Super-charging nonlinear optical processes through collective effects

Joel A. Greenberg and Daniel J. Gauthier

Duke University

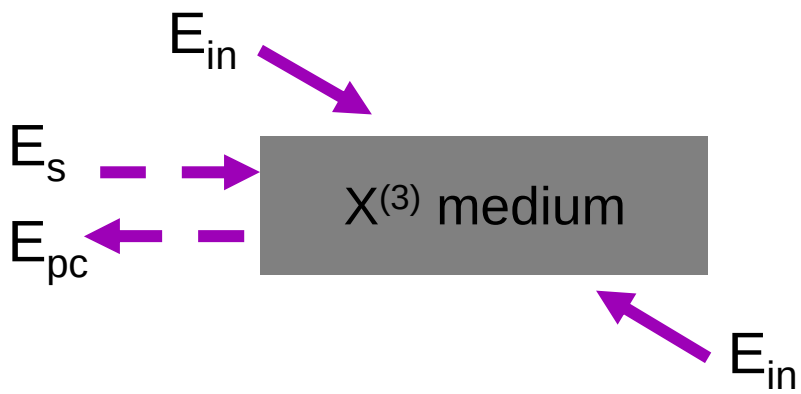
7/6/2010

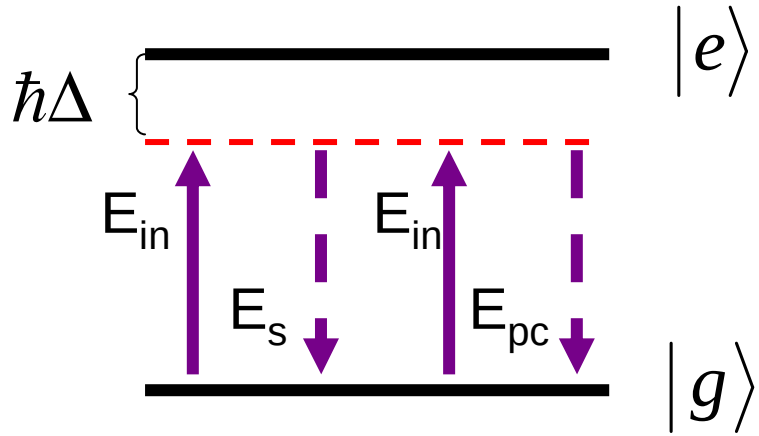
Introduction

- Long-term goal:
  - Realize few-photon nonlinear optical (NLO) effects (for quantum/optical info. networks)
- Short-term goal:
  - Study nonlinear wave mixing processes
- Approach:
  - use collective (rather than single atom) effects to ‘super charge’ NLO processes
    - reduce instability thresholds, enhanced scalings, etc.

Optical FWM

- Optical four-wave mixing (FWM) involves the exchange of energy between four optical fields



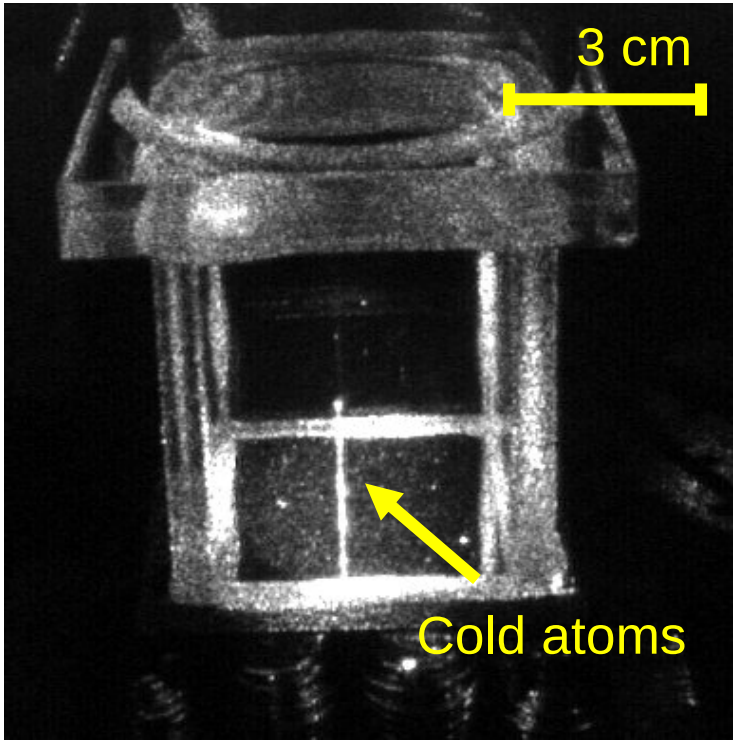


- To occur efficiently, energy and momentum must be conserved in the optical fields

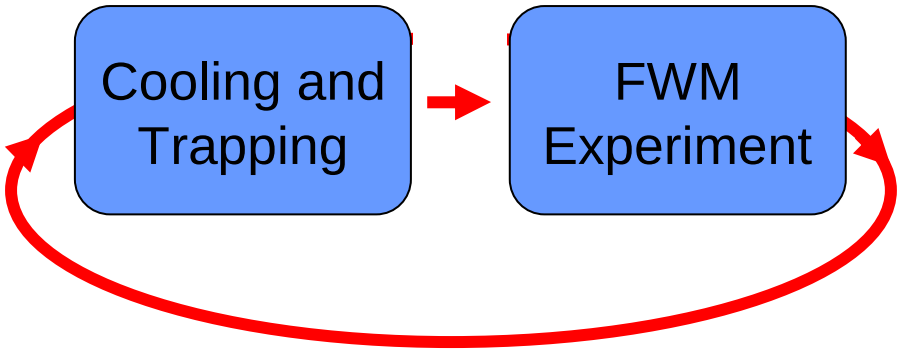
Boyd, *Nonlinear optics*.

Ultracold Atoms

2D Rb Magneto-optical Trap (MOT)



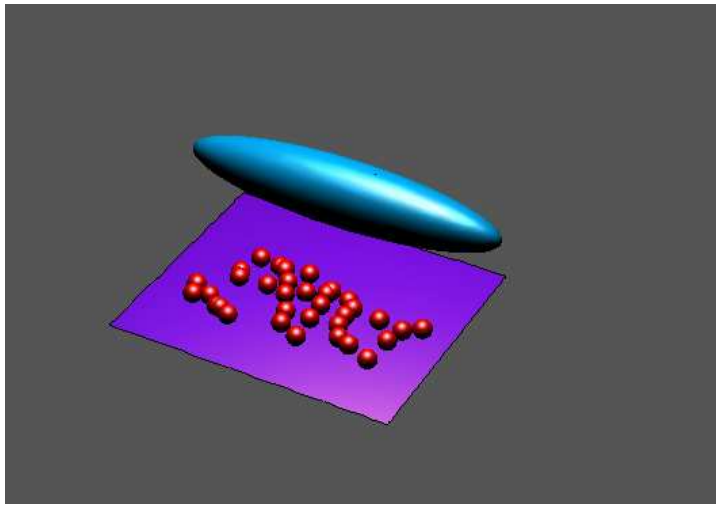
Experimental Scheme



Long. Optical path length = 50-100
Temp = 20-40 μK
Dimensions: R = 150 μm, L = 3 cm

