Theory of whispering gallery mode sensing

Matthew R. Foreman

Imperial College London

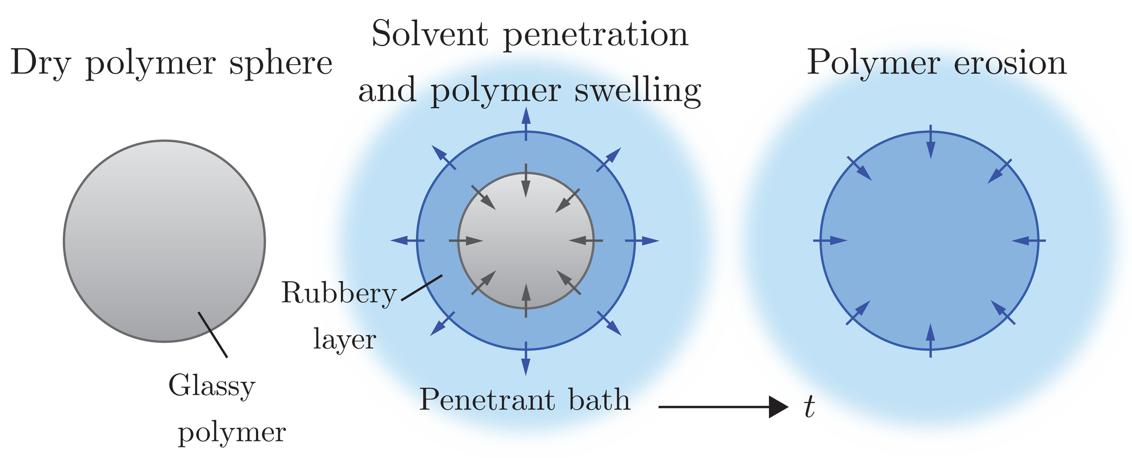
MAX PLANCK INSTITUTE for the science of light

Research Area Overview

Our theoretical research includes topics such as:

- **Tracking diffusion kinetics in polymers**
- **Detection limits in whispering gallery mode sensing**
- **Hybrid photonic-plasmonic resonators**
- **Liquid droplet resonators for enhanced sensing**

