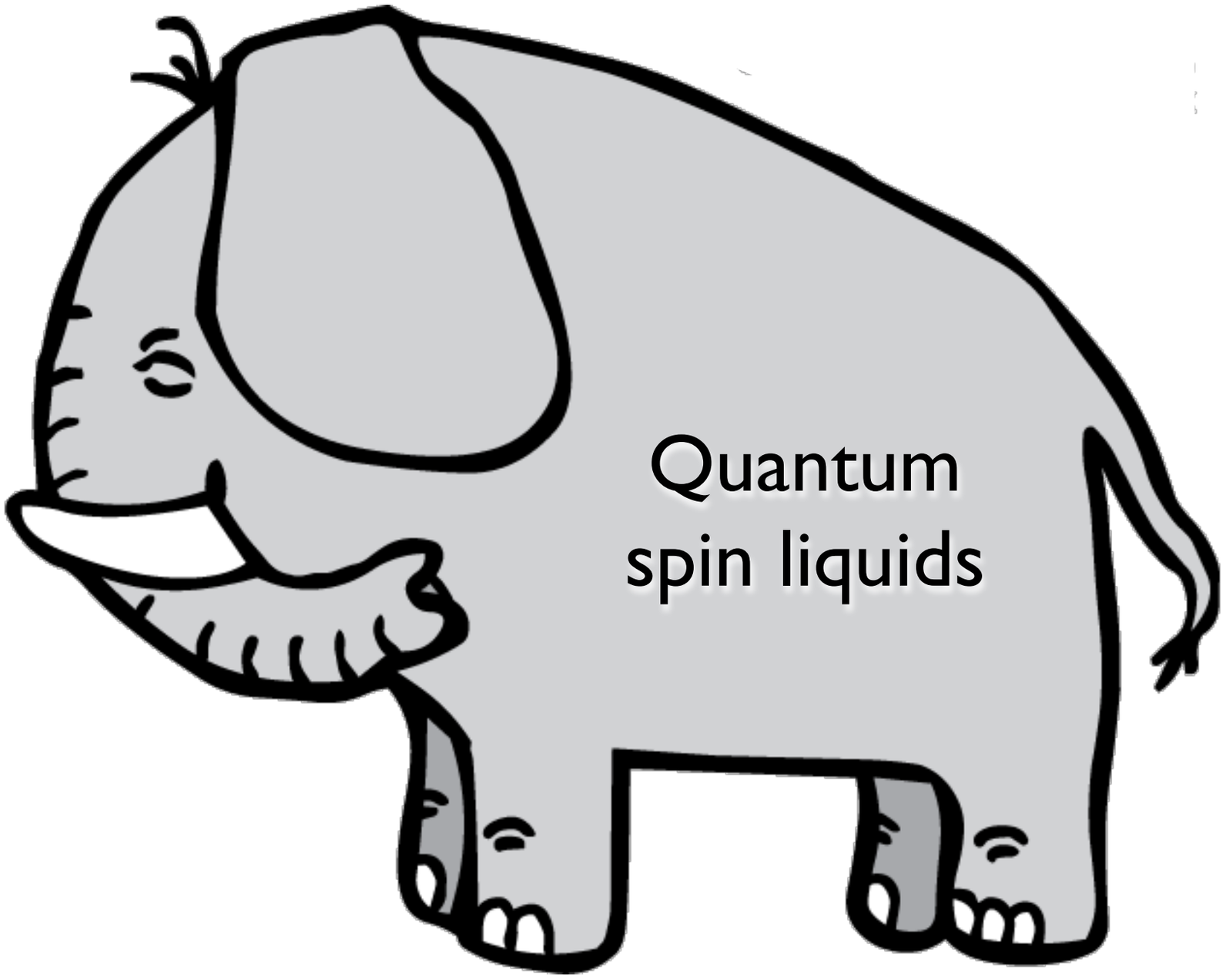
Theory Overview

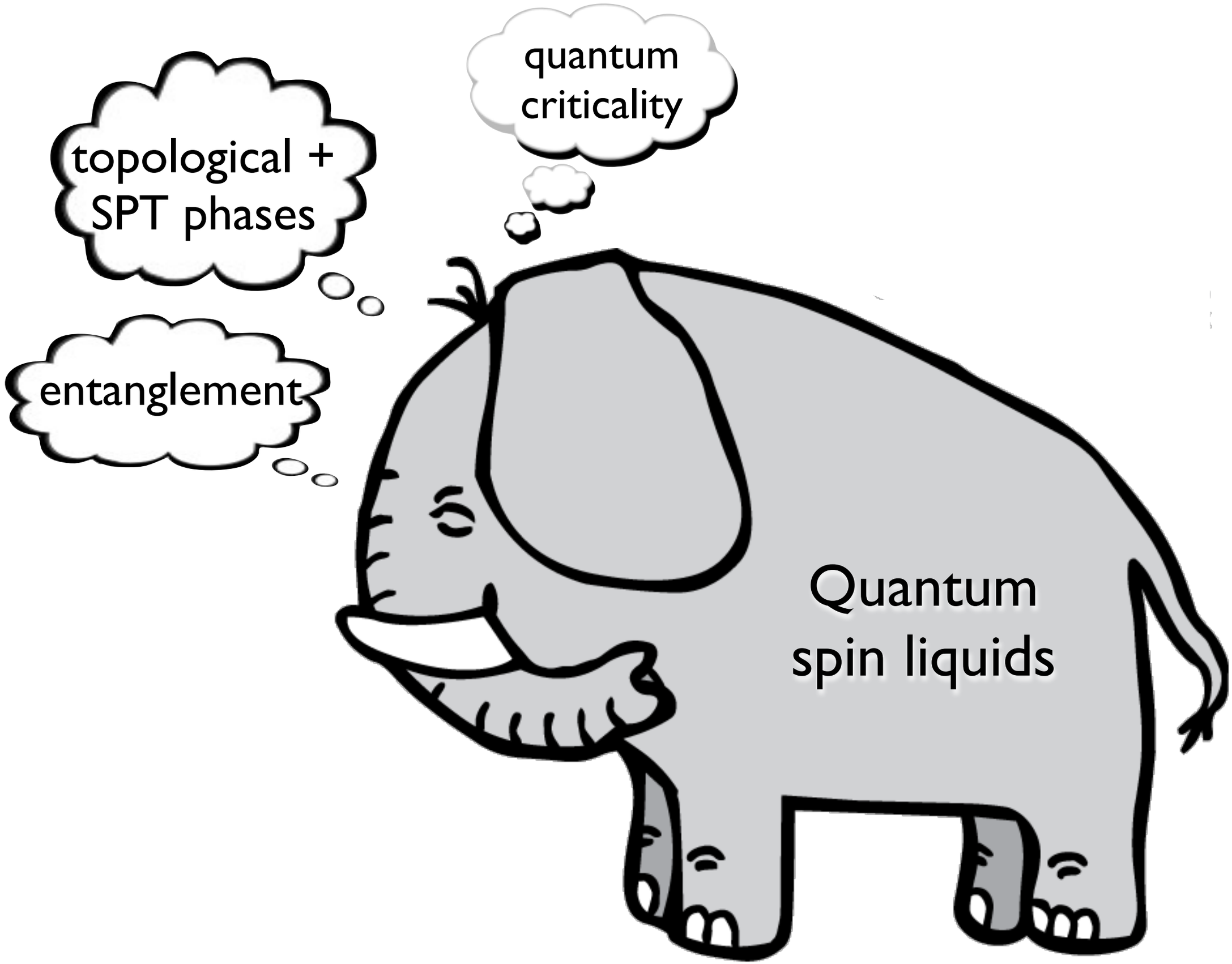
Leon Balents, KITP

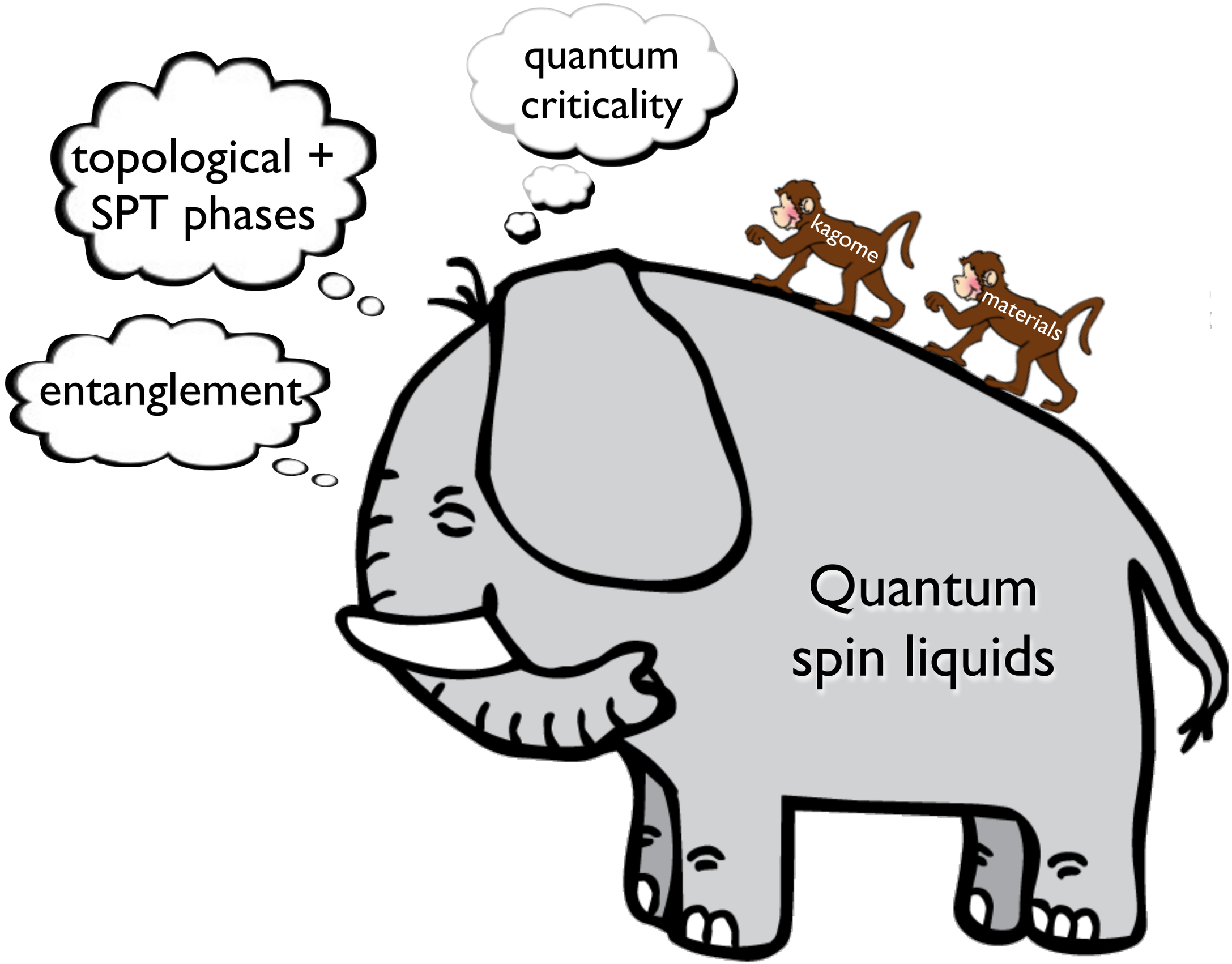
KITP conference on "Exotic Phases of Frustrated Magnets"
October 8, 2012

http://www.tagxedo.com/

Theory topics?


