# Back from the Future to the 1960's ……. and then back again:

# From Atomic Many-Body Physics to Quantum Computing

**Göran Wendin**
**Microtechnology and Nanoscience**
**Chalmers University of Technology**
**Gothenburg, Sweden**

# **MY personal** future: 2015 -….. ?

# **Unconventional computing**

# **UCOMP**

**Quantum, neuromorphic, …..**

The future: 2015 …..
Unconventional computing

**Back from the Future**
**to good old times,**
**the 1960's**

**Fano resonances &**
**Giant dipole resonances (GDR)**
**Multiphoton ionisation**
**1967-1987**

# Back from the Future …

**Lots of hard work in those days, exploring new avenues …..**

The future: 2015 ….
Unconventional computing

Fano resonances &
Giant dipole resonances (GDR)
Multiphoton ionisation
**1967-1987**

# The future: 2015 ….
# Unconventional computing

Carry-le-Rouet, 1975

Fano resonances &
Giant dipole resonances (GDR)
Multiphoton ionisation
**1967-1987**

**Back from the Future to 1975 ☺**

The future: 2015 ….
Unconventional computing

↓

Fano resonances &
Giant dipole resonances (GDR)
Multiphoton ionisation
1967-1987

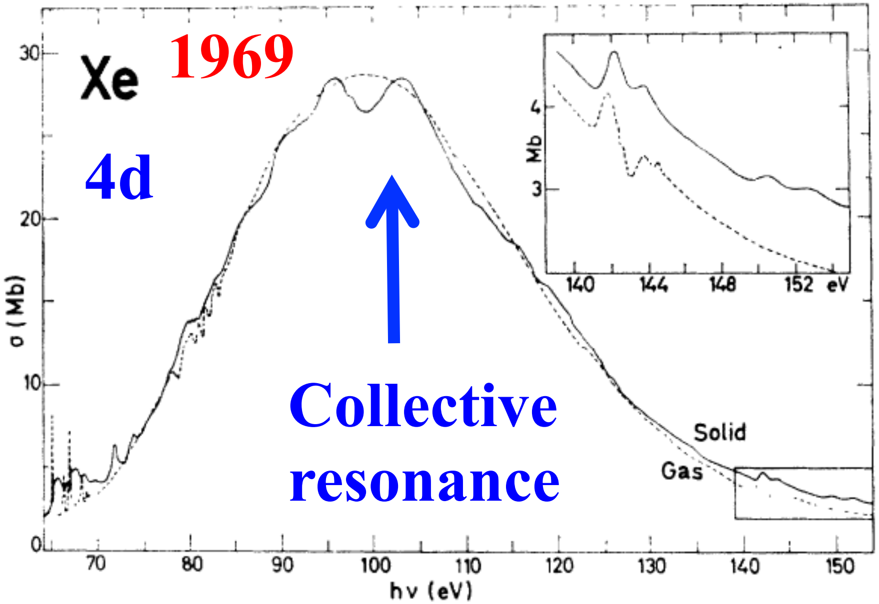
↓

**Giant dipole resonances (GDR) once more.**
**Multiphoton ionisation**

**!!!**
☺

**Well ………**
**back again**
**to 2015 ….**
**And back to the Roots!!**

# 1969 → 2015



1969

4d

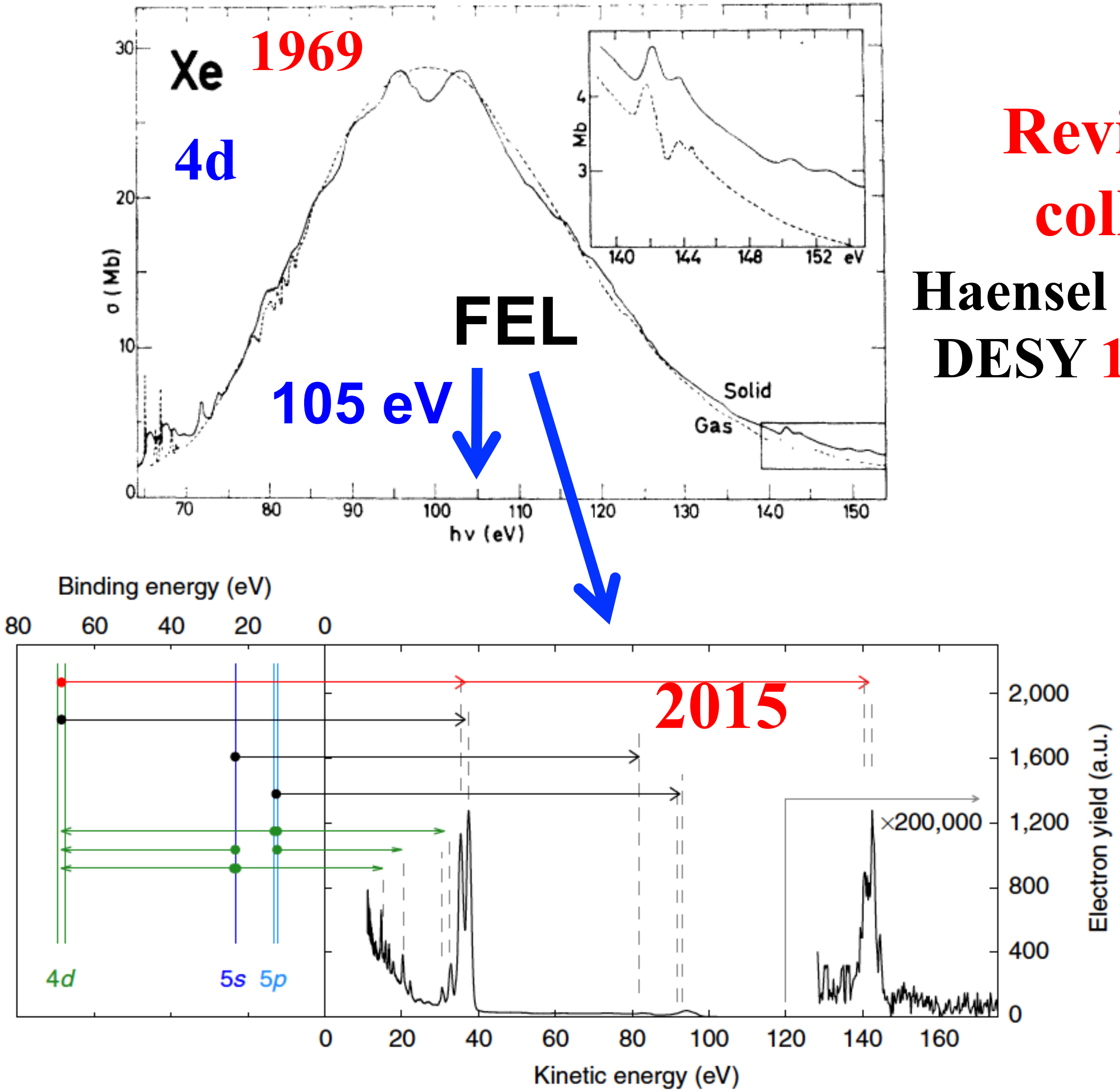
Collective resonance

## 1969 → 2015
## Reviving the Xe GDR
## collective resonance

**Haensel et al.**
**DESY 1969**

**Synchrotron radiation**

# 1969 → 2015



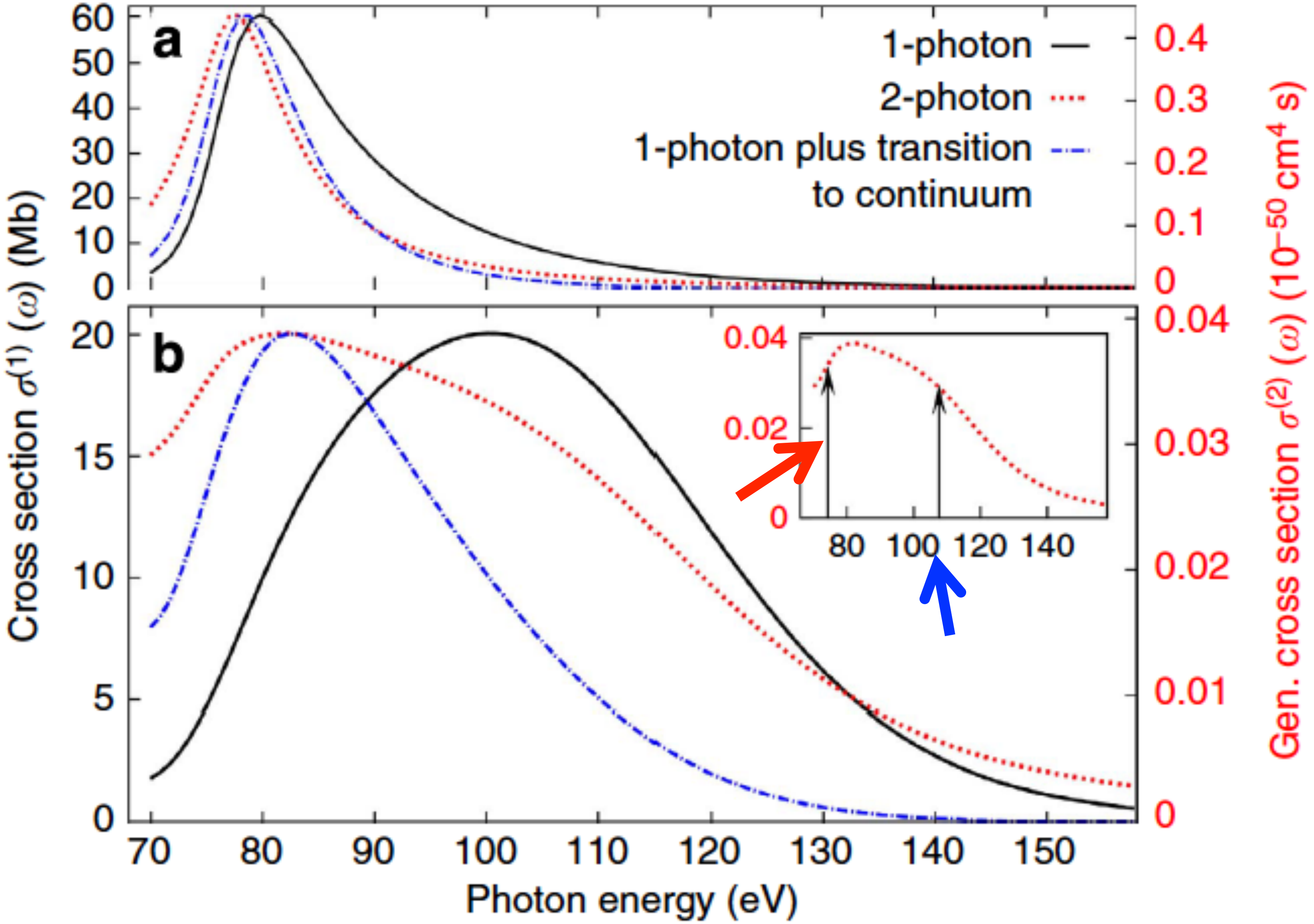
## 1969 → 2015
## Reviving the Xe GDR collective resonance

