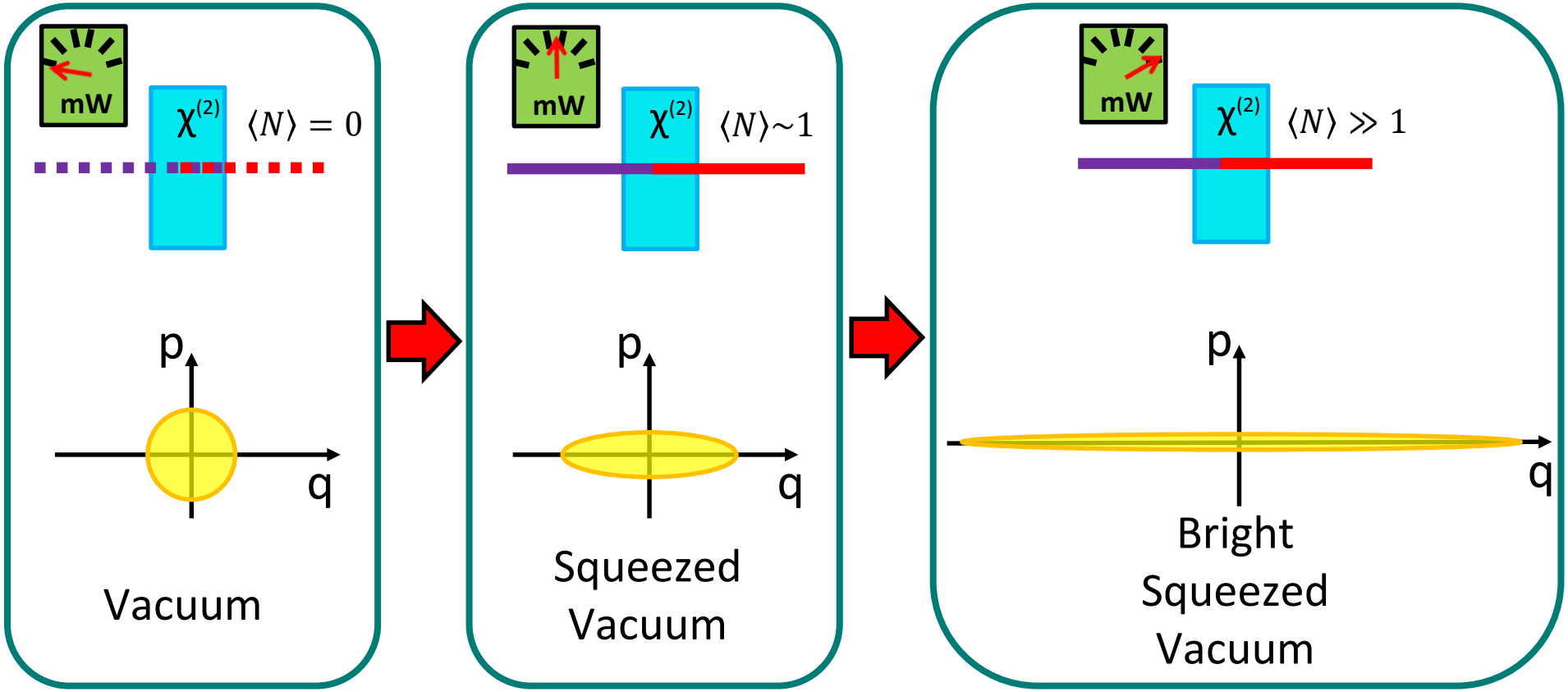



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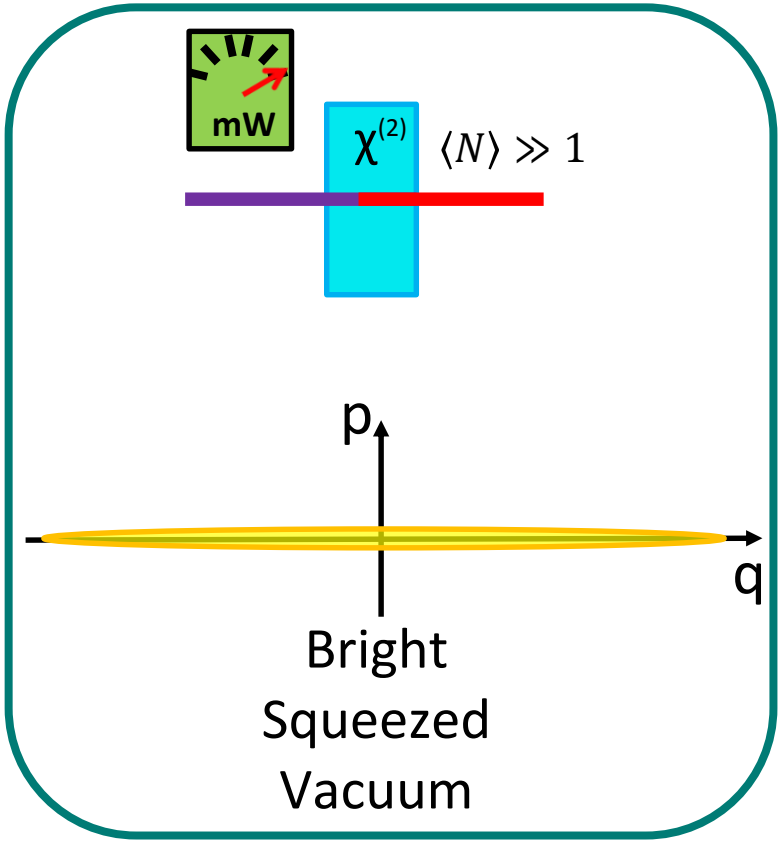
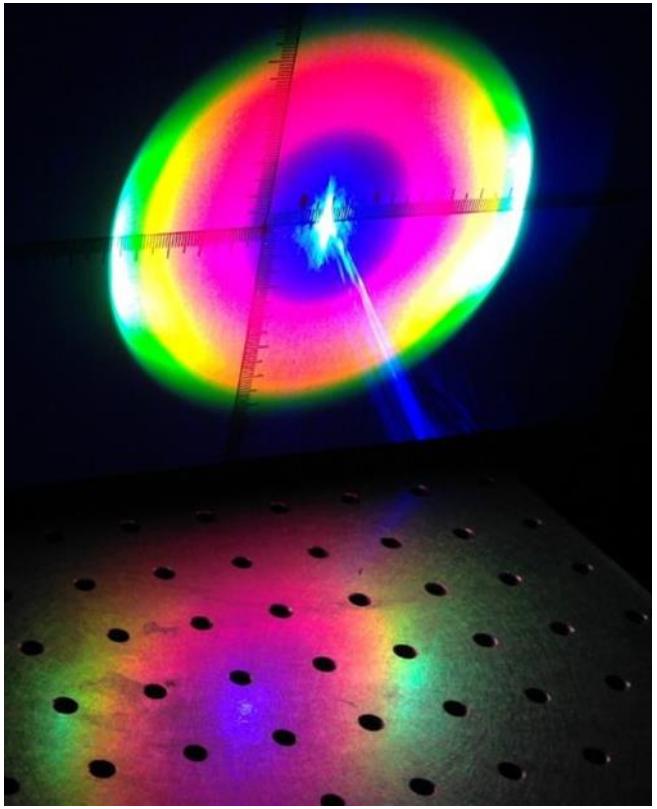



Extremely bright:
up to hundreds mW



Pérez, A.M. et.al., Nat. Commun. 6, 7707 (2015).
KS et.al., Opt. Lett. 41, 2827 (2016).

# Bright Squeezed Vacuum

**Macroscopic** & **Nonclassical**

Nonlinear optics

Squeezing:
quadrature, two-mode

Interactions with matter:
atoms, mechanical
systems, …

Violation of Bell's
inequalities

Slusher, R.E. et. al. PRL 59, 2566 (1987).
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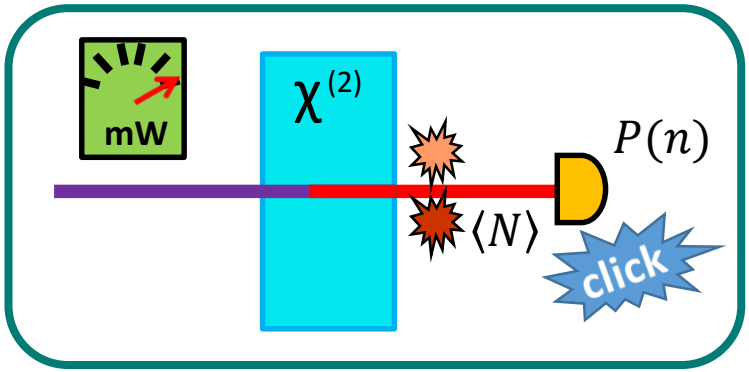
# Fluctuations of Bright Squeezed Vacuum

## Thermal BSV




$$P_{th}(n) = \frac{\langle N \rangle^n}{(\langle N \rangle + 1)^{n+1}}$$

Klyshko, D.N. Phys.-Usp. 39, 573 (1996).

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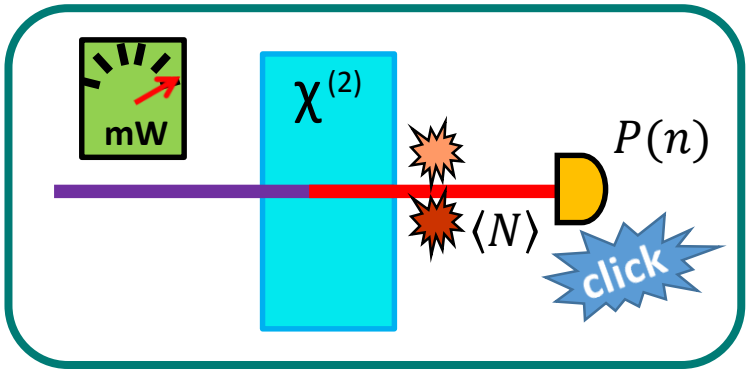


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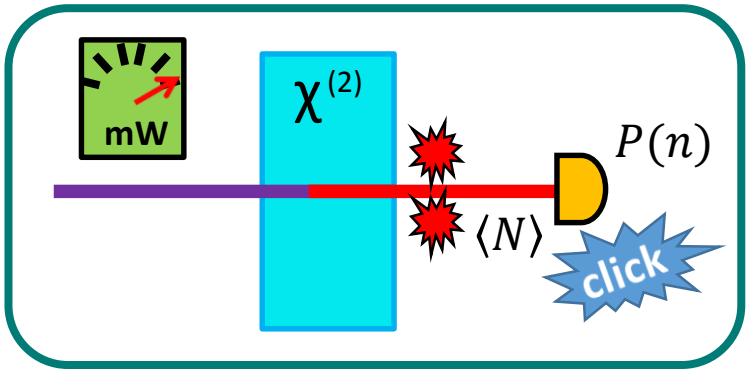
## Superbunched BSV




$$P_{sb}(2n) = \frac{(2n)!}{2^{2n}(n!)^2} \frac{\langle N \rangle^n}{(\langle N \rangle + 1)^{n+1/2}}$$

$$P_{sb}(2n+1) = 0$$

Klyshko, D.N. Phys.-Usp. 39, 573 (1996).

# Fluctuations of Bright Squeezed Vacuum

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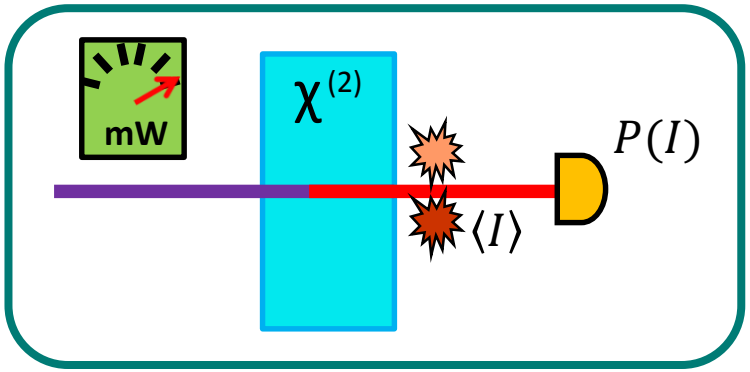
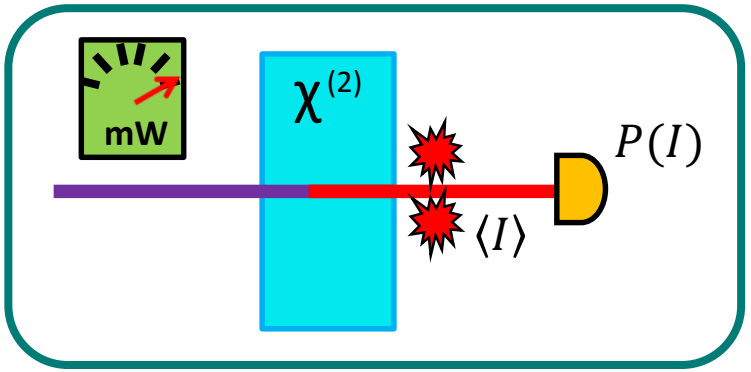



$$P_{th}(I) = \frac{e^{-I/\langle I \rangle}}{\langle I \rangle}$$

## Superbunched BSV




$$P_{sb}(I) = \frac{e^{-I/2\langle I \rangle}}{\sqrt{2\pi I \langle I \rangle}}$$

Leuchs, G. et. al. Phys. Scr. 90, 074066 (2015).

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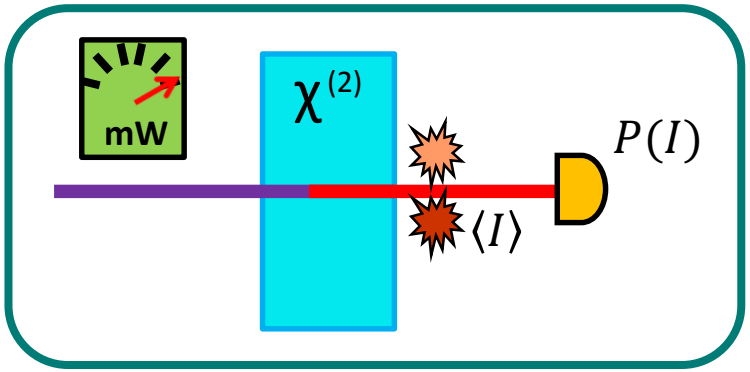


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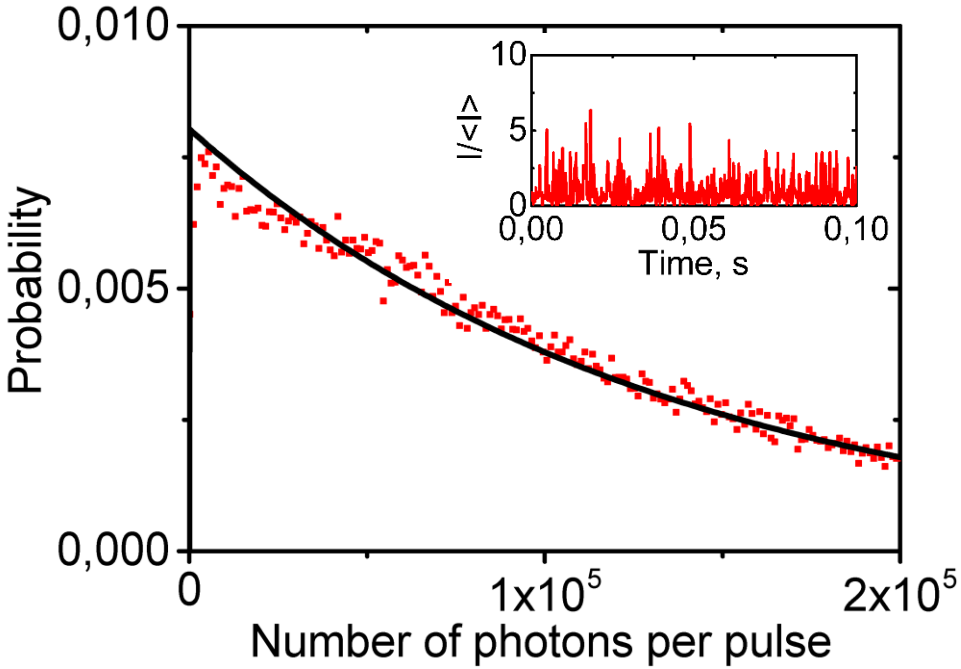


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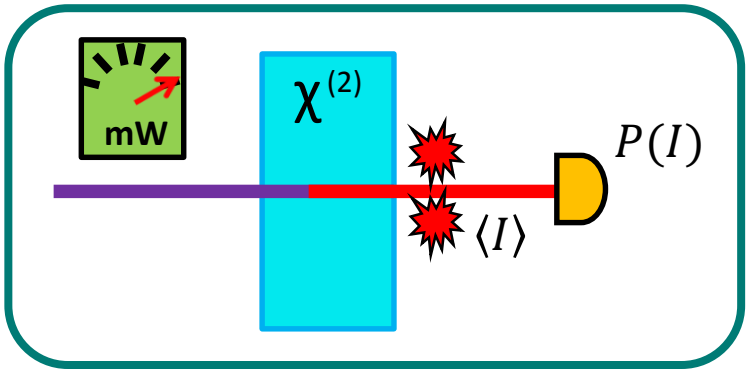


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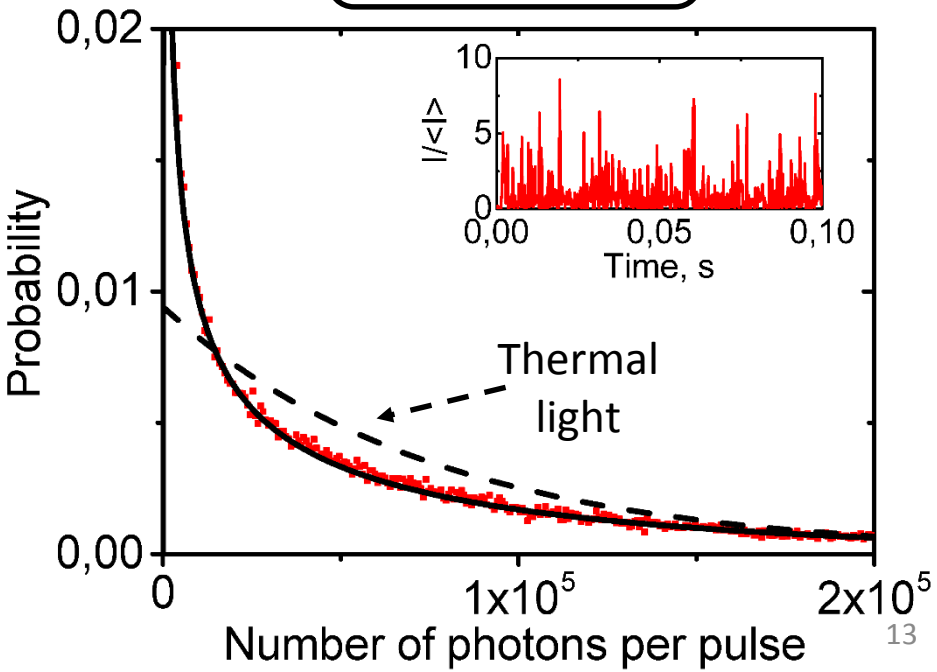

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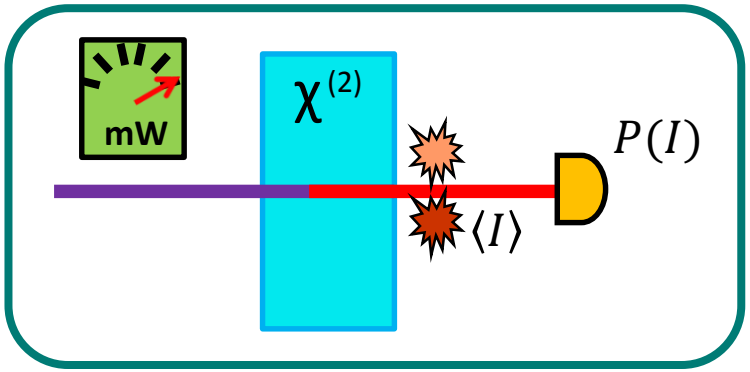


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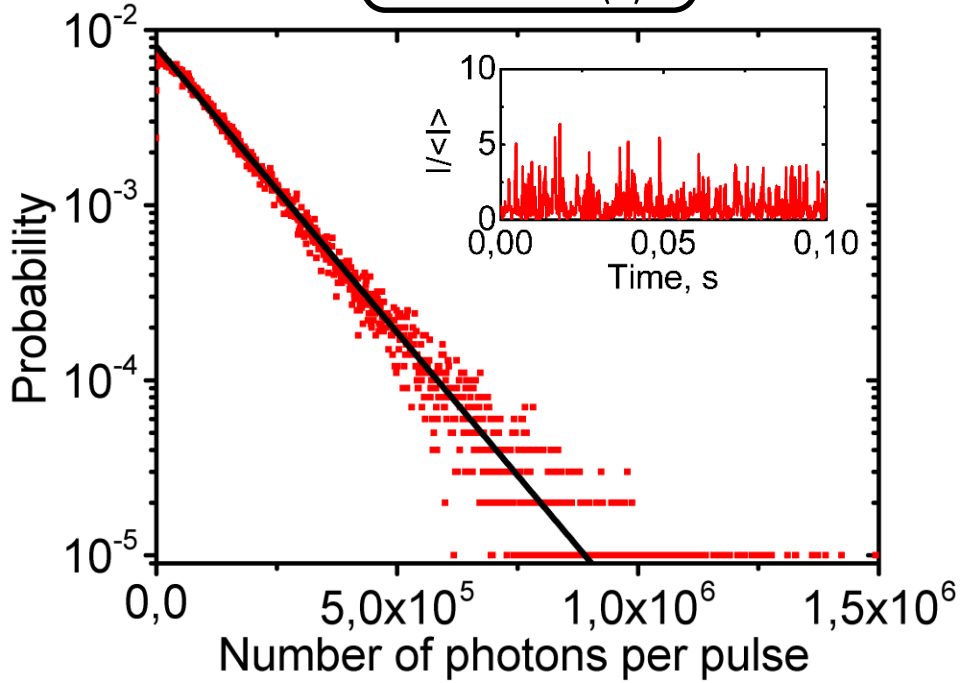


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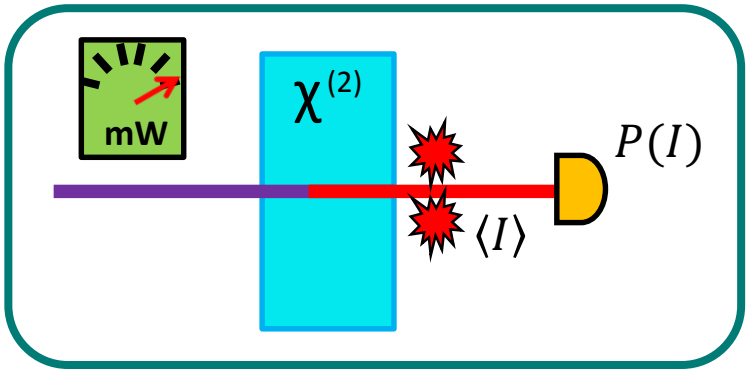


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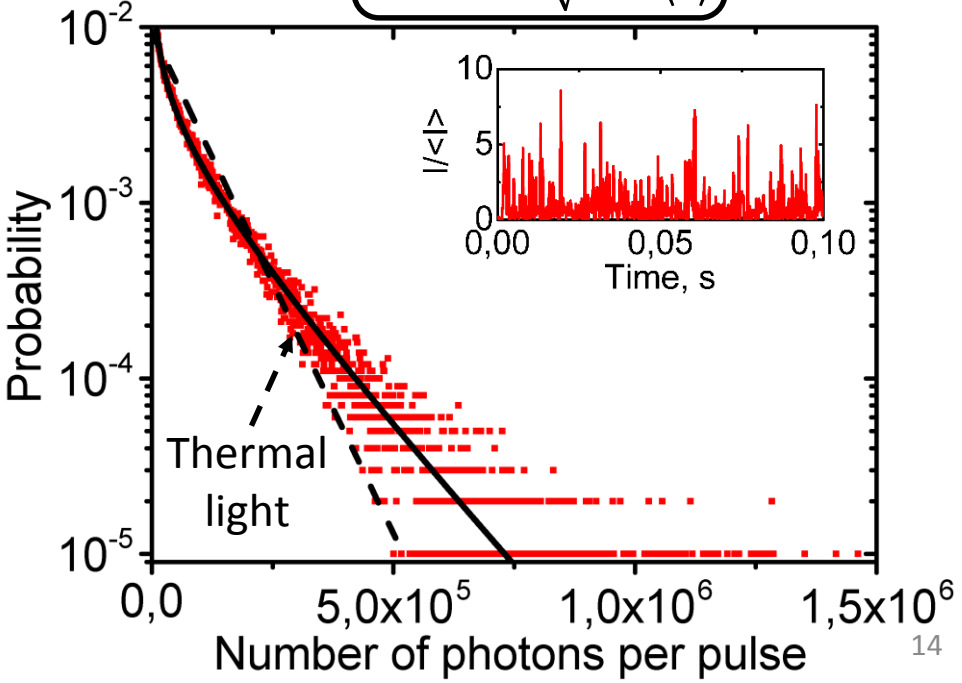
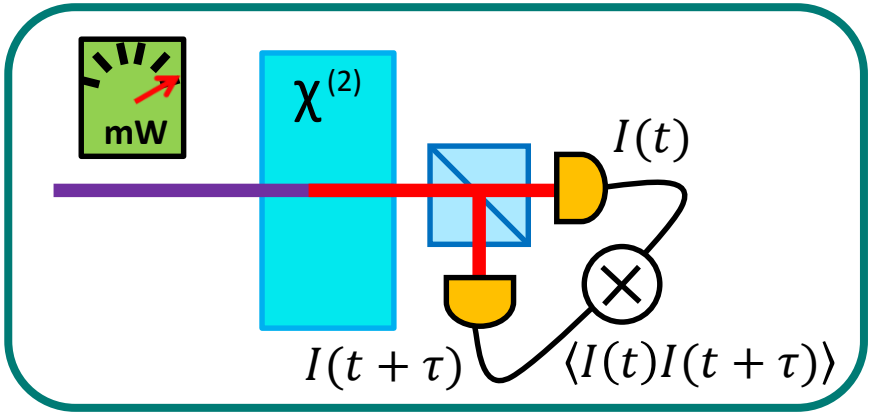
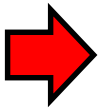


