arXiv:1508.02292

Revising the musical equal temperament

Haye Hinrichsen

arXiv:1508.01223

Reduced sensitivity to charge noise in semiconductor spin qubits via symmetric operation

M. D. Reed *et al.*

Journal Club, Sep 1, 2015

RECALL

arXiv:1203.5101

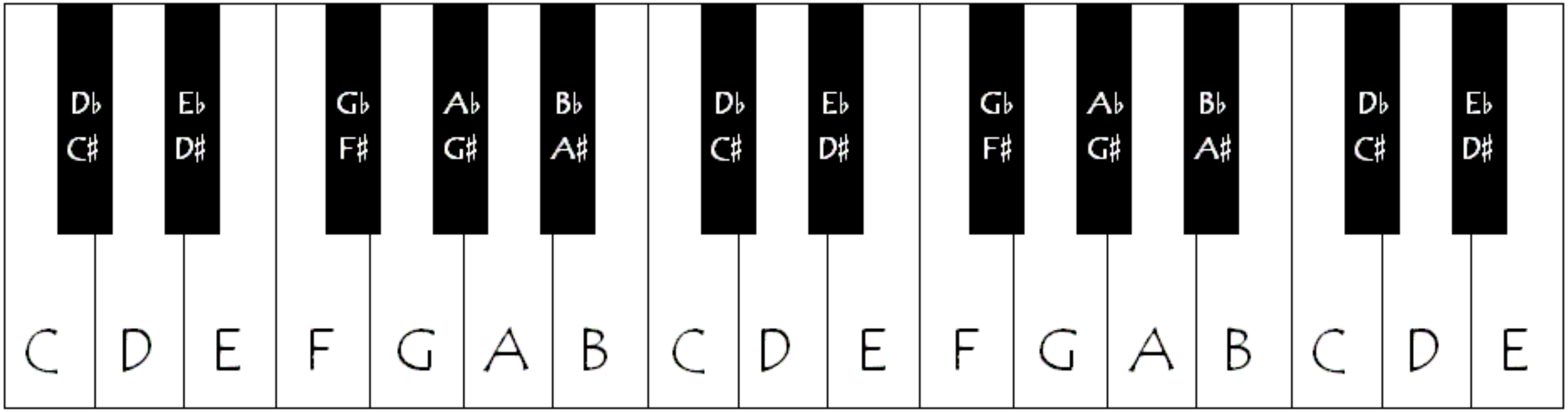
Rev. Bras. Ens. Fis. **34**, 2301 (2012)

Entropy-based Tuning of Musical Instruments

Haye Hinrichsen

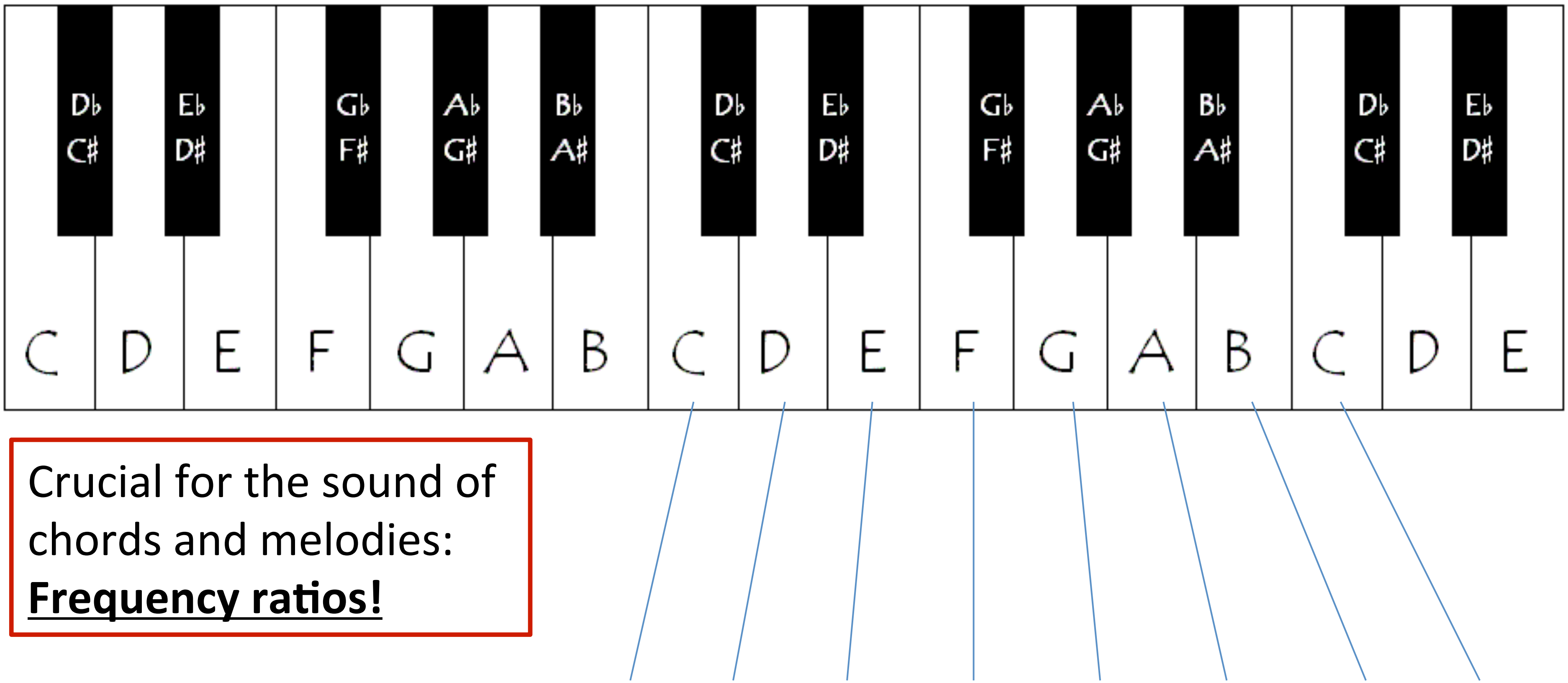
Fakultät für Physik und Astronomie, Universität Würzburg, Germany

Tuning Systems



Crucial for the sound of chords and melodies: **Frequency ratios!**

Tuning Systems

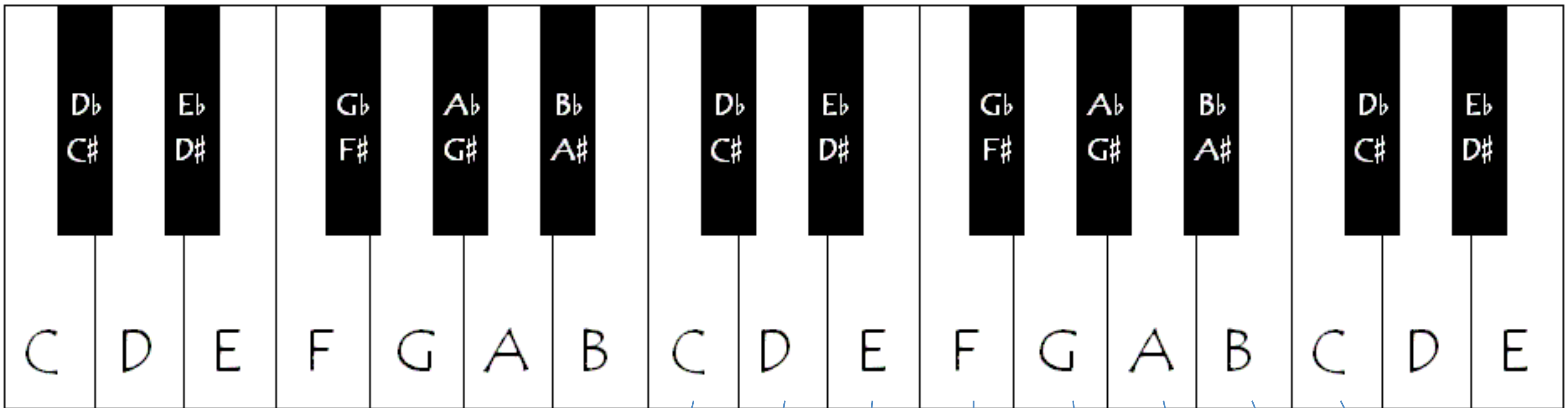


Crucial for the sound of chords and melodies: **Frequency ratios!**

"Just Intonation": 1 9/8 5/4 4/3 3/2 5/3 15/8 2

Here: common example for C-Major scale

Tuning Systems



Crucial for the sound of chords and melodies: **Frequency ratios!**

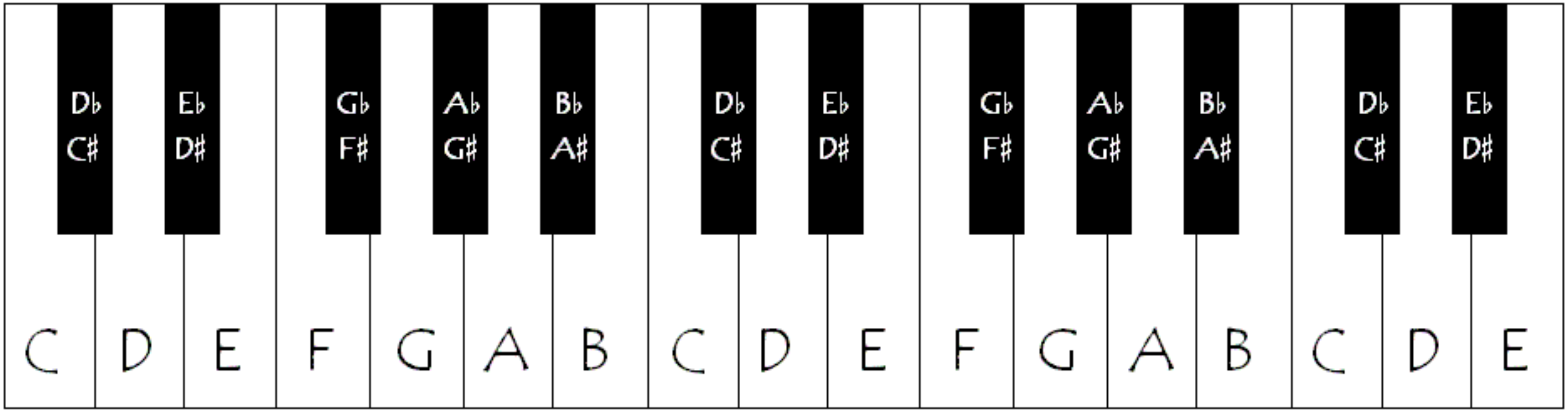
“Just Intonation”: 1 9/8 5/4 4/3 3/2 5/3 15/8 2

Here: common example for C-Major scale

“Equal Temperament”: $1 \quad 2^{2/12} \quad 2^{4/12} \quad 2^{5/12} \quad 2^{7/12} \quad 2^{9/12} \quad 2^{11/12} \quad 2$

Same ratio ($2^{1/12}$) between adjacent notes

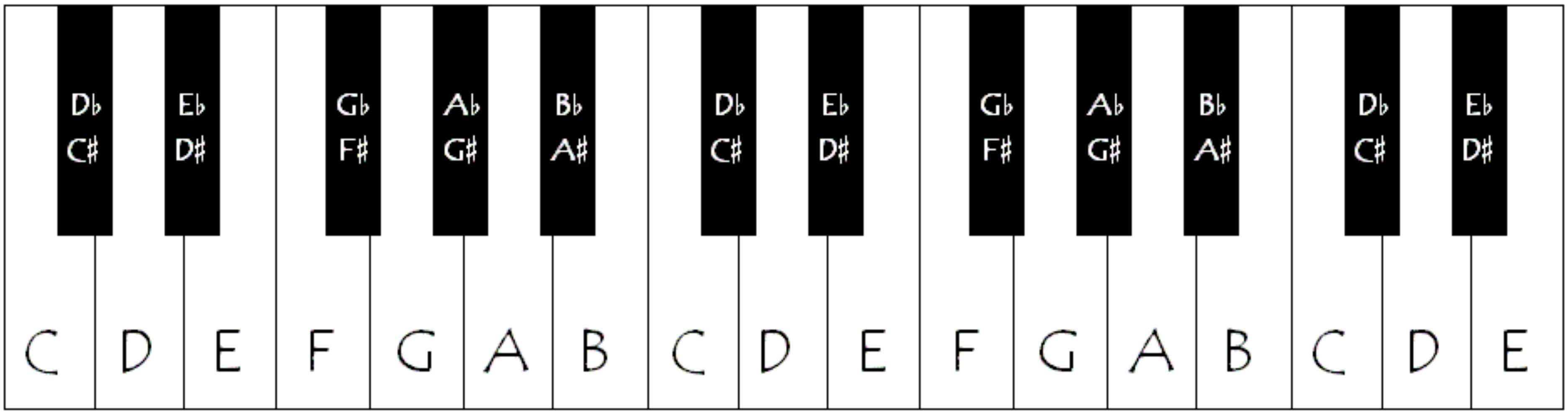
Equal Temperament



Since ~ 19th century, Western music is based on **Equal Temperament**

Adjacent notes differ by factor $\mathbf{2^{1/12}}$ in frequency ⟶ Translational invariance

