# Quantum Kibble-Zurek mechanism v. quantum simulators/annealers

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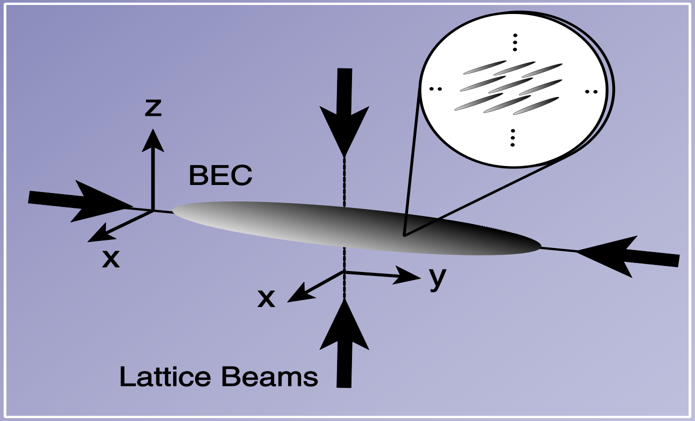
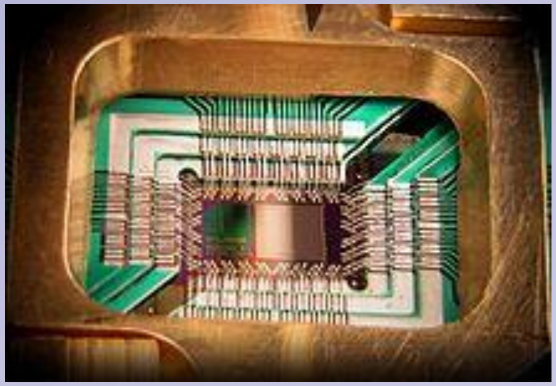
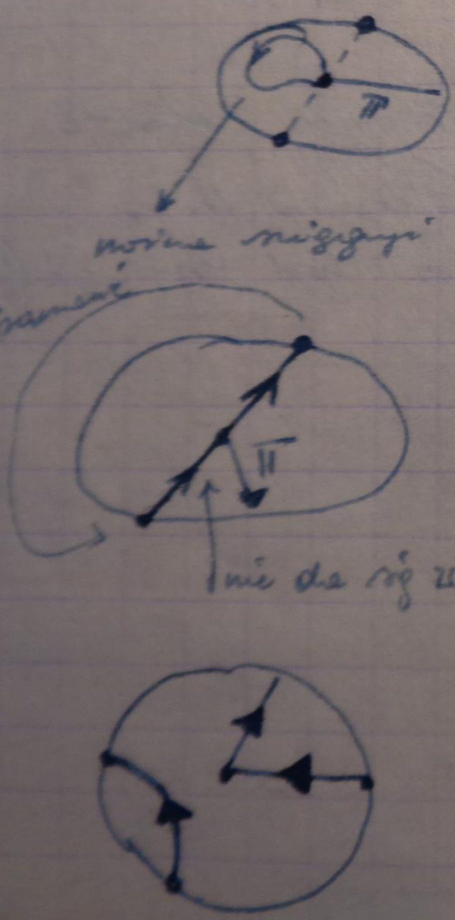


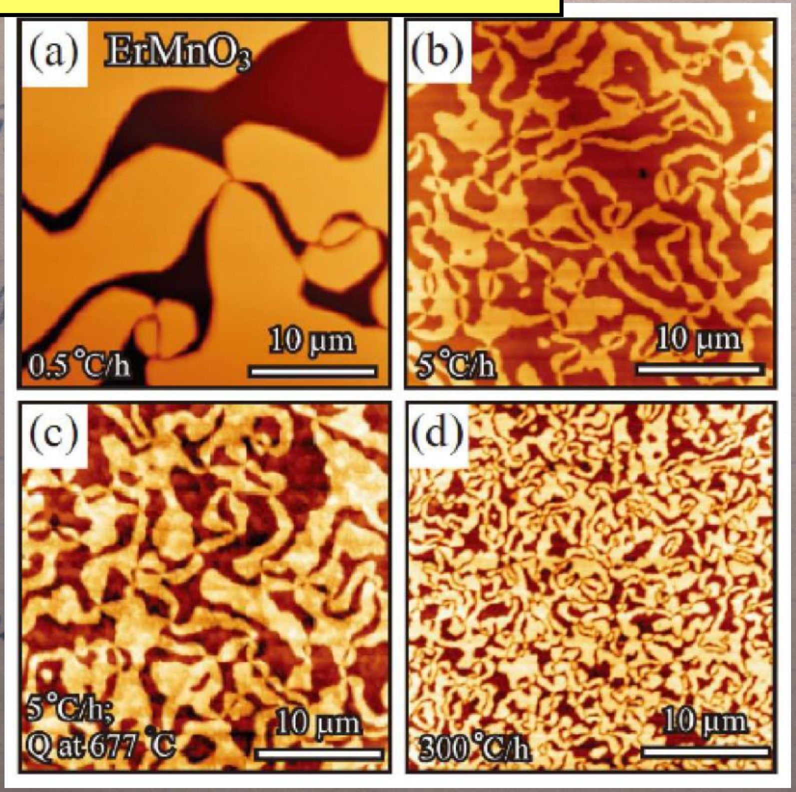
**Tutorial:**
**JD, Adv. in Phys. 2010**

# When symmetry breaks how big are the pieces?

early Universe(?)



e.g. multiferoics




quantum phase transitions

# The workhorse: Quantum Ising Chain

$$H = -\sum_{n=1}^{N} \left( g \sigma_n^z + \sigma_n^x \sigma_{n+1}^x \right)$$

Strong transverse field g>>1

$$\left| \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \ldots \right\rangle$$