# Ultrafast fluctuations




Large bandwidth:
up to 100-150 THz



Ultrafast fluctuations:
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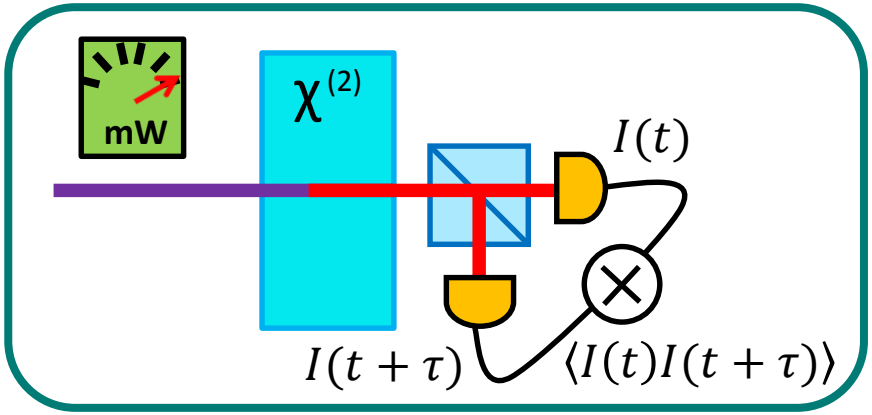


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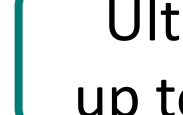

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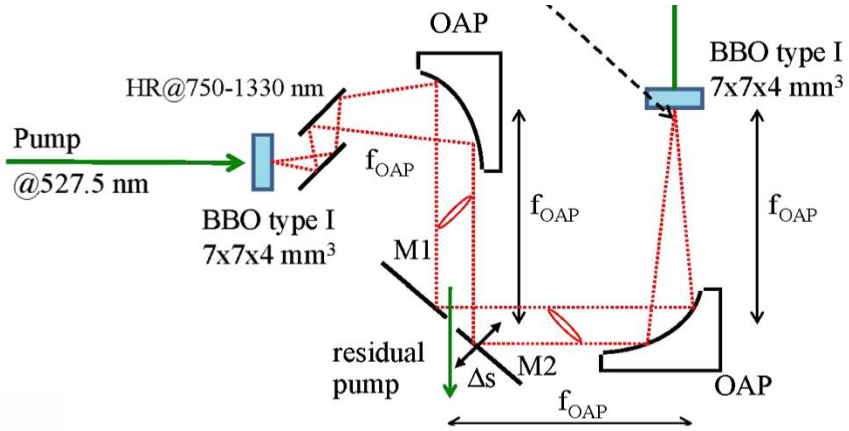


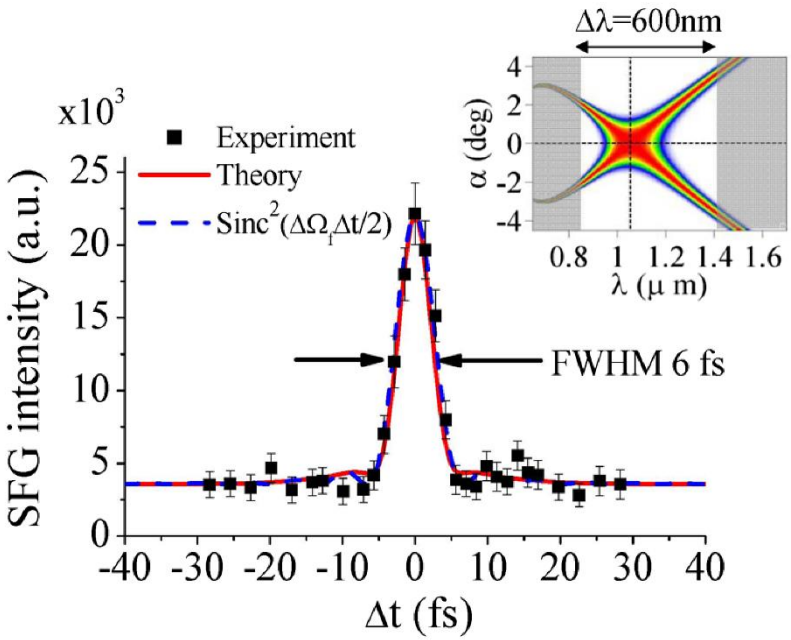


Jedrkiewicz, O. et. al. PRL 108, 253904 (2012).

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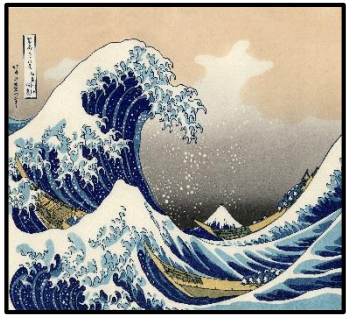
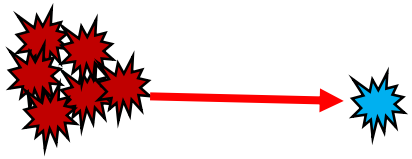
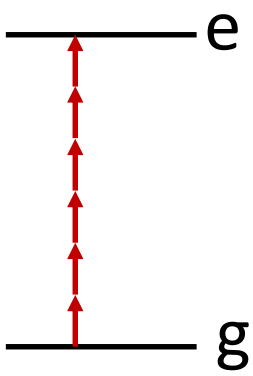


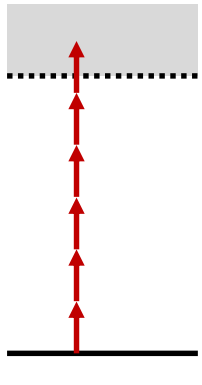
# N-photon effects



Optical harmonic generation




Multi-photon absorption




Multi-photon ionization

$$n \times \hbar\omega$$

Agarwal, G.S. PRA 1 1445 (1970).
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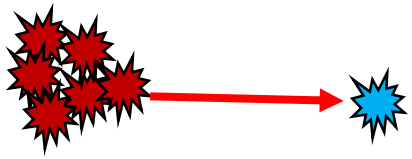

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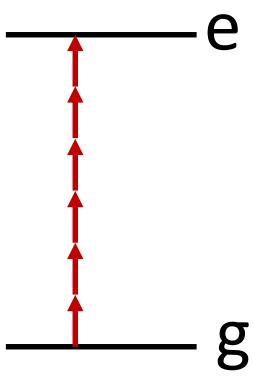


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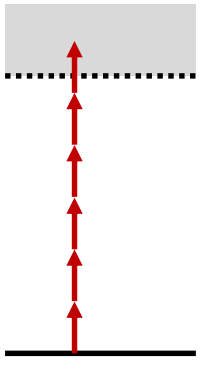


Multi-photon ionization

$$n \times \hbar\omega$$

Rate of n-photon effect

$$R^{(n)} \sim \langle (N_\omega)^n \rangle$$

$$R^{(n)} \sim g^{(n)} \langle N_\omega \rangle^n$$

n[th] order auto-correlation function

$$g^{(n)} = \frac{\langle : N^n : \rangle}{\langle N \rangle^n} \approx \frac{\langle N^n \rangle}{\langle N \rangle^n}$$


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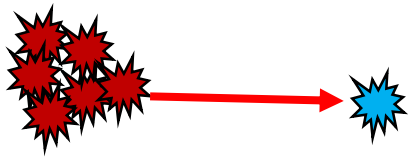

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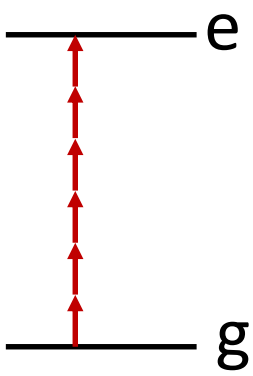


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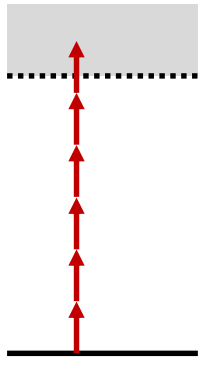


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Photon flux

$$F_\omega = \langle N_\omega \rangle / \mathrm{T}$$


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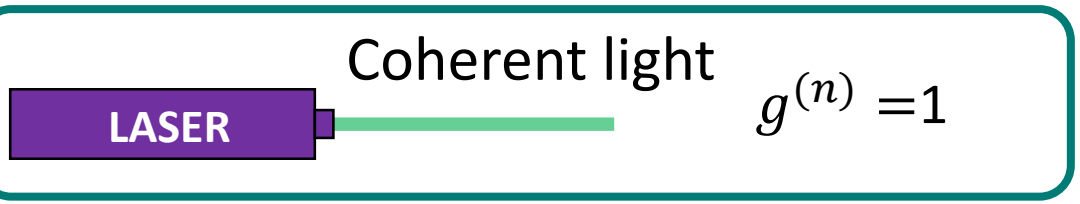


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# Enhancement of N-photon effects

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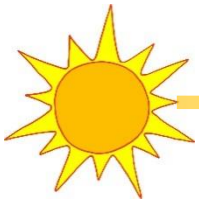
Coherent light


$g^{(n)} = 1$

Thermal light



$g^{(n)} = n!$

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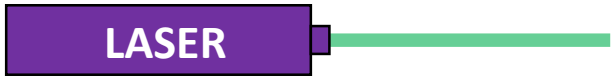


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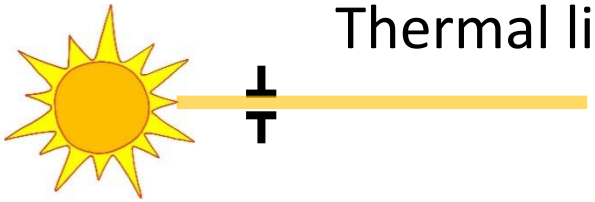

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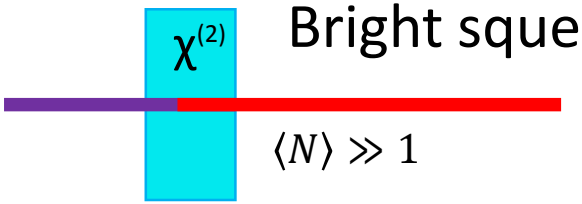
Bright squeezed vacuum




$g^{(n)} = (2n-1)!!$

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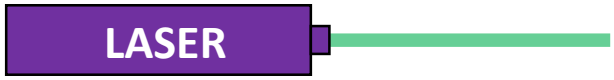


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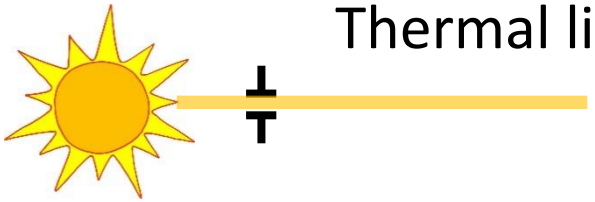

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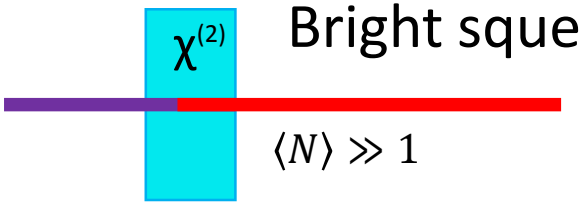
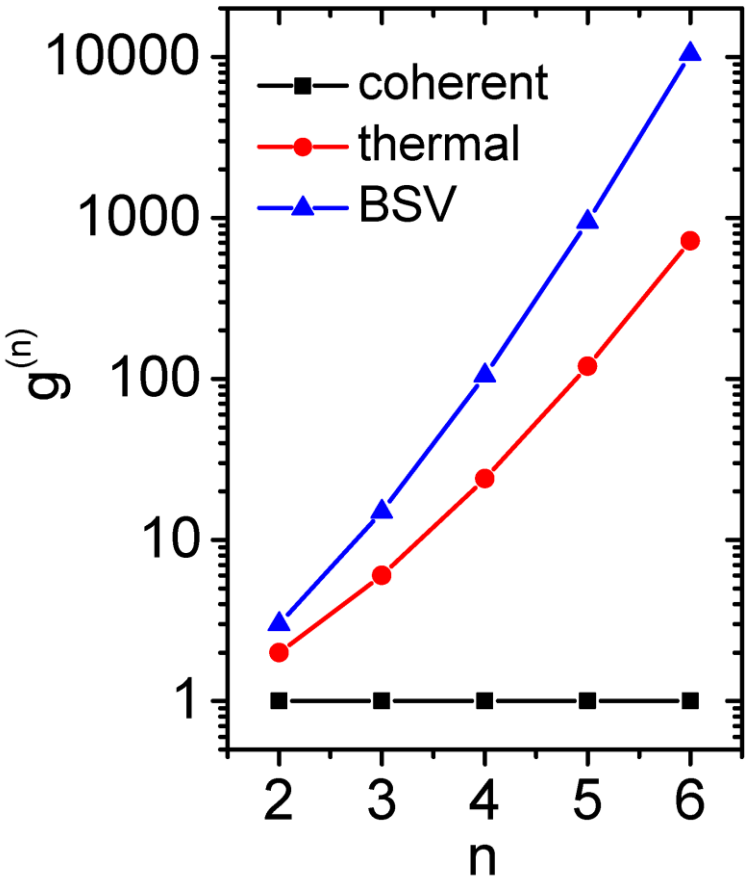
Bright squeezed vacuum




$\langle N \rangle \gg 1$

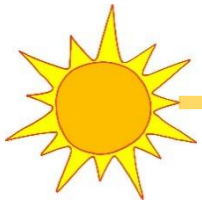
$g^{(n)} = (2n-1)!!$




Benefit for multi-photon effects, especially from fragile objects

Janszky, J. et. al. PRA 36, 1288 (1987).
Iskhakov, T.Sh. et al. Opt. Lett. 37, 1919 (2012).

# Enhancement of N-photon effects

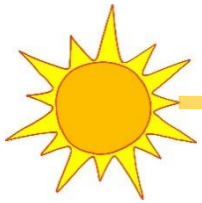


Thermal light

$g^{(n)} = n!$

$$R^{(n)} \sim g^{(n)} (F_\omega)^n$$

# Enhancement of N-photon effects



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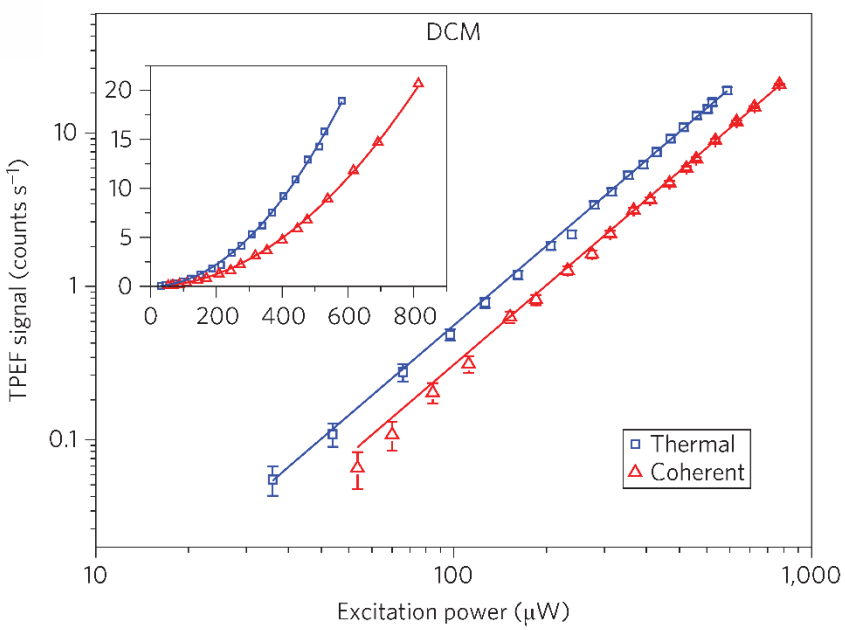
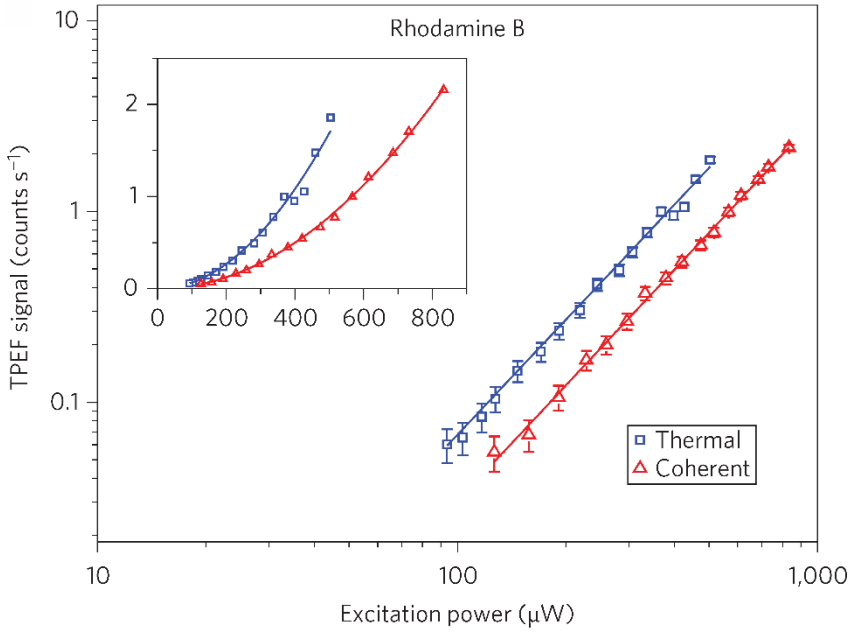
## Superluminescent diode

Dyes: two-photon absorption

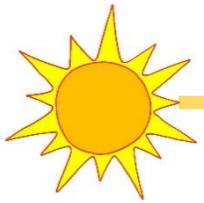



300 fs fluctuations in CW
max power 1 mW

Jechow, A. et al. Nat. Phot. 7, 973 (2013).

# Enhancement of N-photon effects



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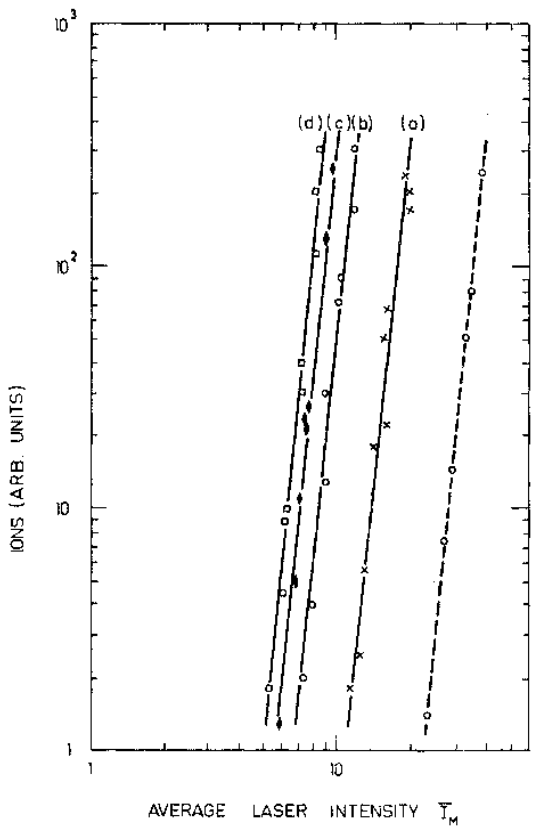
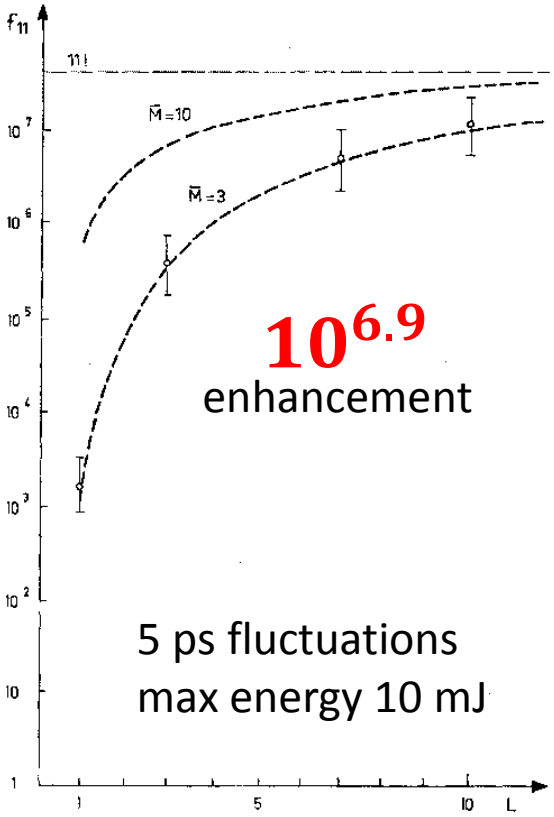
## Multimode laser

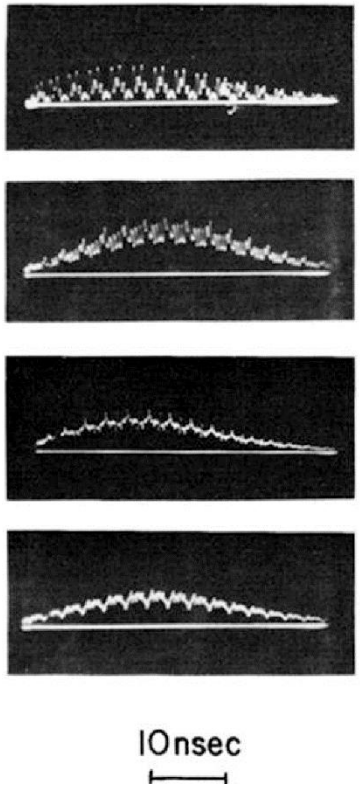
Xe: 11-photon ionization




$10^{6.9}$
enhancement

5 ps fluctuations
max energy 10 mJ




Lecompte, C. et. al. PRA 11, 1009 (1975).

