Diagnosing phases of magnetic insulators via noise magnetometry with spin qubits

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Yao Lab Group Meeting

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Harvard University

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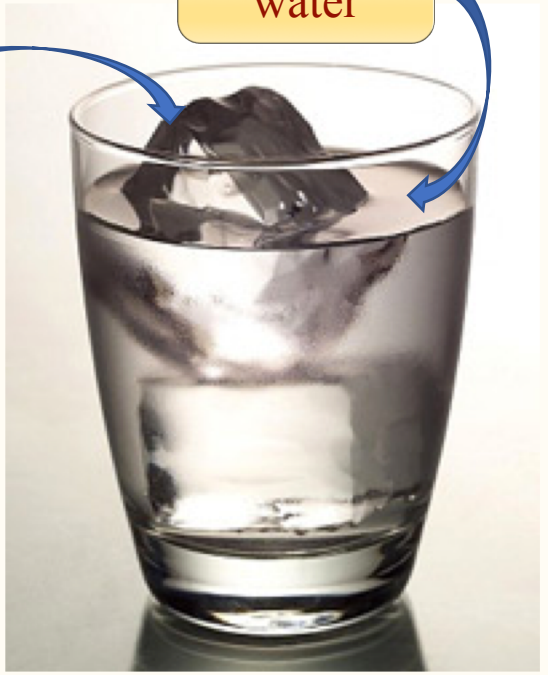
Harvard University

SC, J. F. Rodriguez-Nieva and E. Demler

arXiv:1810.04183

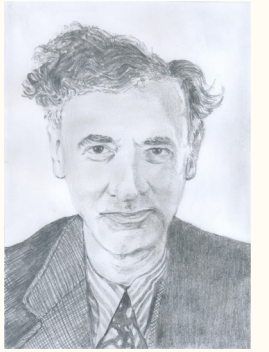
Conventional phases of matter

- Paradigm of symmetry breaking and local order parameters



At room temperature, this magnet attracts iron pins.

When heated, it stops doing so



Lev. D. Landau

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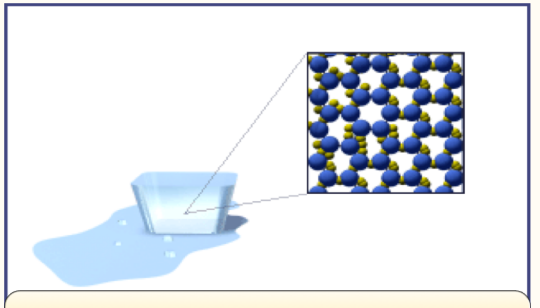
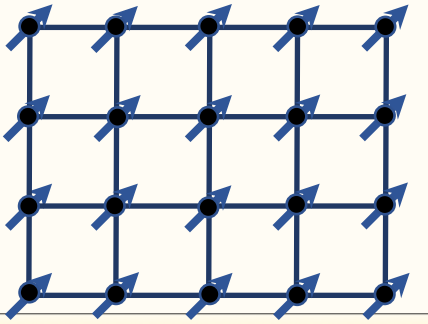
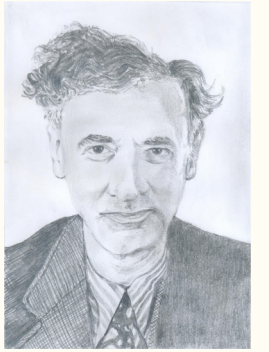


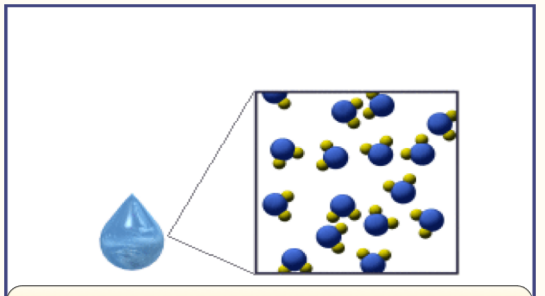
Density is non-uniform



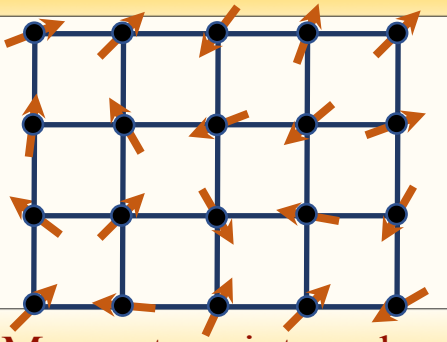
Moments are aligned



Lev. D. Landau



Density is uniform



Moments point random

- Symmetry is broken
- Non-zero local order parameter

Order parameter: Density

Order parameter: Magnetization

Outline

- Unconventional phases of matter in magnetic insulators
- NV centers as quantum sensors in condensed matter
- Footprints of a phase in magnetic noise
- Sensing anyonic statistics using NVs
- Material candidates
- Conclusions and outlook

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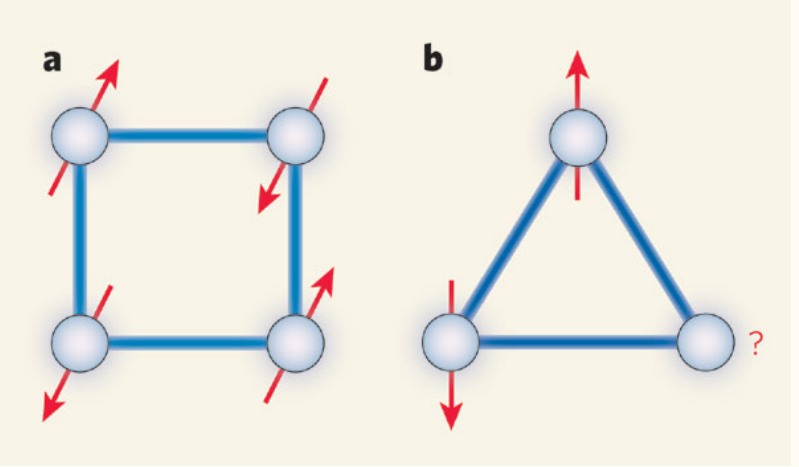
Unconventional phases of matter

- Not described by broken symmetries or local order parameters
- Consider an insulator: Degrees of freedom are spins



Antiferromagnetic exchange causes geometric frustration in non-bipartite lattices

- Frustration or larger quantum fluctuations: Additional possibilities *beyond the paradigm of symmetry breaking*

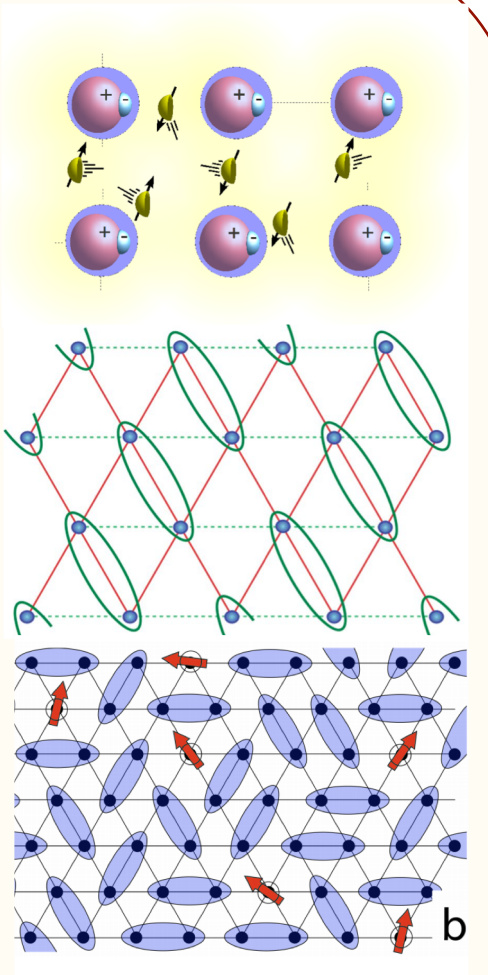
Unconventional phases of matter

Different possible phases of 2d magnetic insulators:

- **Quantum spin liquids**:
  - No broken symmetry
  - Long range entanglement + topological order
  - May be gapped or gapless