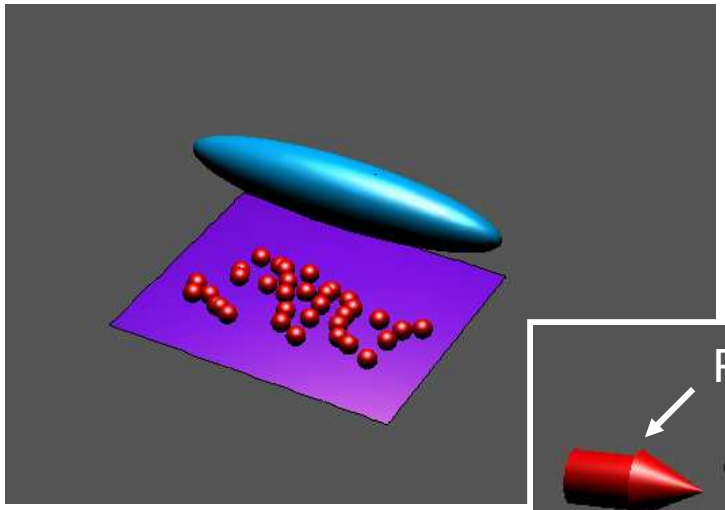
Greenberg, Oria, Dawes, Gauthier, Opt. Express **15**, 17699 (2007)

FWM with Cold Atoms



Initial homogenous distribution of cold atoms

FWM with Cold Atoms



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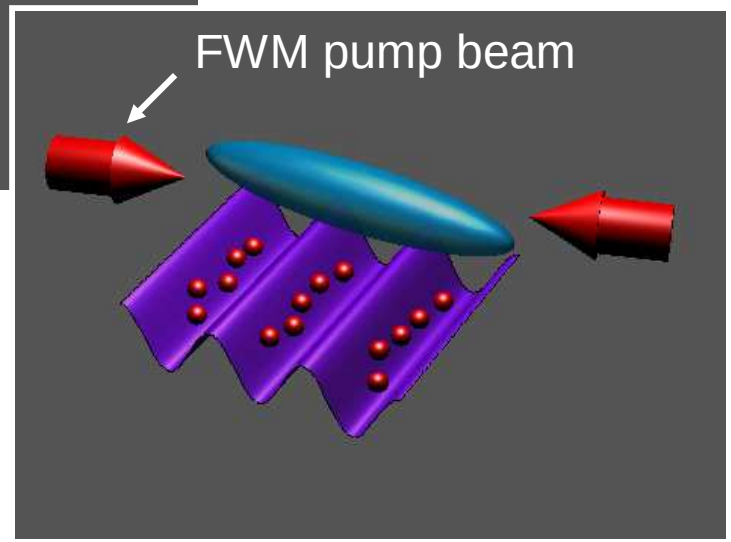
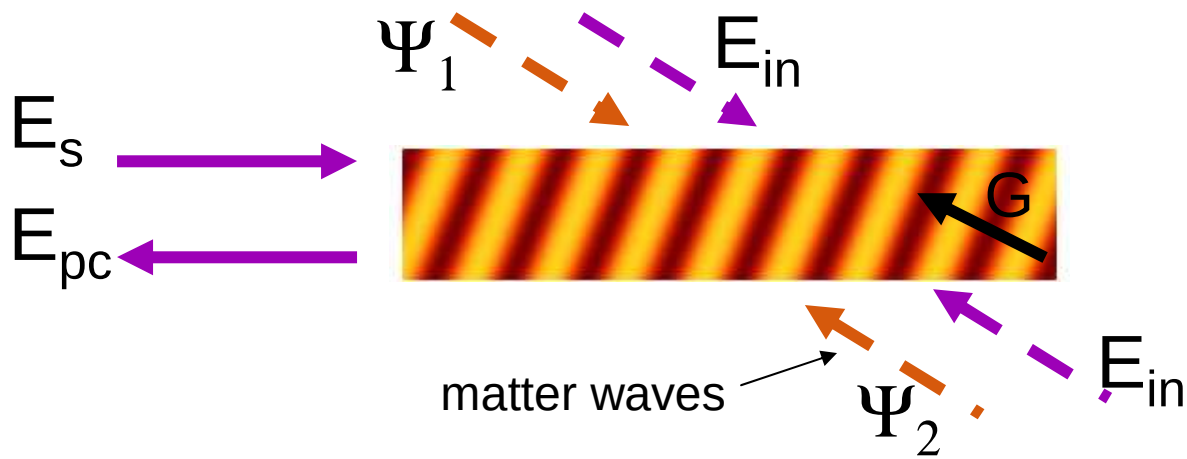


Dipole force begins to spatially organize atoms

Gattobigio et al., **PRA** 74, 043407 (2006)

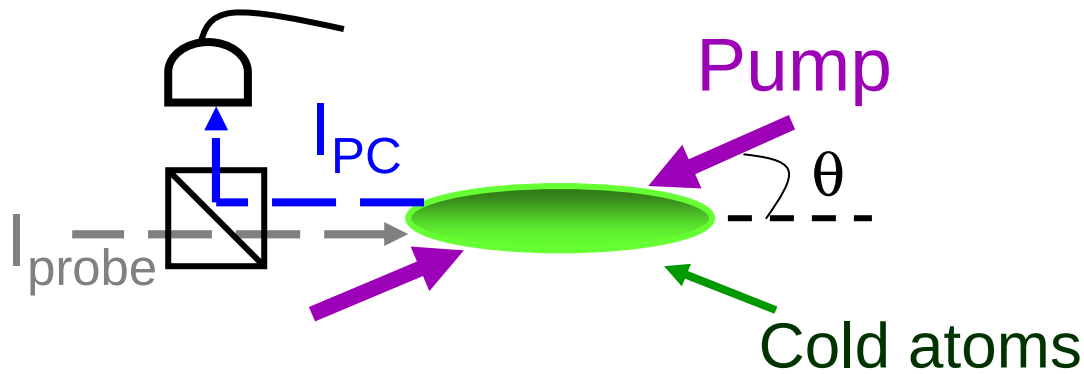
Collective FWM (CFWM)

- Grating self-phase-matches additional FWM processes
  (Bunching allows higher order wave mixing processes to occur)



- Lamb-Dicke effect enhances CFWM through
  - Confining atoms $\Delta x << \lambda$ (enhances bunching gain)
  - Reducing inelastic scattering while allowing elastic scattering (increases coherence time)

PCR Setup



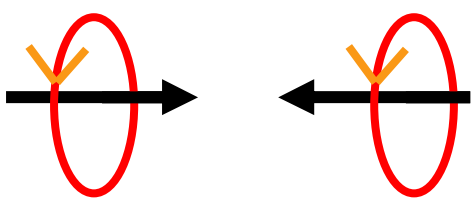
θ =10 deg

Δ = -6 Γ

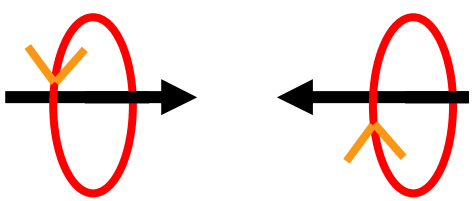
$|R|^2 = I_{PC}/I_{probe}$

Investigate importance of bunching by comparing phase-conjugate reflectivity (PCR) for different pump polarizations

Co-rotating Polarization
(BUNCHING)