Haensel et al.
DESY 1969

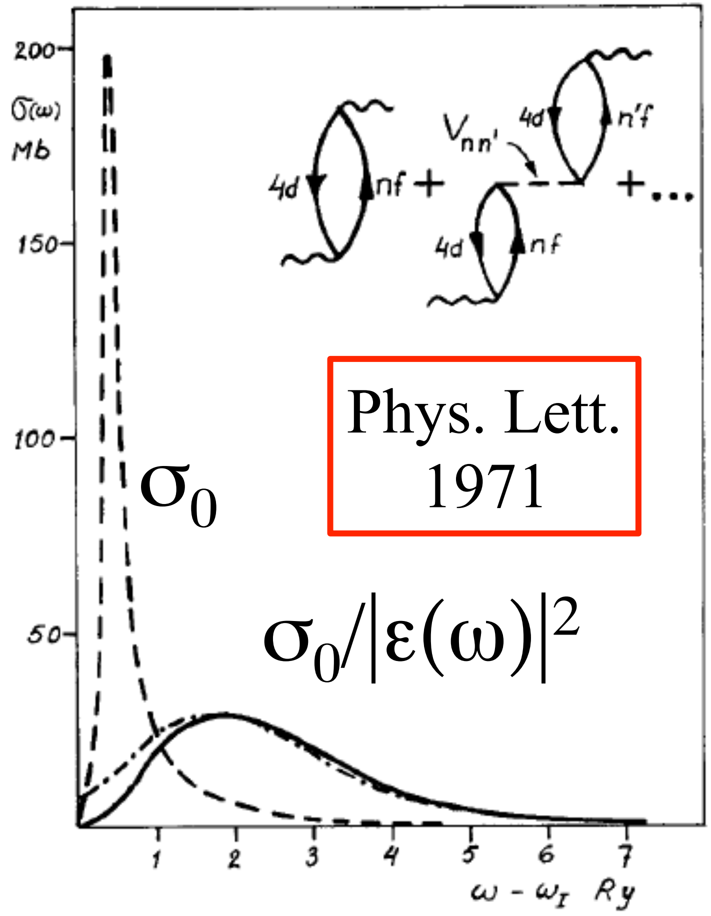
Santra et al.
DESY 2015
Xe 4d
2-photon 1 electron ionisation
FEL
105 eV
TOF $Xe^+$

# 1 or 2 collective resonances ??

## Santra et al. DESY 2015, Theory TDCIS



# COLLECTIVE RESONANCE IN THE 4d 10 SHELL IN ATOMIC Xe



$\sigma_0$

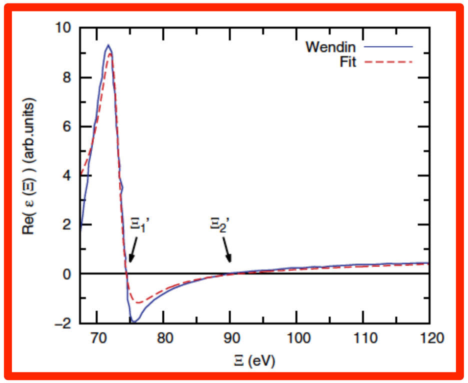
$\sigma_0/|\varepsilon(\omega)|^2$

Phys. Lett. 1971

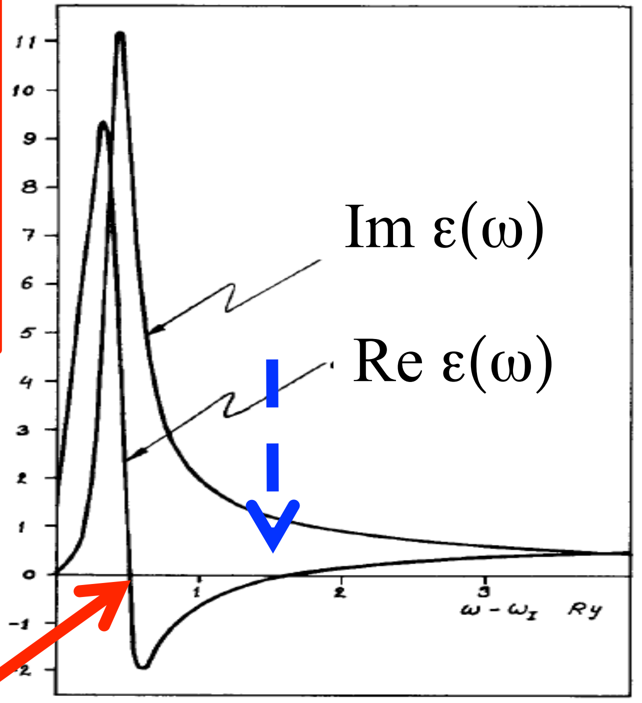
Fig.2. Photoabsorption cross section for the $4d^{10}$ shell in Xe. --- Single particle approximation (first diagram); —— RPAE (sum of diagrams to infinite order); -·-·- Experiment.

$$r(\omega) = r/\epsilon(\omega)$$

$$\epsilon(\omega) = 1 + \sum_{n,j} \frac{C_{nj} V_{njjn}}{(\omega_{nj}^2 - \omega^2)/2\omega_{nj}}$$



**Santra et al. 2015**

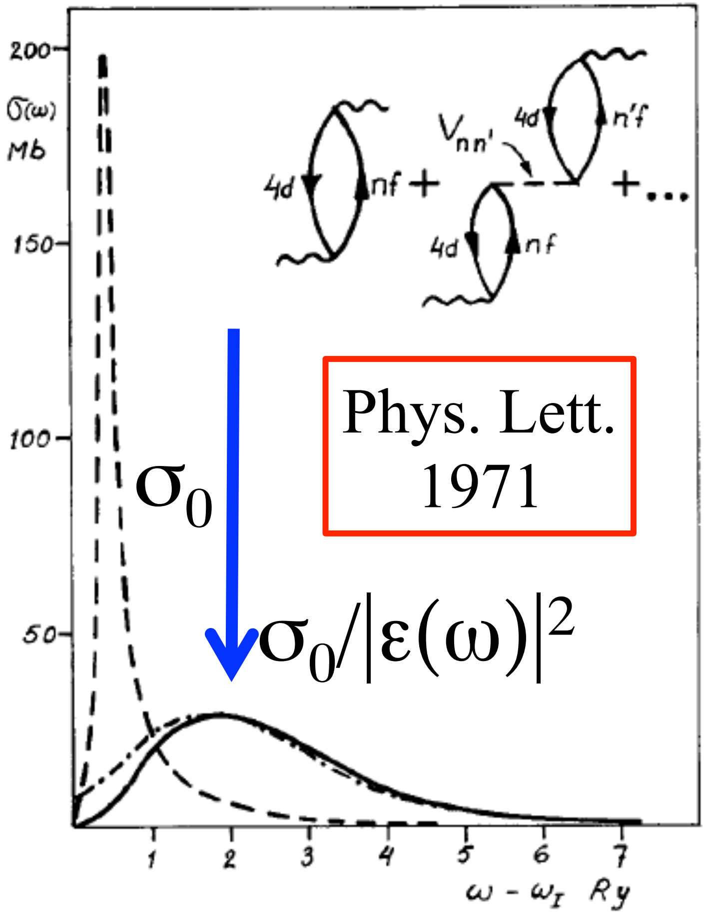


Im ε(ω)

Re ε(ω)

$$\sigma \sim \omega\ |\langle 4d|\ r(\omega)\ |\varepsilon f\rangle|^2$$

# COLLECTIVE RESONANCE IN THE 4d 10 SHELL IN ATOMIC Xe



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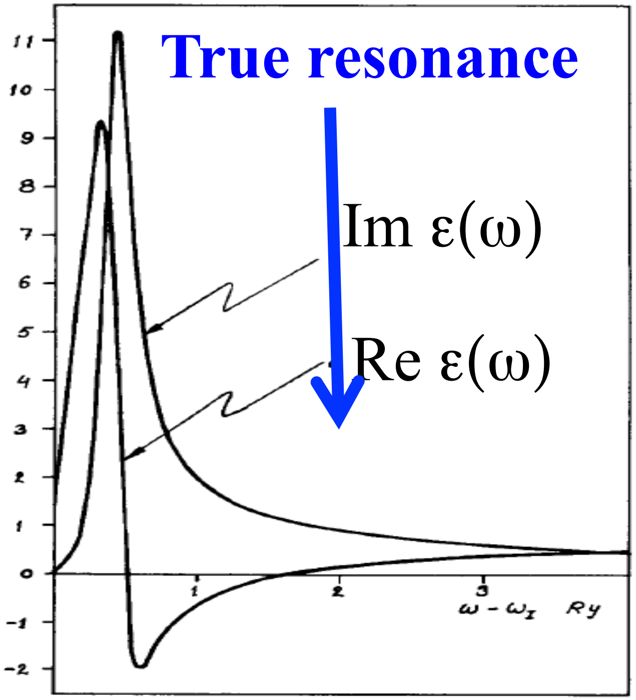
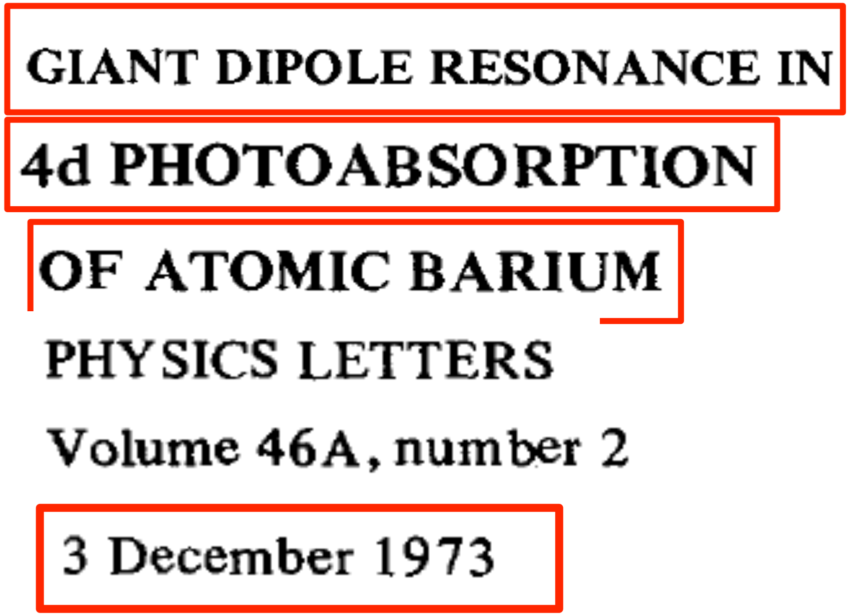


**True resonance**

Im ε(ω)

Re ε(ω)