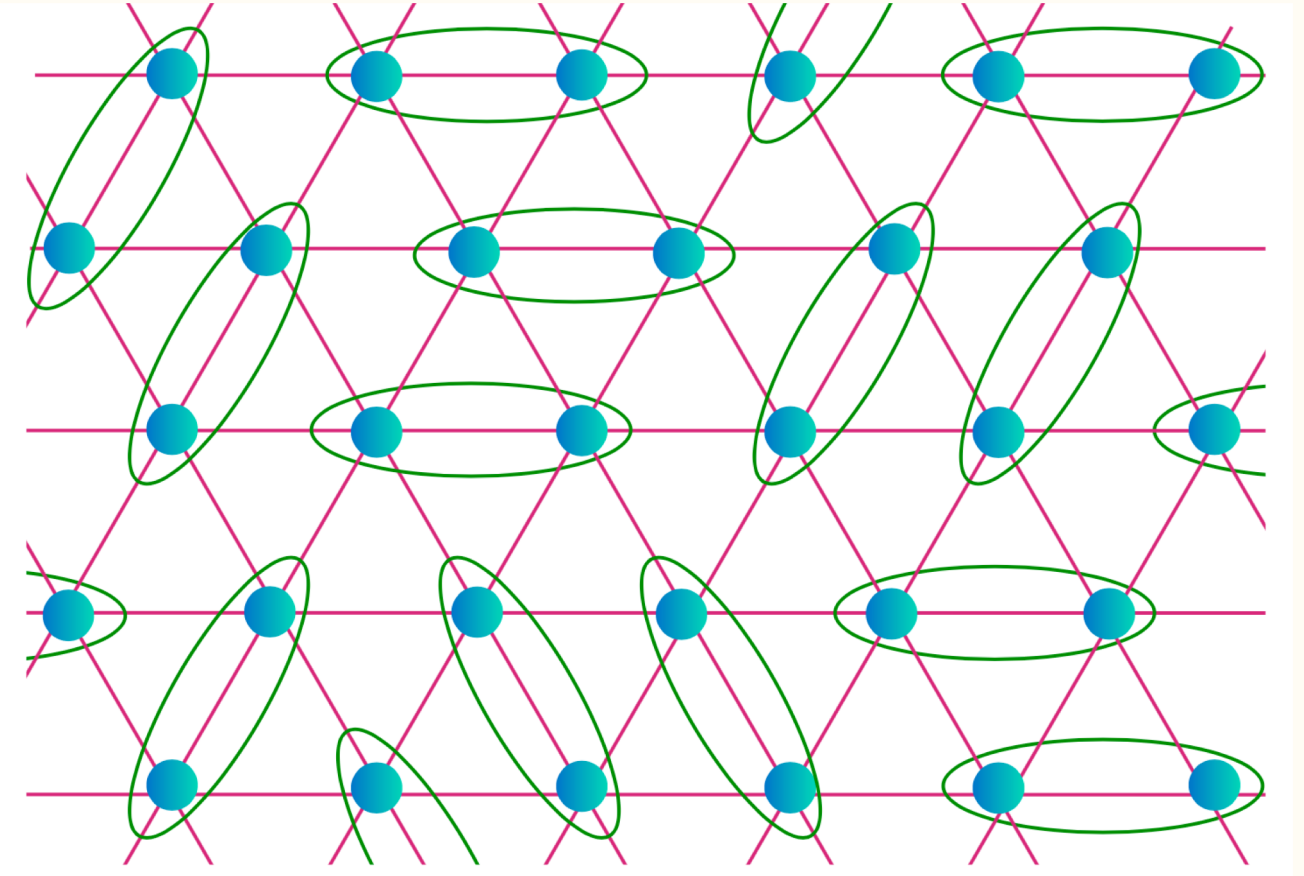
- **Valence bond solids (VBS)**:
  - Broken translation symmetry
  - Gapped triplon (S=1) excitations

- **Disordered random singlet phases**:
  - Statistically preserves translation symmetry
  - Long-range singlets but topologically trivial



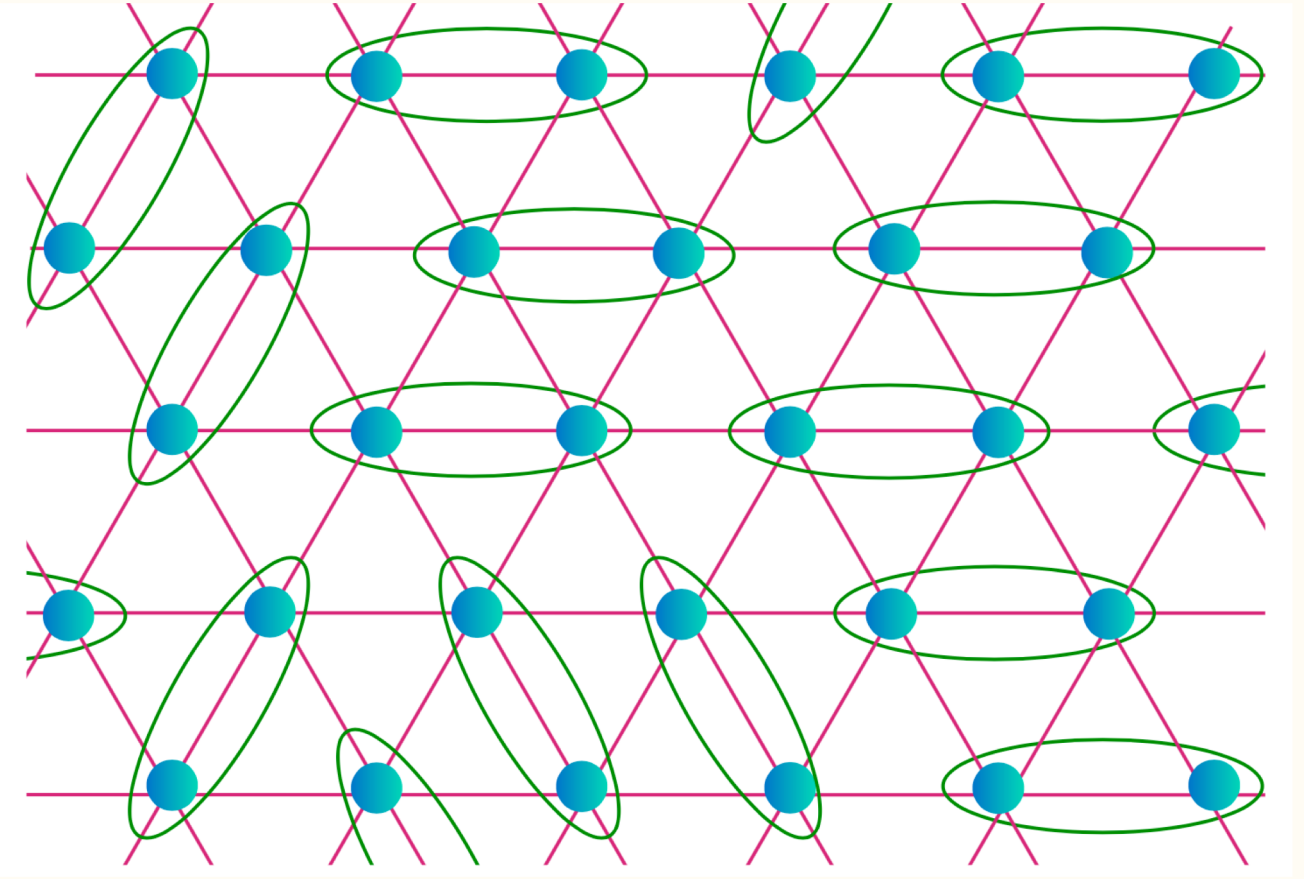
Figures: T. Senthil (MIT), S. Sachdev (Harvard), Kimchi *et al*, PRX 2018

Quantum spin liquids



Anderson 1973, 1987; Kivelson, Rokhsar 1987; Wen 1991, Sachdev 1992, and a lot of others. Figure: S. Sachdev (Harvard)

