odd interactions in quantum magnets and liquids

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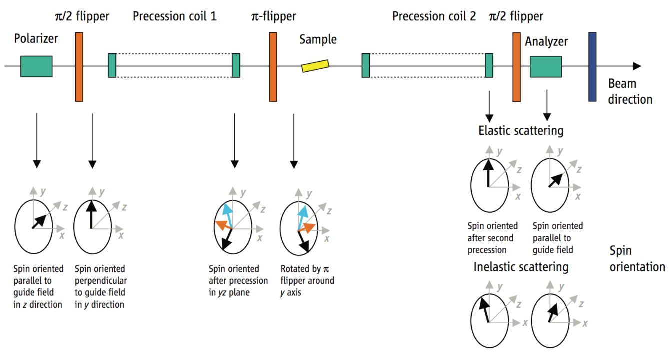
Office of Science

plan

I. ^{4}He, roton

II. XY magnets, lifetime

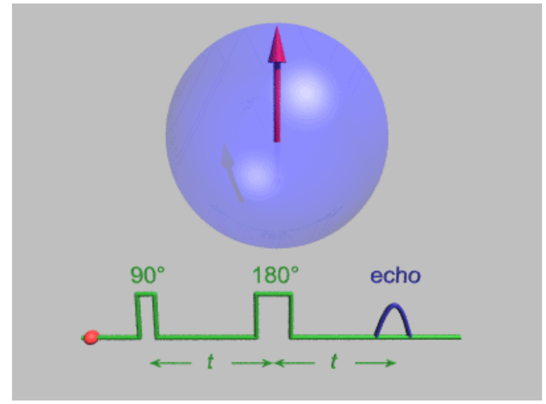
neutron-scattering spin-echo



APPLIED PHYSICS 1888 VOL 312 SCIENCE 2006

The Neutron Spin-Echo Technique at Full Strength

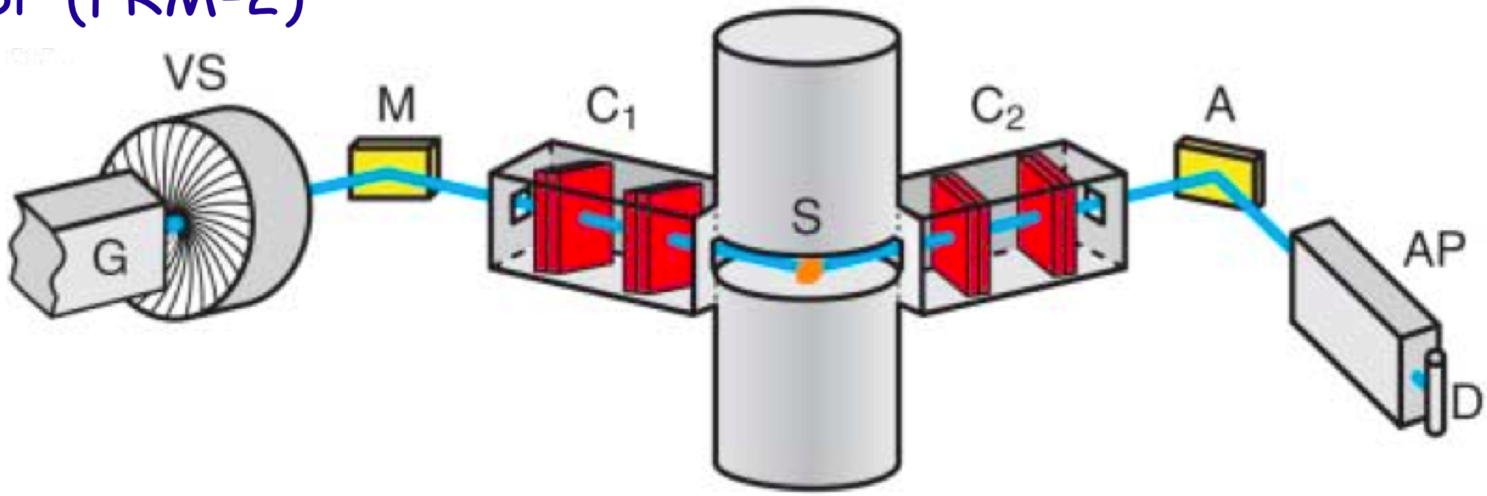
Joël Mesot



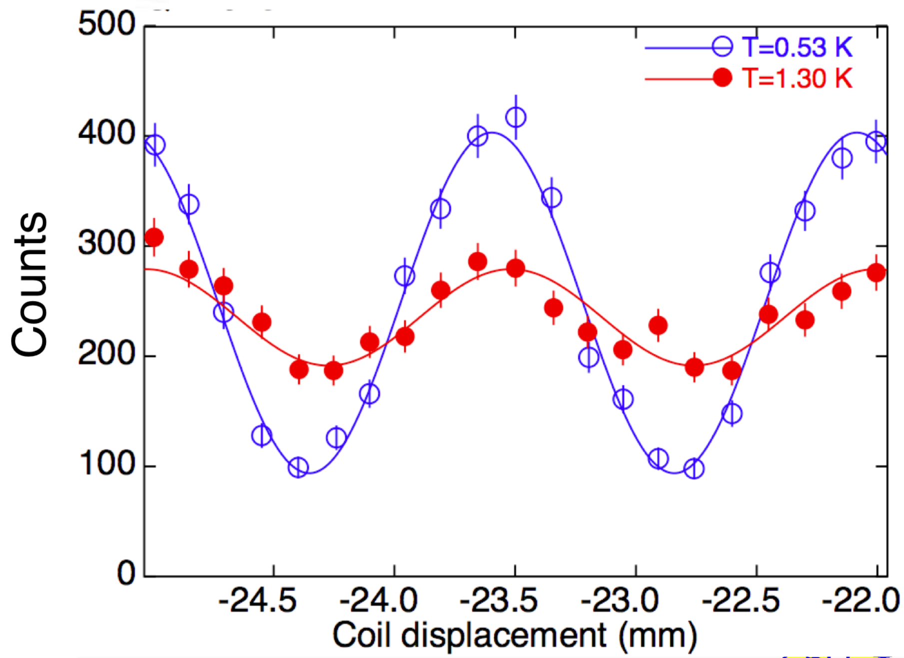
- resolution ~ 1μeV (≈0.01K) !

Neutron Resonant Spin Echo

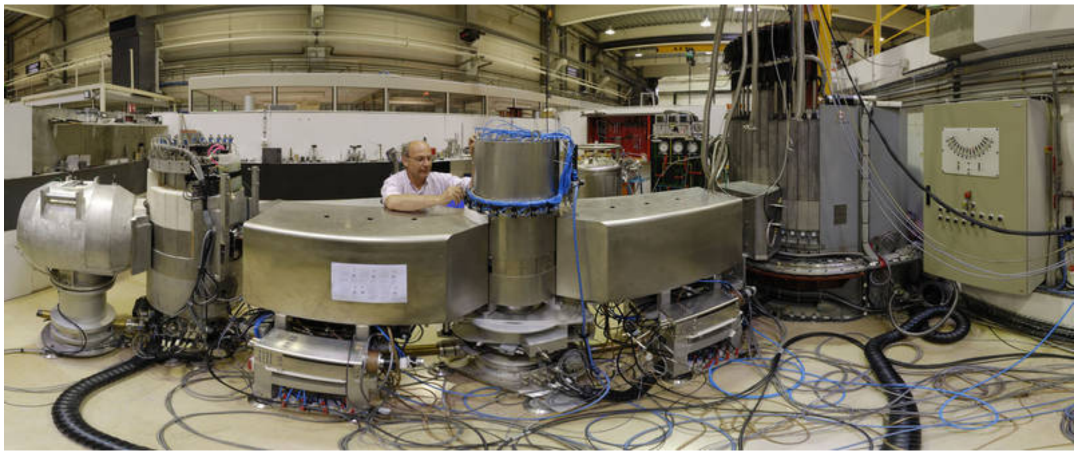
TRISP (FRM-2)

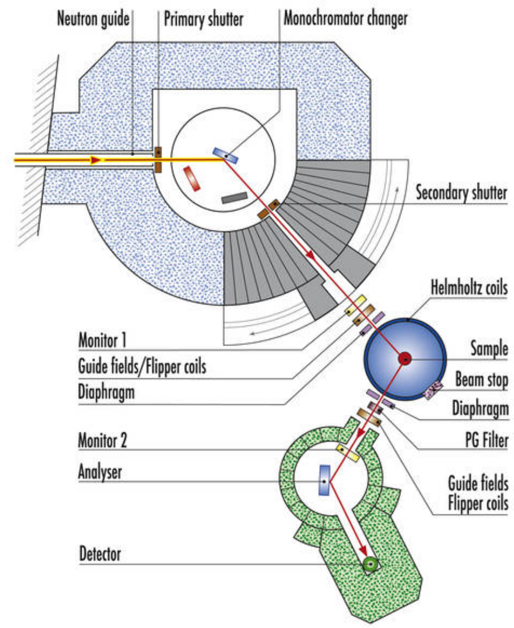


NRSE:
Line widths of dispersive modes
Energy shifts (phase stability)



ILL, IN22, and ZETA





Thermal neutron three-axis spectrometer with polarization analysis IN22

IN22 is a three-axis spectrometer (CRG) equipped for full polarization analysis. The option CRYOPAD and a 15 Tesla cryomagnet are optimised for inelastic scattering. The option ZETA provides neutron resonance spin echo (NRSE).