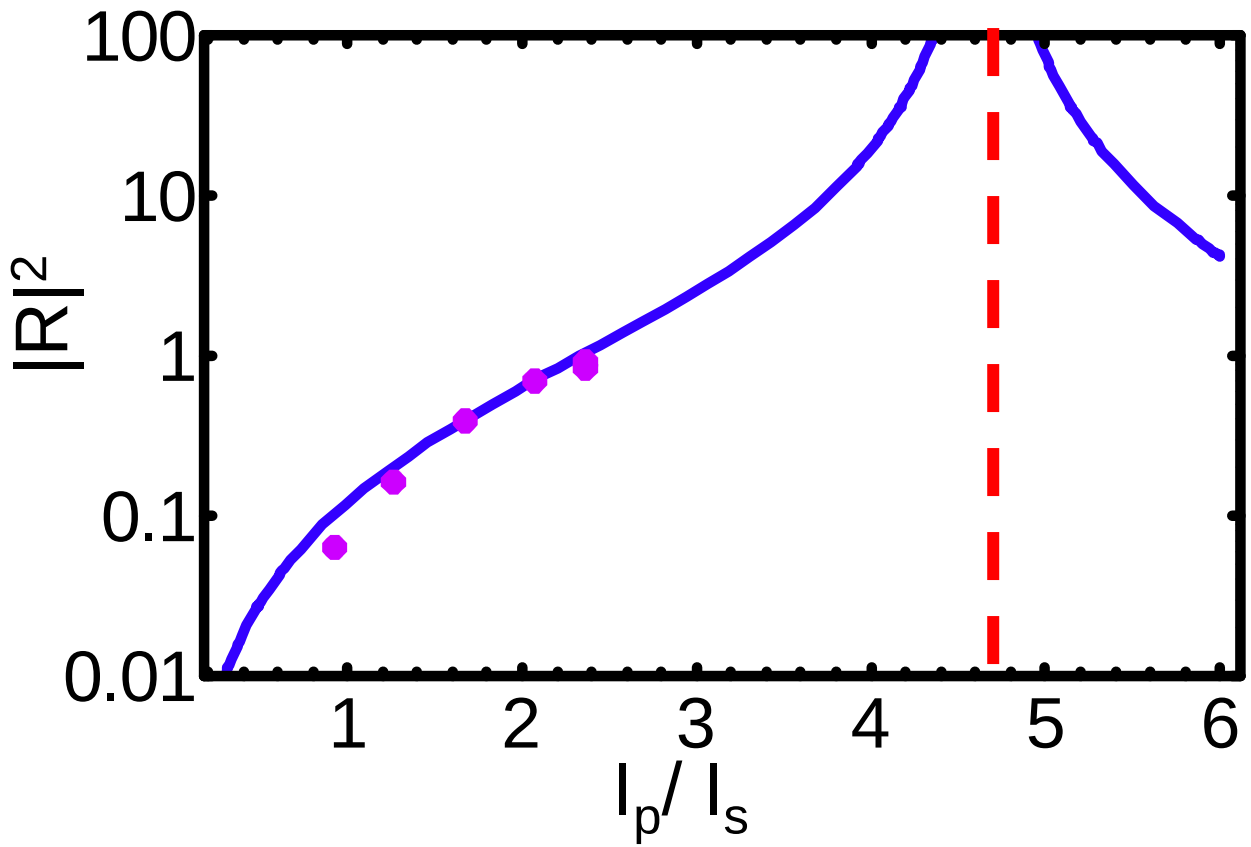


Counter-rotating Polarization
(NO BUNCHING)



PCR Results: No Bunching

Counter-rotating pumps



$|R|^2 = \tan(\beta\, I_p)^2$

exp. data

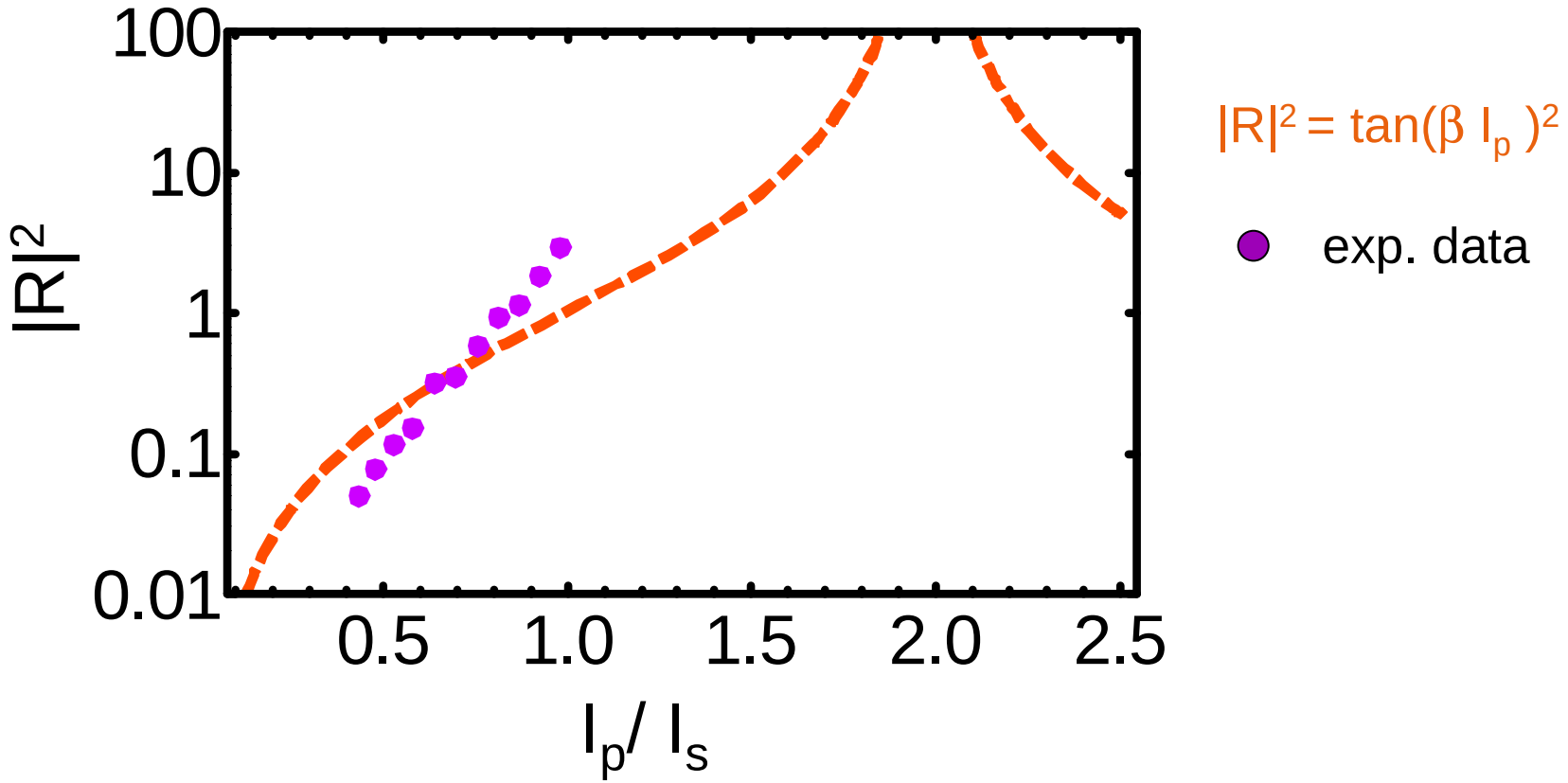
Self-oscillation ($|R|=\infty$) for $\beta\, I_p = \pi/2$