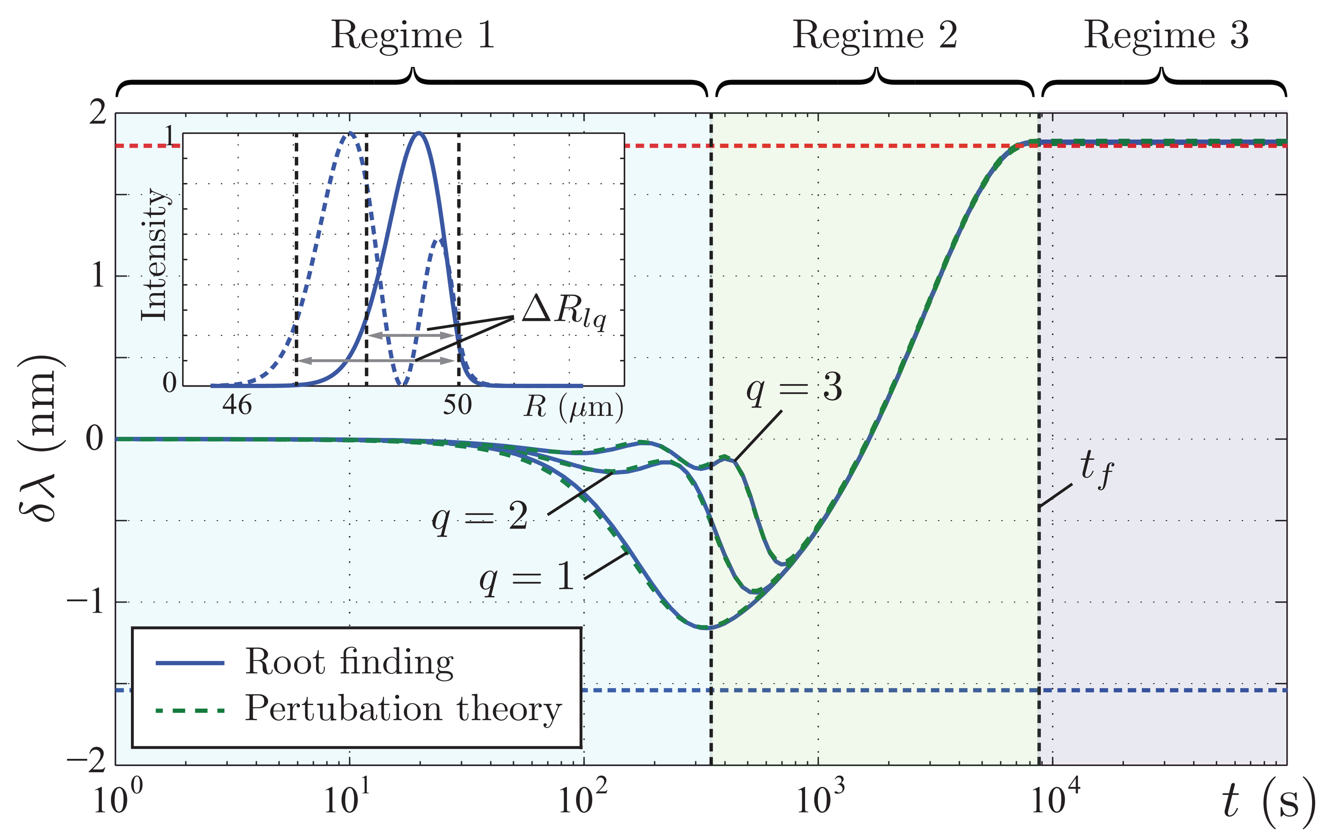
Optical tracking of anomalous diffusion kinetics in polymer microspheres



When a dry glassy polymer microsphere is immersed into a penetrant bath, a complex mixture of diffusion, polymer swelling, and erosion can occur

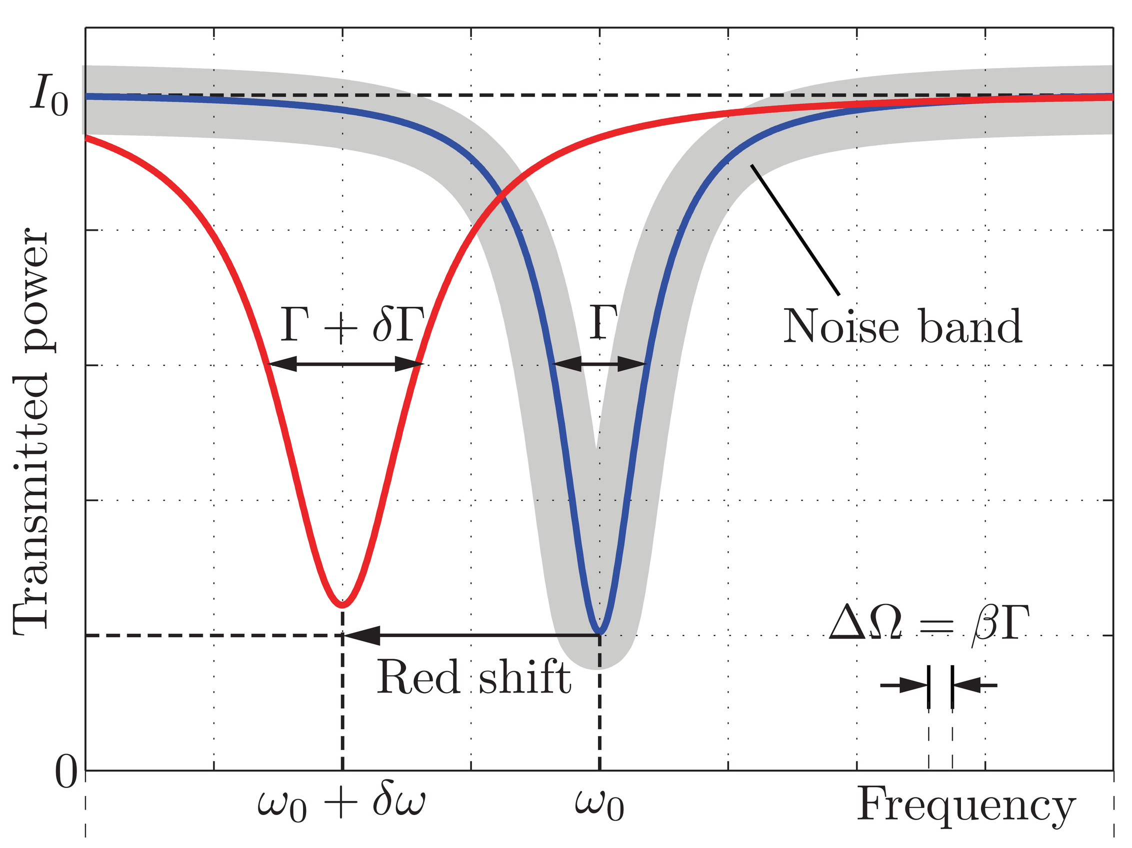
We propose and model WGM tracking as a means to monitor potentially anomalous diffusion kinetics