Quantum phase transition at g=1

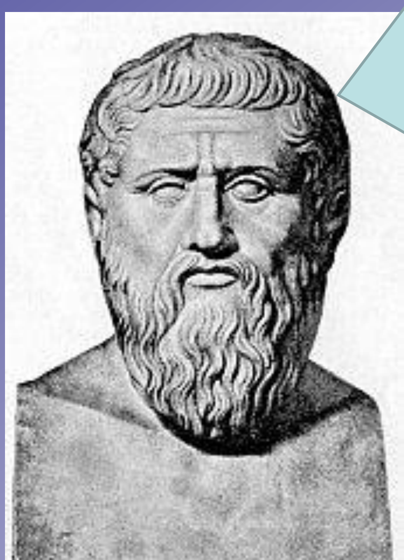
Energy gap $\Delta \to 0$

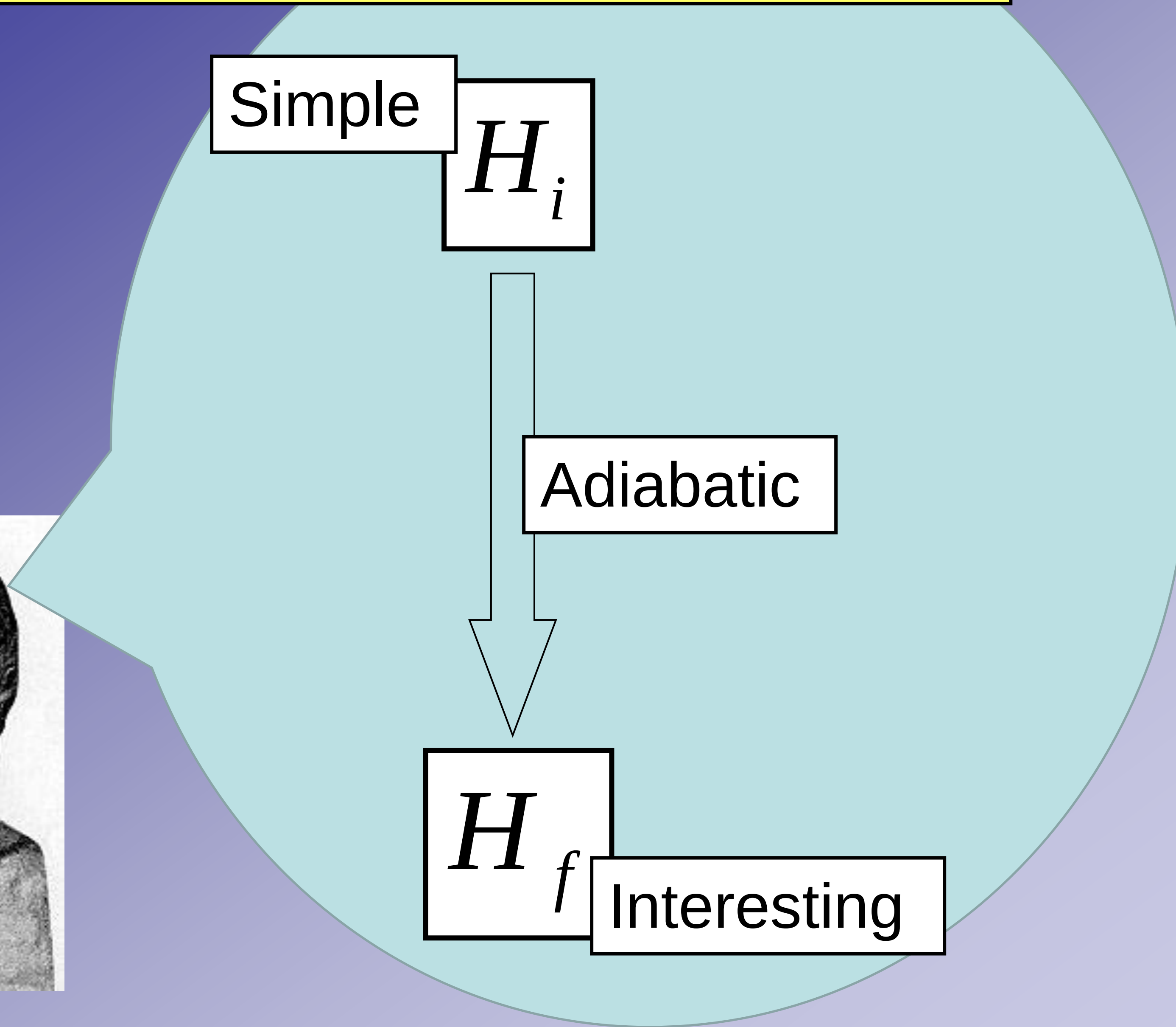
Correlation length $\xi \to \infty$

Ferromagnetic ground states at g=0

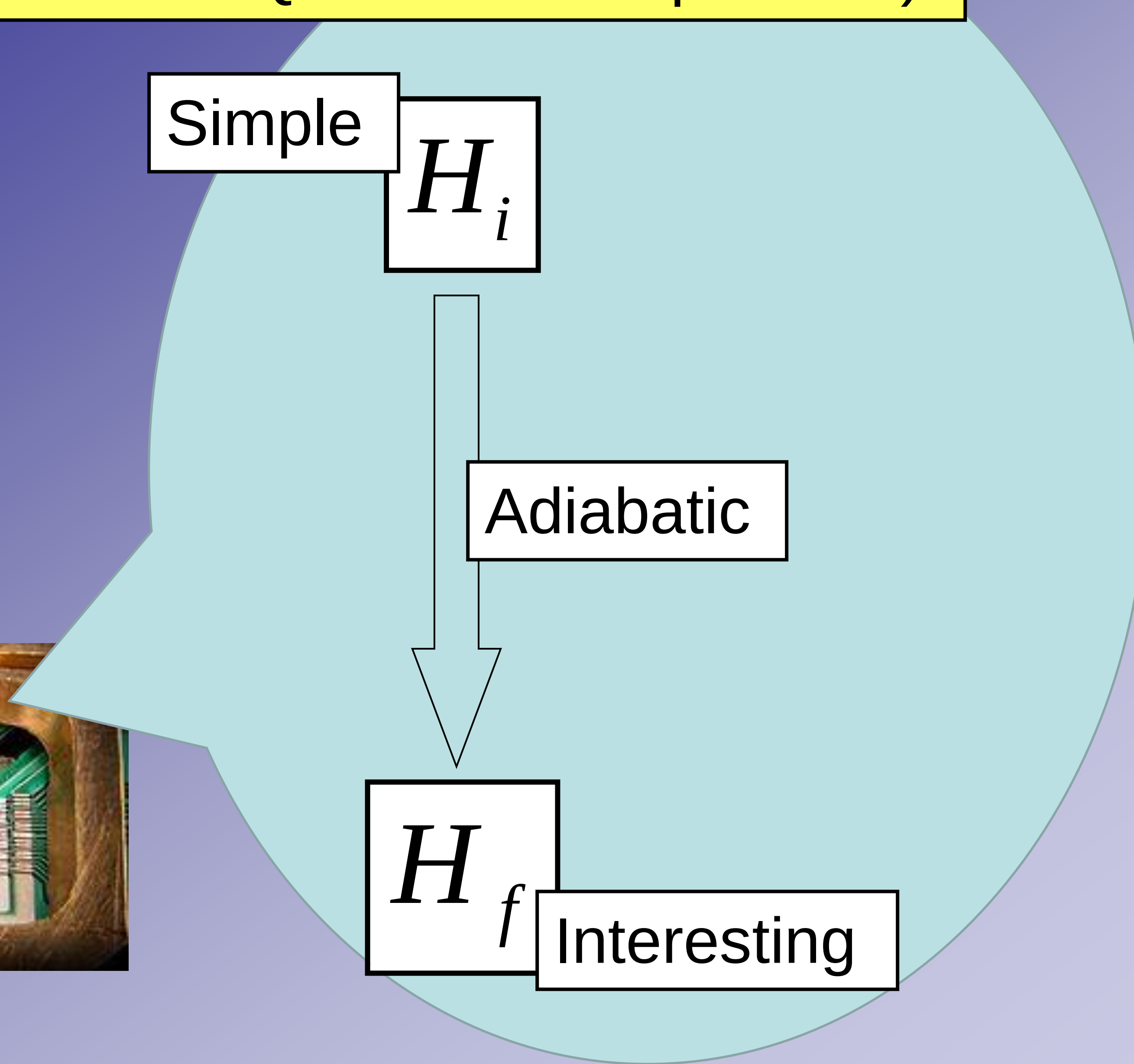
$$\left| \uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow \ldots \right\rangle \text{ or } \left| \downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow \ldots \right\rangle$$

# **Ideal** Adiabatic Quantum State Preparation (or Adiabatic Quantum Computation)

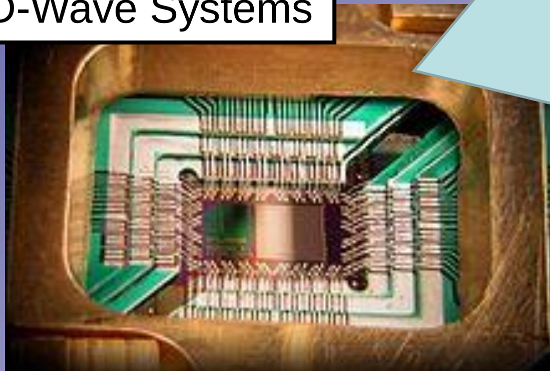




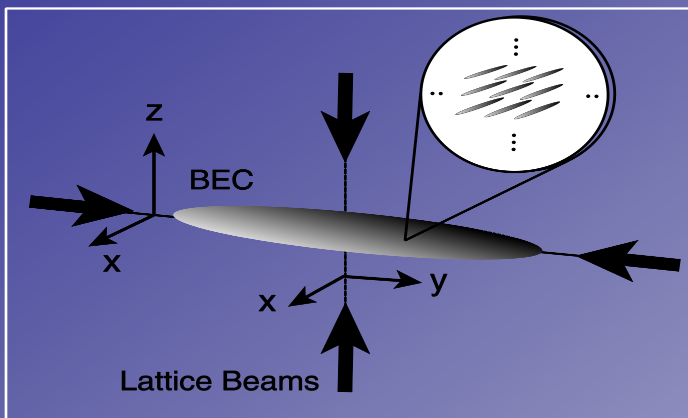
# **Ideal** Adiabatic Quantum State Preparation (or Adiabatic Quantum Computation)

