Photon-Driven Transport in Quantum Cascade Lasers

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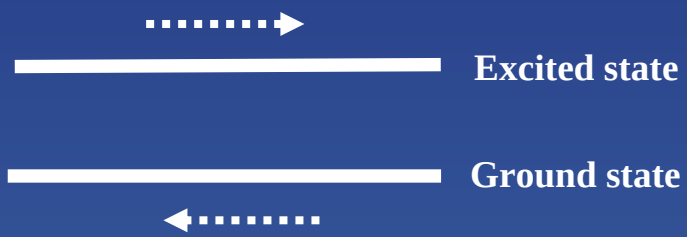
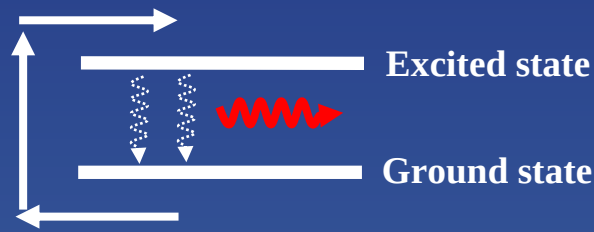
Motivations

- Electron transport in presence of AC electromagnetic field
  - Modern semiconductor devices : transistors, laser diodes, detectors, etc.
  - Classical transport regime : drift-diffusion equations
  - Optical process is separate from electronic transport



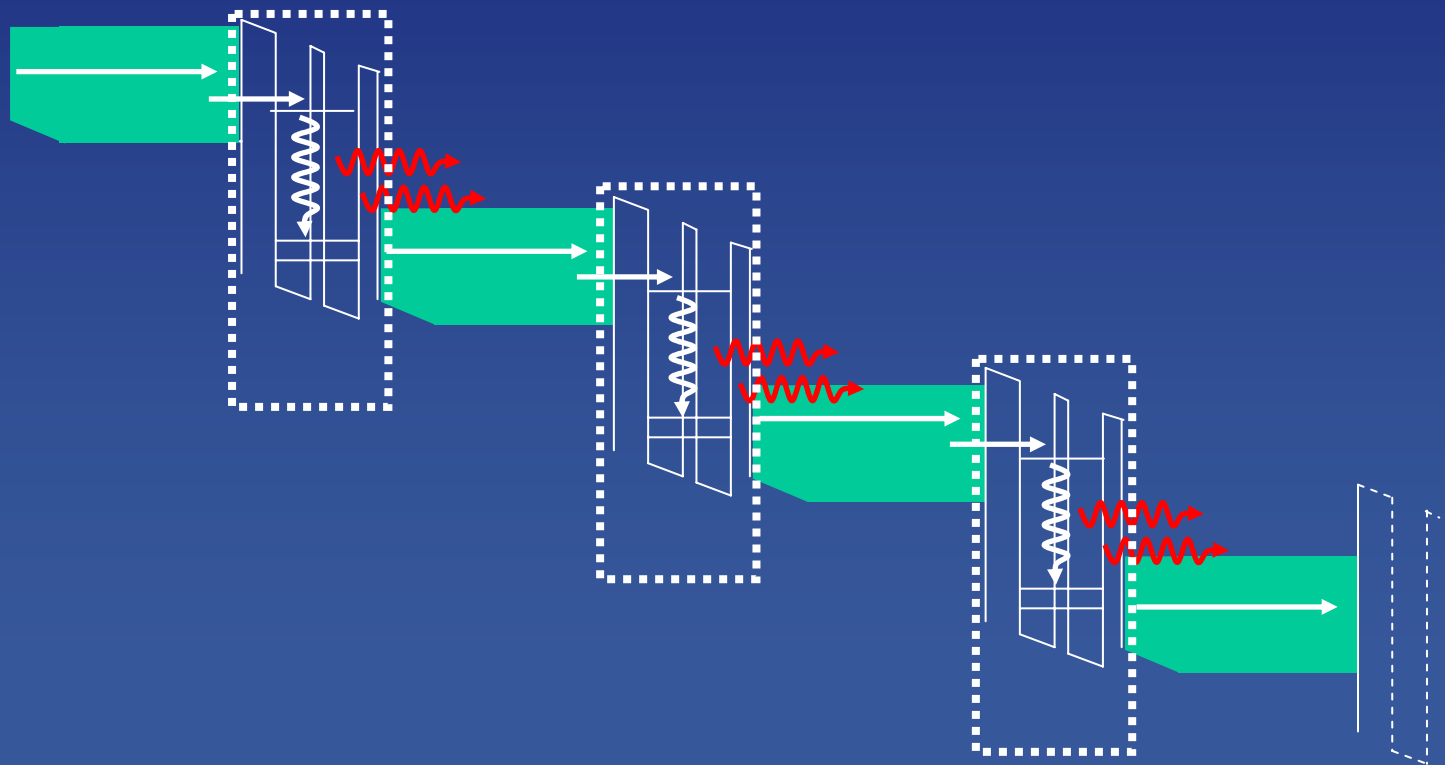


Electronic transport
- Classical transport

Optical process
- Photon generation, detection, etc

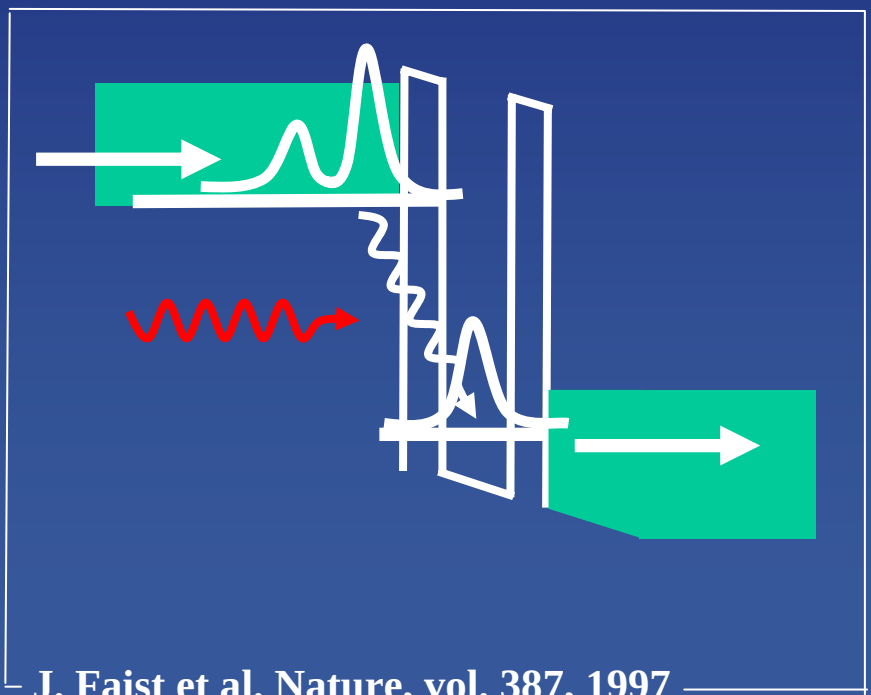
Motivations

- Quantum Cascade Lasers
  - A full quantum-transport system
  - Strong coupling between electron transport and intra-cavity photons