NEUTRONS FOR SCIENCE ®
Institut Laue-Langevin

CRG three-axis spectrometer IN22 with the ZETA resonant neutron spin-echo setup

I. odd interactions in superfluid ^{4}He

experiments: Björn Fåk (CEA, ILL)
Thomas Keller (Munich, Stuttgart)

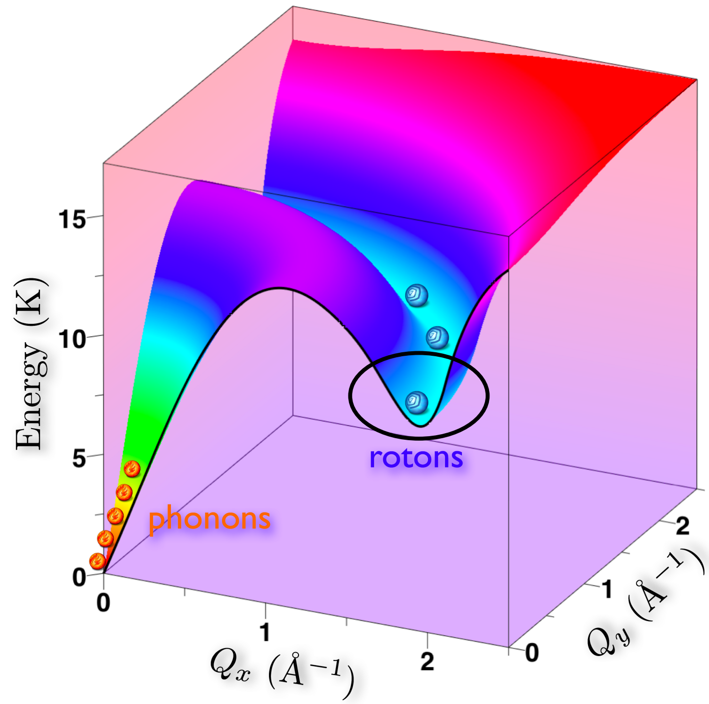
theory: Mike Zhitomirsky (CEA)
Sasha Chernyshev (UC Irvine)

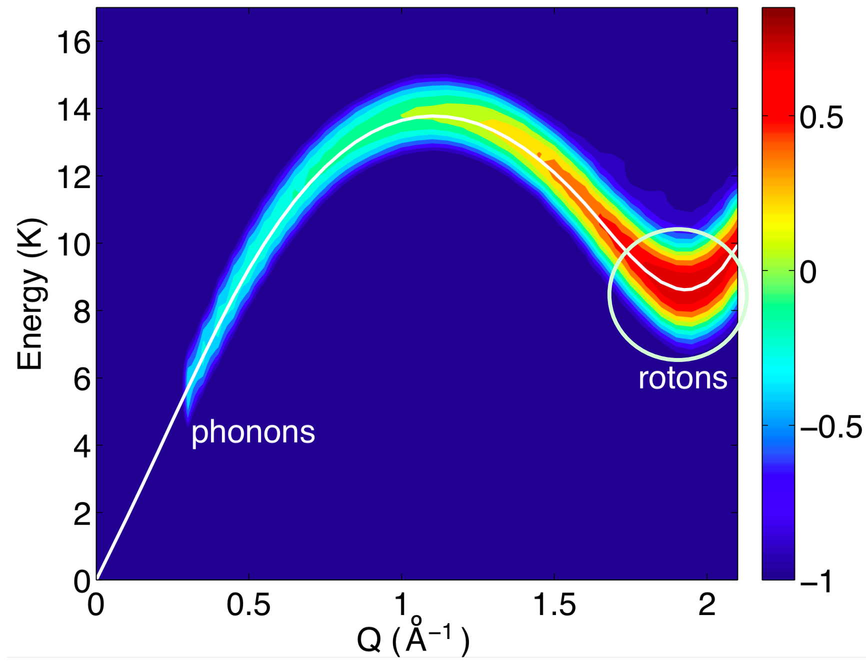
arXiv:1206.1498; PRL **109**, 155305 (2012)

plan

I. history
II. experiments
III. theory/comparison
IV. conclusions/outlook

spectrum of ^{4}He



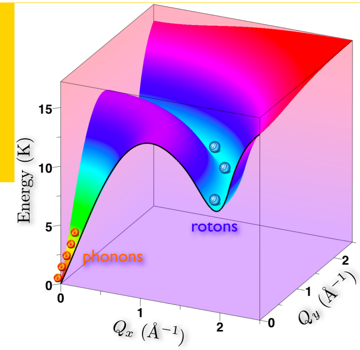


K. H. Andersen *et al*., J. Phys. Cond. Mat. **6**, 821 (1994).

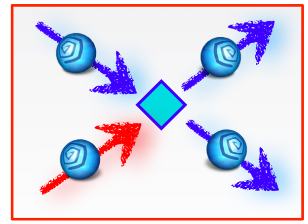
- *T*-dependence of roton's:
  - lifetime
  - energy

BF, TK, MZ, **SC**, PRL **109**, 155305 (2012).

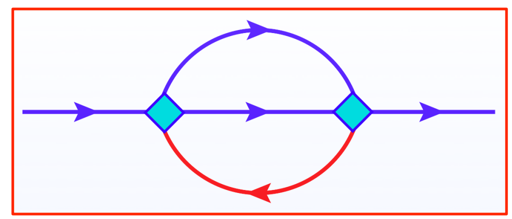
(long) history …



- L. D. Landau and I. M. Khalatnikov, *The theory of the viscosity of helium II: I. Collisions of elementary excitations in helium II,* Zh. Eksp. Teor. Fiz. **19**, 637- 650 (1949).
- roton lifetime (linewidth)



$$\Gamma(T) \propto N_r(T) \propto \sqrt{T}\, e^{-\frac{\Delta(T)}{T}}$$



- K. Bedell, D. Pines, and A. Zawadowskii, PRB **29**, 102 (1984).
- prefactors + energy shift

$$\delta(T) = \Delta(T) - \Delta_0 \propto N_r(T) \propto \sqrt{T}\, e^{-\frac{\Delta(T)}{T}}$$

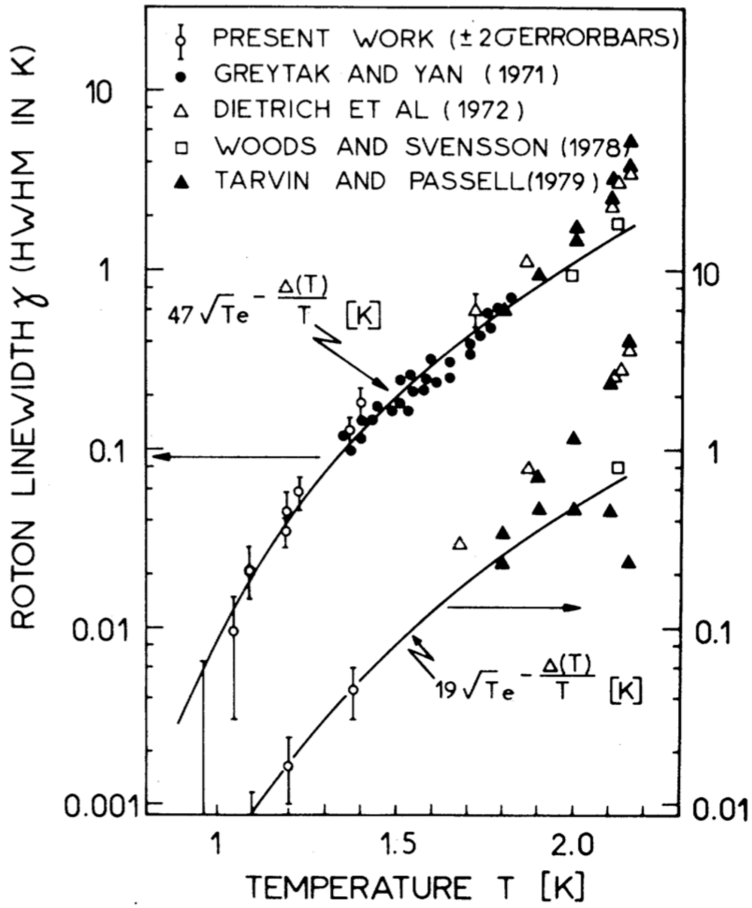
* **<u>no</u>** three-boson interaction needed/directly involved
** Hartree-term gives the same for $\delta(T)$

neutron-scattering spin-echo, (>1.2K)

