Spintronic Devices: From Spin Valves and Spin Lasers to Topological Quantum Computing

Igor Žutić

Department of Physics, University at Buffalo

Spintronics: US Name, but Made in Britain?

Mott 1936: Spin-Dependent Transport
Lord Kelvin 1857: Anisotropic Magnetoresistance

Some History

I. Žutić, J. Fabian, S. Das Sarma, Rev Mod. Phys. **76**, 323 (2004)

Spin, charge and energy transport in novel materials Hvar, October 1-7, 2017

UNITY THROUGH KNOWLEDGE FUND

Collaborators

Alex Matos-Abiague,[*] Benedikt Scharf,[+] Geoffrey Fatin,[#] Gaofeng Xu, Jeongsu Lee,[%] Paulo Faria Junior,[%] University at Buffalo

Predrag Lazić, Rudjer Bosković Institute, Zagreb

Kirill Belashchenko, University of Nebraska

Guilherme Sipahi, University of Sao Paulo

Jaroslav Fabian, University of Regensburg

Hanan Dery, University of Rochester

Experimental Groups: Nils Gerhardt, Ruhr University, Bochum

Roland Kawakami, Ohio State University

Javad Shabani, Andrew Kent, New York University

Present Address:

[*]Wayne State University

[*]University of Wuerzburg

[#]Cornell University (String Theory)

[%]University of Regensburg

Outline

1. Basic Elements of Spintronics

- Spin Injection vs Magnetic Proximity Effects

  intuition from Superconducting Proximity Effects, 1932!

- Spin Valves & Magnetoresistance

2. Graphene Spin Logic
3. Adding Spins to Lasers
4. Majorana Fermions & Quantum Computing

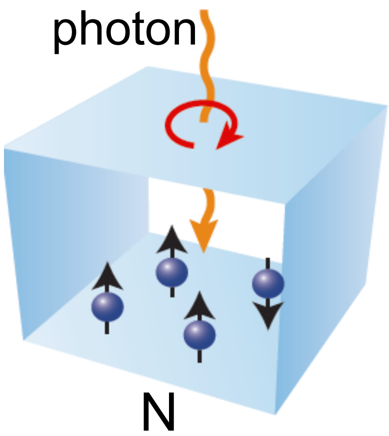
   Superconducting + Magnetic Proximity Effects

5. Conclusions

Generating Spin Imbalance

Transfer of Angular Momentum: Carriers, Excitations, Photons, Nuclei

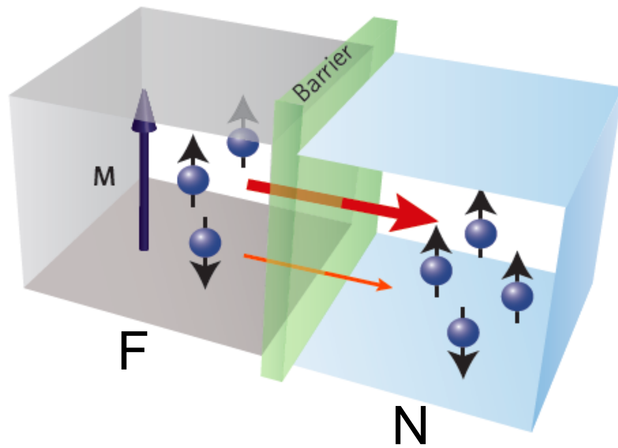
Optical Orientation



Spin-Orbit Coupling
(Friend & Foe)