Quantum spin liquids



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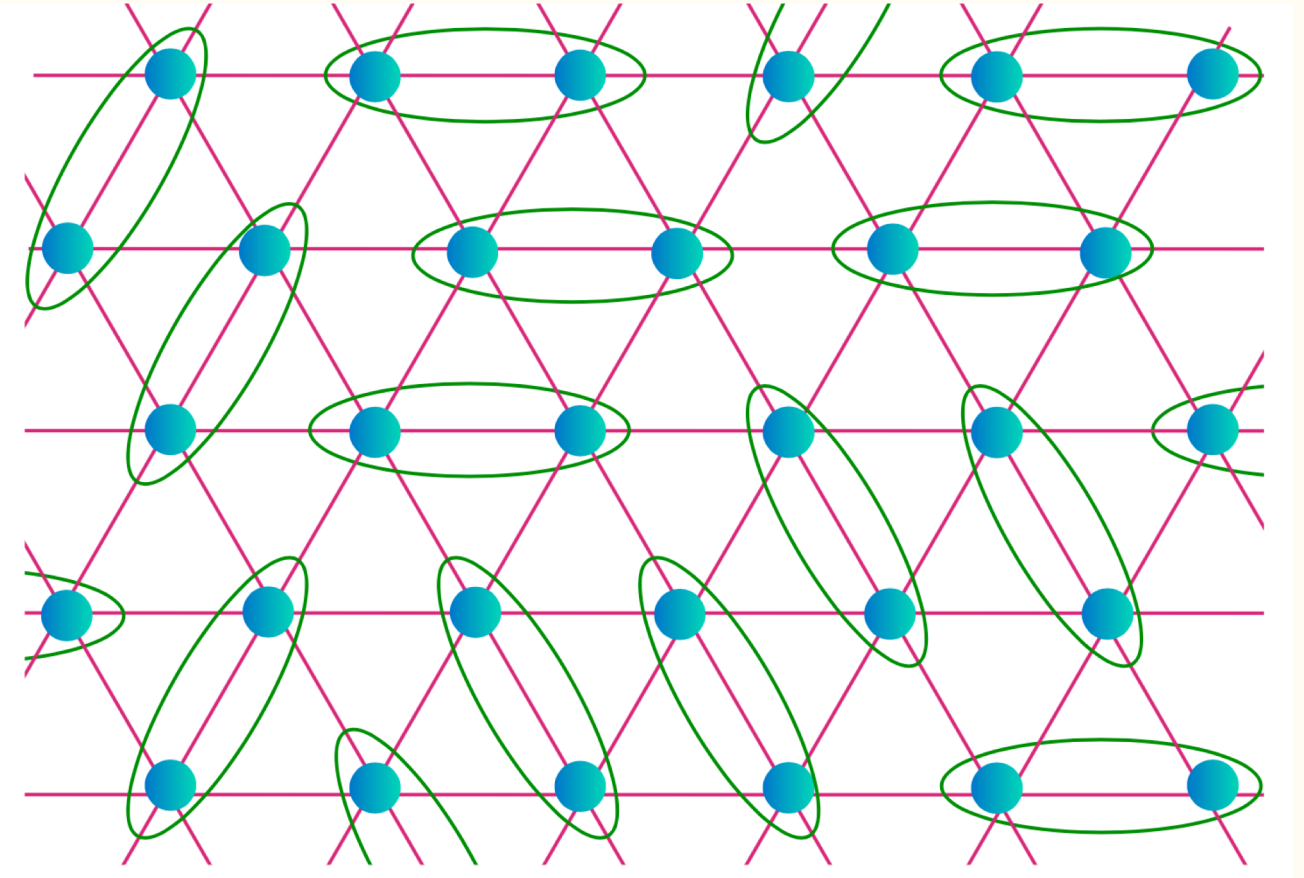

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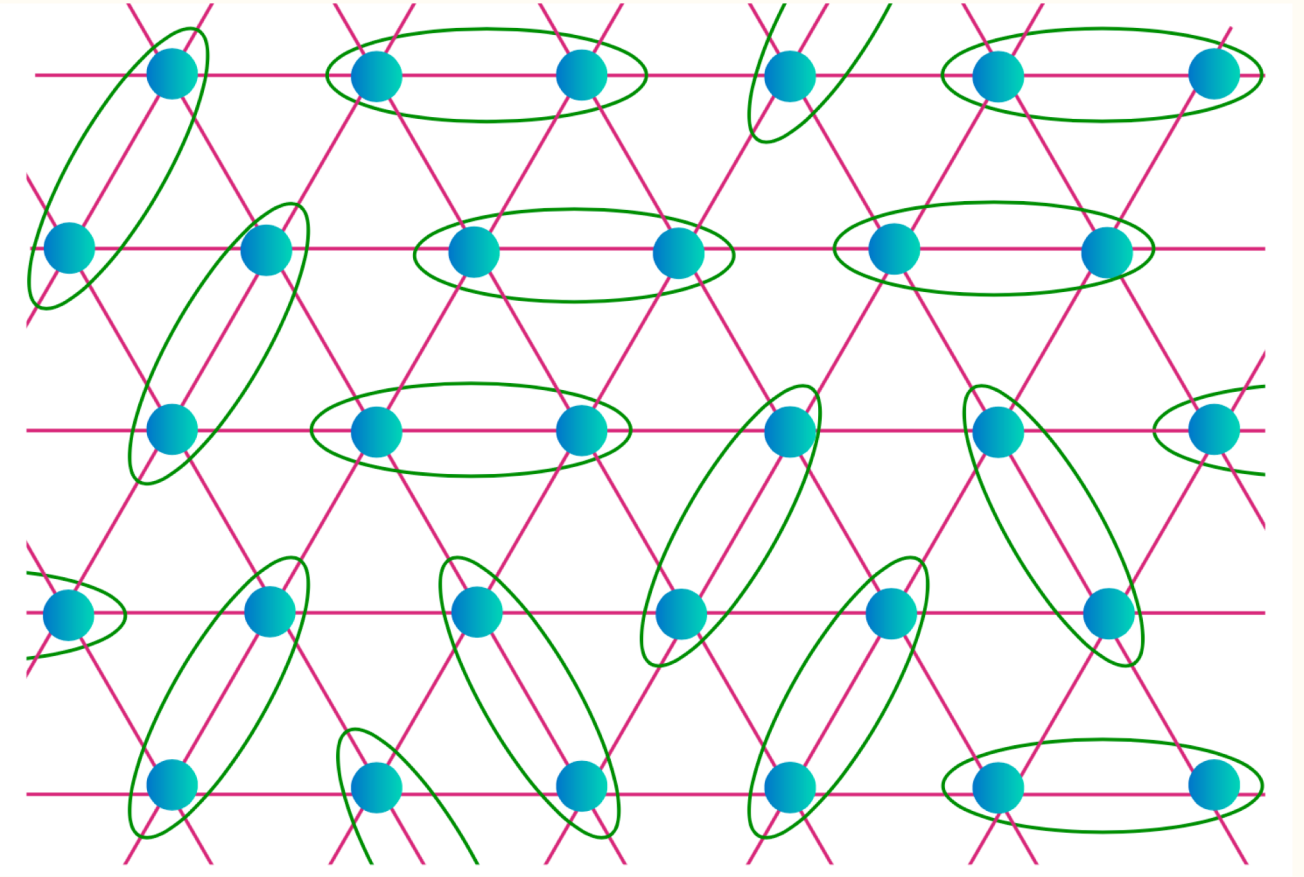


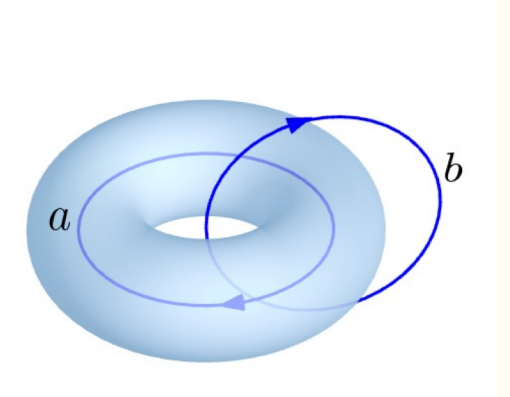
Anderson 1973, 1987; Kivelson, Rokhsar 1987; Wen 1991, Sachdev 1992, and a lot of others. Figure: S. Sachdev (Harvard)

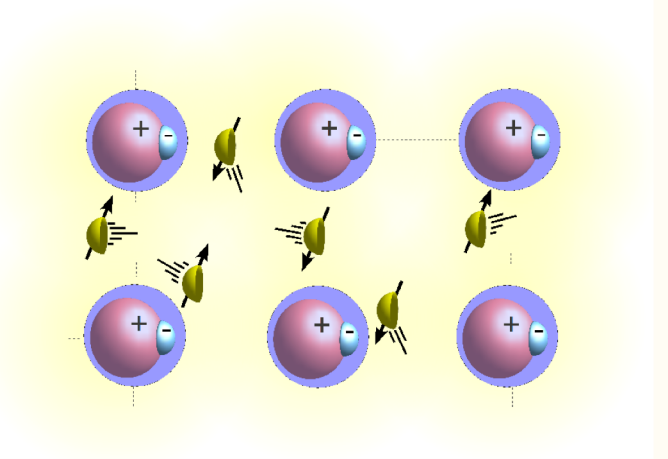
Quantum spin liquids

- Long range entanglement: Non-trivial ground state degeneracy on a cylinder/torus: Can be used as stable qubits for quantum computation!