VOLUME 44, NUMBER 24 PHYSICAL REVIEW LETTERS 16 JUNE 1980

High-Resolution Study of Excitations in Superfluid ^{4}He by the Neutron Spin-Echo Technique

F. Mezei



- LK-theory fits:
  - quantitative

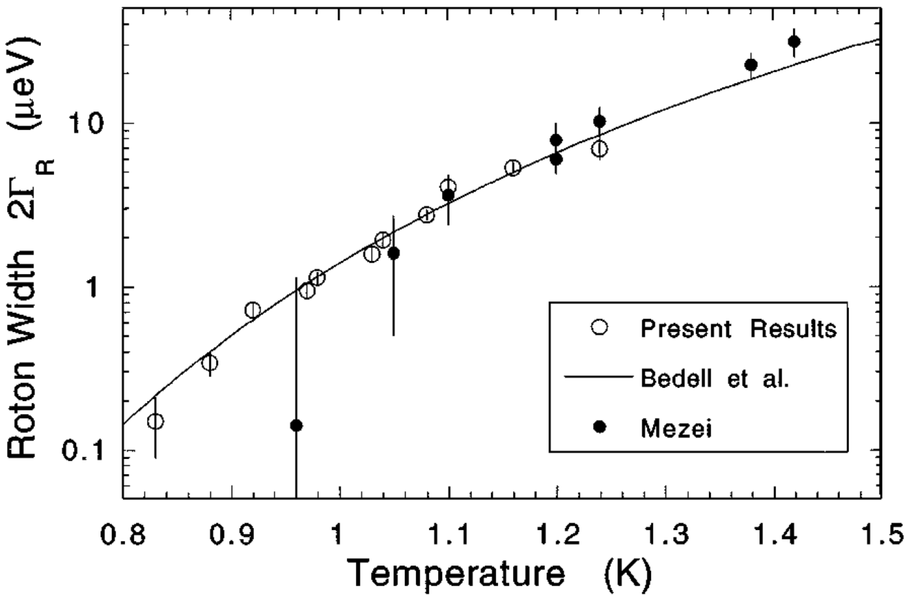
is this the end of the story?

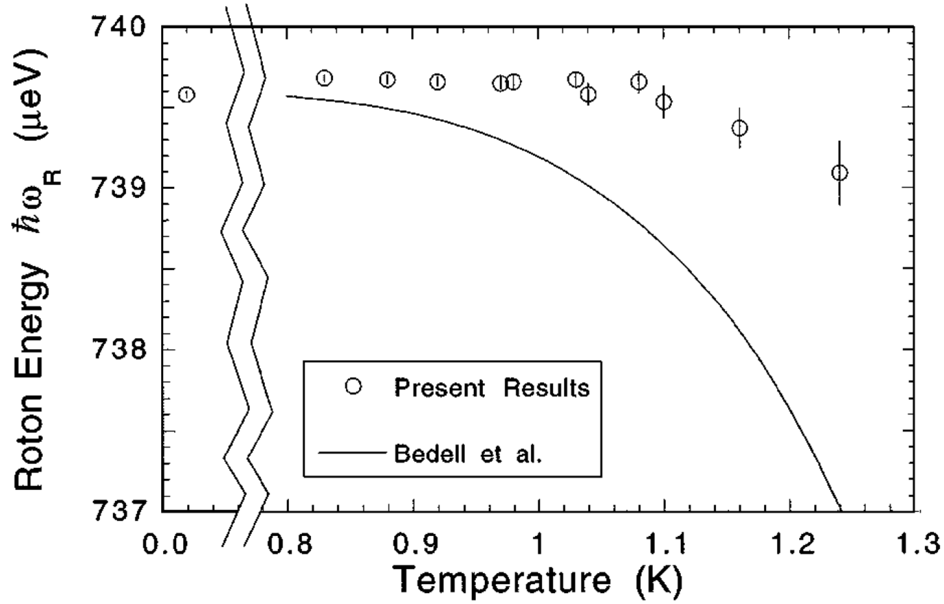
neutron-scattering spin-echo, (>0.88K)

VOLUME 77, NUMBER 19 PHYSICAL REVIEW LETTERS 4 NOVEMBER 1996

High-Resolution Measurements of Rotons in ^{4}He

K. H. Andersen, J. Bossy, J. C. Cook, O. G. Randl, and J.-L. Ragazzoni
Institut Laue-Langevin, B.P. 156, 38042 Grenoble Cedex 9, France
(Received 22 March 1996)



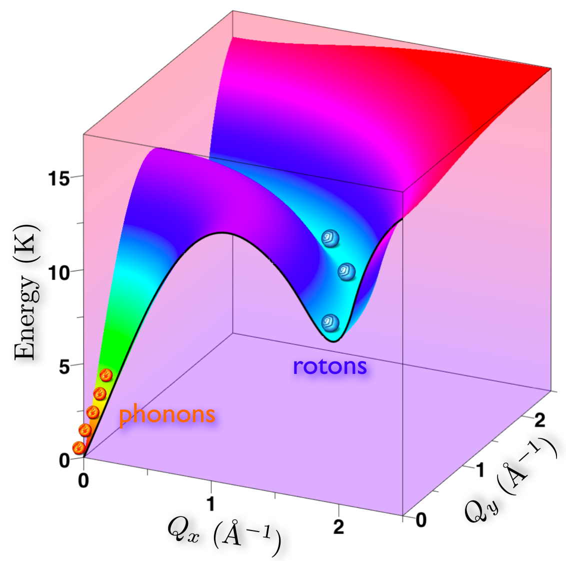


- linewidth:
  LK-theory continues to work

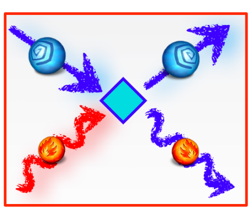
$$\Gamma(T) \propto N_r(T) \propto \sqrt{T}\, e^{-\frac{\Delta(T)}{T}}$$

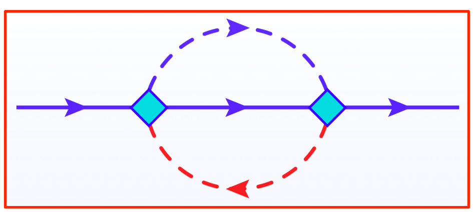
et al. and (2) that the temperature dependence of the roton energy cannot be described by the same theory in this temperature range. In fact, the rather good agreement between theory and experiment previously shown by the NSE technique [3], is now seen to break down below $T = 1.2$ K, while the theory is expected to work best in the $T \rightarrow 0$ limit.

phonons ?



