KEK @ DESY, 20. March 2012

Making Iron Invisible: Quantum Optics with ^{57}Fe Nuclei

Forget Transparent Aluminum, we have Transparent Iron !

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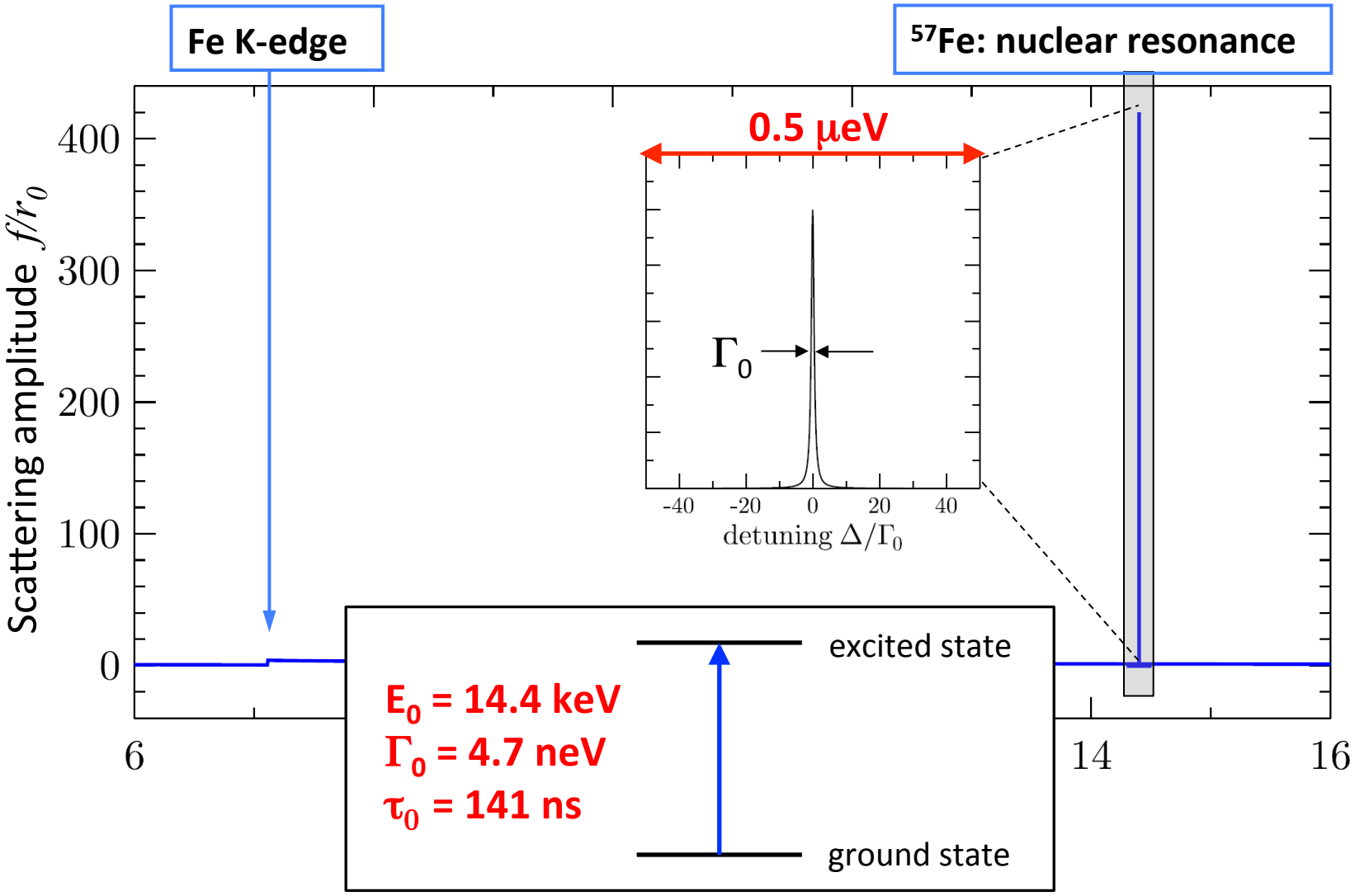
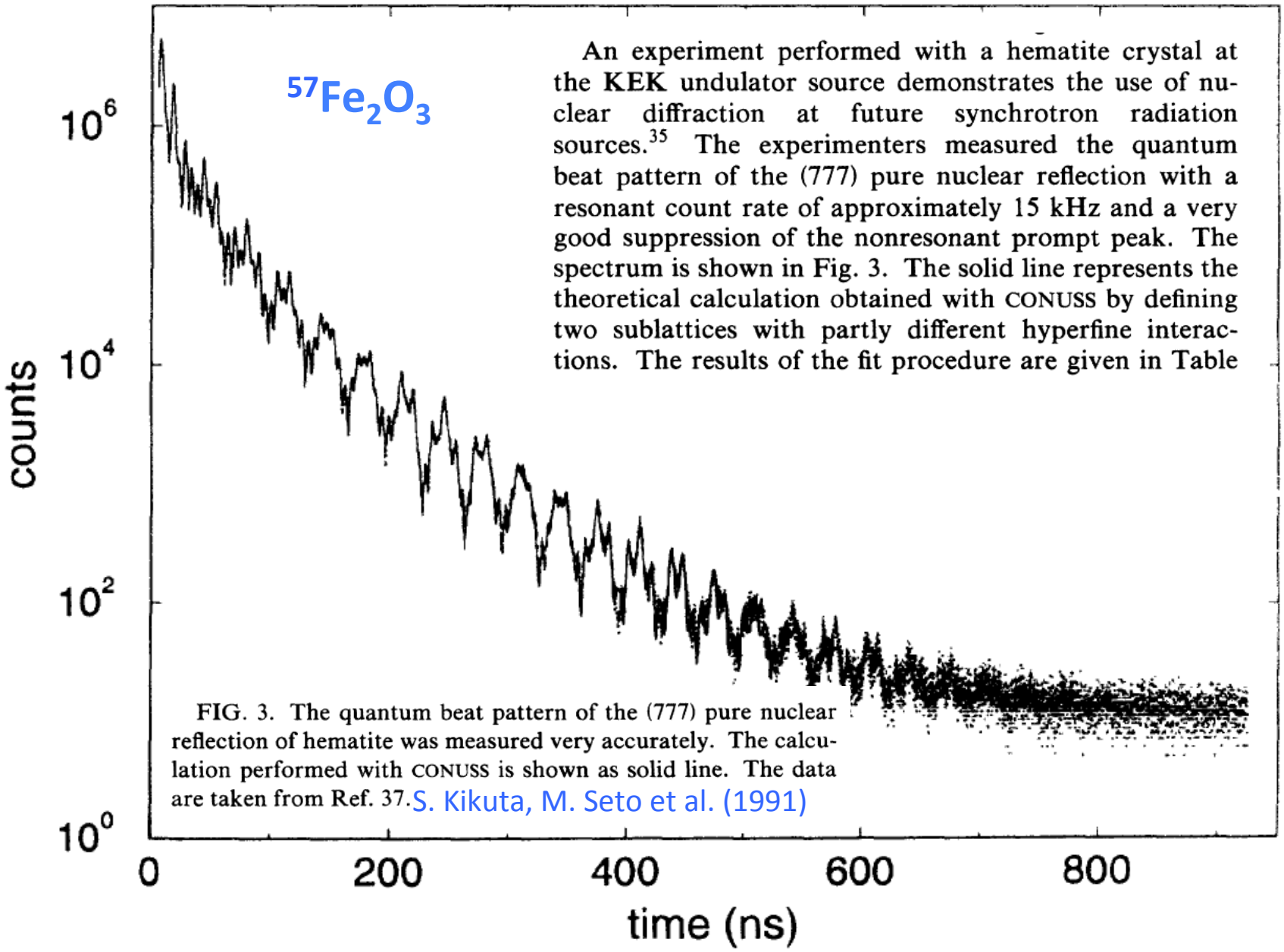
HELMHOLTZ ASSOCIATION