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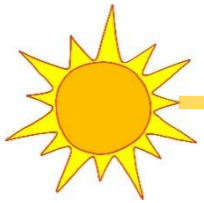

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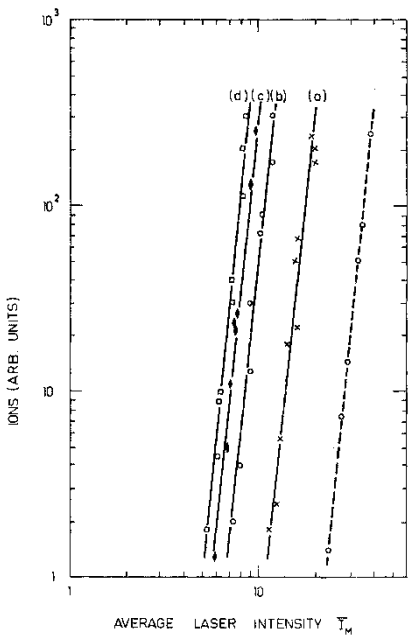


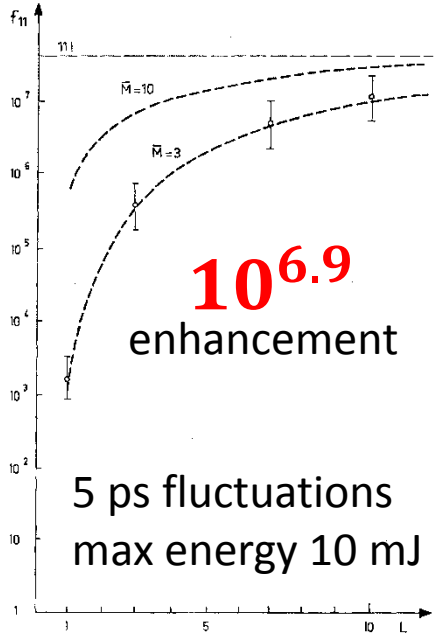


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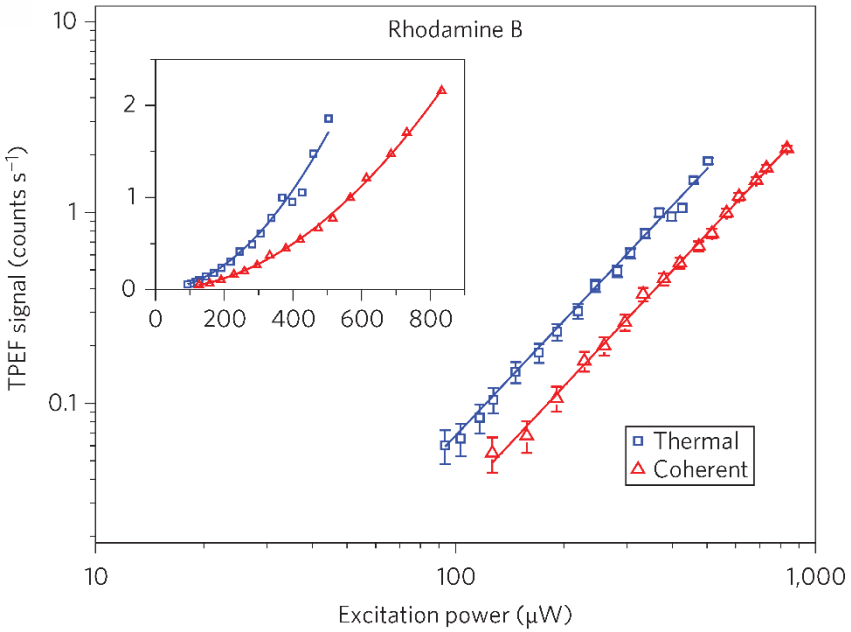


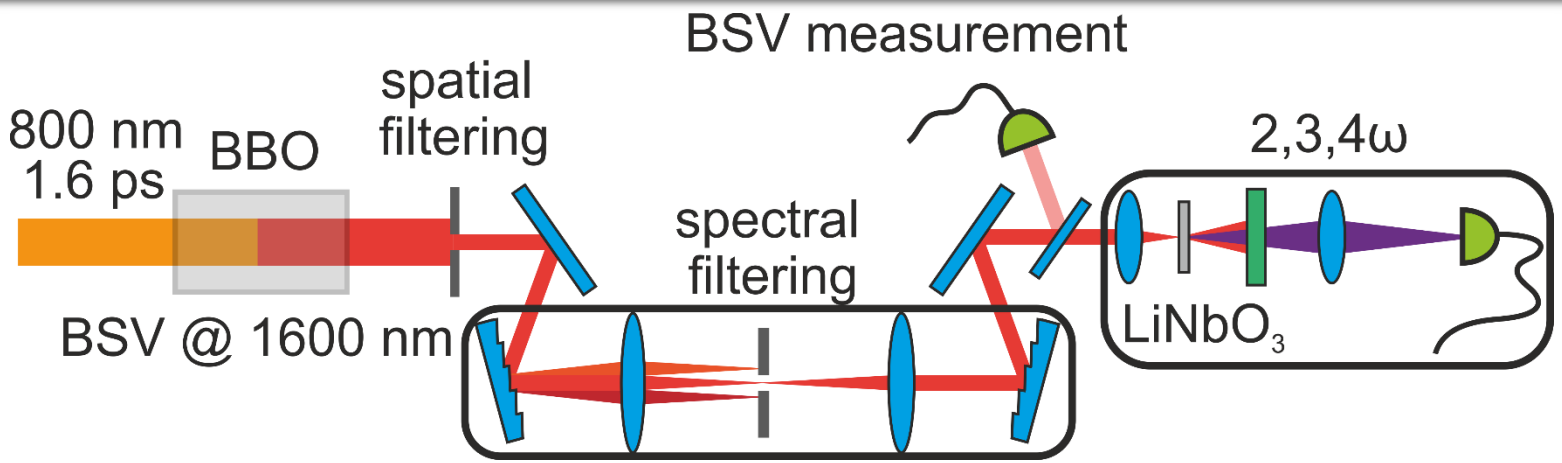

300 fs fluctuations in CW
max power 1 mW

Low powers or slow fluctuations

Lecompte, C. et. al. PRA 11, 1009 (1975).

Jechow, A. et al. Nat. Phot. 7, 973 (2013).

# Experiment: SH, TH, FH generation




KS et. al. PRL 119, 223603 (2017).

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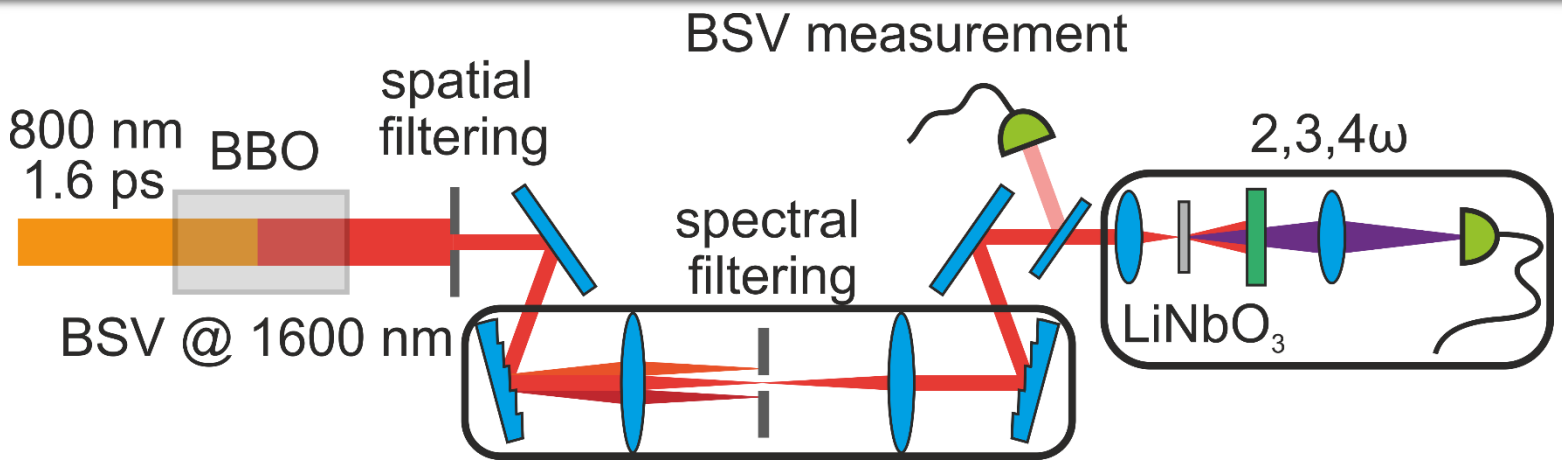
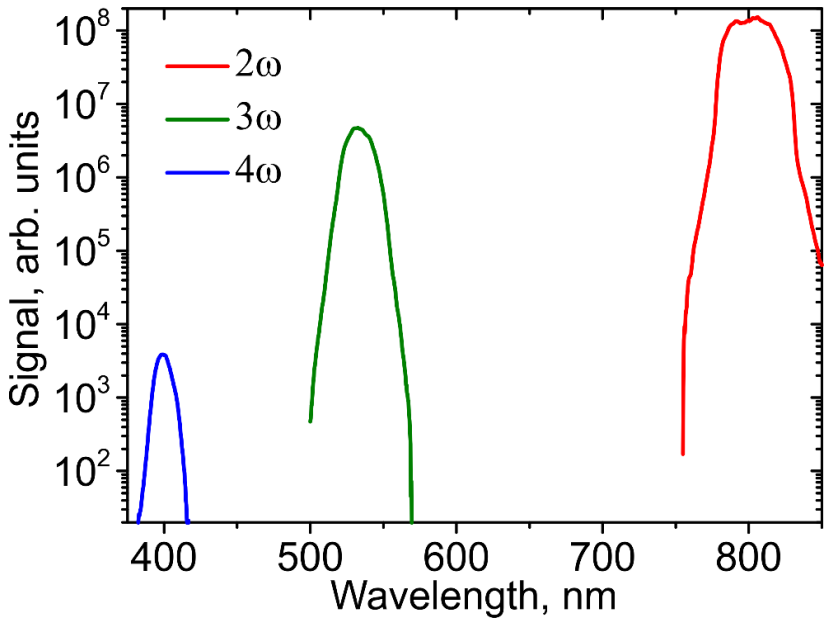


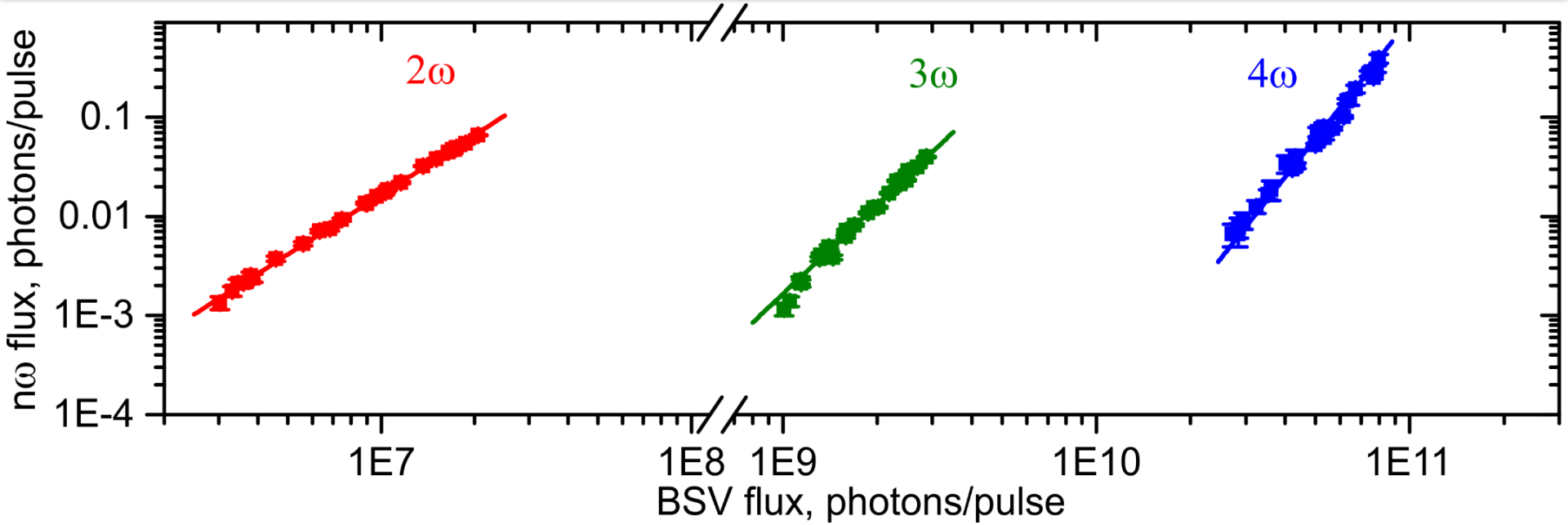

Generation without phase-matching

↓

Broadband harmonics

KS et. al. PRL 119, 223603 (2017).

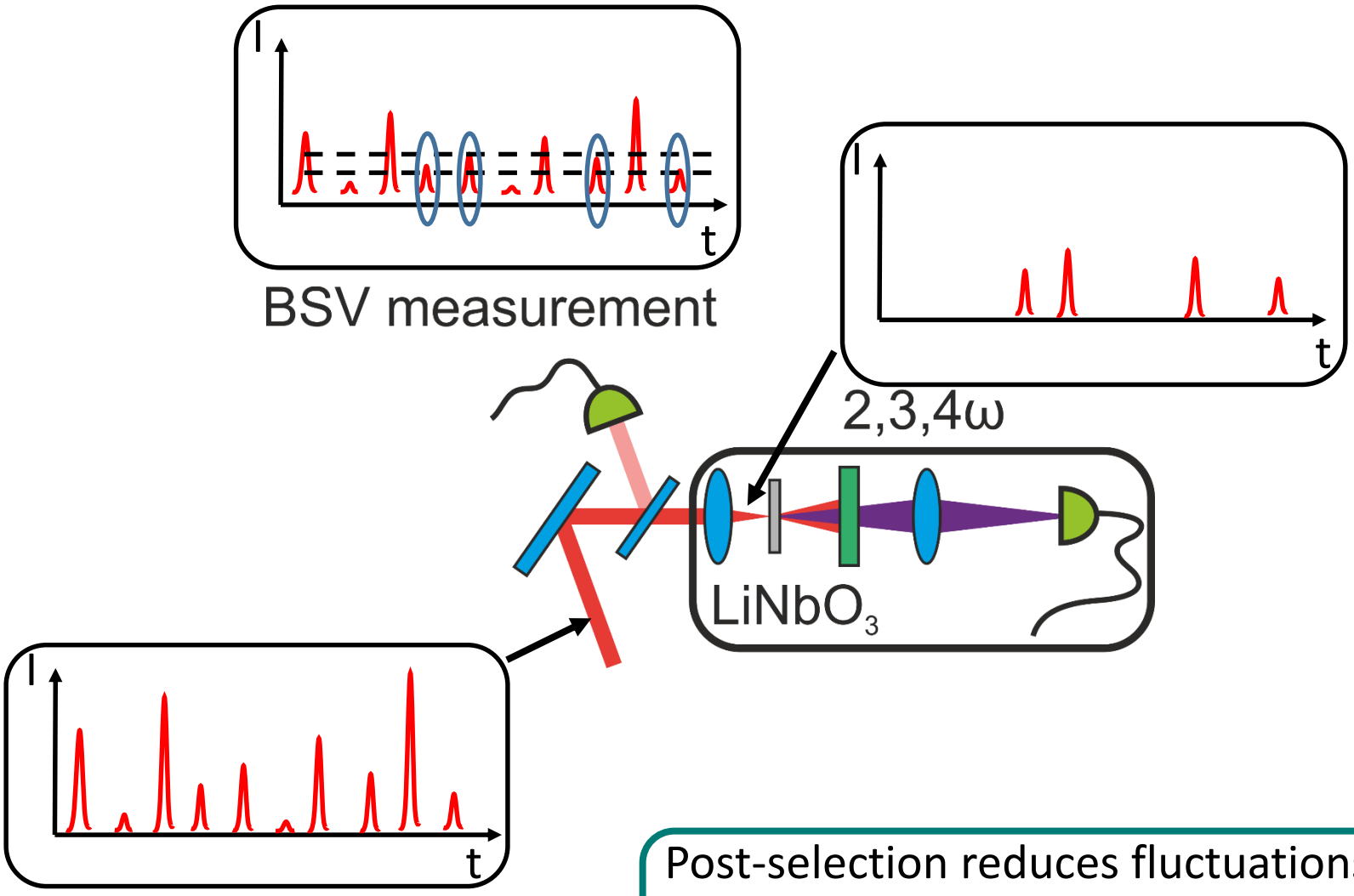
# HG from narrowband BSV




Harmonics show correct power dependence

KS et. al. PRL 119, 223603 (2017).

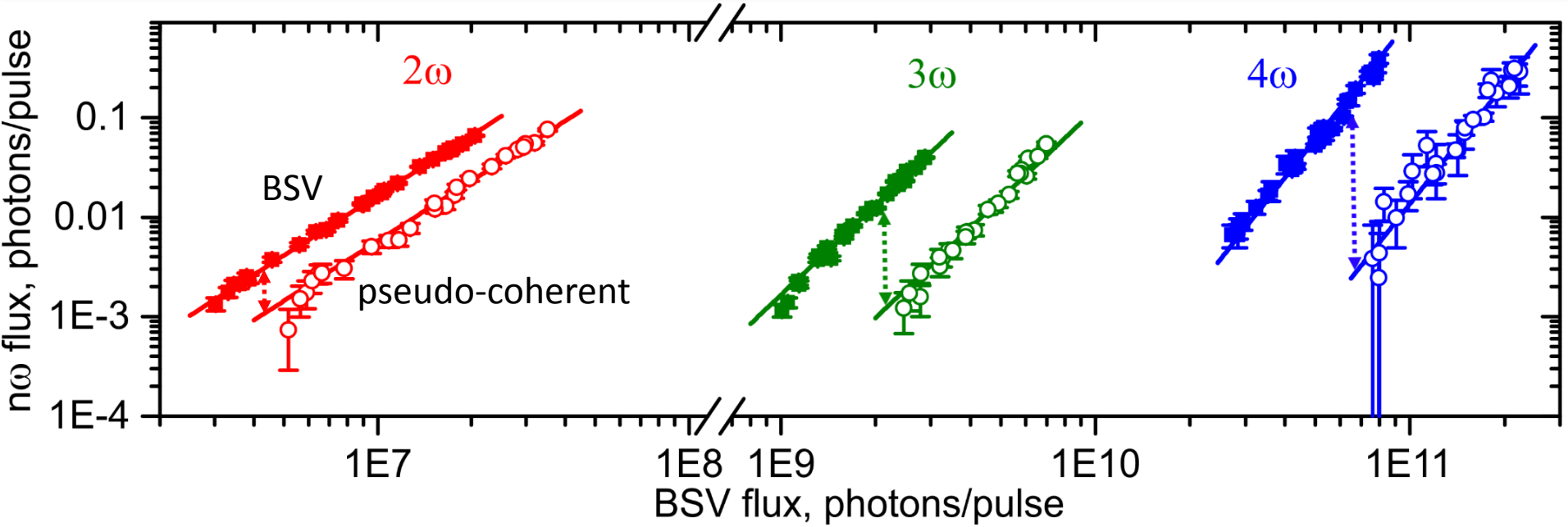
# HG from narrowband BSV: post-selection




Post-selection reduces fluctuations (e.g. $g^{(3)}=15 \rightarrow g^{(3)}=1.02$) gives light with 'pseudo-coherent' statistics

KS et. al. PRL 119, 223603 (2017).

# HG from narrowband BSV




$$F_{n\omega} \sim g^{(n)} (F_\omega)^n$$

Statistical efficiency

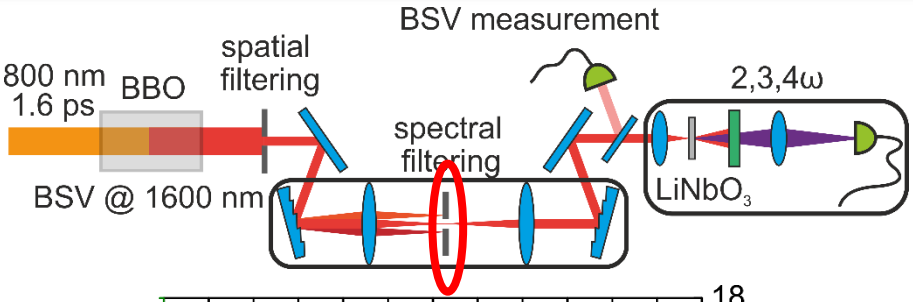
$$\xi^{(n)} \equiv {F_{n\omega}}/{(F_\omega)^n} \sim g^{(n)}$$

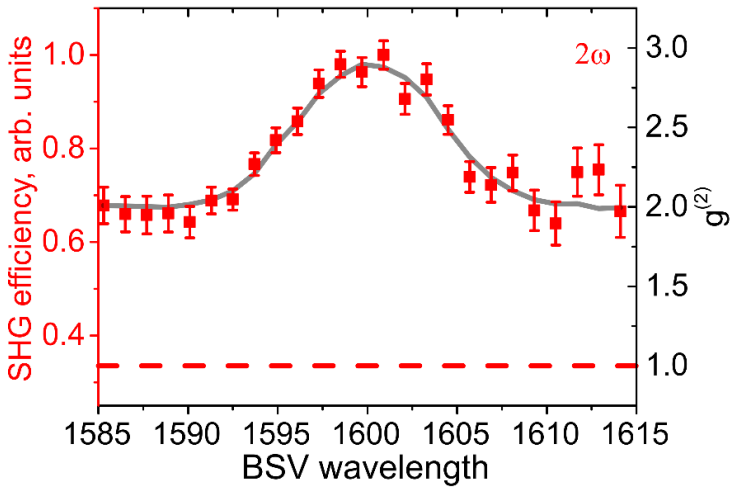
| n | $\xi^{(n)}_{BSV}/\xi^{(n)}_{qc}$ | $g^{(n)}_{BSV}/g^{(n)}_{qc}$ |
|---|---|---|
| 2 | 2.86 | 2.94 |
| 3 | 13.6 | 14.5 |
| 4 | **71** | 63 |

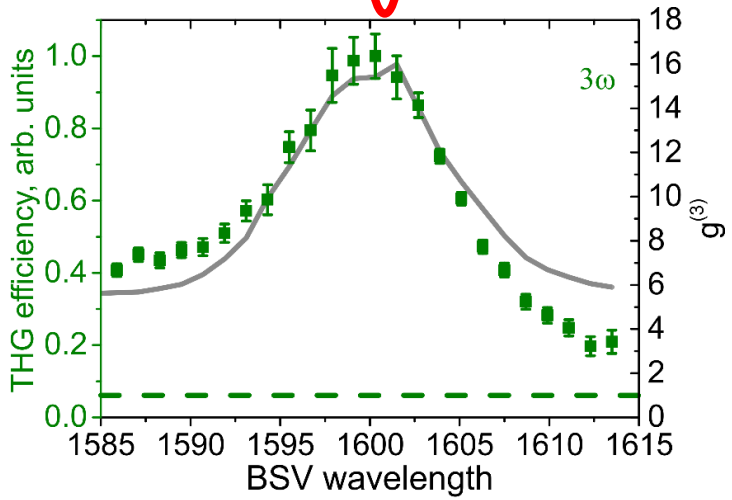
KS et. al. PRL 119, 223603 (2017).

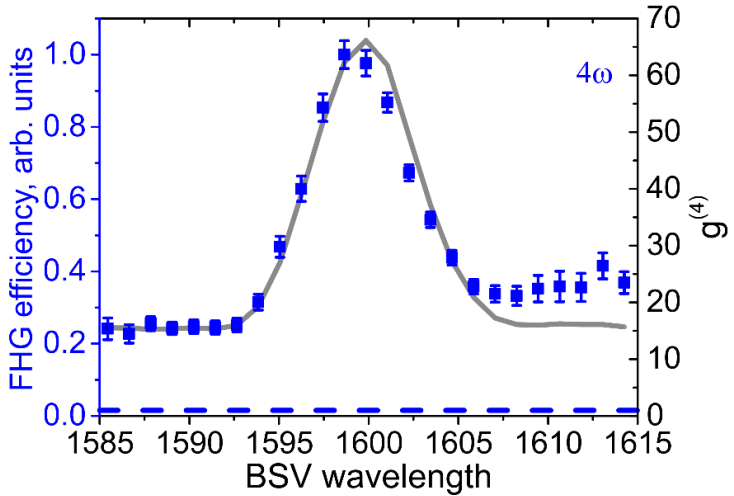
# HG from narrowband BSV

Nondegenerate→ thermal
Degenerate→superbunched



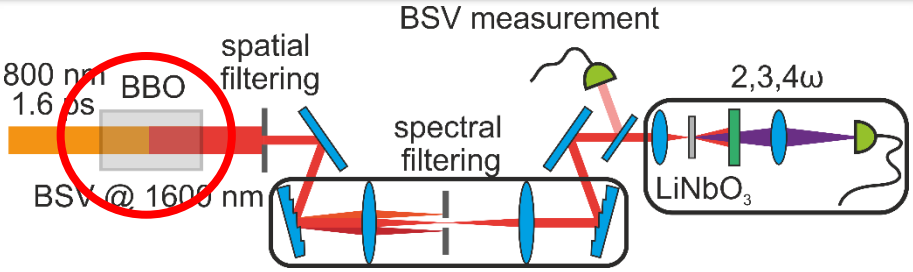




KS et. al. PRL 119, 223603 (2017).

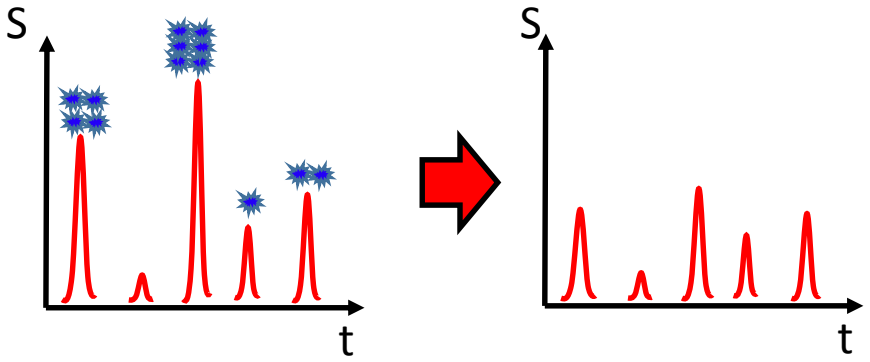
# BSV statistics




Unwanted SH in BBO in the case of efficient BSV

$$2\omega_1 \rightarrow \omega_2$$

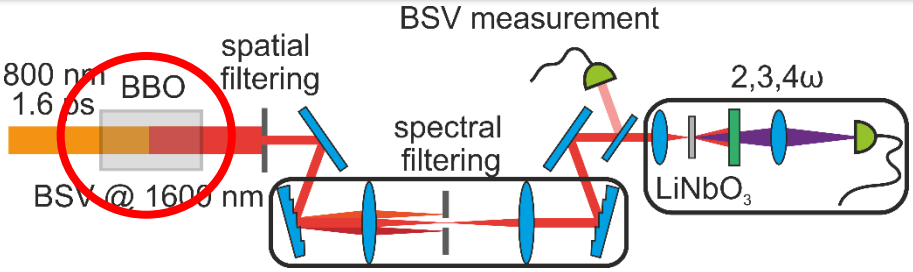
$$1430 - 1830\,nm \rightarrow 715 - 915\,nm$$




Fluctuations reduce and statistics changes

KS et. al. PRL 119, 223603 (2017).