Equal Temperament



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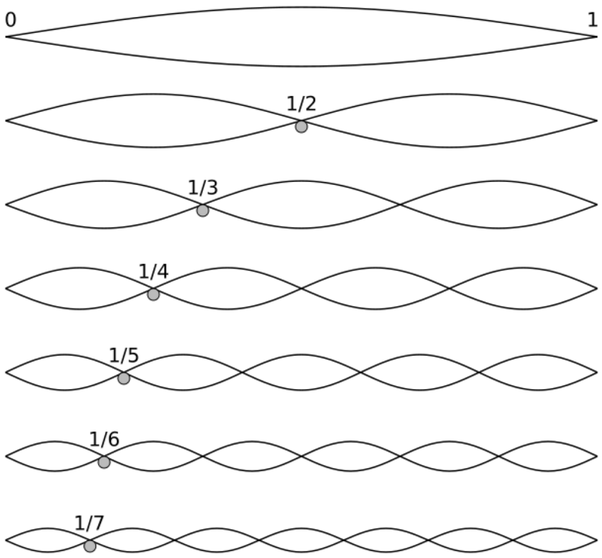
Professional Piano Tuning: Aural

Picture from Wikipedia, by Henry Heatly

Why can't we tune it ourselves?

Overtones & Stiffness of Strings

Besides its **fundamental mode (frequency f_1)**, a string features several **overtones** of **frequencies f_n**



Ideal string: $\ddot{y} \propto -y''$ $\quad f \propto |k|$

$$\longrightarrow \quad f_n = n f_1$$

$$n = 1, 2, \ldots$$

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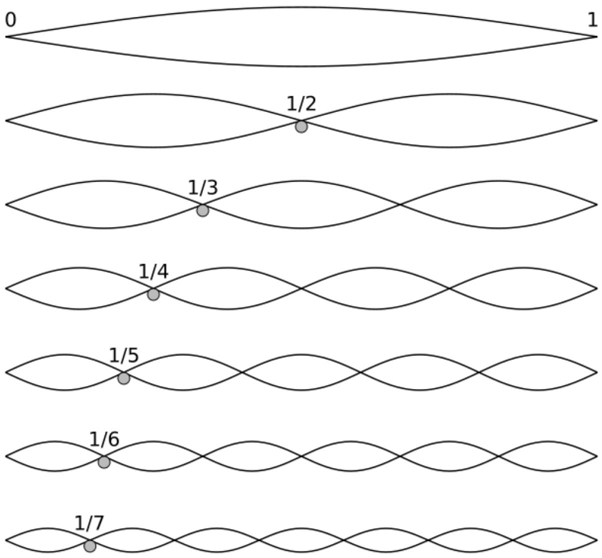

Ideal string: $\ddot{y} \propto -y''$ $\quad f \propto |k|$

$$\longrightarrow \quad f_n = n f_1$$

Stiff bar: $\ddot{y} \propto -y''''$ $\quad f \propto k^2$

Realistic string: $\ddot{y} \propto -y'' - \epsilon y''''$ $\quad f^2 \propto k^2 + \epsilon k^4$

$$\longrightarrow \quad f_n \propto n\, f_1 \sqrt{1 + Bn^2}$$

***B**: Inharmonicity coefficient*

$n = 1, 2, \ldots$

Overtones & Stiffness of Strings

Further complications:

- Inharmonicity coefficient is different for each string (depends on length, diameter, tension, material properties, ...)

- For each string, the amplitudes of the overtones are different (depending on position of hammer, ...)

Realistic string: $\ddot{y} \propto -y'' - \epsilon y''''$ $\quad f^2 \propto k^2 + \epsilon k^4$

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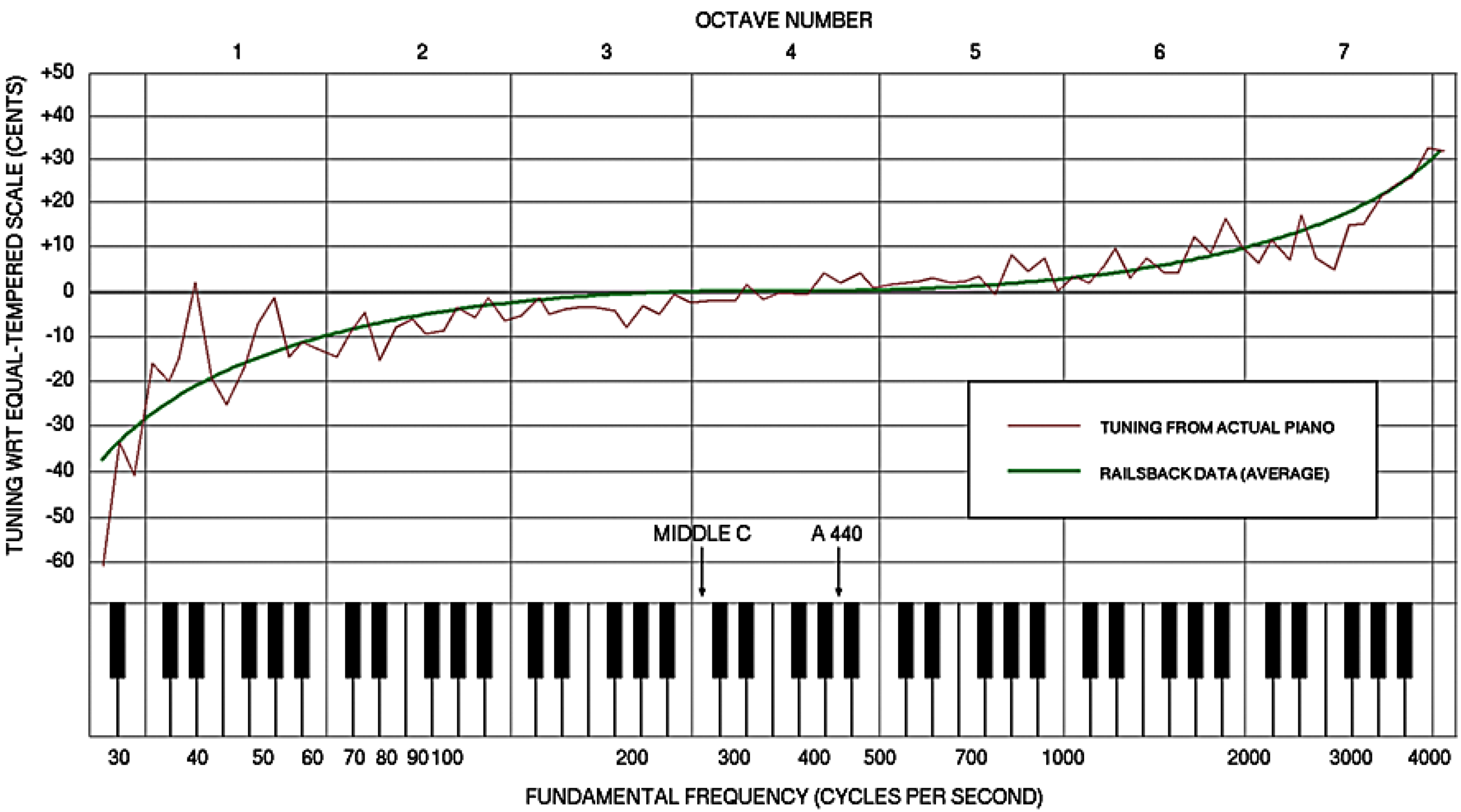
Tuning Curve of High-Quality Aural Tuning



Green: Average

Red: Individual Piano

Tuning via Entropy

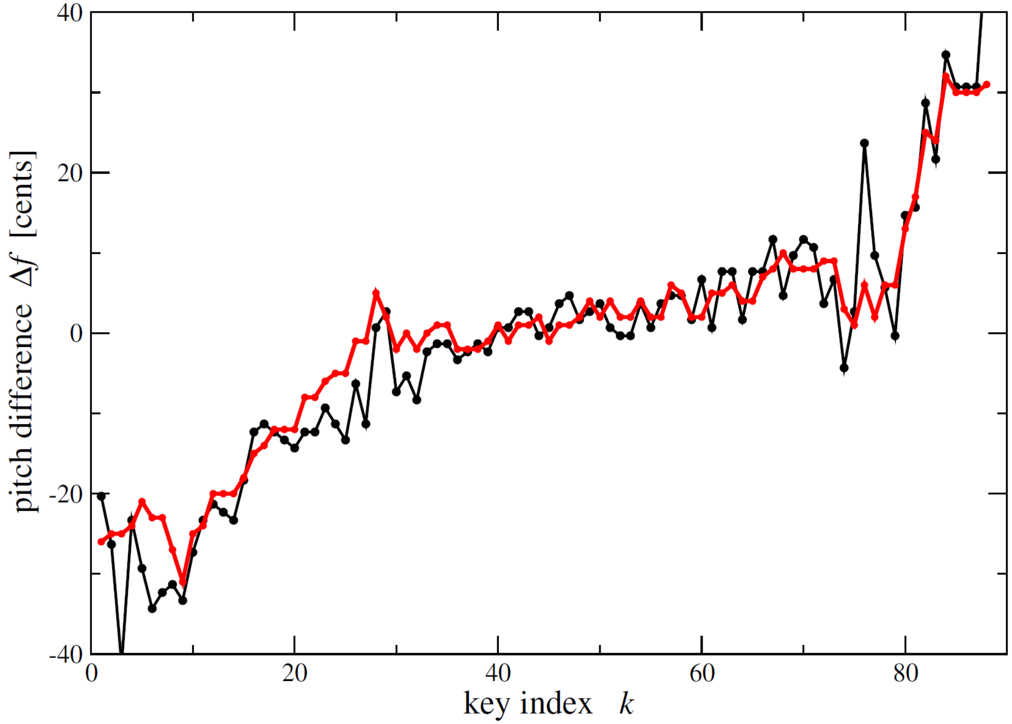
Idea of the paper:

Human brain perceives sounds as “pleasant” (“in tune”) when there is some kind of order

Entropy is a measure of disorder

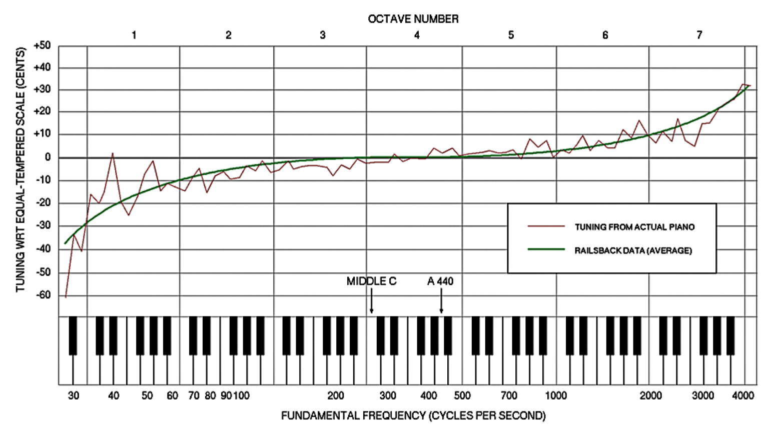
→ **Find tuning curve via entropy minimization**