DESY

The 14.4 keV Nuclear Resonance of ^{57}Fe

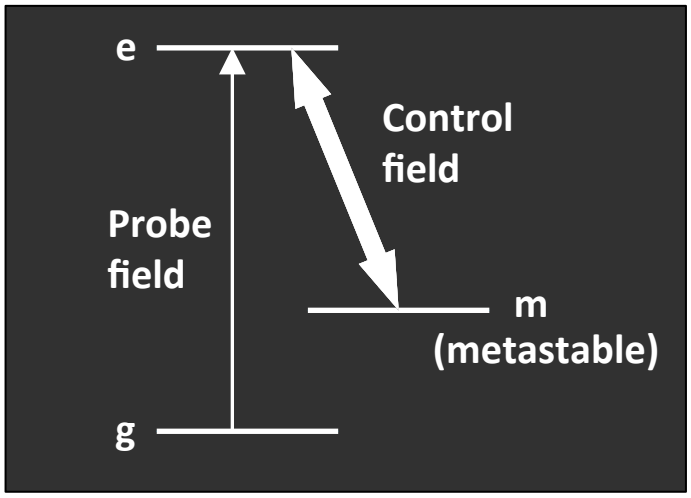


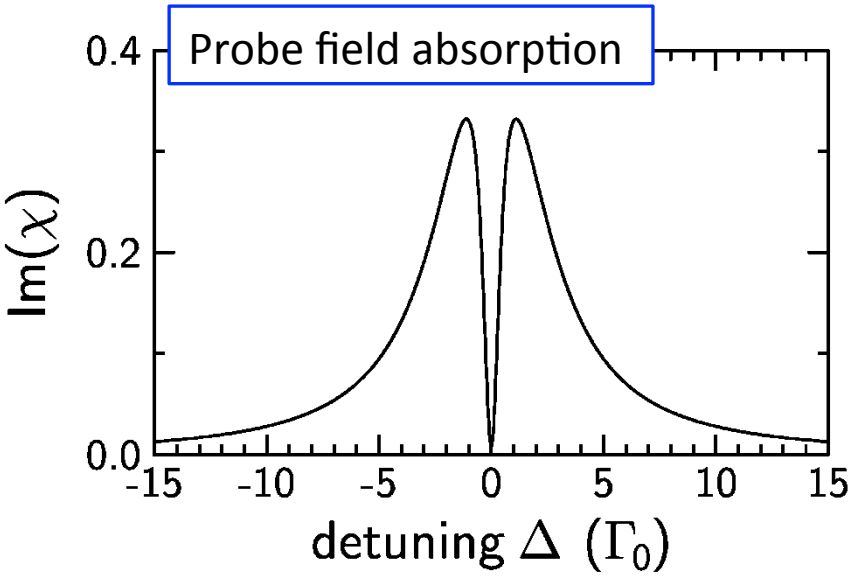


An experiment performed with a hematite crystal at the KEK undulator source demonstrates the use of nuclear diffraction at future synchrotron radiation sources.[35] The experimenters measured the quantum beat pattern of the (777) pure nuclear reflection with a resonant count rate of approximately 15 kHz and a very good suppression of the nonresonant prompt peak. The spectrum is shown in Fig. 3. The solid line represents the theoretical calculation obtained with CONUSS by defining two sublattices with partly different hyperfine interactions. The results of the fit procedure are given in Table

FIG. 3. The quantum beat pattern of the (777) pure nuclear reflection of hematite was measured very accurately. The calculation performed with CONUSS is shown as solid line. The data are taken from Ref. 37.S. Kikuta, M. Seto et al. (1991)