G. Lampel, PRL 1967

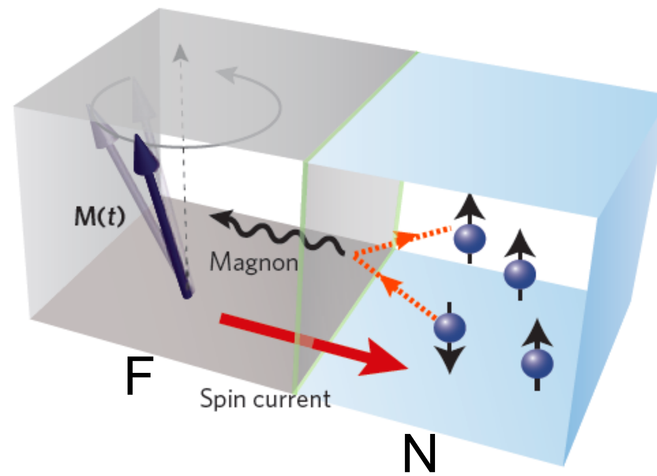
Spin Injection



M. Johnson & R. Silsbee
PRL 1985

Talk: D. Weiss

Spin Pumping



precessing M(t), magnons
K. Ando et al., Nat. Mater. 2011

Early related work TESR
R. H. Silsbee et al., PRB 1979

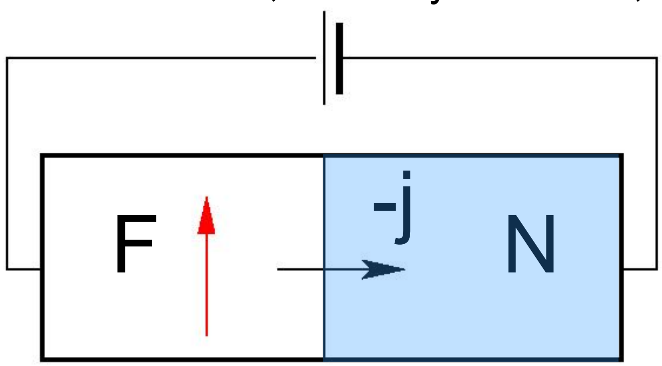
Talk: B. Hillebrands

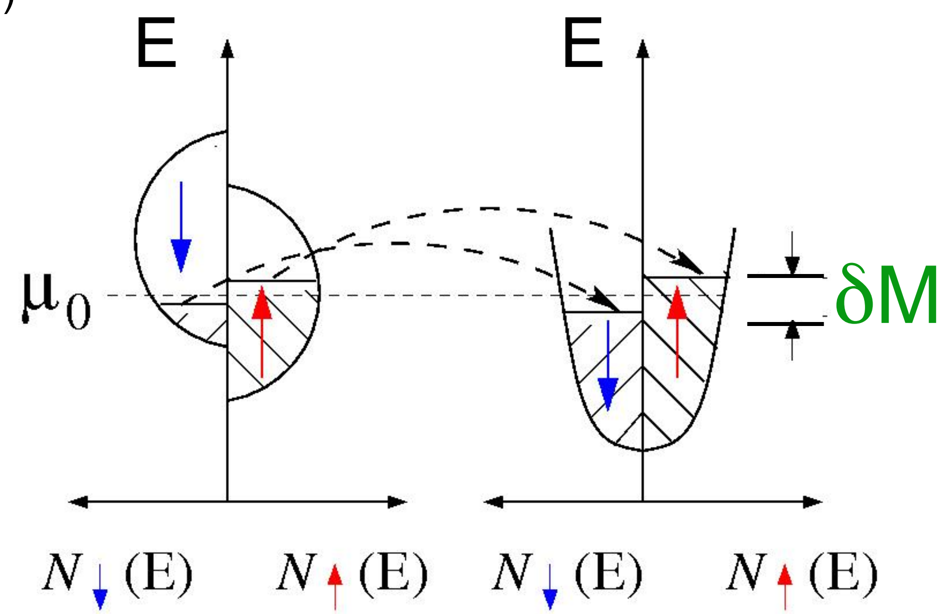
I. Žutić, H. Dery, Nat. Mater. 10, 647 (2011)