Results



Red: Theoretical result

Black: Aural tuning



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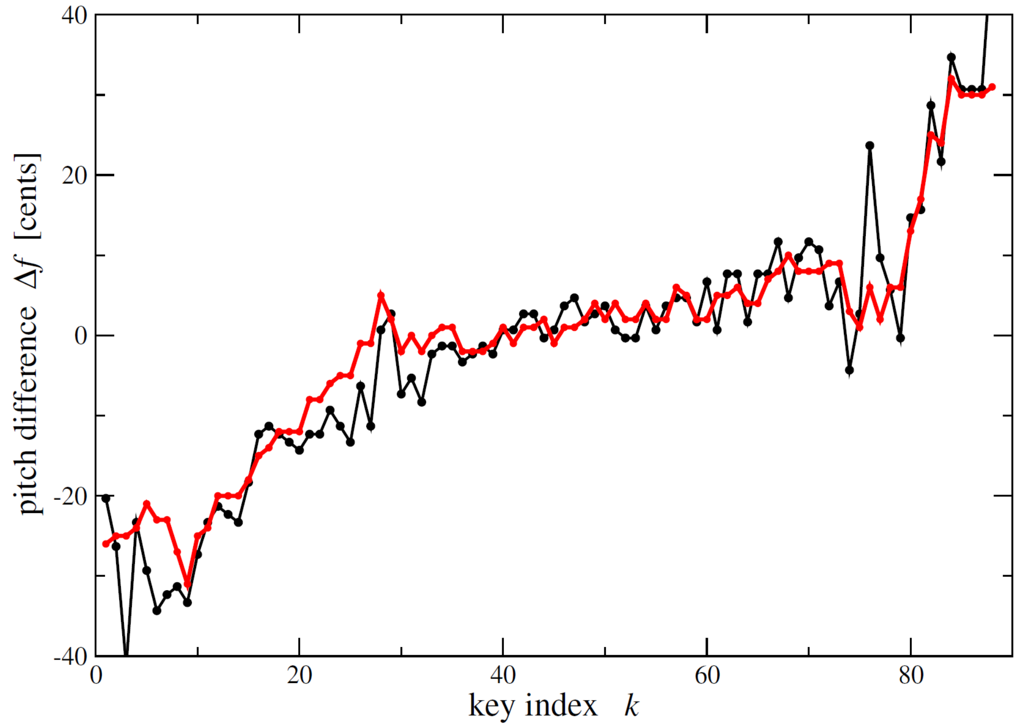

Red: Theoretical result

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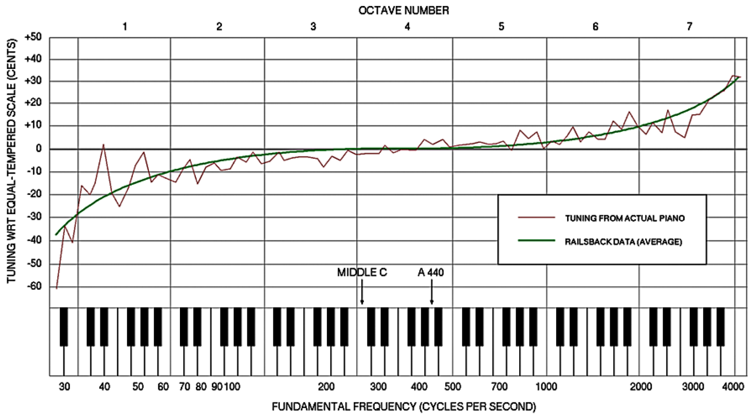
Method reproduces the stretch curve

Fluctuations are correlated (!), especially in the treble and the bass



Conclusions

Author: Several open questions and remaining tasks

- Method tested on only one piano so far
- Apparently there are many local minima, and the present algorithm gives similar but not reproducible results
- ... (see article)

The fluctuations on top of the smooth stretch curve are not random, but to some extent essential for the good results as achieved by professional, aural tuning

Whether or not the presented idea based on entropy minimization can be used to improve existing electronic tuning methods remains to be seen

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MIT Technology Review: *"Algorithm Spells the End for Professional Musical Instrument Tuners"*

Wall Street Journal: *"Are the Days of Human Piano-Tuners Numbered?"*

What Happened Since 2012?

Article reprinted in "Europiano" (2012/4)

Open-source software:

http://piano-tuner.org

(Current version: 1.1.2)

arXiv:1508.02292

Revising the Musical Equal Temperament

Haye Hinrichsen

Fakultät für Physik und Astronomie, Universität Würzburg, Germany

Important Difference to Study from 2012

Assumption in this paper

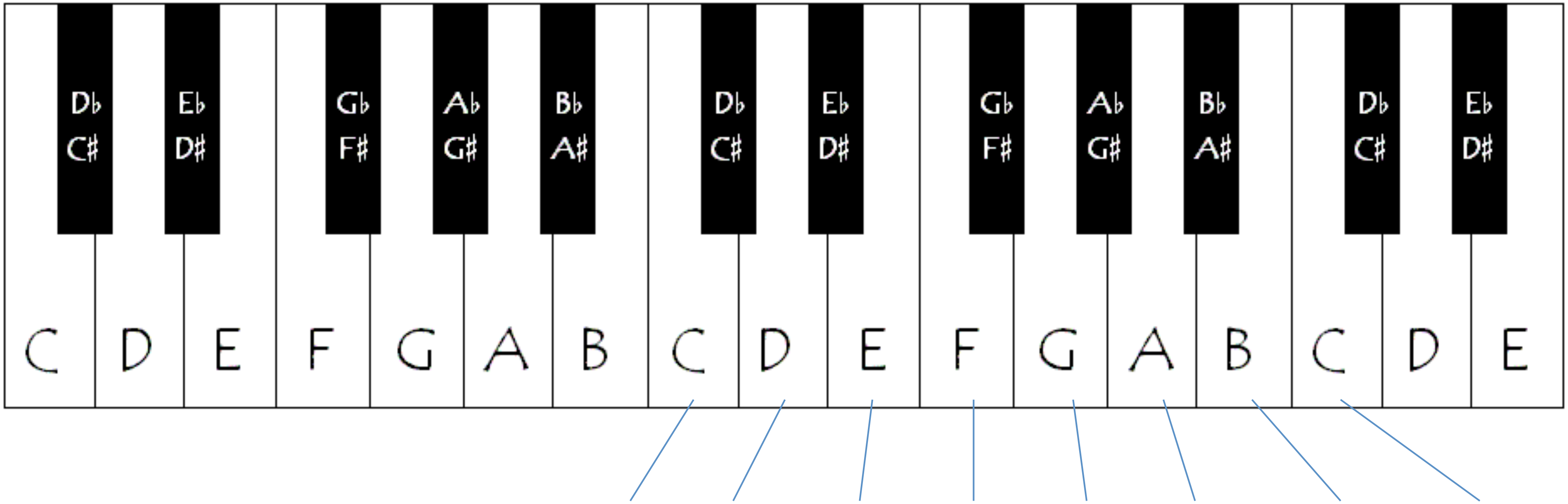
For each note, the frequencies f_n of overtones are integer multiples of the fundamental frequency f_1

$$\longrightarrow \quad f_n = n f_1$$

(Ideal strings are assumed)

→ **A discussion of the equal temperament itself**

Equal Temperament



"Equal Temperament": 1 $2^{2/12}$ $2^{4/12}$ $2^{5/12}$ $2^{7/12}$ $2^{9/12}$ $2^{11/12}$ 2

Same ratio ($2^{1/12}$) between adjacent notes

Since ~ 19th century, Western music is based on **Equal Temperament**

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Stretched Equal Temperaments

Some musicians have repeatedly expressed their discomfort with the harmonicity of certain intervals. Are improvements possible?

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Proposals: Stretched equal temperaments

Stretch parameter

$$f^{(k)} = f_{\mathrm{ref}}\, 2^{\frac{(1+\epsilon/100)}{12}(k-k_{\mathrm{ref}})}$$

Reference tone
(usually A4, 440 Hz)

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Stopper Tuning: **ϵ = 0.103**
The duodecime is pure, not the octave
B. Stopper, 1988

Cordier Tuning: **ϵ = 0.279**
The fifth is pure, not the octave
S. Cordier, 1995

Circular Harmonic System: **ϵ = 0.038**
No interval is pure
A. Capurso, 2009

Entropy Minimization

Idea of the paper, similar to the author's work from 2012:

Human brain perceives sounds as "pleasant" ("in tune") when there is some kind of order

Entropy is a measure of disorder

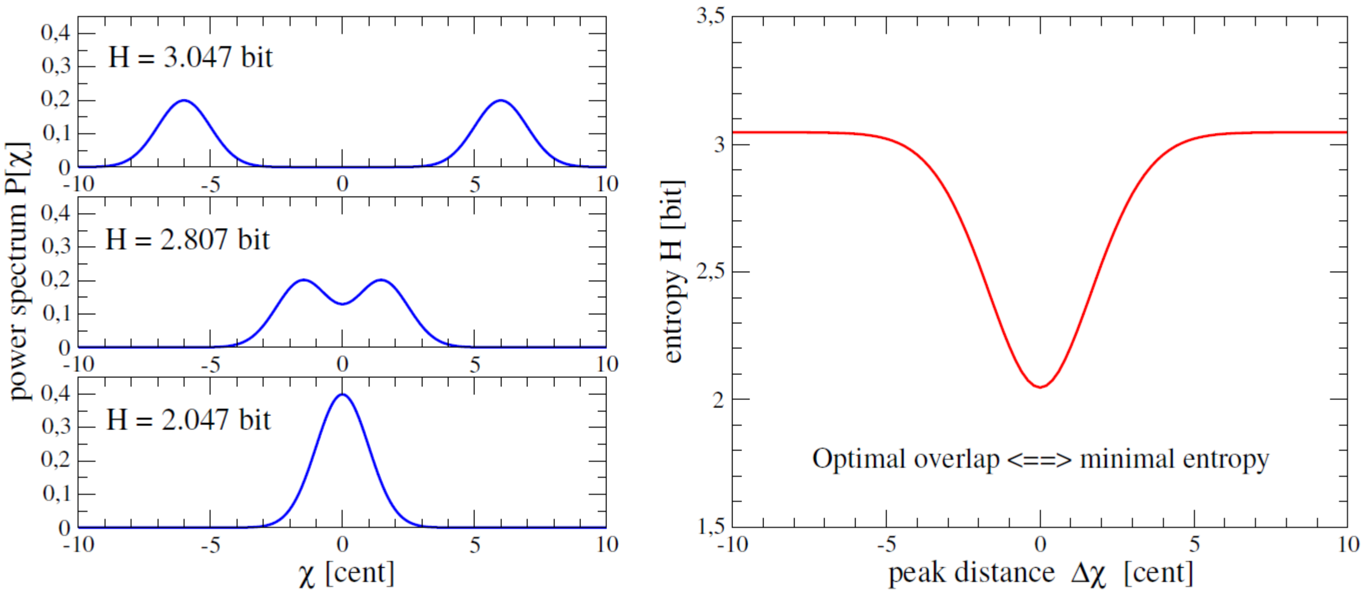
→ **Find stretch parameter via entropy minimization**

Entropy Minimization

Example: Two Gaussian peaks of width σ, separated by a distance $\Delta\chi$

$$p(\chi) = \frac{1}{2}\Big[p_\sigma(\chi + \Delta\chi/2) \;+\; p_\sigma(\chi - \Delta\chi/2)\Big]$$
$$= \frac{1}{2\sigma\sqrt{2\pi}}\left(e^{-\frac{(\chi+\Delta\chi/2)^2}{2\sigma^2}} \;+\; e^{-\frac{(\chi-\Delta\chi/2)^2}{2\sigma^2}}\right)$$

Entropy: $\quad H = -\int \mathrm{d}\chi\, p(\chi)\log_2 p(\chi)$



Model

- Probability density for the entropy is a normalized power spectrum

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- All (over)tones are Gaussians with a width σ

Typical value for σ:
2 to 16 cents
(Deviations of Equal Temperament from pure tuning, may be considered as a reasonable tolerance for human hearing)

"Cent":
1/100 of a step in the chromatic scale

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$$P_n^{(k)} := P_1^{(k)} e^{-(n-1)/\lambda} \propto e^{-n/\lambda}$$

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  Standard piano:
  K = 88, reference tone A4 (440 Hz)