Quantum
spin liquids


topological +
SPT phases
quantum
criticality
entanglement
Quantum
spin liquids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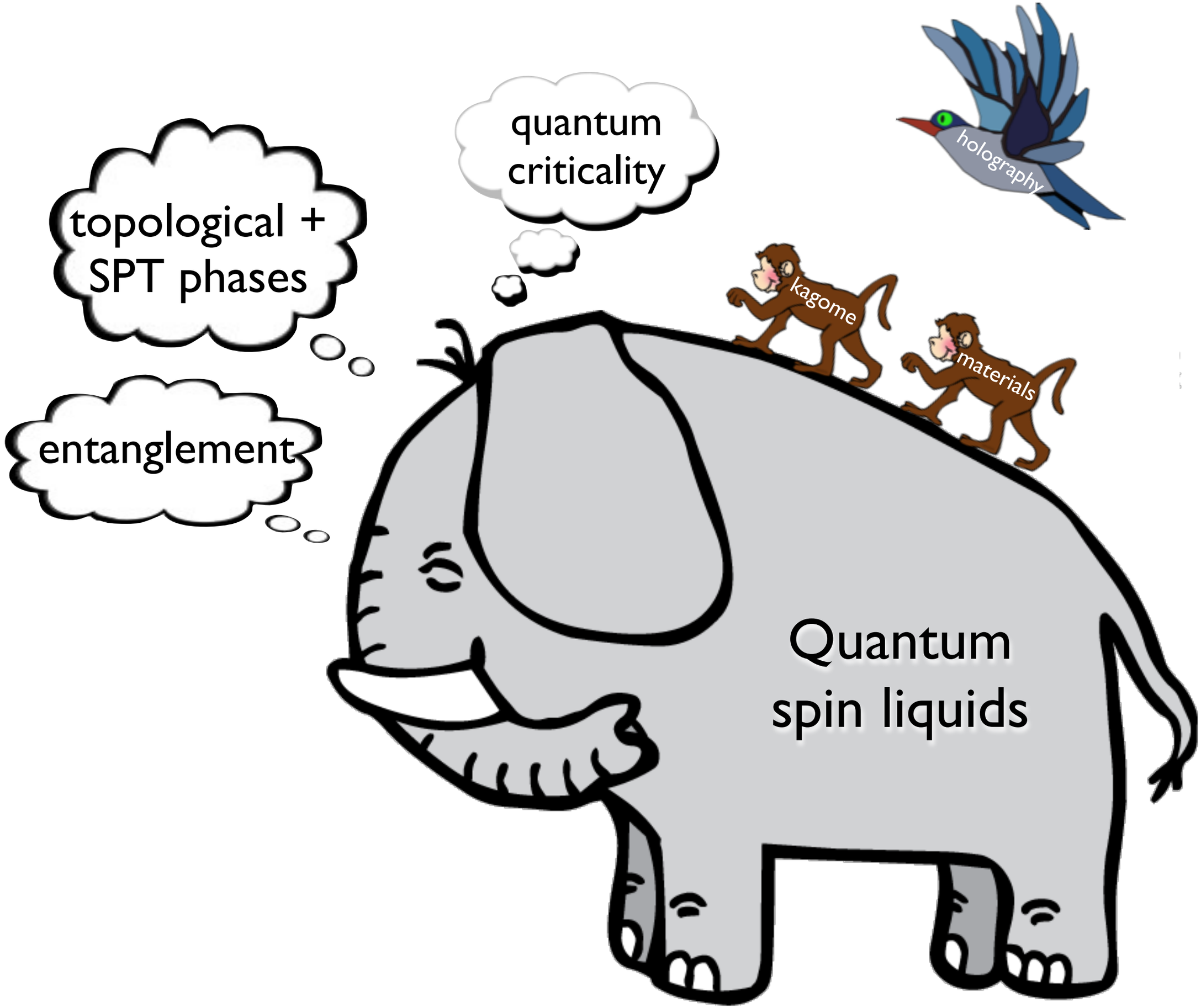
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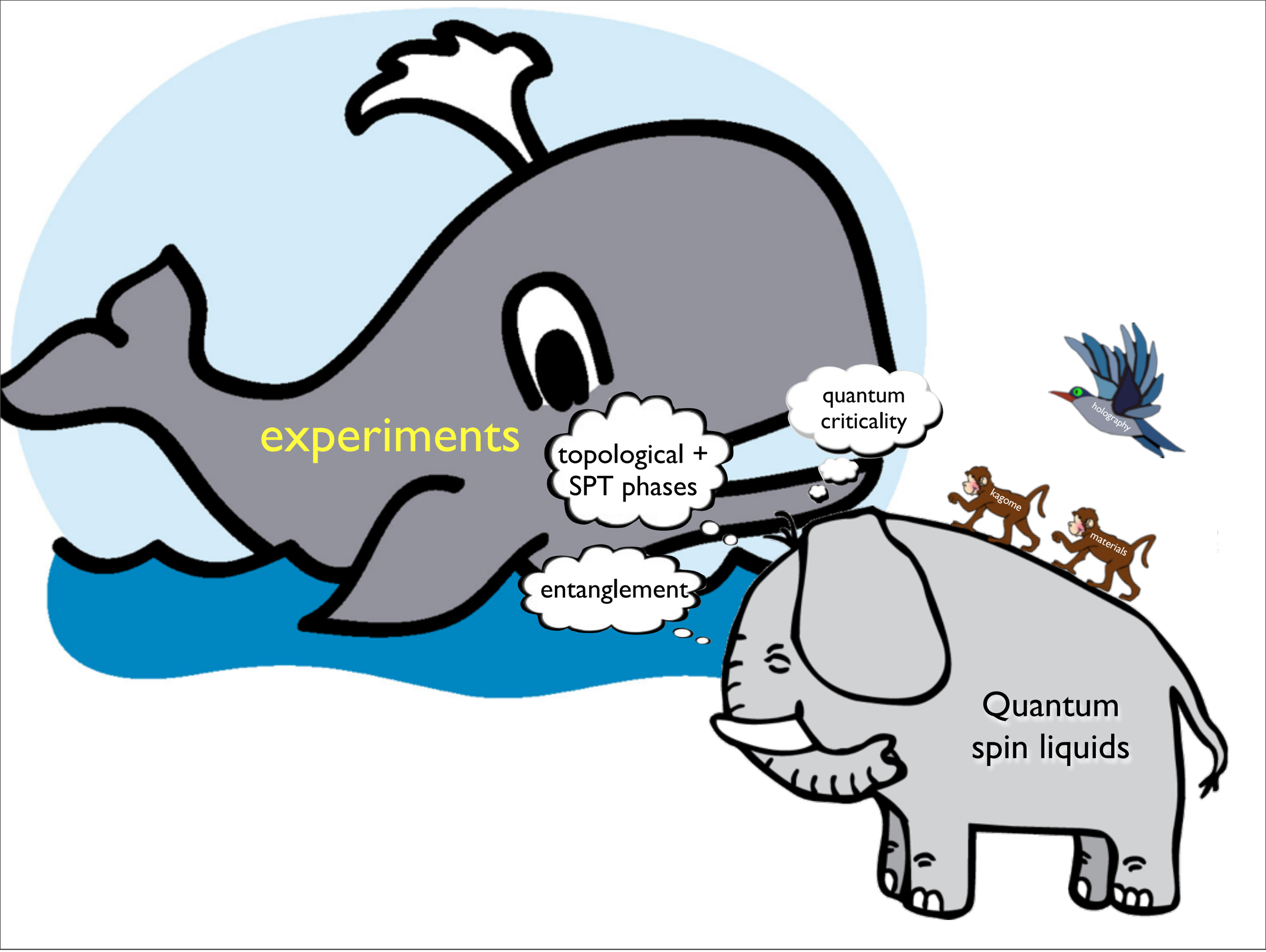
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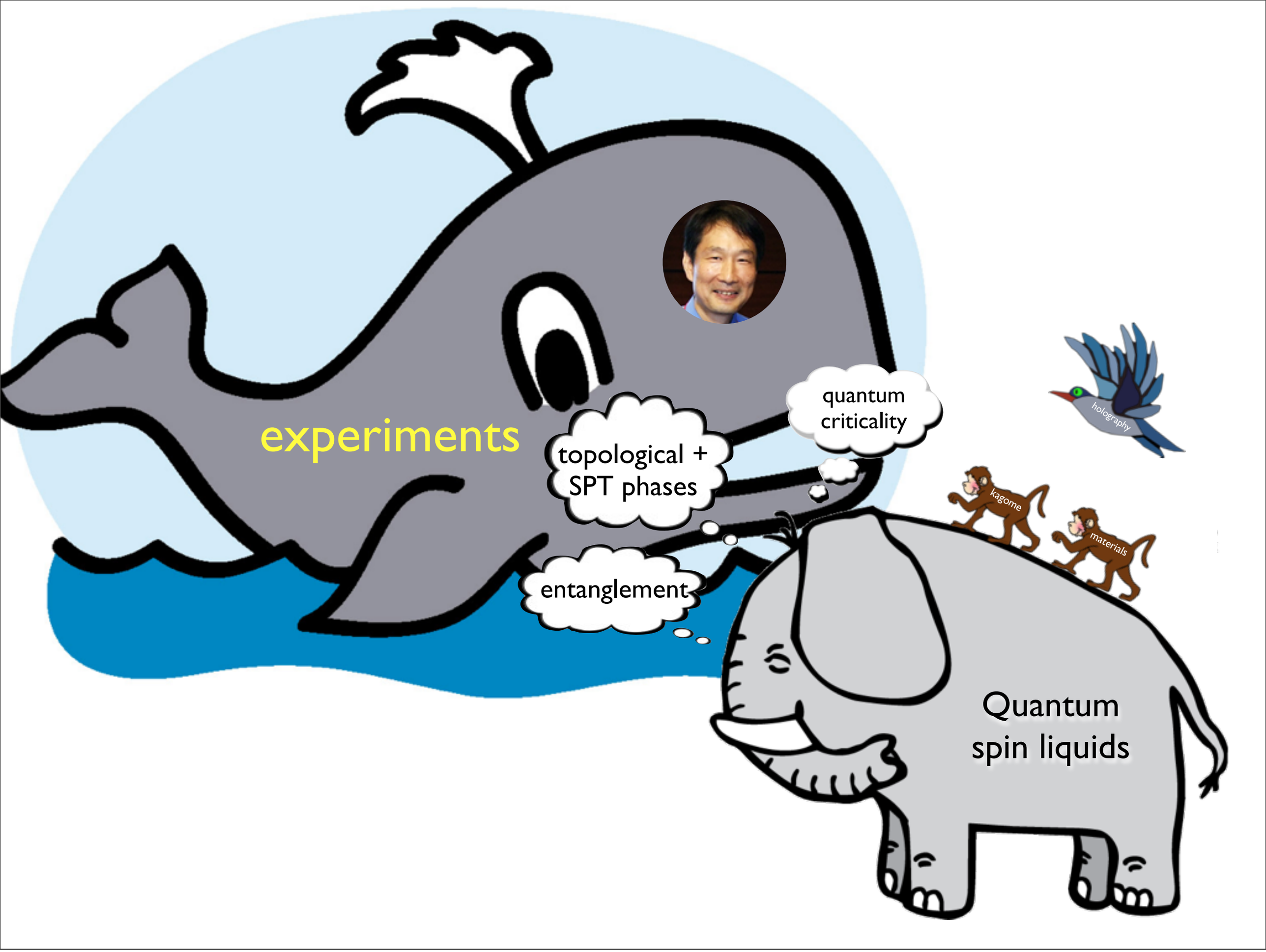
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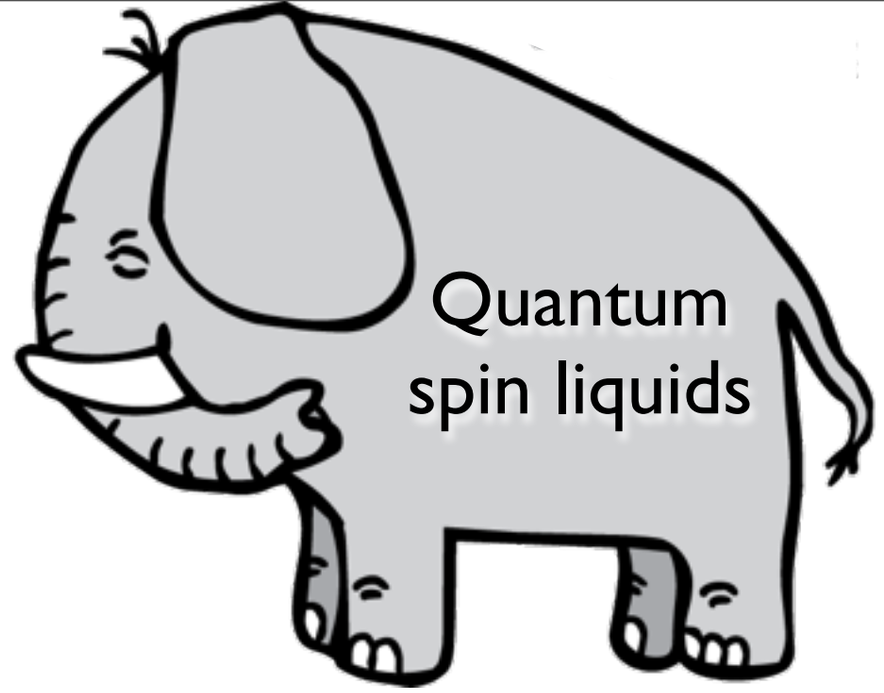
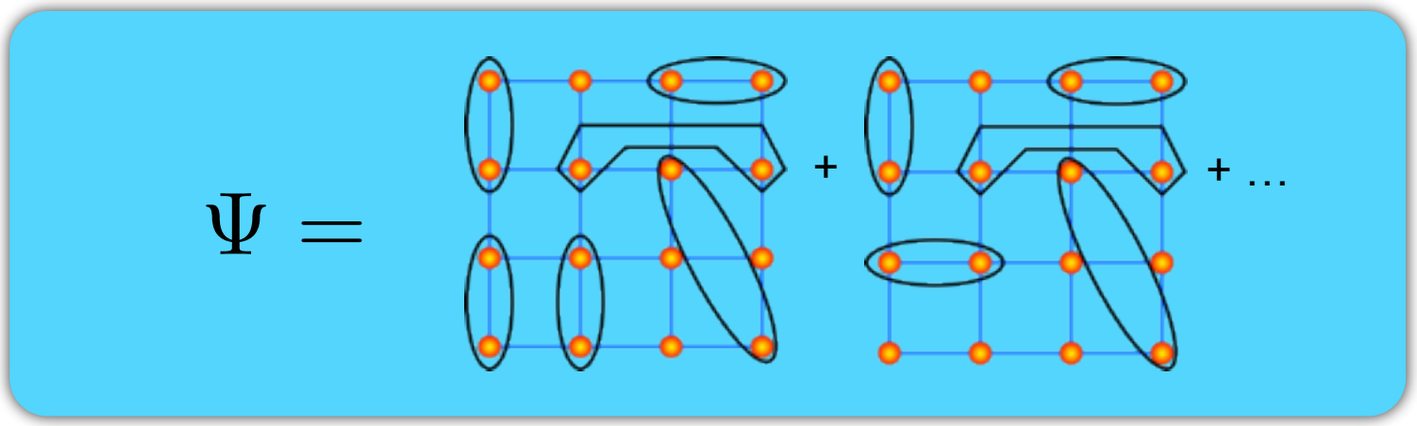
This talk