Electromagnetically Induced Transparency (EIT)





Possibilities to reach the excited state (e) in the presence of the control field:

A_1 : g → e

A_2 : g → e → m → e

A_3 : g → e → m → e → m → e

⋮

$$\sum A_i = 0 \quad \text{at resonance } (\Delta = 0)$$

(Destructive interference of multiple pathways to the excited state)

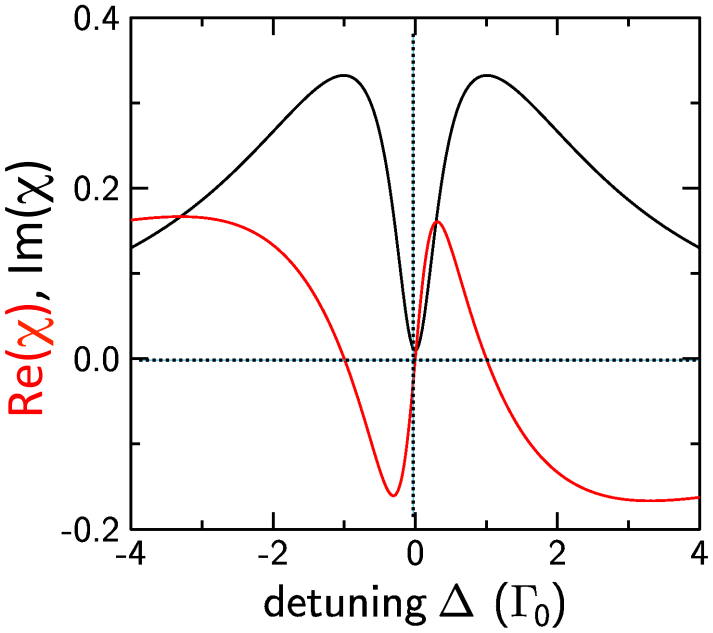
This is Electromagnetically Induced Transparency (EIT) !

K. Boller, A. Imamoglu, S. Harris, PRL 66, 2593 (1991)

Applications of EIT

EIT opens the door to control the optical properties of matter :

a) Slow light



Group velocity of light :

$$v_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}} = \frac{2c}{\omega \frac{d\chi}{d\omega}}$$

v_g < 10 m/s in atomic gases

Lene V. Hau et al.
Nature 397, 594 (1999)

b) Nonlinear optics

Higher-order (nonlinear) contributions become ‚visible' :

Index of refraction: $n = \cancel{n_0} + n_2 I$ ← can be resonantly enhanced

EIT

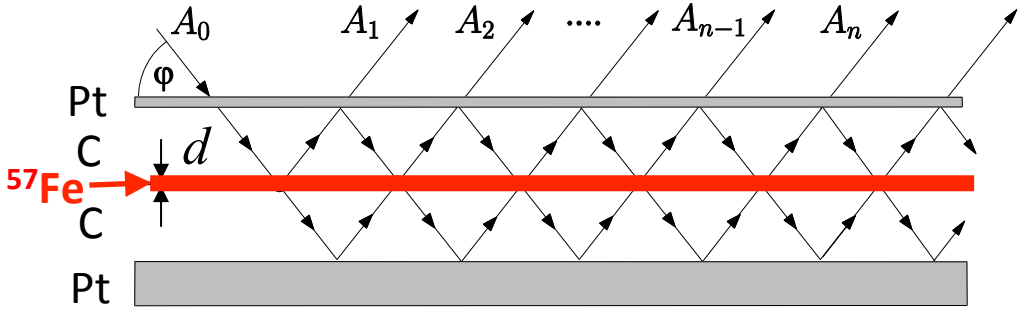
How to convert ^{57}Fe into a 3-level system ?