- More curiously, the excitations carry fractional quantum numbers of global symetry (like S = 1/2 spinons) and are coupled to emergent gauge fields

- Gauge flux and spinon are mutual semions (like e and m particles of the Kitaev toric code)

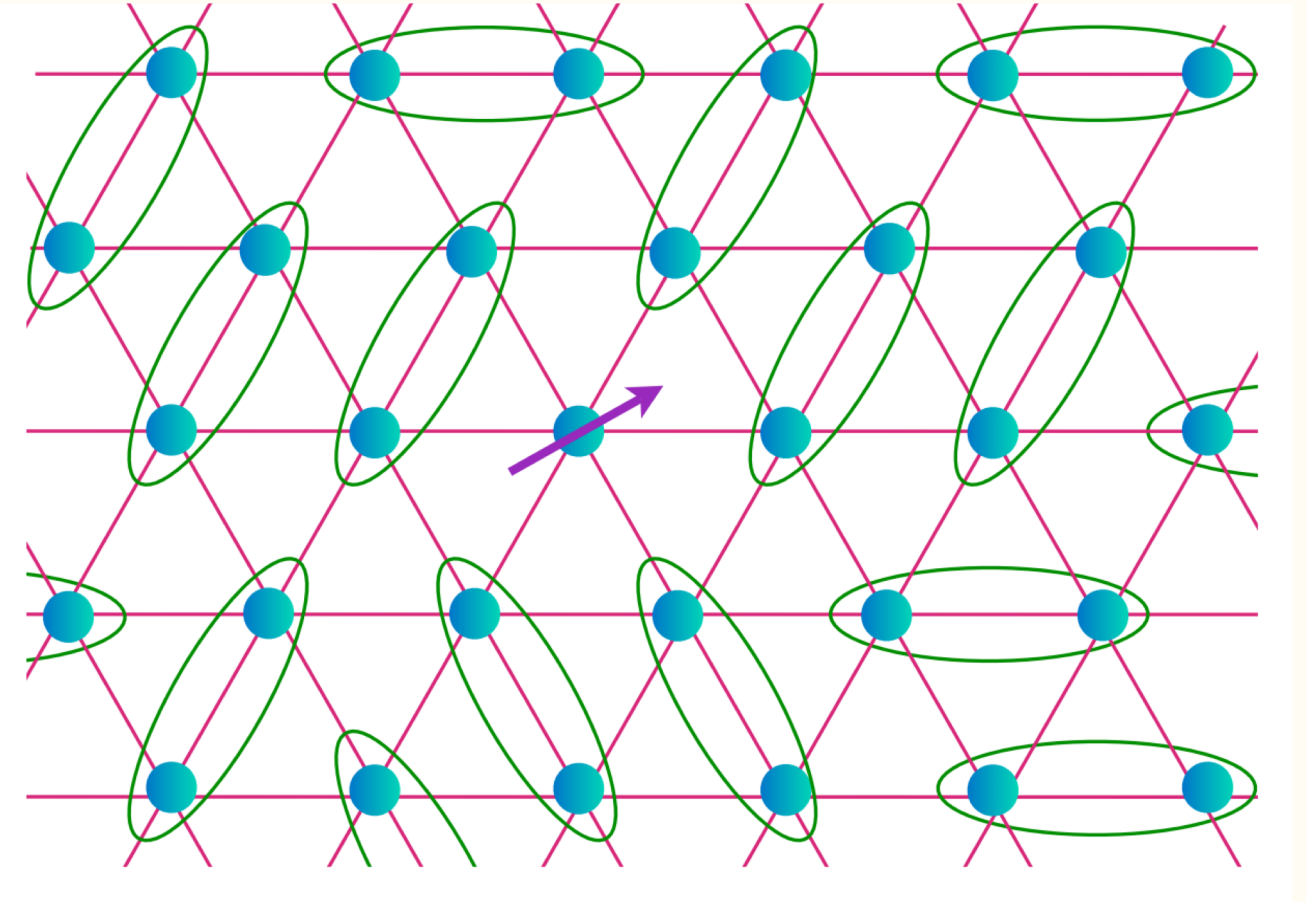




A. Kitaev, Annals Phys. (2003)

Figures: Barkeshli *et al*, arXiv: 1410.4540, T. Senthil (MIT)

Excitations in spin liquids: S = 1/2 Spinons



- Low energy excitations: S = ½ spinons, must occur in pairs

Figure: S. Sachdev (Harvard)

Excitations in ordered phases: S = 1 Magnons

- Contrast this with a magnetically ordered phase (ferromagnets or antiferromagnets)
- Low energy excitations: S = 1 magnons, Goldstone bosons of broken spin-rotation symmetry

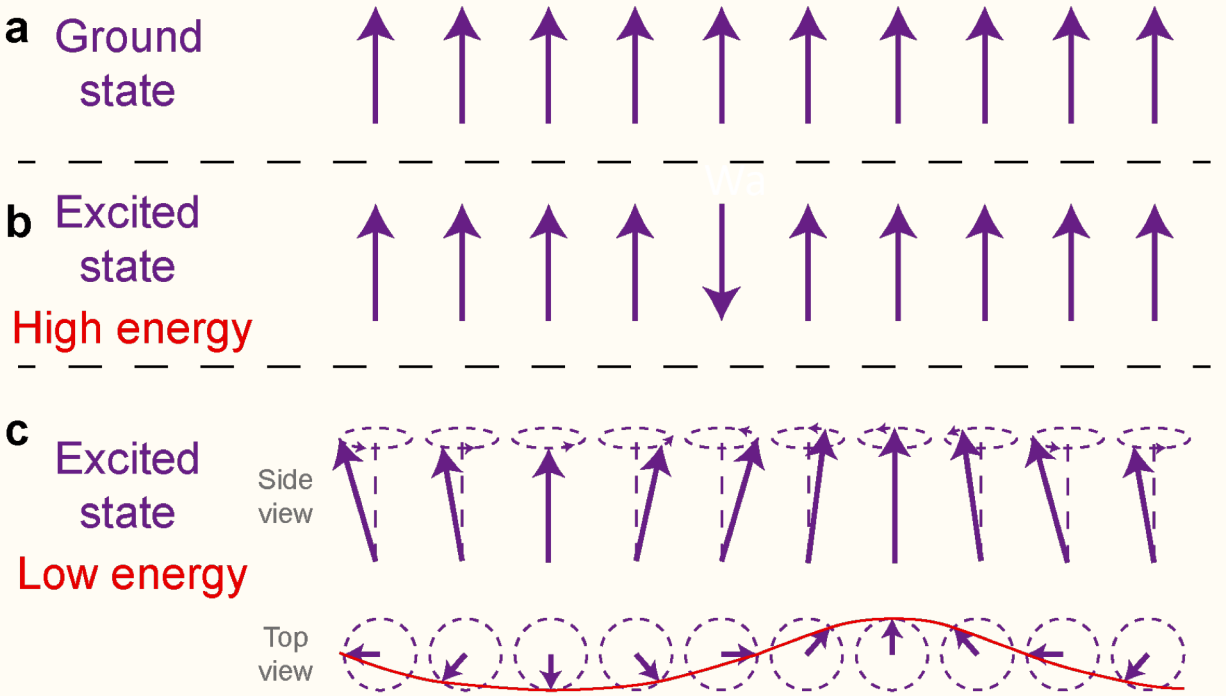


Figure: rug.nl/research/zernike

VBS phases

- Clean VBS phases break lattice translation symmetry
- Gapped S = 1 triplon excitations (discrete broken symmetry, no Goldstone modes)
- May have non–trivial triplon bands with gapless chiral edge modes