- where are the phonons ?
- roton-*phonon* scattering:

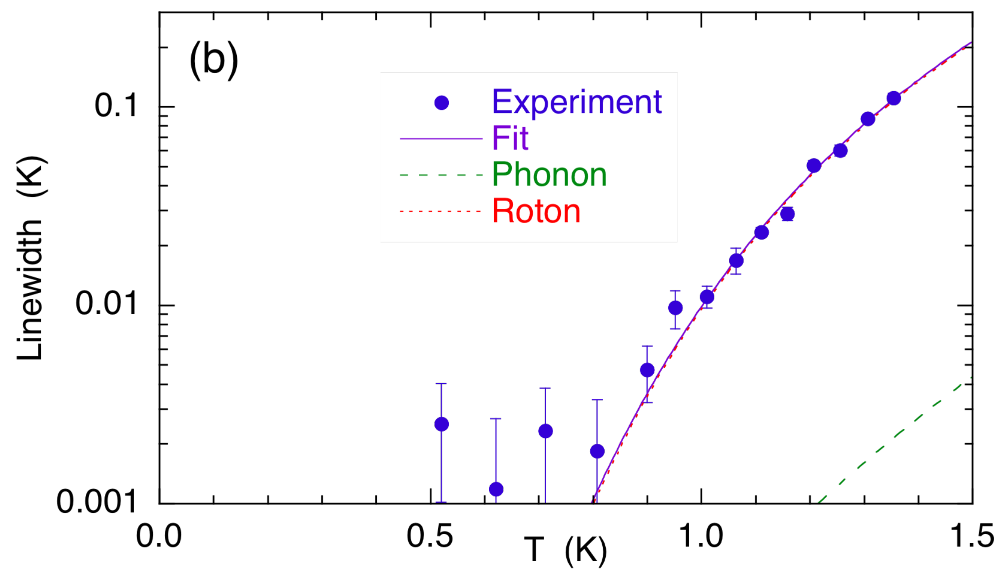




$$\left.\begin{array}{l}\Gamma(T)\\[1em] \delta(T)\end{array}\right\} \propto T^3 \times T^4 = T^7 \left(= \widetilde{A}\cdot\frac{T^7}{c^7}\right)$$

population × Rayleigh scattering

- using numbers: very small effect

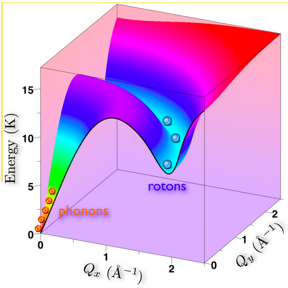


- linewidth: LK-theory is fine !

$$\Gamma(T) \propto N_r(T) \propto \sqrt{T}\, e^{-\frac{\Delta(T)}{T}}$$

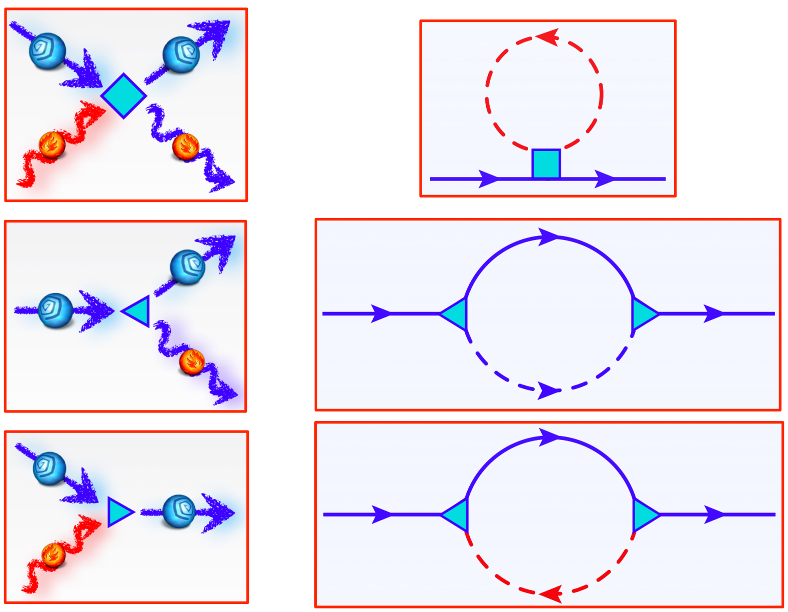
BF, TK, MZ, **SC**, PRL **109**, 155305 (2012).

* (= r-r at T=0.5K, where both ~10^{-6} K)



phonons to the rescue

- **more** roton-*phonon* scatterings:



Hartree

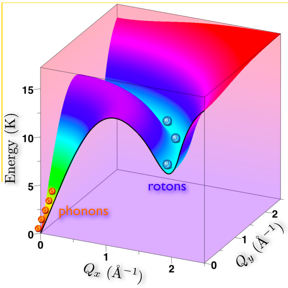
decay

coalescence

$$\Gamma \equiv 0$$
$$\Rightarrow \delta(T) \propto T^4$$

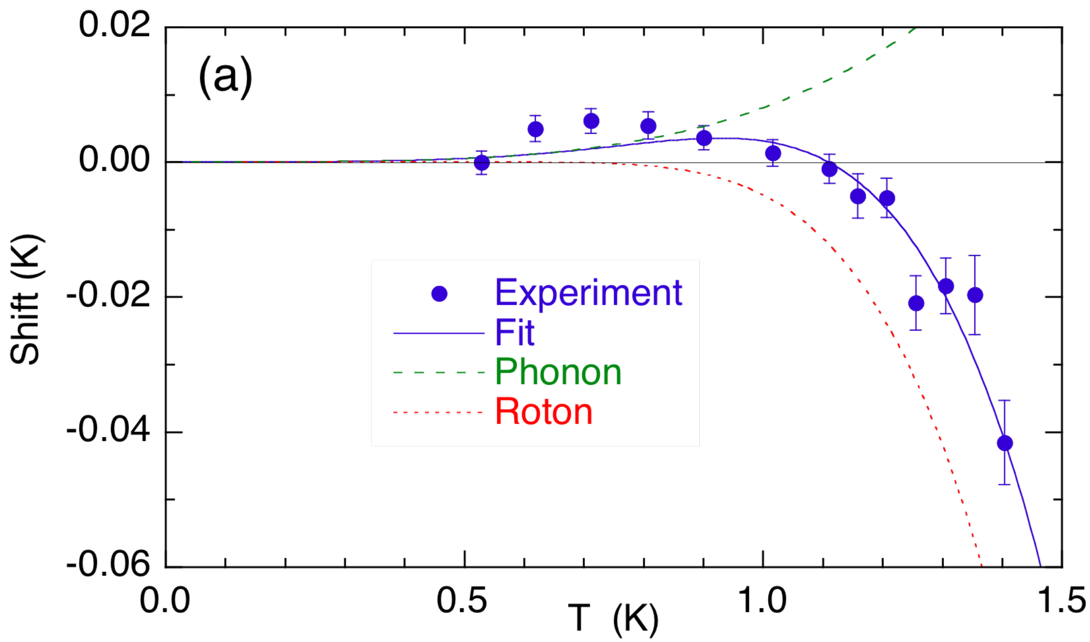
- three-particle (decay, coalescence) are necessarily positive

BF, TK, MZ, **SC**, PRL **109**, 155305 (2012).



theory vs experiment

$$\delta(T) = -\delta_r \sqrt{T}\left(1 + \alpha\sqrt{T}\right) e^{-\Delta(T)/T} + \delta_{ph} T^4$$