- Review the background: what we *should* agree on (do we?)
- Survey the talks: what are the issues?



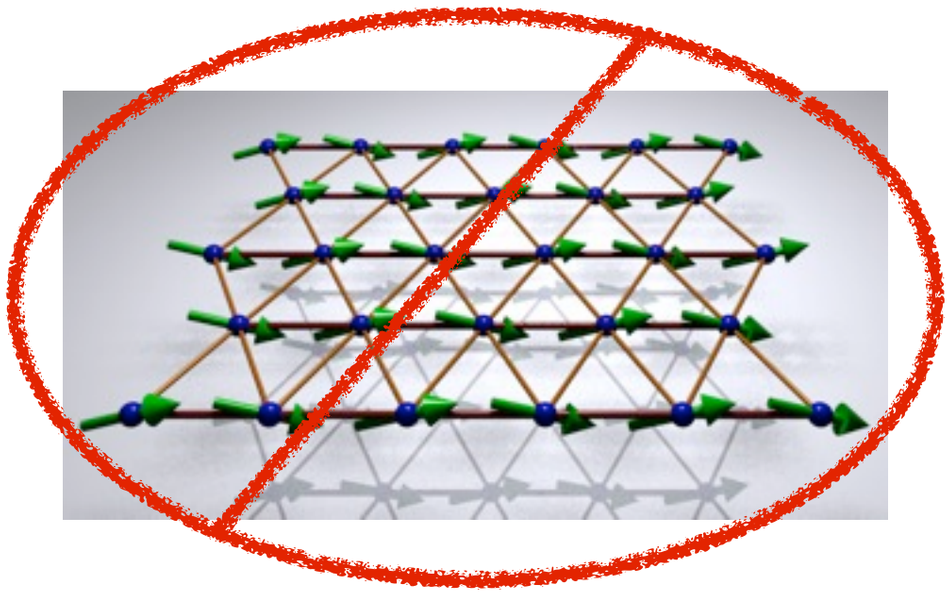
- 1973: Anderson proposes the "Resonating Valence Bond" state (for triangular lattice)

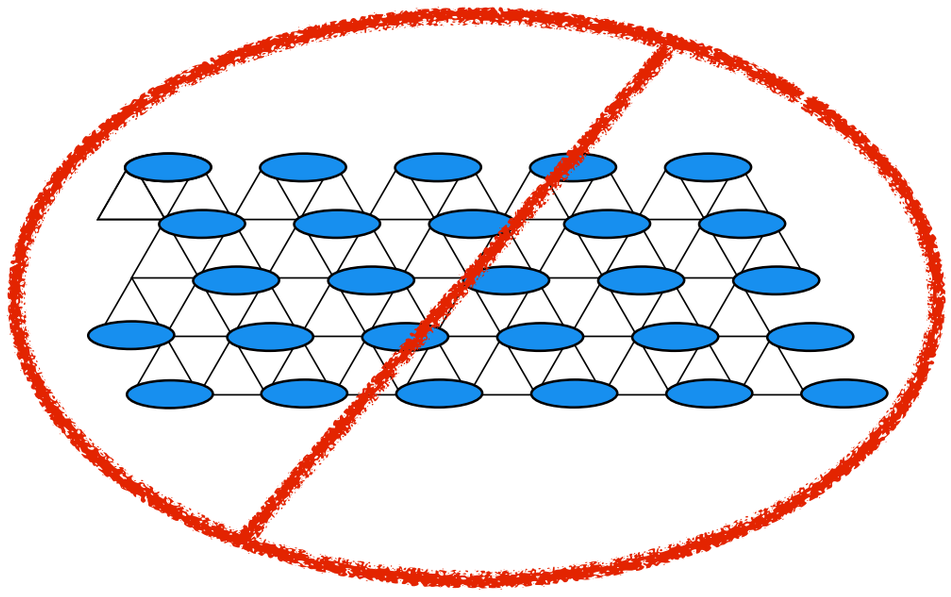


- prototype of the modern QSL

A modern view

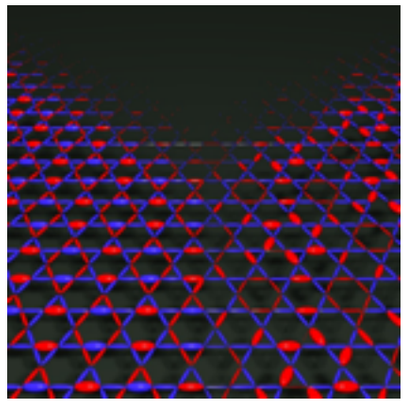
- Instead of just being a disordered state, the key element of a QSL is *long range entanglement*
- i.e. it cannot be regarded or even approximated as a product state over any finite blocks





Symmetry

- Phases characterized by measurable order parameters
- Phases can "collapse" if symmetry is *explicitly* broken



Long Range Entanglement

- Phases are distinct even in absence of any symmetry
- LRE can be measured directly *non-locally*, e.g. by *entanglement entropy*
- Supports excitations with *exotic quantum numbers and statistics*
- Describable by *emergent gauge structure*

Symmetry

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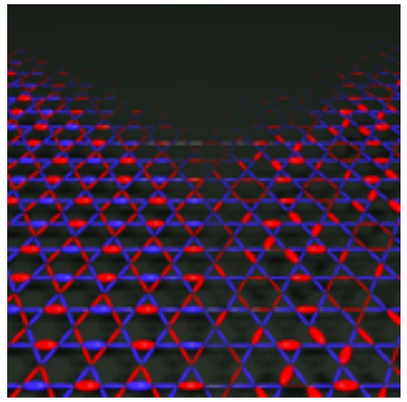
- Phases can "collapse" if symmetry is *explicitly* broken

SPT phases



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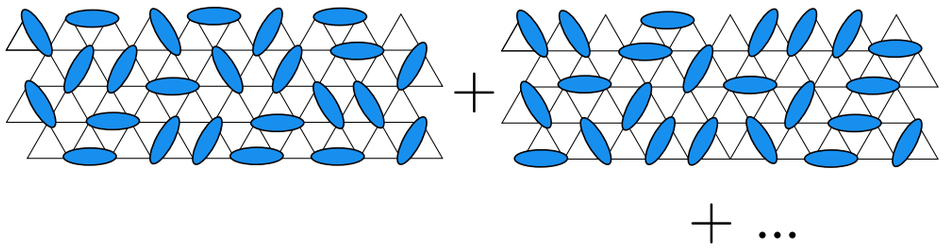
Theoretical Descriptions