Joshi, Schnyder PRB 2017

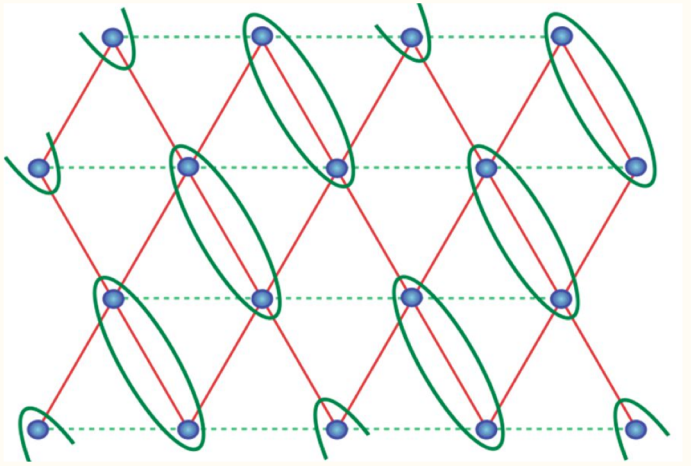
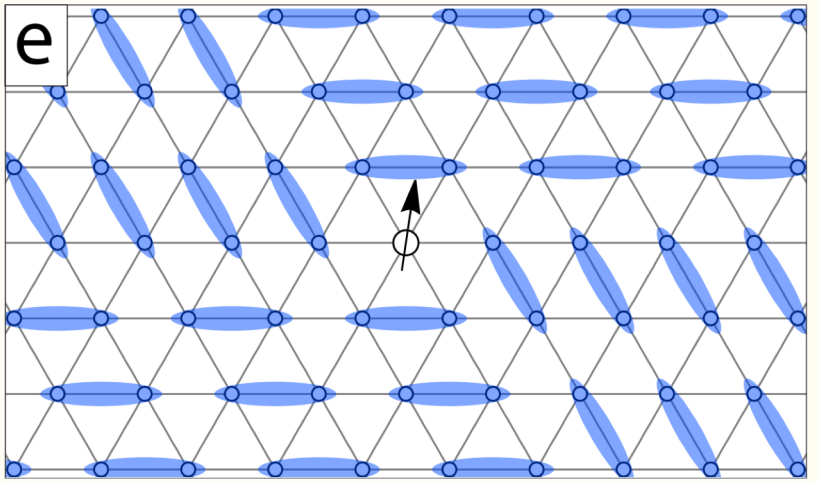


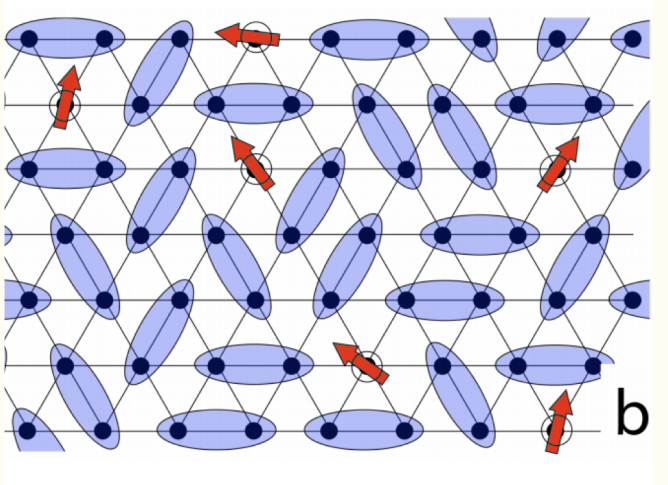
Figure: S. Sachdev (Harvard)

What is the fate of the VBS phase in presence of disorder?

Disordered VBS phases

- Disordered VBS phases in two dimensions naturally nucleate defects
- Defects carry spin-half because of topological reasons



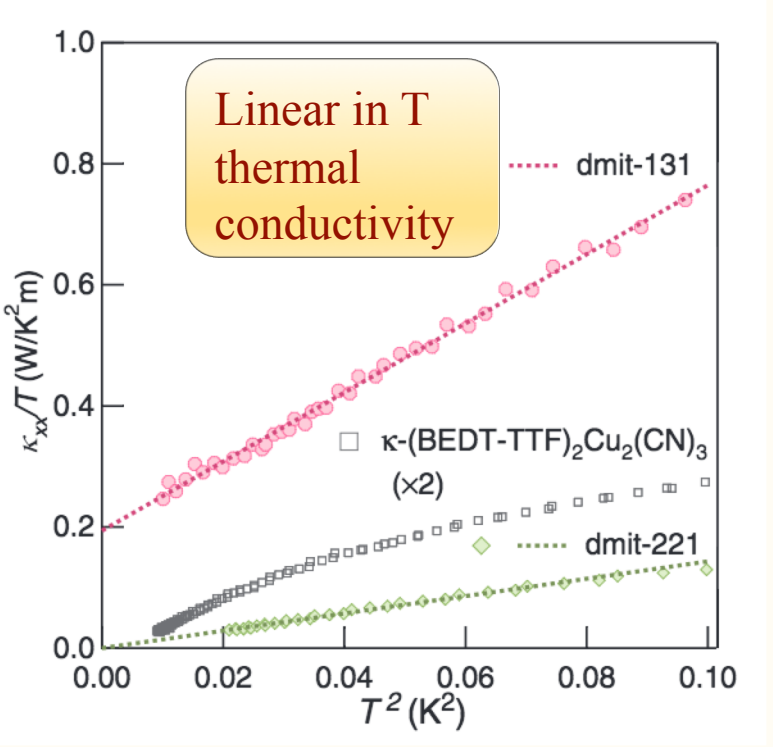


- The low energy physics is governed by this random network of weakly coupled spins $H_{eff} = \sum_{i,j} J_{i,j}^{eff} \, \mathbf{S}_i \cdot \mathbf{S}_j$

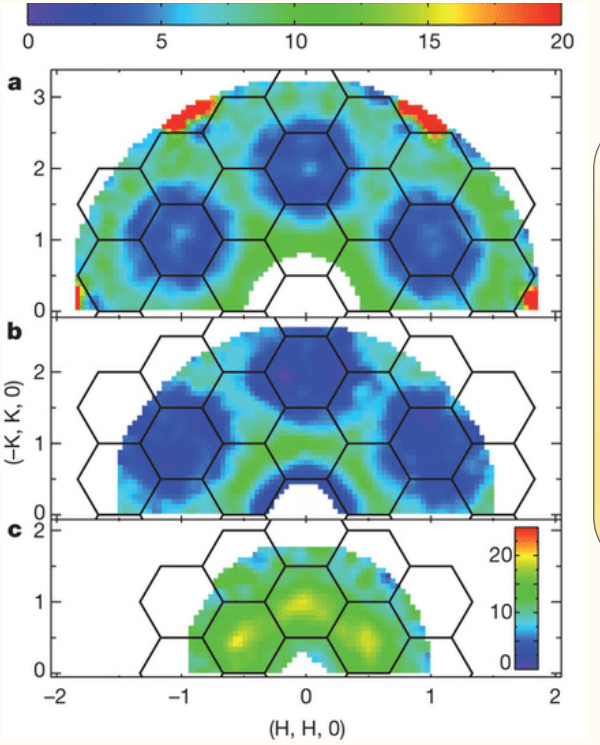
Kimchi *et al*, PRX 2018

Quantum spin liquids in experiments

- Traditionally, cool down to very low temperatures, and look for signatures of *nothing*



M. Yamashita *et al*, Science, **328,** 5983 (2010)



Broad continuum of two-particle like spectrum in neutron scattering

Han *et al*, Science, **328,** 7429 (2012)

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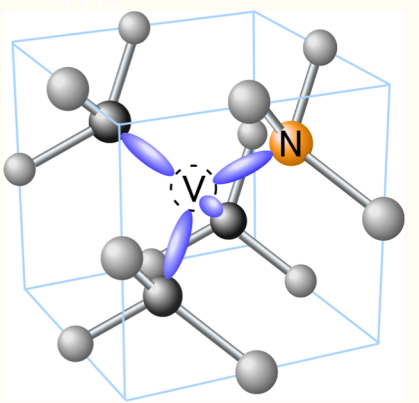
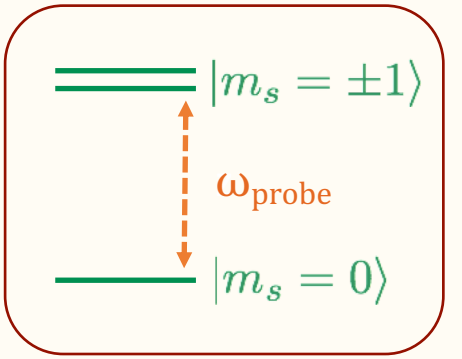
NV centers as quantum sensors

- Issues with transport/neutron scattering: contamination by phonons, lack of low energy resolution, etc

Can we probe the fractional spin-excitations directly and exclusively?