^{57}Fe in a Cavity

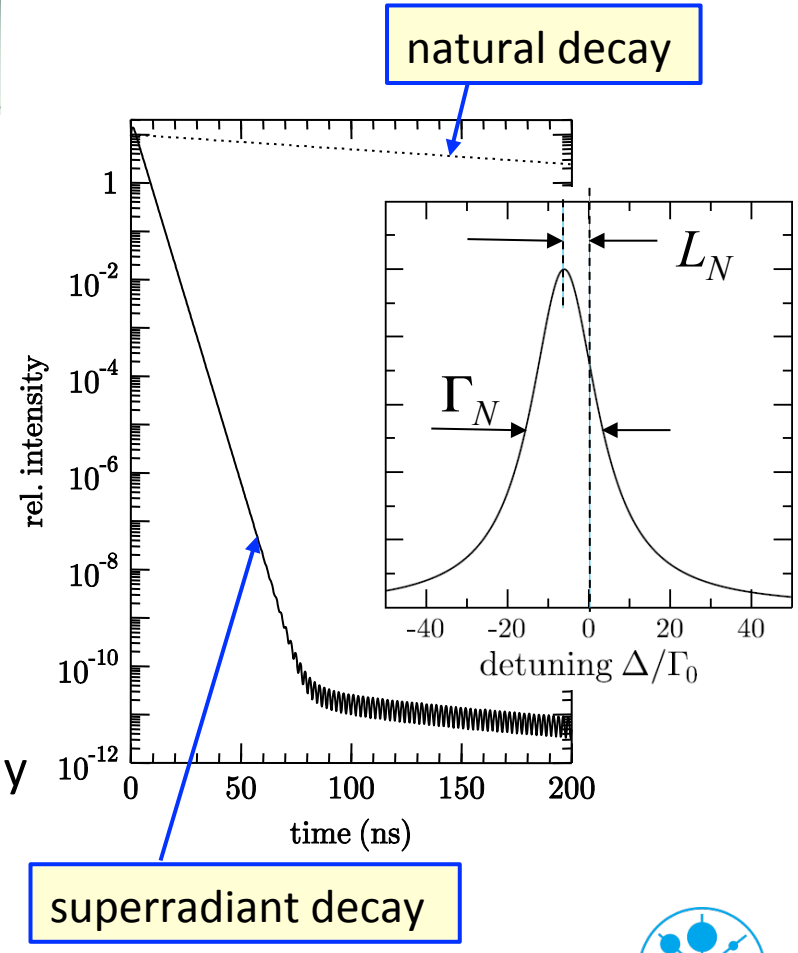
The Collective Lamb Shift L_N

R.R., K. Schlage, B. Sahoo, S. Couet and R. Rüffer, **Science 328, 1248 (2010)**

Reflectivity $R = \sum A_i$



Evanescent coupling under grazing angles
φ ~ 3 mrad into a guided mode



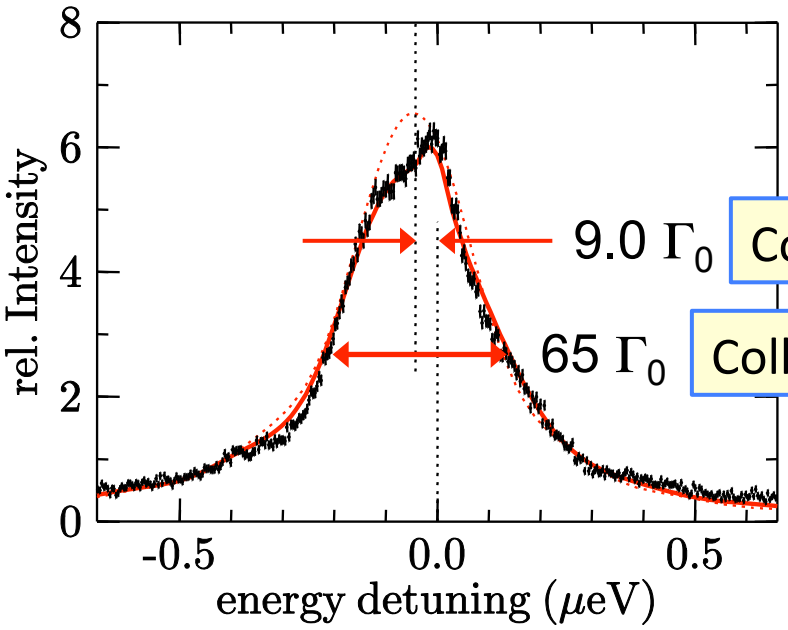
Coherent excitation:

Preparation of an entangled excited state

→ Nuclei respond collectively, not individually

Superradiance → accelerated emission

^{57}Fe in a Cavity: The Collective Lamb Shift

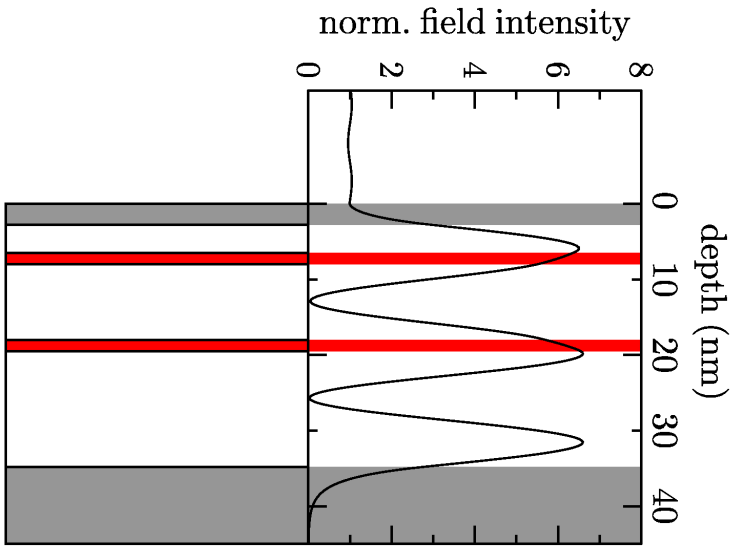


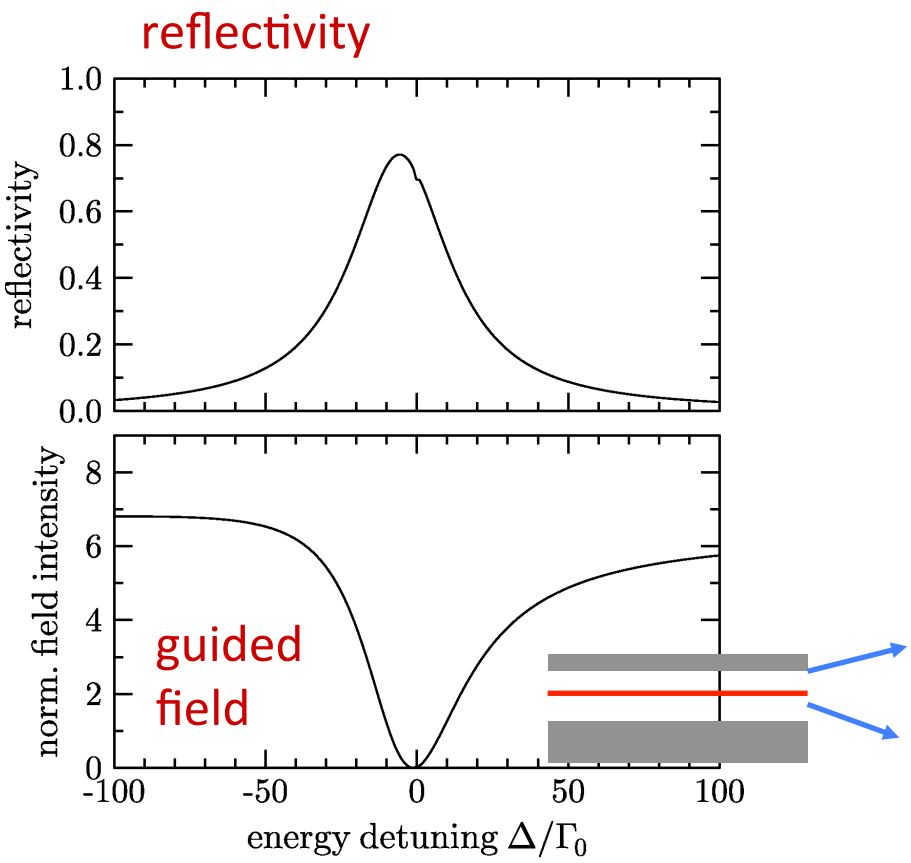
Collective Lamb shift L_N

Collective decay width Γ_N

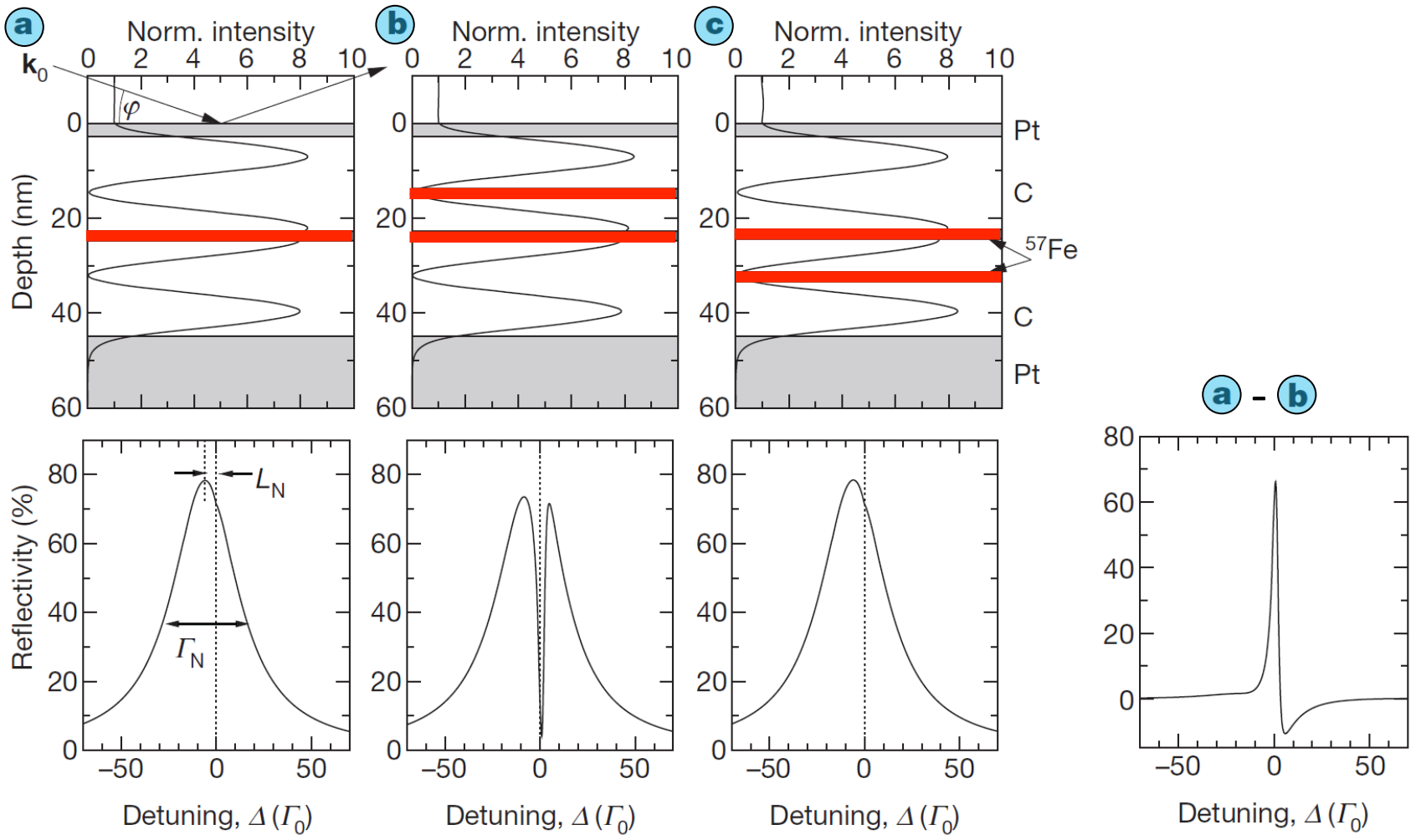
R.R., K. Schlage, B. Sahoo, S. Couet and R. Rüffer, **Science 328, 1248 (2010)**

Two resonant layers in a cavity !