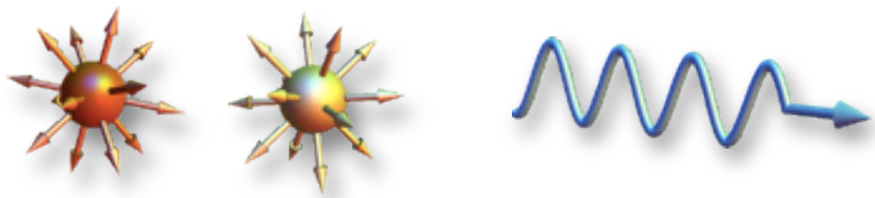
- Slave particles/Gutzwiller projected fermionic wavefunctions
- Gauge theories
- TQFTs
- Tensor network/string net states
- Numerics

Classes of QSLs

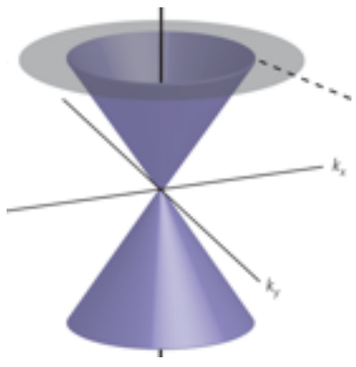
- Topological QSLs
  - full gap



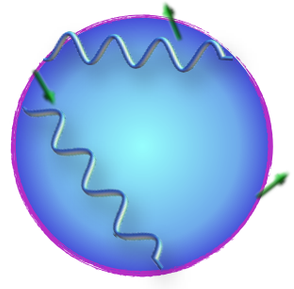
- U(1) QSL
  - gapless emergent "photon"



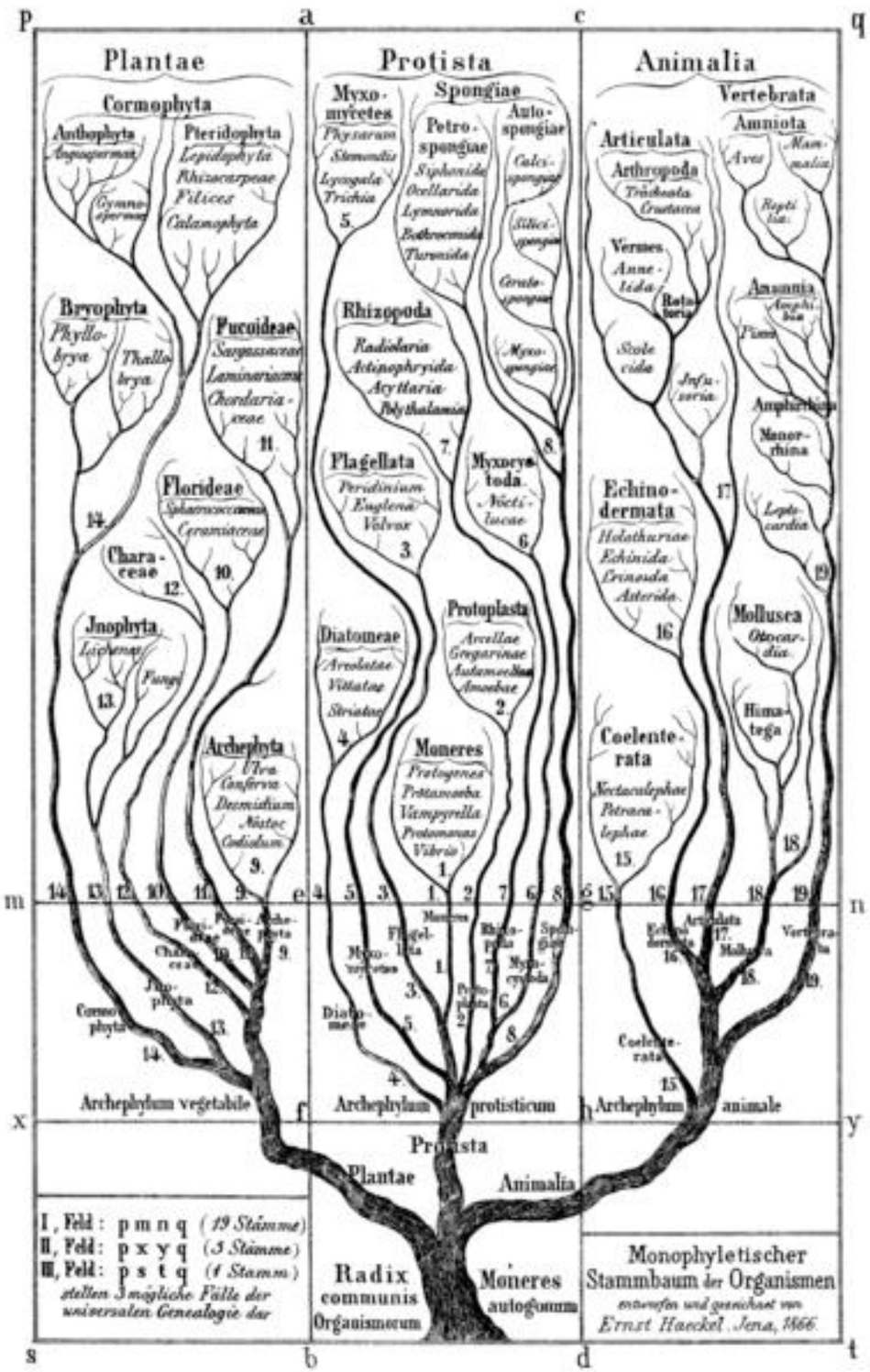
- Algebraic QSLs
  - Relativistic CFT (power-laws)



- Spinon Fermi surface QSL



Classification



Michael Hermele (Univ. of Colorado) *Symmetry Classification of Gapped Z2 Spin Liquids*

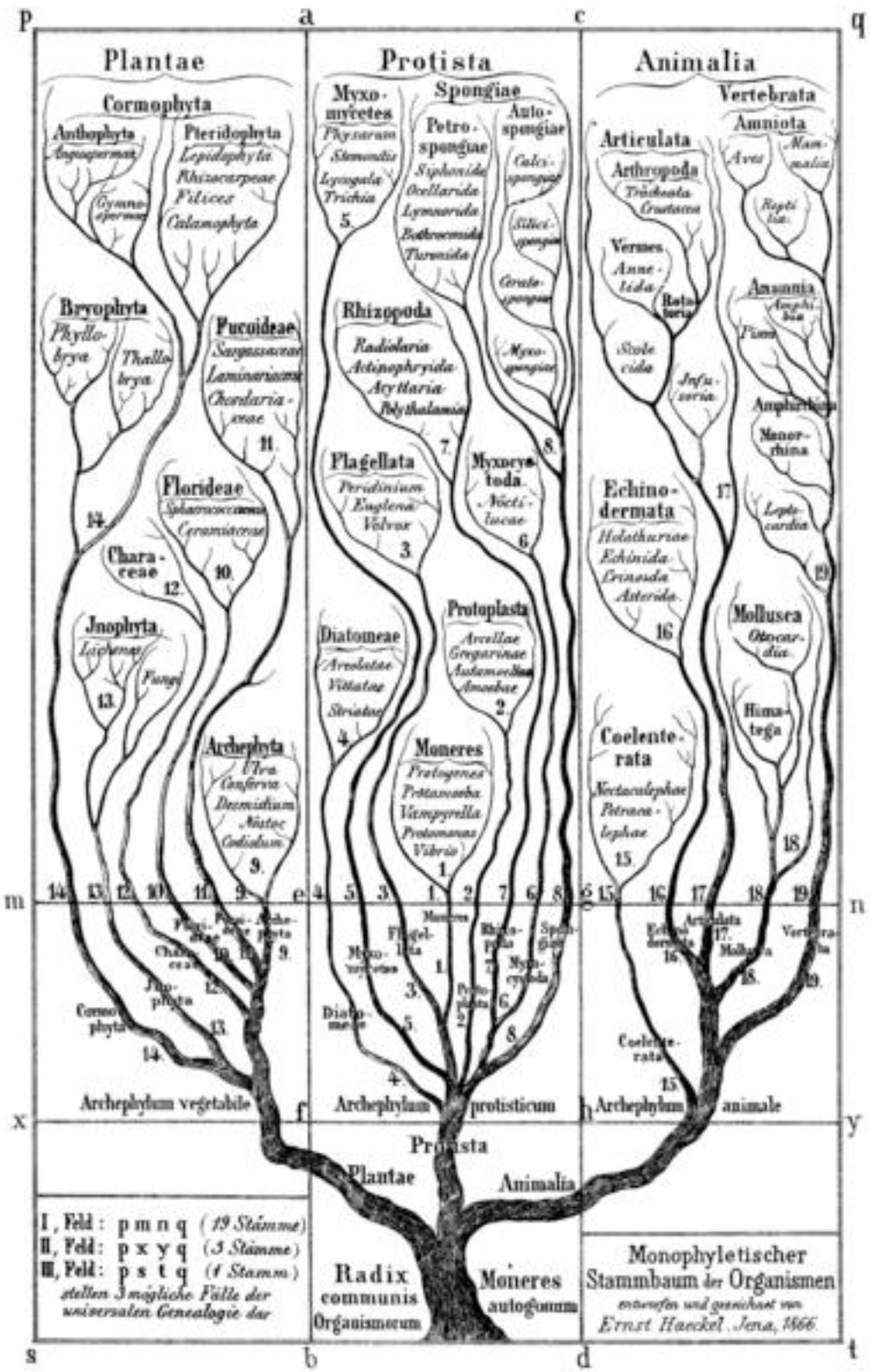
Ying Ran (Boston College) *Spin Liquids, Symmetry Fractionalization and Beyond*

Xiao-Gang Wen (MIT) *From Topological Order to Long-Range Entanglements*

Cenke Xu (UCSB) *Symmetry Protected Topological Phase and Symmetry Protected Criticality in Two and Three Dimensions*

- What can be classified?
- Topology, symmetry, quasiparticles?
- Really complete?
- Only gapped phases?
- Minimal scheme?
- Practical use?