- **Regime 1:** Ingress into whispering gallery mode volume changes effective refractive index: blue shift
  - fast and mode dependent
- **Regime 2:** Swelling of sphere from polymer relaxation and plasticisation: red shift
  - attolitre sensitivity
- **Regime 3:** dissolution causes sphere shrinkage: blue shift
  - dissolution rates ~μm/yr detectable



M. R. Foreman and F. Vollmer, Phys. Rev. Lett. **114**, 118001 (2015)

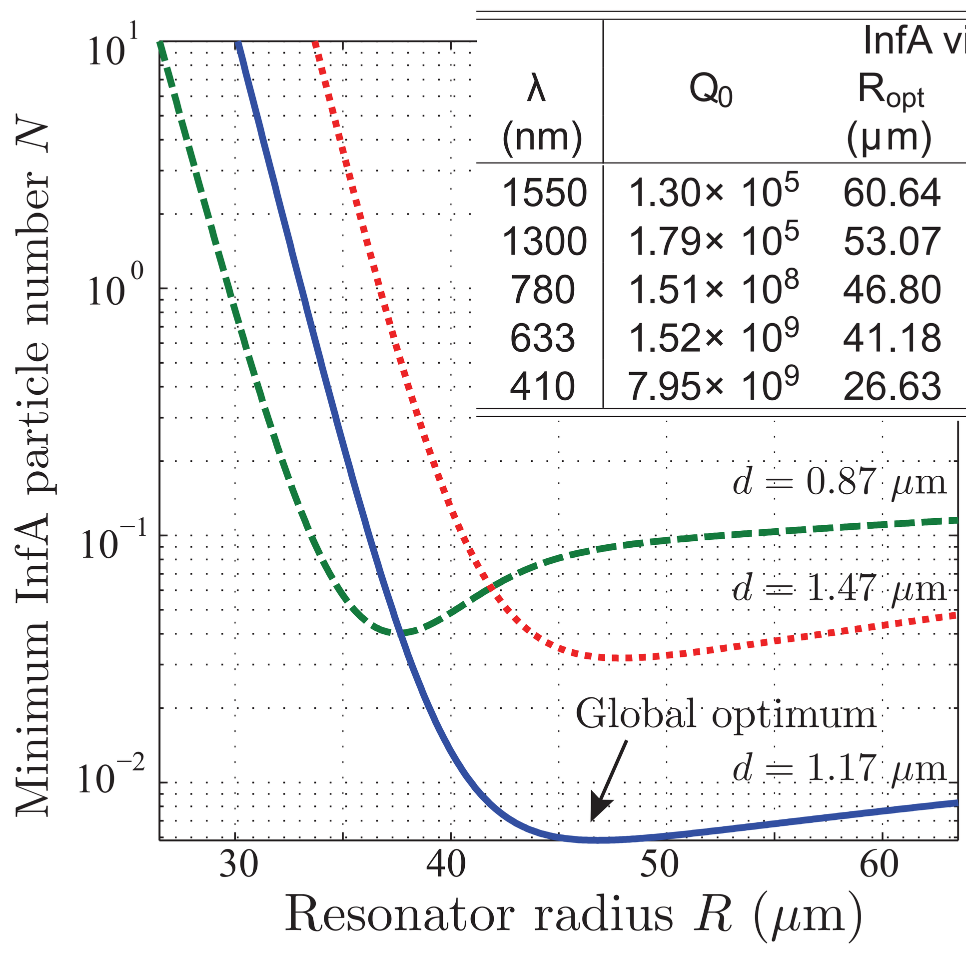
Optimising detection limits in whispering gallery mode biosensing