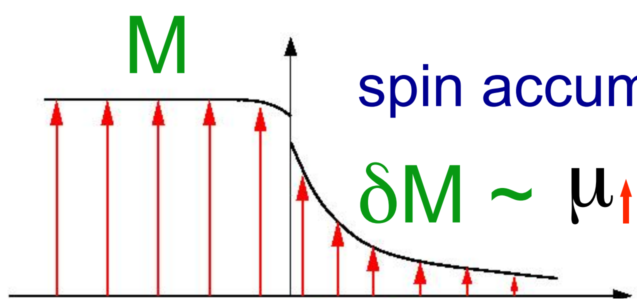
Spin Injection vs Magnetic Proximity Effect

I. Žutić, J. Fabian, S. Das Sarma, RMP **76**, 323 (2004)
J. Fabian et al., Acta Phys. Slovaca, 57, 565 (2007)

Talk: D. Weiss







spin accumulation

$\delta M \sim \mu_\uparrow - \mu_\downarrow$

$L_S > 30\mu m$ (graphene)

M. Drögeler et al., Nano Lett. 16, 3533 (2016)

Talk B. Beschoten

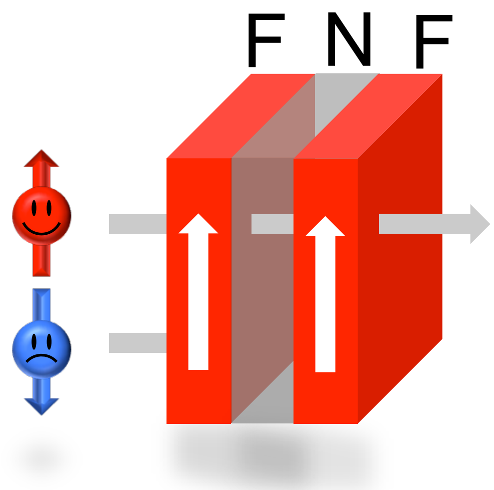
proximity effect (zero bias)
spin-dependent properties &
mag. moment in the N region

metals ~ 1 nm very short!

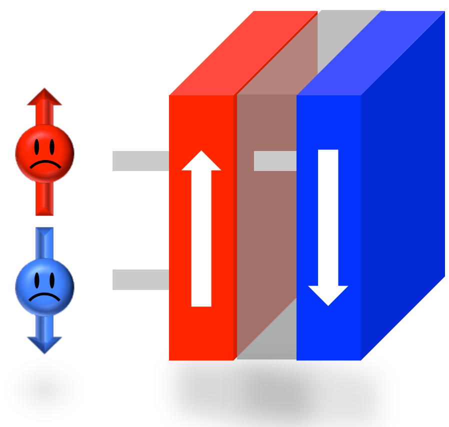
J. J. Hauser, Phys. Rev. 187, 580 (1969)