Classification



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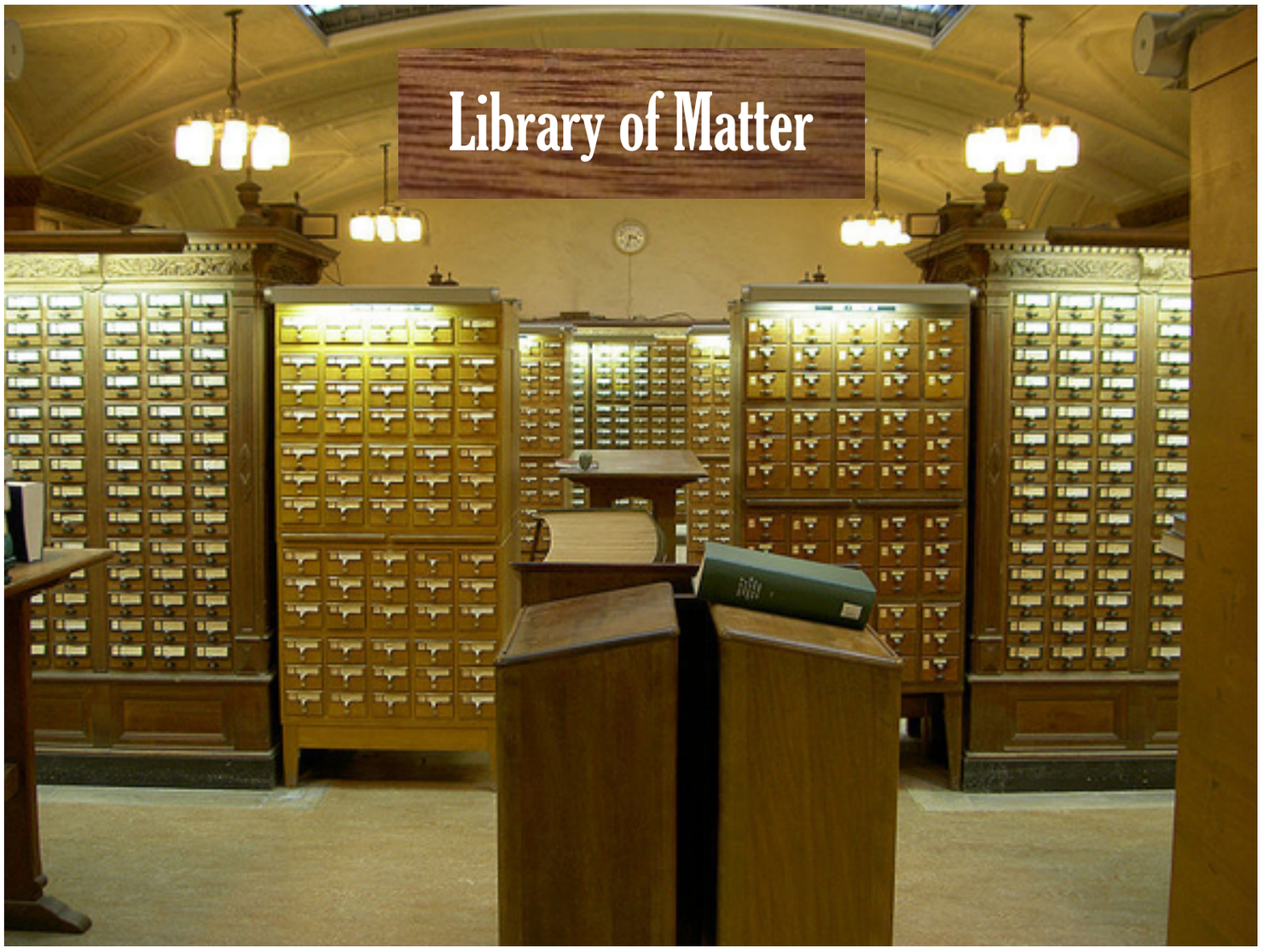
- Many schemes:
  - TQFTs
  - Cohomology
  - K-matrix
  - PSG
  - Tensor category
  - ...

How are different schemes related?



Dewey	LC	General Subject
000, 040, 080	AC	General Collections
010, 020, 090	Z	Library Science
030	AE	Encyclopedias
050	AP	Periodicals
060	AS	Academies, Societies
070	PN	Literature (Gen.)
100	B-BJ	Philosophy (Gen.)
110-120	BD	Speculative Philosophy
130, 150	BF	Psychology
140, 180, 190	B	Philosophy (Gen.)
160	BC	Logic
170	BJ	Ethics
200, 210, 290	BL	Religions. Mythology
220	BS	The Bible
230	BT	Doctrinal Theology
240, 250	BV	Practical Theology
260, 270	BR	Christianity
280	BX	Christian Denominations
300	H	Soc. Sci. (General)
310	HA	Statistics
320	J	Gen. Legislative papers
330	HB	Economic Theory
340	K	Law
350	JF-JS	Political Institutions
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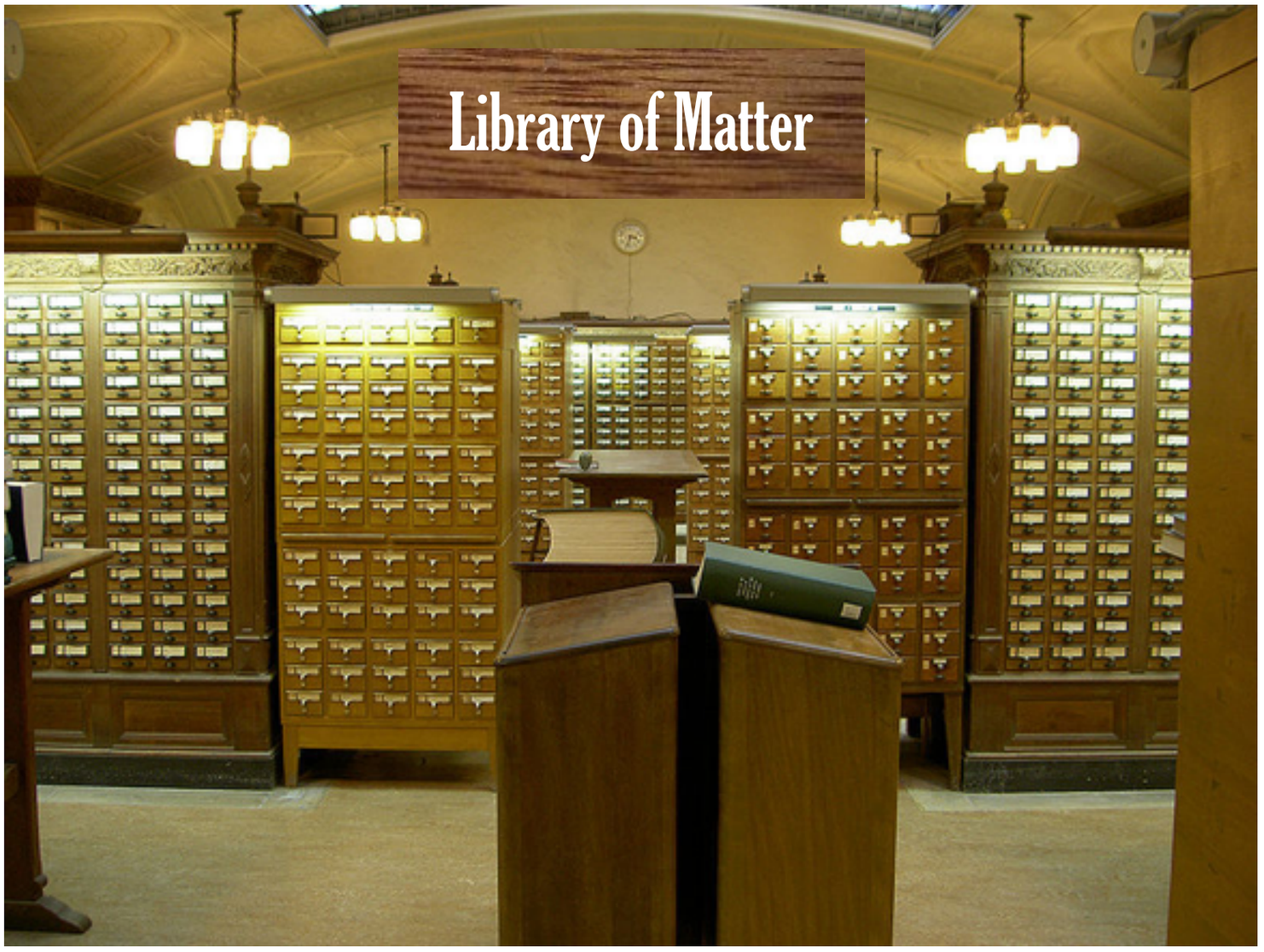
390	GT	Manners and customs
400, 410	P	Philology. Linguistics

How are different schemes related?



cohomology	K-matrix	General Subject
000, 040, 080	AC	Z_2
010, 020, 090	Z	fibonacci
030	AE	IQHE
050	AP	ASL
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Numerics: technique development and study of realistic models

DMRG/Tensor

Steven White (Irvine) *Exact Topological Degeneracies on Finite Kagome Clusters*

Hong Chen Jiang (UCSB) *Topological Quantum Spin Liquid in Physical Realistic Models: Unbiased Large-Scale Numerical Evidence*

Guifre Vidal (Perimeter Inst.) *Towards a Complete Characterization of Emergent Topological Order From a Microscopic Hamiltonian on the Lattice*

Zhengcheng Gu (UCSB, KITP) *Tensor Product State Approach to Strongly Correlated Systems: From Spin Liquid to Doped-Mott-Insulator*

QMC

Fakher Assaad (Univ. Würzburg) *Phase Diagram of the Hubbard Honeycomb Lattice*

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Gutzwiller++

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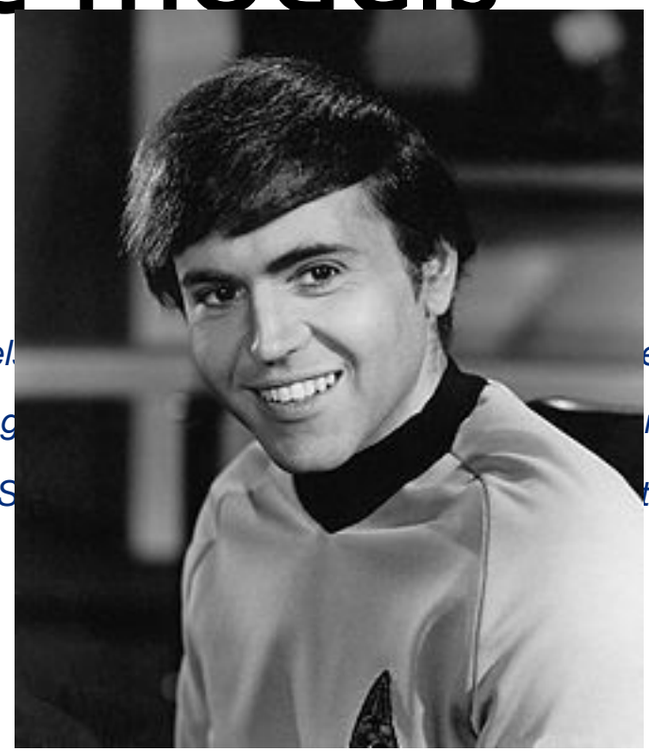

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Issues

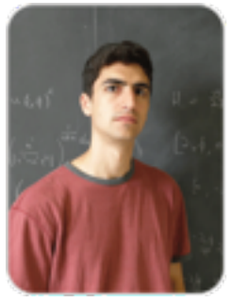
- Which techniques can be fruitfully applied and where?
  - To accurately predict QSL phases?
  - To calculate their measurable properties?
  - To verify universal aspects?
- What would it take to convincingly demonstrate reliability of Gutzwiller(++) wavefunctions in predicting phases?