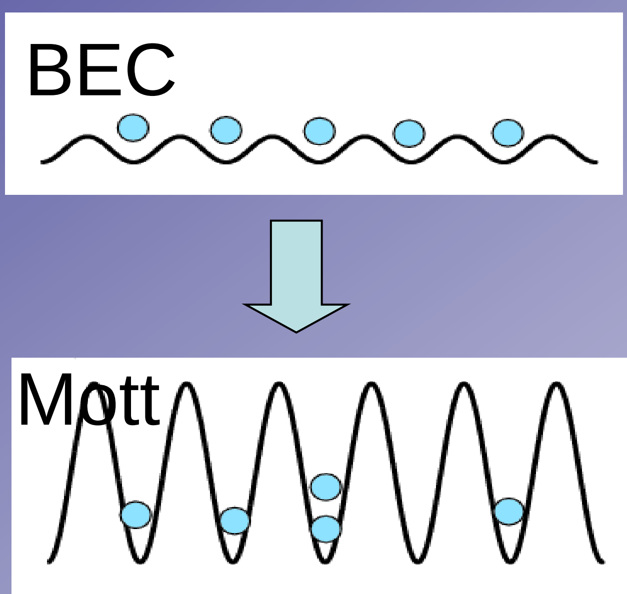



D-Wave Systems



# **Real** Adiabatic Quantum State Preparation




Simple $H_i$

↓

Simple ≠ Interesting

$\Downarrow$

Quantum Phase Transition

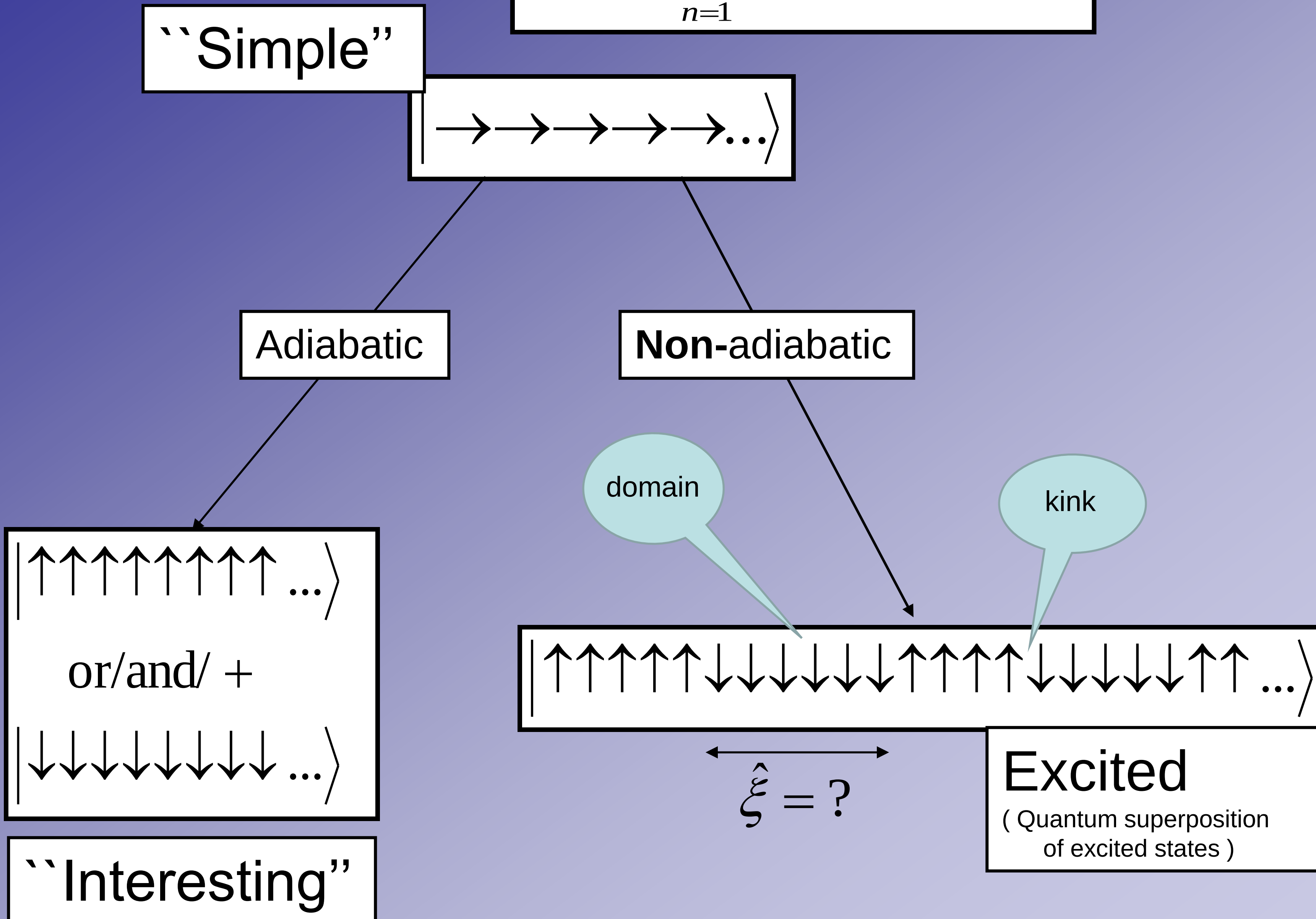
**Non-**adiabatic

↓

$H_f$ Interesting

# Quantum Ising Chain

$$H = -\sum_{n=1}^{N} \left( g\sigma_n^z + \sigma_n^x \sigma_{n+1}^x \right)$$



# Quantum Kibble-Zurek mechanism (KZM)

$$\varepsilon = \frac{g_c - g}{g_c}$$

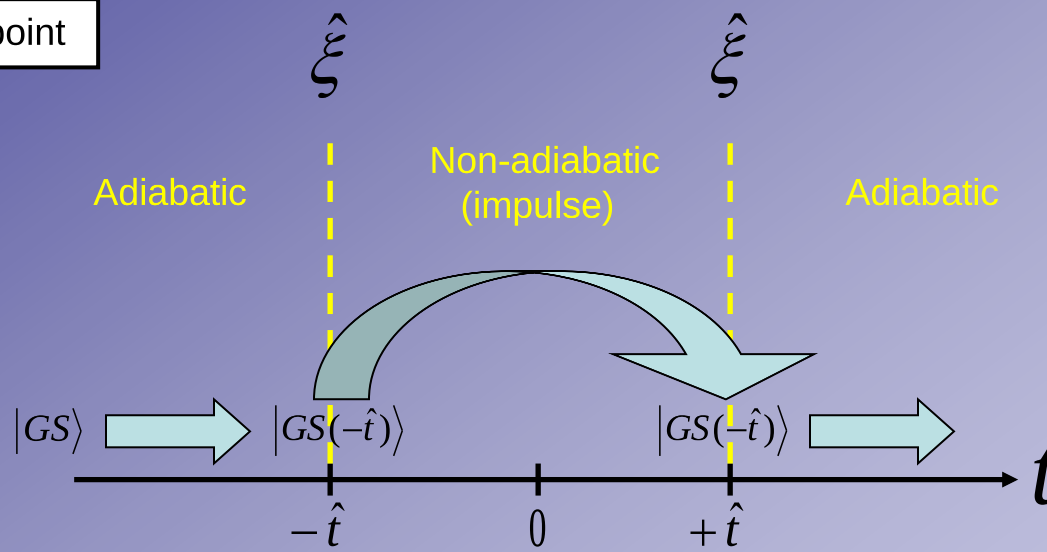
distance from the critical point

$$\Delta \propto |\varepsilon|^{z\nu}$$

energy gap

$$\xi \propto |\varepsilon|^{-\nu}$$

correlation length

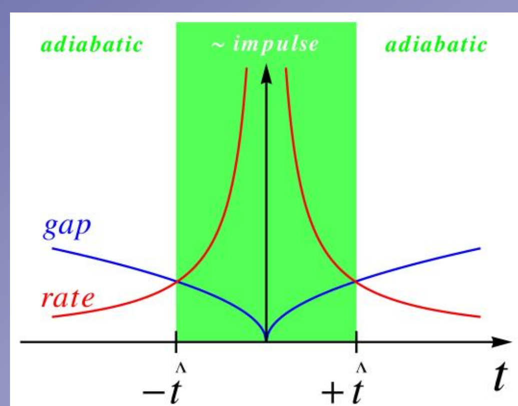



linear(ized) quench

$$\varepsilon = \frac{t}{\tau_Q}$$

$$\left|\frac{d\varepsilon/dt}{\varepsilon}\right| = \frac{1}{|t|}$$

transition rate




RATE = GAP at $t = -\hat{t}$

where $\hat{t} \propto \tau_Q^{\frac{z\nu}{1+z\nu}}$ and $\hat{\xi} \propto \tau_Q^{\frac{\nu}{1+z\nu}}$