# BSV statistics

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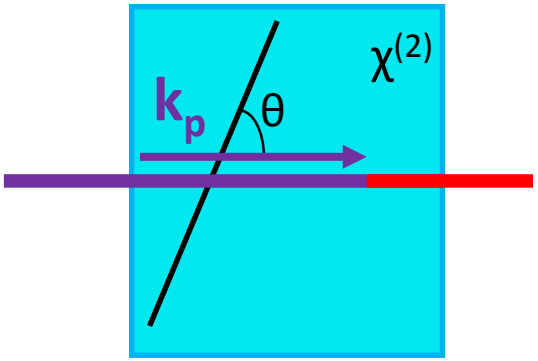
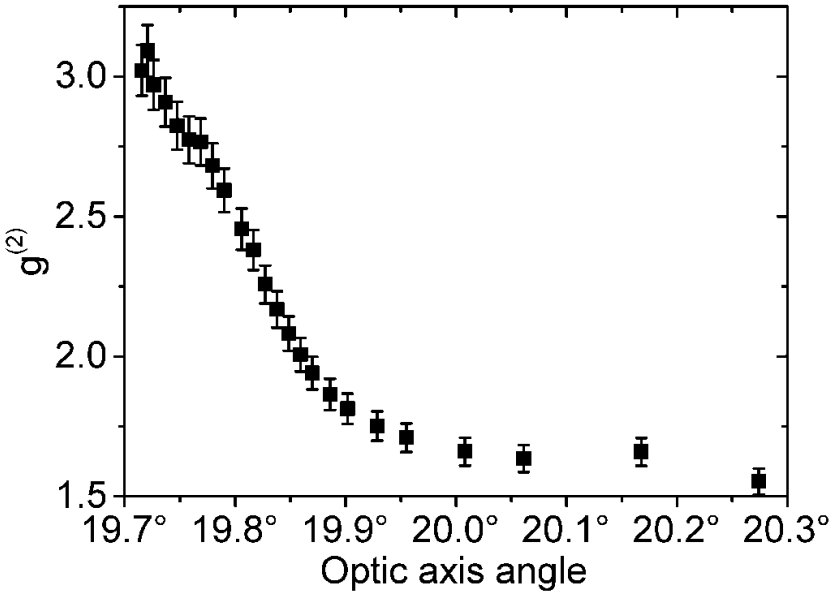
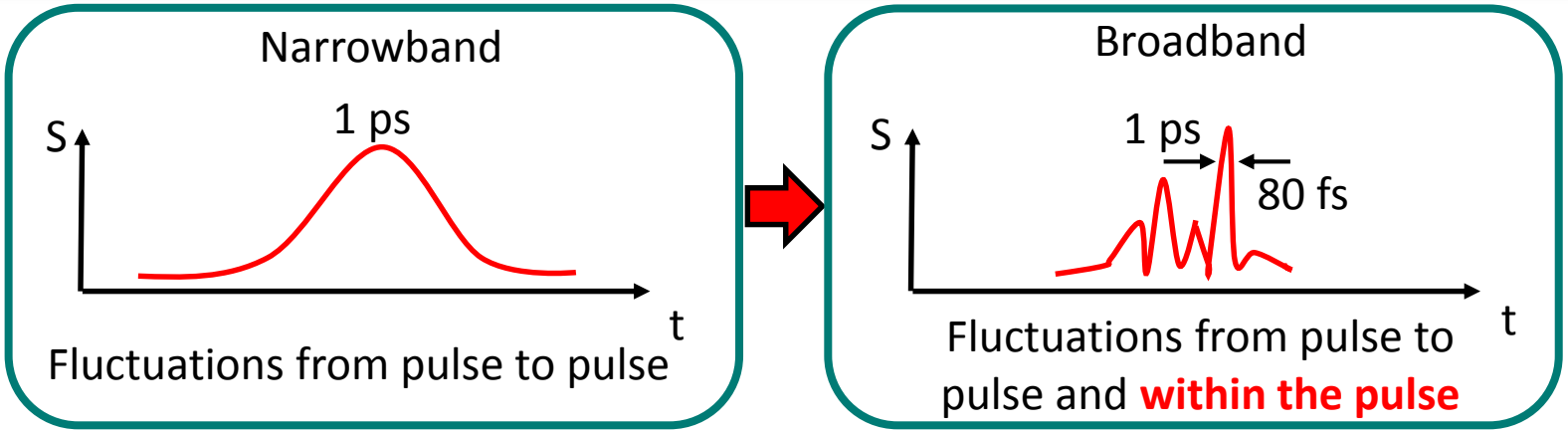



KS et. al. PRL 119, 223603 (2017).

# HG from broadband BSV




KS et. al. PRL 119, 223603 (2017).

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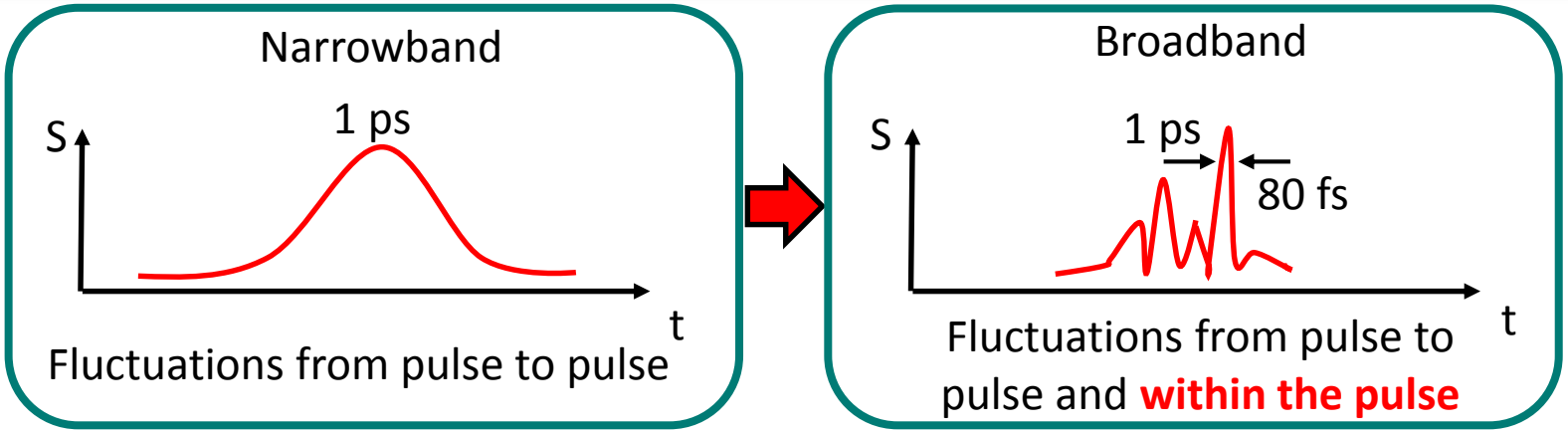
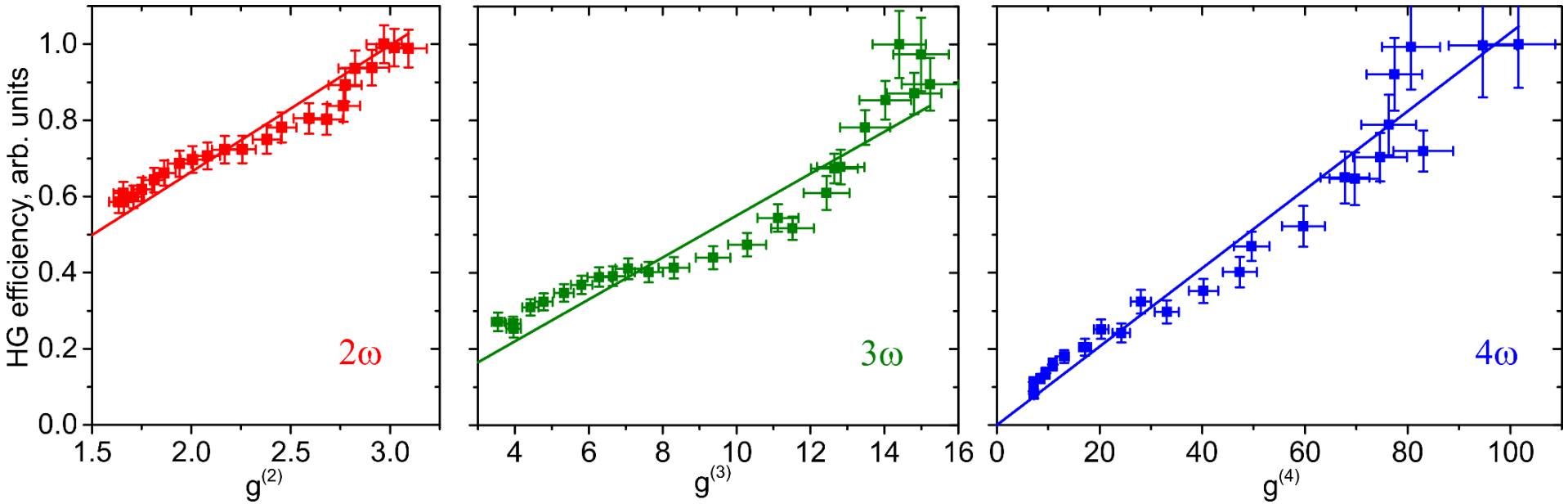



$$\xi^{(n)} \sim g^{(n)}$$

$$\Delta\lambda = 75\ nm$$

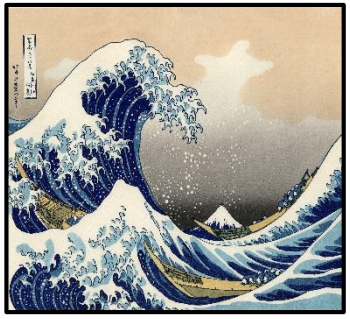



Enhancement due to ultrafast fluctuations

KS et. al. PRL 119, 223603 (2017).

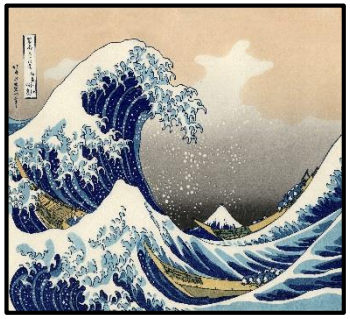
# Outline

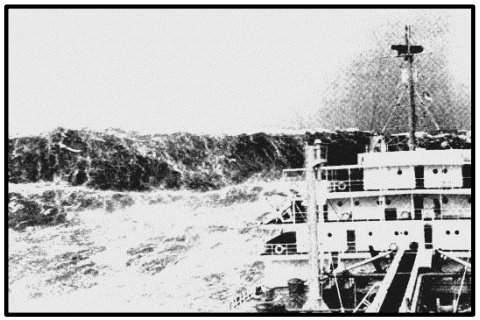
- Ultrafast fluctuations via bright squeezed vacuum
- Efficiency enhancement
  - SH, TH and FH generation
- Enhancement of rogue-wave behavior
  - Harmonics generation
  - Supercontinuum generation
- Summary

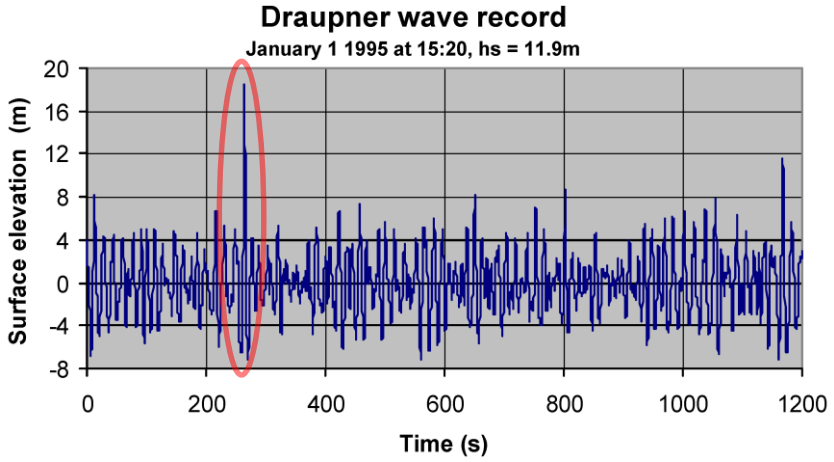



# Extreme events and rogue waves

## Ocean








S. Haver, Statoil Tech. Rep. (2003).

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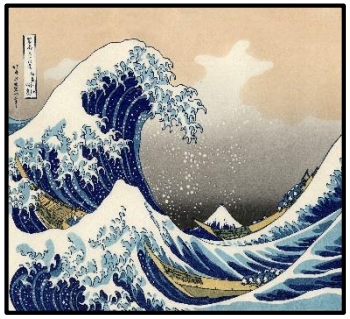

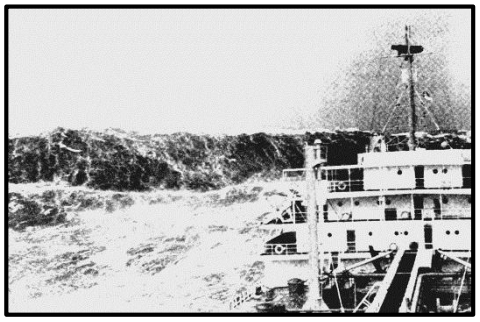

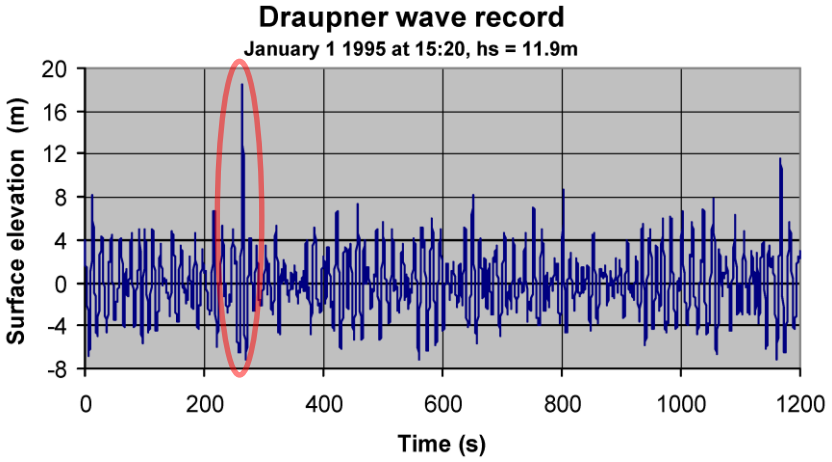


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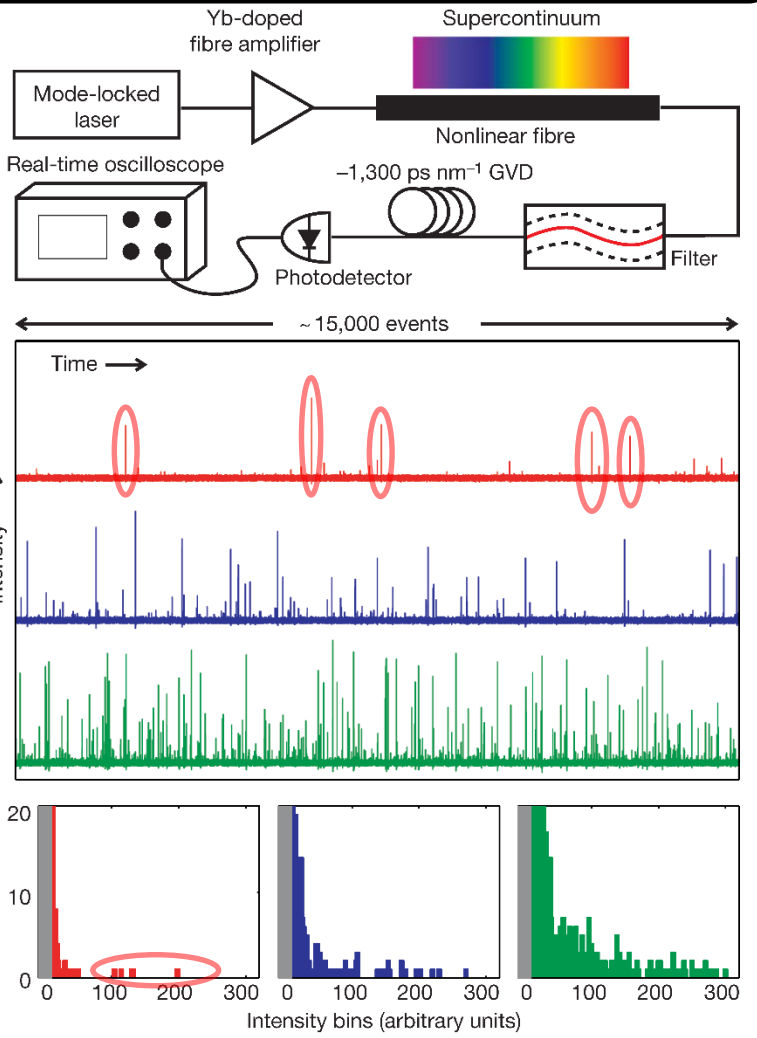
## Light



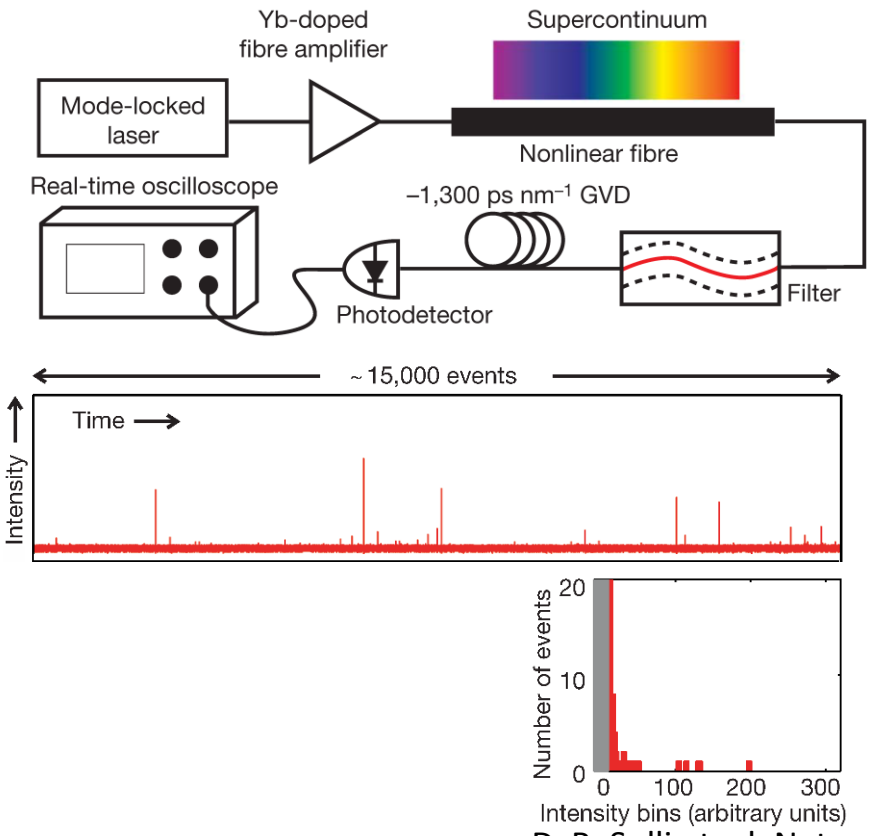

D. R. Solli et. al. Nature 450, 1054 (2007).

# Optical rogue waves

## Definition?

A *rogue wave* is a *wave* that is much higher than others around it, and which has a habit of appearing unpredictably.

## Light

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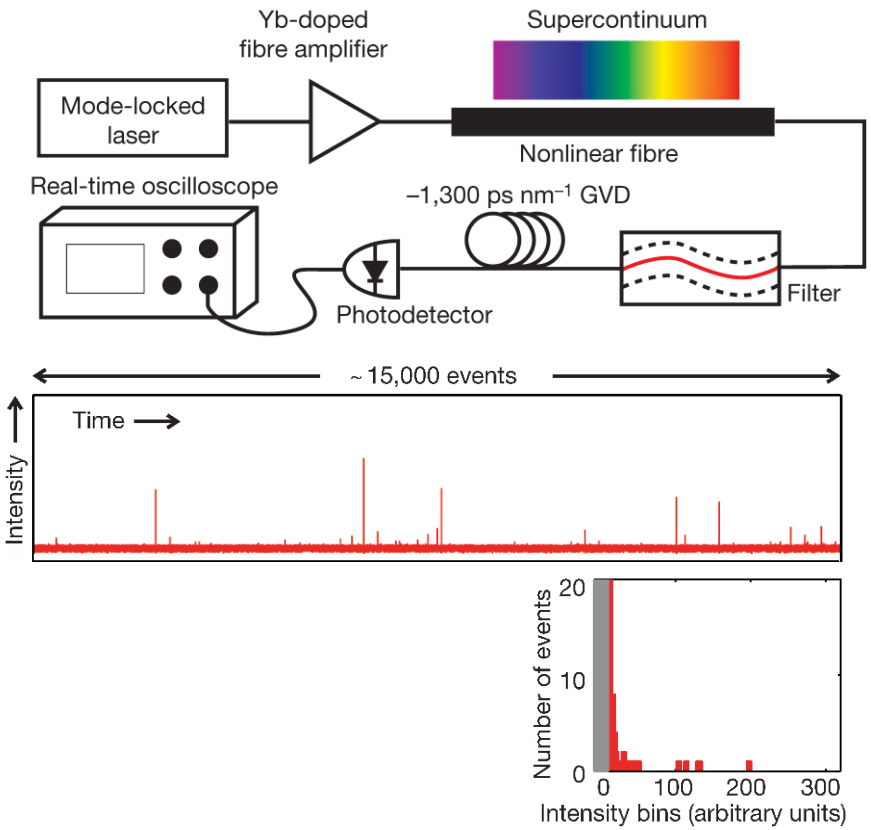
**Chaotic**
**(Random)**

## Light

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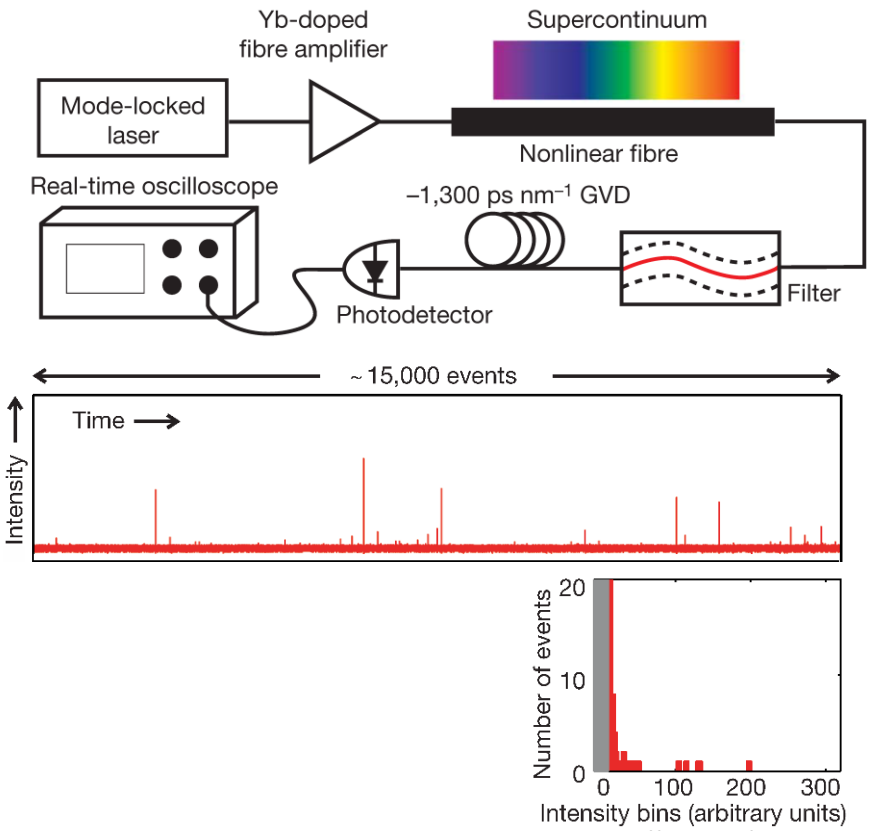


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Intensity – exponential distribution

$$P_{th}(I) = \frac{e^{-I/\langle I \rangle}}{\langle I \rangle}$$

**Strong deviation from thermal statistics**

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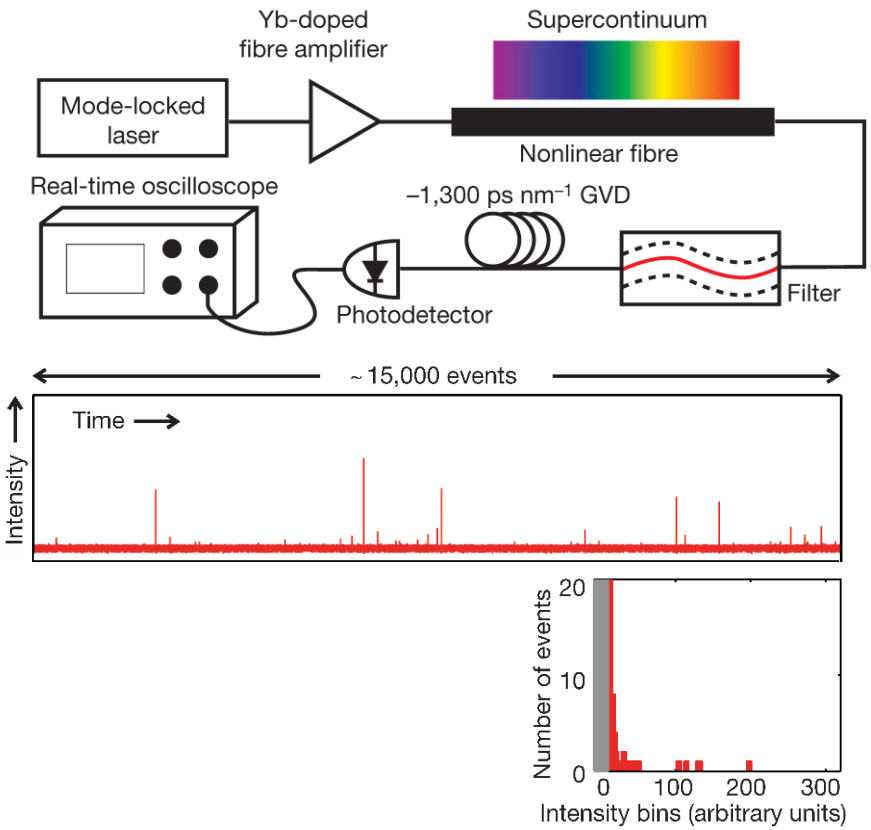
## Light