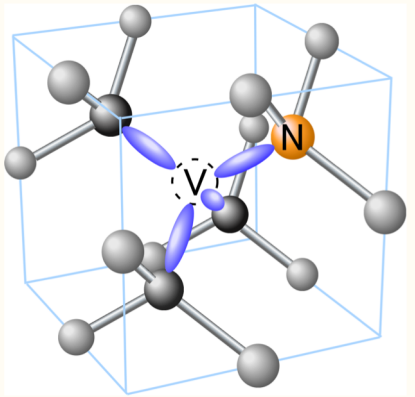
- Enter NV centers as quantum sensors of magnetic fluctuations!
- Measures AC magnetic noise at frequency ω_{probe}





- *In insulators, dominated by spin fluctuations due to large charge gap*

NV centers as quantum sensors



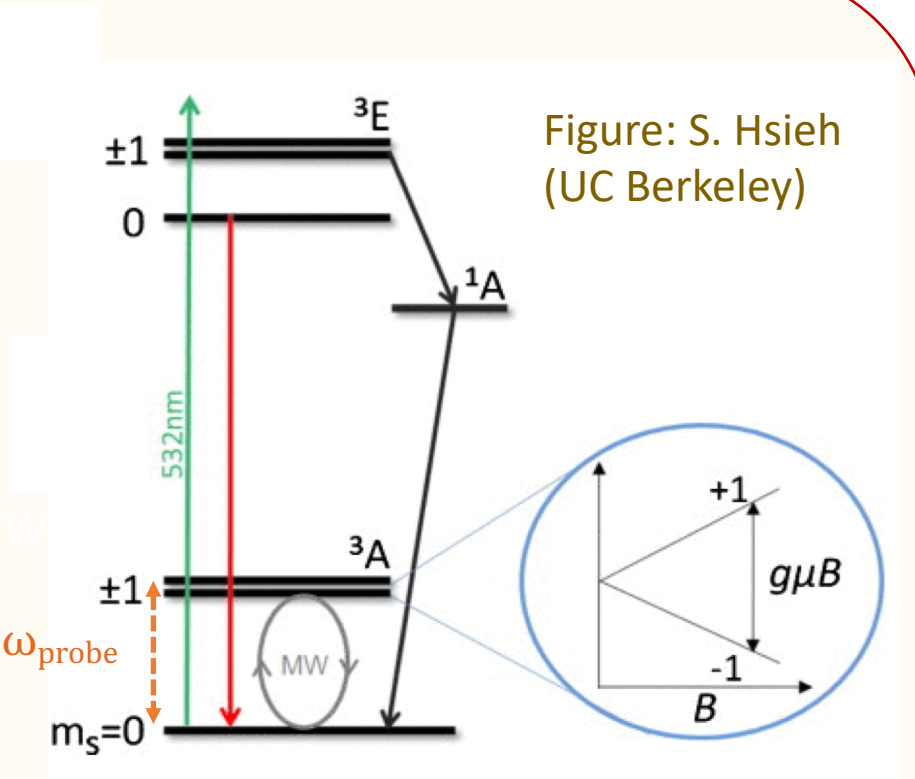
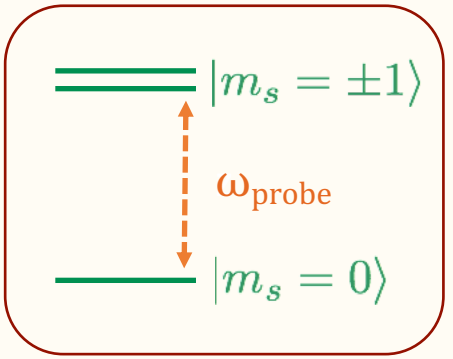


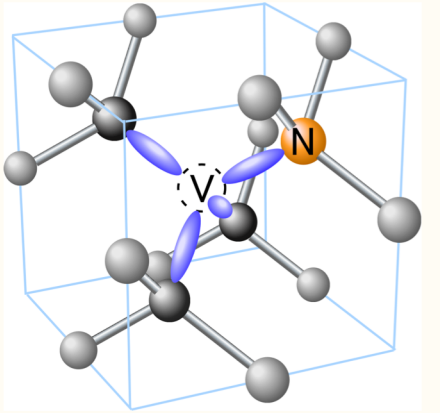
Figure: S. Hsieh (UC Berkeley)



- Polarized/Initialized via laser pumping
- Read-out via spin-dependent fluorescence

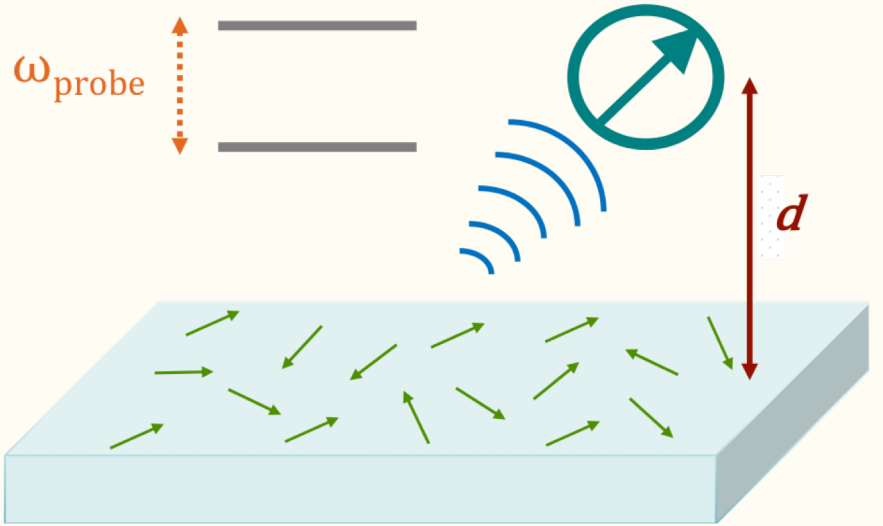
NV centers as quantum sensors

- Couples efficiently to magnetic field created by fluctuating spins
- Sensitive to only spin-correlations (avoids phonons, charged disorder, localized modes etc)
- Excellent momentum (up to few nm) and energy resolution (up to few mK)
- Optical initialization and readout capabilities
- Minimally invasive (no external drive required)



NV centers as quantum sensors

- Relaxation time is sensitive to magnetic noise at momenta $q \sim d^{-1}$ and energy $\omega = \omega_{probe}$



$$\frac{1}{T_1} = \left(\frac{g_\sigma \mu_B \mu_0}{2}\right)^2 \coth\left(\frac{\omega}{2T}\right) \int \frac{d^2q}{(2\pi)^2} F(d,\mathbf{q}) \left[\frac{1}{4}\left(S_{-+}(\mathbf{q},\omega) + S_{+-}(\mathbf{q},\omega)\right) + S_{zz}(\mathbf{q},\omega)\right], F(d,\mathbf{q}) \sim q^2 e^{-2qd}$$

- $S_{\alpha\beta}(\mathbf{q},\omega)$ is the retarded spin-spin correlation function in Fourier space