$$|\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\ldots\rangle$$

Final excited state

$$\hat{\xi} \propto \sqrt{\tau_Q}$$

Quantum Ising chain

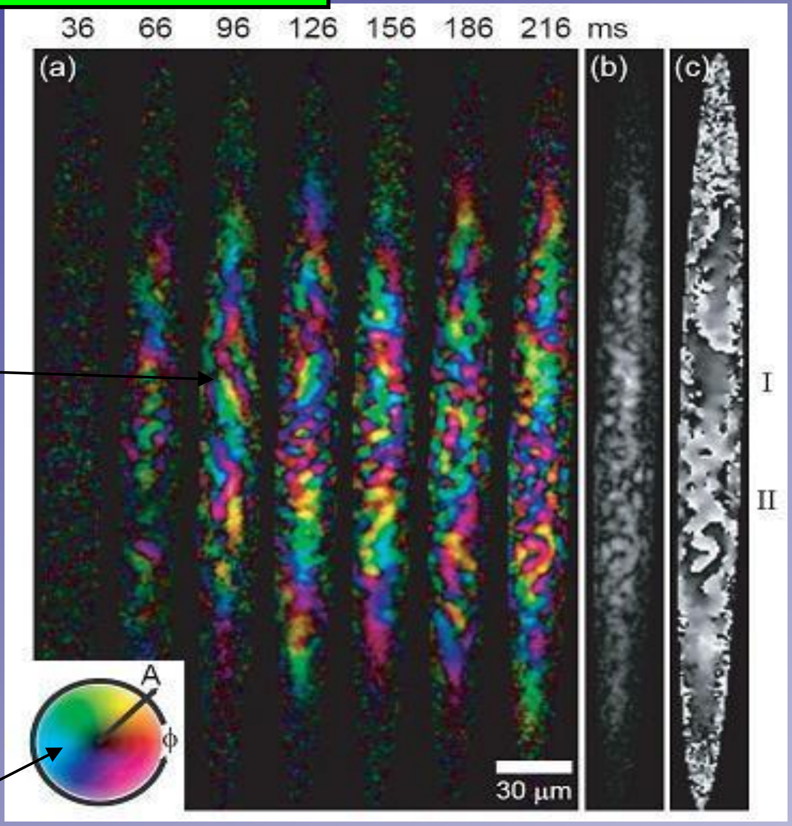
$$\hat{\xi} \propto \sqrt{\tau_Q} \quad \text{and} \quad \hat{t} \propto \sqrt{\tau_Q}$$

**Exact: JD, PRL 2005**

# Experiment: S=1 condensate

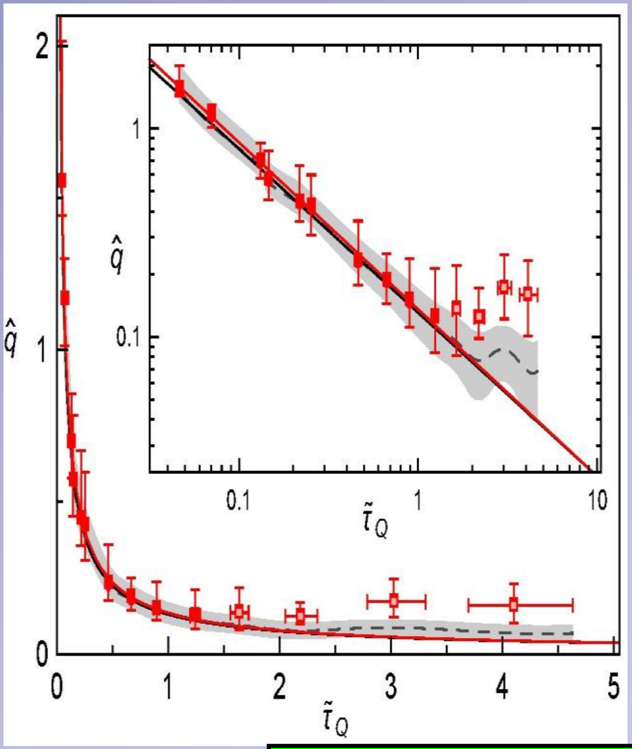
PARA → FERRO

Sadler et al., Nature 2006




Finite ferromagnetic domains

Planar spin orientation




Anquez et al., PRL 2016

# K-Z scaling hypothesis

scaled time

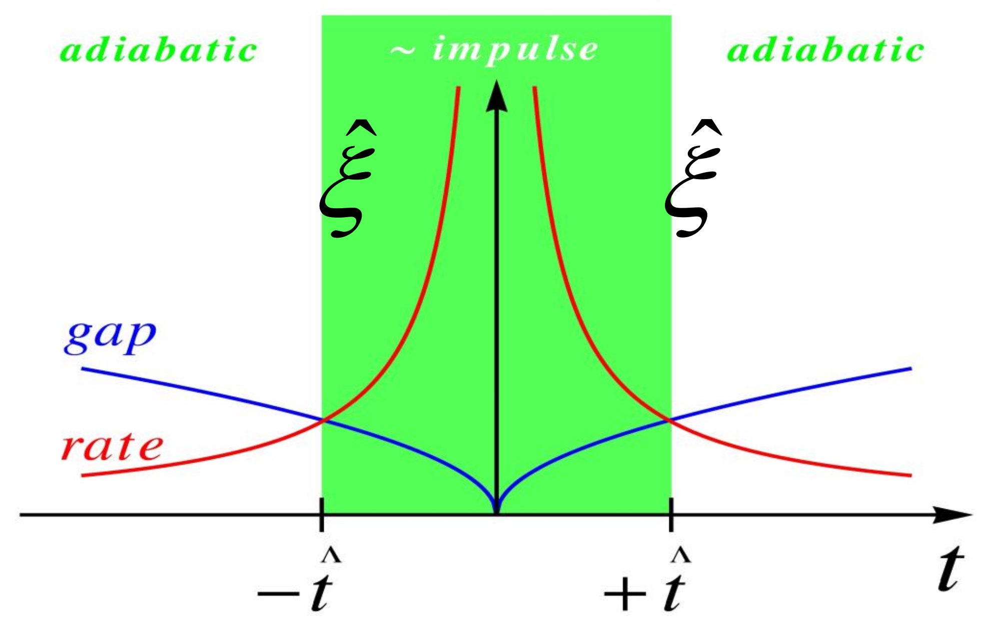
$$t/\hat{t}$$

scaled distance

$$x/\hat{\xi}$$

they are not independent

$$\hat{t} \propto \hat{\xi}^{z}$$




scaling dimension

$$\langle \psi(t) | \hat{O}(x) | \psi(t) \rangle = \hat{\xi}^{-\Delta_O} F_O(x/\hat{\xi}, t/\hat{\xi}^{z})$$