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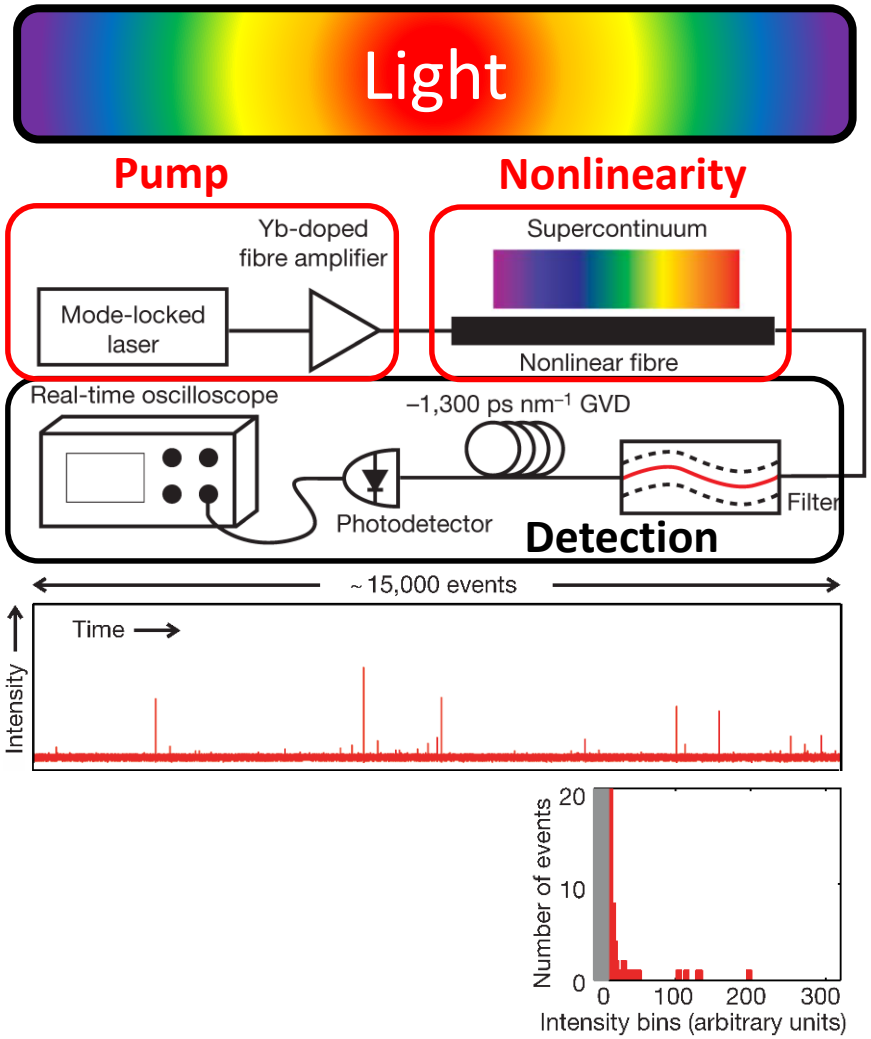


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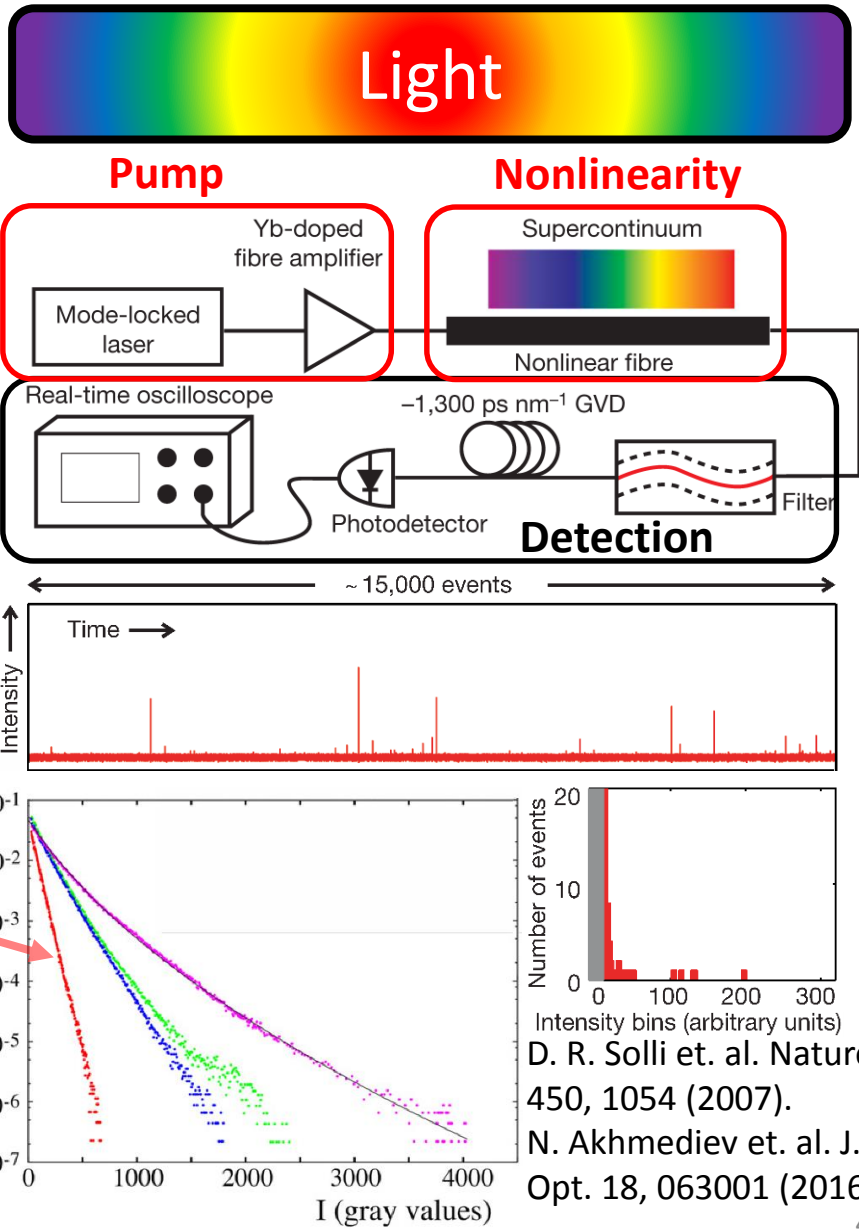


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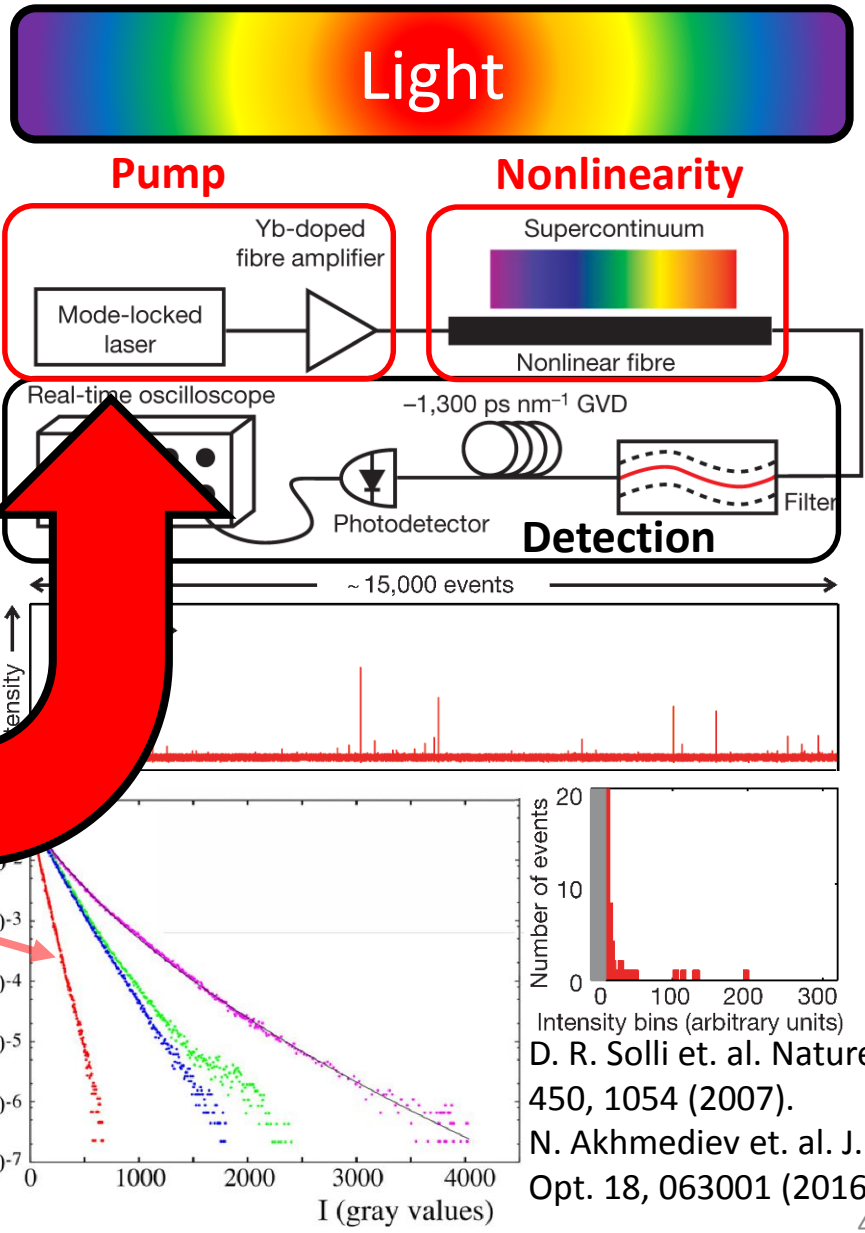
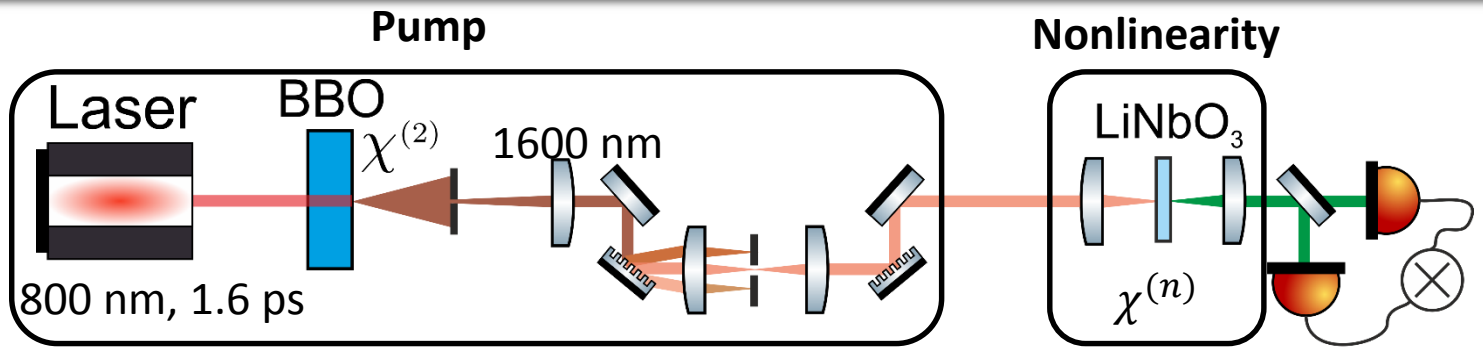
**Nonlinear process**

N. Akhmediev and E. Pelinovsky, Eur. Phys. J. ST 185, 1 (2010).



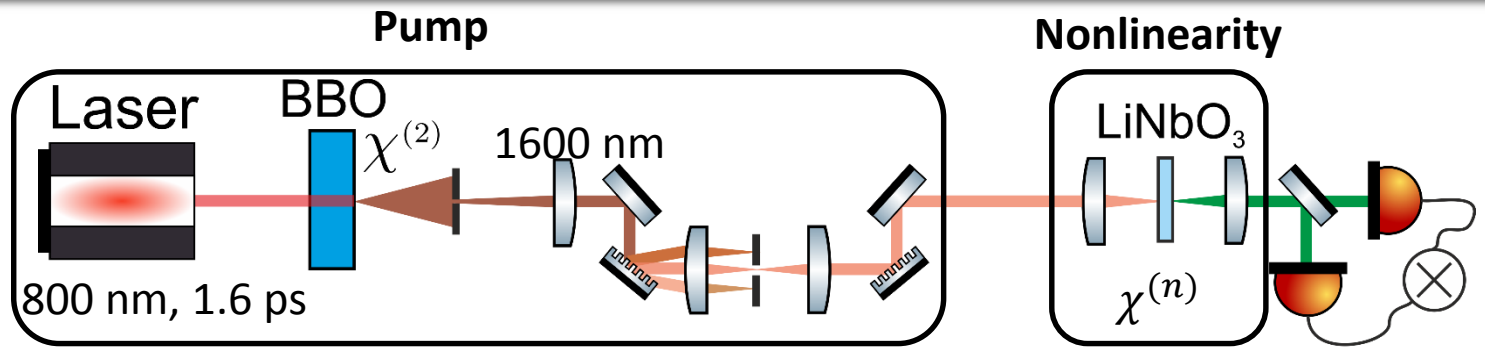

D. R. Solli et. al. Nature 450, 1054 (2007).
N. Akhmediev et. al. J. Opt. 18, 063001 (2016).

# Rogue waves via harmonic generation




KS et. al. PRL 119, 223603 (2017).

# Rogue waves via harmonic generation

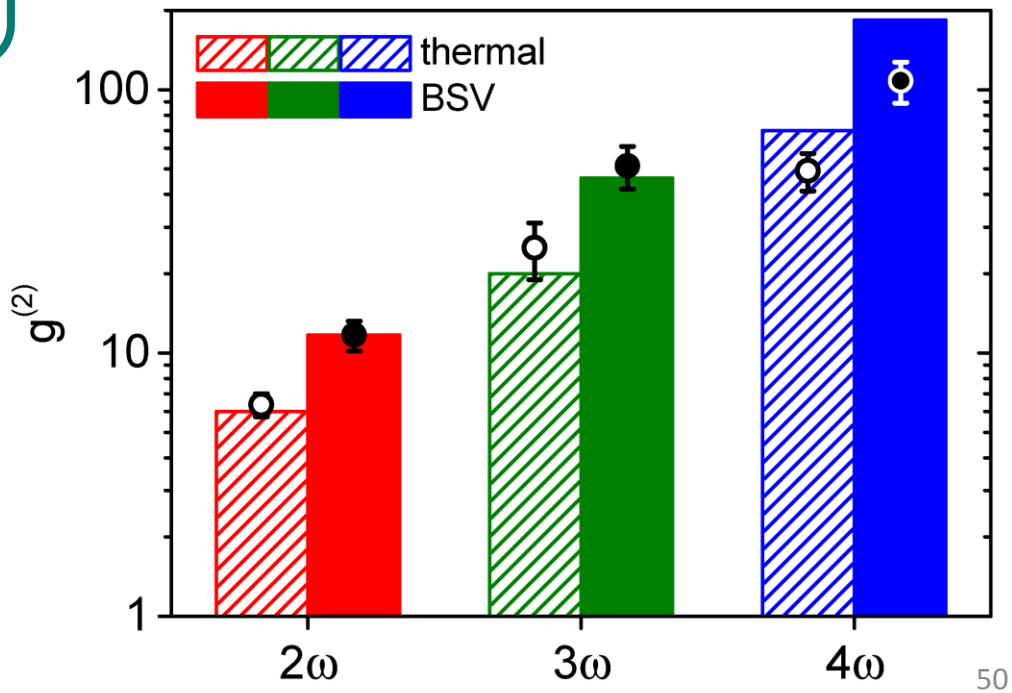



Fluctuating pump

⬇

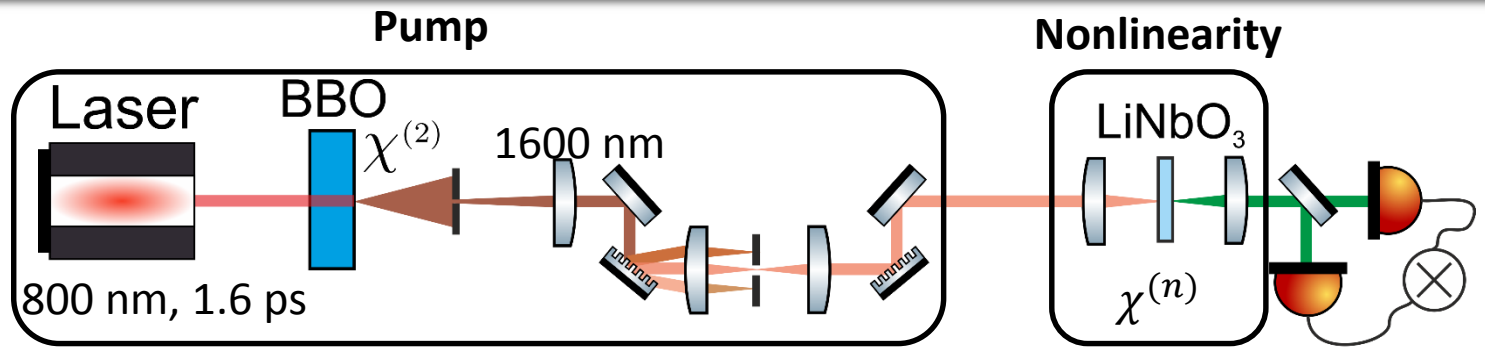
Even stronger fluctuations

$g^{(2)}_{4\omega} = 110$




KS et. al. PRL 119, 223603 (2017).

# Rogue waves via harmonic generation



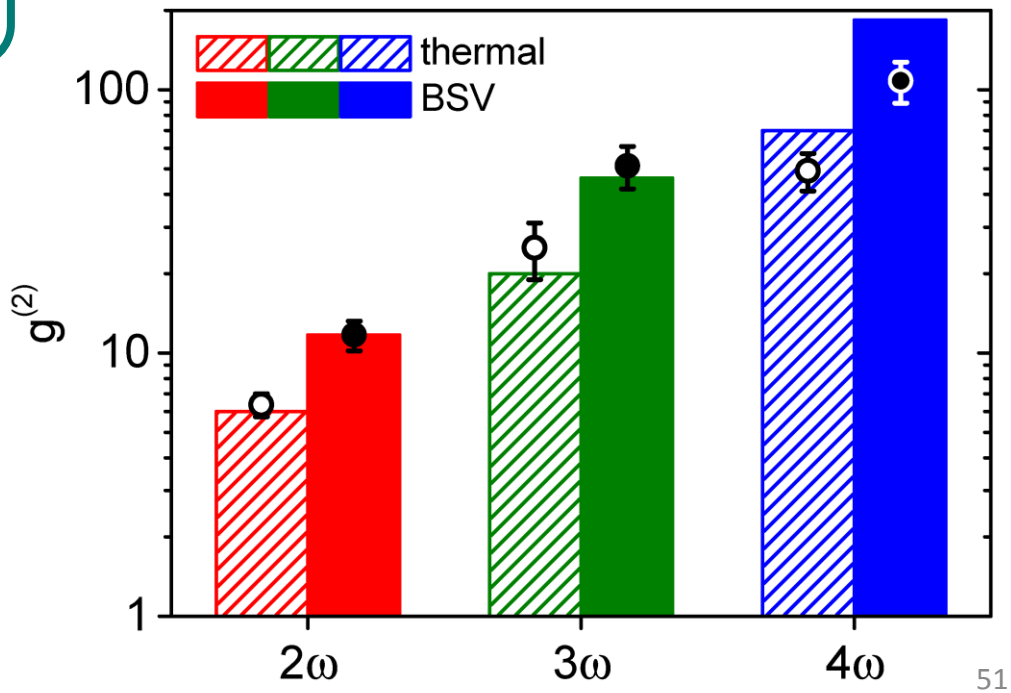

Fluctuating pump

⇓

Even stronger fluctuations

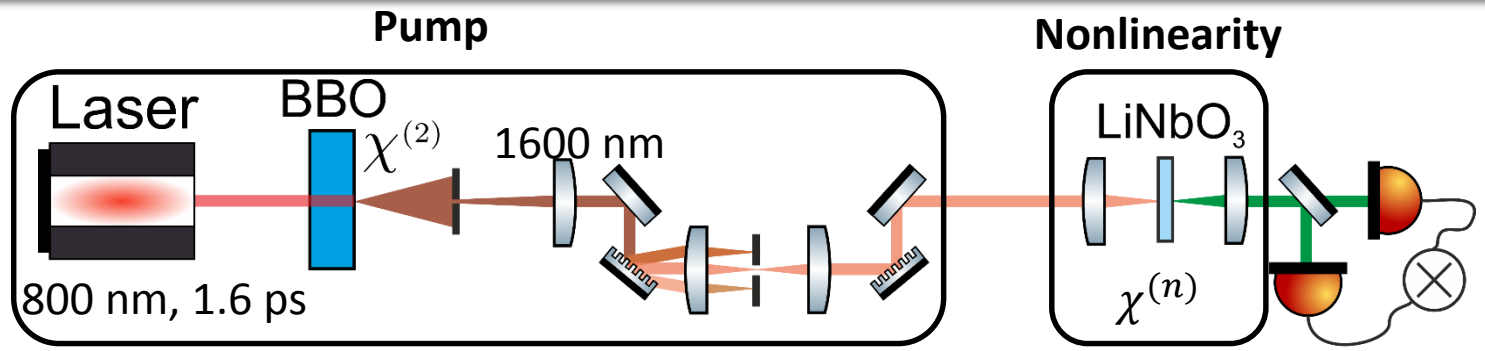
$$g^{(2)}_{4\omega} = 110$$

$$g^{(2)}_{n\omega} = \frac{g^{(2n)}_{\omega}}{(g^{(n)}_{\omega})^2}$$




KS et. al. PRL 119, 223603 (2017).

# Rogue waves via harmonic generation




Fluctuating pump

⇓

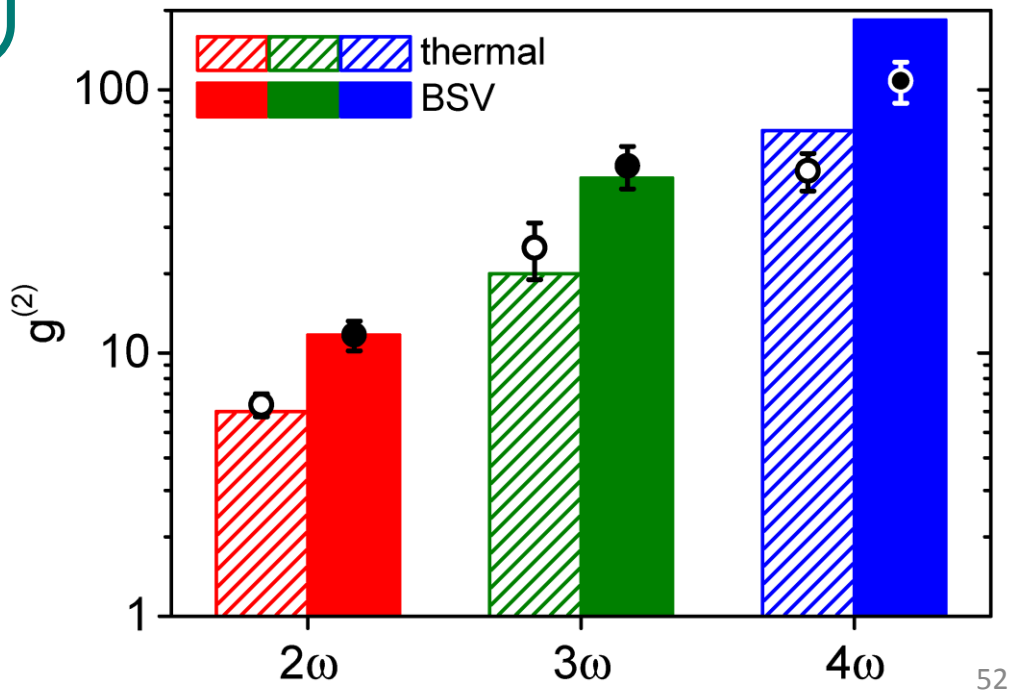
Even stronger fluctuations

$$g^{(2)}_{4\omega} = 110$$

$$g^{(2)}_{n\omega} = \frac{g^{(2n)}_{\omega}}{(g^{(n)}_{\omega})^2}$$

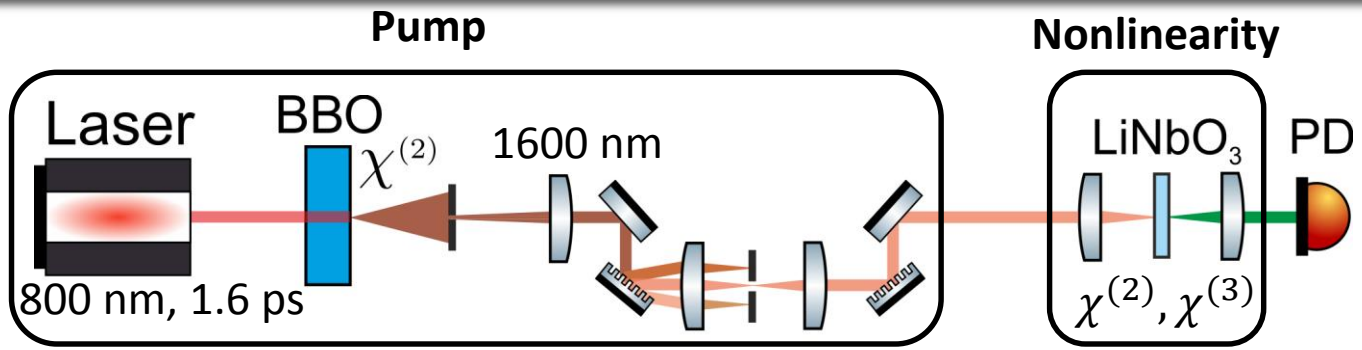
Coherent pumping

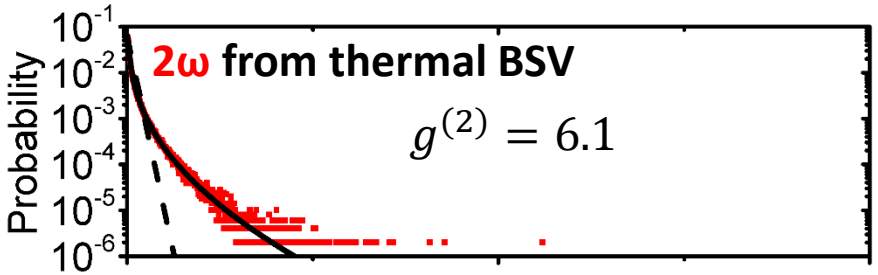
$$g^{(2)}_{n\omega} = 1$$



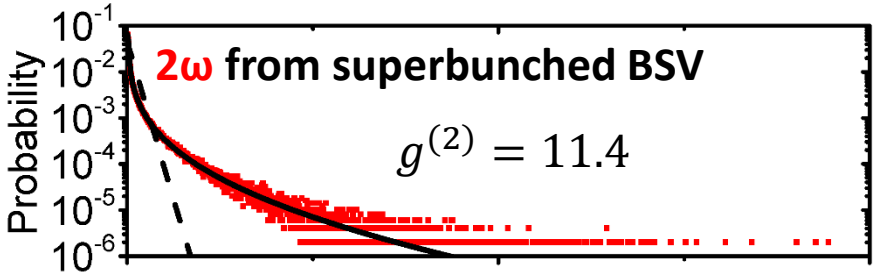

KS et. al. PRL 119, 223603 (2017).