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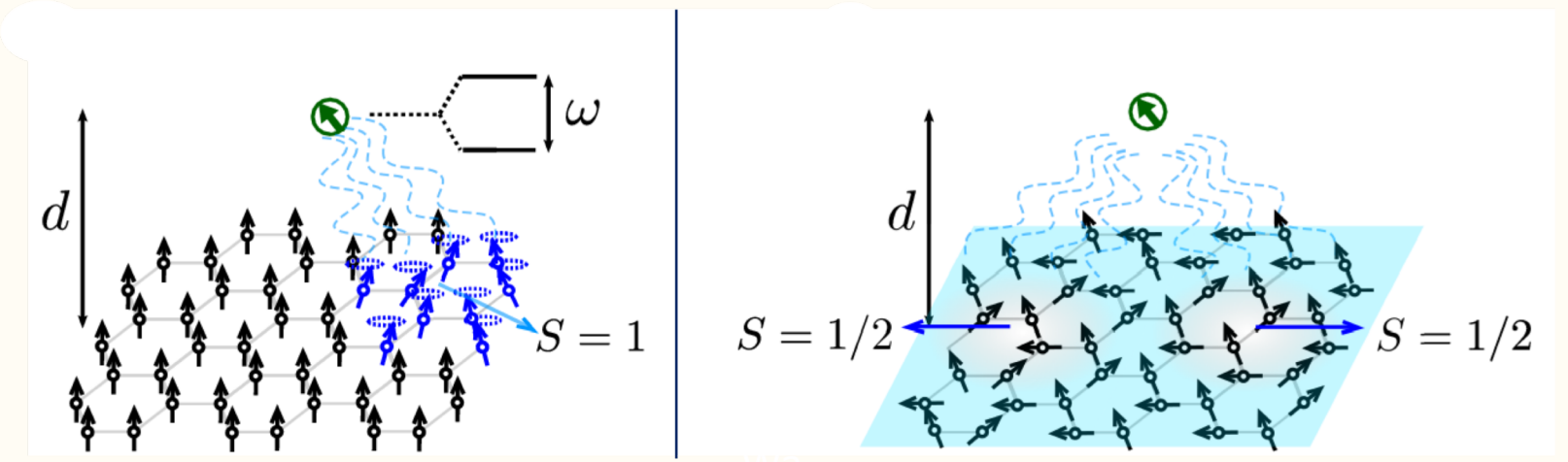
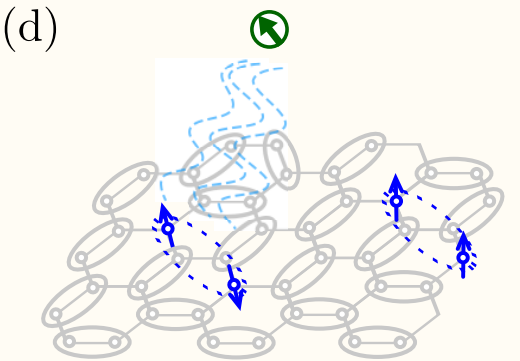
Sensing quantum spin liquids

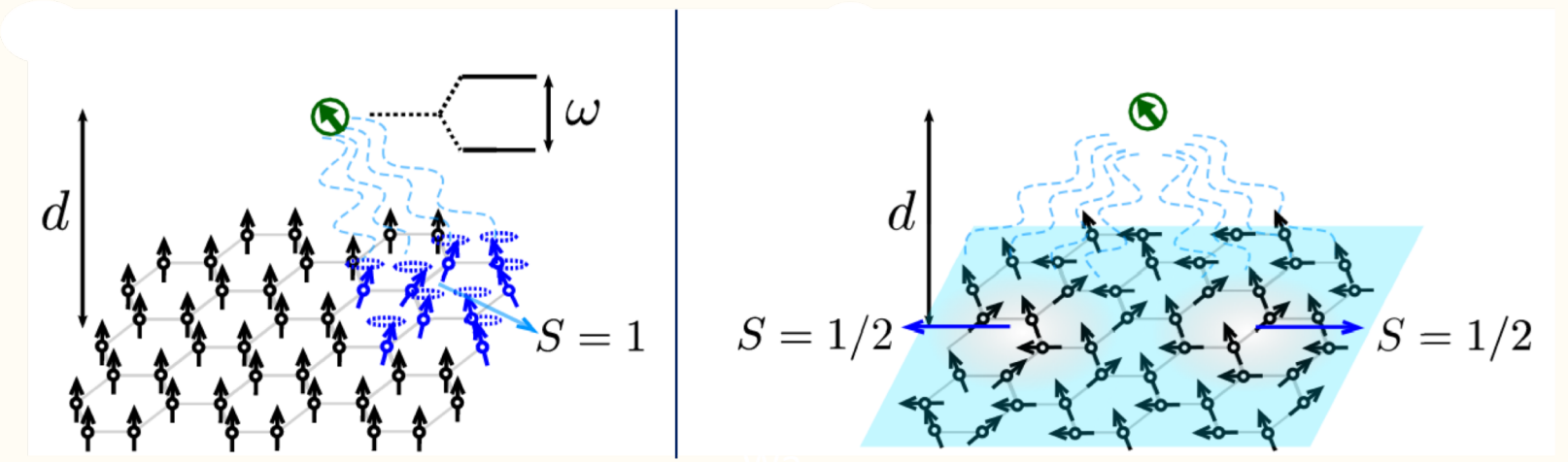


- Distinct behavior of $1/T_1$ as a function of experimentally tunable knobs:

1. Probe frequency ω
2. Temperature T
3. Sample-probe distance d



Sensing quantum spin liquids



- For a single magnetic dipole, $B \sim \mu_0 \mu_{\mathrm{B}} S_i / D^3$

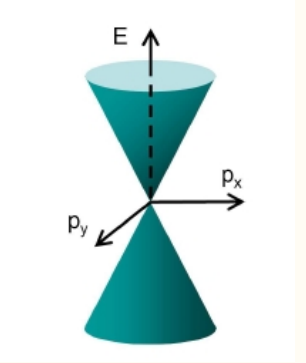
$$\frac{1}{T_1} \approx \mu_0^2 \mu_{\mathrm{B}}^4 \sum_{i,j} \langle [S_{i\alpha}/D^3, S_{j\alpha}/D^3] \rangle_\omega = \frac{\mu_0^2 \mu_{\mathrm{B}}^4}{D^6} \int d^2\mathbf{R} \int d^2\mathbf{r} \langle [S_\alpha(\mathbf{r}), S_\alpha(0)] \rangle_\omega$$

- For a paramagnet, $\langle [S_\alpha(\mathbf{r}), S_\alpha(0)] \rangle \sim e^{-r/\xi}$ so $\frac{1}{T_1} \sim D^{-4}$
- For a gapless spin liquid, $\langle [S_\alpha(\mathbf{r}), S_\alpha(0)] \rangle \sim 1/r^\delta$ so $\frac{1}{T_1} \sim D^{-(2+\delta)}$

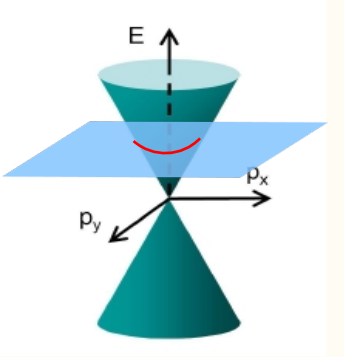
Sensing quantum spin liquids

- Concrete computation on Kitaev's honeycomb model
- Exactly solvable model with a spinon Dirac cone (time-reversal preserved), spinon Fermi surfaces (time-reversal broken)
- Effect of disorder can be studied by mapping onto the problem of phase transition between trivial and integer quantum hall phase

Ludwig *et al*, PRB 1994



Time reversal symmetry preserved



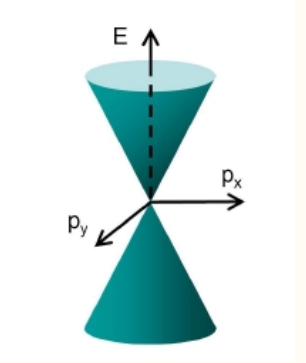
Time reversal symmetry broken

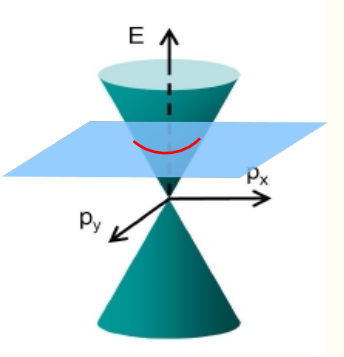
A. Kitaev, Annals Phys. 2006
Song, You, Balents, PRL 2016

Sensing quantum spin liquids

Parameter dependences of $1/T_1$

$\omega \ll T$	T dependence		d dependence	
	Clean	Dirty	Clean	Dirty
$\mathbb{Z}_2$ Dirac	T^2	$T^{2-\alpha_1}$	d^{-3}	$d^{-3+\alpha_2}$
$\mathbb{Z}_2$ FS	T^0	T	d^{-3}	d^{-2}
U(1) FS	T	T	d^{-3}	d^{-2}