Spin Valves and Magnetoresistance

Low Resistance



High Resistance



N — Conductor GMR

N — Insulator TMR

Magnetic Tunnel Junctions

1st Reproducible TMR

S. Maekawa, U. Gafvert, IEEE TM 18, 707 (1982)

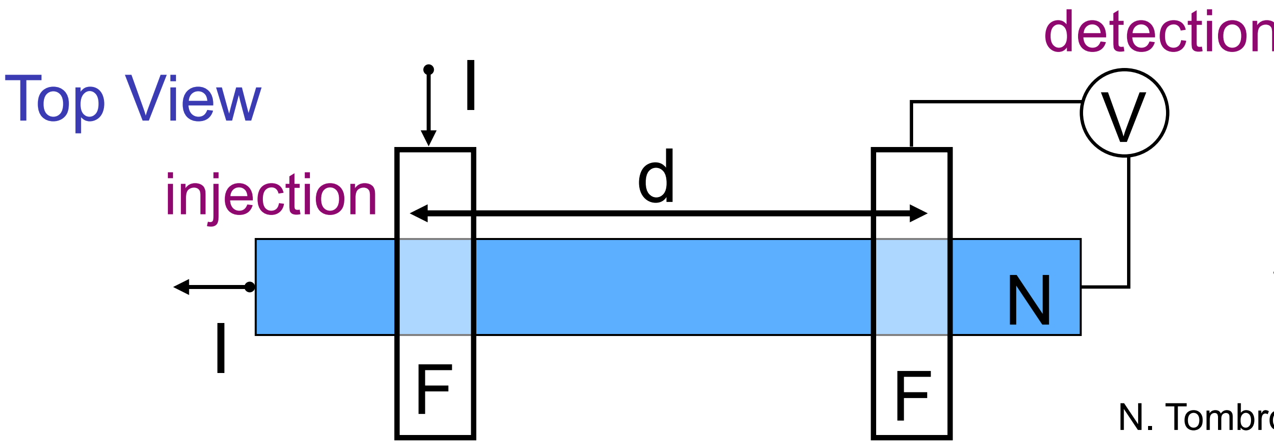
TMR MgO-boost

S. S. P. Parkin et al., Nature Mater. **3**, 862 (2004)…

This Talk: Novel Method to “Switch” Spin Valves

Spin Valves to Engineer Topological States

Spin Injection & Detection in Lateral Spin Valves

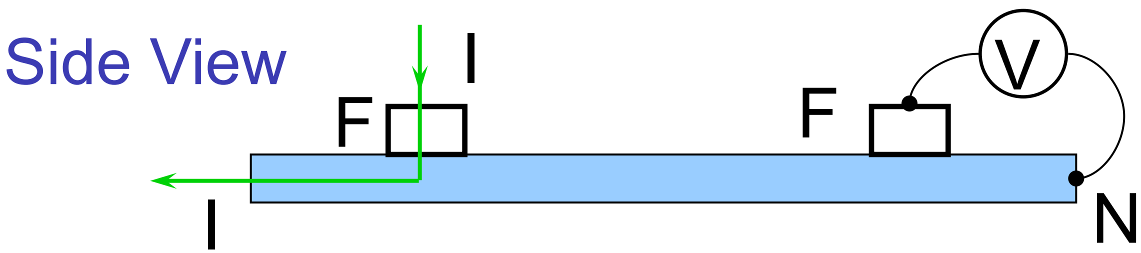