Detection limits in WGM sensing are set by a balance of noise and the magnitude of induced resonance shifts

- **Cramer-Rao lower bound:** gives measurement resolution
- **Reactive sensing principle:** perturbative approach to calculate WGM shifts and broadening
- **Measurement acuity factors:** $N = \frac{\Delta\omega}{|\delta\omega|}$ analytically found under differing noise regimes
- **Optimisation:** Detection limits can be maximised through choice of correct experimental design e.g. coupling strength

		InfA viron		
λ (nm)	Q_0	R_{opt} (μm)	d_{opt} (μm)	$\log_{10}N_{opt}$
1550	1.30× 10^5	60.64	0.972	1.23
1300	1.79× 10^5	53.07	0.866	0.92
780	1.51× 10^8	46.80	1.169	-2.23
633	1.52× 10^9	41.18	1.127	-3.41
410	7.95× 10^9	26.63	0.799	-4.65

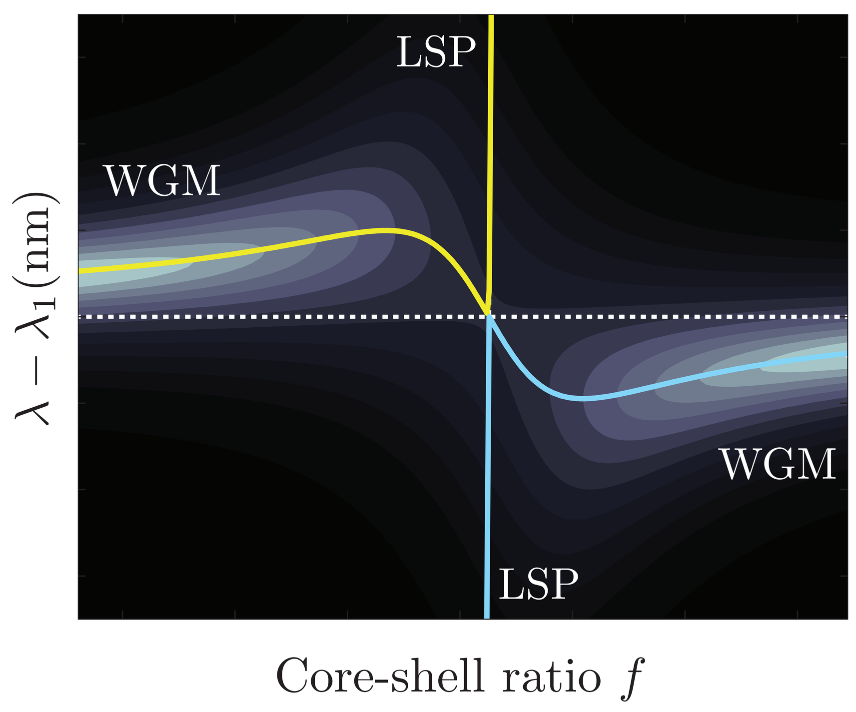


M. R. Foreman et al., Opt. Express **22**, 5491-5511 (2014)

Hybrid plasmonic-photonic WGM sensors

Coupling between WGM resonators and plasmonic nanoparticles investigated beyond perturbative regime