Topological Entanglement Entropy

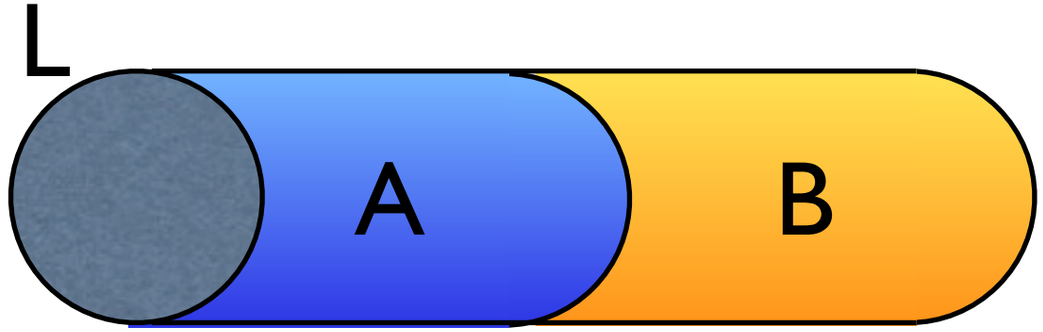
- For gapped QSLs, can define a quantitative measure of long-range entanglement

$$S(L) \sim \alpha L - \gamma$$






2006



$$\rho_A = \mathrm{Tr}_B |\psi\rangle\langle\psi|$$

$$S = -\mathrm{Tr}_A[\rho_A \ln \rho_A]$$

Topological Entanglement Entropy

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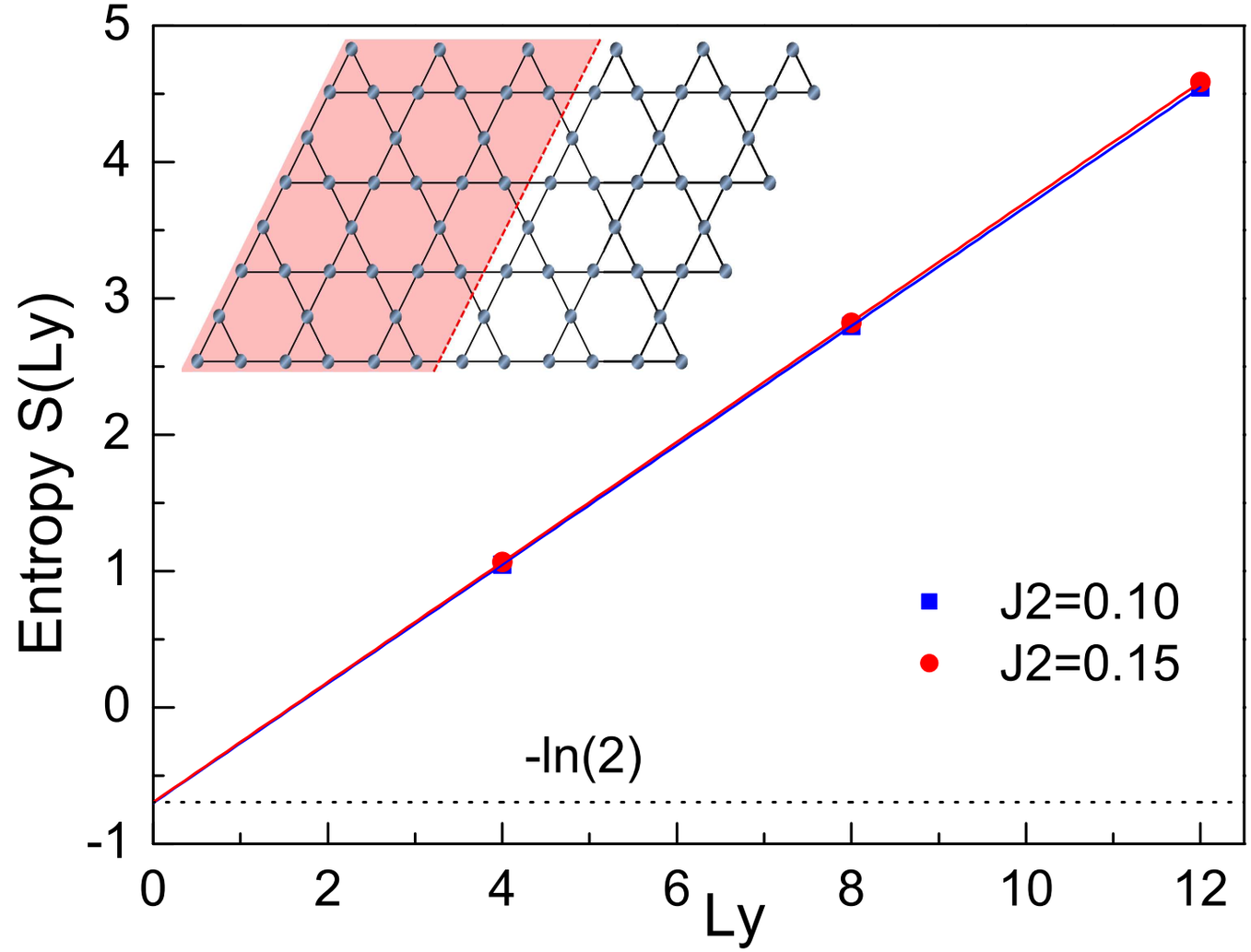
$$S(L) \sim \alpha L - \gamma$$

$\gamma_{DMRG}=0.698(8)$

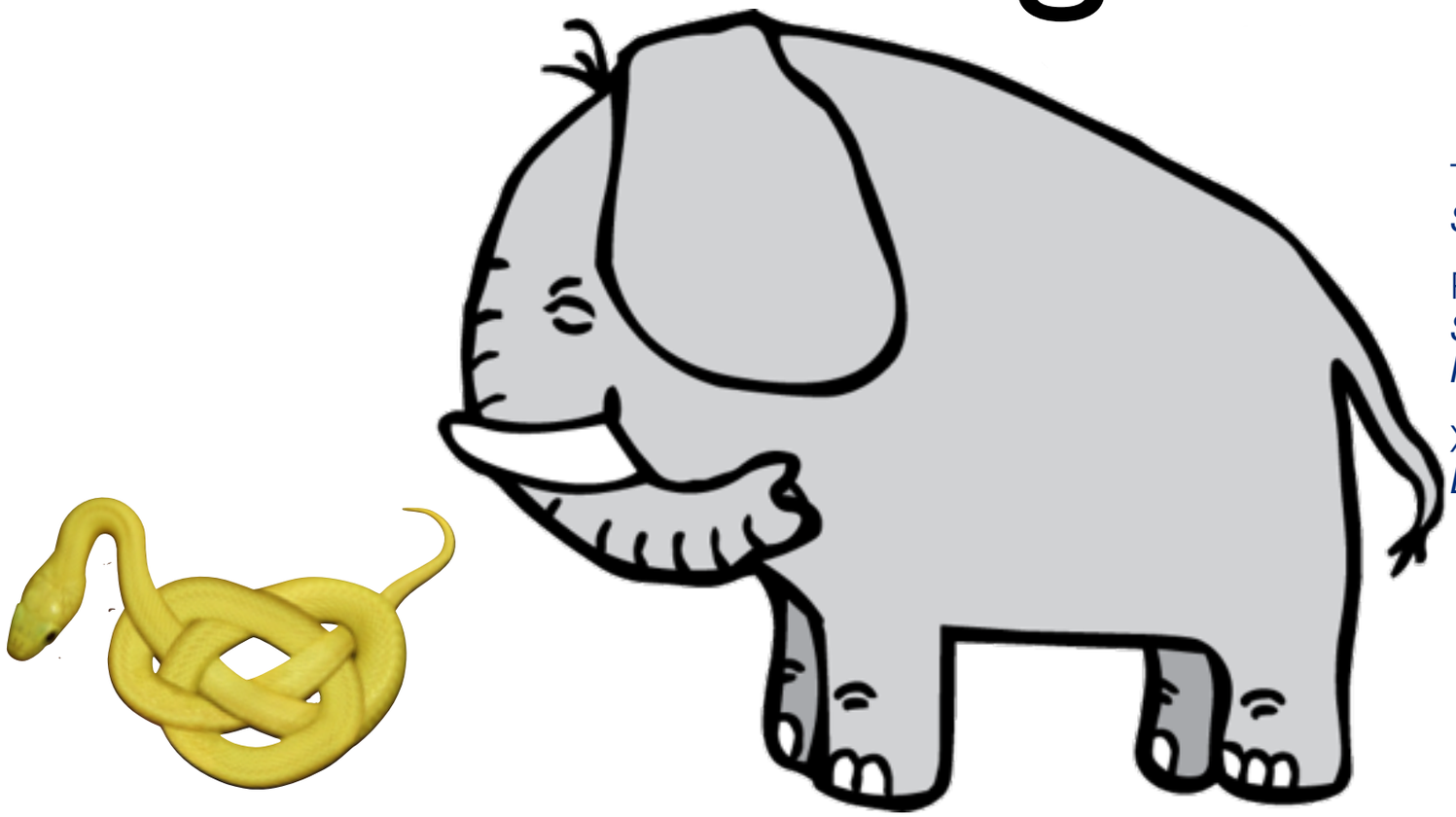
$\gamma_{th}=\ln(2)=0.693$

H.C. Jiang, Z. Wang, LB
arXiv:1205.4289

Tuesday morning session



Entanglement



Tarun Grover (KITP) *Quantum Entanglement and Strongly Correlated Topological Phases*

Roger Melko (Univ. Waterloo) *Entanglement Entropy in Spin Liquids, Gapless Phases and Quantum Critical Points*

Xiao-Gang Wen (MIT) *From Topological Order to Long-Range Entanglements*

- What more information can be extracted from entanglement measures?
- Entanglement spectrum?
- Useful for non-topological spin liquids?

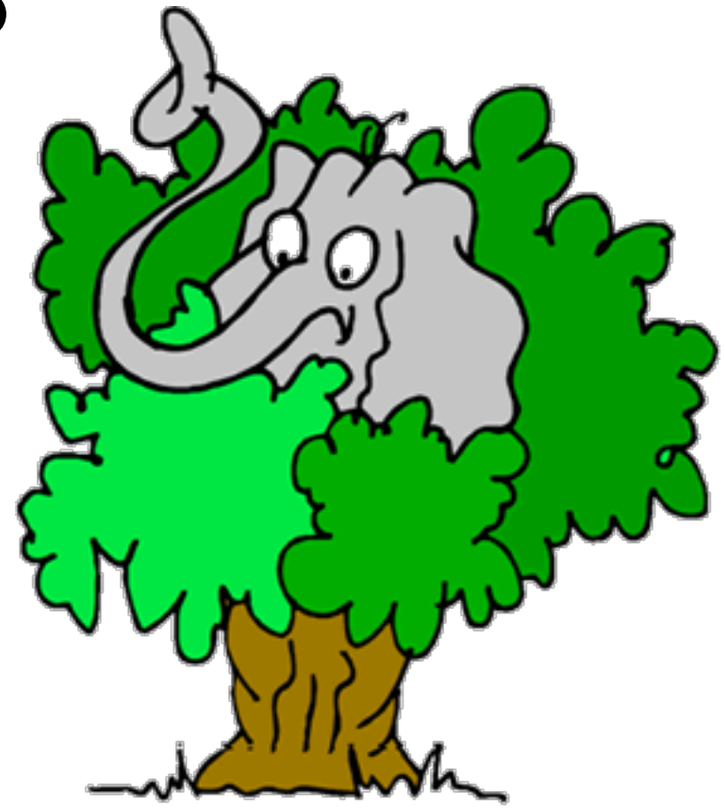
Finding QSLs

T. Senthil (MIT) *Quantum Spin Liquids and Continuous Metal-Insulator Transitions*

Roser Valentí (Univ. Frankfurt) *Correlation Effects in Organic Charge-Transfer Salts: A Combined Ab Initio and Many-Body Investigation*