$I_s = 1.6\ \mathrm{mW/cm^2}$

Gaeta et al. IEEE J. Quant. Elec. **22**, 1095 (1986)

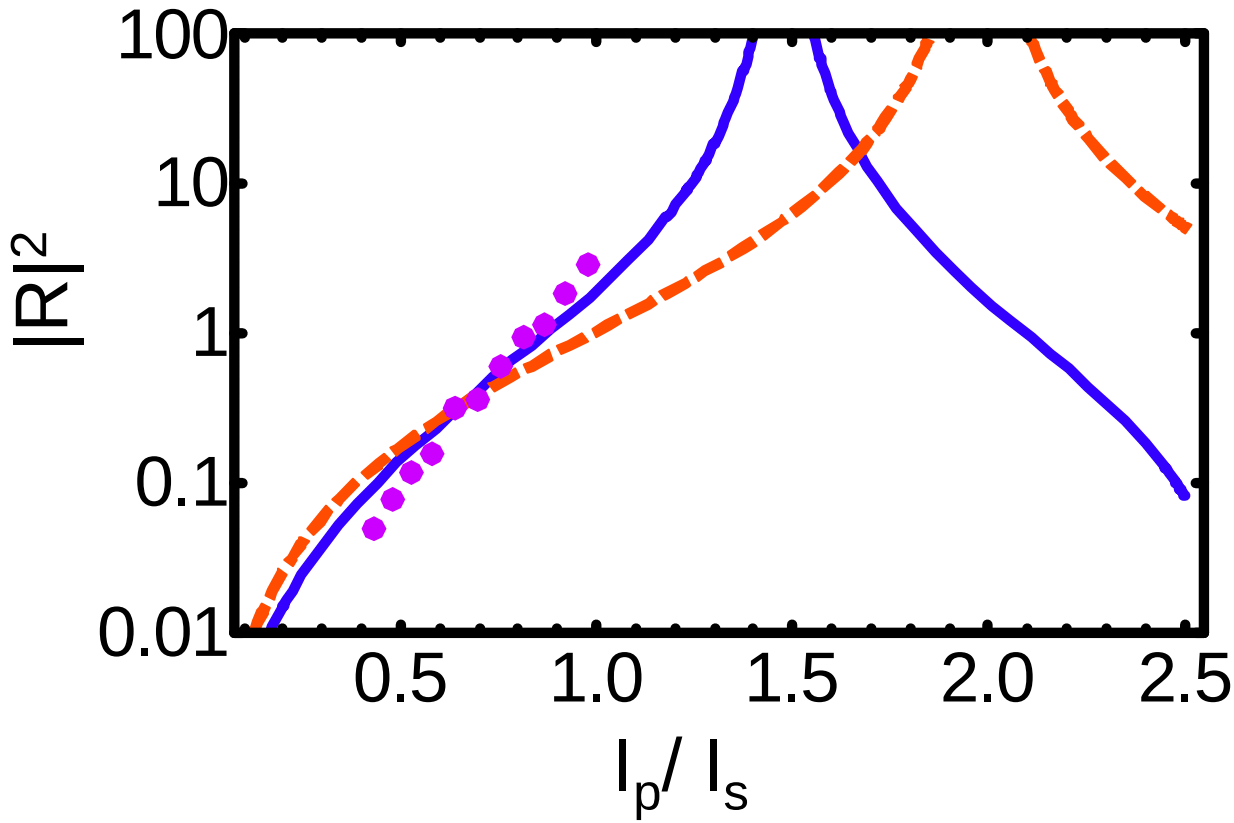
PCR Results: With Bunching

Co-rotating pumps



PCR Results: With Bunching

Co-rotating pumps



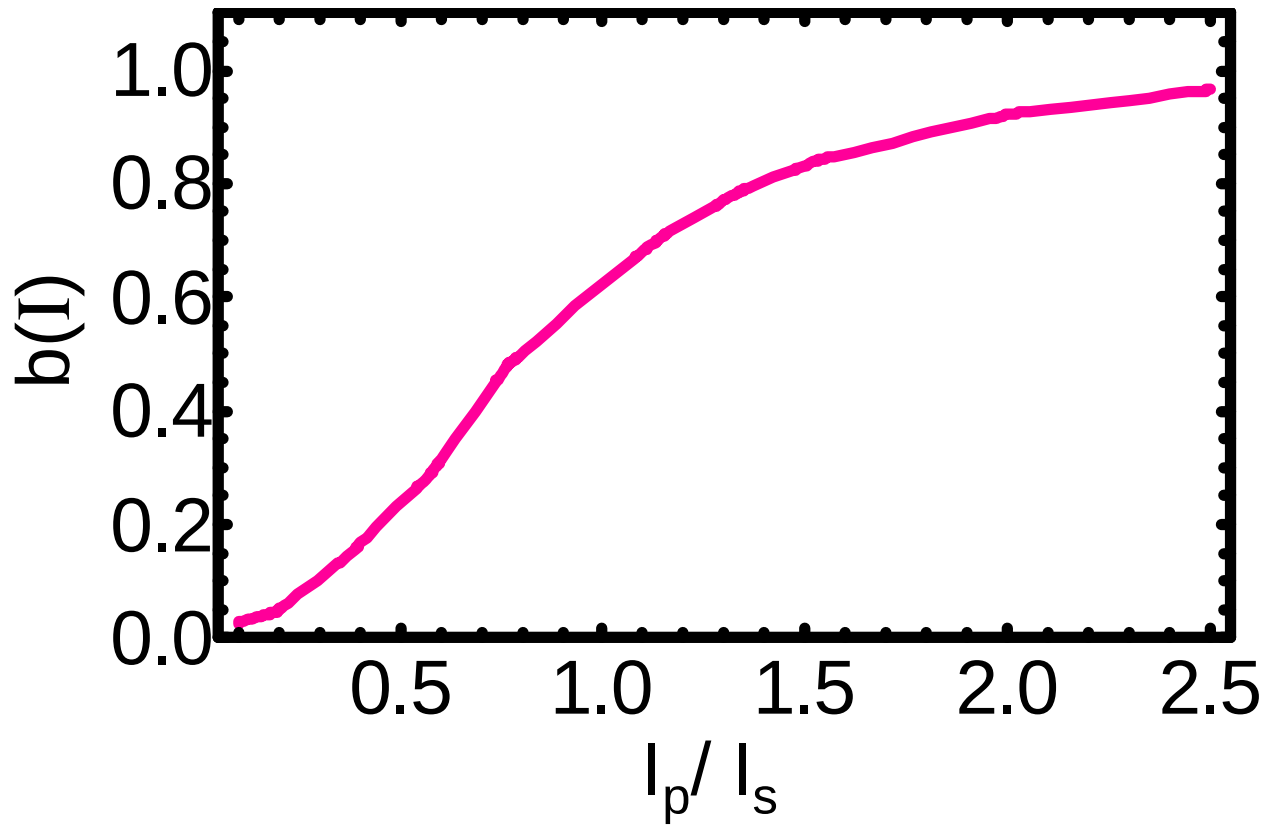