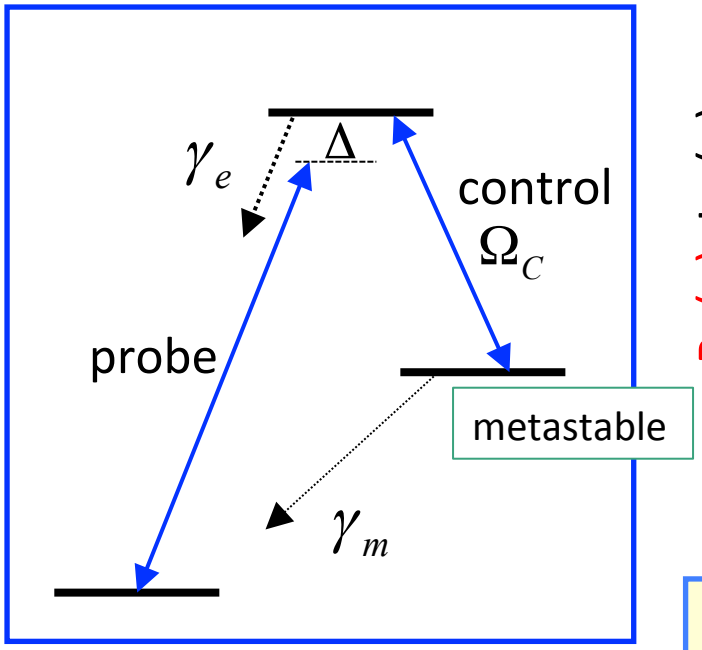
Superradiance in a Cavity and EIT

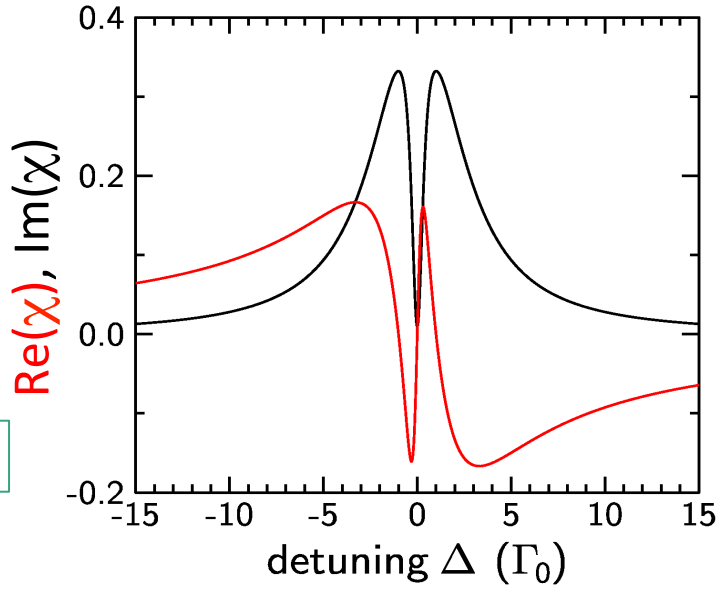


Fano – profile = Signature of EIT !

U. Fano, Phys. Rev. 124, 1866 (1961) Y. Li, M. Xiao, Phys. Rev. A 51, 4959 (1995)

Electromagnetically Induced Transparency (EIT)





M. Fleischhauer, A. Imamoglu, J. P. Marangos, Rev. Mod. Phys. 77, 633 (2005)

$$\chi(\Delta) = \frac{g^2 N(i\Delta + \gamma_m)}{(i\Delta + \gamma_m)(i\Delta + \gamma_e) + |\Omega_C|^2}$$

Rabi frequency

$$\hbar\Omega_C = \vec{\mu}\cdot\vec{E}_C$$

Cavity reflectivity

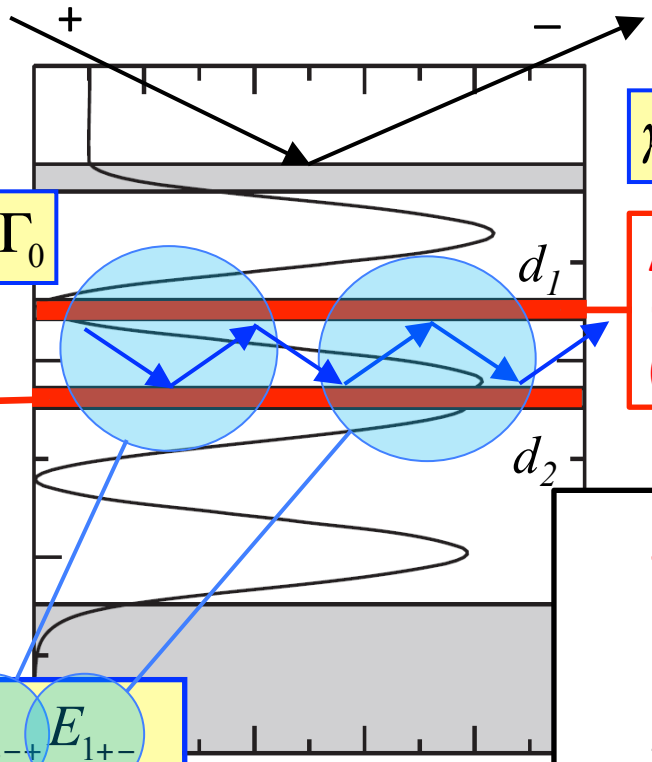
$$R(\Delta) = \frac{id_2 f_0 E_{2-+}(i\Delta + \Gamma_0)}{(i\Delta + \Gamma_0)(i\Delta + \Gamma_0[1 + d_2 f_0 E_{2--}]) + d_1 d_2 f_0^2 \Gamma_0^2 E_{2-+} E_{1+-}}$$

obtained via perturbation expansion in powers of the nuclear scattering amplitude f_N

$$f_N = \frac{i f_0 \Gamma_0}{i\Delta + \Gamma_0}$$

Interpretation

$$R(\Delta) = \frac{i d_2 f_0 E_{2-+}\left(i\Delta + \Gamma_0\right)}{\left(i\Delta + \Gamma_0\right)\left(i\Delta + \Gamma_0\left[1 + d_2 f_0 E_{2--}\right]\right) + d_1 d_2 f_0^2 \Gamma_0^2 E_{2-+} E_{1+-}}$$