# Giant dipole resonance



GIANT DIPOLE RESONANCE IN

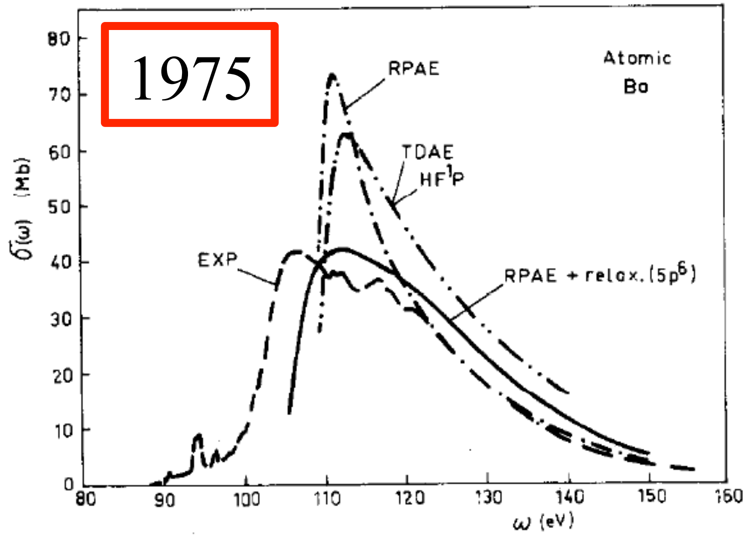
4d PHOTOABSORPTION

OF ATOMIC BARIUM

PHYSICS LETTERS

Volume 46A, number 2

3 December 1973

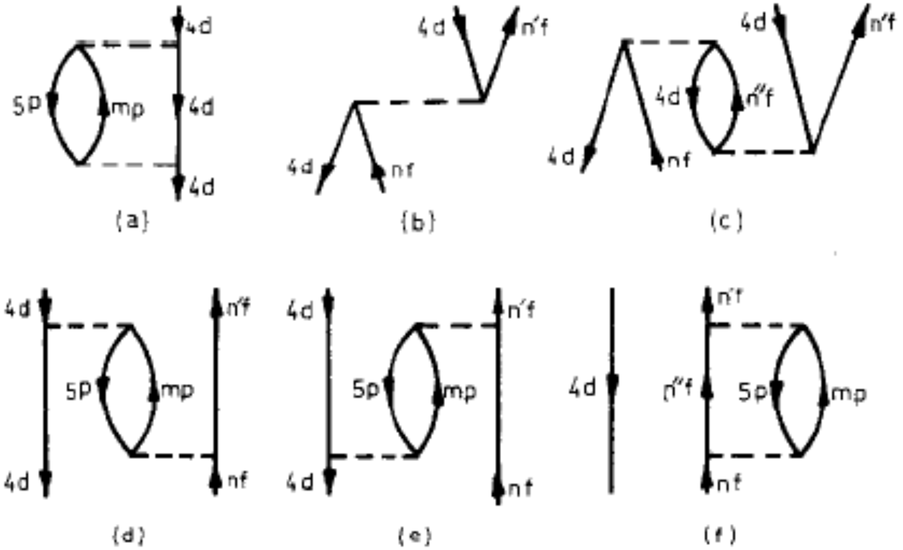


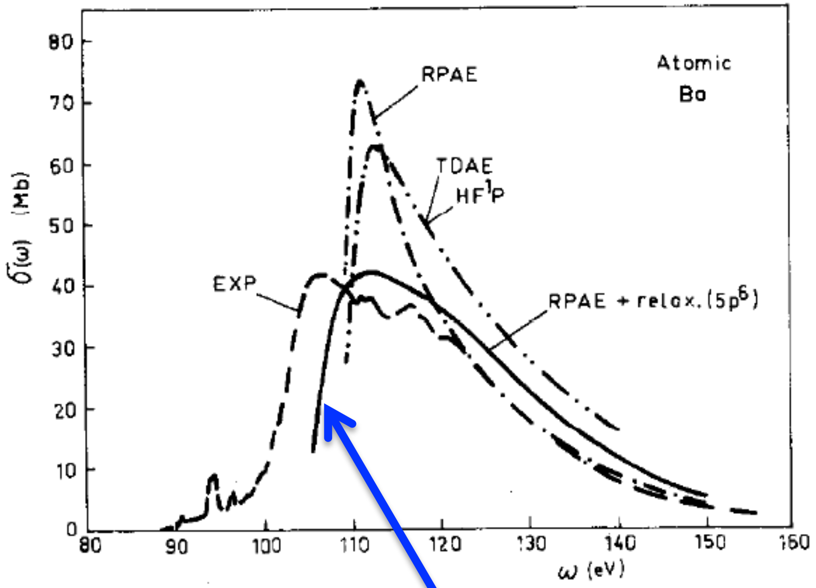
1975

Introduction of the concept of
atomic Giant Dipole Resonance;
Cocept borrowed from nuclear physics
Collective effects from solid-state and plasma physics

# 4d Ba RPAE + 5p-relaxation 1975

**4d-f singles + 4d5p-fp doubles → "TDCISD"**





4d-f RPAE
+ 5p6
relaxation

$$V_{nn'}(\omega) = V_{nn'} - \sum_{n''} \frac{V_{nn''}V_{n''n'}(\omega)}{\omega_{n''} - \omega - \Sigma(\omega_{n''} - \omega)}$$

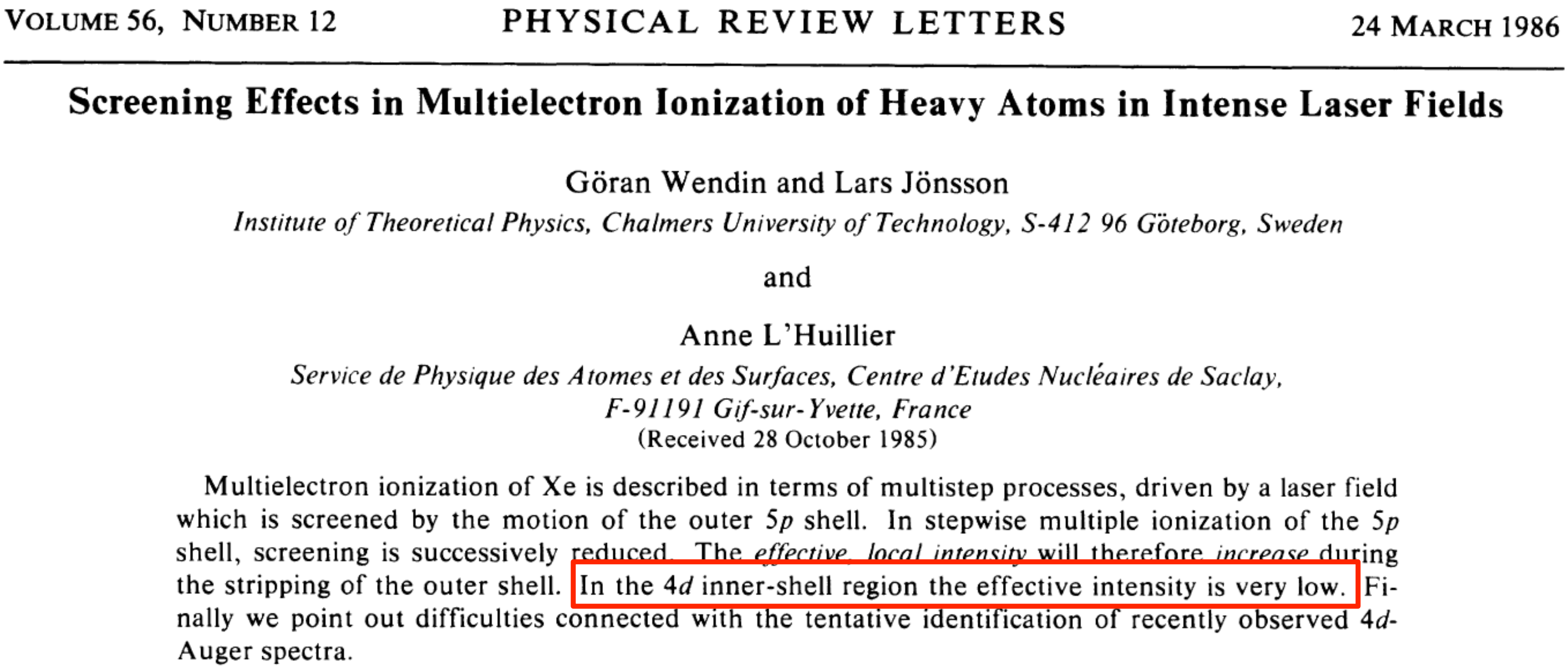
# Journal of Physics B: Atomic and Molecular Physics Volume 11 Number 24

1978

# Perturbation theory in a strong-interaction regime with application to 4d-subshell spectra of Ba and La

**G Wendin and A F Starace**

# Screening in multi-photon ionisation



VOLUME 56, NUMBER 12 PHYSICAL REVIEW LETTERS 24 MARCH 1986

## Screening Effects in Multielectron Ionization of Heavy Atoms in Intense Laser Fields

Göran Wendin and Lars Jönsson
*Institute of Theoretical Physics, Chalmers University of Technology, S-412 96 Göteborg, Sweden*

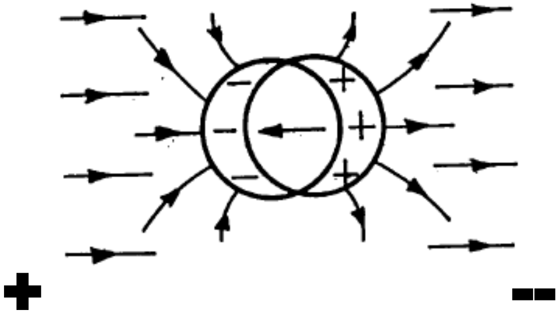
and

Anne L'Huillier
*Service de Physique des Atomes et des Surfaces, Centre d'Etudes Nucléaires de Saclay,*
*F-91191 Gif-sur-Yvette, France*

(Received 28 October 1985)

Multielectron ionization of Xe is described in terms of multistep processes, driven by a laser field which is screened by the motion of the outer $5p$ shell. In stepwise multiple ionization of the $5p$ shell, screening is successively reduced. The *effective, local intensity* will therefore *increase* during the stripping of the outer shell. In the $4d$ inner-shell region the effective intensity is very low. Finally we point out difficulties connected with the tentative identification of recently observed $4d$-Auger spectra.

$$\mathbf{E}\cdot\mathbf{r}(\omega)=\mathbf{E}\cdot\mathbf{r}-\sum_{n,j}\frac{\langle j\,|\,1/r_{12}\,|\,n\,\rangle\langle n\,|\,\mathbf{E}\cdot\mathbf{r}(\omega)\,|\,j\,\rangle}{(\omega_{nj}^2-\omega^2)/2\omega_{nj}}$$



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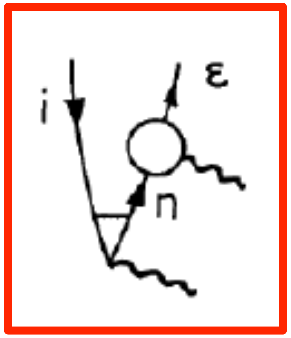
# Screening in multi-photon ionisation

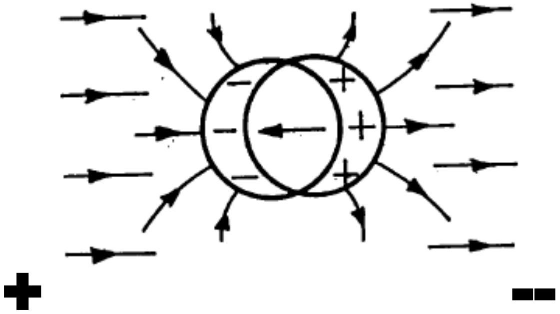
$$t^{c}_{\varepsilon i}(\omega)=\sum_{n}\frac{\langle \varepsilon\,|\,\mathbf{E}\cdot\mathbf{r}(\omega)\,|\,n\rangle\langle n\,|\,\mathbf{E}\cdot\mathbf{r}(\omega)\,|\,i\rangle}{\omega_{ni}-\omega}$$



$$\mathbf{E}\cdot\mathbf{r}(\omega)=\mathbf{E}\cdot\mathbf{r}-\sum_{n,j}\frac{\langle j\,|\,1/r_{12}\,|\,n\rangle\langle n\,|\,\mathbf{E}\cdot\mathbf{r}(\omega)\,|\,j\rangle}{(\omega_{nj}^{2}-\omega^{2})/2\omega_{nj}}$$

$$\mathbf{E}\cdot\mathbf{r}(\omega)=\mathbf{E}\cdot\mathbf{r}-\sum_{n,j}\frac{\langle j\,|\,1/r_{12}\,|\,n\rangle\langle n\,|\,\mathbf{E}\cdot\mathbf{r}\quad|\,j\rangle}{(\omega_{nj}^{2}-\omega^{2})/2\omega_{nj}}\;/\epsilon(\omega)$$

$$\boxed{\epsilon(\omega)=1+\sum_{n,j}\frac{C_{nj}V_{njjn}}{(\omega_{nj}^{2}-\omega^{2})/2\omega_{nj}}}$$