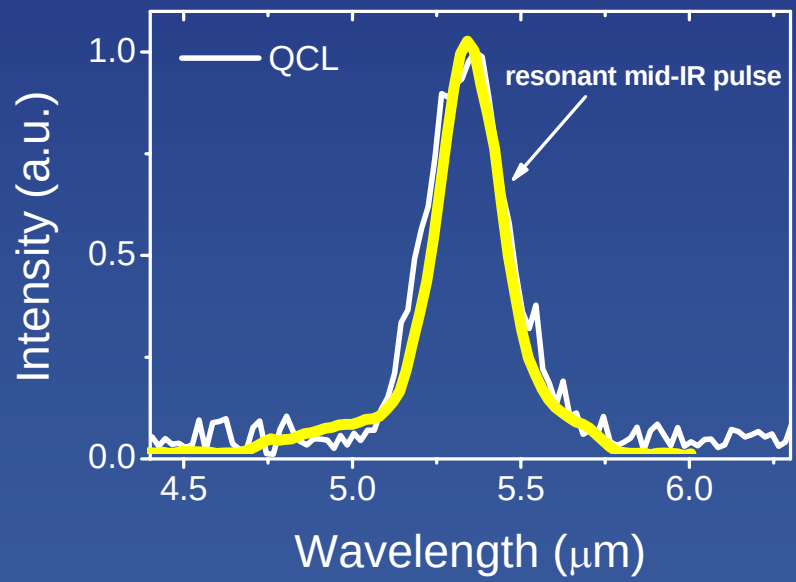


Gain recovery dynamics in QCLs

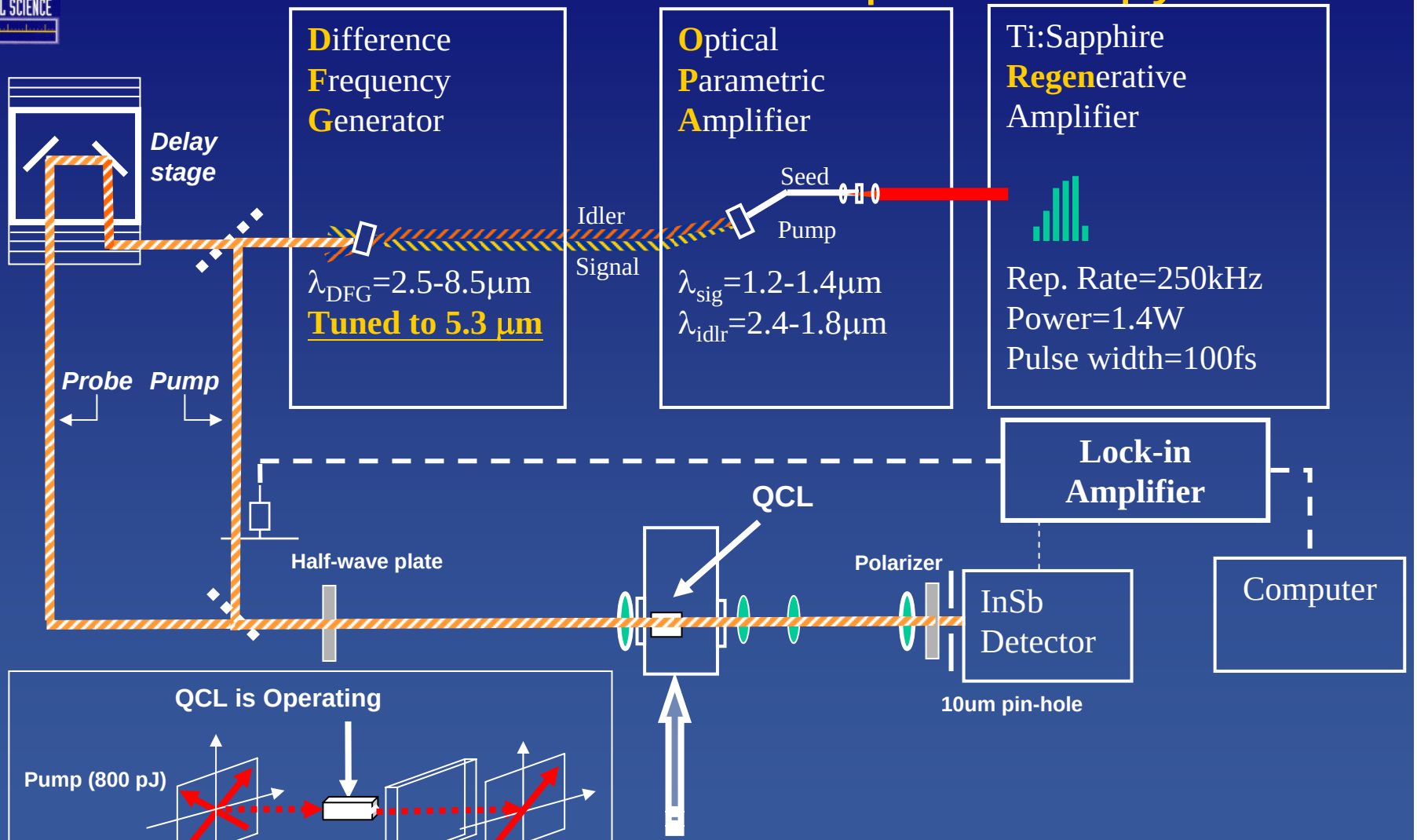
- Our approaches : Time-resolved pump-probe by resonant perturbation
  - Degenerate mid-IR pump-probe (250 fs) pulses
  - Spectrum of mid-IR resonant with QCL emission wavelength