$|R|^2 = \tan(\beta\ I_p)^2$

exp. data

$|R|^2 = \tan(\beta\ (1+b(I_p)\ I_p)^2$

bunching

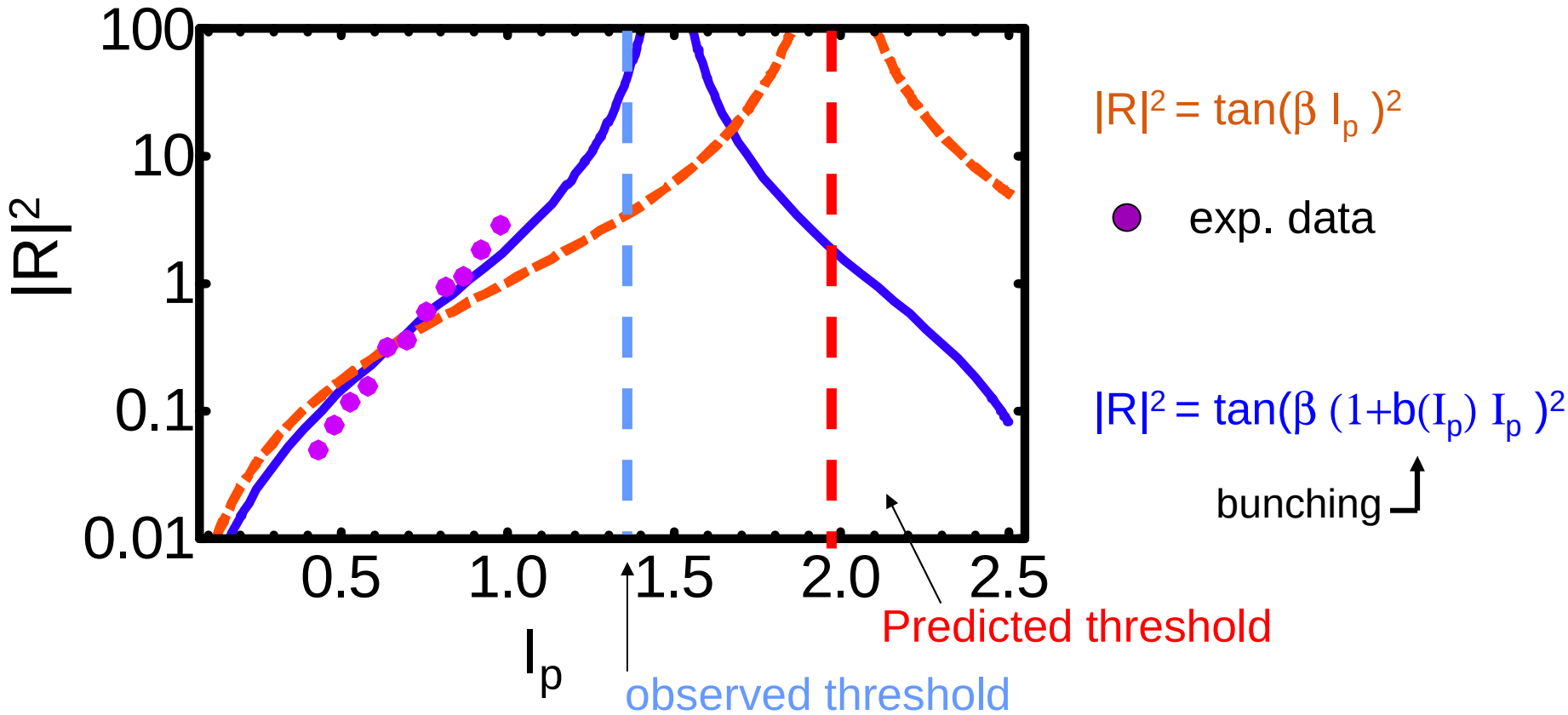
Degree of Bunching



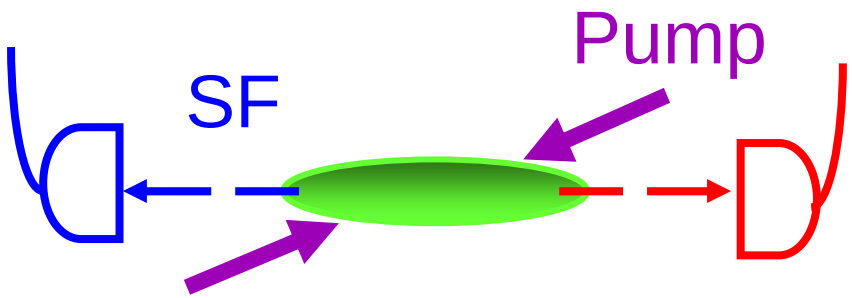
- semi-classical, 1D model
- only pump-pump grating
- phenomenological rethermalization rate