# Rogue waves via harmonic generation

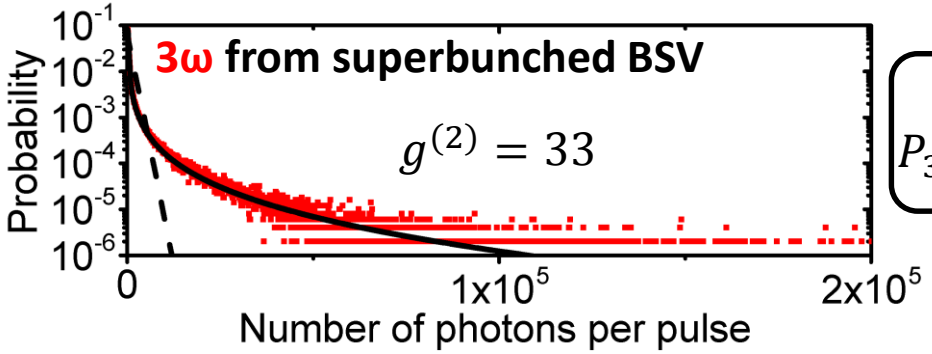



$$P_{2\omega\ th}(I) \sim \frac{e^{-\sqrt{2I/\langle I\rangle}}}{\sqrt{I}}$$

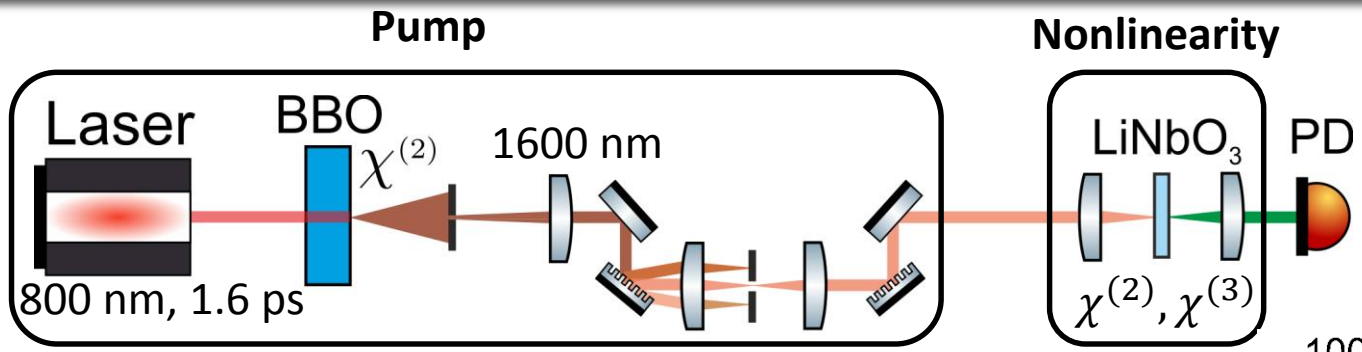


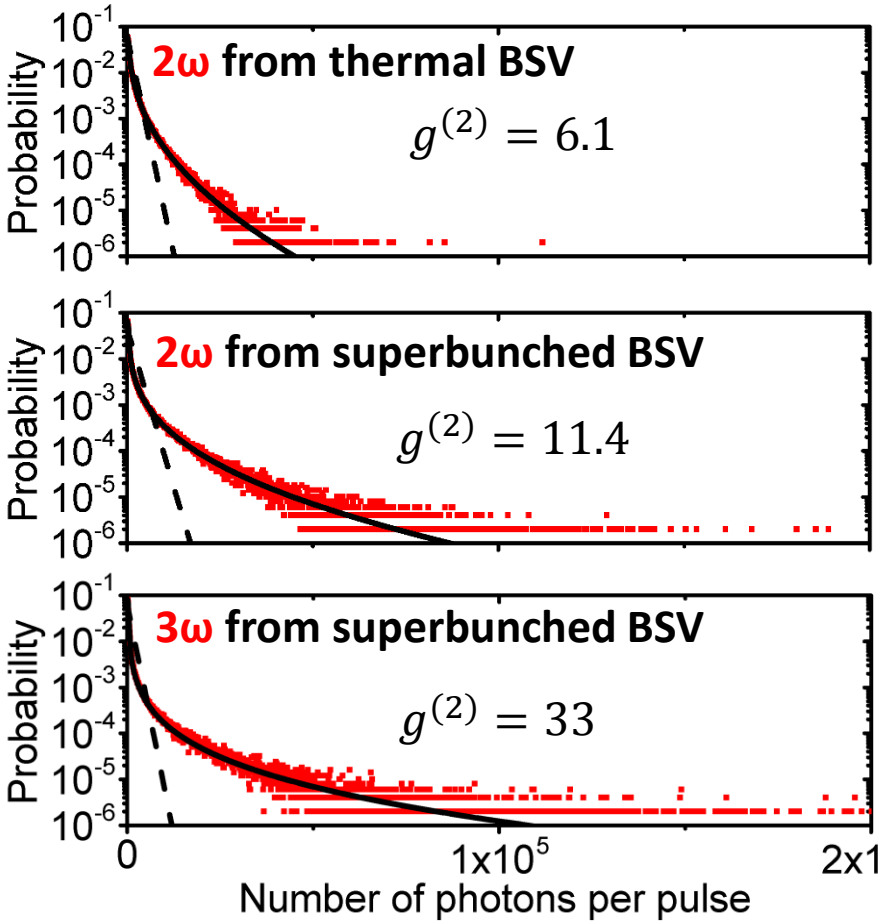

$$P_{2\omega\ sb}(I) \sim \frac{e^{-\frac{1}{2}\sqrt{3I/\langle I\rangle}}}{I^{3/4}}$$




$$P_{3\omega\ sb}(I) \sim \frac{e^{-\frac{1}{2}\sqrt[3]{15I/\langle I\rangle}}}{I^{5/6}}$$

# Rogue waves via harmonic generation

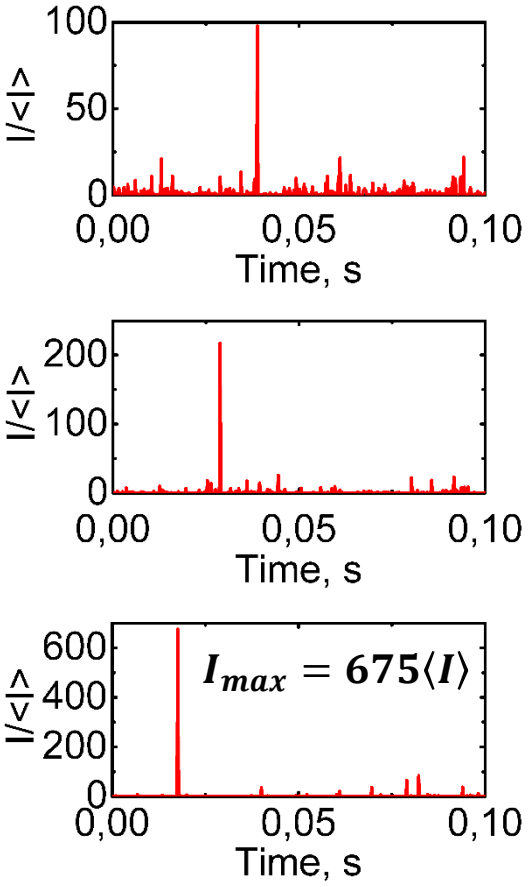


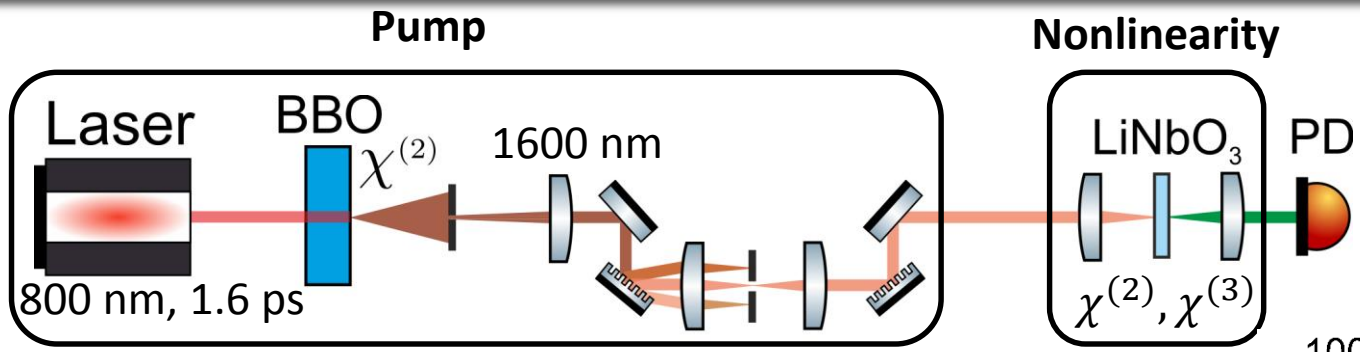

$$P_{2\omega\ th}(I) \sim \frac{e^{-\sqrt{2I/\langle I\rangle}}}{\sqrt{I}}$$

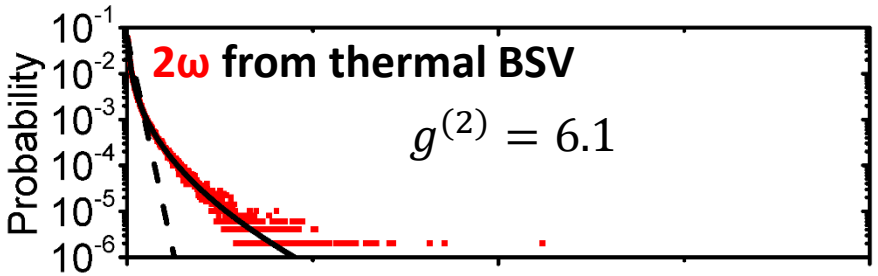
$$P_{2\omega\ sb}(I) \sim \frac{e^{-\frac{1}{2}\sqrt{3I/\langle I\rangle}}}{I^{3/4}}$$

$$P_{3\omega\ sb}(I) \sim \frac{e^{-\frac{1}{2}\sqrt[3]{15I/\langle I\rangle}}}{I^{5/6}}$$

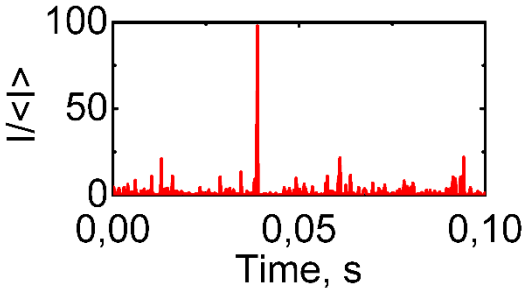


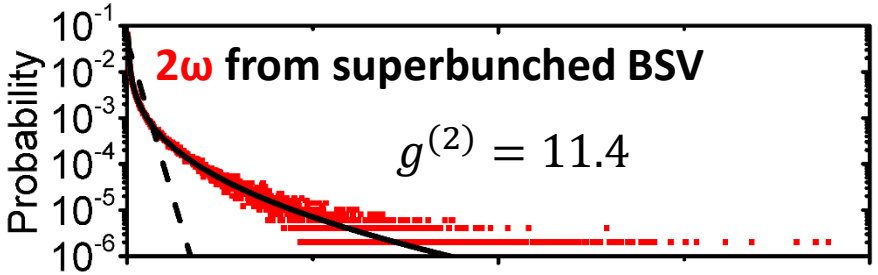
# Rogue waves via harmonic generation



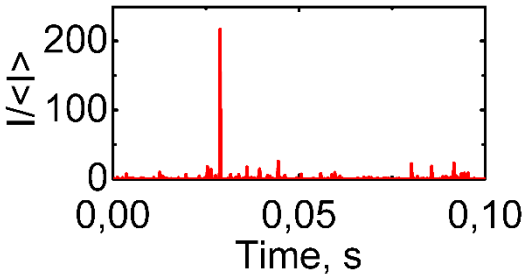



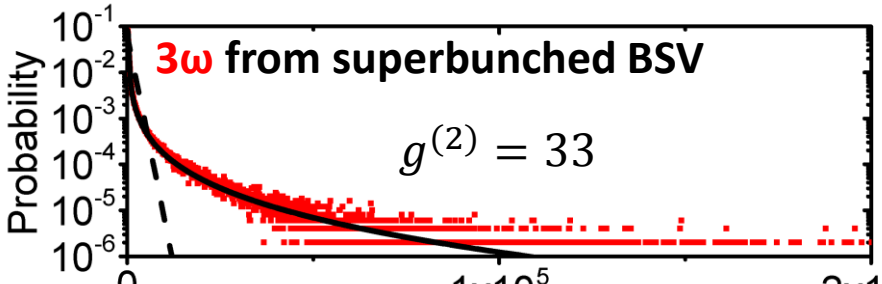

$$P_{2\omega\ th}(I) \sim \frac{e^{-\sqrt{2I/\langle I\rangle}}}{\sqrt{I}}$$



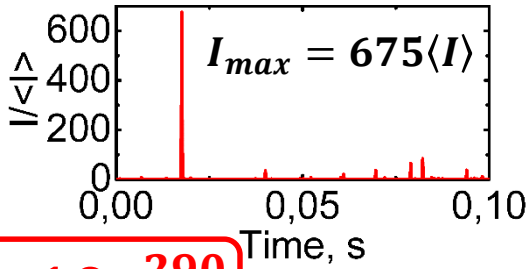




$$P_{2\omega\ sb}(I) \sim \frac{e^{-\frac{1}{2}\sqrt{3I/\langle I\rangle}}}{I^{3/4}}$$



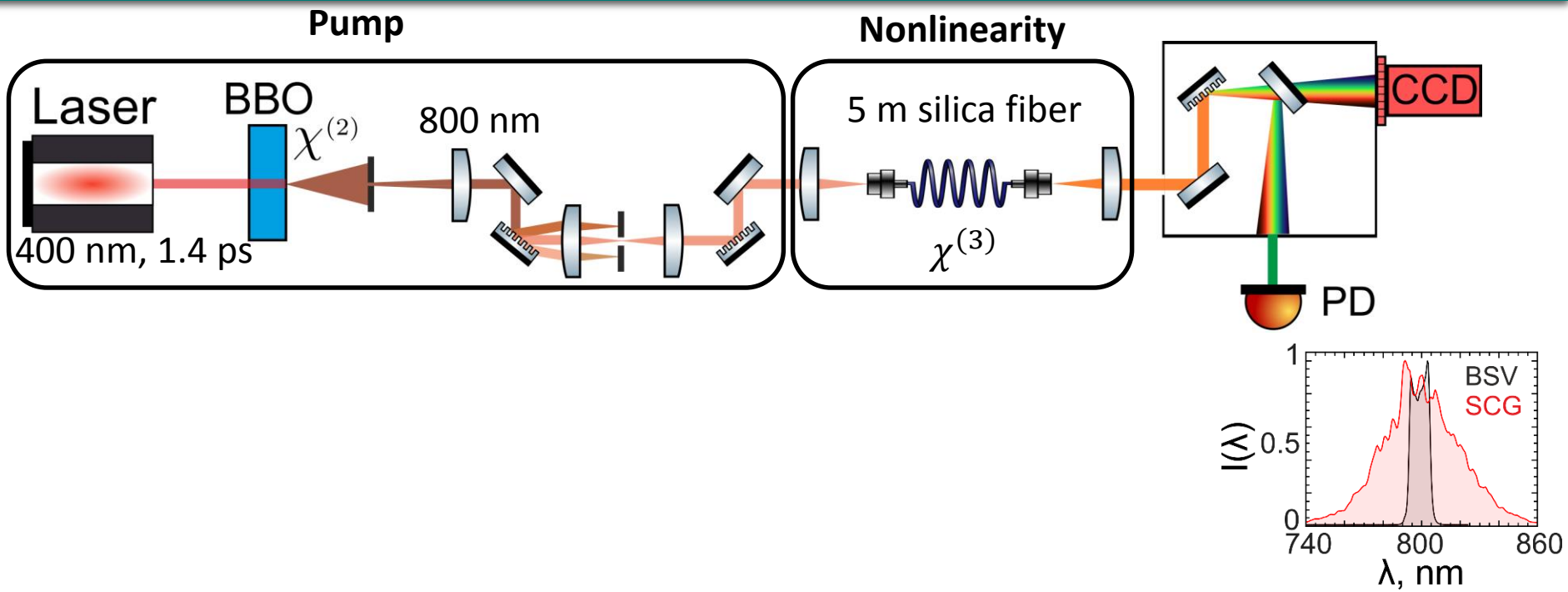




$$P_{3\omega\ sb}(I) \sim \frac{e^{-\frac{1}{2}\sqrt[3]{15I/\langle I\rangle}}}{I^{5/6}}$$

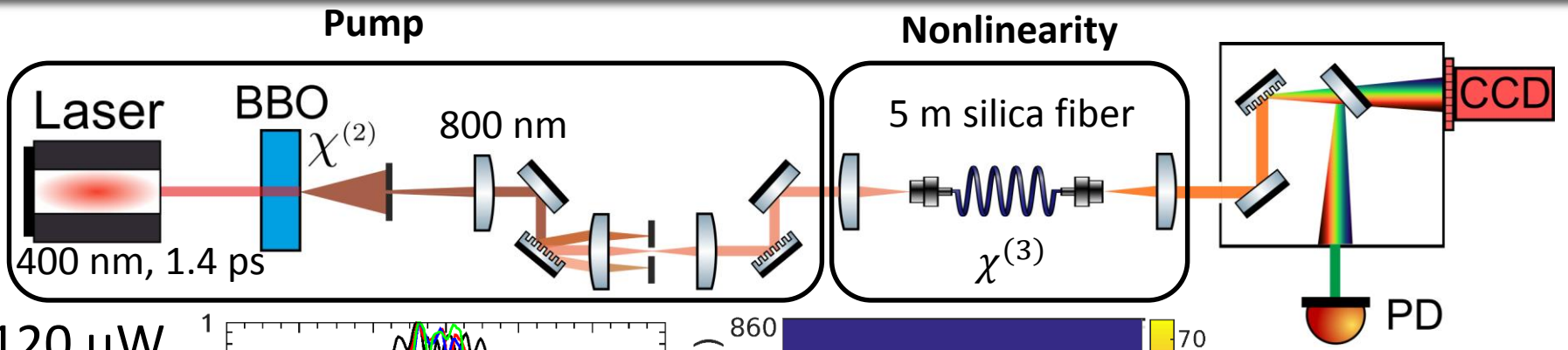



$$P_{th}(I > 670\langle I\rangle) \sim \mathbf{10^{-290}}$$

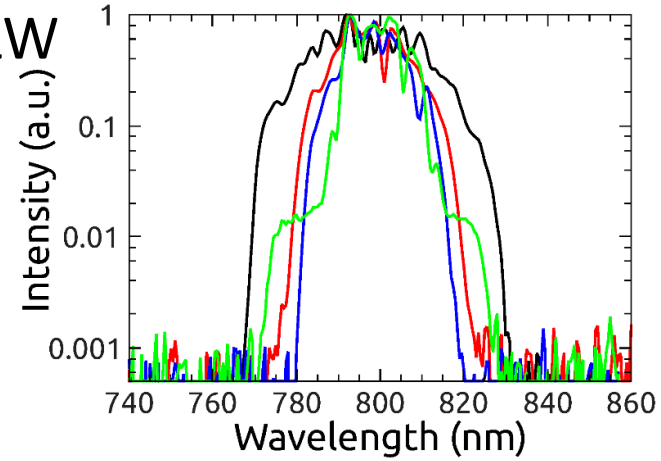
# Rogue waves via supercontinuum generation

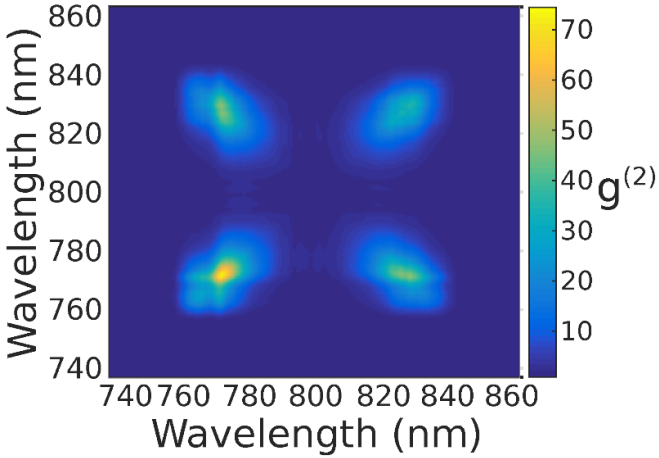


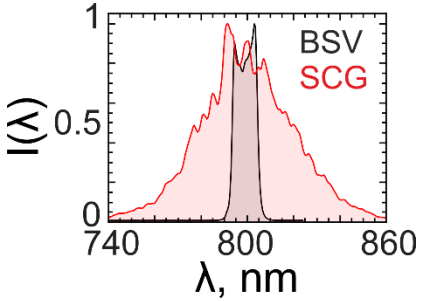
# Rogue waves via supercontinuum generation




120 µW

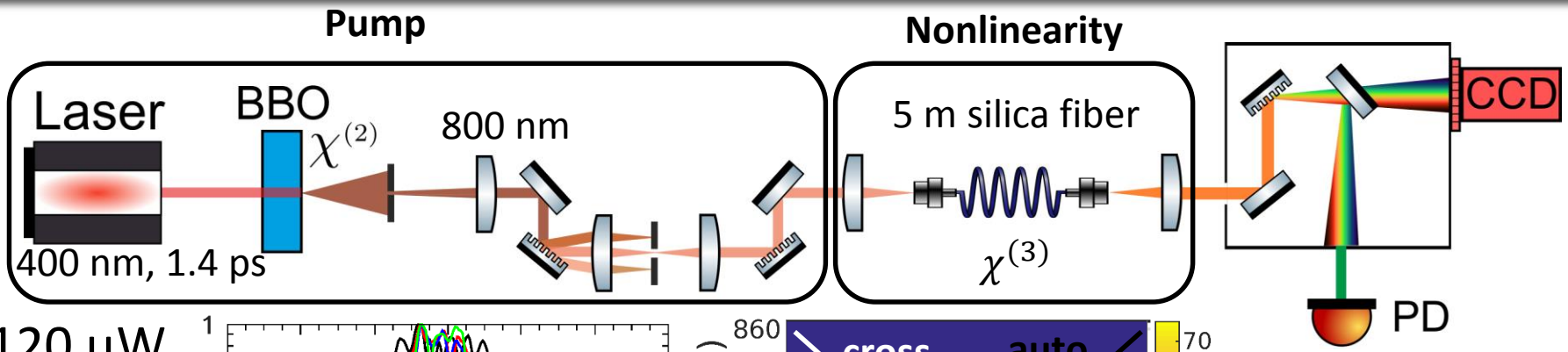


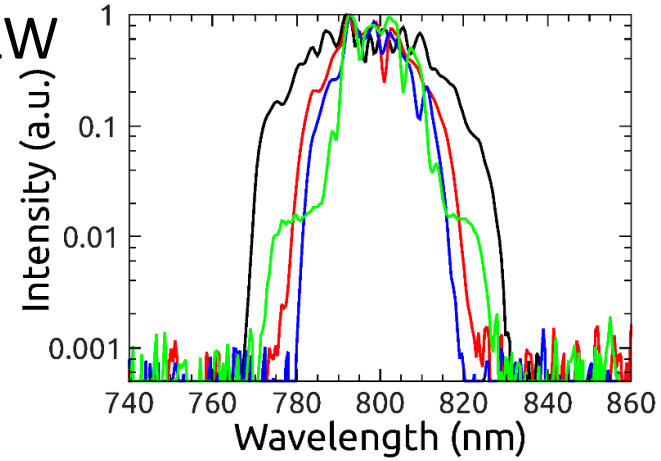



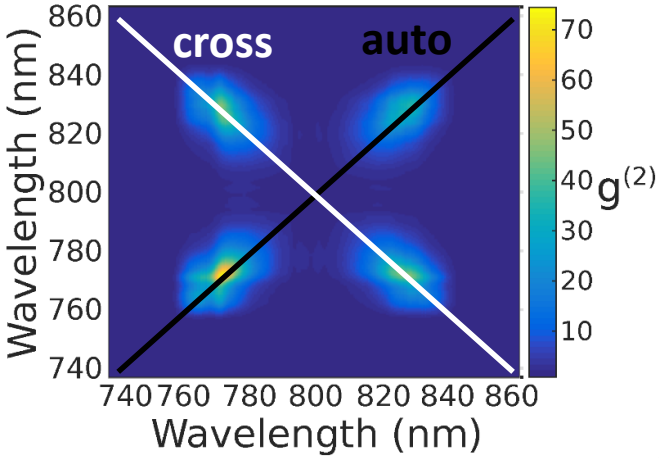

$$g_{12}^{(2)} = \frac{\langle I(\lambda_1) I(\lambda_2) \rangle}{\langle I(\lambda_1) \rangle \langle I(\lambda_2) \rangle}$$