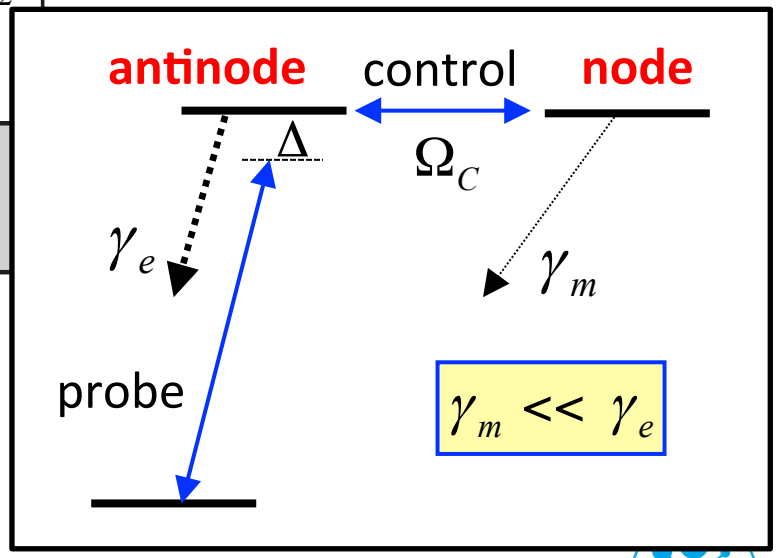
$\gamma_m = \Gamma_0$

$\gamma_e = \left[1 + d_2 f_0 E_{2--}\right]\Gamma_0$

Atoms in node → slow decay (subradiant)

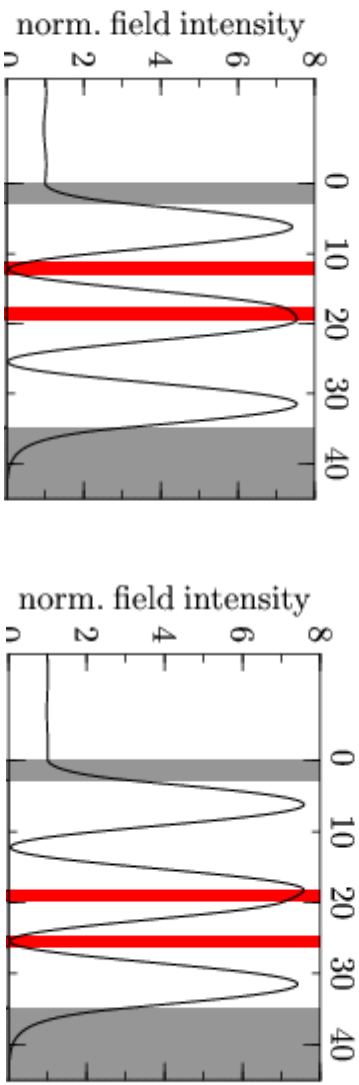
Atoms in antinode → fast decay (superradiant)

$\Omega_c^2 = d_1 d_2 f_0^2 \Gamma_0^2 E_{2-+} E_{1+-}$



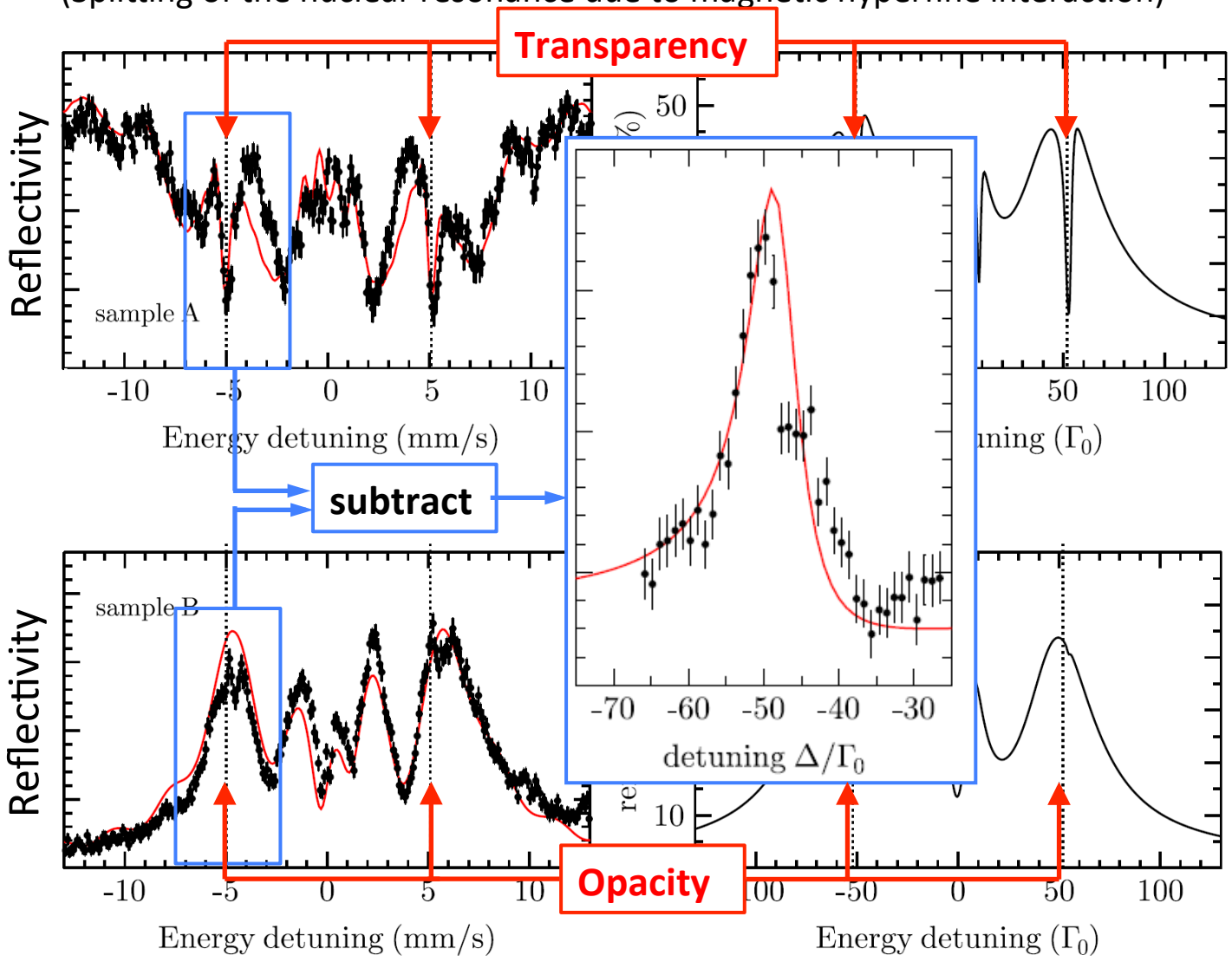
The control field Ω_C originates from the coupling between the atomic ensembles via the cavity field