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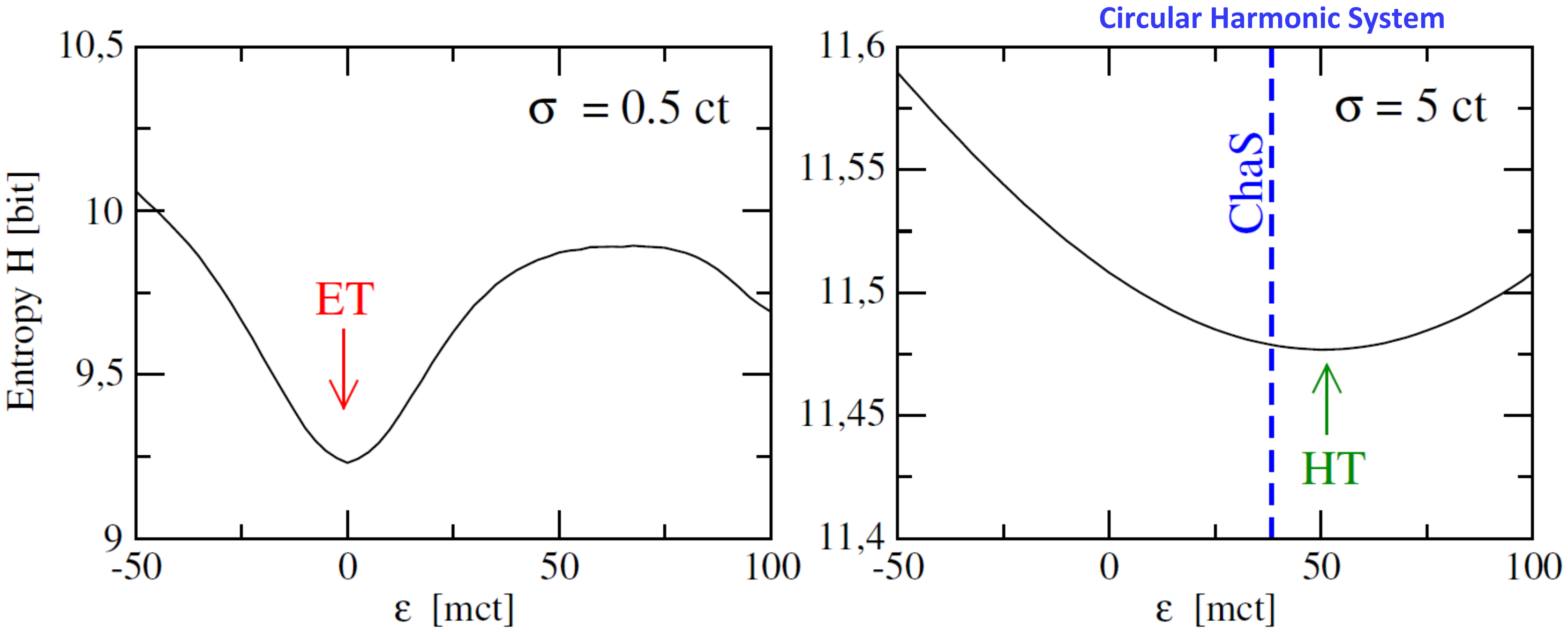
Standard piano:
K = 88, reference tone A4 (440 Hz)

The integral for the entropy is calculated with C++, with a step size of 0.001 cents

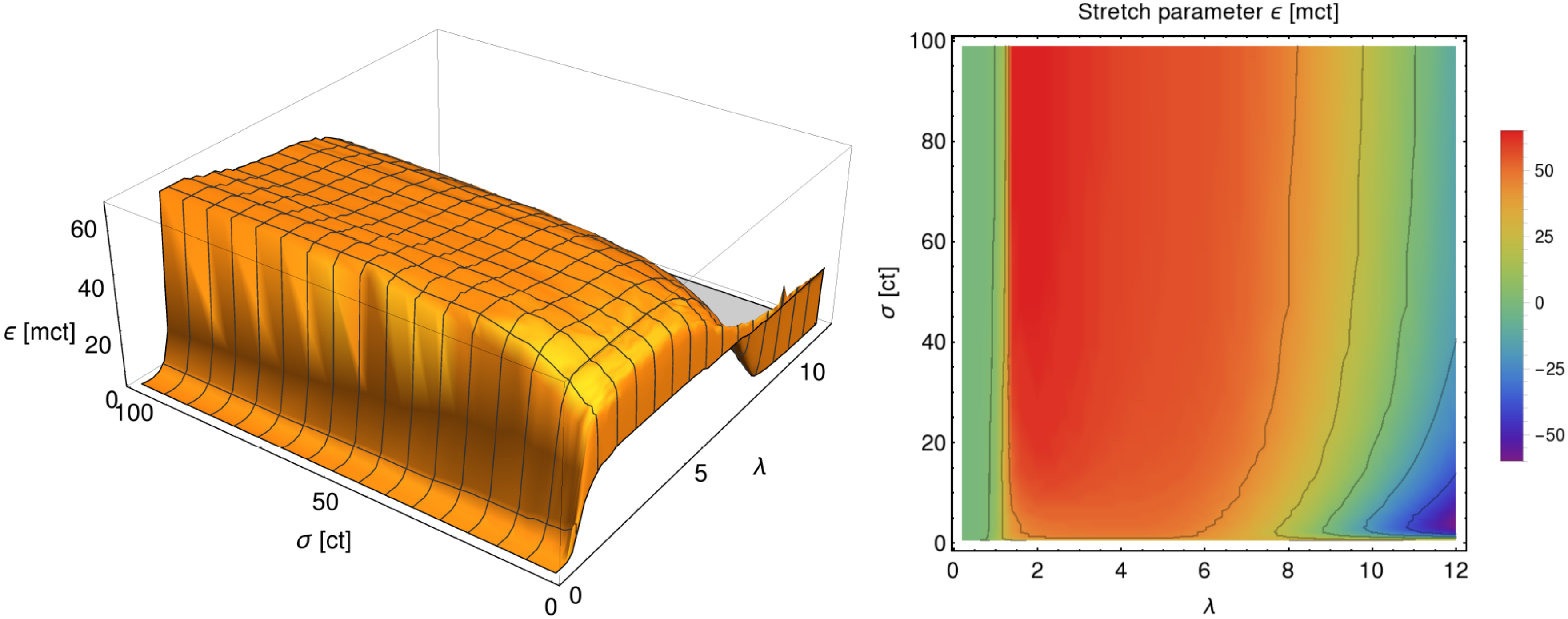
Results

Example for K = 88 and λ = 10



Results

Example for K = 88



For a wide range of parameters, the model yields $0.035 < \epsilon < 0.065$, with a plateau near $\epsilon = 0.052$

Conclusions

The model based on entropy minimization suggests that the equal temperament should be replaced by a stretched equal temperament

$$f^{(k)} \;=\; f_{\rm ref}\, 2^{\frac{(1+\epsilon/100)}{12}(k-k_{\rm ref})}$$

with ϵ around 0.05.

The calculated value for ϵ is similar to that of the Circular Harmonic System (ϵ = 0.038), but smaller than those of the Stopper (ϵ = 0.103) and Cordier (ϵ = 0.279) tunings.

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The proposed corrections to the temperament itself are rather small compared with those of typical tuning curves for pianos (resulting from the stiffness of the strings), around 5–10% for the lowest/highest keys.

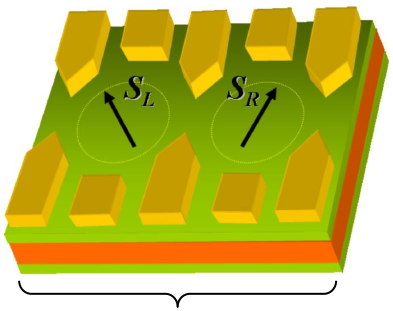
arXiv:1508.01223

Reduced sensitivity to charge noise in semiconductor spin qubits via symmetric operation

M. D. Reed, B. M. Maune, R. W. Andrews, M. G. Borselli, K. Eng, M. P. Jura, A. A. Kiselev, T. D. Ladd, S. T. Merkel, I. Milosavljevic, E. J. Pritchett, M. T. Rakher, R. S. Ross, A. E. Schmitz, A. Smith, J. A. Wright, M. F. Gyure, and A. T. Hunter

HRL Laboratories, LLC, 3011 Malibu Canyon Road, Malibu, CA 90265, USA

Spin Qubits in Quantum Dots

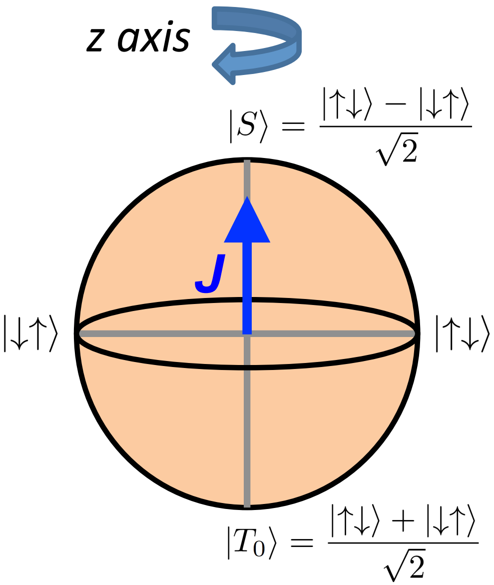


two single-spin qubits
or
one singlet-triplet qubit

Loss/DiVincenzo, Phys. Rev. A **57**, 120 (1998)

Common approach:
Singlet-triplet qubits
in double quantum dots

Levy, PRL (2002)
Petta *et al*., Science (2005)
Shulman *et al*., Science (2012)
Klinovaja *et al*., PRB (2012)



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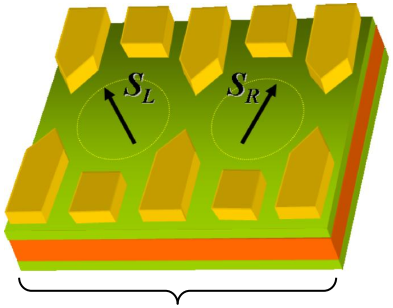

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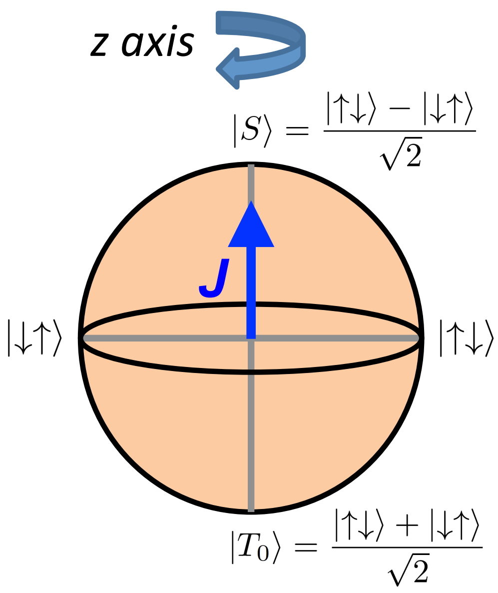
Exchange splitting *J*

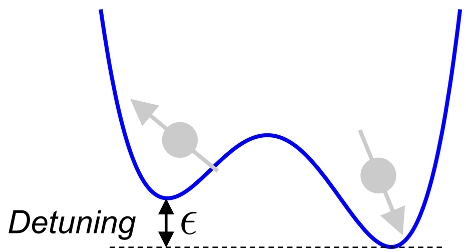
Two-qubit gate for single-spin qubits

Single-qubit gate for singlet-triplet qubits

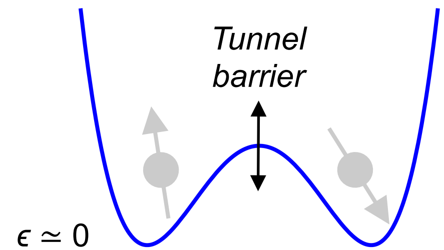


Operation Schemes

Control via detuning



Control via tunnel barrier



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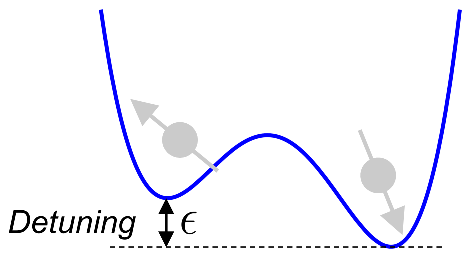

Approach chosen in almost all experiments

Petta *et al*., Science (2005)
Shulman *et al*., Science (2012)
Dial *et al*., PRL (2013)
...