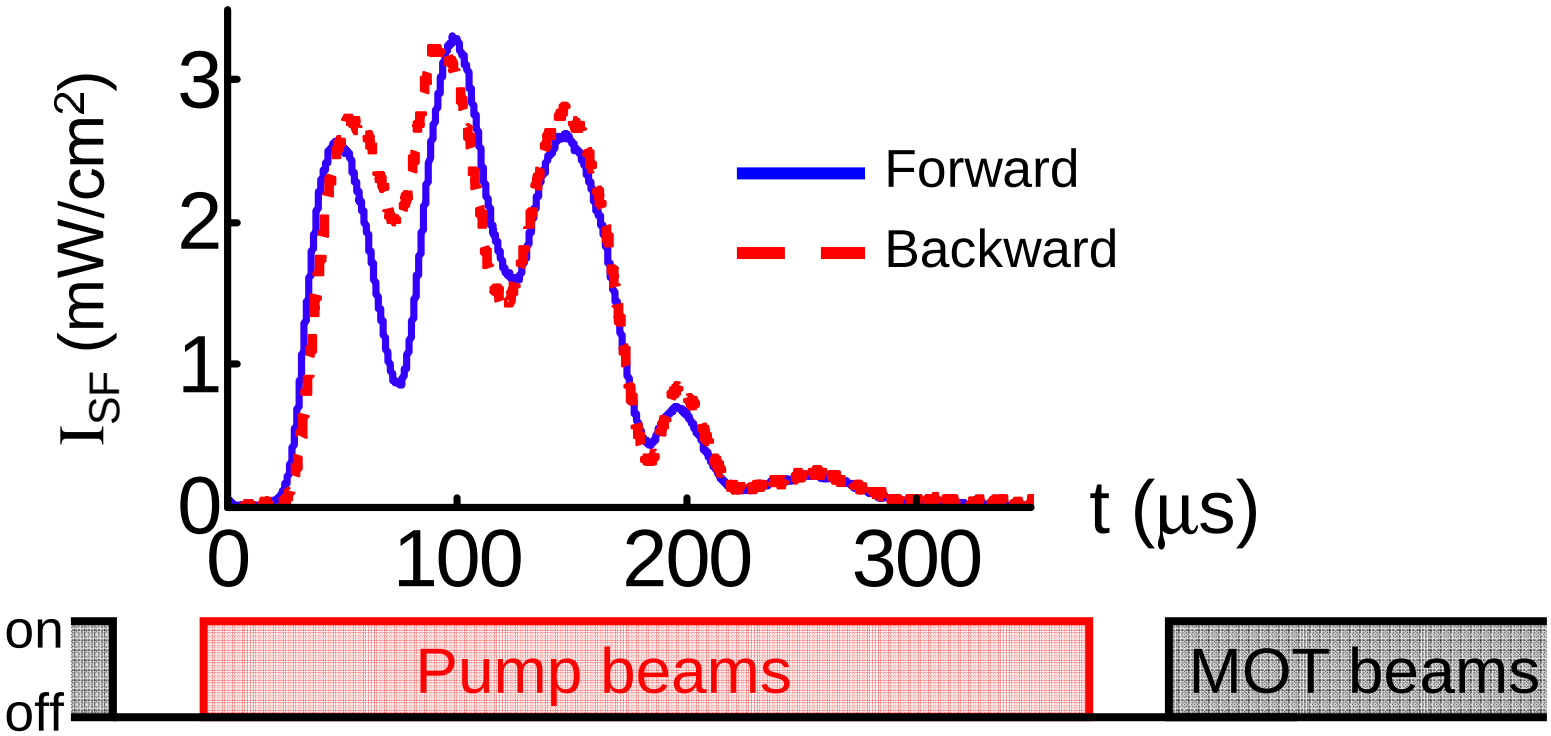
PCR Results: With Bunching

Co-rotating pumps

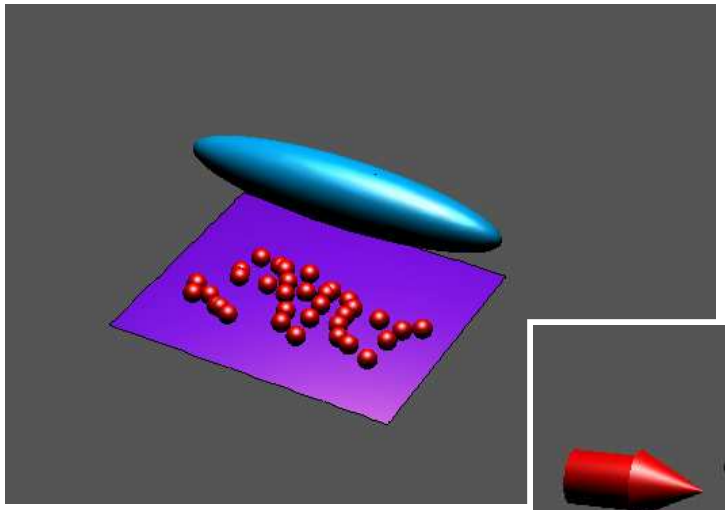


Observation of Self-oscillation





Collective Instability



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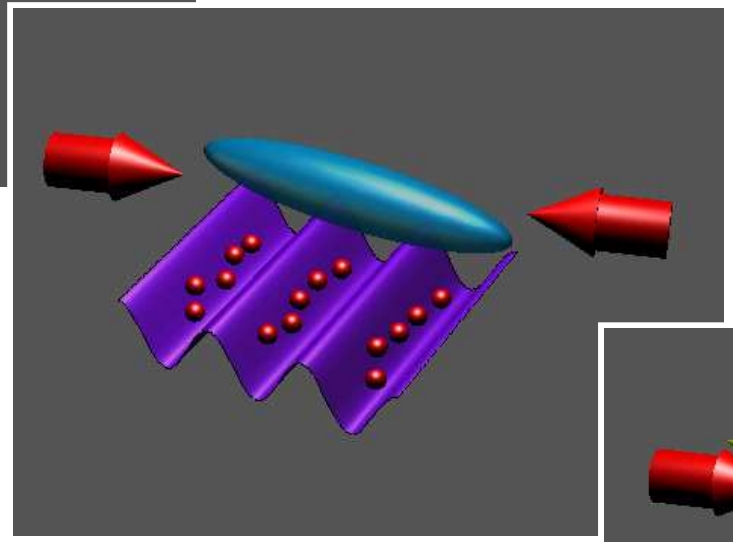
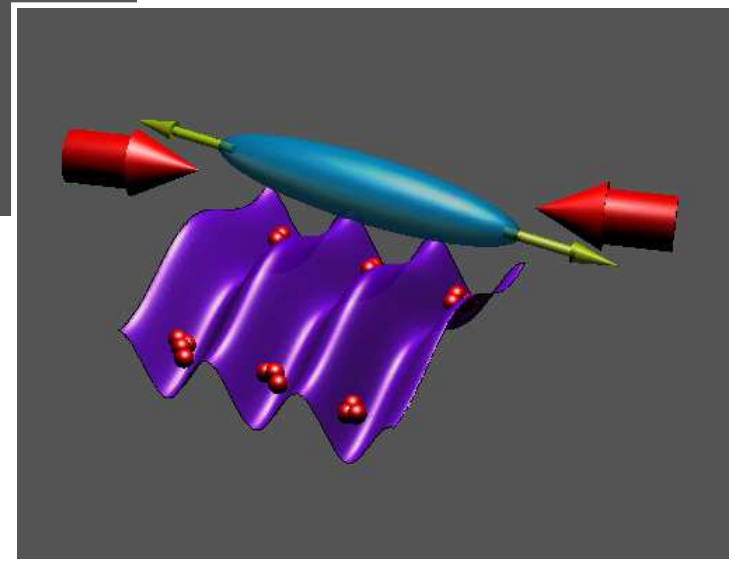
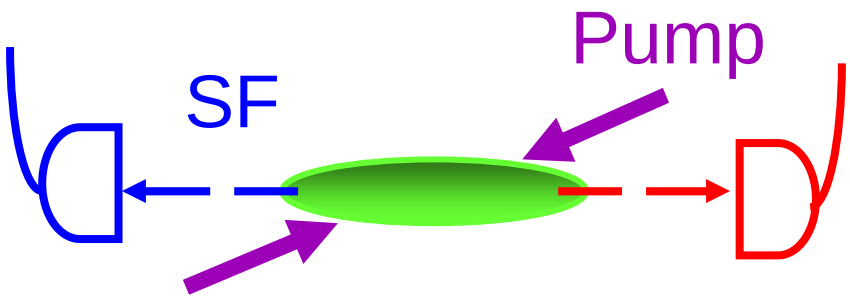