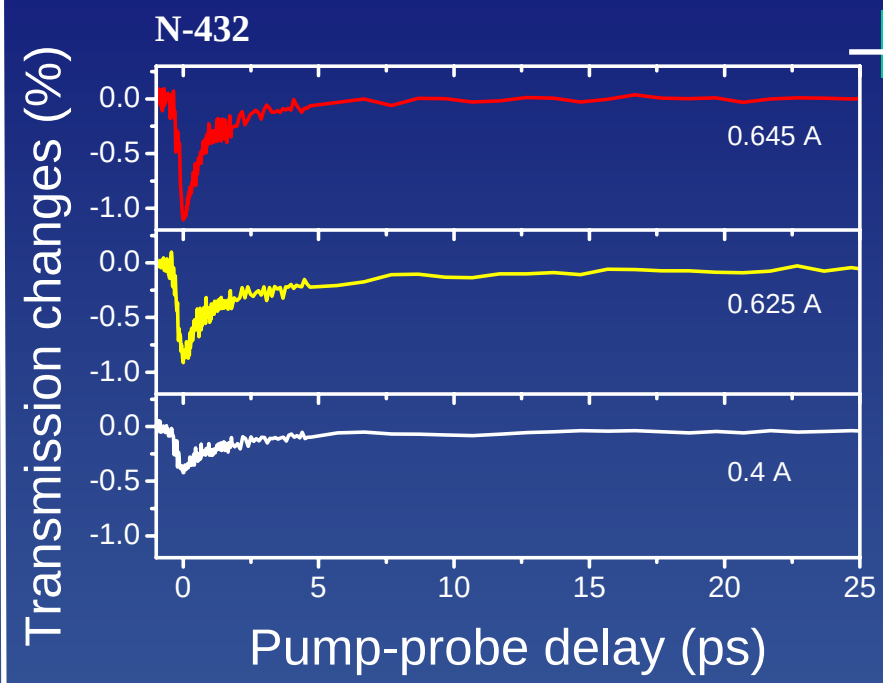
J. Faist et al. Nature, vol. 387, 1997

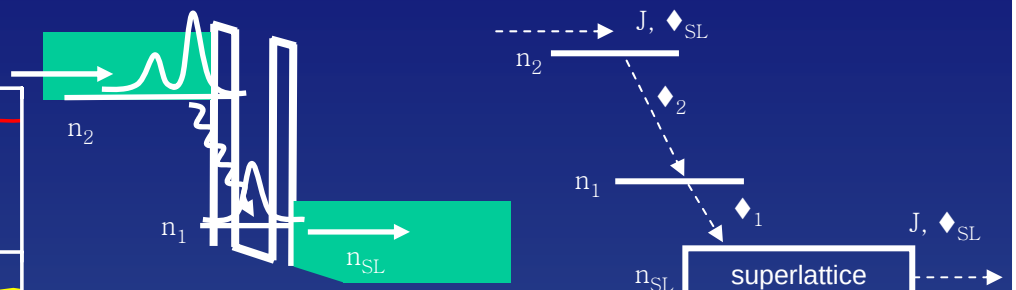


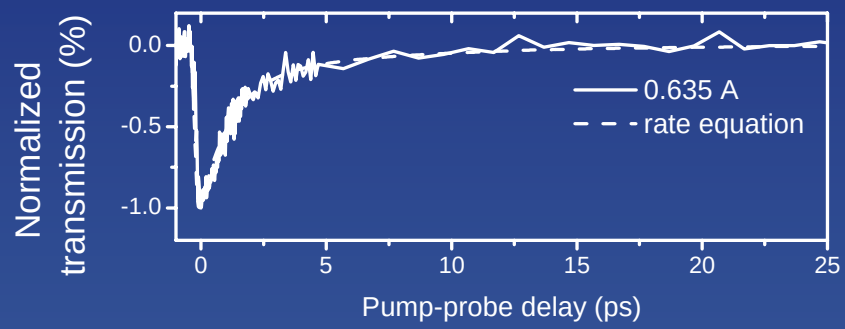
Degenerate mid-IR Pump-Probe Differential-Transmission Spectroscopy



Gain Recovery Dynamics at 30 K

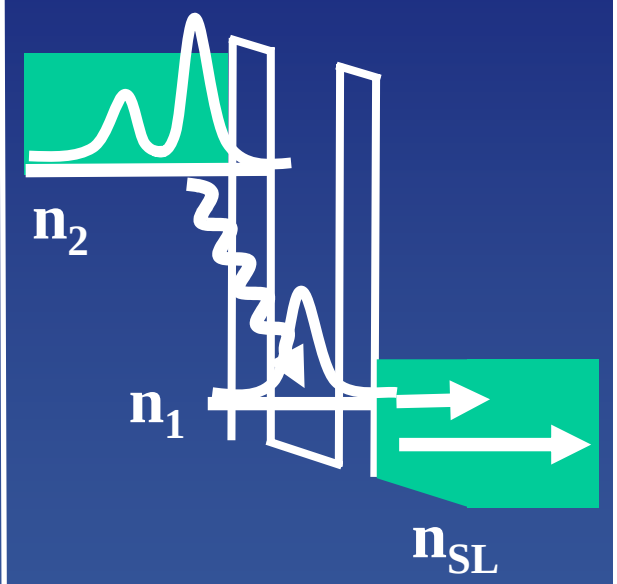






- Bias-dependent recovery: 3 time-constants are observed.
  - 0.7 ps, 2 ps, and 20-50 ps recovery
- 3-level rate equation: directly following the QCL level diagram
  - Used to model steady-state L-I curve (self-consistent picture)
  - Excellent agreement within 0.03 % DT noise level

3-Level Rate-Equation Model



$$\frac{dS}{dt} = \left[N_p \Gamma_P v_g g_c (n_2 - n_1) - \frac{1}{\tau_p} \right] S + N_p \beta \frac{n_2}{\tau_{sp}}$$

Upper lasing state

$$\frac{dn_2}{dt} = \frac{n_{SL}}{\tau_{SL}} - \frac{n_2}{\tau_2} - \Gamma_P v_g g_c (n_2 - n_1) S$$