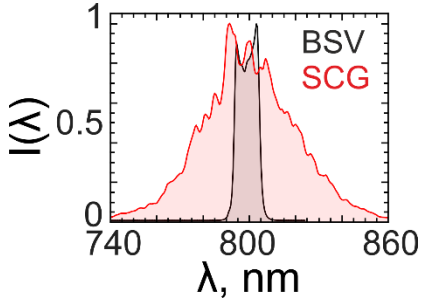
# Rogue waves via supercontinuum generation




120 µW

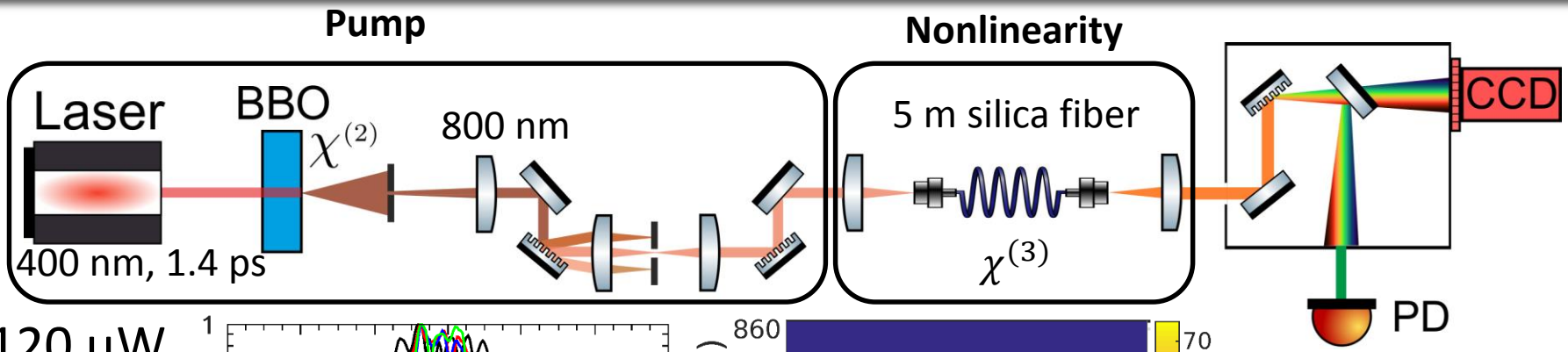


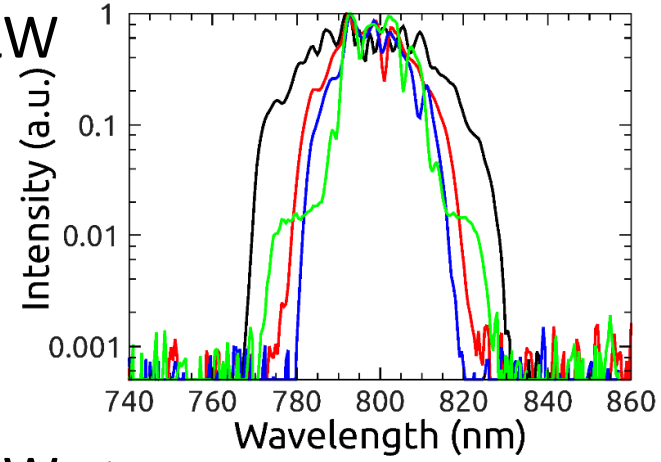



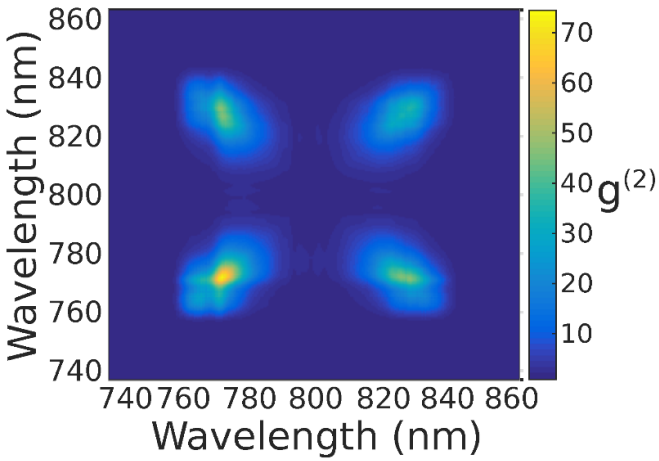

$$g_{12}^{(2)} = \frac{\langle I(\lambda_1) I(\lambda_2) \rangle}{\langle I(\lambda_1) \rangle \langle I(\lambda_2) \rangle}$$

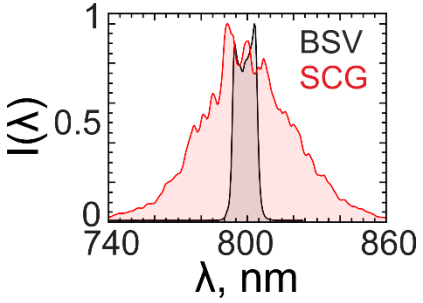
# Rogue waves via supercontinuum generation



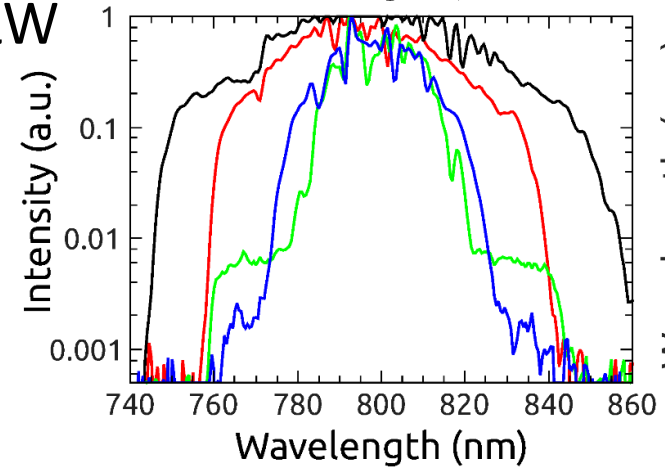

120 μW

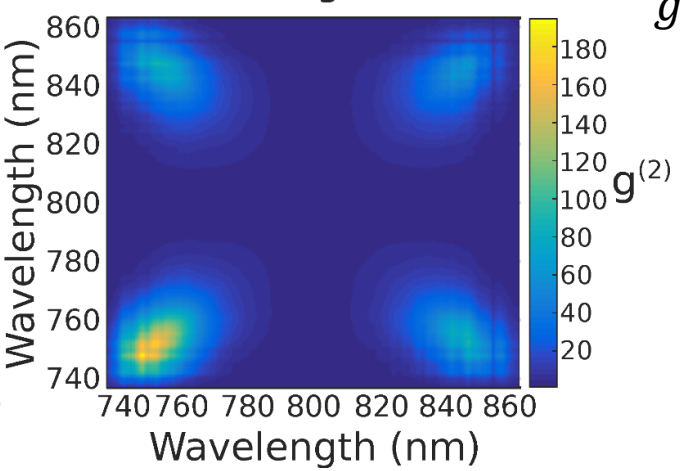



200 μW

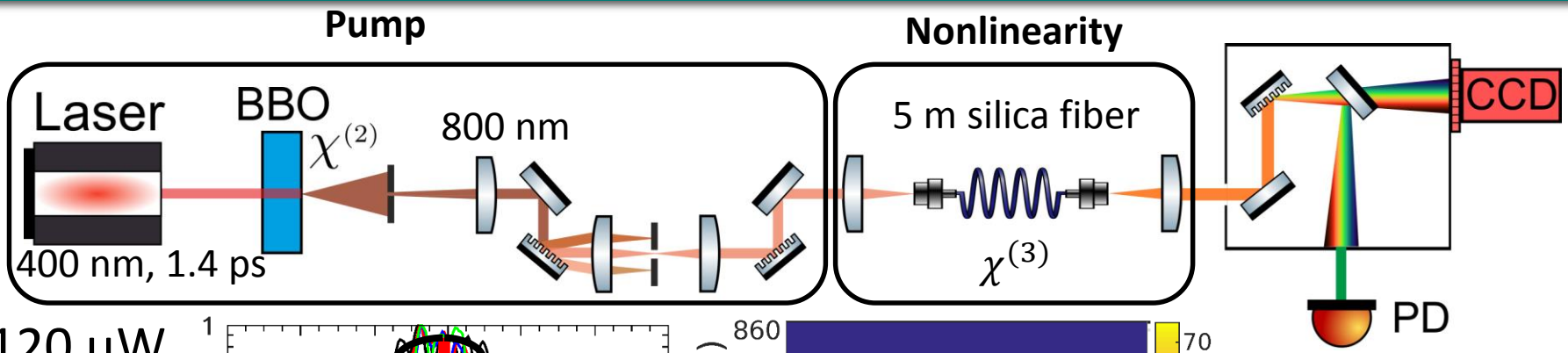


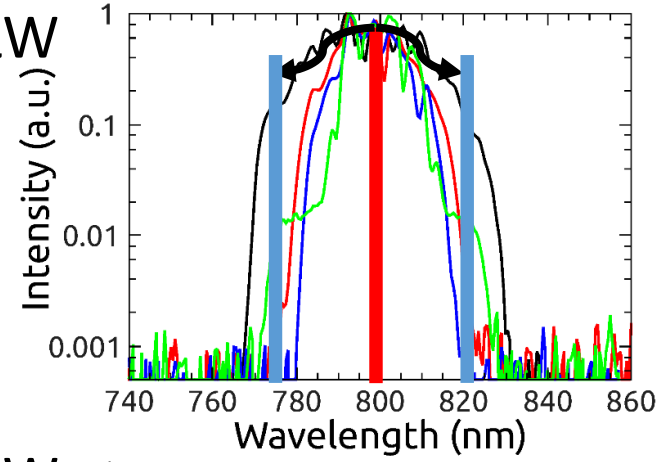

$$g_{12}^{(2)} = \frac{\langle I(\lambda_1) I(\lambda_2) \rangle}{\langle I(\lambda_1) \rangle \langle I(\lambda_2) \rangle}$$

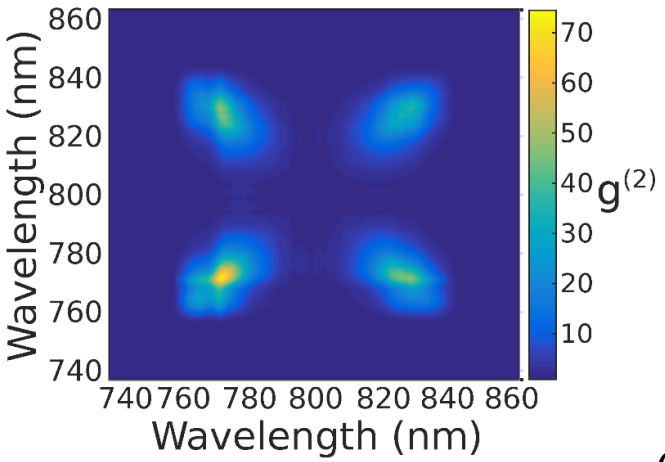
Range of fluctuations shifts with power

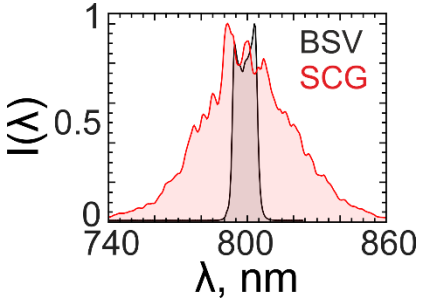
# Rogue waves via supercontinuum generation



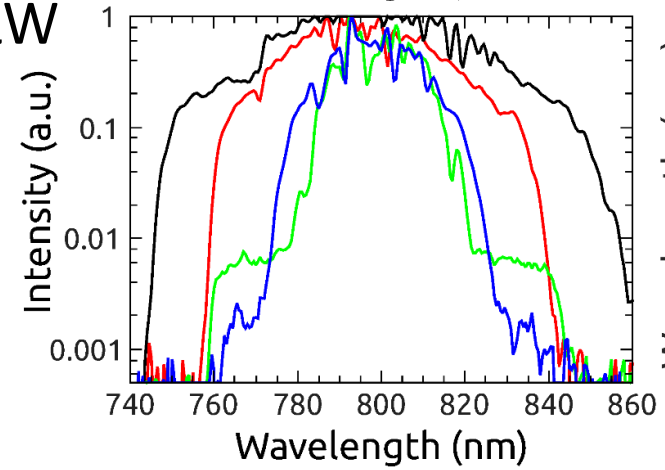

120 μW

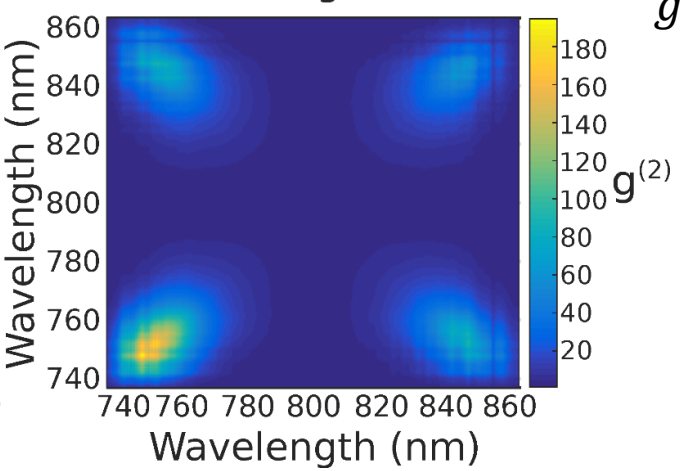



200 μW

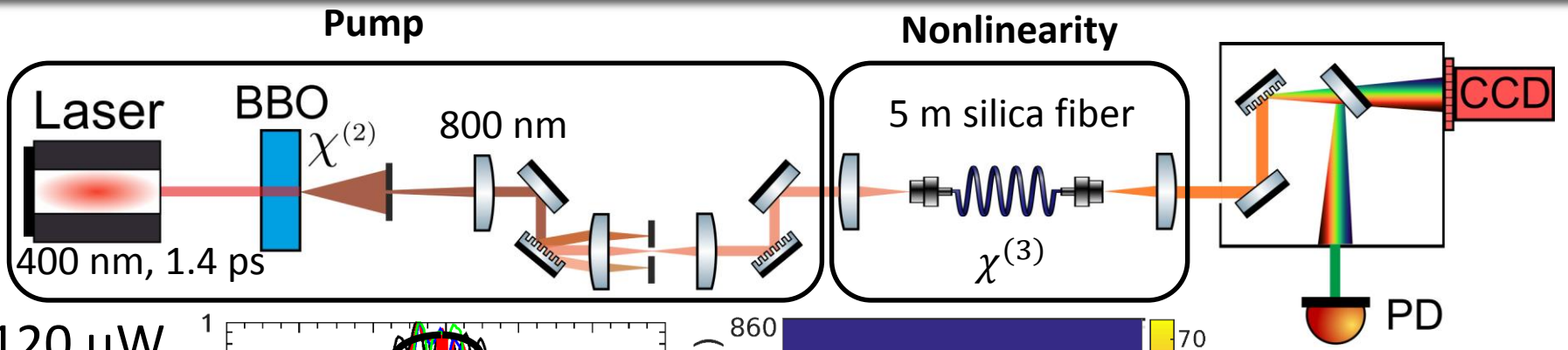


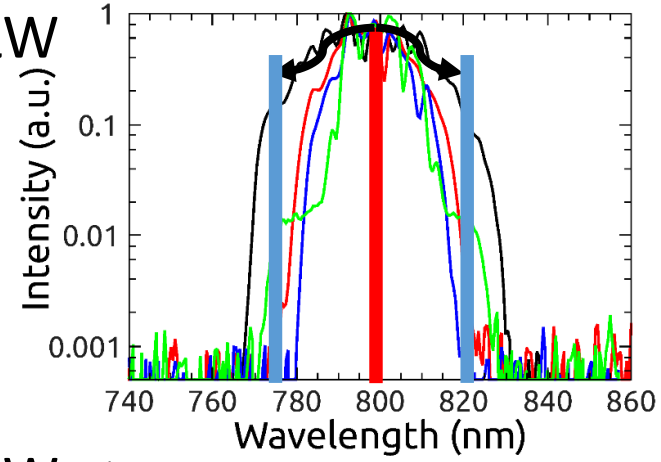

$$g_{12}^{(2)} = \frac{\langle I(\lambda_1) I(\lambda_2) \rangle}{\langle I(\lambda_1) \rangle \langle I(\lambda_2) \rangle}$$

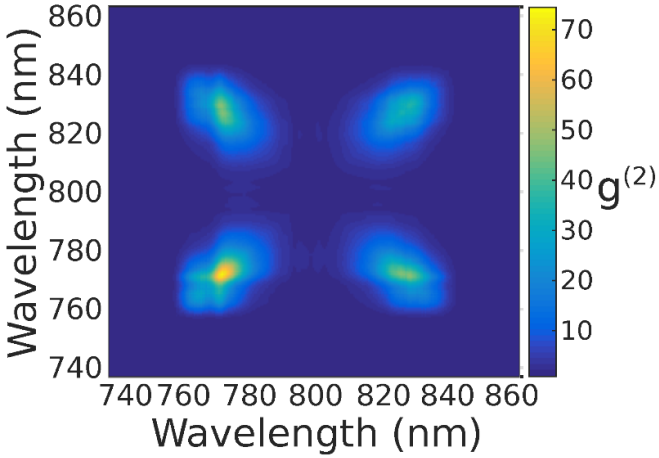
Range of fluctuations shifts with power

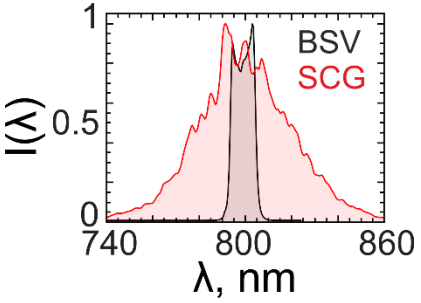
# Rogue waves via supercontinuum generation



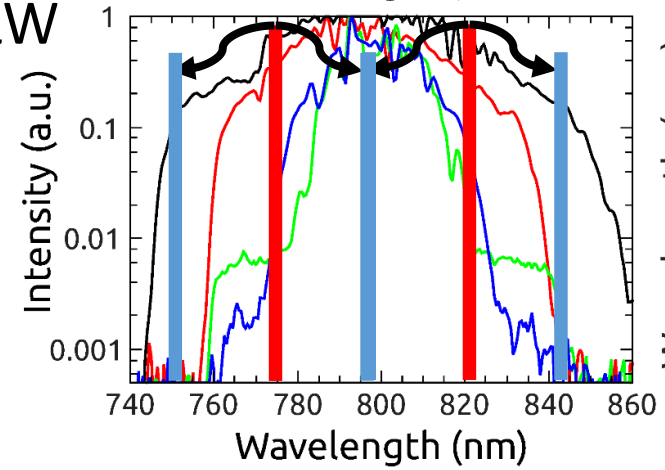

120 μW

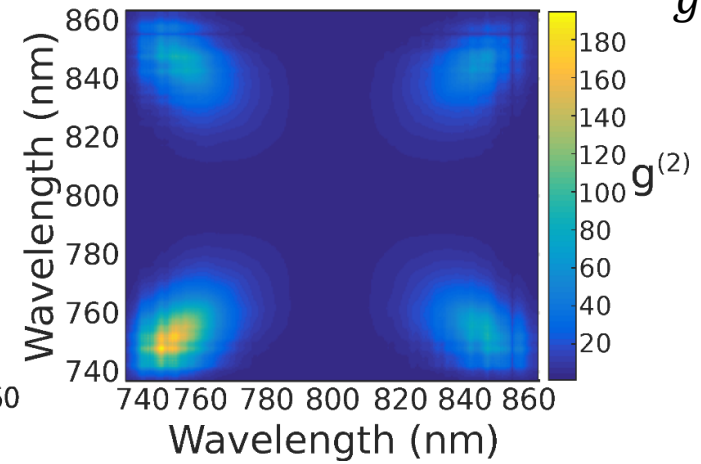



200 μW

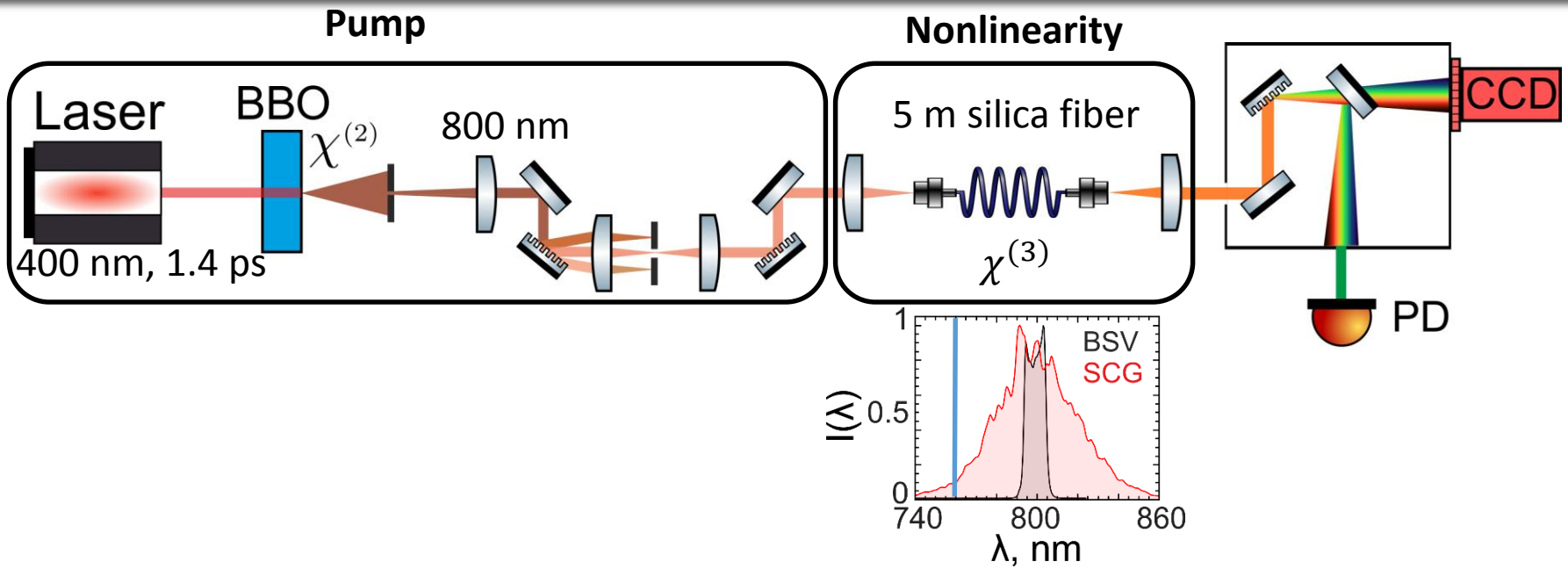


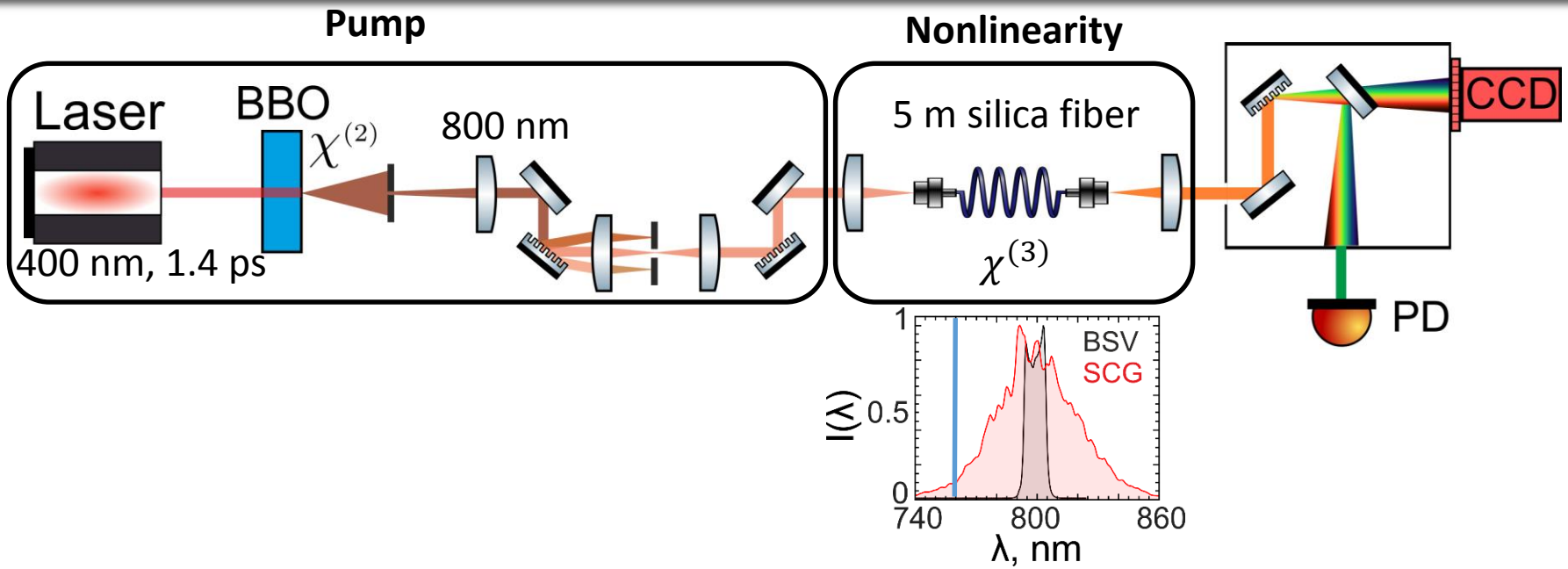

$$g_{12}^{(2)} = \frac{\langle I(\lambda_1) I(\lambda_2) \rangle}{\langle I(\lambda_1) \rangle \langle I(\lambda_2) \rangle}$$