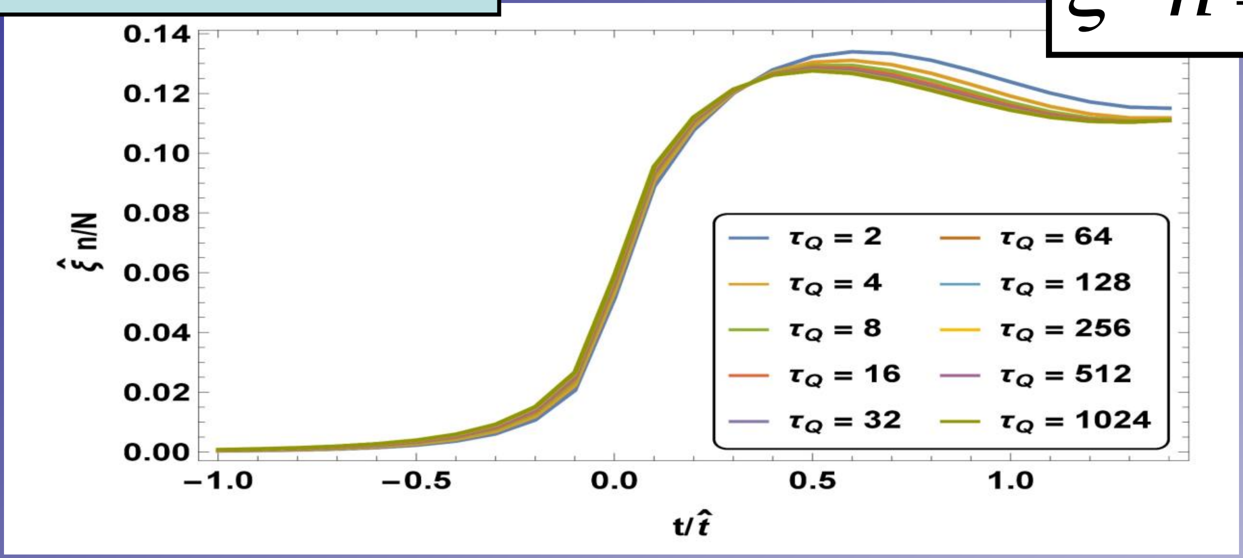
scaling function

Francuz et al., PRB 2015

# Quantum Ising Chain

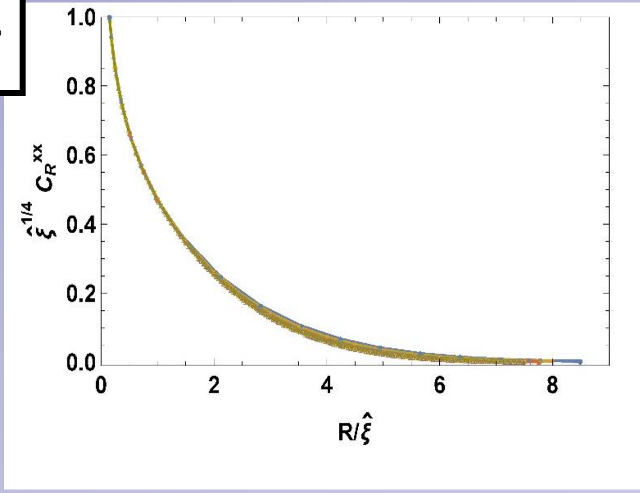
density of excitations

$$\hat{\xi}^1 n = F_n(t / \hat{\xi})$$




ferromagnetic correlator

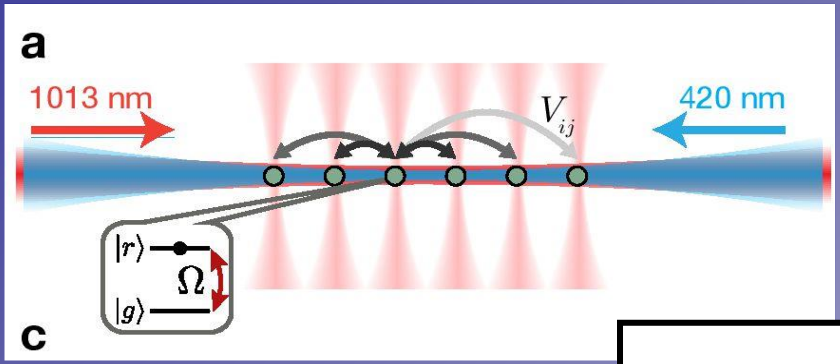
$$C_R^{xx} = \langle \sigma_{n+R}^x \sigma_n^x \rangle - \langle \sigma_{n+R}^x \rangle \langle \sigma_n^x \rangle$$



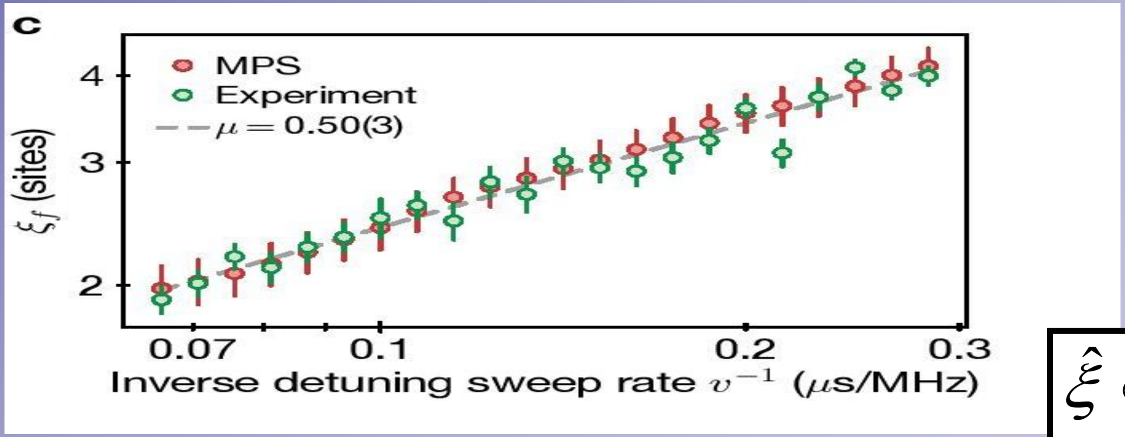
# Experiment: Rydberg atoms

## Or Ising model 13 years later

**Lukin's group, Harvard & MIT, 2018**




$$H = -\sum_{n=1}^{N}\left(\Omega\sigma_n^z + h\sigma_n^x - \sigma_n^x\sigma_{n+1}^x\right)$$




$$\hat{\xi} \propto \sqrt{\tau_Q}$$

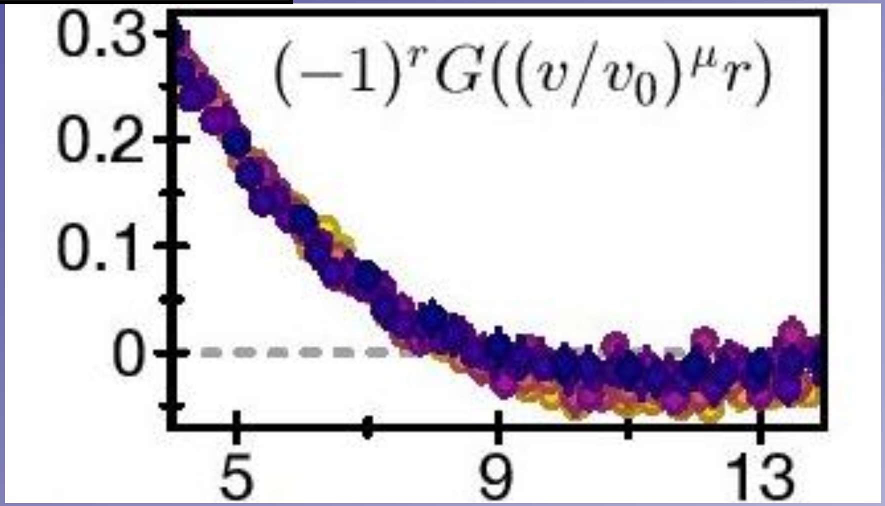
# Experiment: Rydberg atoms

## Or Ising model 13 years later

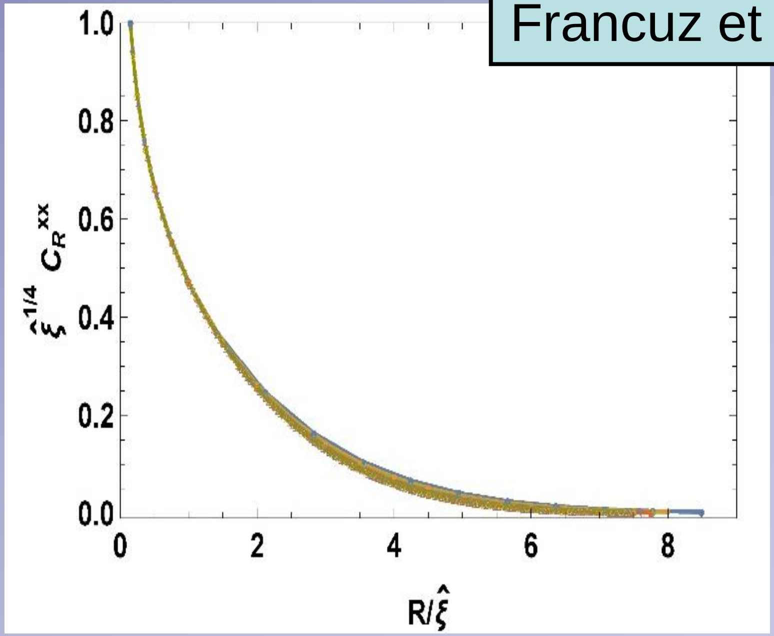
**Lukin's group, Harvard & MIT, 2018**

scaled correlator

experiment




prediction
Francuz et al..