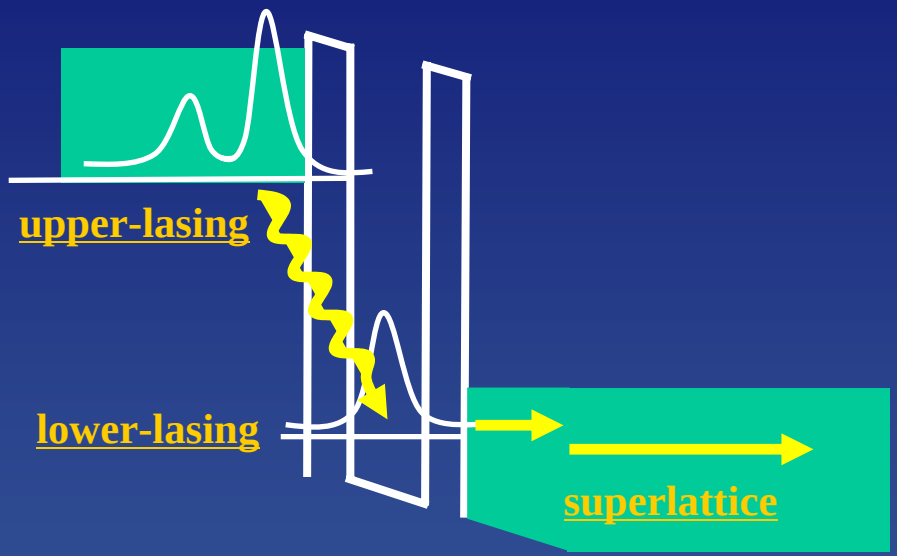
Lower lasing state

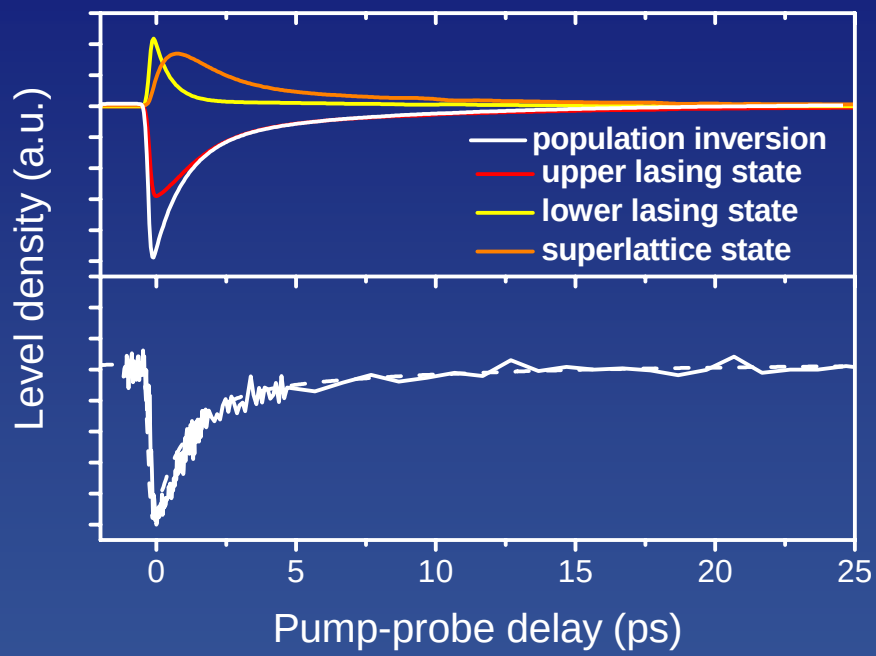
$$\frac{dn_1}{dt} = \frac{n_2}{\tau_2} - \frac{n_1}{\tau_1} + \Gamma_P v_g g_c (n_2 - n_1) S$$

Superlattice state

$$\frac{dn_{SL}}{dt} = \frac{n_1}{\tau_1} - \frac{n_{SL}}{\tau_{SL}}$$

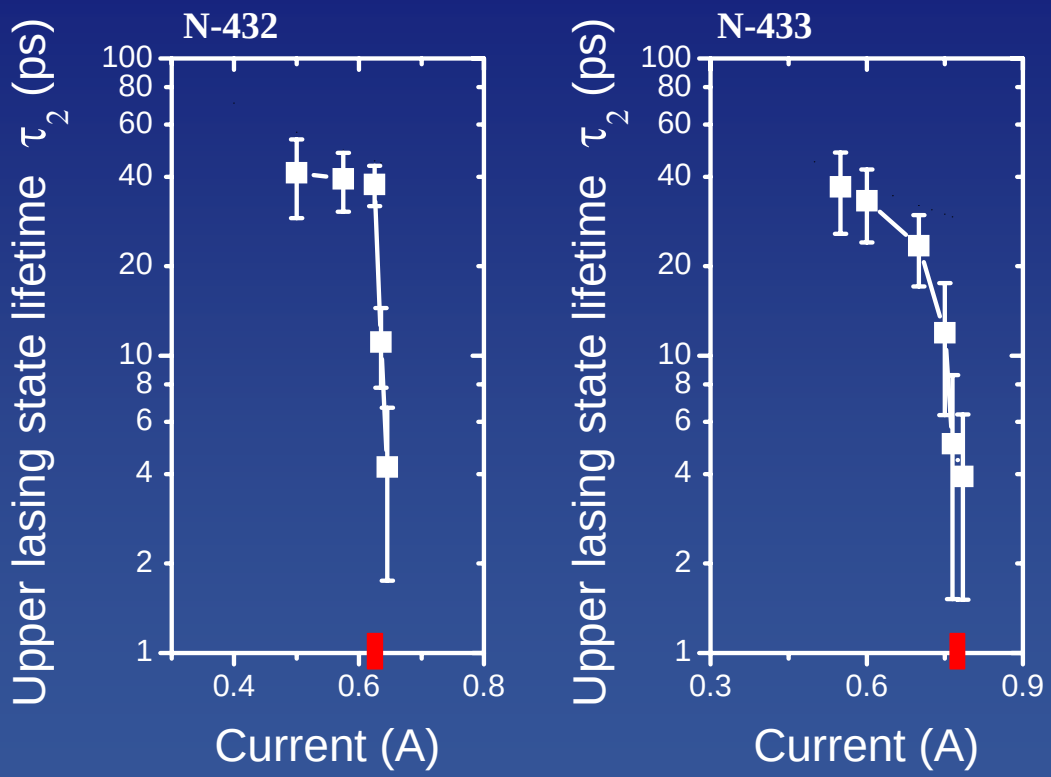
Relaxation Dynamics in Energy Level





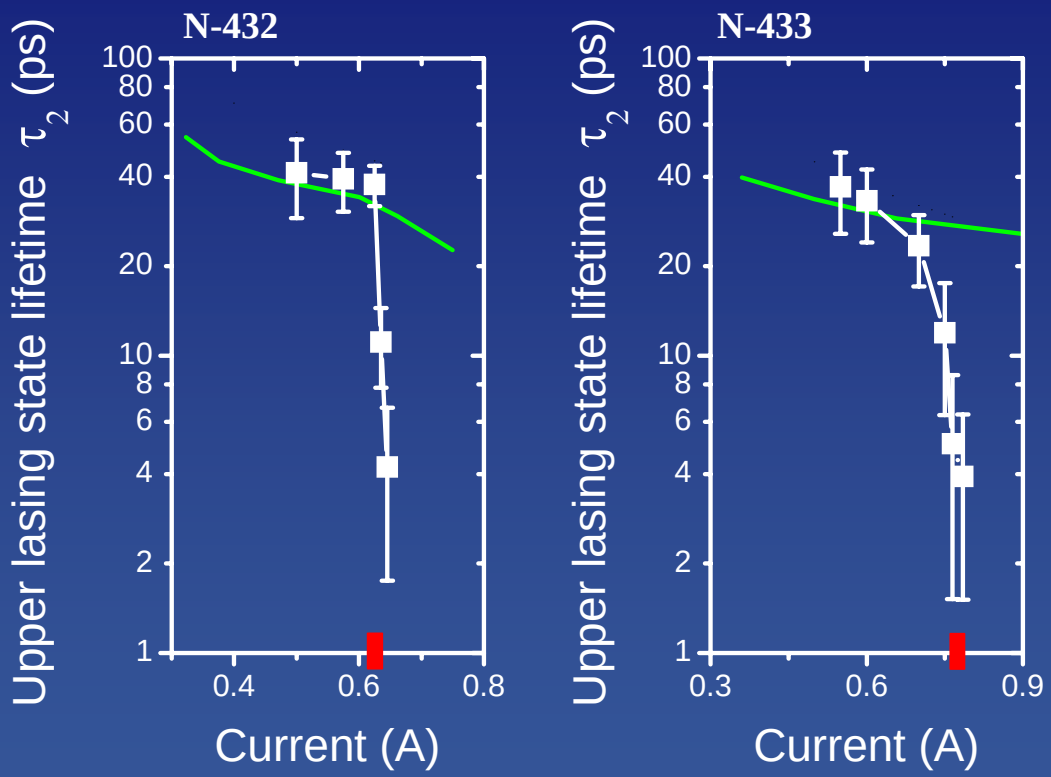
- 3 Recovery Components from rate-equation model
  - Upper-lasing state : 20-50 ps, phonon-limited lifetime (below th)
  - Lower-lasing state : ~ 1 ps, emptying via tunneling
  - Superlattice transport : coupling with adjacent active region