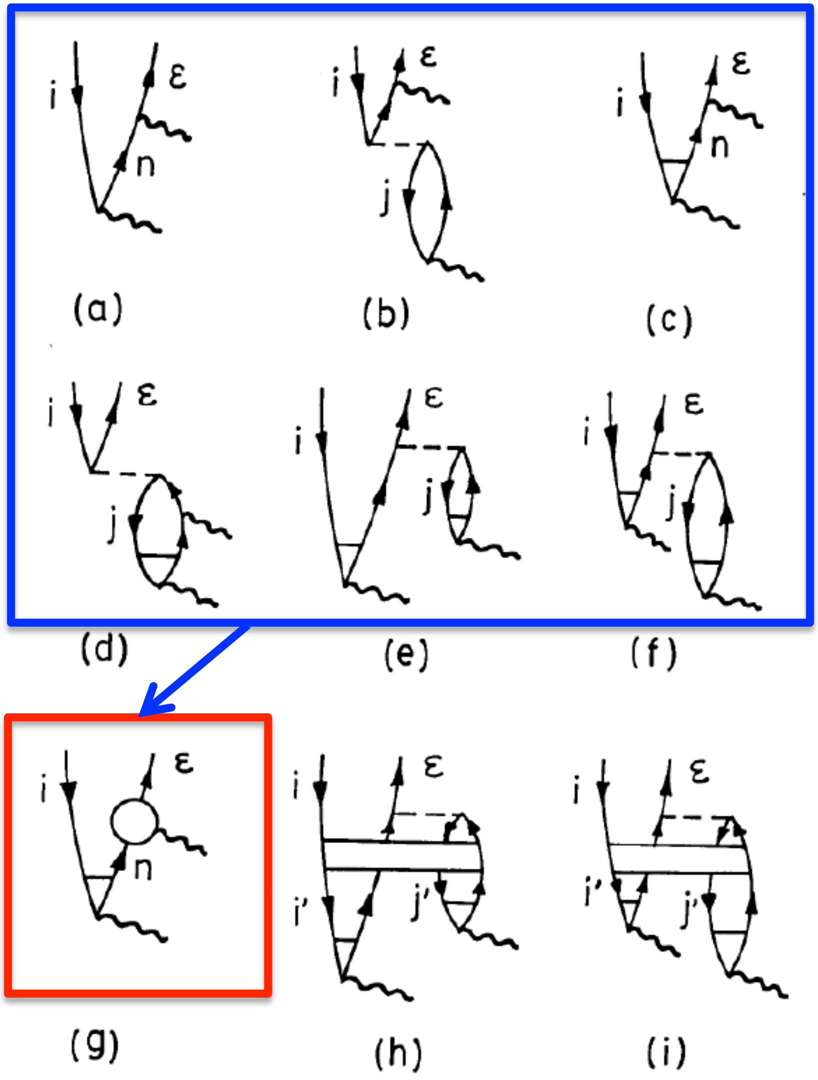


**Effective driving field/dipole op.**
**All e-ph vertices screened**

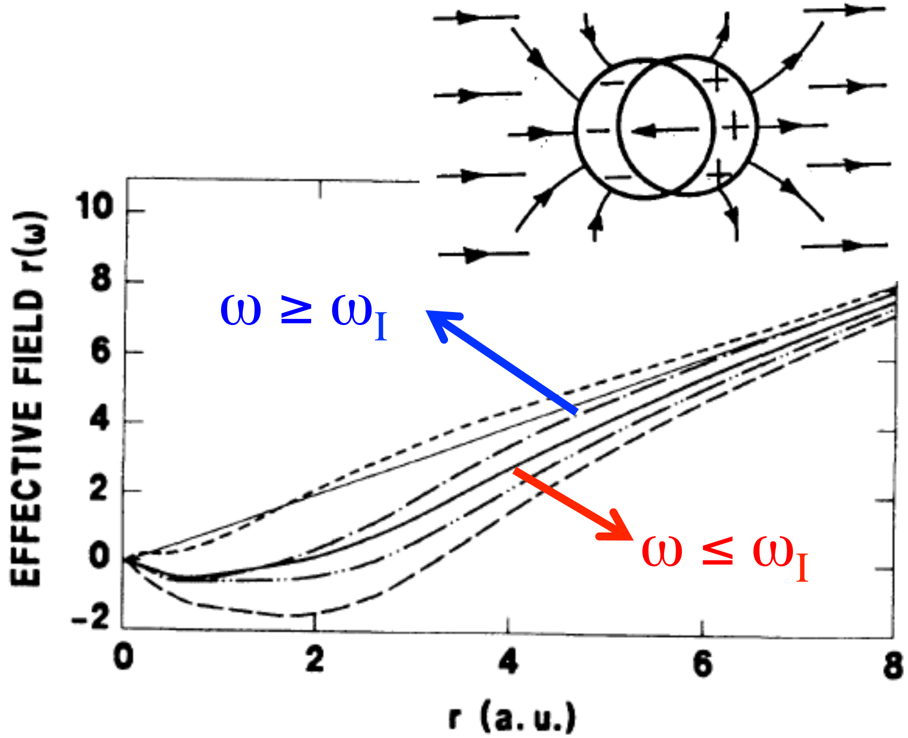
# Xe 5p 2-photon 1-electron ionisation

**with Anne L'Huillier & Lars Jönsson**

836 J. Opt. Soc. Am. B/Vol. 4, No. 5/May 1987



$$\mathbf{E}\cdot\mathbf{r}(\omega)=\mathbf{E}\cdot\mathbf{r}-\sum_{n,j}\frac{\langle j\,|\,1/r_{12}\,|\,n\,\rangle\langle\, n\,|\,\mathbf{E}\cdot\mathbf{r}(\omega)\,|\,j\,\rangle}{(\omega_{nj}^{2}-\omega^{2})/2\omega_{nj}}$$



$\omega \geq \omega_I$

$\omega \leq \omega_I$

# Xe 5p 2-photon 1-electron ionisation

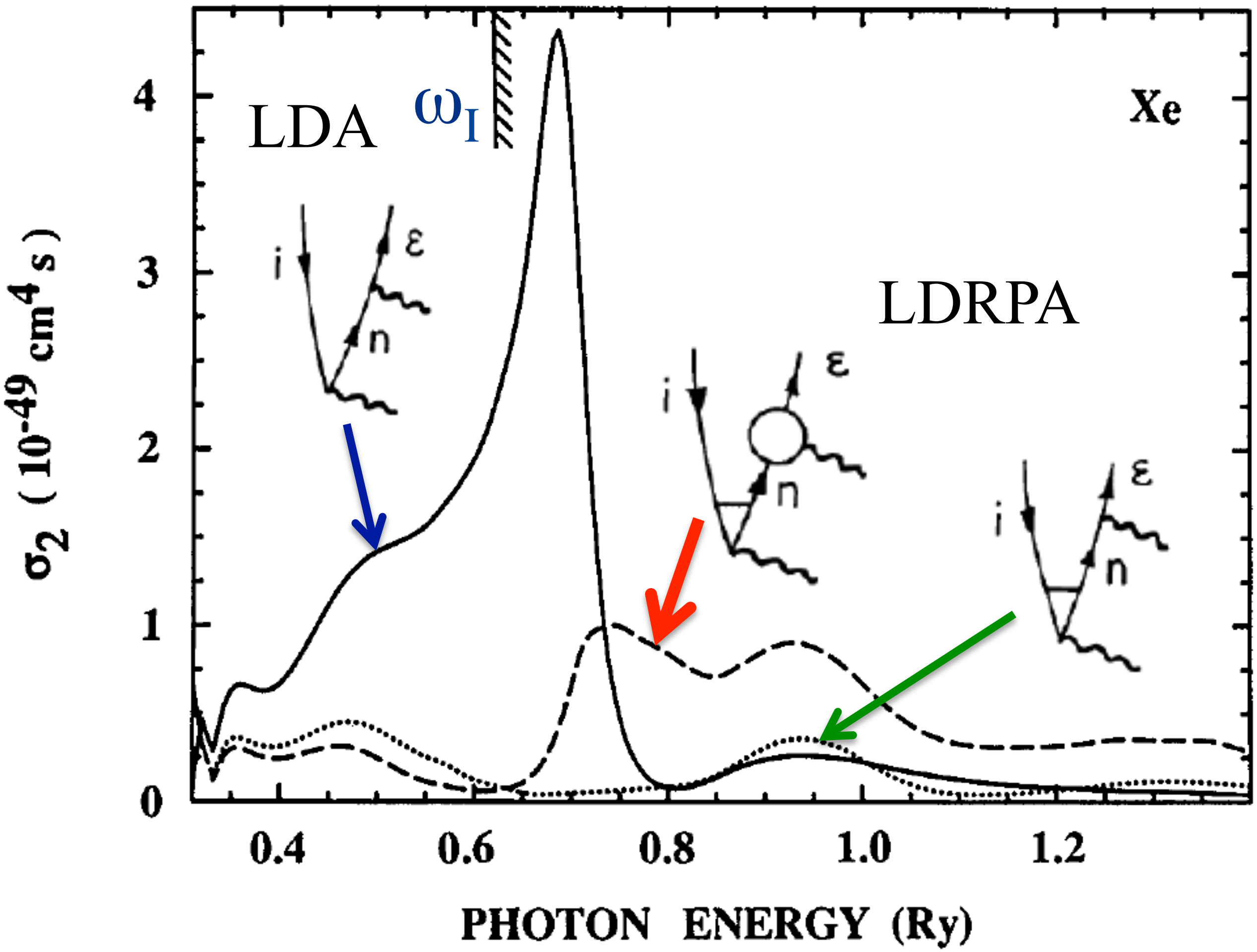


Fig. 3. Two-photon one-electron ionization cross sections of Xe (linear polarization): (—) independent-electron approximation (LDA), (– – – –) screened electron–photon interactions (LDRPA), (• • • • •) only the first interaction screened.