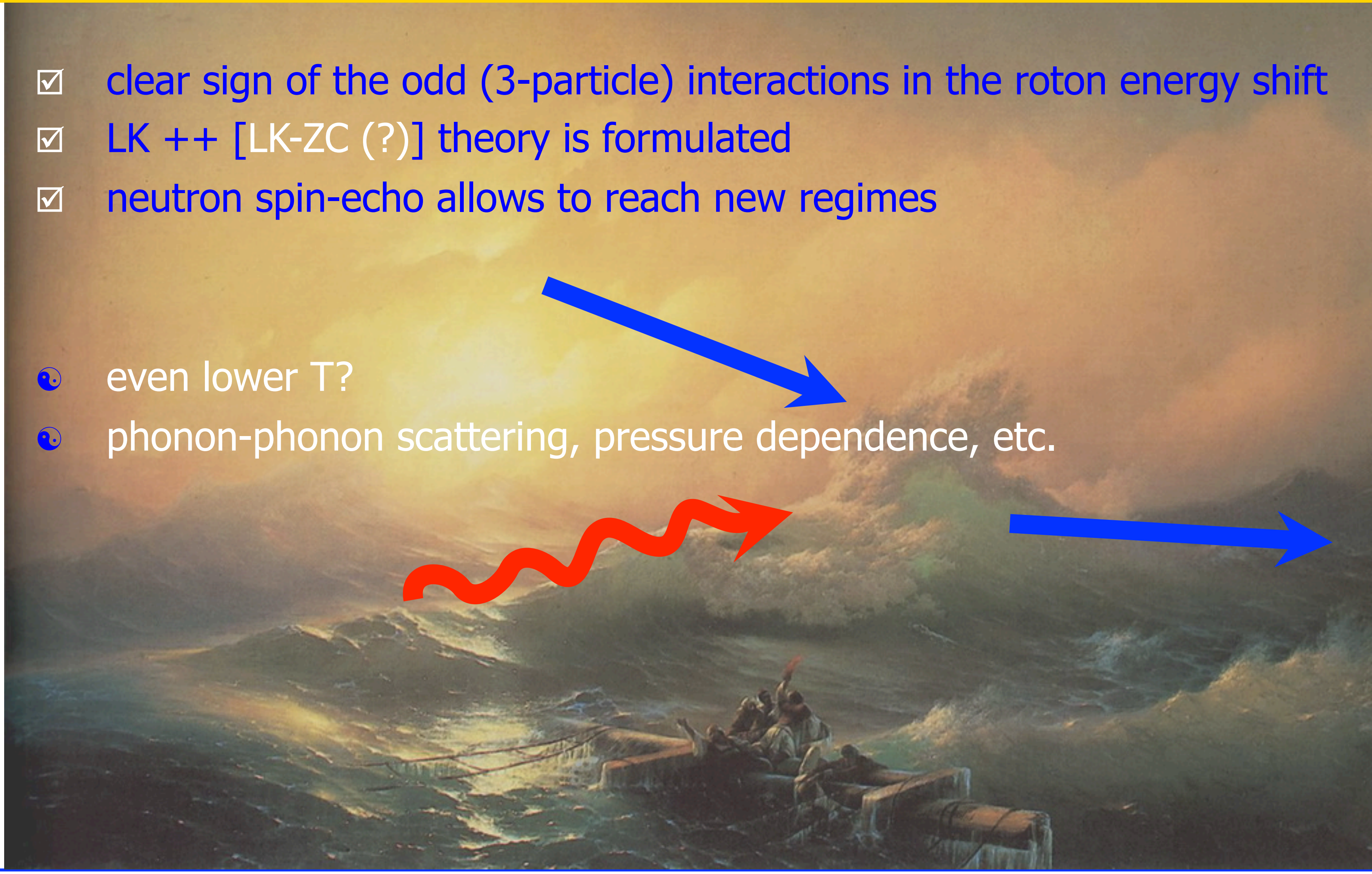
- theory:
  - quantitatively (!) explains positive shift at low *T*
  - provides reasonable fit
  - three-particle interactions dominate the new effect

BF, TK, MZ, **SC**, PRL **109**, 155305 (2012).

conclusions/outlook

- ☑ clear sign of the odd (3-particle) interactions in the roton energy shift
- ☑ LK ++ [LK-ZC (?)] theory is formulated
- ☑ neutron spin-echo allows to reach new regimes

- ☯ even lower T?
- ☯ phonon-phonon scattering, pressure dependence, etc.



I. Aivazovsky, “*The Ninth Wave*” (1850)

II. **lifetime** of gapped excitations in (collinear) antiferromagnets

theory: Sasha Chernyshev (UC Irvine)
Mike Zhitomirsky (CEA)

experiments: Louis-Pierre Regnault,
Nicolas Martin (CEA, ILL)

NHSCP2014, 6-25-14

arXiv: 1206.4690; PRL **109**, 097201 (2012)

material

L. P. REGNAULT AND J. ROSSAT-MIGNOD

PHASE TRANSITIONS IN QUASI TWO-DIMENSIONAL PLANAR MAGNETS

L. J. De Jongh (Ed.), Magnetic Properties of Layered Transition Metal Compounds 271—321.
© 1990 *Kluwer Academic Publishers. Printed in the Netherlands.*

$BaNi_2(PO_4)_2$

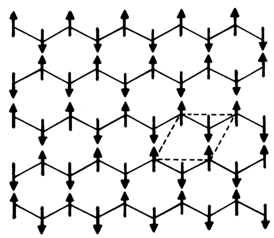
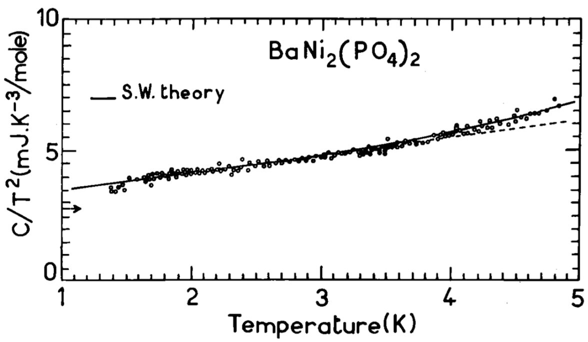
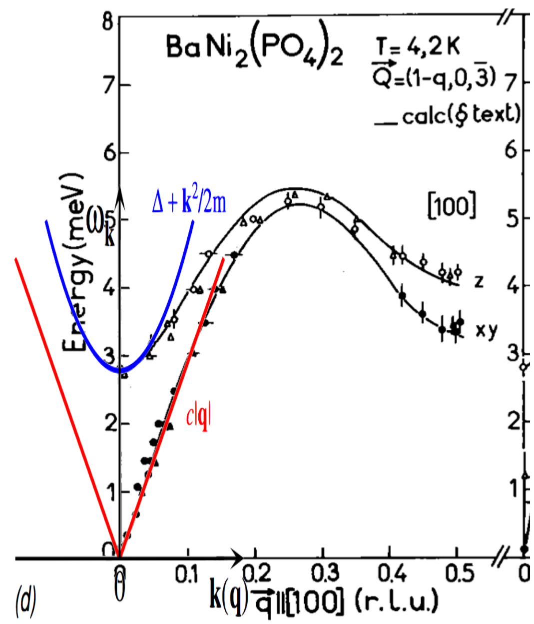
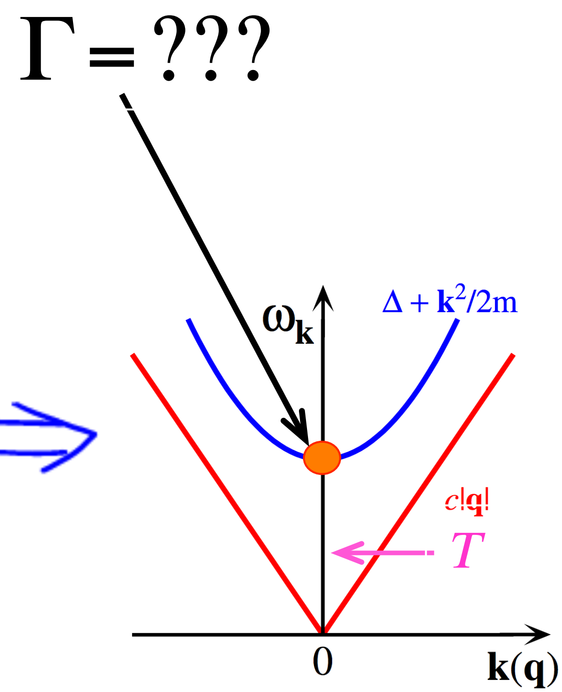


Fig. 3. Antiferromagnetic structure of $BaNi_2(PO_4)_2$.