Dynamics of the Upper-Lasing State



DT measurement

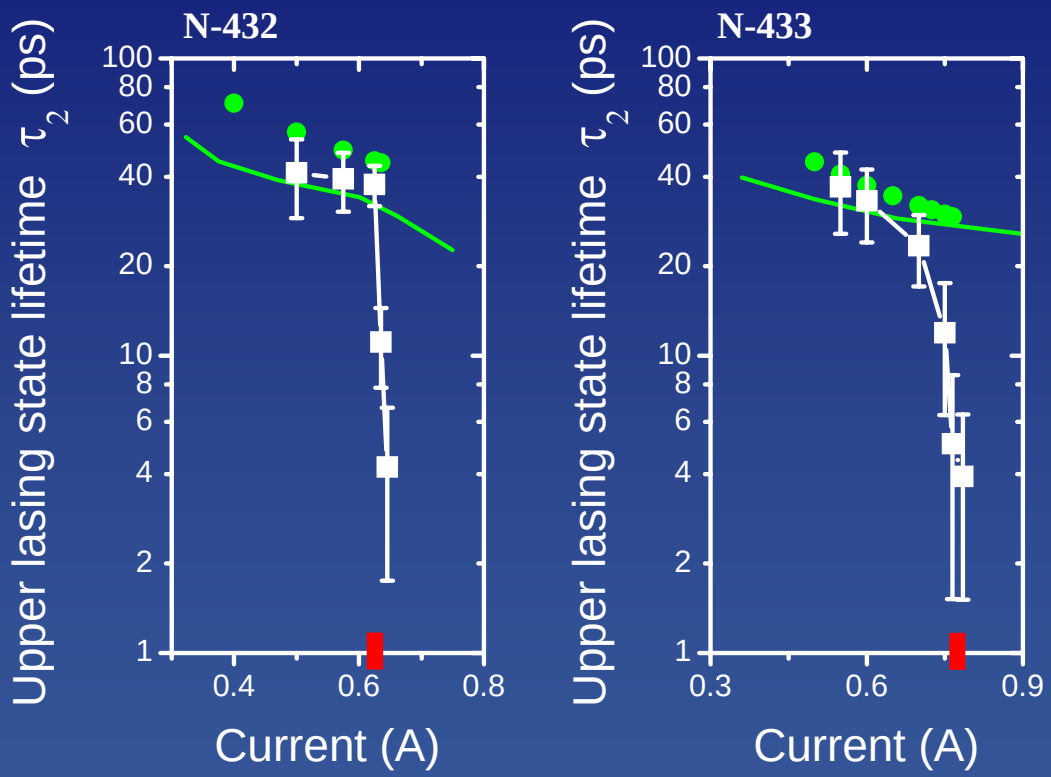
Dynamics of the Upper-Lasing State



DT measurement

Phonon-limited relaxation (non-radiative lifetime)

Dynamics of the Upper-Lasing State

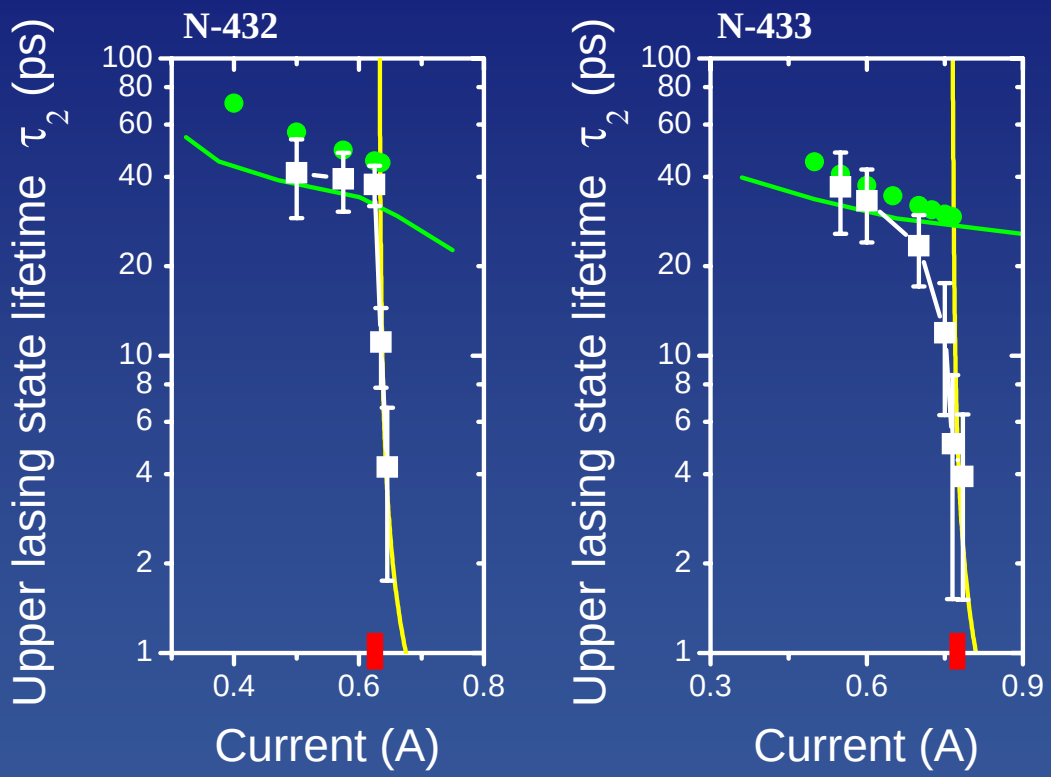


DT measurement

Phonon-limited relaxation (non-radiative lifetime)

Current-continuity equation (non-radiative lifetime)

Dynamics of the Upper-Lasing State



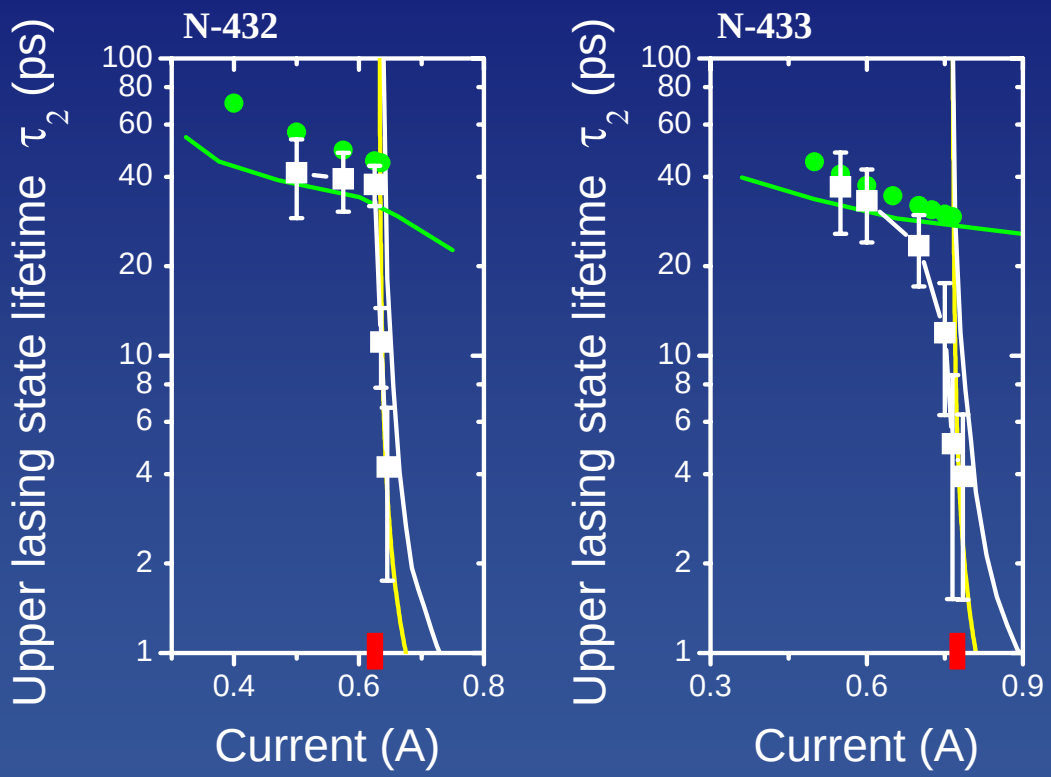
DT measurement

Phonon-limited relaxation (non-radiative lifetime)