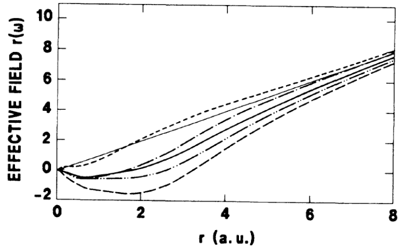
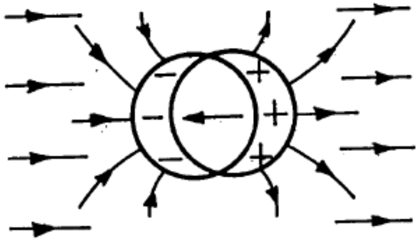
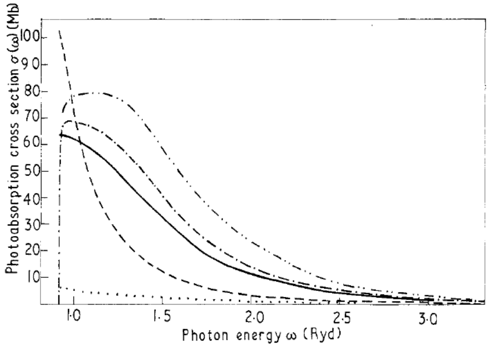
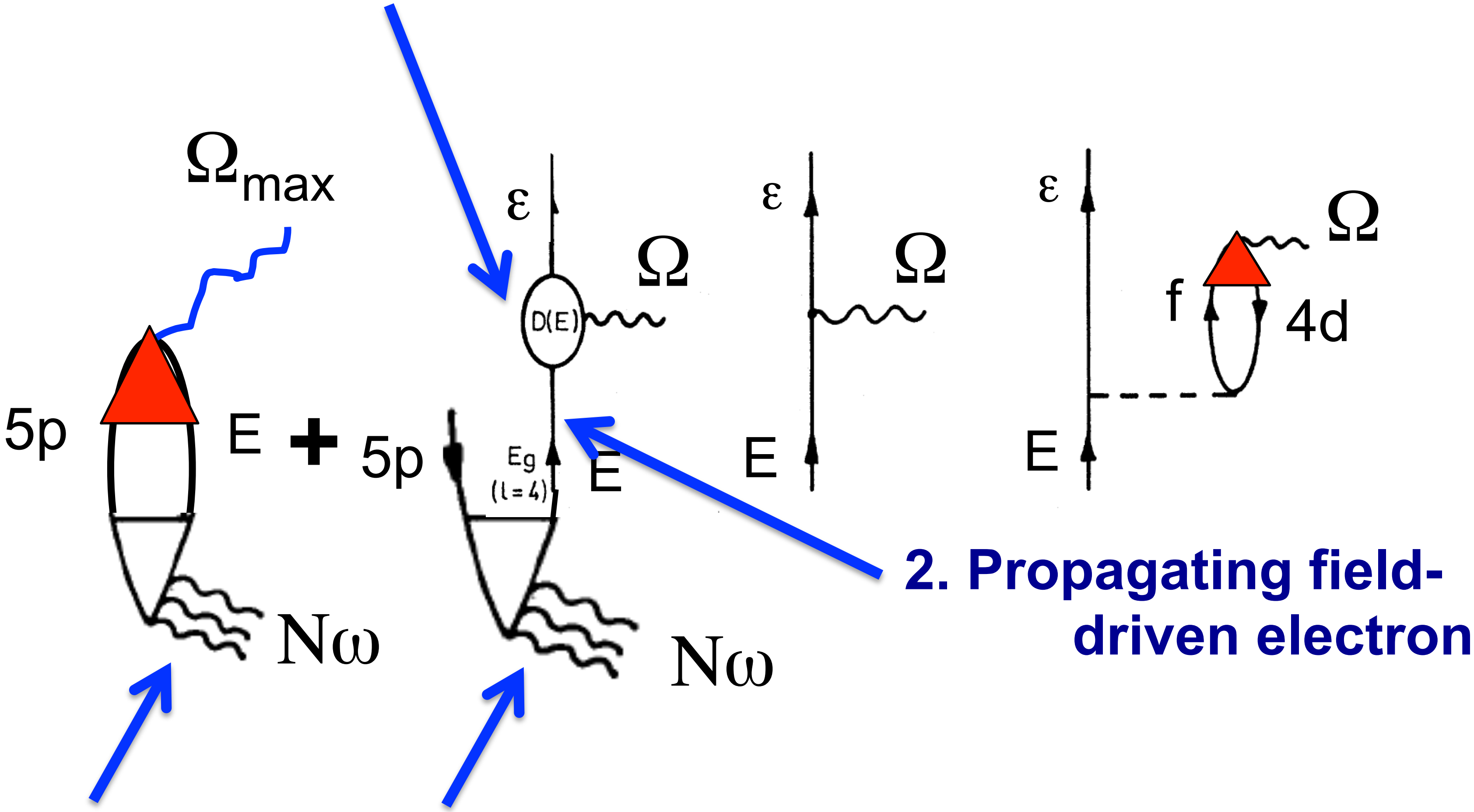


FIG. 5. Effective field $r(\omega)$ as a function of $r$ (in a.u.). (——), 0.31 Ry; (–··–··–··–), 0.6 Ry; (— — —), 0.7 Ry; (—·—·—·), 1 Ry; (-----), 1.5 Ry. Above 0.62 Ry, the real part of $r(\omega)$ is plotted.





# Canonical 3-step Harmonic Generation (HHG)

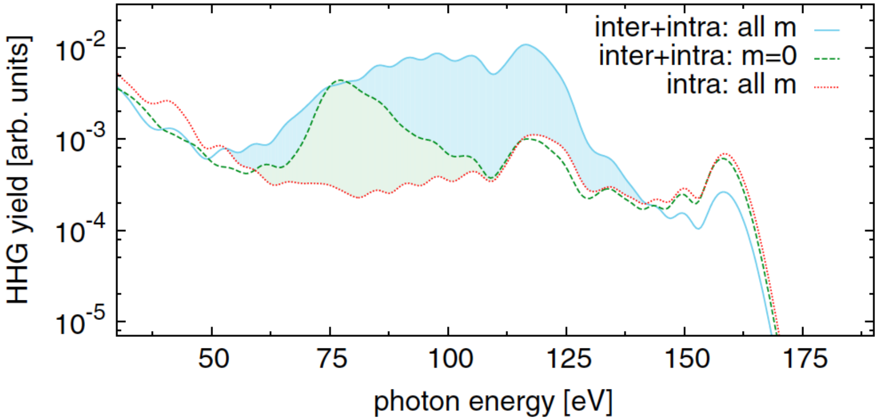


**3. (Resonant) radiative recombination:**

**2. Propagating field-driven electron**

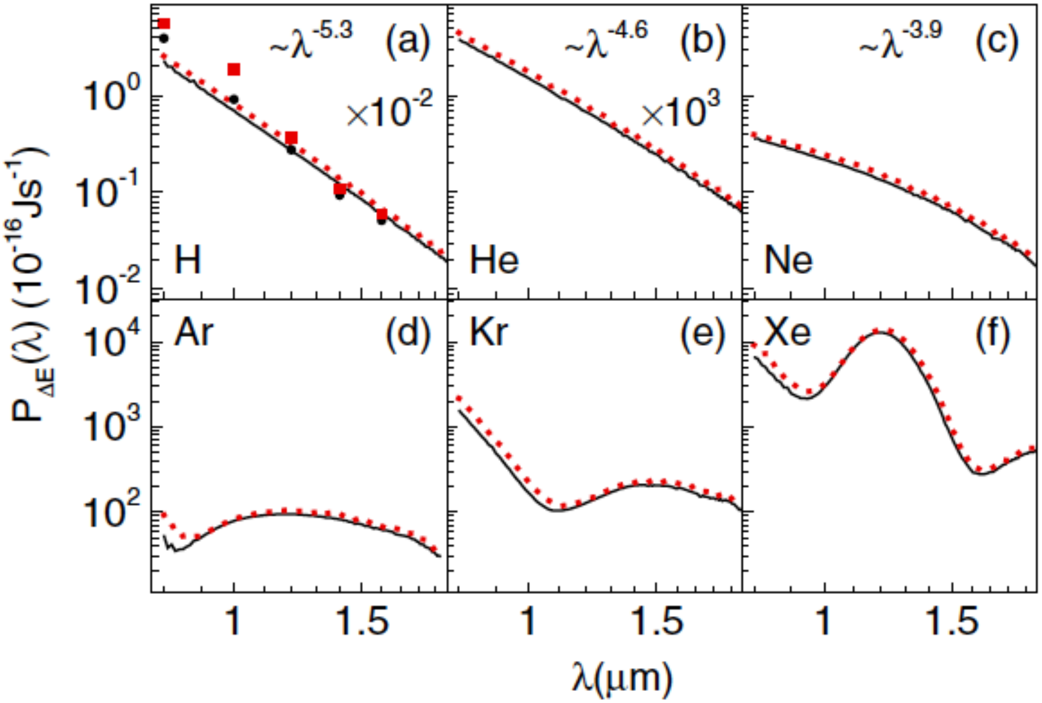
**1. Quasi-static Ponderomotive field ionisation**

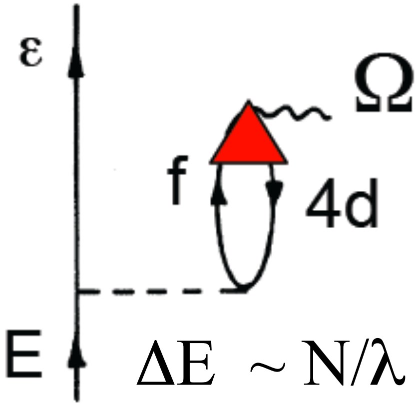
# HHG resonant enhancement



## HHG enhancement due to 4d-f collective resonance

Stefan Pabst and Robin Santra





Wendin: 4d-f collective resonance enhancement

**Left: Frolov, ..., Starace, PRL, 2009.**

# From Atomic Many-Body Physics to Quantum Computing

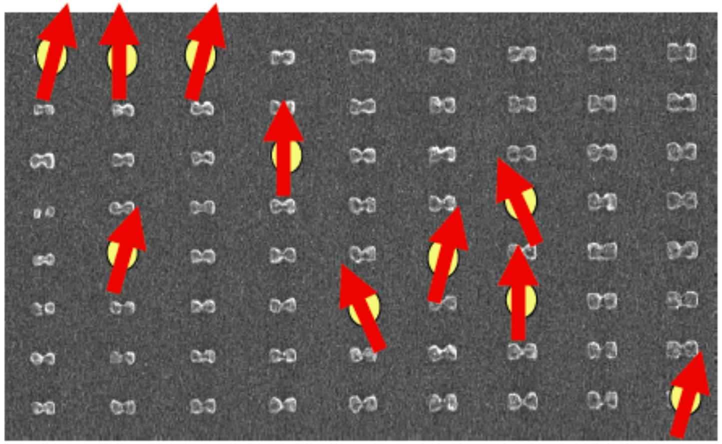
# Quantum computing challenges

- **Coherence**
- **Superposition**
- **Parallelism**
- **Entanglement**
- **Scaling up**
- **Beating Nature …..**

QC solves problems by generating and interpreting **dynamics of quantum wave patterns** in registers of quantum bits (qubits; ) – “quantum matter”