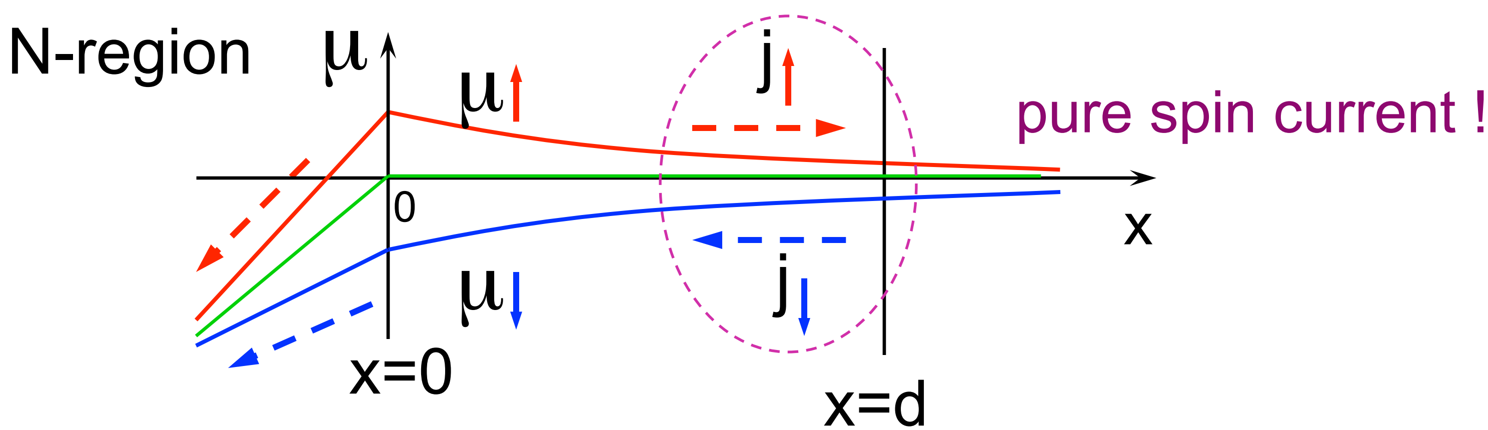
Talk: D. Weiss

M. Johnson,
Science 260, 320 (1993)

with graphene

N. Tombros et al., Nature 448, 571 (2007)

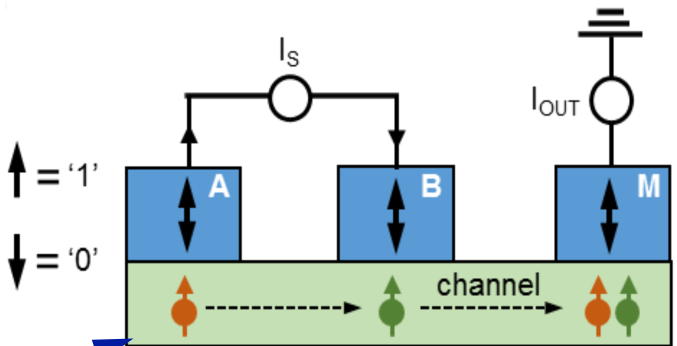




Graphene Spin Logic

building block:
F/graphene junctions

Spin-Logic @ 300 K



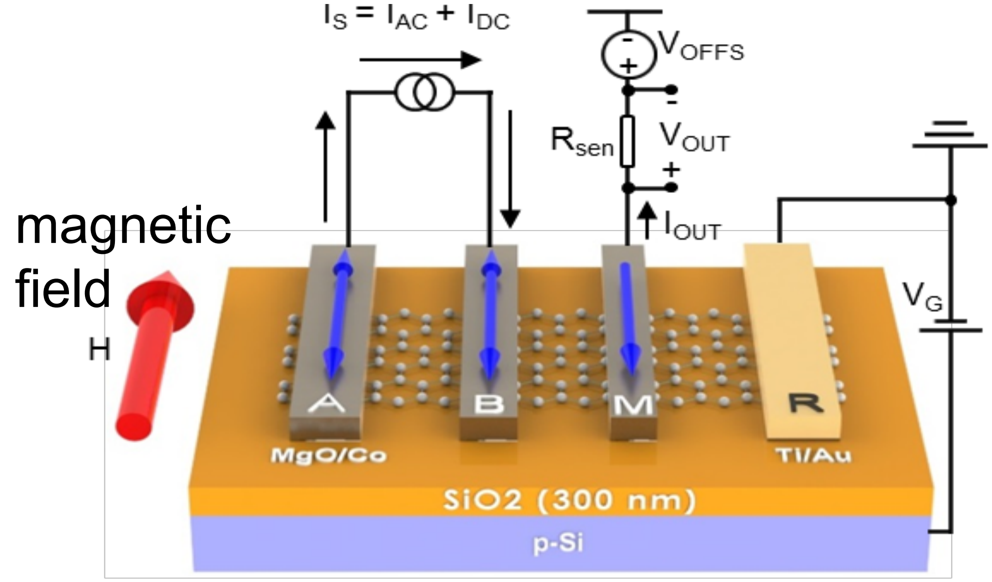
graphene

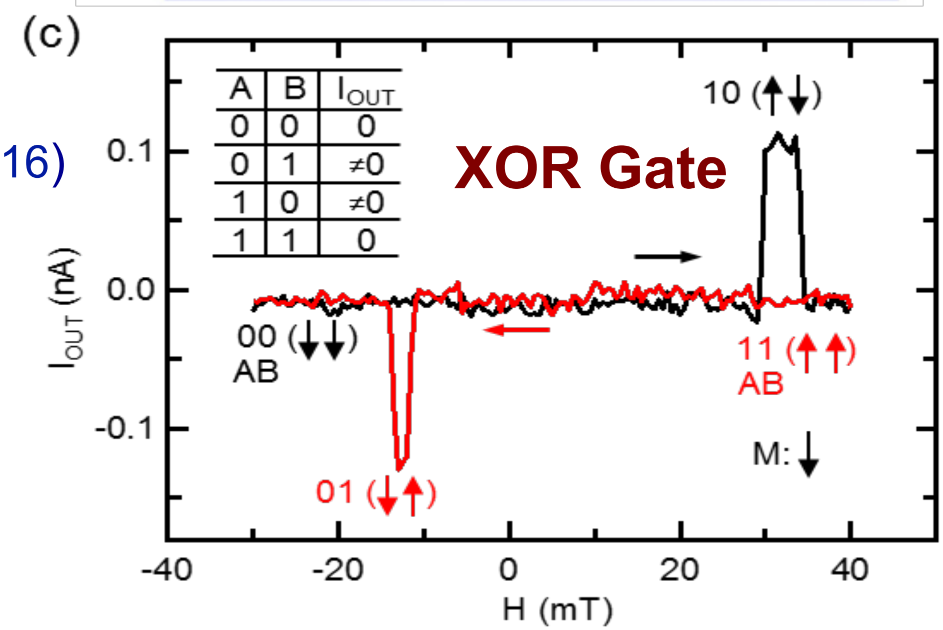
pure spin current

H. Wen et al., Phys. Rev. Appl. **5**, 044003 (2016)

avoid **"von Neumann bottleneck"**

instead of using magnetic field, spin switching by gating?