Range of fluctuations shifts with power

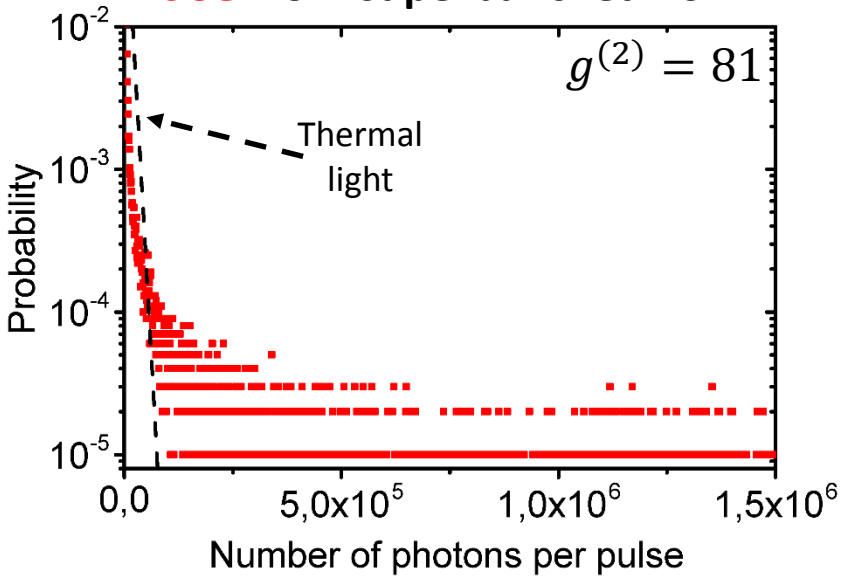
# Rogue waves via supercontinuum generation



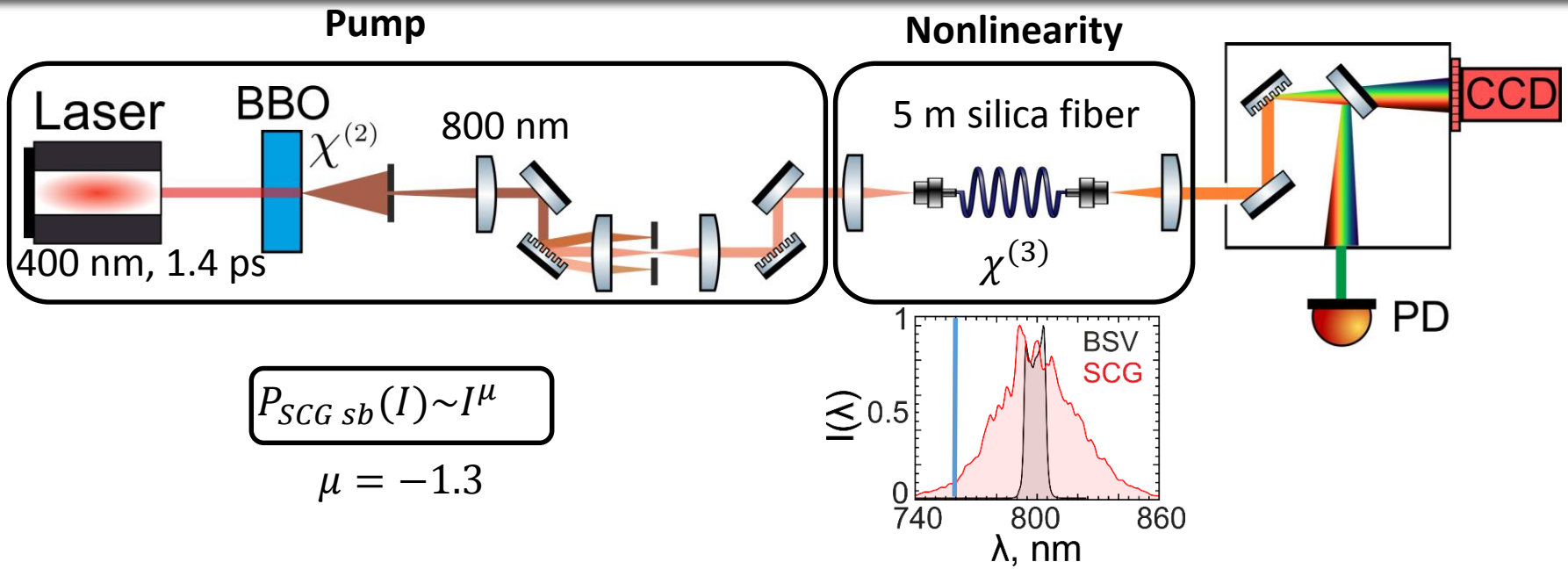
# Rogue waves via supercontinuum generation




**SCG from superbunched BSV**

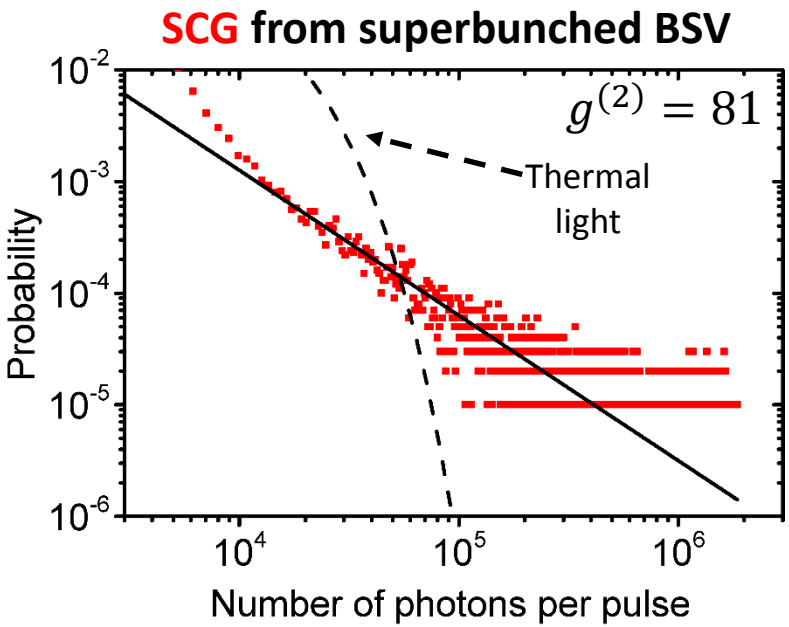


# Rogue waves via supercontinuum generation

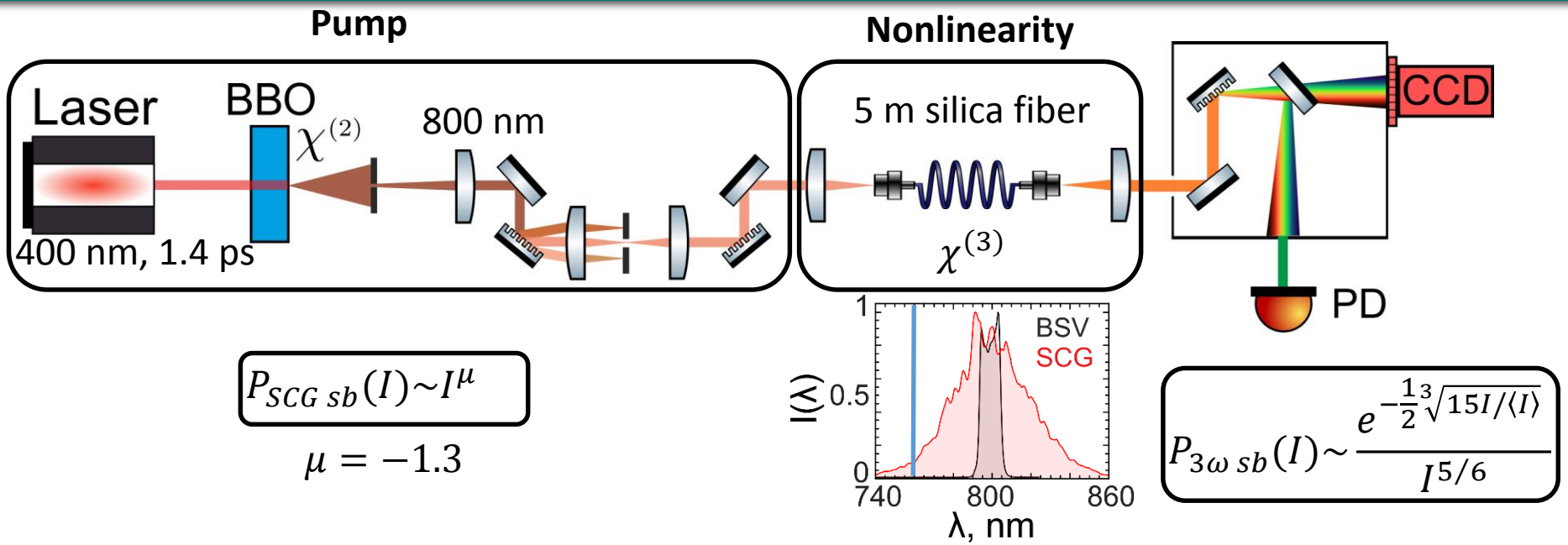


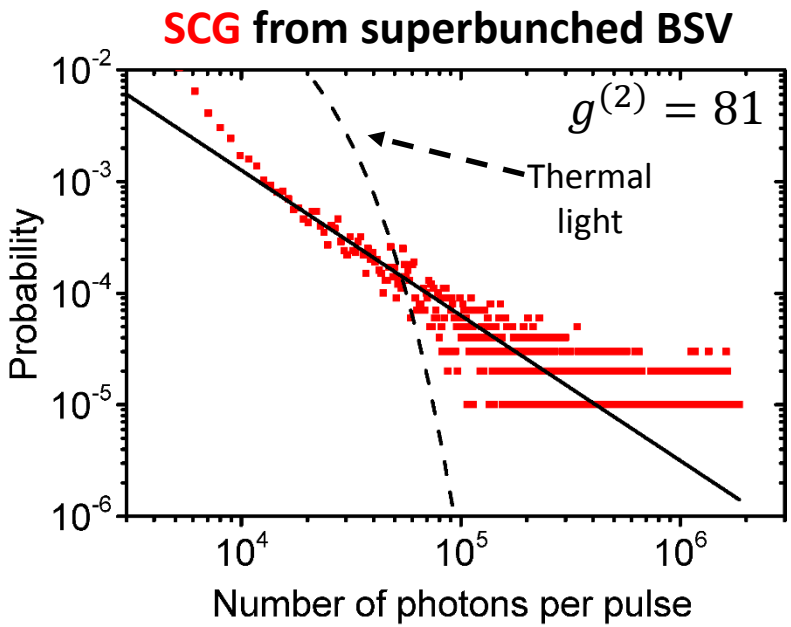

$$P_{SCG\ sb}(I) \sim I^{\mu}$$

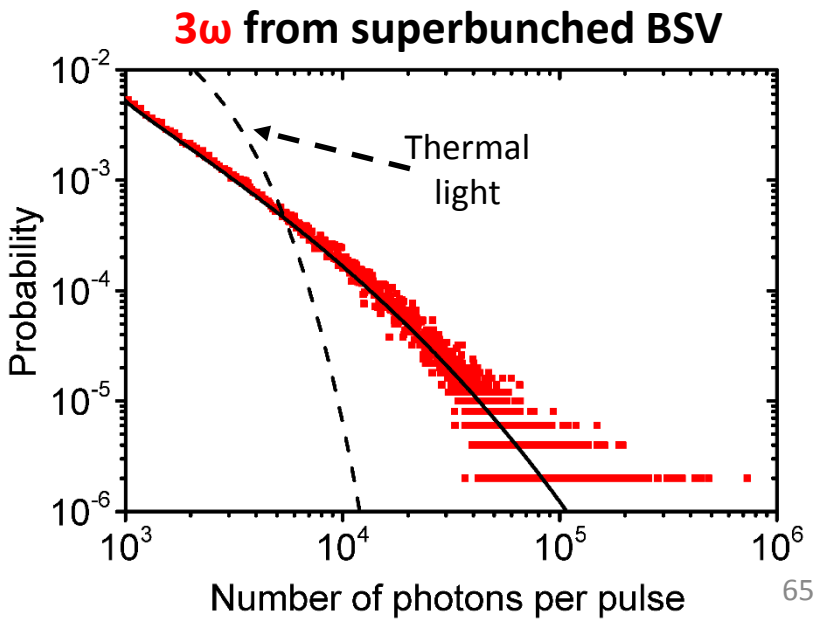
$$\mu = -1.3$$



# Rogue waves via supercontinuum generation



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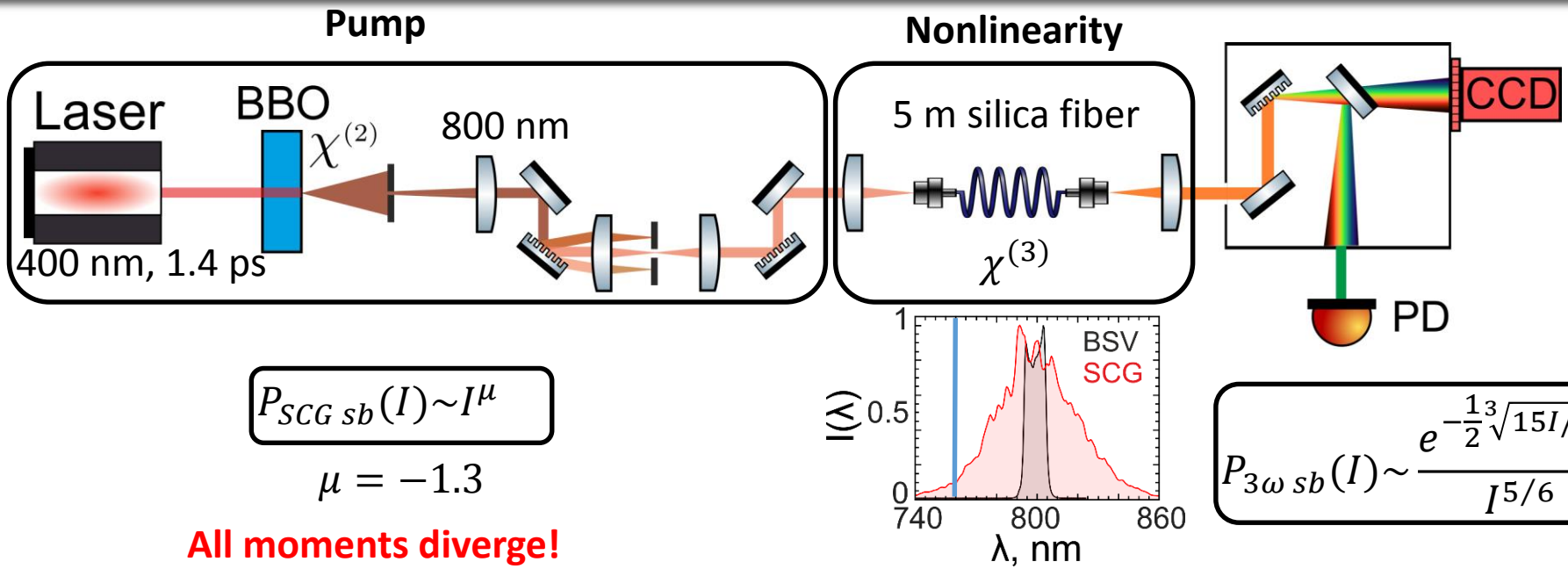
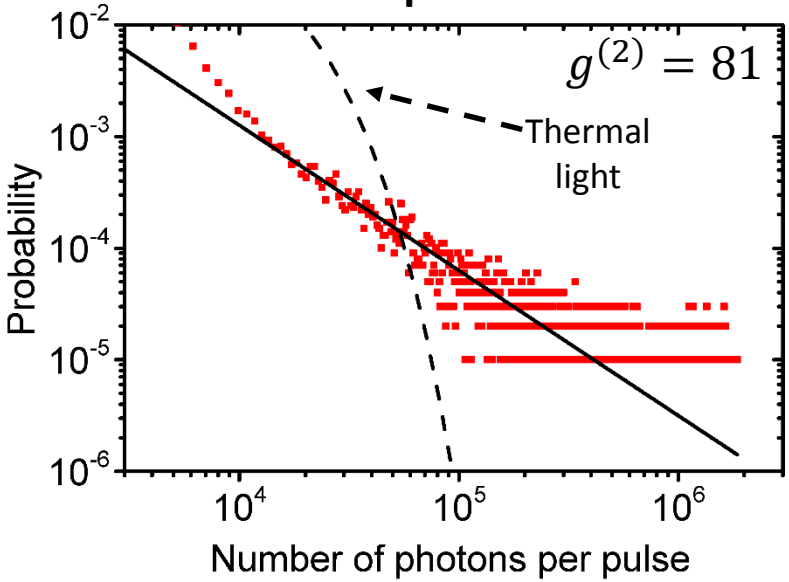
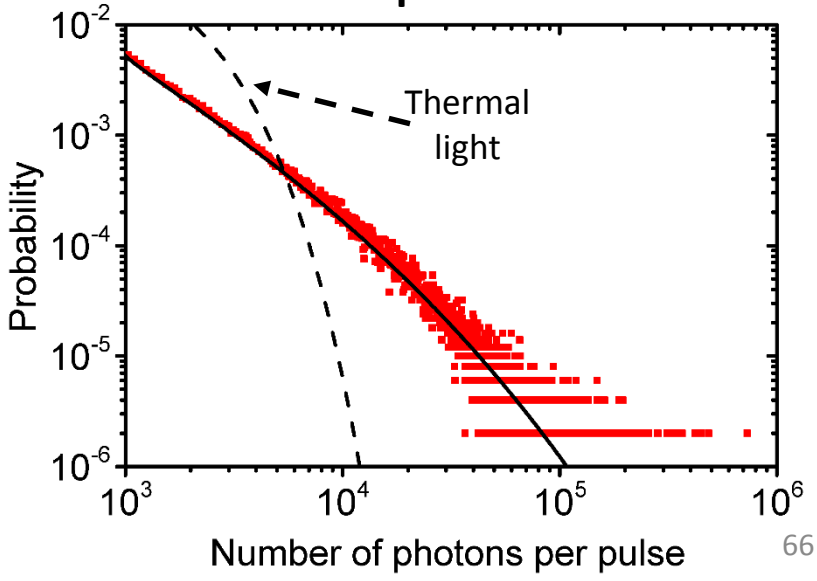



**All moments diverge!**

**SCG from superbunched BSV**

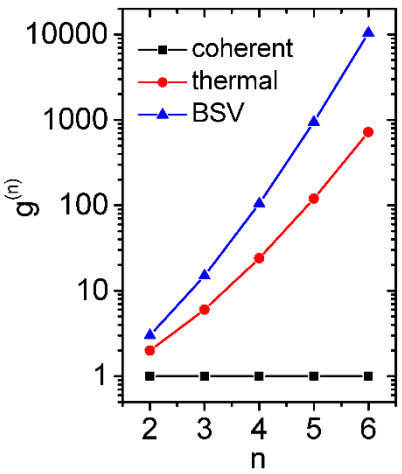


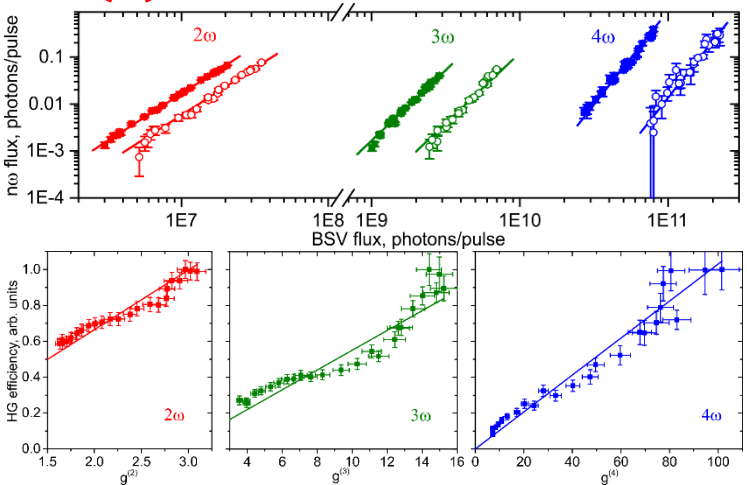

**3ω from superbunched BSV**

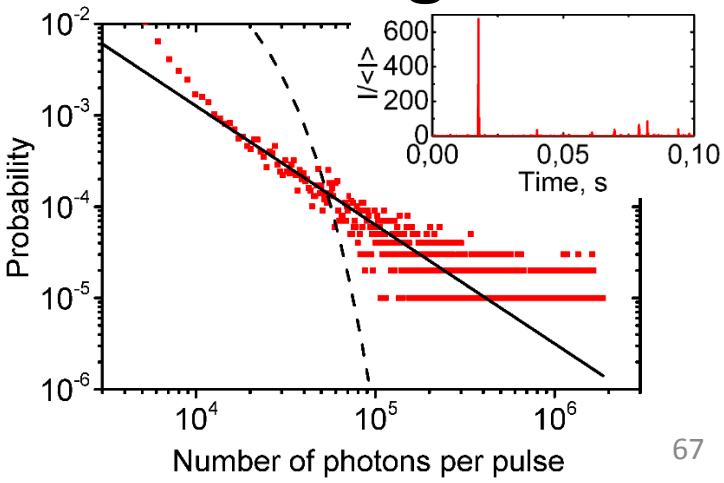


# Summary

- **Efficiency and rogue-wave behavior dramatically increases if nonlinear effects are pumped by fluctuating light. BSV is very useful, because it has strong and fast fluctuations.**
- **Certain rate of 4-photon effect is achieved with BSV with the mean power about 3 times less than with coherent light - important for fragile structures.**
- **We observed a record 'bunching' ($g^{(2)}>100$) and pulses with I exceeding <I> by 675 times. For thermal light the probability of such events is less than $10^{-290}$.**
- **The supercontinuum has power law probability distribution $P(I)\sim I^{-1.3}$. For it all moments diverge.**



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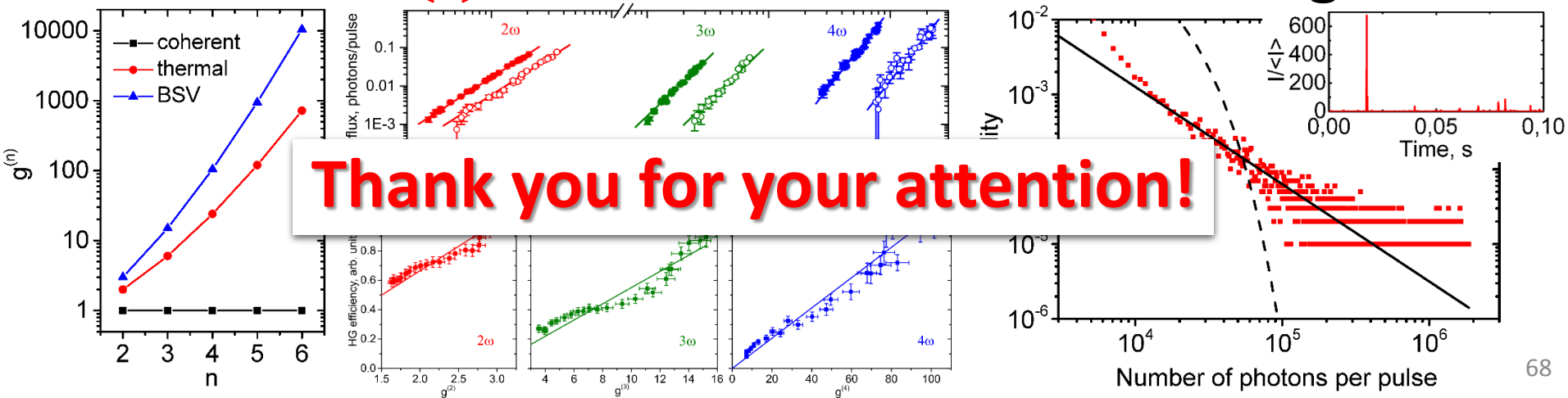


**Thank you for your attention!**