Measured decoherence times for exchange-based gates are rather short

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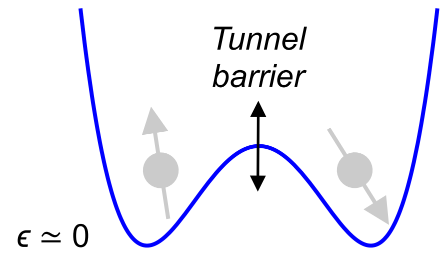

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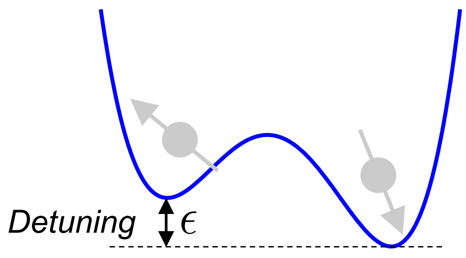

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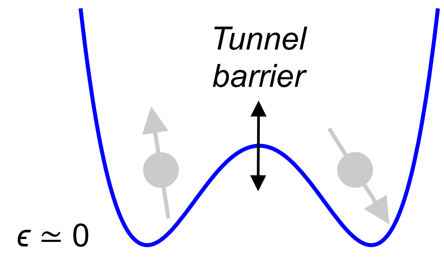


Suggested approach

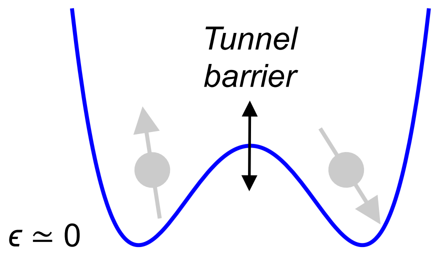
Loss/DiVincenzo, PRA (1998)

- Qubit protected against charge noise as $dJ/d\epsilon \simeq 0 \simeq \langle dJ/d\epsilon \rangle$
  Burkard/Loss/DiVincenzo, PRB (1999)
- Dephasing via phonons suppressed
  Kornich/Kloeffel/Loss, PRB (2014)

Long decoherence times expected

Operation Schemes

Control via tunnel barrier



Recent experiments:

Marcus Group, GaAs
Improvement of decoherence time by orders of magnitude!

Reed et al., Si
This Paper

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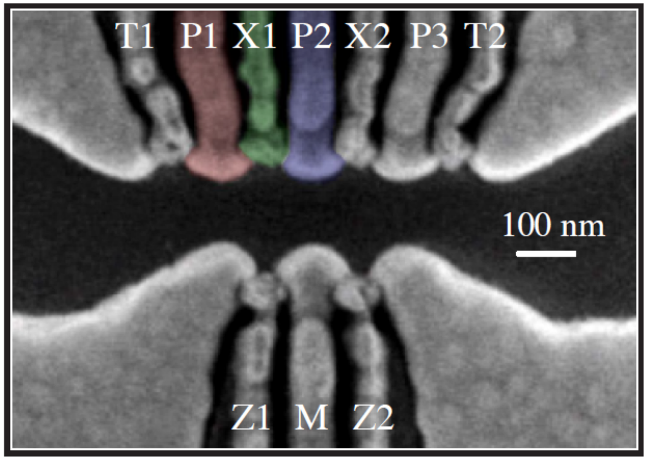
Setup

The authors study several samples, all of which are similar (but not exactly identical)



Heterostructure: Si/SiGe

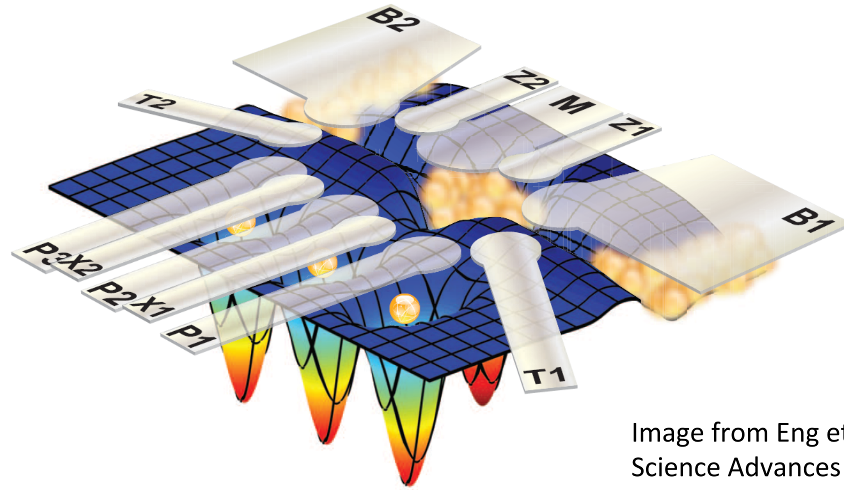
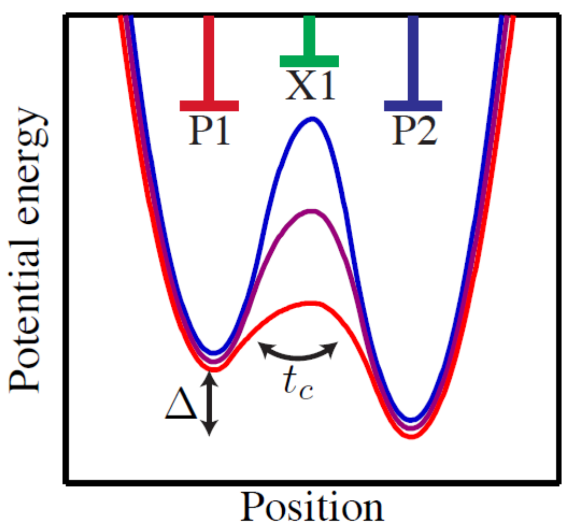
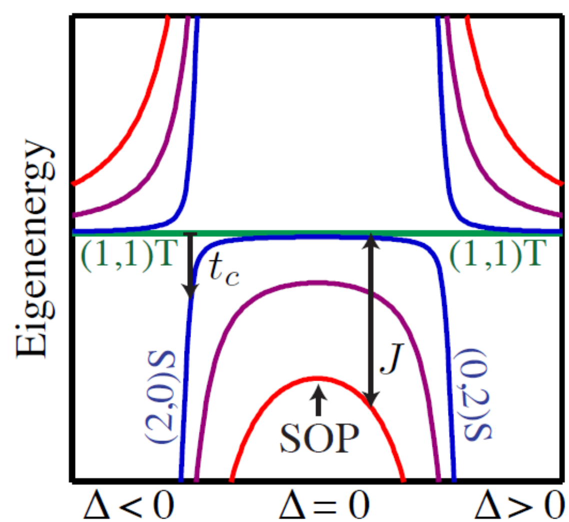


Image from Eng et al., Science Advances (2015)

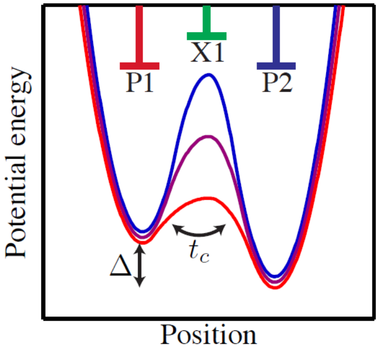




Basic Experiment

- Prepare system in (1,0,2) charge configuration, spin singlet in the right dot
- Change to (1,1,1) configuration and let the system evolve for the desired evolution time, with a given tunnel coupling and detuning between the left and middle dot
- Move to (1,1,1)-(1,0,2) transition and read out the singlet probability

→ One expects oscillations between 100% and 25%



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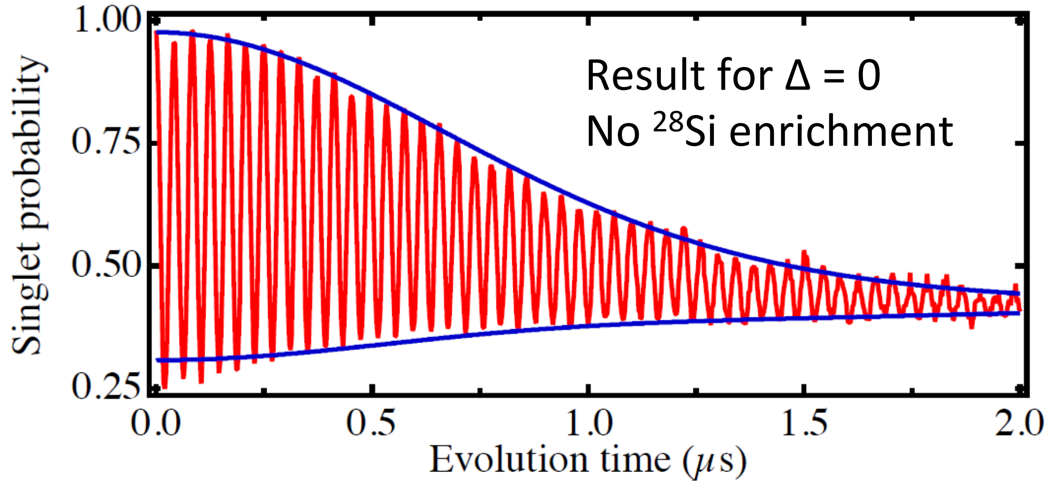
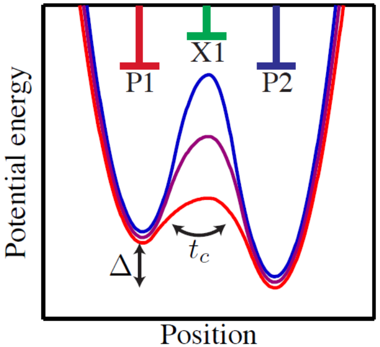


Model for hyperfine-induced decay: T. D. Ladd, PRB (2012)

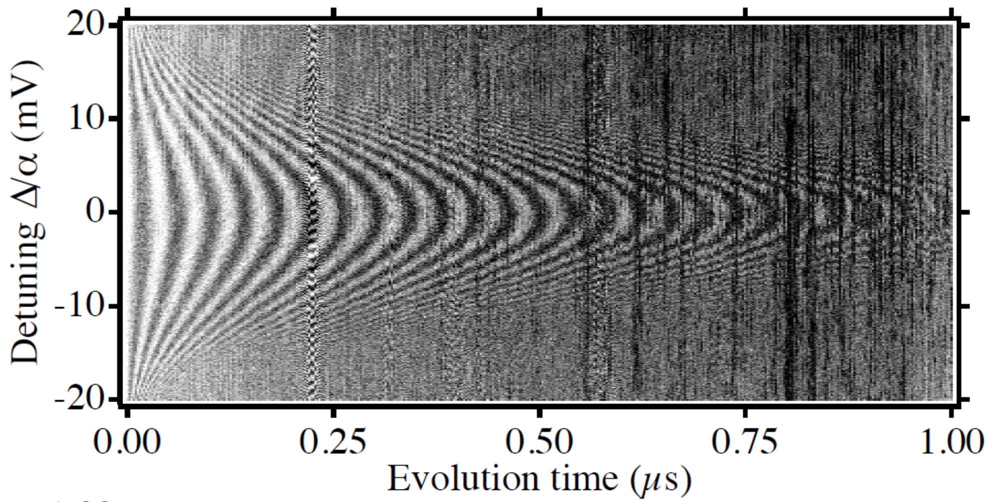


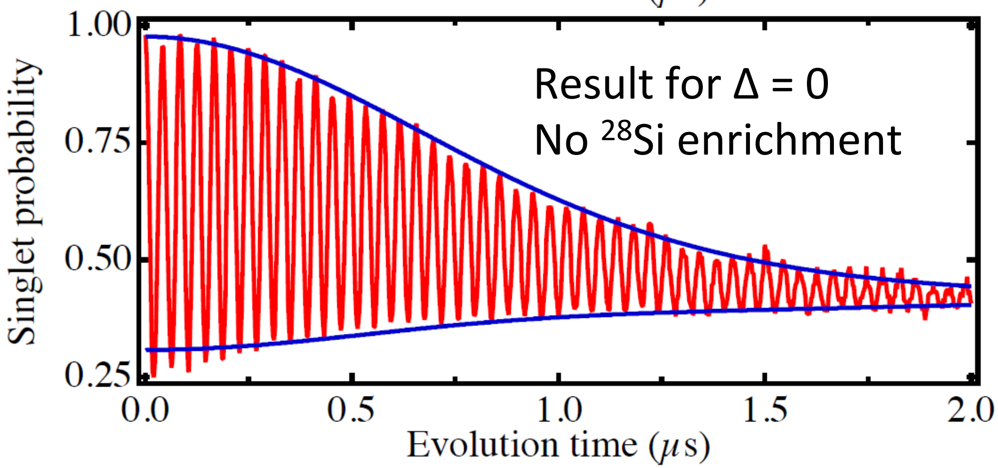
Fit:
Double Gaussian decay with 1/e decay time of 1.0 μs for hyperfine interactions and 1.5 μs due to charge noise