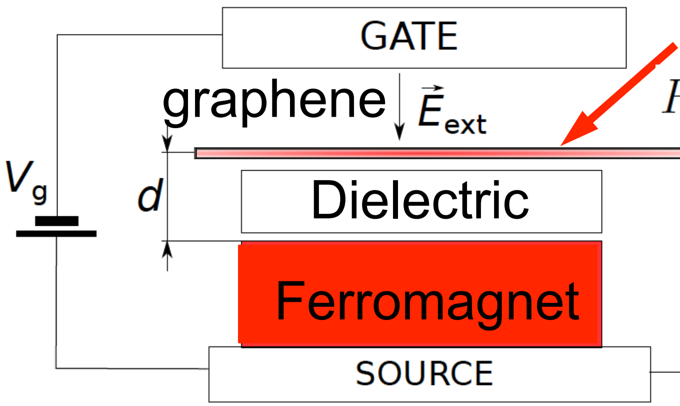




Proximity Spin Polarization Switching

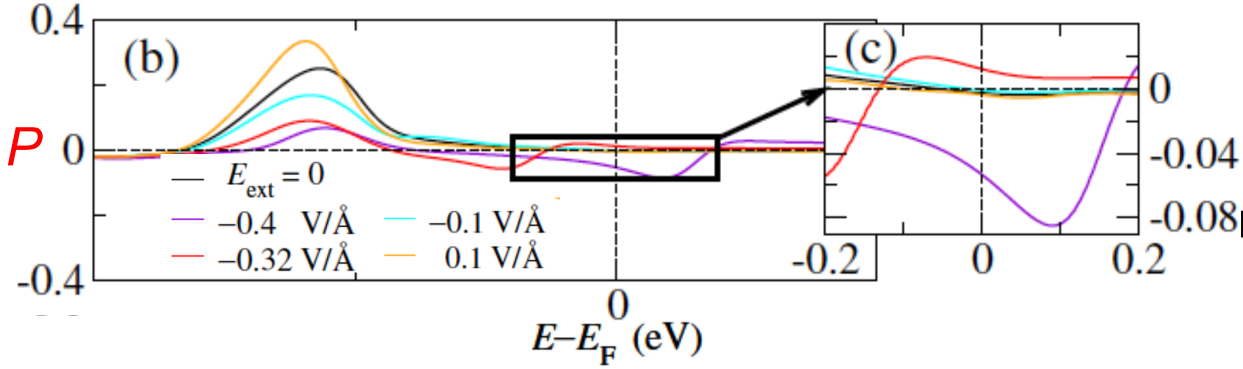
proximity-induced
spin polarization

$$P = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow)$$



P. Lazić, K. Belashchenko, I. Žutić, PRB **93**, 241401(R) (2016)

prediction *P:* gate tunable sign & magnitude