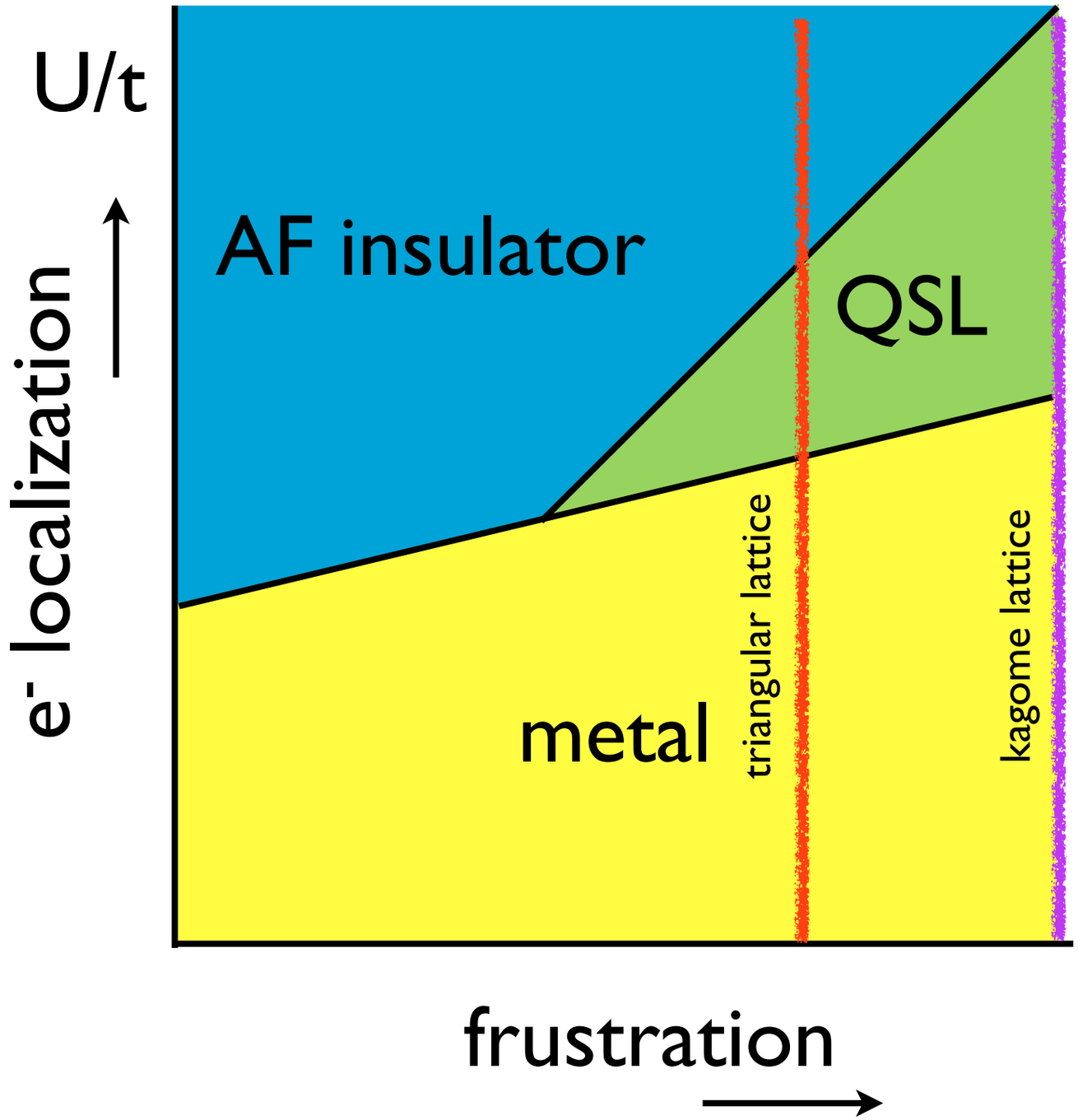
Nic Shannon (OIST) *Quantum Ice*

George Jackeli (MPI FKF) *Spin-Orbit Coupling in Mott Insulators: Unusual Interactions and Possible Exotic Phases*

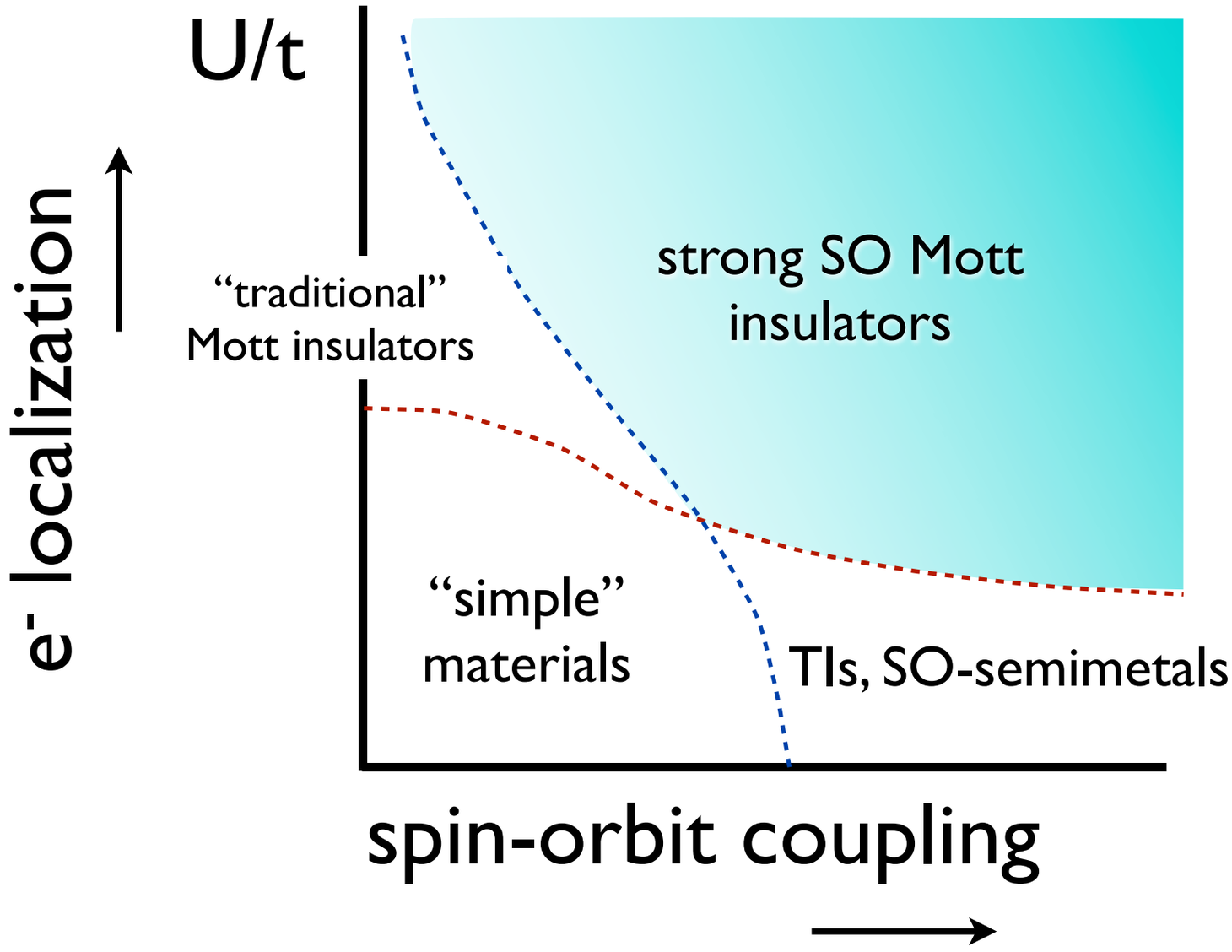


- Can theory guide the search for new QSLs?
  - Appropriate regimes
  - Ab initio calculations
  - Microscopic mechanisms

Weak Mott insulators?



Spin Orbit?



QSLs here?

$Na_4Ir_3O_8$

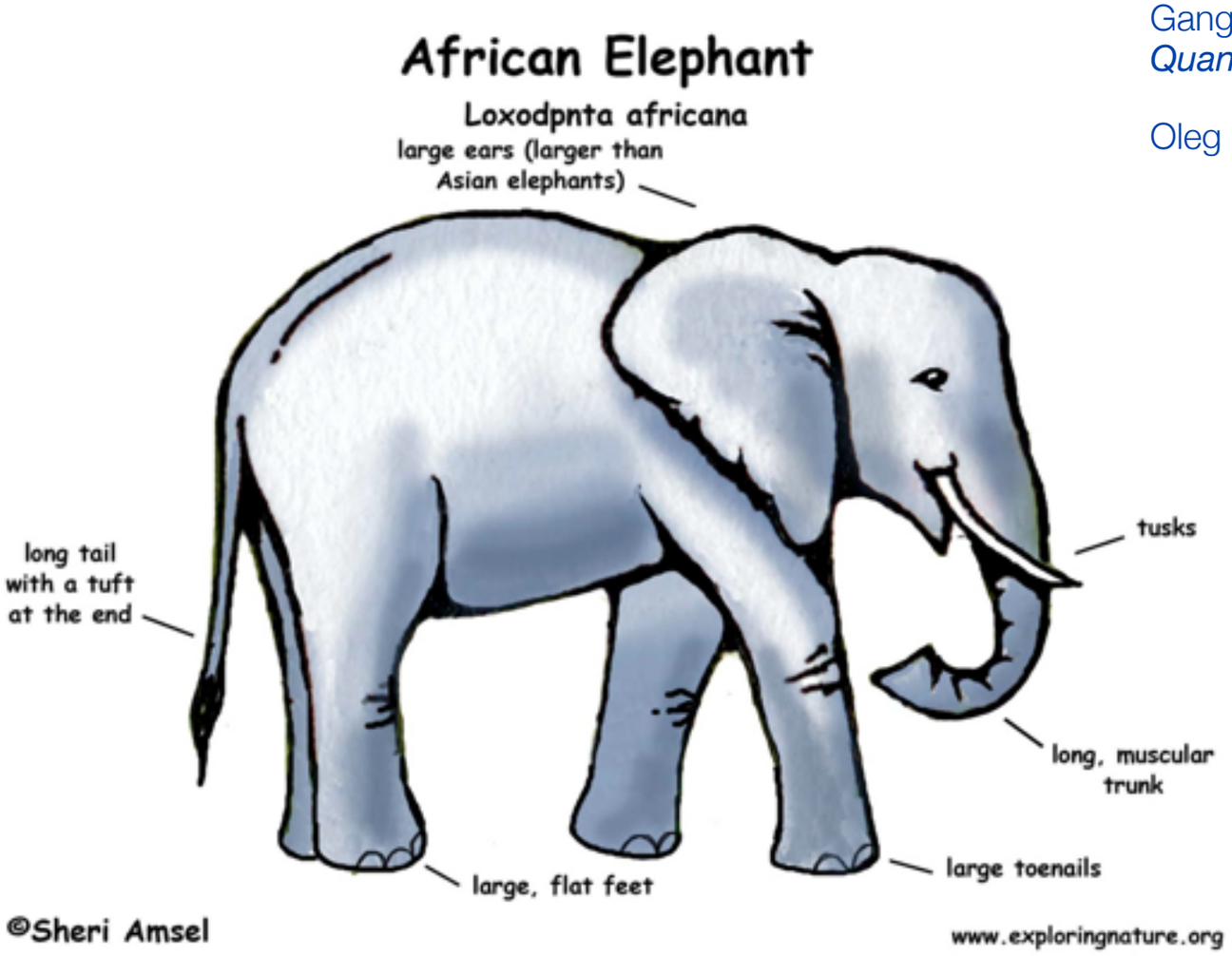
Ba_2YMoO_6

$Yb_2Ti_2O_7$

$Pr_2Zr_2O_7$

Na_2IrO_3

What to look for?