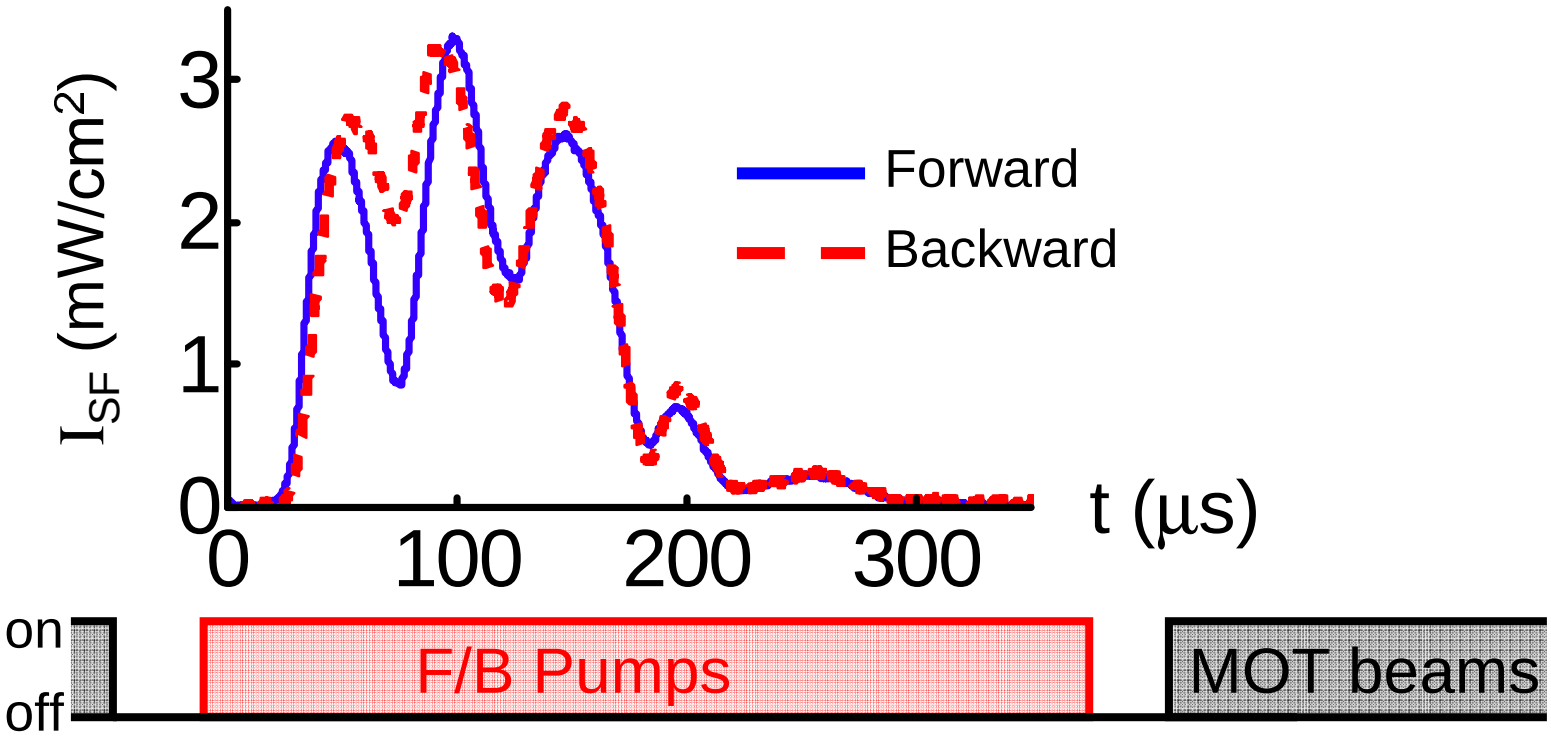
Dipole force begins to spatially organize atoms



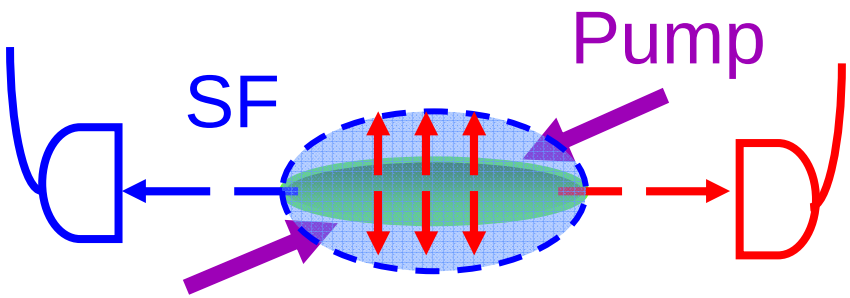
Generated light acts back on atoms to self-organize atoms and further enhance scattering