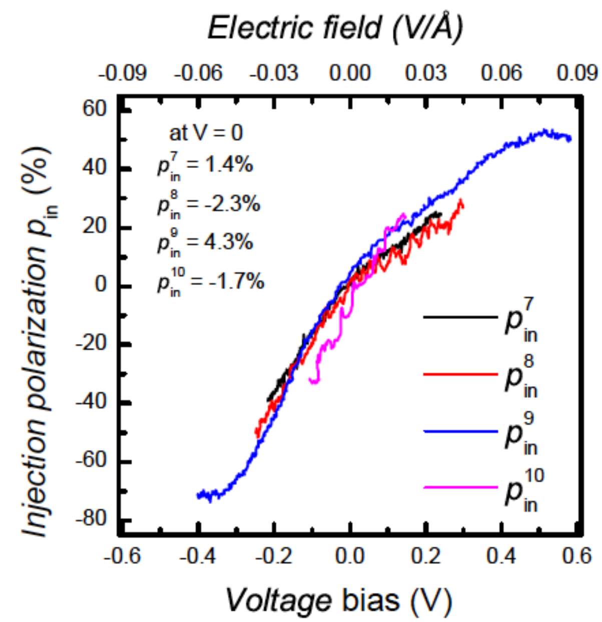
Co/hBN/graphene
real space ab initio calculations

related work K. Zollner et al., PRB 94,155441 (2016)

Experiments:

Co/hBN/graphene

Bias-Induced Switching



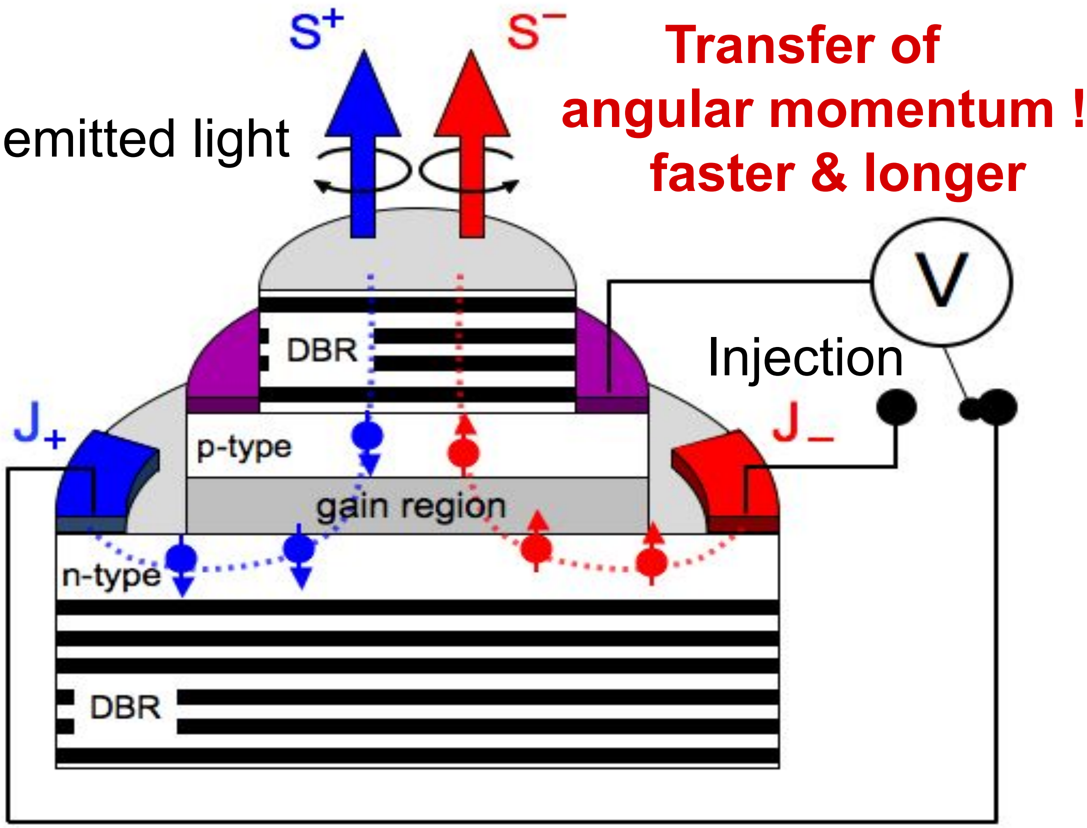
M. Gurram, S. Omar, B. J. van Wees
Nat. Commun. 8, 248 (2017)