Current-continuity equation (non-radiative lifetime)

Stimulated emission rate 1 (Photon-density via rate-eq)

Dynamics of the Upper-Lasing State



DT measurement

Phonon-limited relaxation (non-radiative lifetime)

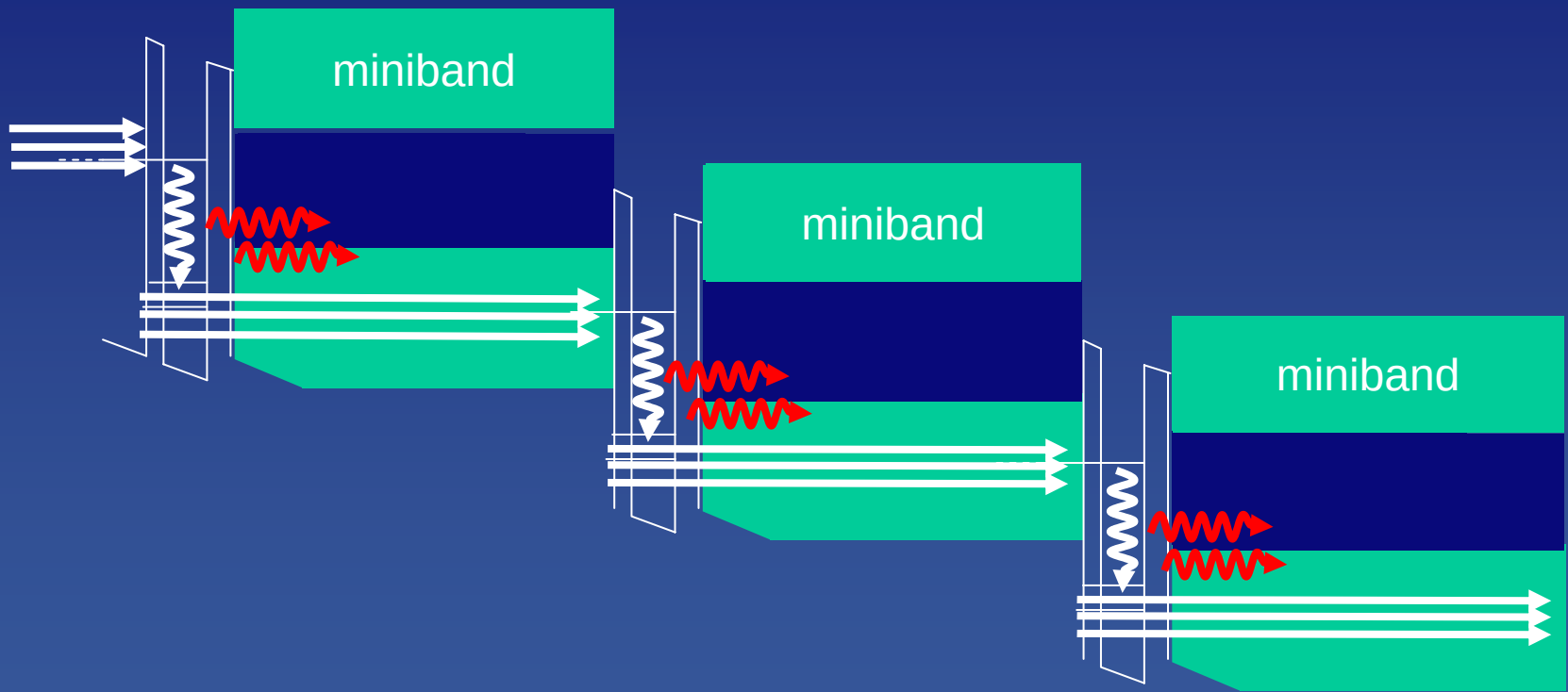
Current-continuity equation (non-radiative lifetime)

Stimulated emission rate 1 (Photon-density via rate-eq)

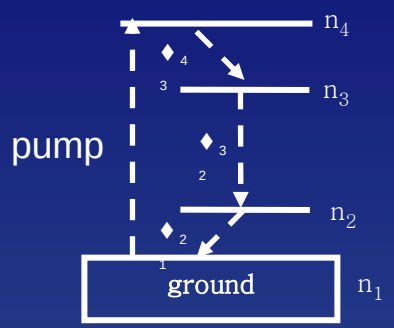
Stimulated emission rate 2 (Photon-density via L-I curve)

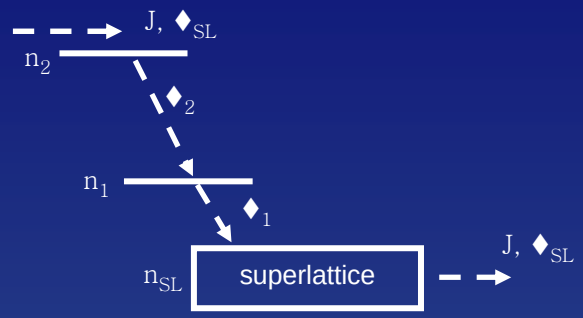
- Remarkable speed-up of the gain recovery (50 ps → few ps)
  - Near threshold : # of intra-cavity photon density (a few hundred)
  - **Electron transport is driven by quantum stimulated emission !**