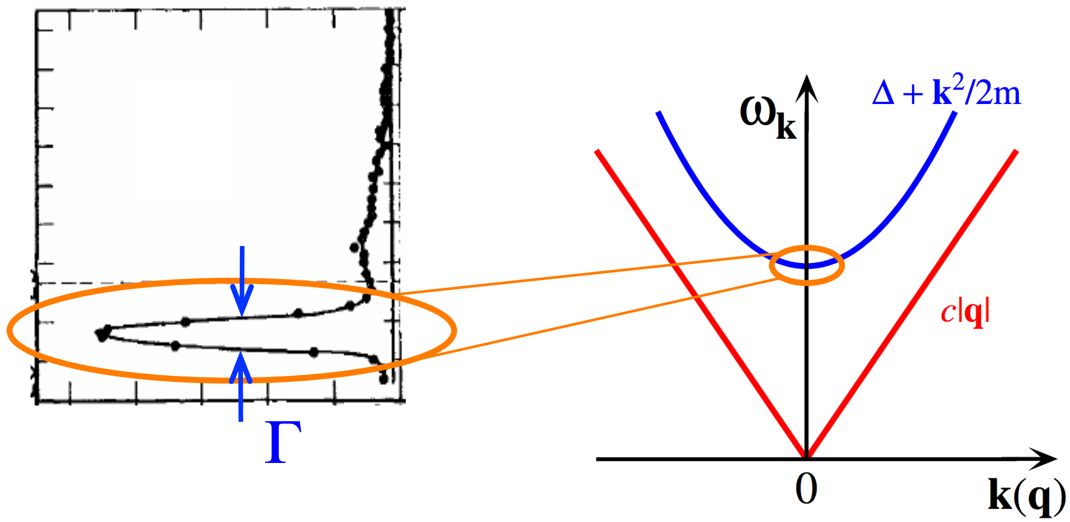




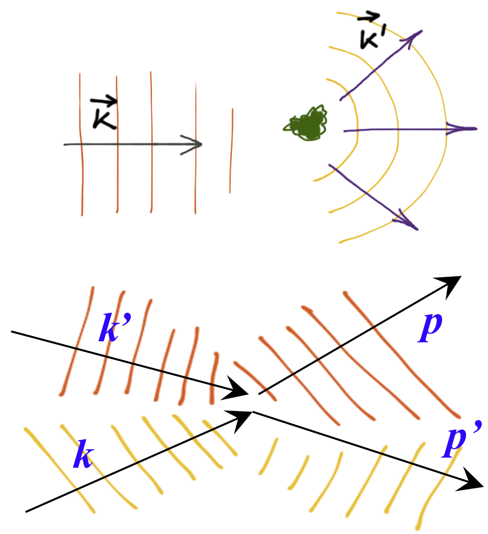
- $S = 1$, 2D, planar (XY)
- has gapped
- and acoustic modes

$$\boxed{\mathcal{H} = \sum_{\langle i,j \rangle} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + D \sum_i (S^z)^2}$$

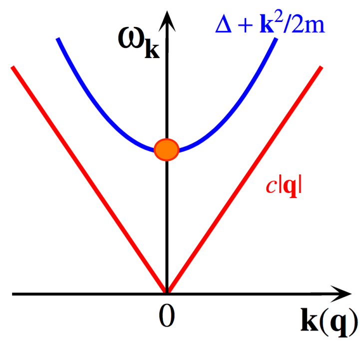
lifetime/linewidth/damping/decay rate

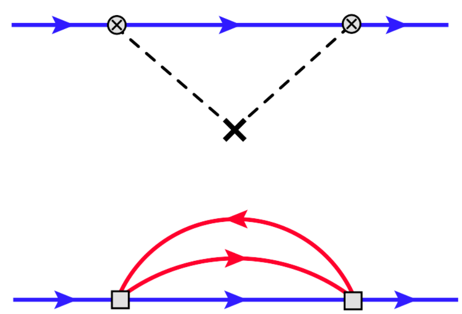


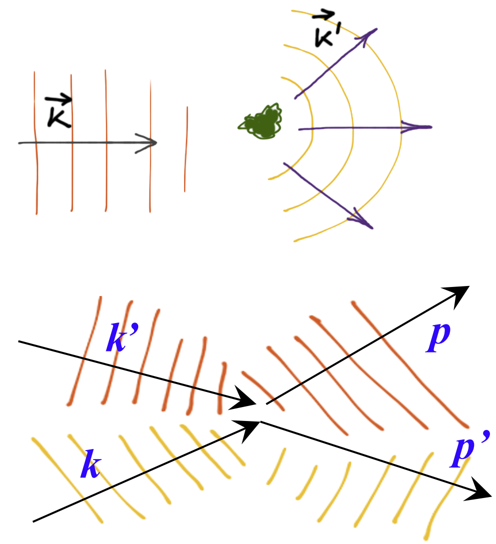
- lifetime^{-1} = linewidth in "simple" AFs
- spin waves: scattering on?
  - impurities
  - themselves
  - combination of the two (impurity-assisted)



damping, theory expectations, I







- local distortions → δD, δJ → conventional impurity scattering (2D):

$$\boxed{\Gamma^{\mathrm{imp}}_{\mathbf{k}} \approx \Gamma_0 \propto n_{\mathrm{imp}} \overline{\delta D}^2 \, \frac{m\,\omega^2_{\mathrm{max}}}{\Delta^2}}$$

- gapped on thermally excited gapless: $\boxed{\Gamma^{\mathrm{m-m}}_{\mathbf{k}\to 0} \approx \frac{\pi^3}{15}\frac{\tilde{g}^2}{c}\left(\frac{T}{c}\right)^5}$

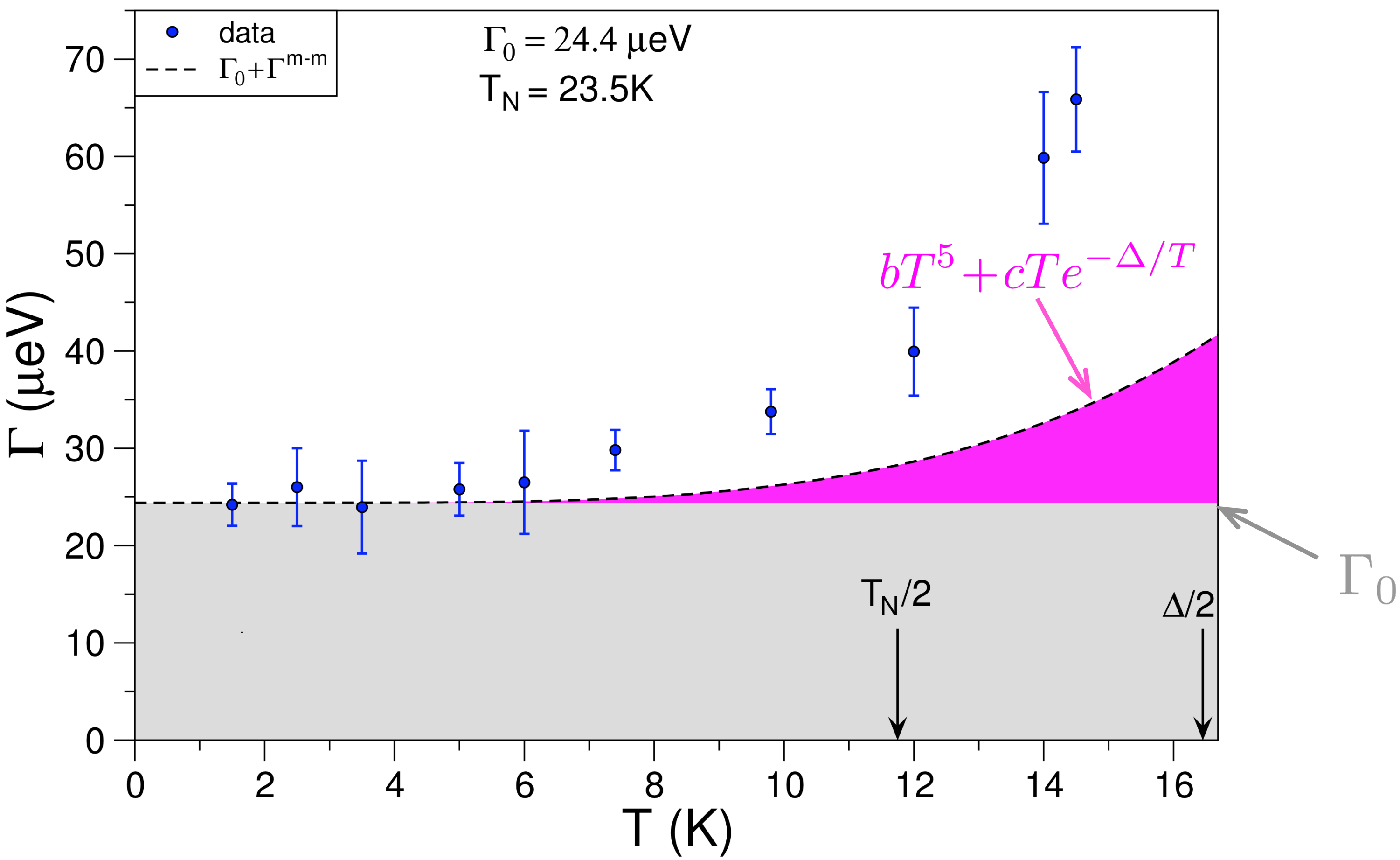
- (and on gapped): $\boxed{\Gamma^{\beta\beta\to\beta\beta}_{\mathbf{k}\to 0} \approx \frac{g_\beta^2 m^2 T}{4\pi}\, e^{-\Delta/T}}$

- numbers for m-m scattering are known/derivable!