**Schrödinger cat problem:**
**Keeping a large quantum memory alive “forever”**

**Needs sophisticated technology**
**High-fidelity gate operations**
**Quantum Error Correction (QEC)**

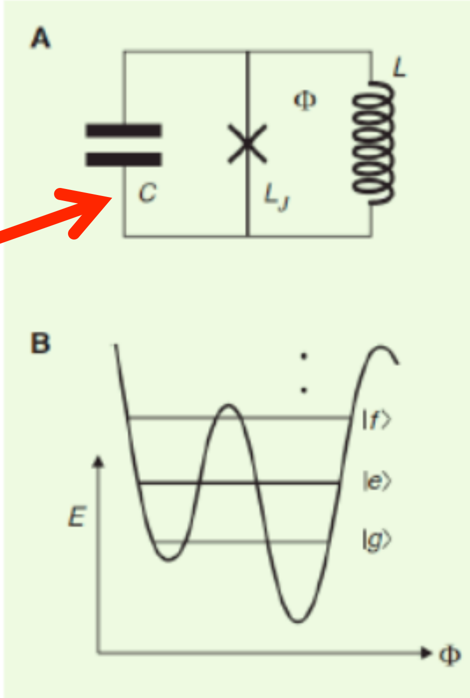


# Status of Quantum computing

## ♣ What are different types of quantum computers?

**Only small systems for proof-of-concept exist - "toy QC":**

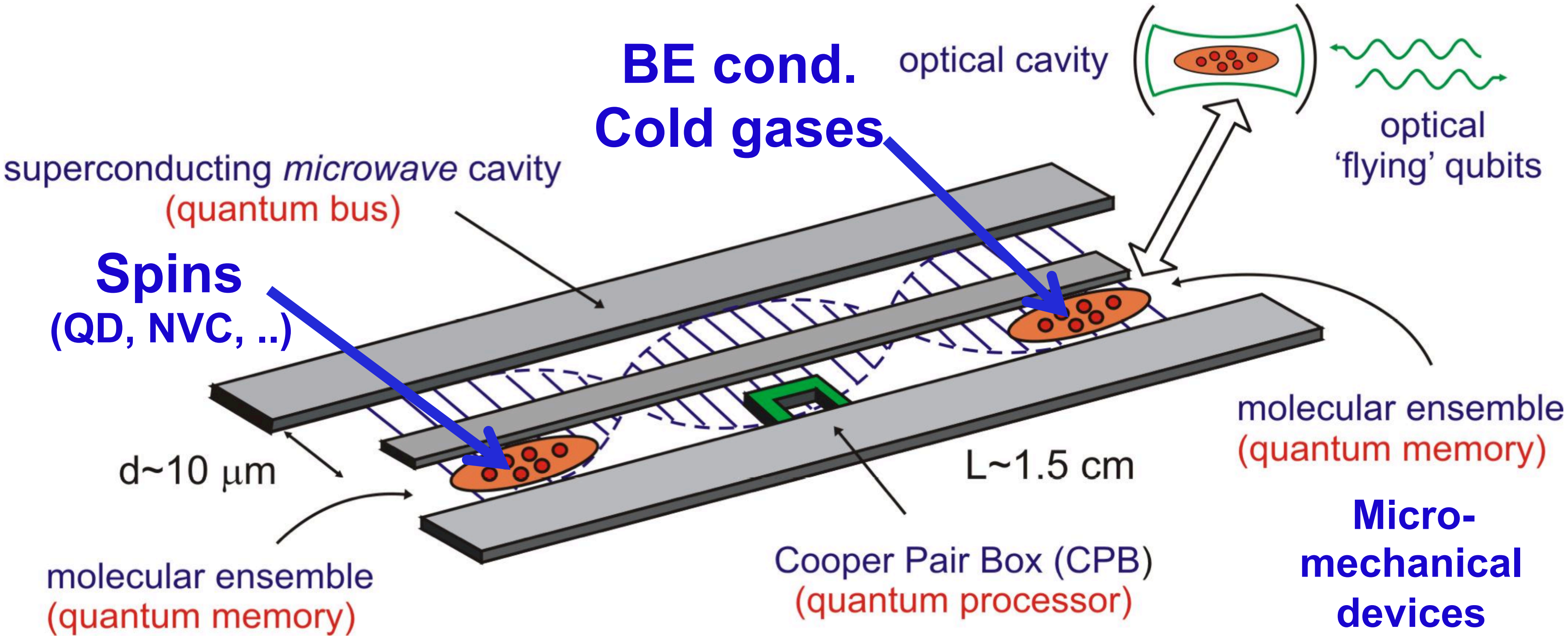
- NMR (12 qubits)
- Ion traps (14 qubits)
- Superconducting Transmon qubits-circuit-QED (9 qubits)
- Spins in diamond NV centers (6 qubits)
- Photonics (6 qubits?)



NOTE: The incoherent(?) D-Wave 1100 flux-qubit machine is not a QC – probably represents a QA (quantum annealer)

# Hybrid cavity/circuit QED

## Processing - memory – communication



**BE cond.**
**Cold gases**

**Spins**
**(QD, NVC, ..)**

**Micro-mechanical devices**

**Josephson junctions (JJ)**

**Picture adapted from Peter Zoller et al. (2005)**

# Applications

## ♣ What are the applications and implications of quantum computing?

**Short/medium term:**

**Optimisation, quantum annealing for Ising models**

**Simulation of problems in Physics beyond the reach of classical computers**

**Long-term:**

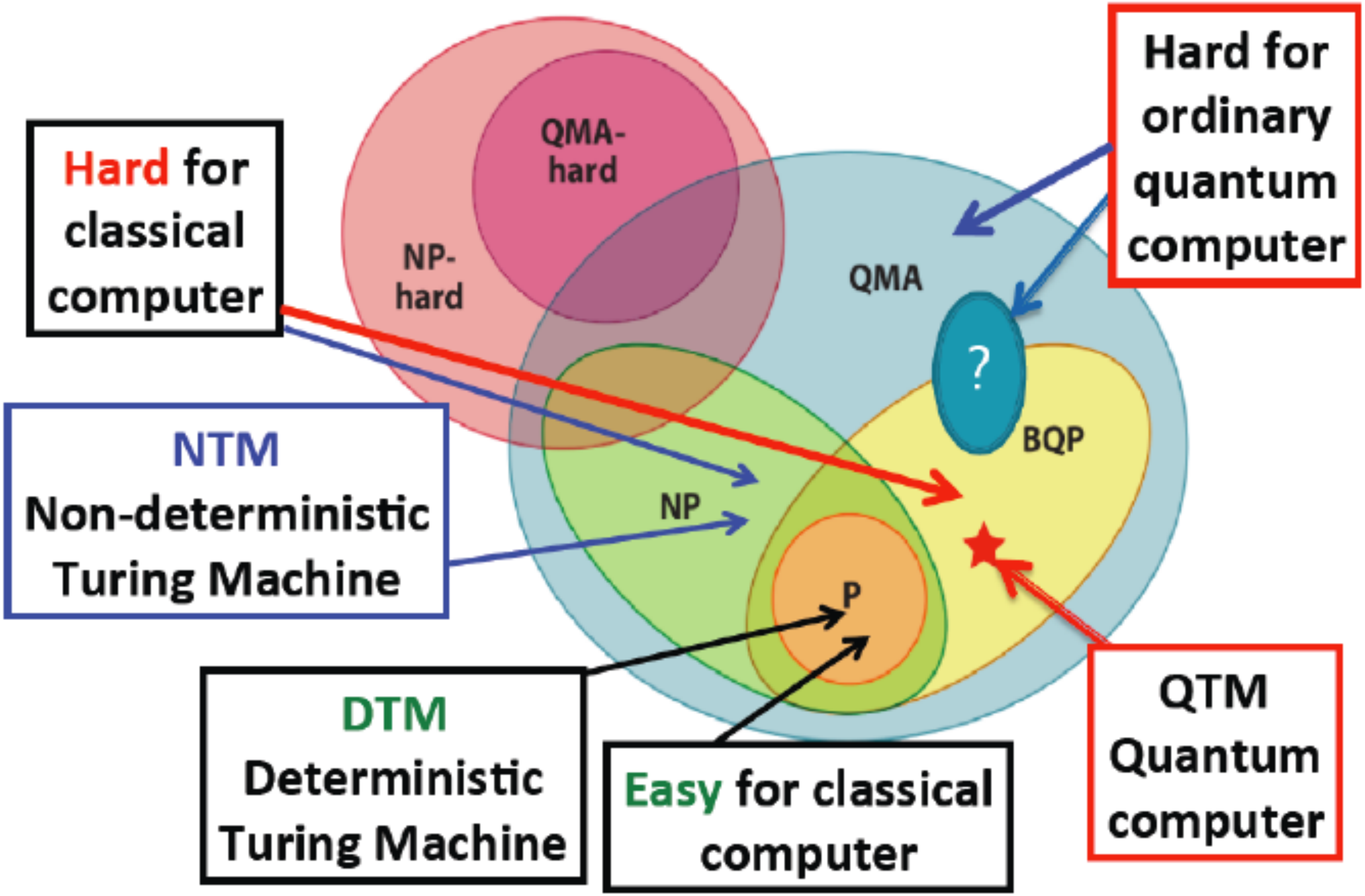
**Analog computing: simulation, Ising models, Chemistry, …**

**Digital computing:**

**Big data, search, machine learning ….**

**Simulation of problems in Chemistry and Materials science**

# Computational Complexity



**Hard** for classical computer

Hard for ordinary quantum computer

**NTM**
Non-deterministic Turing Machine

**DTM**
Deterministic Turing Machine

**Easy** for classical computer

QTM
Quantum computer

# Computational Complexity

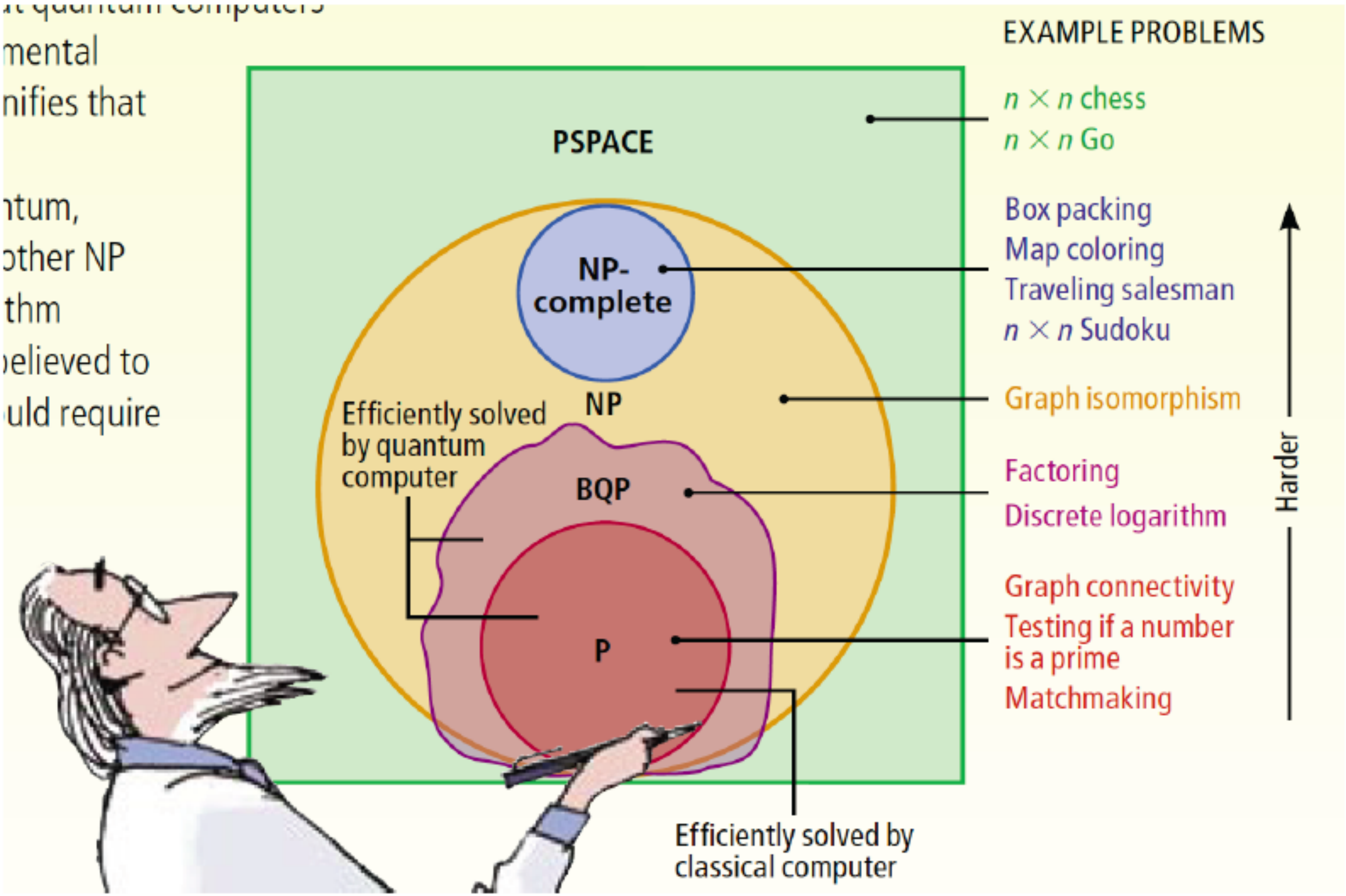
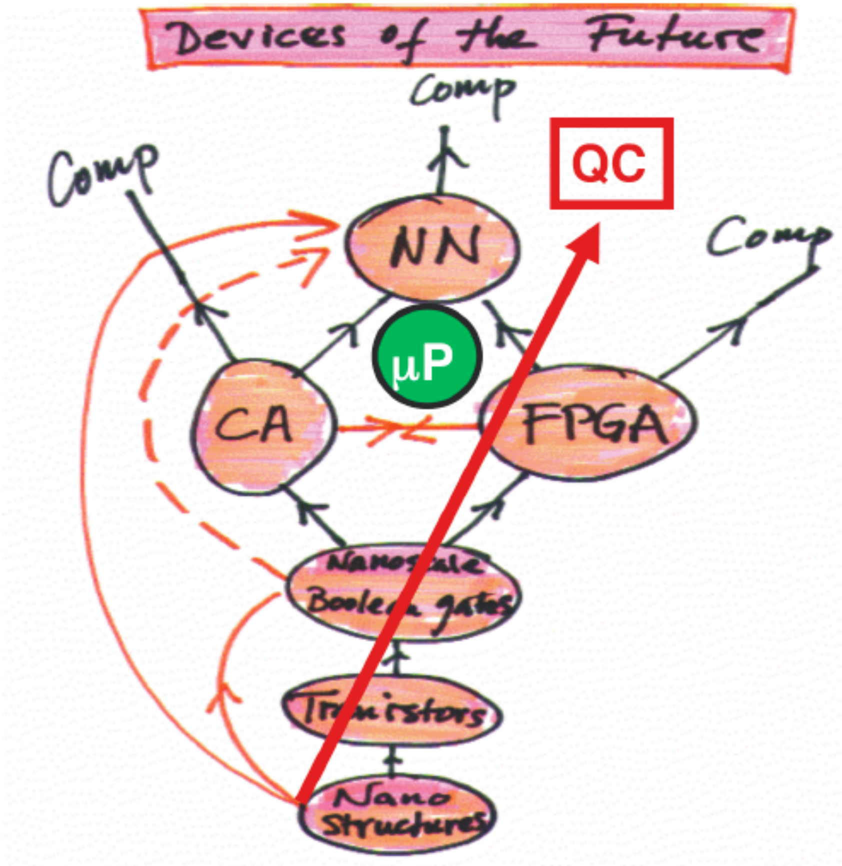