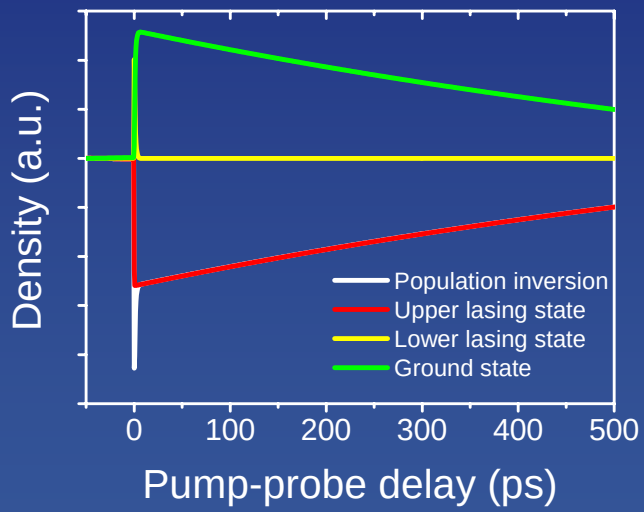
Intra-Cavity Photon-Driven Transport

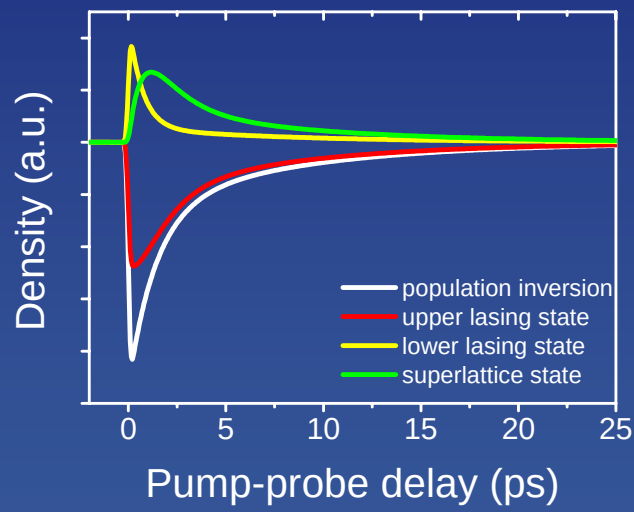


Atomic, Solid-State, Interband Diode Lasers vs. Quantum Cascade Lasers



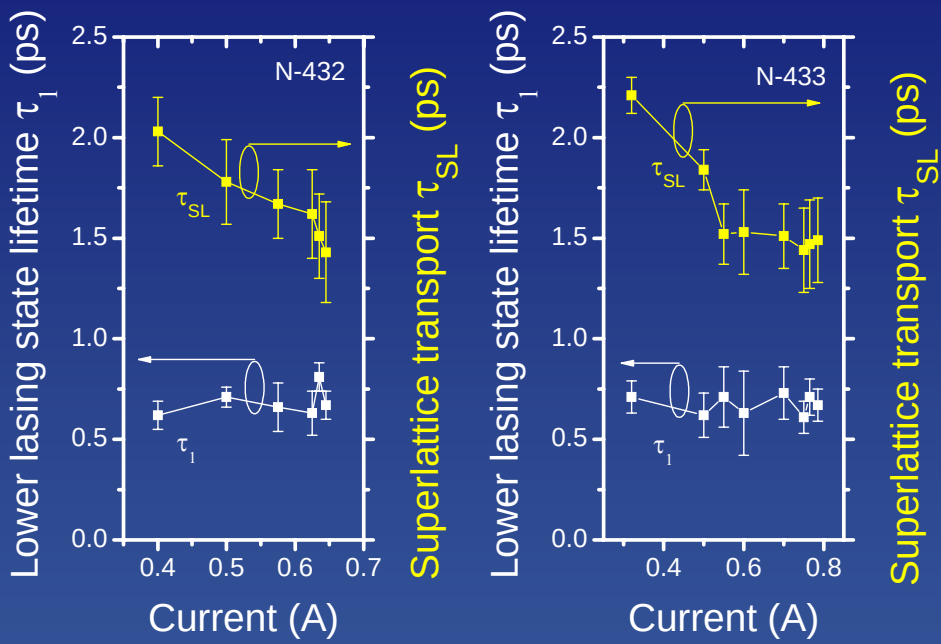


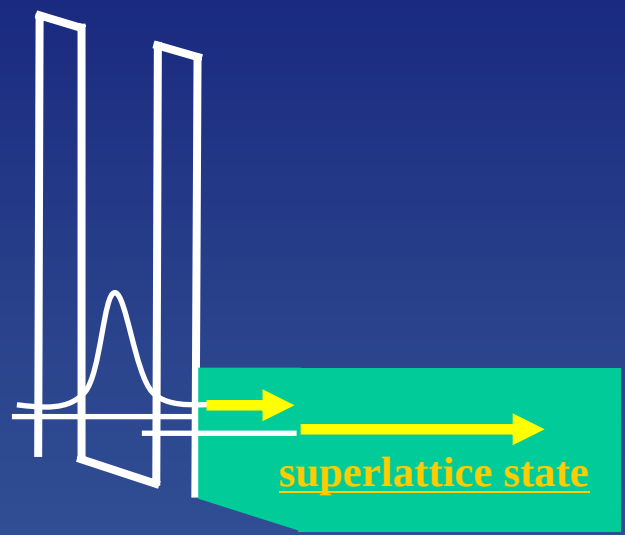




- Closed- or open-system gain-recovery dynamics
  - Transport delay : no analogues in any laser systems.
  - Large spontaneous emission factor in QCL: $10^{-2} \sim 10^{-3}$