- **WGM-LSP hybridisation:** resonance condition found for arbitrary nanoparticles using T-matrix approach
- **Triplet splitting**
- **Optimal nanoparticle labels:** > 60× enhancement for core-shell nanoparticles



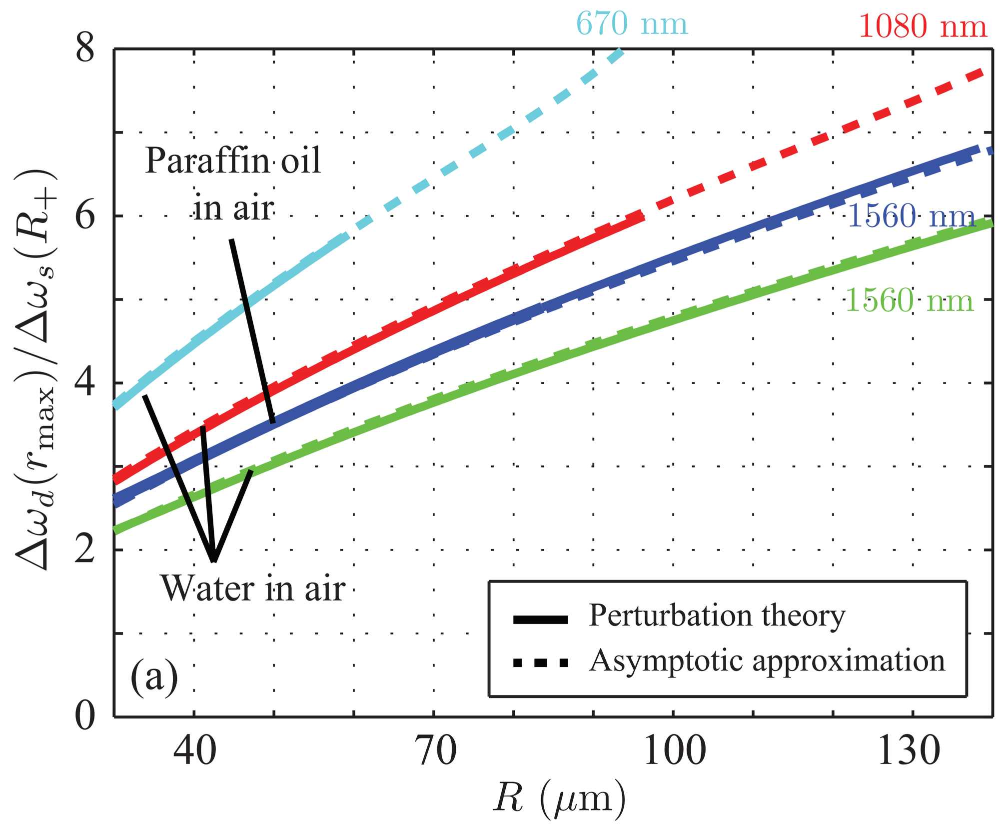
M. R. Foreman and F. Vollmer New J. Phys. **15**, 083006 (2013)

M. R. Foreman and F. Vollmer Phys. Rev. A. **88**, 023831 (2013)

Enhanced particle detection with droplet resonators

We have considered the feasibility and properties of liquid droplet WGM sensors

- **Increased sensitivity:** sensing region not limited to weak evanescent field
- **Surface and volume effects:** bound and freely diffusing particles give differing perturbations
- **Asymptotic approximations** to enhancement factors and mode energies derived



M. R. Foreman et al. Eur. Phys. J. Spec. Top. **223**, 1971-1988 (2014)