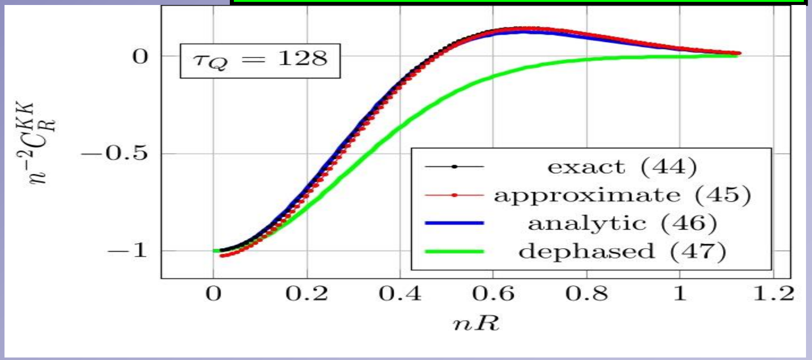
# More theory: kink-kink correlations

Quantum coherence =>
Peak in the kink-kink correlator

kink          kink

$$|\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\ldots\rangle$$

**Radek Nowak & JD, PRB 2018**

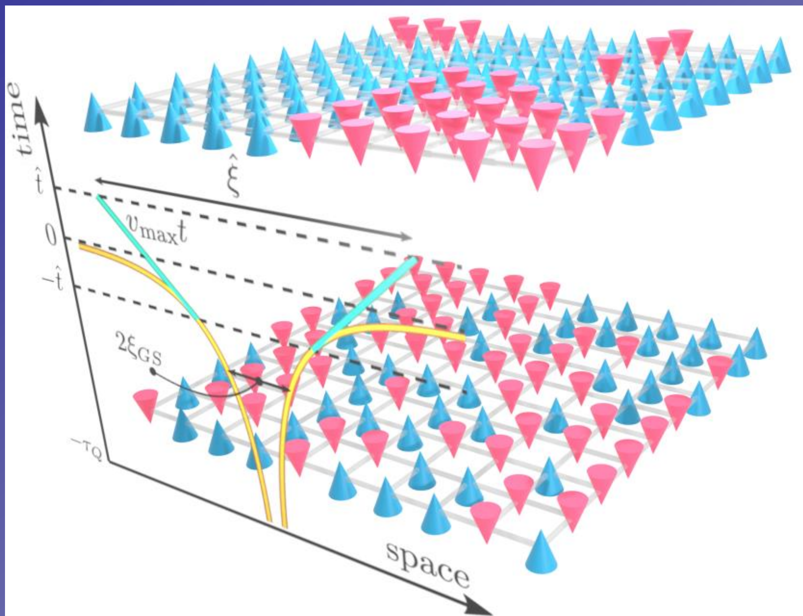



$$C_R^{KK} = \langle K_n K_{n+R} \rangle_c$$
$$= \langle K_n K_{n+R} \rangle - \langle K_n \rangle \langle K_{n+R} \rangle$$

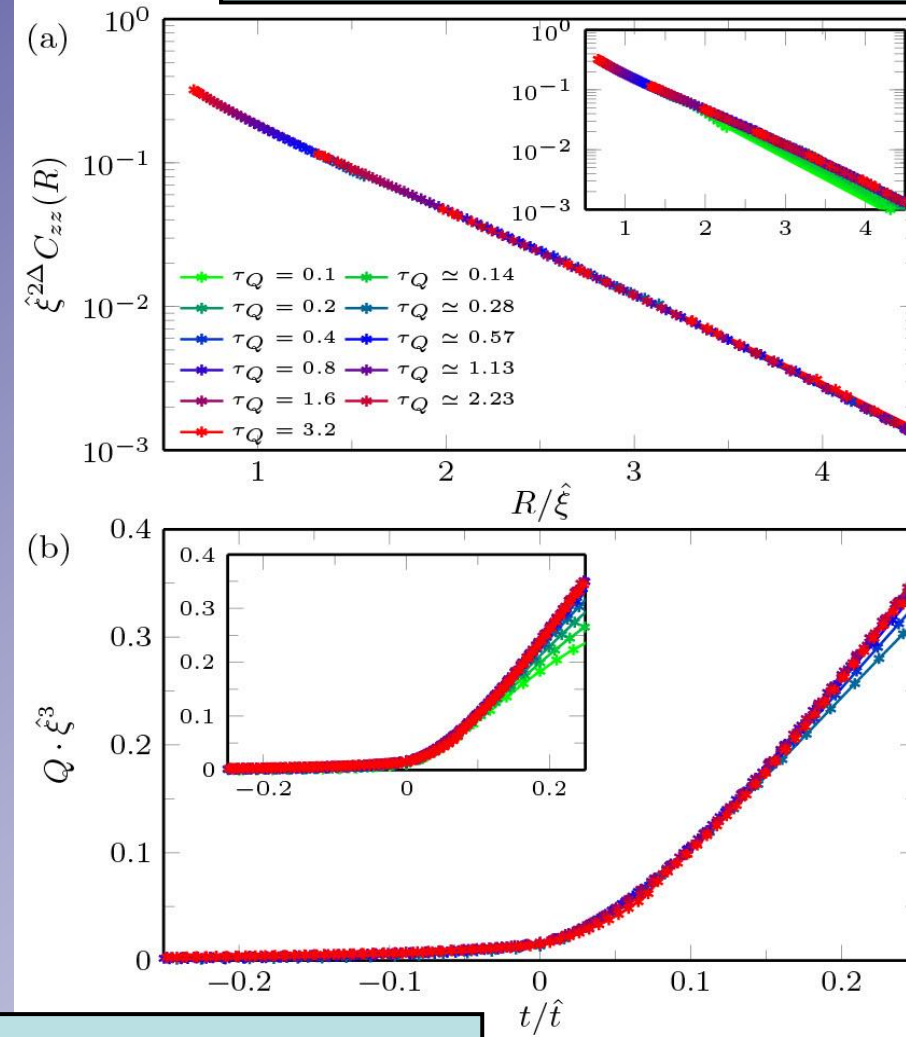
Simple test of quantumness

# More numerics: quantum Ising in 2D

**Schmitt, Rams, D, Heyl, Zurek, arxiv:2106.09046**




Correlation function (iPEPS)

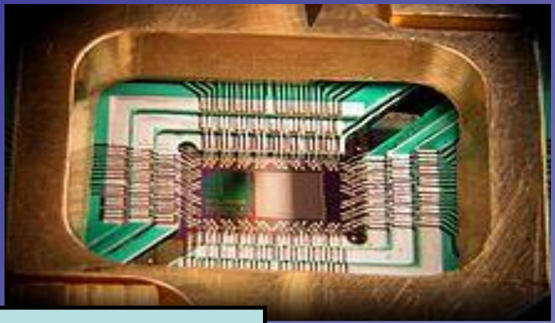



State of the art. numerics:
TDVP (M. Rams)
iPEPS (JD)
Neural networks (M. Schmitt)