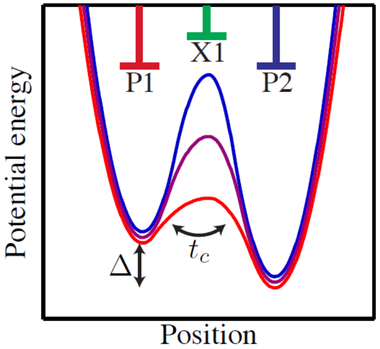
Basic Experiment

Dependence on detuning:

$$\Delta = \alpha(V_{P1} - V_{P2})$$







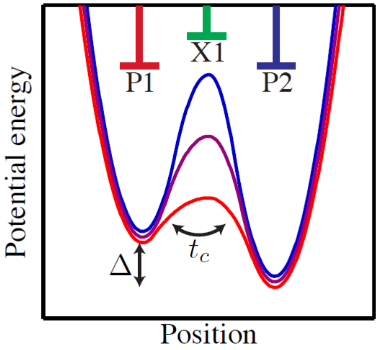
Model and Insensitivity

Details:
See supplementary information

Model for the decay of the amplitude due to charge noise:

$$\exp(-\sigma_V^2 \sum_j |dJ/dV_j|^2 t^2/\hbar^2)$$

Variance of the noise



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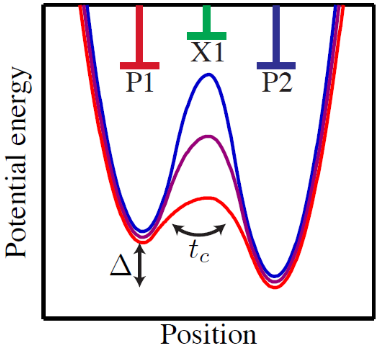

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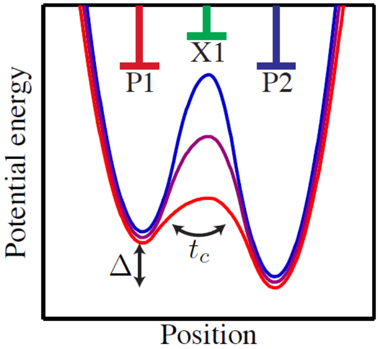
Number N_{Rabi} of Rabi oscillations before the amplitude decays by a factor 1/e:

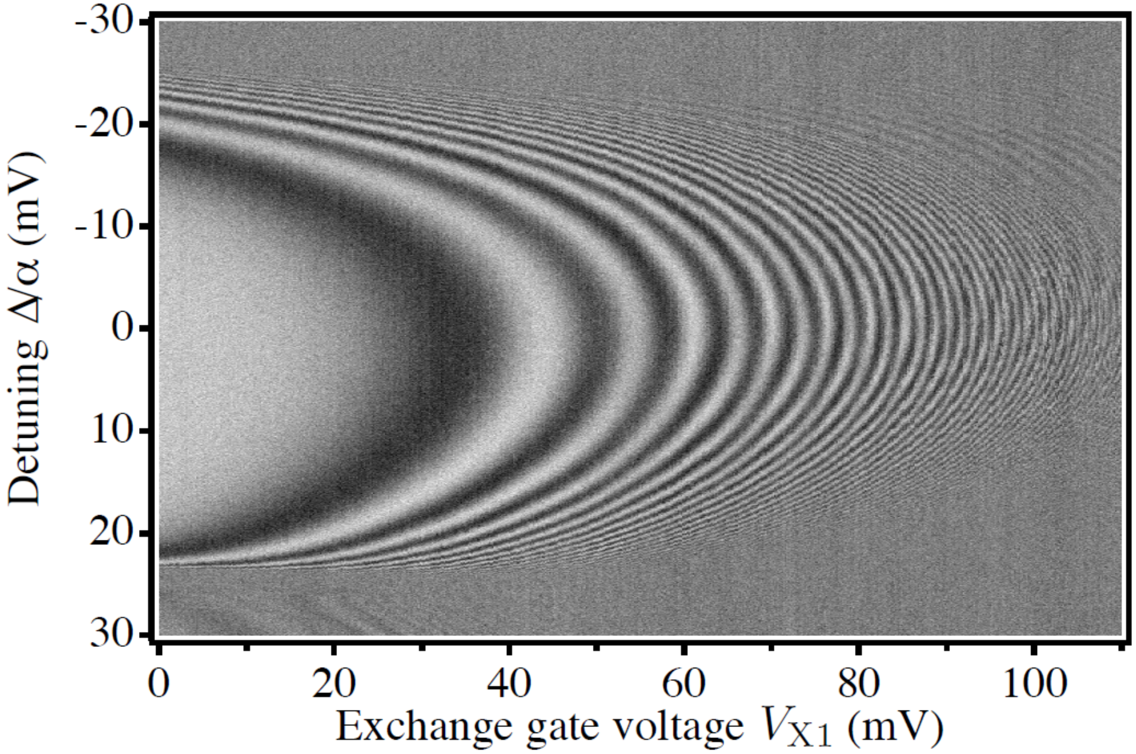
$$\mathcal{I}/(2\pi\sigma_{\text{V}})$$

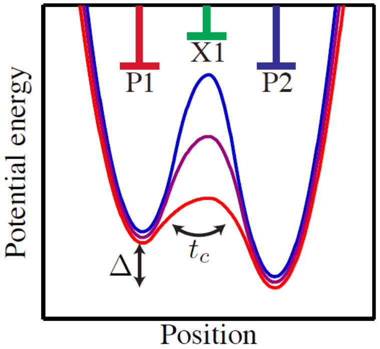


Experiments with Isotopically Purified Si

Example for sample with 800 ppm enriched ^{28}Si
and an additional screening gate

Here: Evolution time fixed!





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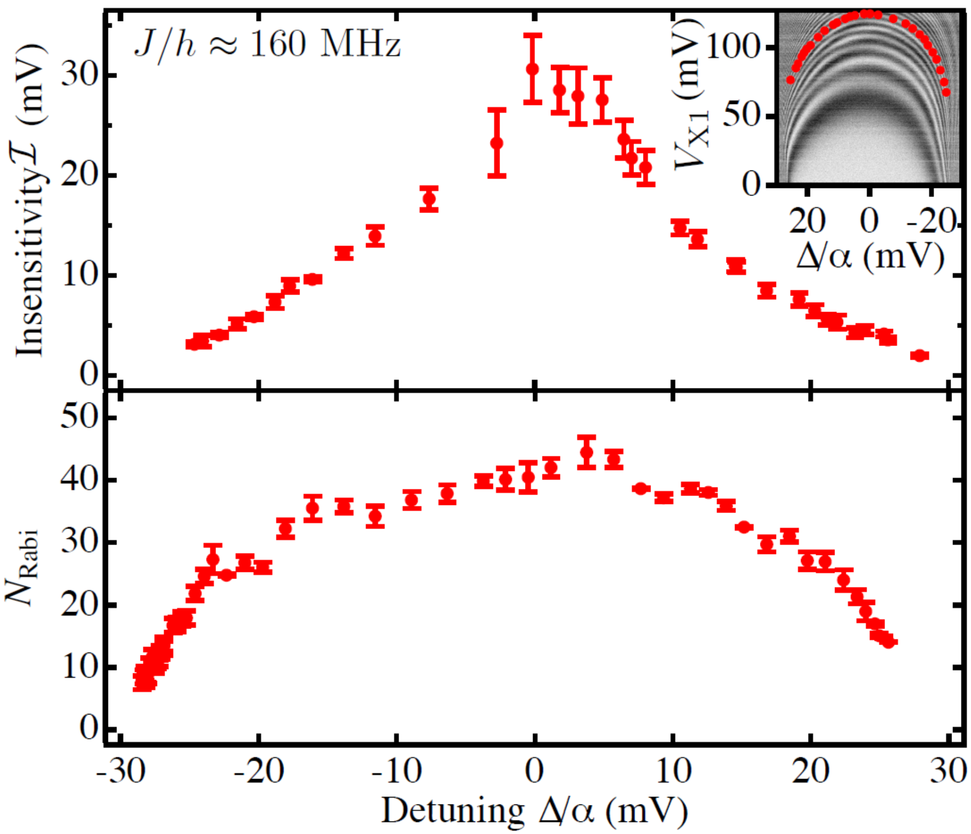
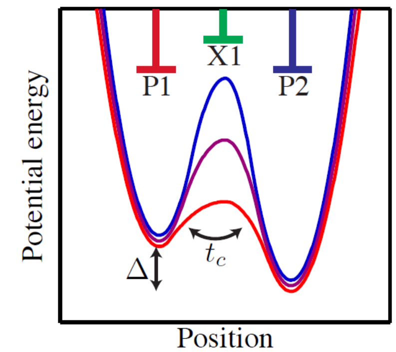




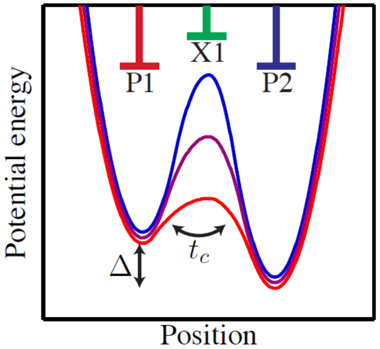
N_{Rabi} is maximal/minimal when the insensitivity is maximal/minimal

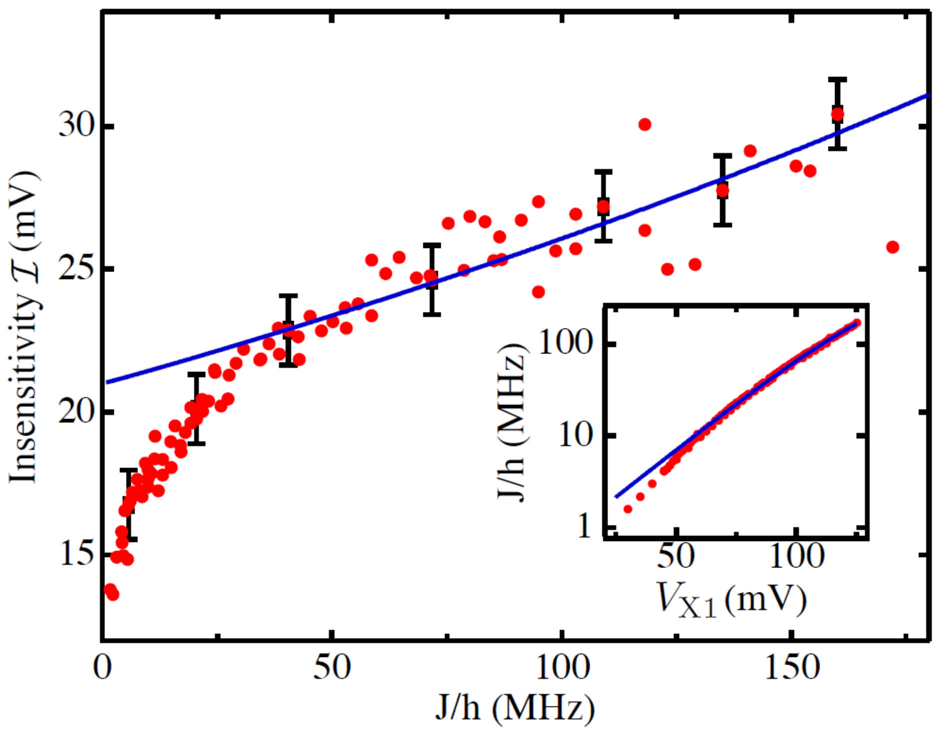
The direct proportionality expected from the model is not observed

The best results are achieved at zero detuning

Insensitivity at Zero Detuning

At zero detuning, the dominant derivative is dJ/dV_{X1}





Model (blue line):
1D Wentzel-Kramers-Brillouin (WKB) approximation appropriate for shallow barrier tunneling

The largest insensitivity is achieved at large *J*

Conclusions

Experimental confirmation with Si quantum dots that qubits are less sensitive to charge noise when the detuning is zero (number of observable Rabi oscillations is maximal)

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Some samples show additional oscillations (other samples do not!), which probably results from excited states. Whether this is due to orbital or valley excited states is unclear and will be subject of future investigations.