Nuclear Resonant EIT in a Cavity: Experiment



Experiment performed at PETRA III, DESY, Hamburg (May 2011)

(Splitting of the nuclear resonance due to magnetic hyperfine interaction)



More details

Nature 482, 199 (2012)

LETTER

doi:10.1038/nature10741

Electromagnetically induced transparency with resonant nuclei in a cavity

Ralf Röhlsberger[1], Hans-Christian Wille[1], Kai Schlage[1] & Balaram Sahoo[1]

Summary and Outlook

- **EIT: Quantum Optics in the X-ray Regime with Nuclei**
- **X-ray Cavities/Waveguides:**

  - Convert 2-level into 3-level systems
  - Induce atomic coherence between levels
  - Laboratory to study dynamics of superradiant emission

- **The concept is generally applicable when an extra atomic level is needed**

Nuclear Quantum Optics

Exciting applications at existing and new light sources (PETRA III with 20 m undulator, XFELs)

- **Nonlinear optics, lasing without inversion, modeling quantum control**
- **Propagation of „slow light“ in waveguides under EIT conditions → Improve cavity design and coupling**

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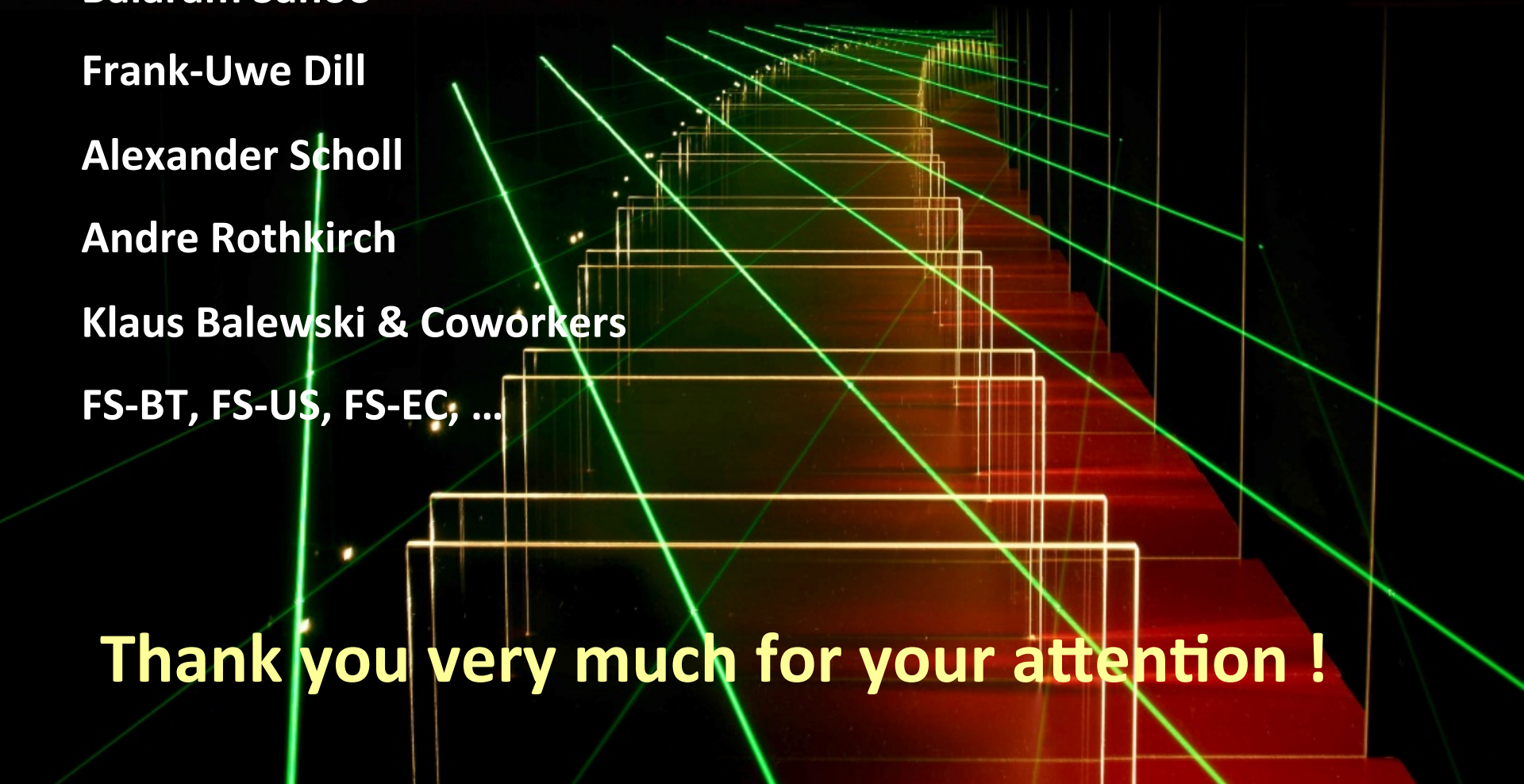
Texas A&M University, USA



Thank you very much for your attention !