Figure 2: *Borrowed from Scott Aaronson, Sci. Am. 2005*

# Unconventional computing

## Unconventional Computation -- UCOMP

Hypercomputation = beyond Turing
quantum computing,
optical computing,
analogue computing,
chemical computing,
reaction-diffusion systems,
molecular computing,
biocomputing,
embodied computing,
amorphous computing,
self-assembling and
self-organising computers,
mem-computing



**Can UCOMP solve NP-hard problems ??**

# Solve NP-hard problems ????

There is a widespread(?) view that you can solve NP-hard problems with UCOMP .

E.g. the Adleman's DNA solution of the Travelling Salesman (TSP) problems in 1994 indeed solved a small NP-hard problem.

TSP an NP-hard problem, but it is all about SCALING and hard instances.

One way or another, ultimately you will need exponential resources (time or space).

Even for Quantum Computers.

# Solve NP-hard problems?

**So, there is a widespread view that you can solve NP-hard problems with UCOMP**

# Solve NP-hard problems? … hardly!!

But then there is also

**Wendin's Laws of Computing: ☺**

**"1st Law":**
**"You don't solve NP-hard problems unless you have an ORACLE giving you a solution to be verified."**

**"2nd Law":**
**"You don't have any ORACLE, and you will never get one".**

**"3rd Law":**
**Nature is physical and does not solve NP-hard problems**

# How come we exist …. ??

## The Problem:

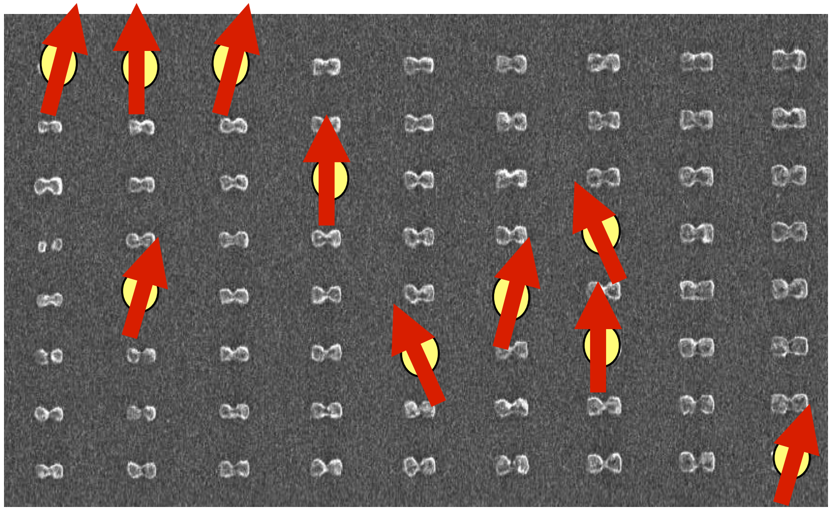
- Nature is physical and does not solve NP-hard problems
- Many physical problems are NP-hard (e.g. the exact ground state wave function of a molecule, or the exact Kohn-Sham density functional.
- The Brain (?)

## How come we exist … ??

I guess Nature is

- An analog "computer/simulator"
- Optimising things
- Providing approximate solutions
- Evolution does the rest ….

# Qubit register - both memory and processor



**Quantum computing means performing operations directly on the qubit memory:**

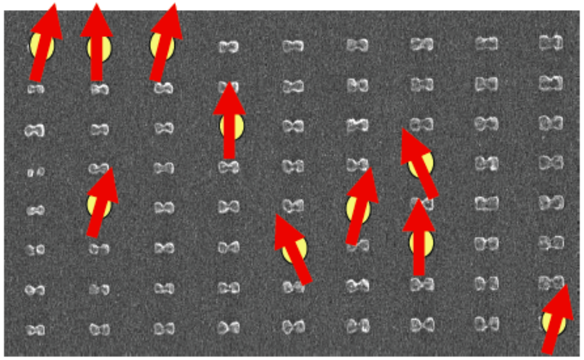
**Driving individual qubits with**
- static electric & magn. fields
- Microwave transmission lines
- lasers

**Coupling pairs of qubits by**
- hardwired circuits
- Driving/biasing fields switched on and off

**Reading out the state of a selection of qubits (memory) by**
- switching on and off coupling to measurement devices

**Digital QC: Gate operations, protocols, algorithms**
**Analog QC: Optimization – toward minimum in energy landscape**

# Qubit register - both memory and processor



**Digital QC:** Gate operations, protocols, algorithms

**Analog QC:** Optimization – toward minimum in energy landscape

$$\hat{H}(t) = \hat{H}_{syst}(t) + \hat{H}_{noise}(t) + \hat{H}_{ctrl}(t)$$

$$\hat{H}_{syst}(t) = -\frac{1}{2}\sum_{\nu i}\Delta_i(t)\,\sigma_{zi} + \sum_i g_i(t)\,\sigma_{xi}\,(a + a^+)$$

$$+\frac{1}{2}\sum_{i,j;\nu}\lambda_{\nu,ij}(t)\,(\sigma_{+i}\sigma_{-j} + \sigma_{-i}\sigma_{+j})$$

$$\boxed{|\psi(t)\rangle = \hat{U}(t,t_0)|\psi(t_0)\rangle = e^{-\frac{i}{\hbar}\int_{t_0}^{t}\hat{H}(t')dt'}|\psi(t_0)\rangle}$$

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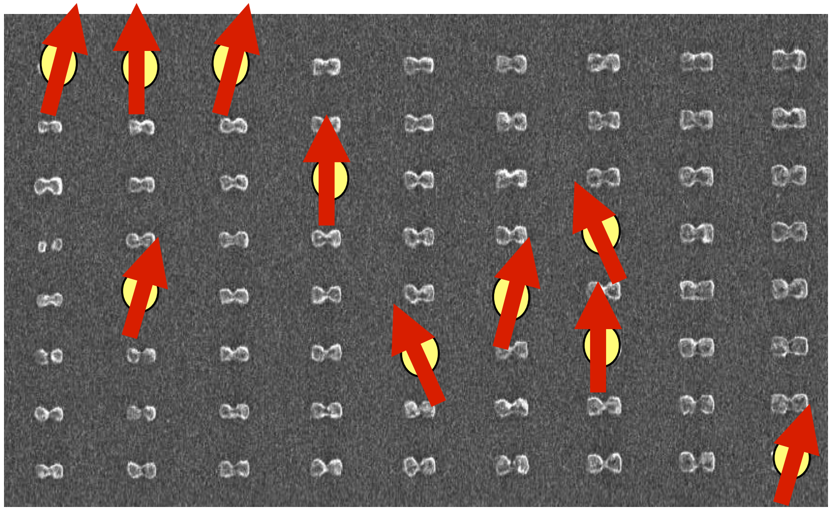
# Qubit memory register of spins (like e.g. in NMR)



**Classically:** ↑ or ↓ , 0 or 1

**Quantum:** ↑ and ↓ , $|0\rangle$ and $|1\rangle$

$|\psi\rangle = a_1$ ↑ $+ a_2$ ↓ = ↖ Linear superposition

$|\psi\rangle = a_1 |0\rangle + a_2 |1\rangle$ (vector sum)

N-(qu)bit register: $2^N$ configurations (e.g. 1 Byte, $2^8 = 256$ states)

Classically: One at a time: 0..00, or 0..01, or 0..10 , .. or 1..11

Quantum: Superposition of all $2^N$ configurations →

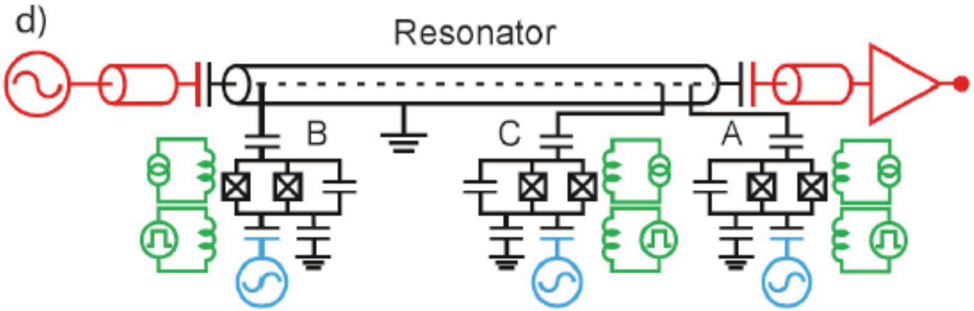
$|\psi\rangle = a_1 |0..00\rangle + a_2 |0..01\rangle + a_3 |0..10\rangle + \ldots + a_{(2^N-1)} |1..11\rangle$

(1 coher. state – 1 vector !!)