Excitation energy, Q

**2D Rydberg atoms experiment:**
**Ebadi et al., Harvard & MIT, Nature 2022**

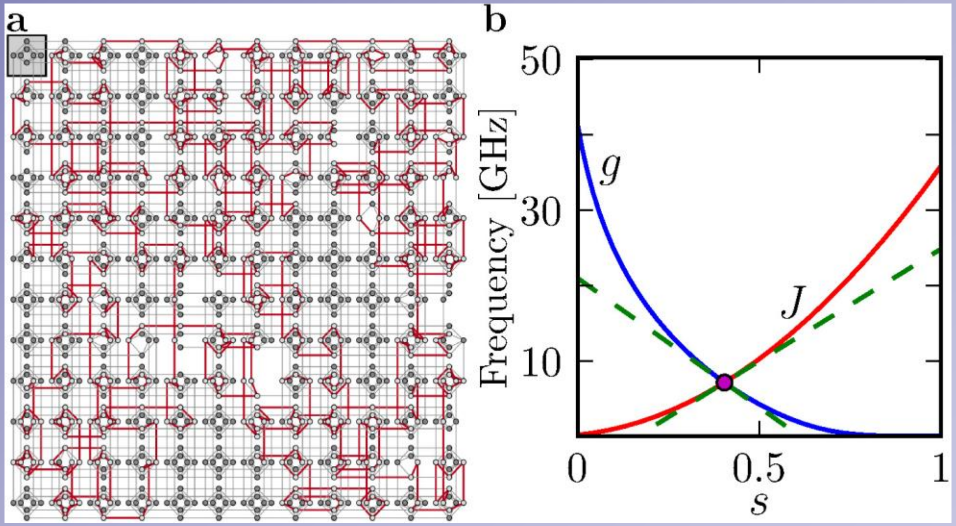
# Experiment: 1D Ising on D-Wave



~ 2000 qubits

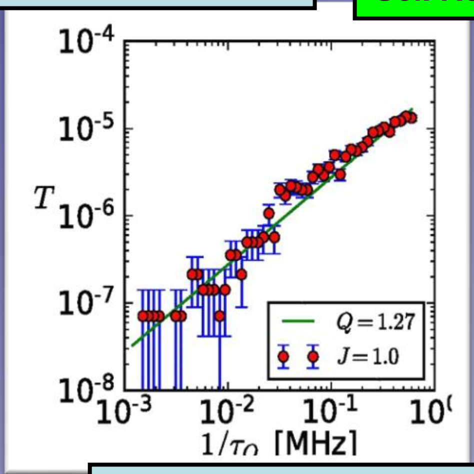
programmable Hamiltonian, e.g.

$$H = -g(t)\sum_{i=1}^{L}\sigma_i^x - J(t)\sum_{i=1}^{L-1}\sigma_i^z\sigma_{i+1}^z,$$




scaling law….

**Gardas, D, Zurek & Zwolak, Sci. Rep. 2018**



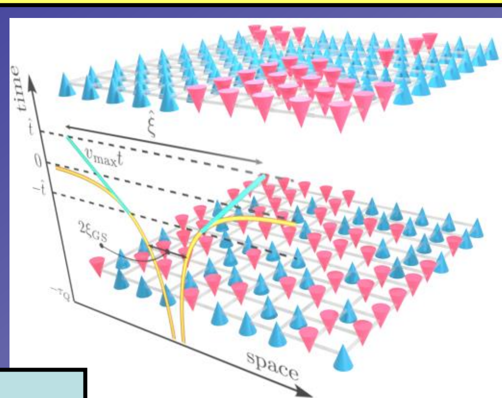

Confirmed by D-Wave Staff!

…..decoherence, not quantum KZ

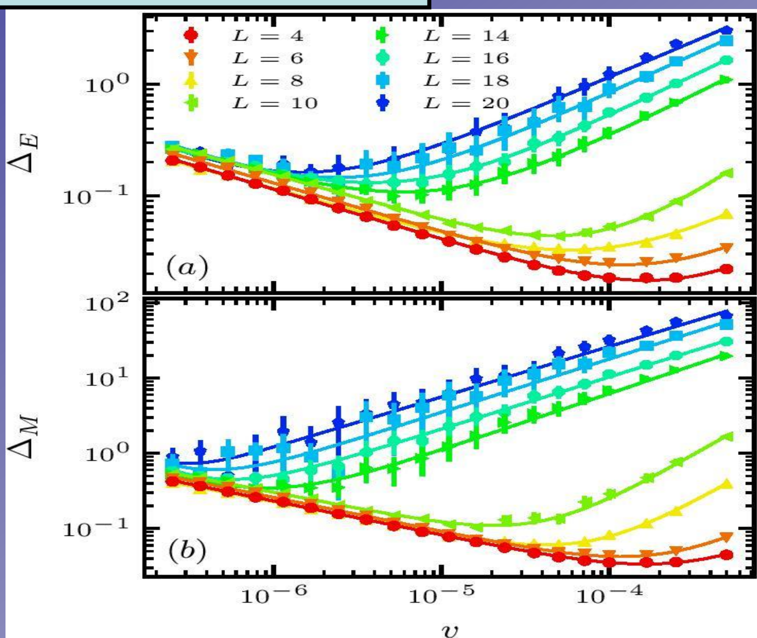
Depends on embedding, time of the day….

# Experiment: 2D quantum Ising on D-Wave

**Weinberg, Tylutki, …., Sandvik, PRL 2020**

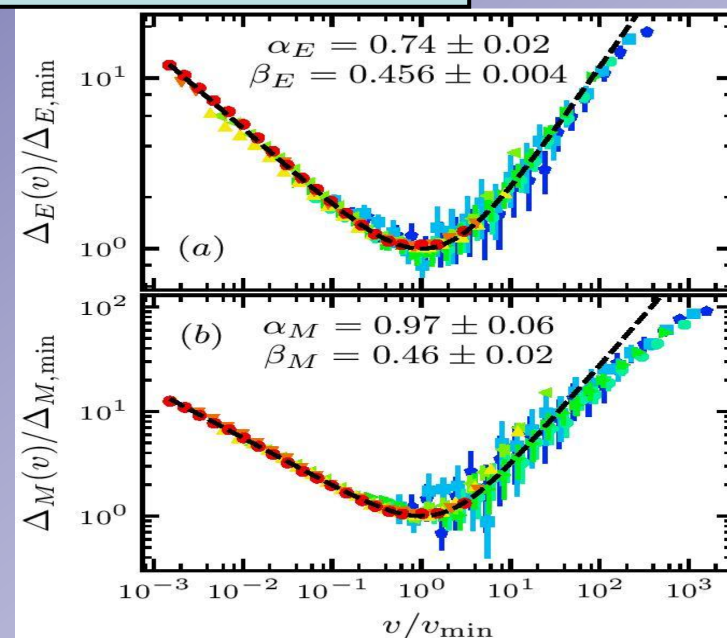



Excitation energy




Magnetization deficit(?)

Power law fits…..