Experimental Results

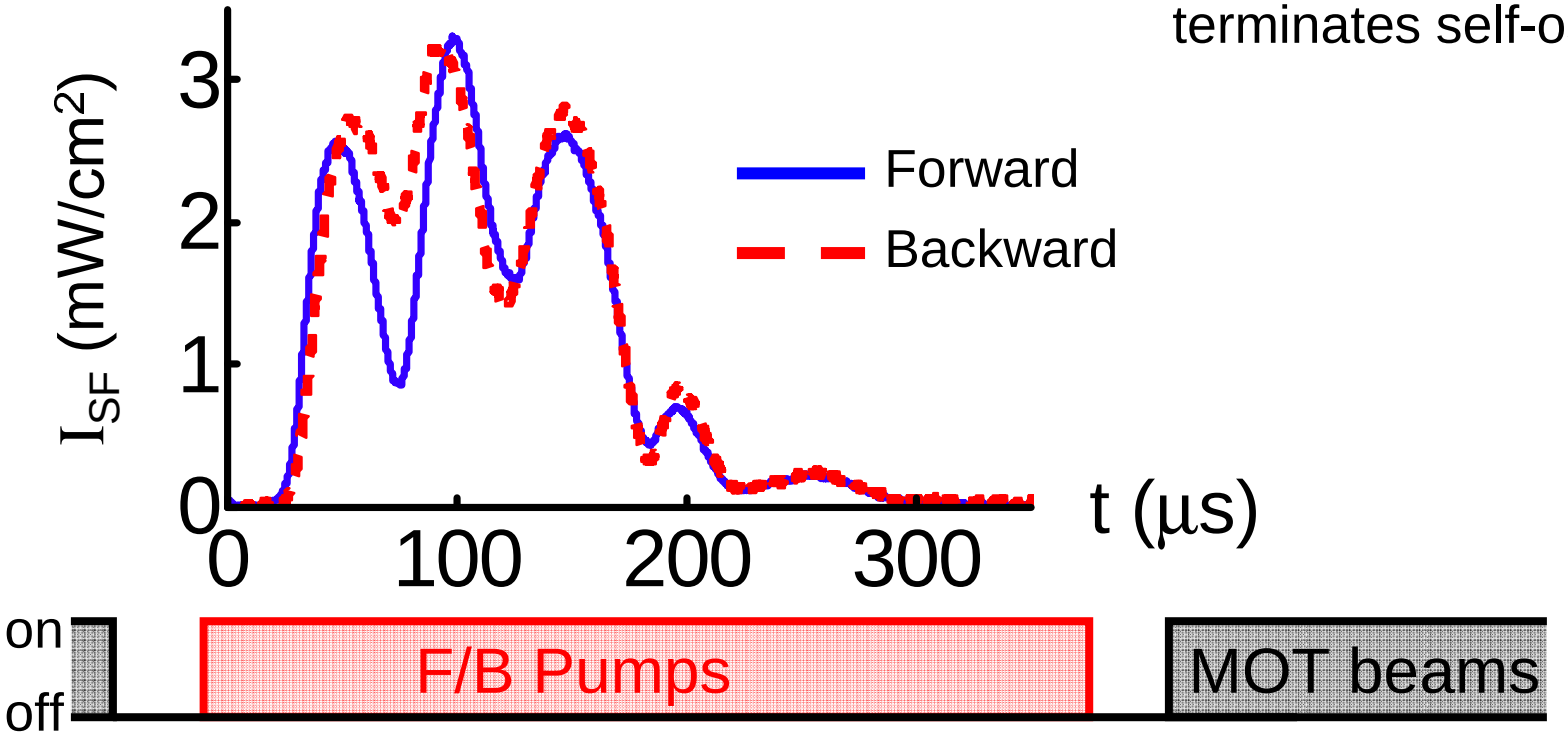




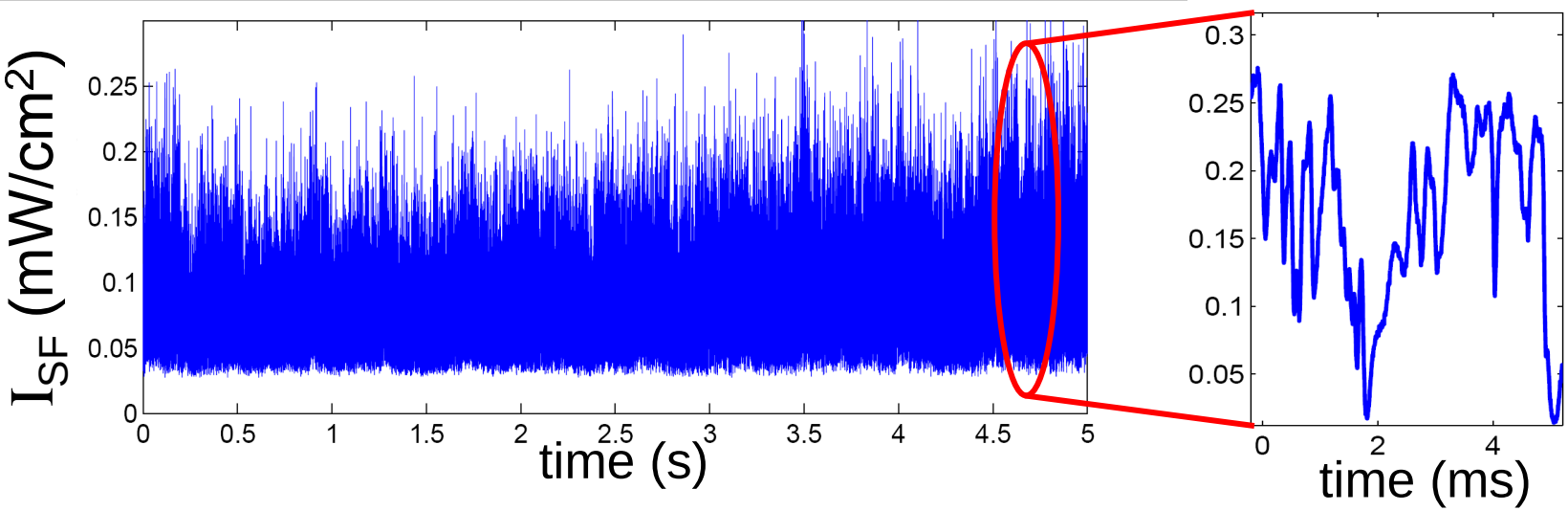
Experimental Results

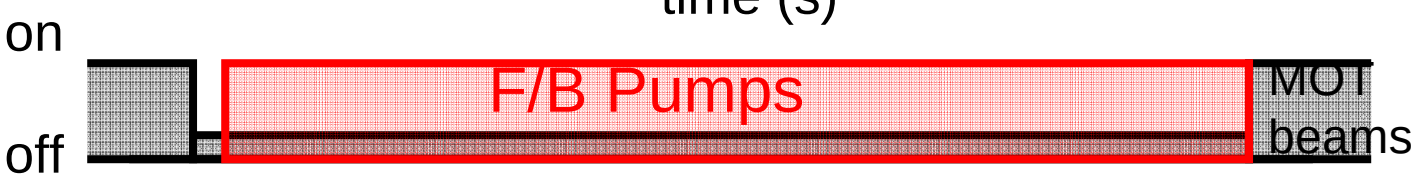


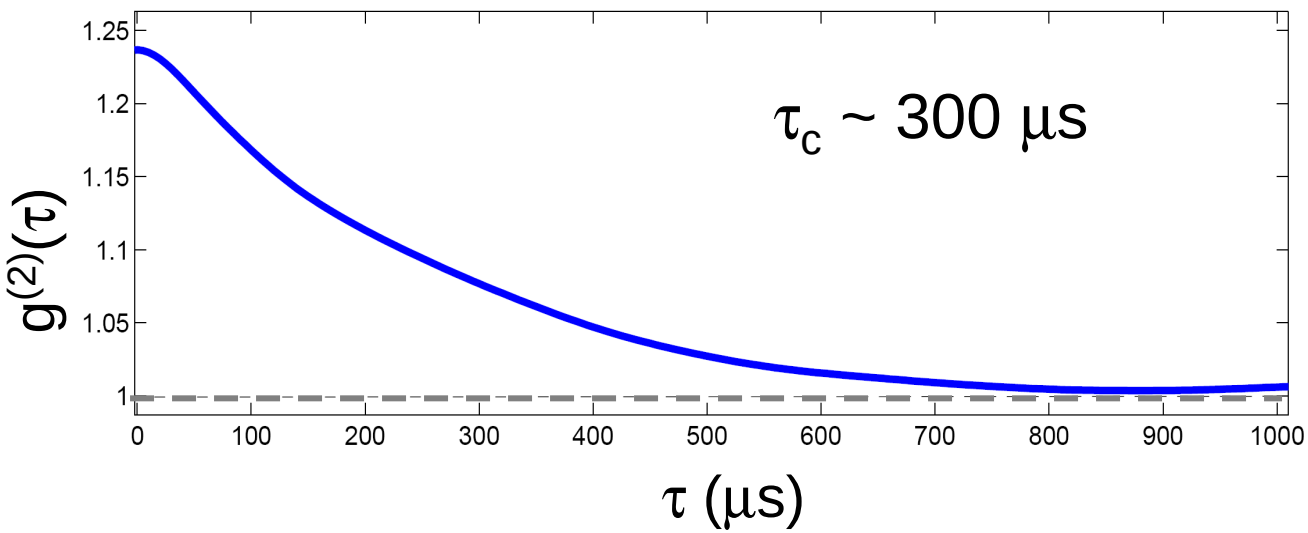
Cloud expansion terminates self-oscillation



Persistent CFWM via Trapping







$$g^{(2)}(\tau) = \frac{\langle I^2 \rangle}{\langle I \rangle^2}$$

Decoherence Mechanisms

Atomic Motion

- Expect gratings to decay due to ballistic atomic motion in a time τ_c

$$\tau_c = 1/\Lambda_g v_{av} = 0.76\ \mu s \text{ for } T=30\ \mu K,\ \Lambda_g \sim 400nm$$

Λ_g = grating wavelength

v_{av} = av. velocity

Atoms confined to wells diffuse much more slowly

Incoherent Scattering

- Free atom scattering rate of Γ_{free}~300 kHz

Lamb-Dicke effect reduces inelastic scattering

$$\frac{\Gamma_{free}}{\Gamma_{bound}} = \frac{E_r}{\hbar\Omega_{vib}} \sim 50-100 \rightarrow \Gamma_{bound} \sim 3-6 \text{ kHz}$$

E_r = recoil energy

Ω_{vib} = vibrational frequency

Conclusions/Outlook

Conclusion: Self-organization can reduce NLO instability thresholds and give rise to new, more sensitive parameter dependences

Future: Study how collective effects may enhance other NLO processes

- quantum correlated photon pair generation
- quantum memories