Time reversal symmetry preserved

Time reversal symmetry broken

Contrast with ordered phases

$\omega \ll T$	ω, T	d
FM	T	d^0
AFM	$\omega^3 T$	d^0

A. Kitaev, Annals Phys. 2006
Song, You, Balents, PRL 2016

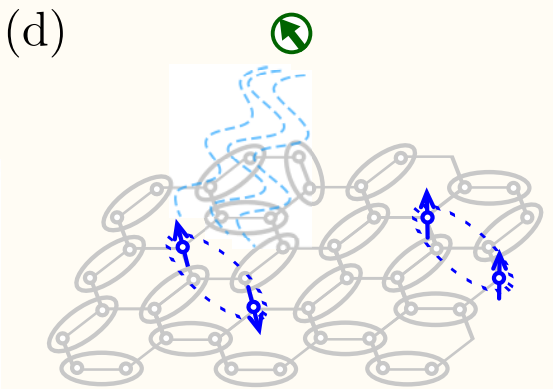
Contrast with trivial paramagnet

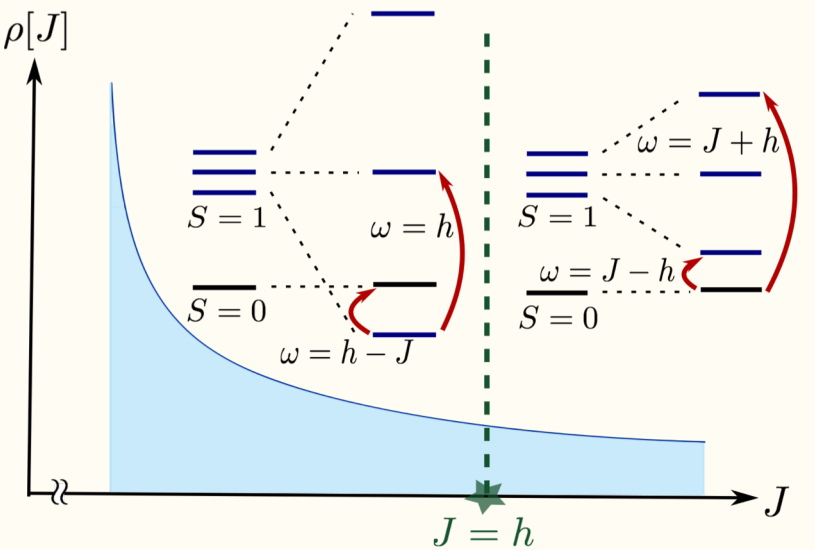
$$\frac{1}{T_1} \propto d^{-4}$$

Sensing disordered VBS phases

- Clean VBS phases are gapped $\frac{1}{T_1} \sim (\omega - \Delta_T) e^{-2d\sqrt{2m(\omega-\Delta_T)}} \Theta(\omega - \Delta_T)$
- For a disordered VBS phase, the low energy physics is governed by a random network of weakly coupled spins, with a power law behavior of coupling J (appears gapless)

Kimchi *et al*, PRX 2018





- Characteristic dip in T_1 at $\omega = h$ due to resonance

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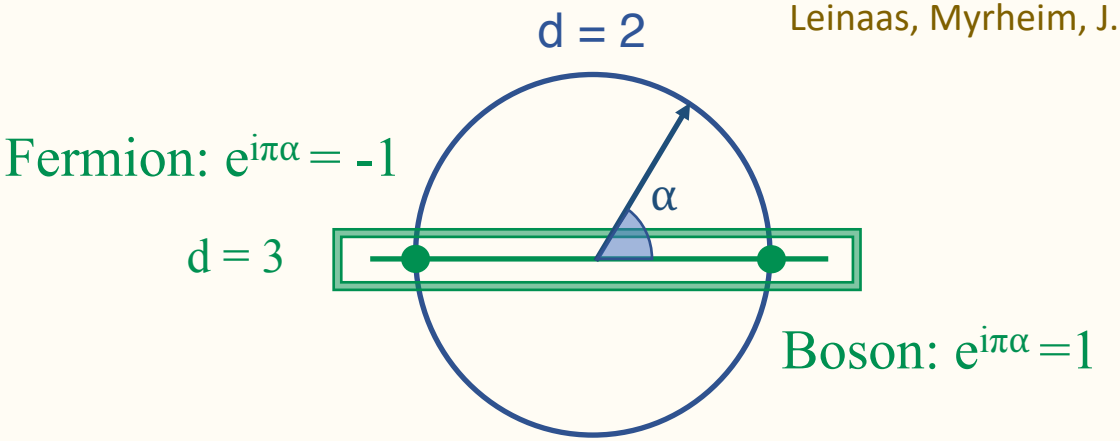
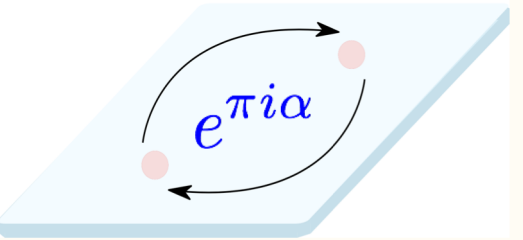
Sensing anyonic statistics

- Identical particles in a two-dimensional world can have arbitrary phases under exchange – neither bosons nor fermions!

Leinaas, Myrheim, J. Nuovo Cim B 1977



- Correlation functions of local observables have a robust universal threshold behavior depending on statistics parameter α



Morampudi *et al* , PRL 2017
Arovas *et al* , N. Phys. B 1989

Sensing anyonic statistics

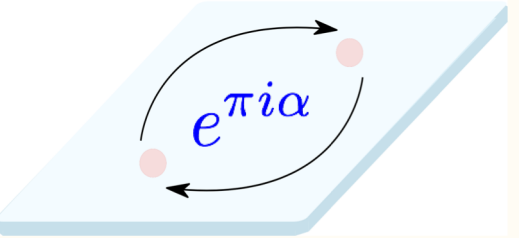
- If the anyons carry spin, this translates to a universal relaxation rate at low energy for NV centers

$$\frac{1}{T_1} \sim (\omega - \Delta_s)^{2+\alpha}\, \Theta(\omega - \Delta_s)$$

- Example: chiral spin liquid state with spin-ful semions ($\alpha = ½$)

Laughlin, Kalmeyer, PRL 1987

- Robust to short-range interactions because of statistical repulsion (except bosons that have logarithmic corrections)



Morampudi *et al* , PRL 2017
Arovas *et al* , N. Phys. B 1989

Outline

- Unconventional phases of matter in magnetic insulators
- NV centers as quantum sensors in condensed matter
- Footprints of a phase in magnetic noise
- Sensing anyonic statistics using NVs
- Material candidates
- Conclusions and outlook

Confusion in the material world

- Spin-orbit coupled iridates, like α-$RuCl_3$ are well-described by a Kitaev Hamiltonian, but order at low T. Magnetic order can be suppressed by magnetic fields – what is the nature of the tentative spin-liquid phase?

  Banerjee *et al*, Nat. Mater. 2016
  Lampen-Kelly *et al*, PRL 2017
  Y. Kasahara *et al*, PRL 2018

- Inorganic compounds like $YbMgGaO_4$ are a subject of debate – spinon Fermi surface vs disordered VBS phase?

  Shen *et al*, Nature. 2016
  Kimchi *et al*, PRX 2018

- Frustrated S = 1 compound $Ba_3NiSb_2O_9$: Candidate for quadratic band touching spin liquid and spinon Fermi surface.

  Xu *et al*, PRL 2012
  Fak *et al*, PRB 2017

Noise magnetometry can help answer all these questions

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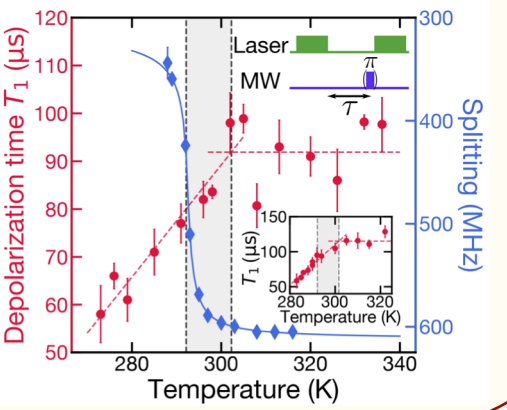
- Single spin qubits (like NV centers) can be used to distinguish exotic ground states of magnetic insulators from conventional magnets
- They can also detect elusive anyonic statistics in gapped systems, provided the anyons carry spin
- They offer several advantages over conventional solid-state probes
- Similar experiments have been done for magnetic metals in this group, so I hope insulators are not far away!

Hsieh *et al*, arXiv: 1812.08796



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Thank you for your attention!