Conclusions

Thank you for your attention

Experimental confirmation with Si quantum dots that qubits are less sensitive to charge noise when the detuning is zero (number of observable Rabi oscillations is maximal)

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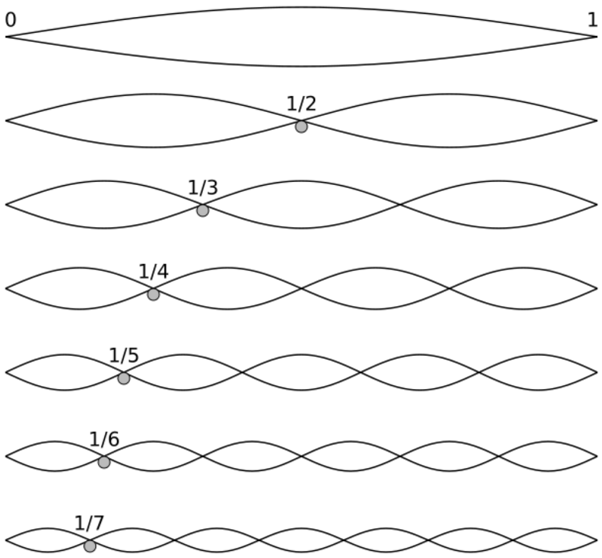
APPENDIX

Overtones & Stiffness of Strings

Besides its **fundamental mode (frequency f_1)**, a string features several **overtones** of **frequencies f_n**

Ideal string: $\ddot{y} \propto -y''$ $\quad f \propto |k|$

$$\longrightarrow \quad f_n = n f_1$$



$$n = 1, 2, \ldots$$

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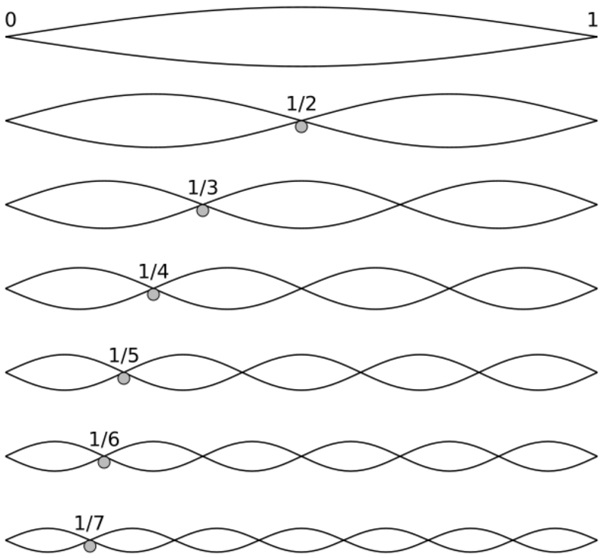

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Stiff bar: $\ddot{y} \propto -y''''$ $\quad f \propto k^2$

Realistic string: $\ddot{y} \propto -y'' - \epsilon y''''$ $\quad f^2 \propto k^2 + \epsilon k^4$

$$\longrightarrow \quad f_n \propto n\, f_1 \sqrt{1 + Bn^2}$$

***B**: Inharmonicity coefficient*

$n = 1, 2, \ldots$

Overtones & Stiffness of Strings

Further complications:

- Inharmonicity coefficient is different for each string (depends on length, diameter, tension, material properties, ...)
- For each string, the amplitudes of the overtones are different (depending on position of hammer, ...)

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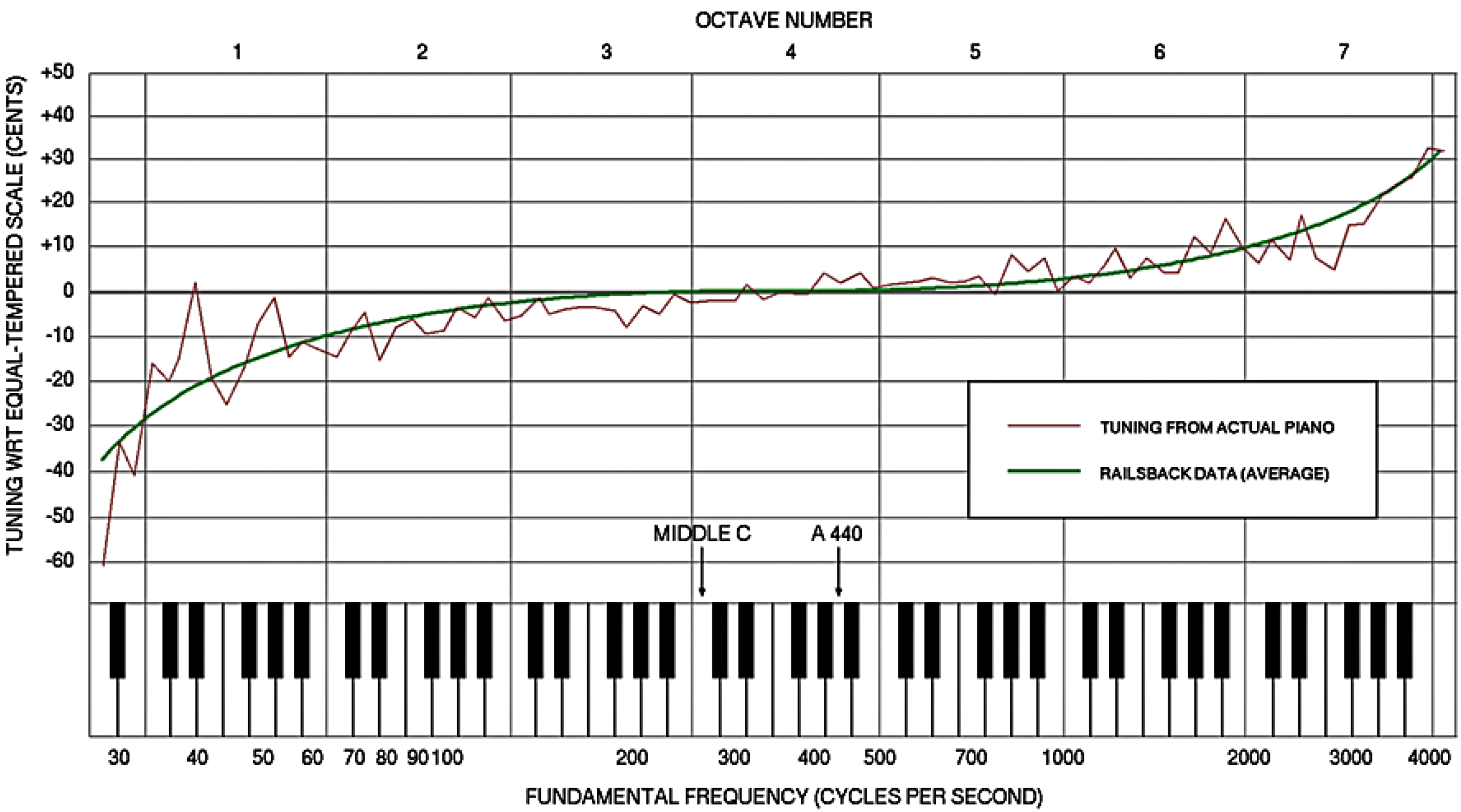
Tuning Curve of High-Quality Aural Tuning



Green: Average

Red: Individual piano

Tuning via Entropy

Idea of the paper:

Human brain perceives sounds as "pleasant" ("in tune") when there is some kind of order

Entropy is a measure of disorder

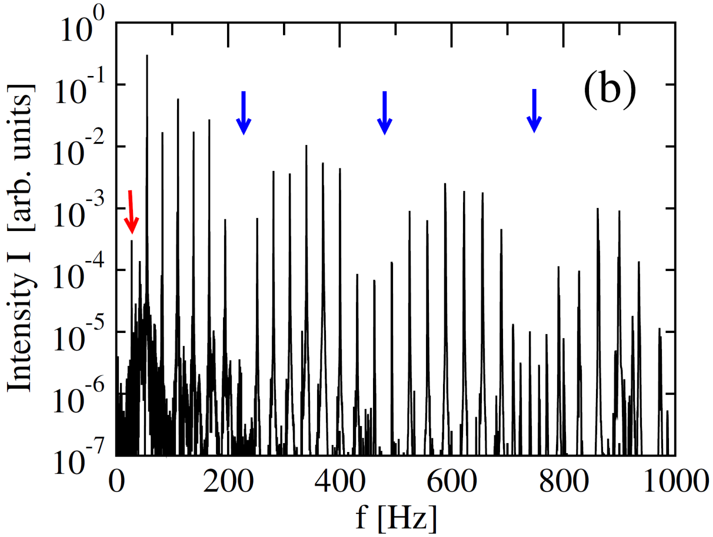
→ **Find tuning curve via entropy minimization**

Entropy-Based Tuning: Preparation

Step 1: Play and record each of the keys

Entropy-Based Tuning: Preparation

Power spectrum for the lowest key (out of 88)
Red arrow: Fundamental mode
Blue: Suppressed overtones (position of hammer, ...)



Step 1: Play and record each of the keys

Step 2: Calculate power spectrum

$$I(f) = |\text{Fourier transform}|^2$$

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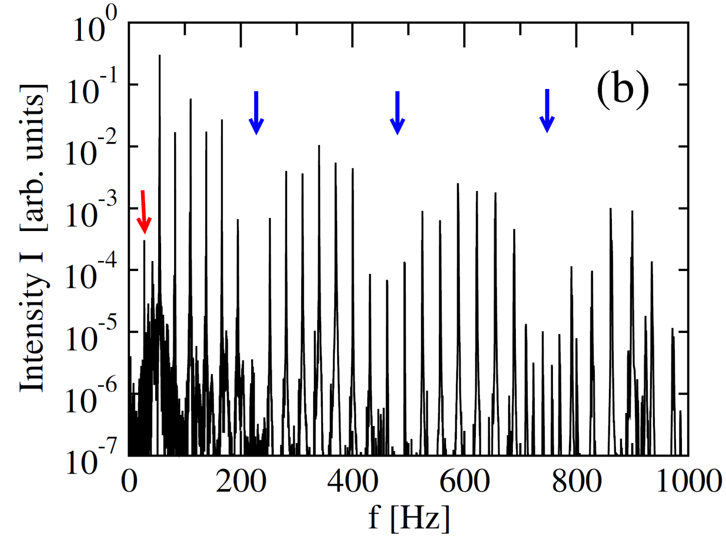

Step 1: Play and record each of the keys

Step 2: Calculate power spectrum
I(f) = |Fourier transform|^2

Step 3: Calculate **A-weighted sound pressure level L_A(f)** (in dBA)

Can be considered a rough measure of frequency-dependent energy deposition in the inner ear (cochlea)

$$L_A(f) = \Big(2.0 + 20\log_{10} R_A(f)\Big)\; L(f)$$

Filter function: Outer → Inner ear

$$L(f) = 10\log_{10}\Big(\frac{I(f)}{I_0}\Big) \qquad R_A(f) = \frac{12200^2 f^4}{(f^2+20.6^2)(f^2+12200^2)\sqrt{(f^2+107.7^2)\,(f^2+737.9^2)}}$$

Entropy-Based Tuning: Algorithm (Start)

Start configuration:

- Quantize frequency, ranging from 10 Hz to 10 kHz, in steps of cents:

$$f_m = 2^{m/1200} \cdot 10 \text{ Hz} \qquad\qquad 0 \le m \le 12000$$

- For each of the 88 keys *k*, map the A-leveled sound pressure level $L_A(f)$ onto f_m to obtain $L_m^{(k)}$
- Shift $L_m^{(k)}$ such that the fundamental modes of the keys correspond exactly to that of an equal temperament (with A4 = 440 Hz)
- Compute the sum p_m over all keys: $p_m = \sum_{k=1}^{88} L_m^{(k)}$
- Normalize: $\sum_m p_m = 1$

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Start configuration is a quantized (cents) probability distribution based on the power spectrum generated in the inner ear when the piano is exactly tuned to equal temperament

Entropy-Based Tuning: Algorithm (Dynamics)

Entropy: $$H = -\sum_m p_m \ln p_m$$

Monte-Carlo dynamics:

- Randomly shift one of the keys by ± 1 cent
- Compute again the sum p_m over all keys: $p_m = \sum_{k=1}^{88} L_m^{(k)}$
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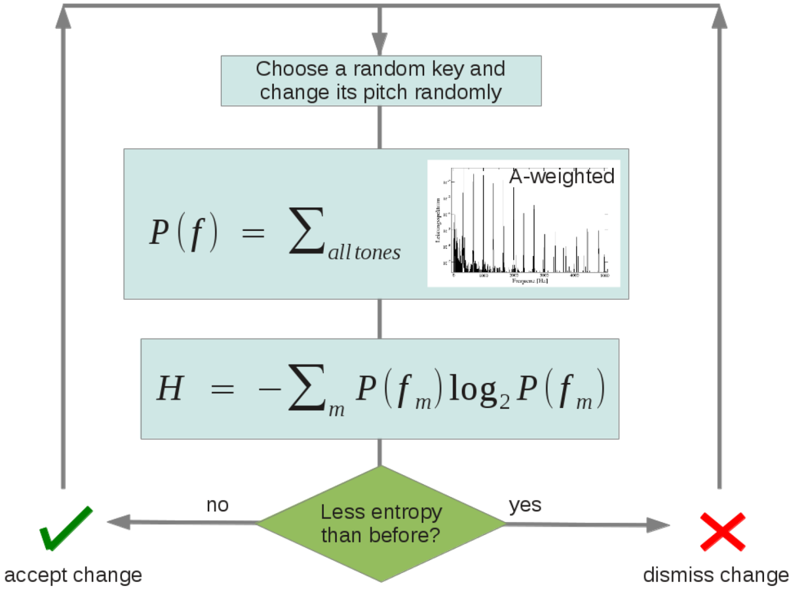
- Compute the entropy
- If entropy decreased, keep the change, otherwise undo it



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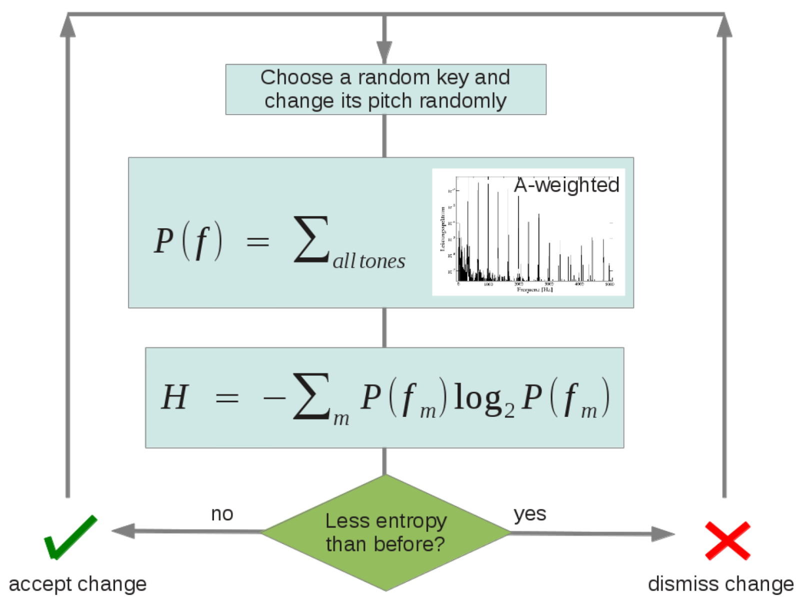
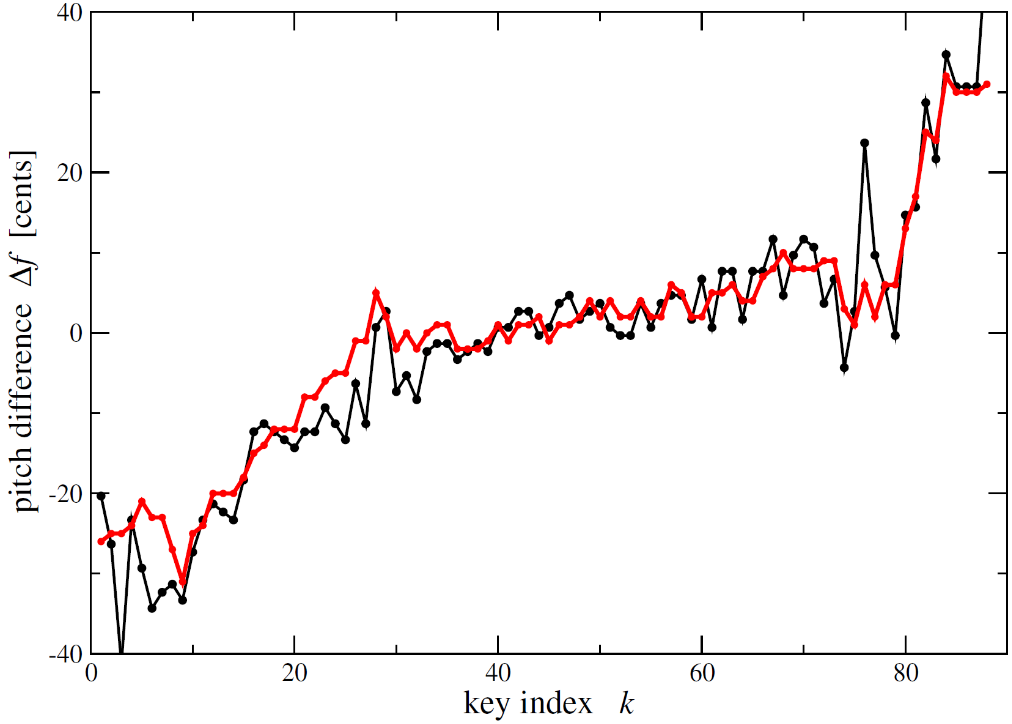
→ **Find minimum and return the tuning curve**

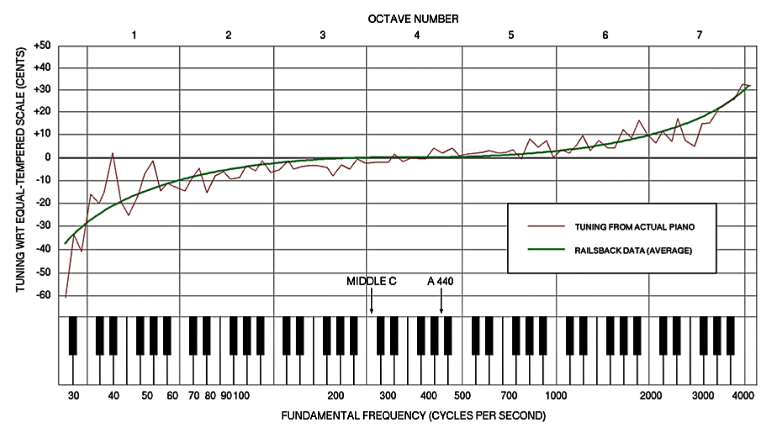


Results



Red: Theoretical result

Black: Aural tuning



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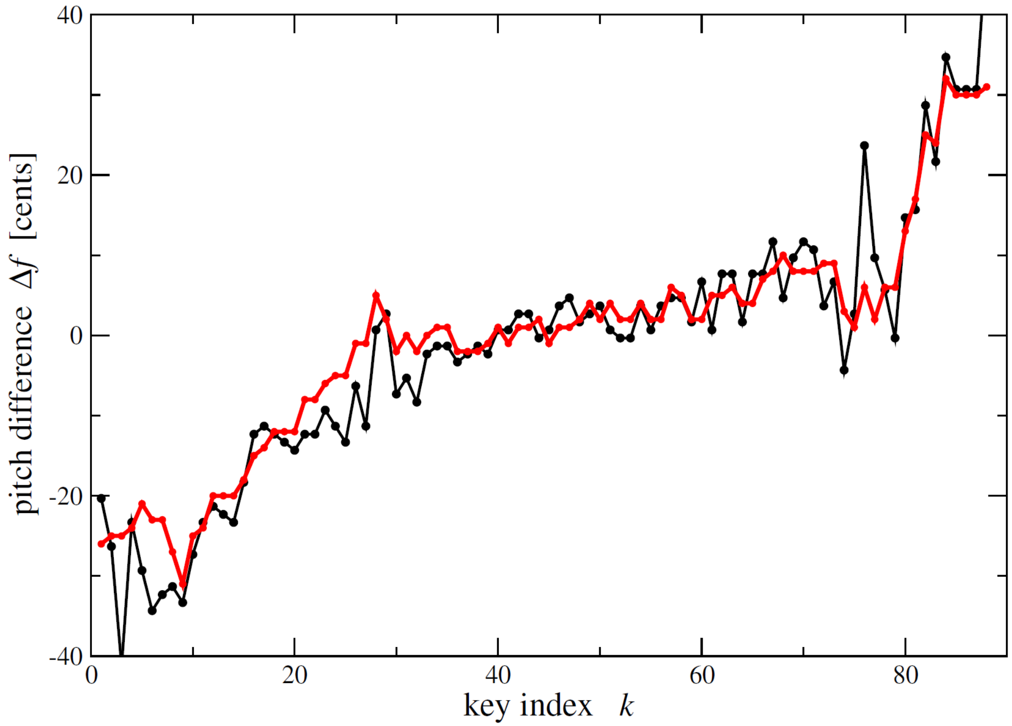

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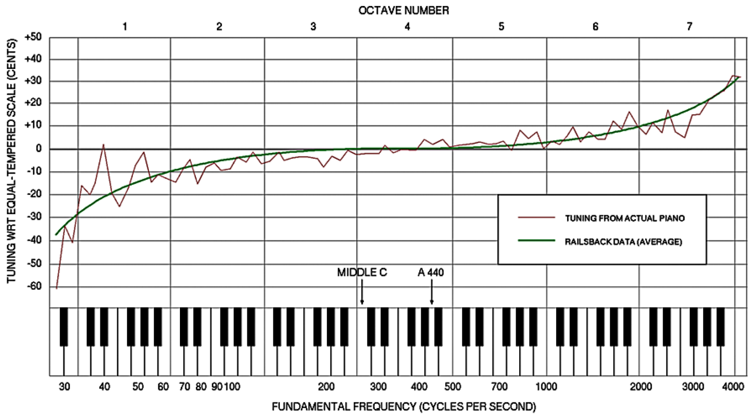
Method reproduces the stretch curve

Fluctuations are correlated (!), especially in the treble and the bass



Media Interest: Articles, Blogs, ...

English

IOP PhysicsWorld.com
MIT Technology Review
The Wall Street Journal
Daily Mail – Mail Online
Discover Magazine
Pano News Archiv
Microsoft Future Tech
Physics4me
The Week behind
Quantummaniac
33rd Square
Piano Tuner Technicians Forum
Tune a Piano Yourself Blog
Editorial RBEF
...

German

Heise Newsticker
Technology Review Heise Online
Deutschlandradio Kultur
Pressestelle Uni Würzburg
showmedia.de
Nürnberger Zeitung (NZ)
Wiley Interscience pro-physik
Codex Flores: Viel Aufregung...
Medizin&Technik: Wir wollen Spaß
Neurosociology & Neuromarketing
Interview Klassikradio
Interview BR2
Mainpost
...

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Author: Several open questions and remaining tasks

- Method tested on only one piano so far
- Apparently there are many local minima, and the present algorithm gives similar but not reproducible results
- Step-size of one cent is smaller than the resolution of the ear
- When additional filter function for “inner ear → brain” (“loudness”) are included, one obtains unreasonable stretches in the bass
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MIT Technology Review, ... : *"Algorithm Spells the End for Professional Musical Instrument Tuners"*