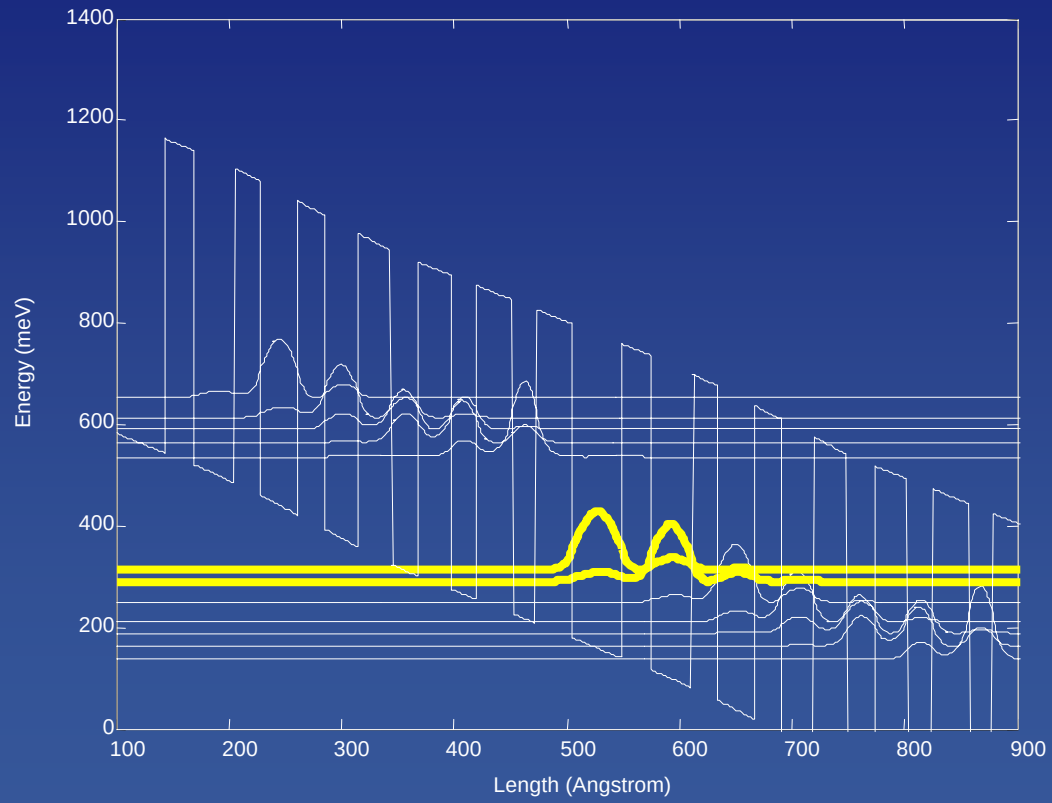
Other Recovery Components



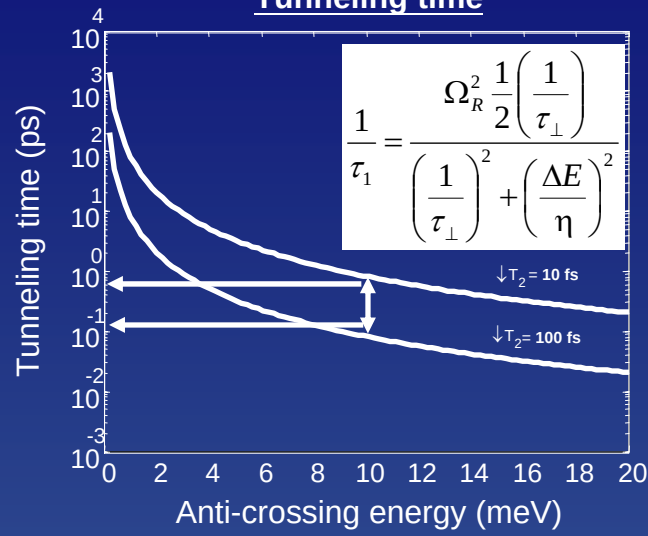


- Two other recovery dynamics
  - Lower-lasing state: emptying via scattering assisted tunneling
  - Superlattice state: analogue to dielectirc relaxation

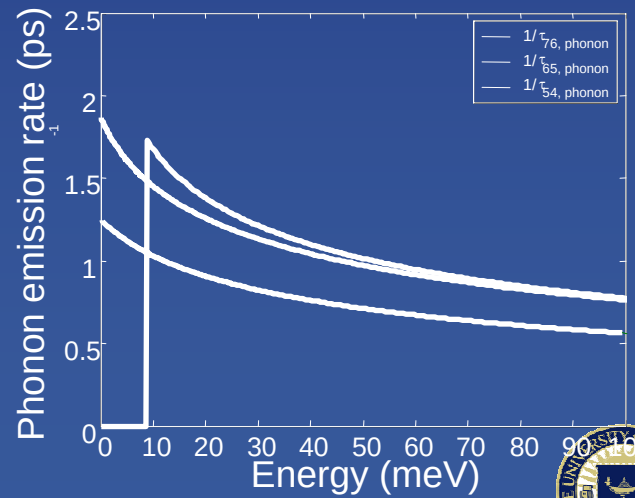
Dynamics of the Lower-Lasing State



Tunneling time



Electron-polar-optical-phonon scattering



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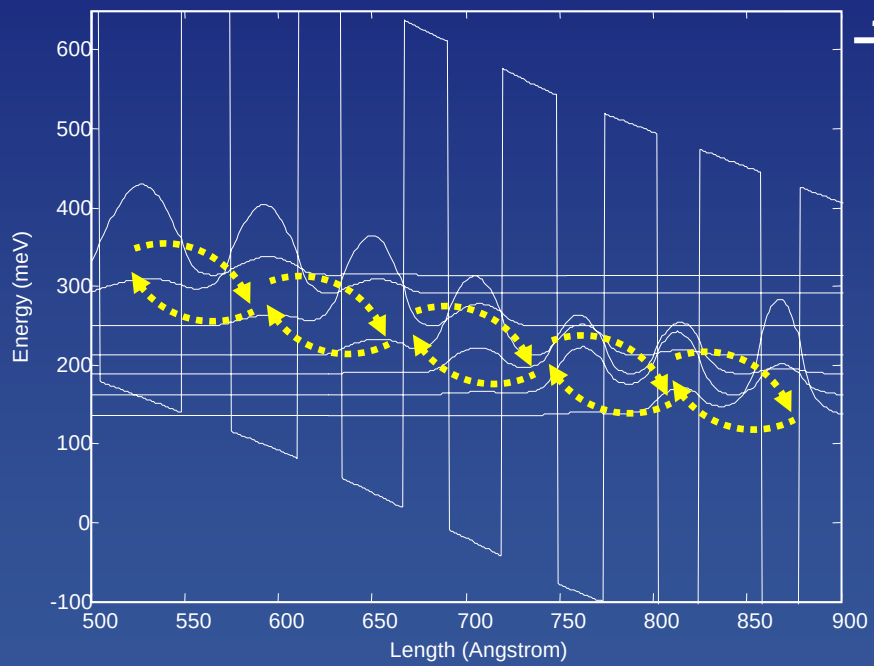
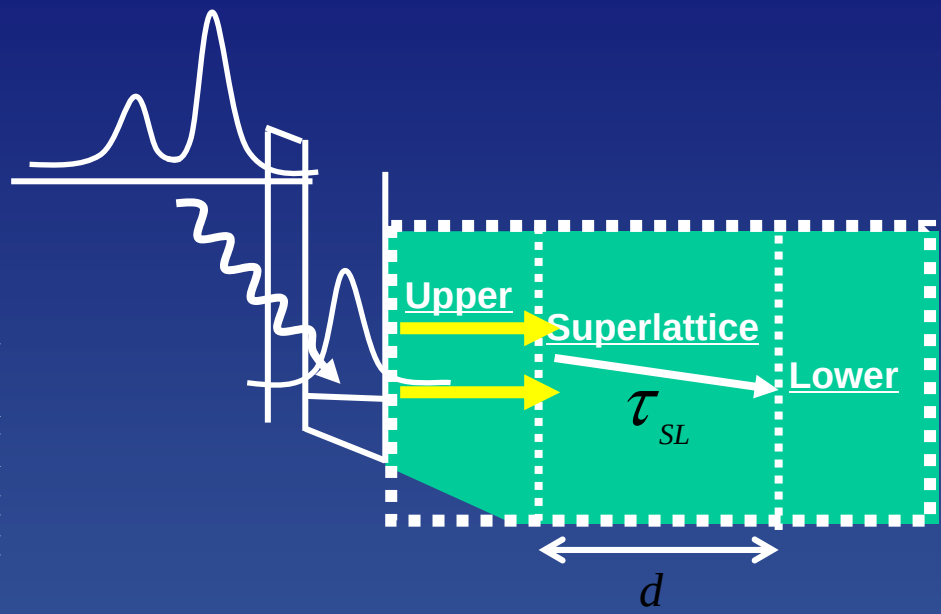
Dynamics of the Superlattice State

Superlattice Miniband



Dielectric relaxation in superlattice



Monte-Carlo Simulation

- **Scattering : intersubband optical-phonon scattering**
- **Can include impurity and Auger-type e-e scattering**
- **Back-scattering : $\blacklozenge_{if} \propto \exp(-\Delta/kT)$**
- **In progress…**

- Inverse bias-dependence
  - Observed in a various QC structures
  - Transport channel between active regions

Summary

- Electronic transport in presence of oscillating electromagnetic fields
- Femtosecond time-resolved QCL gain recovery dynamics
  - Upper-lasing state, lower-lasing state, superlattice dynamics
- Electronic transport is driven by Intra-cavity photon density