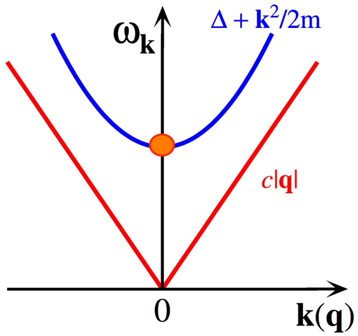
* ~T^5 **not** in HKHH, [3D → T^7]

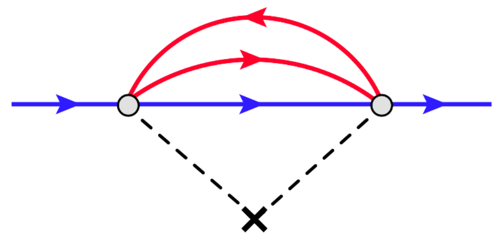
standard lore: $\varrho = \varrho_0^{\text{imp}} + \varrho^{ee}(T)$

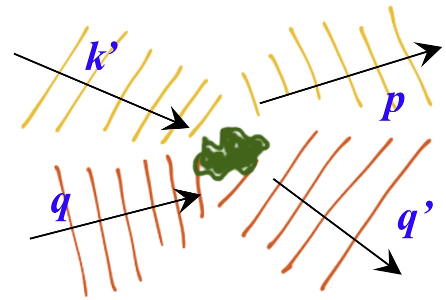
$$\Gamma = \underbrace{\Gamma_0}_{\text{imp}} + \underbrace{bT^5 + cTe^{-\Delta/T}}_{\text{m}-\text{m}}$$



damping, theory expectations, II







- impurity facilitates stronger m-m scattering

$$V^{\mathrm{imp}}_{\mathbf{k},\mathbf{q};\mathbf{k}',\mathbf{q}'} \approx \tilde{g}_{\mathrm{imp}}/\sqrt{\tilde{q}\tilde{q}'} \qquad \text{vs} \qquad V^{\mathrm{m-m}}_{\mathbf{kq};\mathbf{k}'\mathbf{q}'} \propto \sqrt{qq'}$$

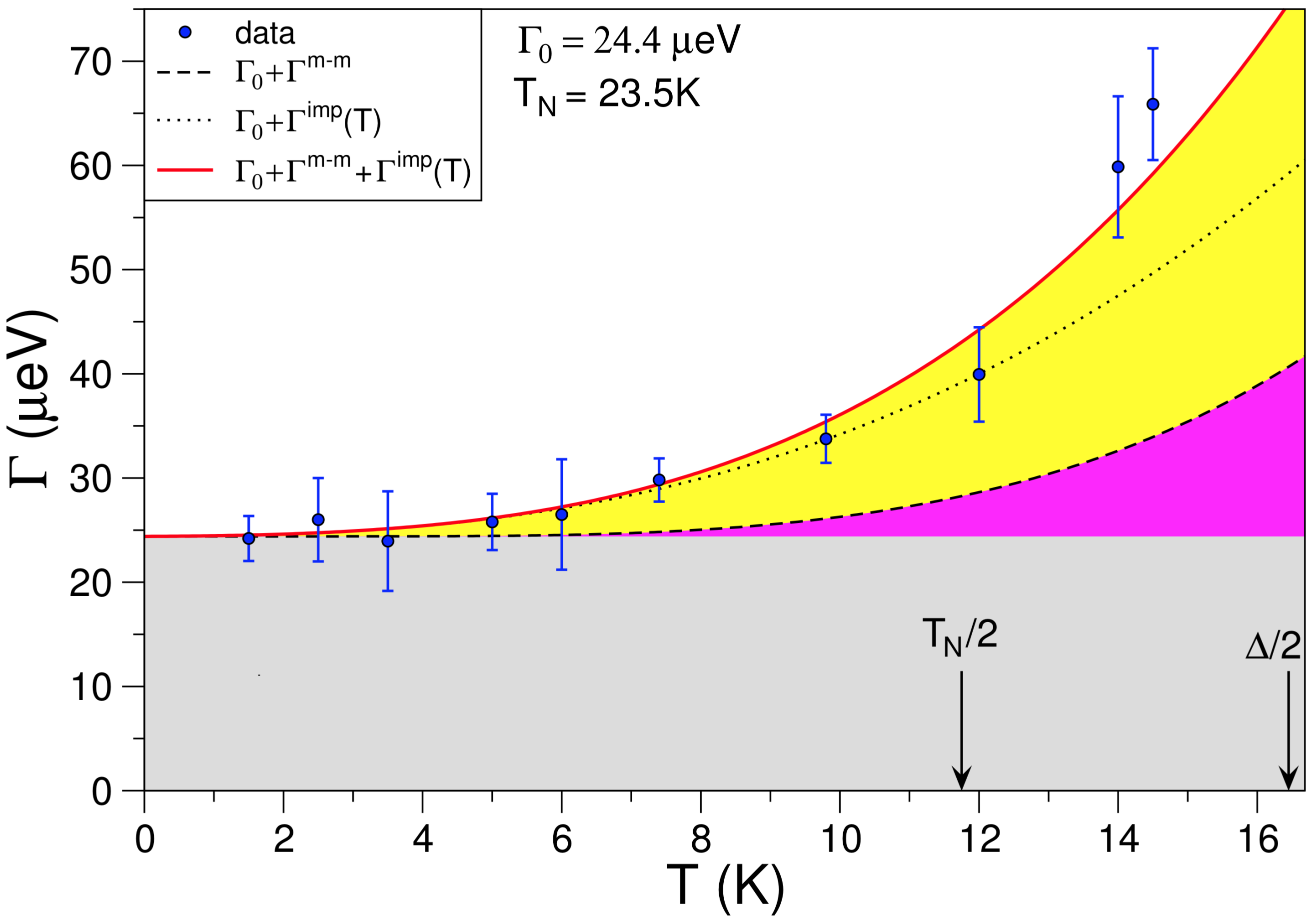
- → lower power of T in Γ

$$\boxed{\Gamma^{\mathrm{imp},T}_{\mathbf{k}\to 0} \approx \widetilde{A}\left(\frac{T}{c}\right)^2 \left[\left(\ln\frac{T}{\omega_0}\right)^2 + \frac{\pi^2}{3}\right]} \qquad \boxed{\widetilde{A} \sim n_{\mathrm{imp}}\overline{\delta D}^2 m}$$