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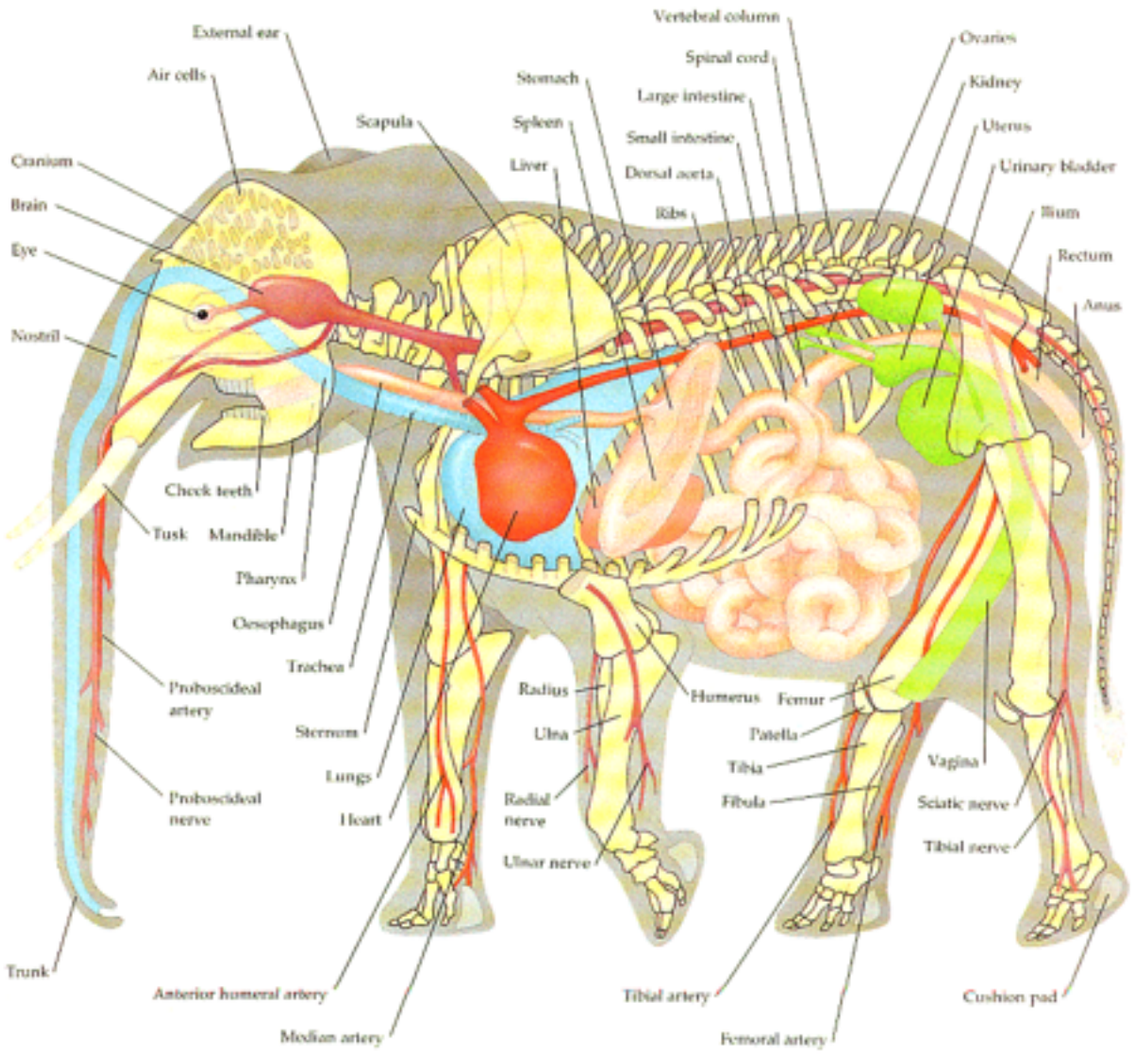
Gang Chen (Univ. Colorado) *Wilson Ratio Enhancement in a Quantum Spin Liquid Candidate: Na4Ir3O8 (Hyperkagome)*

Oleg Starykh (Univ. Utah) *Electron Spin Resonance of Spinon Gas*

What to look for?



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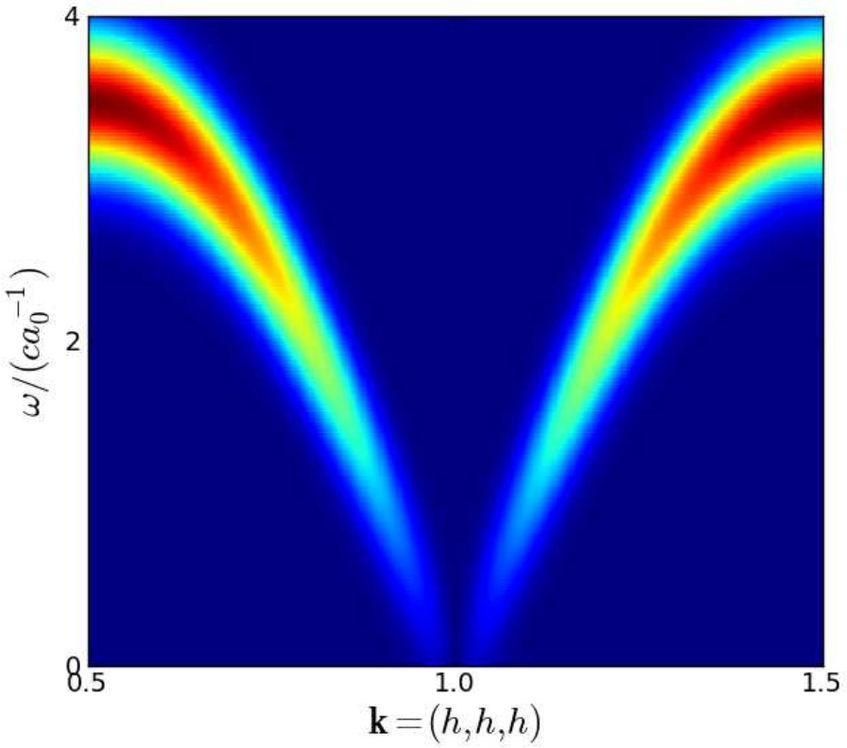
- Smoking gun?
  - detailed predictions for neutron scattering
  - novel ideas for new measurements
- Maybe theory needs to be more quantitative?

What to look for?



"photon" mode predicted in INS of quantum spin ice

L. Savary + LB, 2012

O. Benton *et al*, 2012

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- Smoking gun?
  - detailed predictions for neutron scattering
  - novel ideas for new measurements
- Maybe theory needs to be more quantitative?

Other Topics

Roderich Moessner (MPI PKS) *Fluctuation-induced Ordering on the Kagome Lattice*

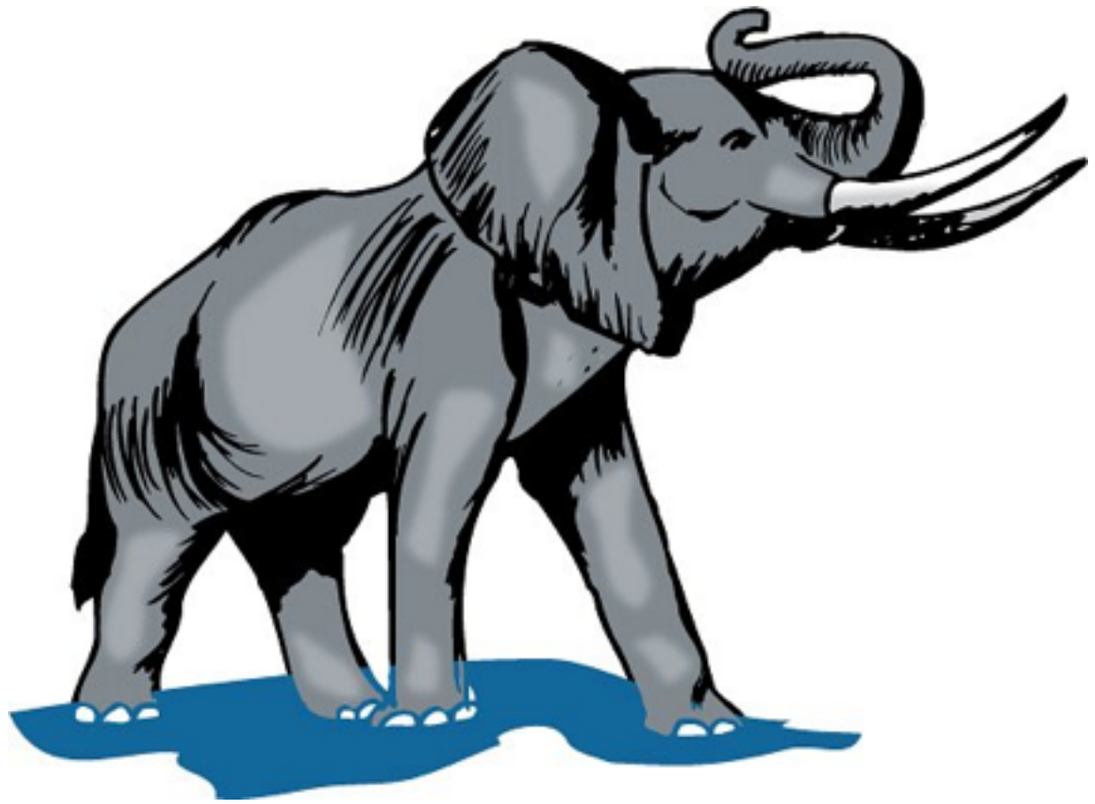
Kedar Damle (TIFR, India) *Vacancy Induced Spin Texture and Their Interactions in a Classical Spin Liquid*

Lesik Motrunich (Caltech) *Monte Carlo Studies of Phases and Phase Transitions in U(1)xU(1) Systems with Theta-statistical Interactions*

Ribhu Kaul (Kentucky) *Numerical Simulations of Quantum Criticality in Spin Models*

Sung-Sik Lee (McMaster Univ.) *From Renormalization Group to Emergent Gravity: Holographic Description of Quantum Many-body Systems*

- When in real materials is order by disorder interesting and relevant?
- Does disorder have reproducible effects in spin liquids that can be understood without detailed microscopic characterization of impurities?
- How far beyond Landau criticality can we go?
- AdS-CMT: good for us or for string theory?



- Looking forward to lots of discussions about spin liquids and beyond!