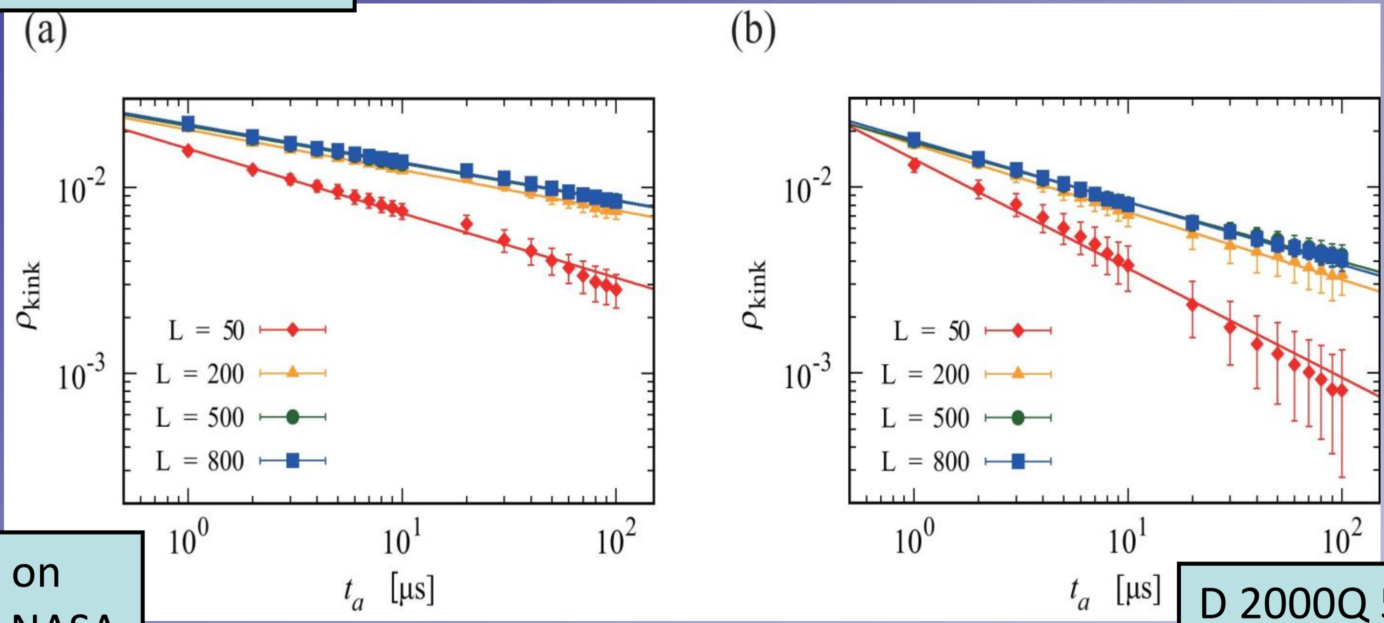

…. in adiabatic regime

Decoherence, not quantum KZ

# Experiment: 1D quantum Ising on D-Wave, again

**Bando, …., del Campo,….,Nishimori, PRR 2020**

Number of kinks




C16 solver on DW2KQ at NASA

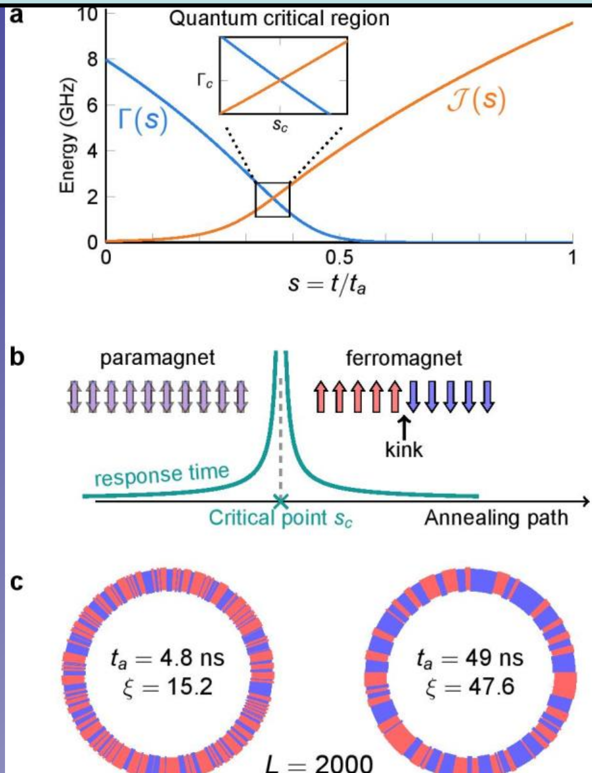
D 2000Q 5 solver on DW2KQ in Burnaby

Power laws explained by Ohmic environment

# Experiment: 1D quantum Ising on ``coherent D-Wave''

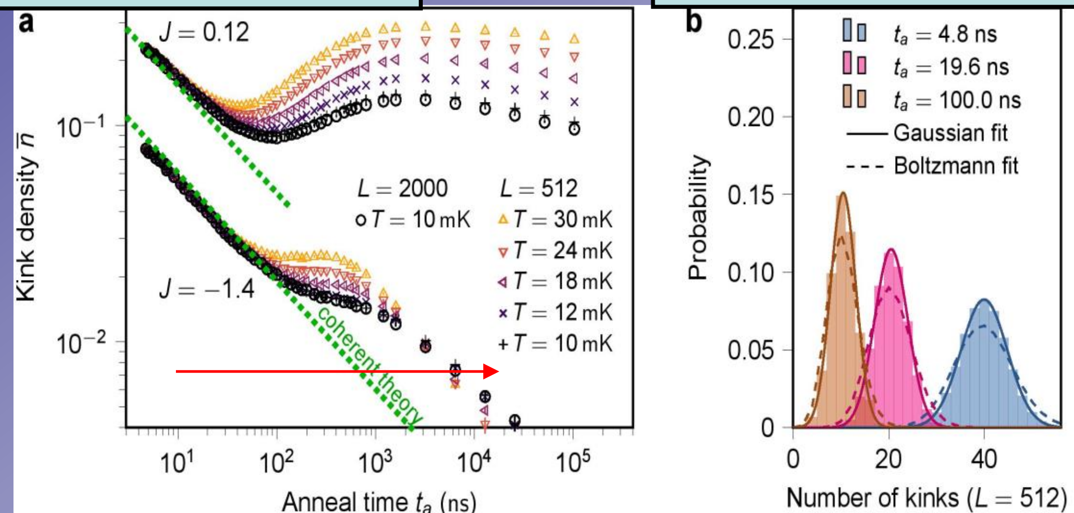
**Andrew King & 23 al. , arXiv:2202.05847**

D-Wave at 1000x speed limit

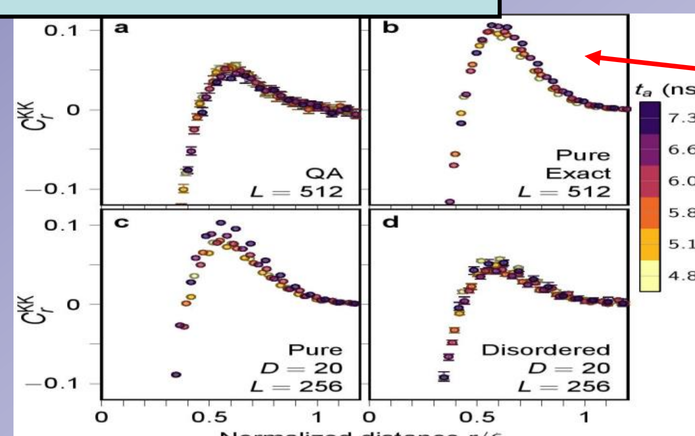



Number of kinks

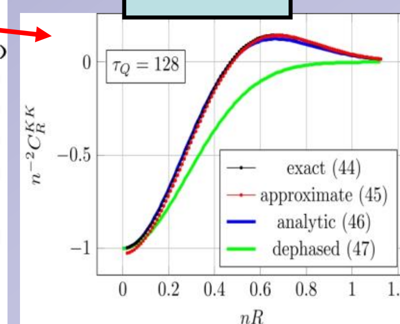
Kink distributions




Kink-kink correlator



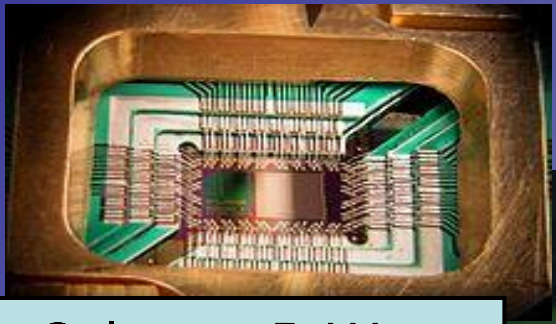

Peak




$|\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow \ldots\rangle$

Peak <= Coherence

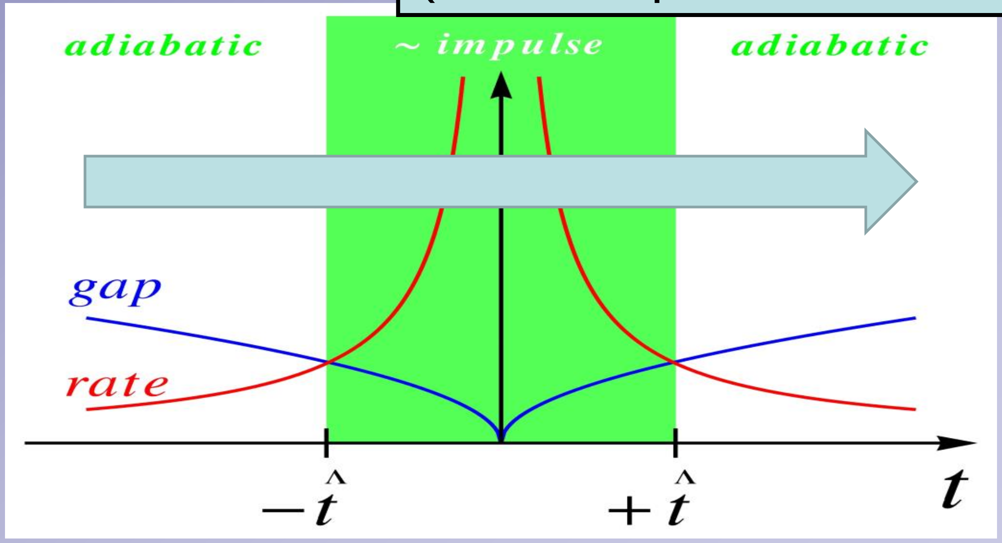
# Summary ….



Coherent D-Wave
(after engine tuning)

## ….and outlook

Shortcuts to adiabaticity
(across a phase transition)

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