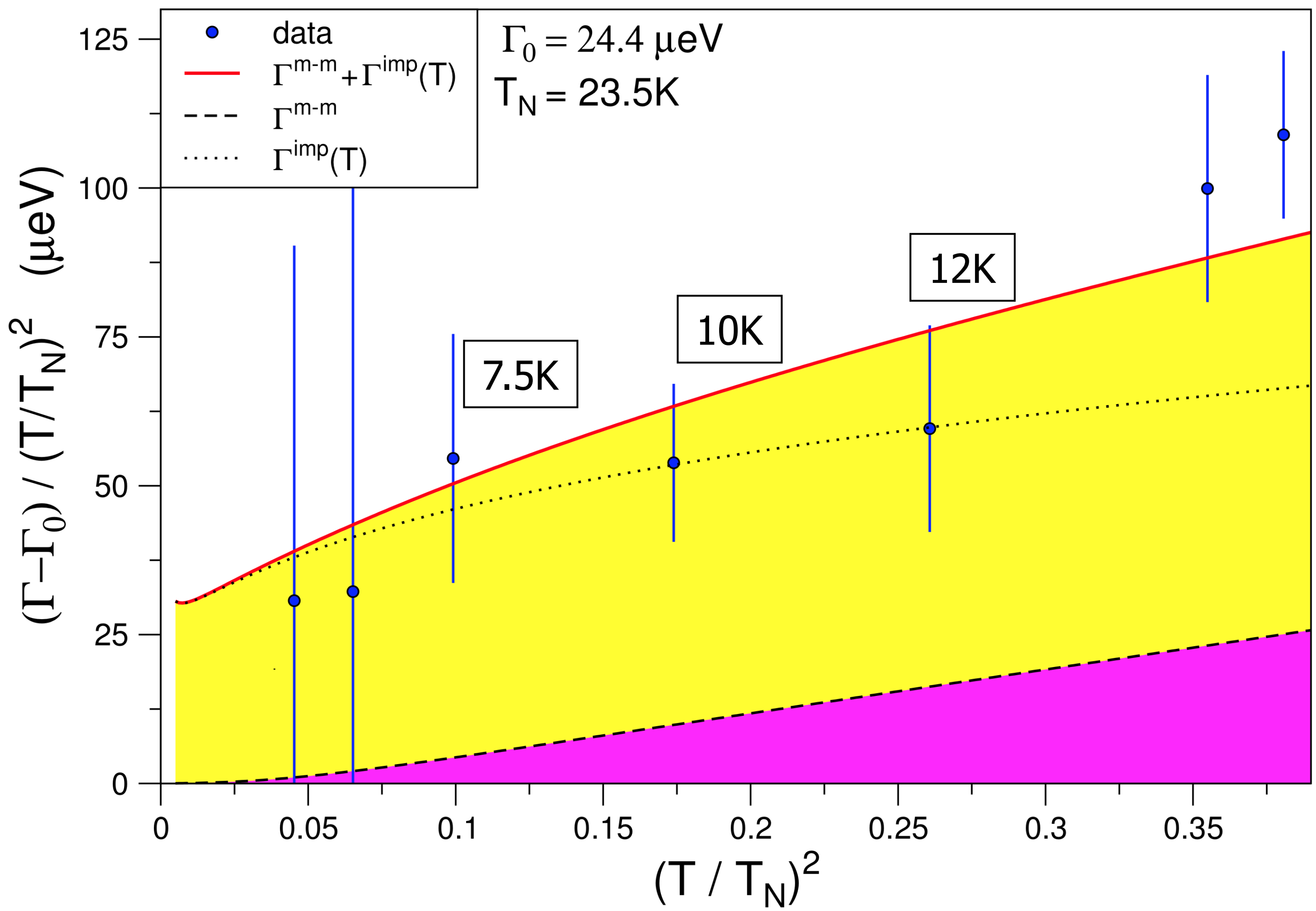
- reasons for "stronger" potential:
  - m-m interactions are singular but cancel out
  - impurities violate that cancellation
  - dynamically-induced "strong" disorder:
    optical spin-flip "sits" at impurity,
    scatters acoustic mode stronger …

beyond the standard model ...

$$\Gamma = \underbrace{\Gamma_0}_{\text{imp}} + \underbrace{aT^2\left[\left(\ln\frac{T}{\omega_0}\right)^2 + \frac{\pi^2}{3}\right]}_{\text{imp. finite}-T} + \underbrace{bT^5 + cTe^{-\Delta/T}}_{\text{m}-\text{m}}$$



better picture …



cross-checks, predictions

T=0 and *T>0* impurity terms must be related ($\Gamma_0 \sim \widetilde{A} \sim n_{\rm imp}\overline{\delta D}^2 m$)

☑ true, in our fit: $\Gamma_0 \approx \widetilde{A} \approx 25\ \mu\text{eV}$

does disorder strength make sense?

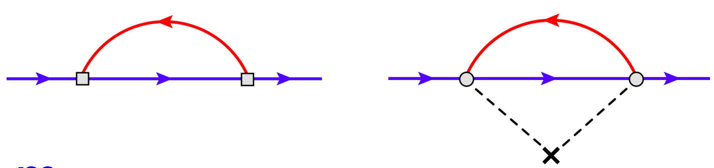
☑ estimate: $n_{\rm imp}(\overline{\delta D}/D)^2 \approx \Gamma_0/\omega_{max} \approx 10^{-2}$

translates into a (very reasonable) statement that in $BaNi_2(PO4)_2$, strong modulation of magnetic couplings of order 1 is spread over 1 in 100 unit cells

---

predictions:

- 3D: $\Gamma_{3D}^{\rm imp} \propto n_{\rm imp} T^{9/2}$
- AFs with non-collinear order → 3-magnon coupling $\quad \mathrm{BaCo_2(AsO_4)_2}$

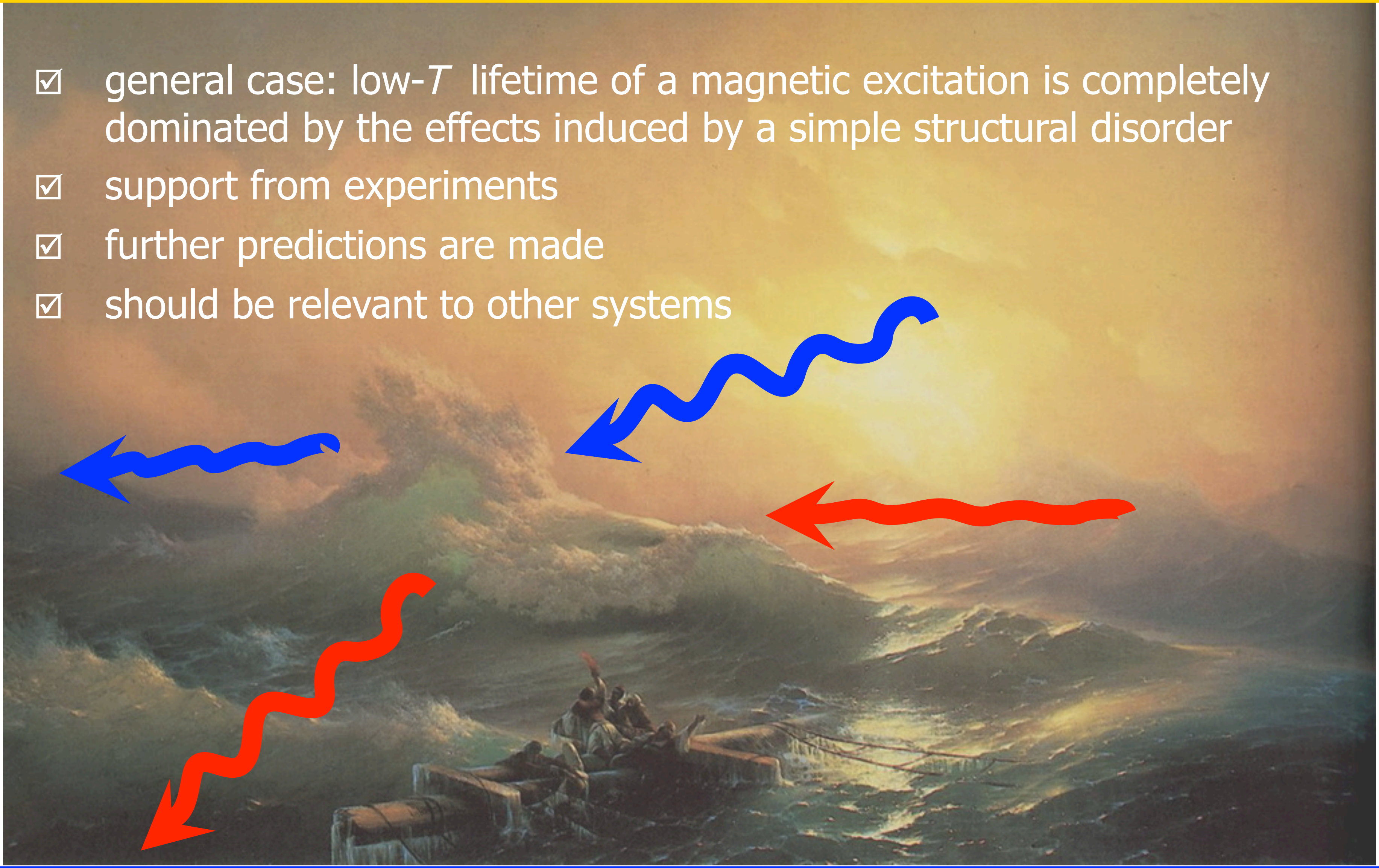
new diagrams: 

no change in m-m

lower power of T in impurity-induced: $\boxed{\Gamma_{\mathbf{k}\rightarrow 0}^{{\rm imp},T} \approx \widetilde{A}_3 \left(\frac{T}{c}\right) \ln\frac{T}{\omega_0}}$ $\quad \widetilde{A}_3 \propto n_{\rm imp}|\delta g_3|^2$

conclusions

- ☑ general case: low-T lifetime of a magnetic excitation is completely dominated by the effects induced by a simple structural disorder
- ☑ support from experiments
- ☑ further predictions are made
- ☑ should be relevant to other systems



I. Aivazovsky, "*The Ninth Wave*" (1850)