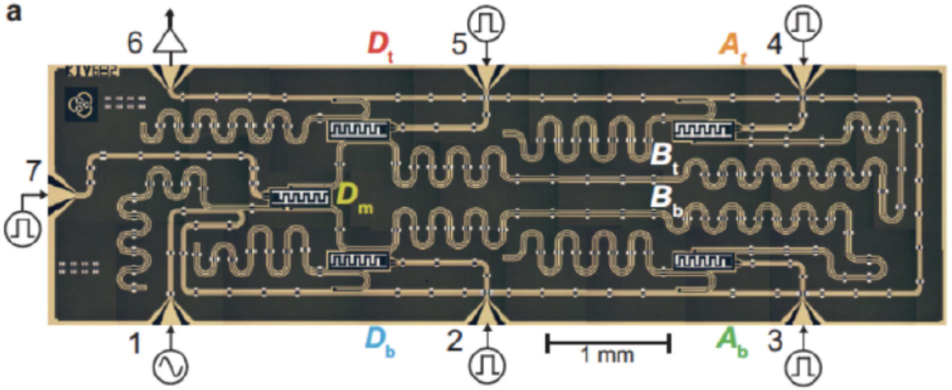
⇒ Coherence, superpostion, parallelism, entanglement

⇒ Non-classical correlations - ”spooky action at a distance”

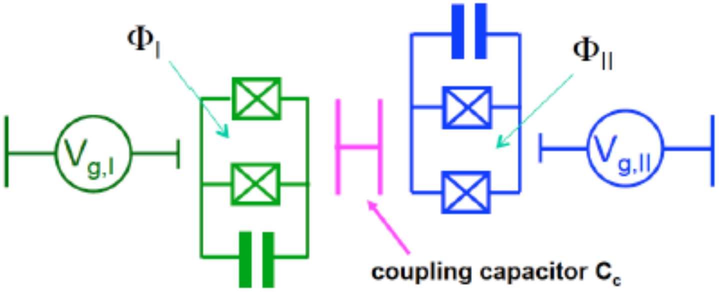
# Coupled transmon qubits



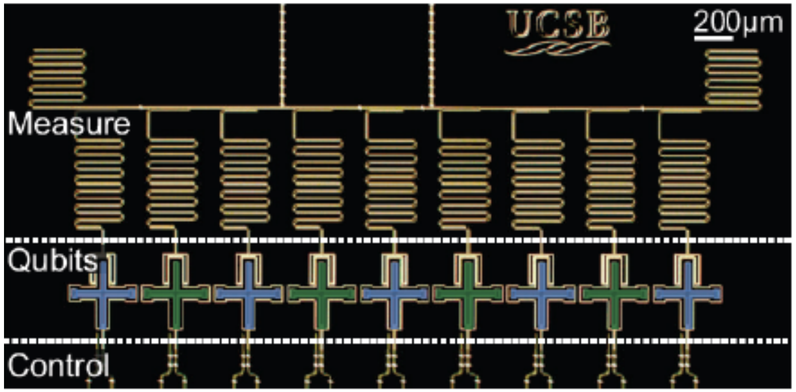
**3 Tmon-cQED**
**Circuit/cavity QED**
**Resonator coupling**



**DiCarlo group, TU Delft (2014)**



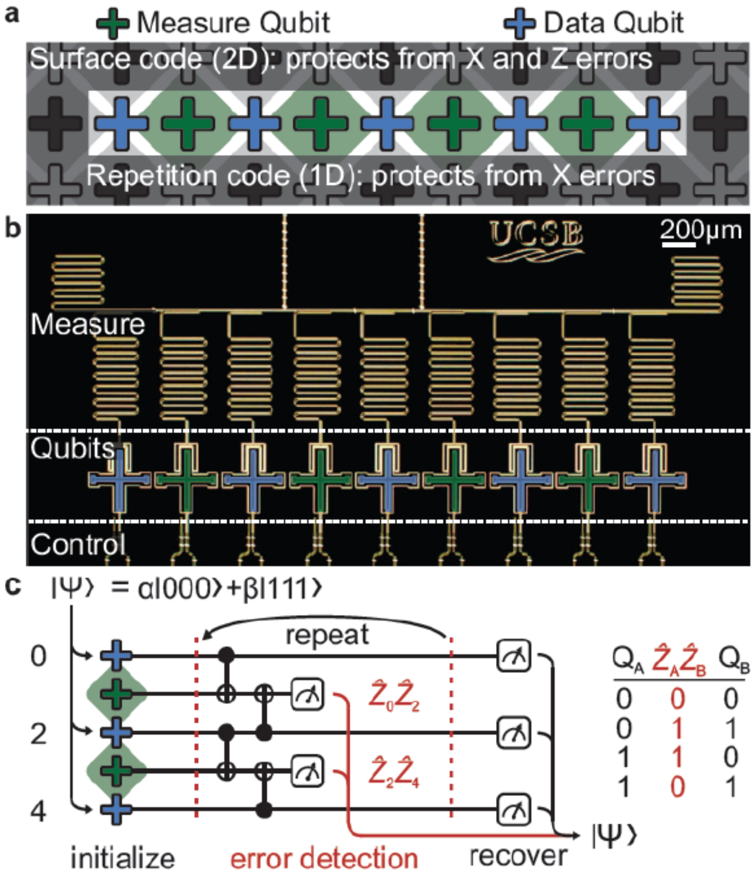
**2 Tmons (Xmon),**
**Capacitive coupling**

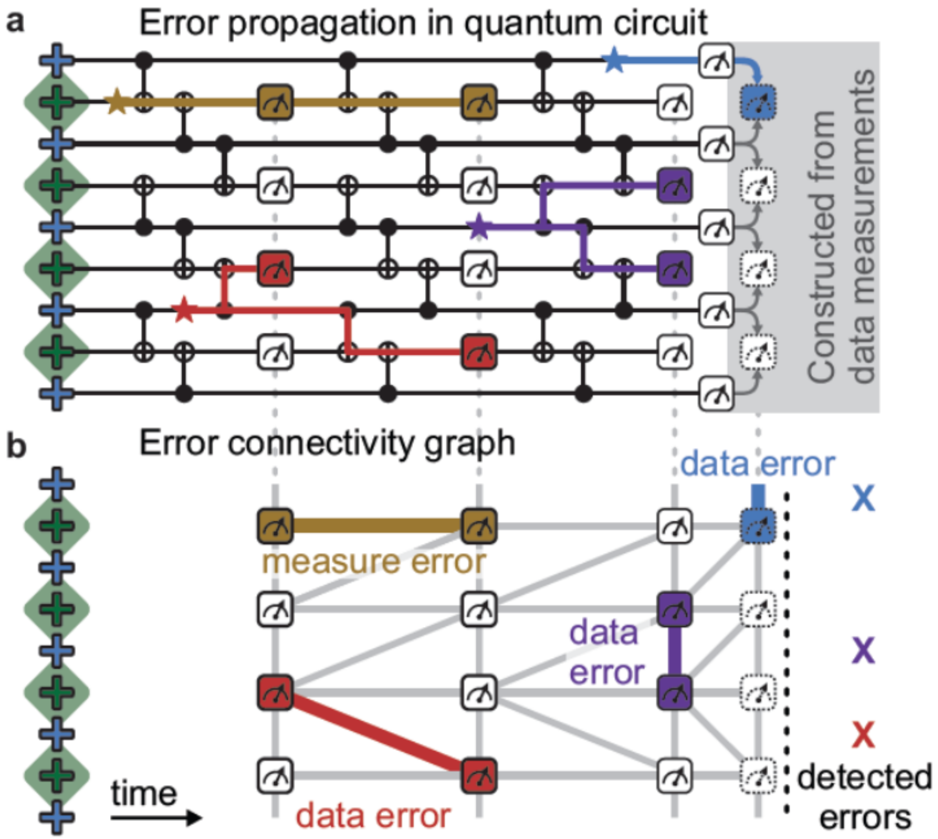


**Martinis group, UCSB (2014)**

# Quantum computing results (2015)

## First steps toward QEC with the Surface Code



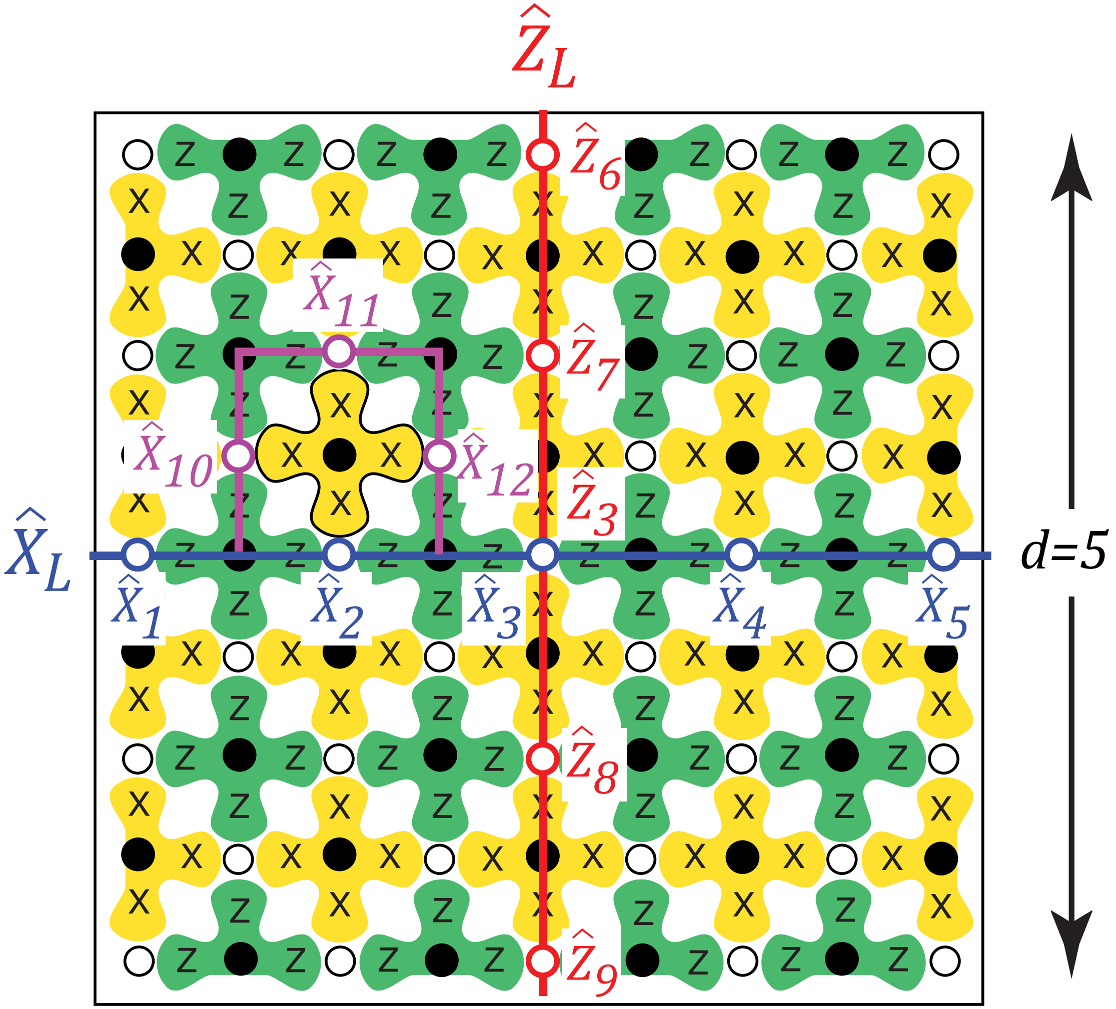


**Martinis group, UCSB (2014)**

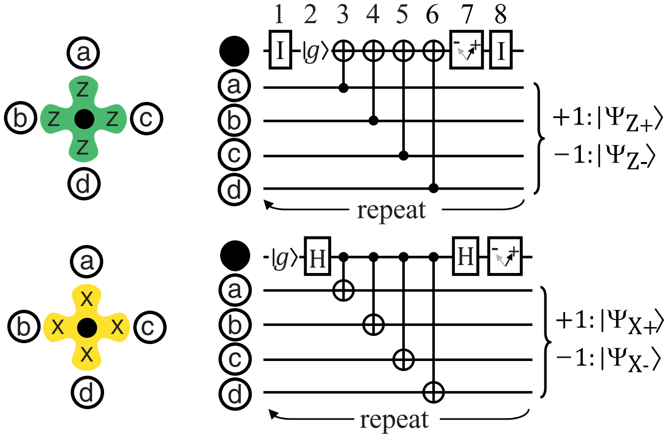
# The Surface Code Architecture, UCSB

## 81 transmon-type qubits

○ **41 data qubits**
● **40 measurement qubits**
**1 logic qubit**



## 4-qubit parity measurements



4-qubit stabilizers
ZaZbZcZd and XaXbXcXd

Fowler, Mariantoni, Martinis, Cleland
Phys. Rev. A **86**, 032324 (2012)