Gate-Induced Switching

J. Xu et al., preprint, Kawakami Group

spin logic without B-field?

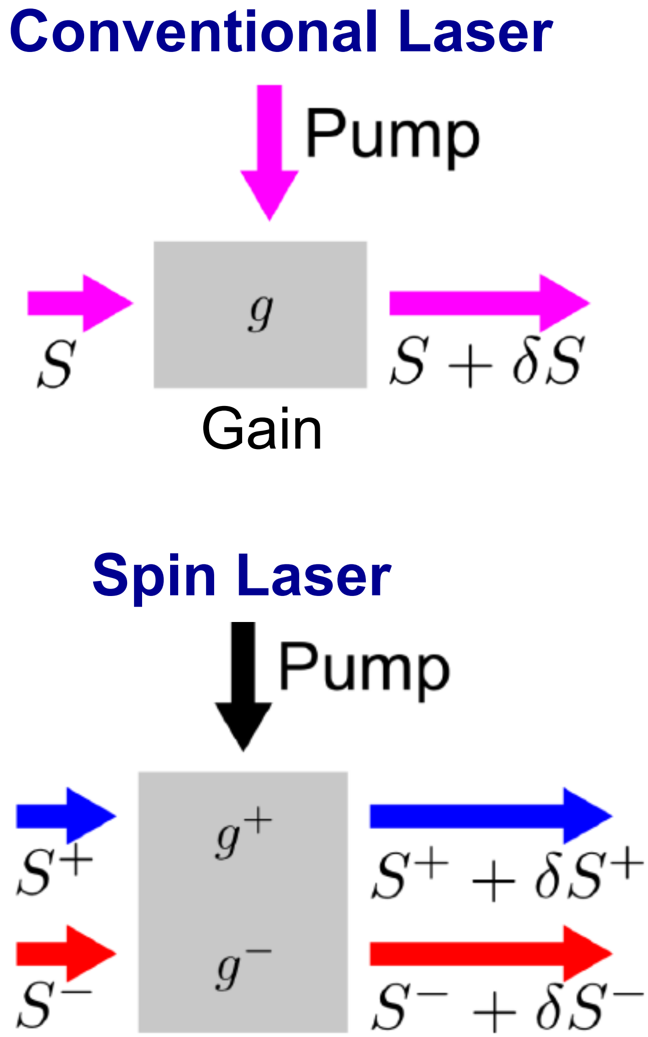
Spin Lasers



DBR: distributed Bragg reflector mirrors

Vertical Cavity Surface Emitting Lasers (VCSELs)

J. Sinova, I. Žutić, Nat. Mater. **11**, 368 (2012)

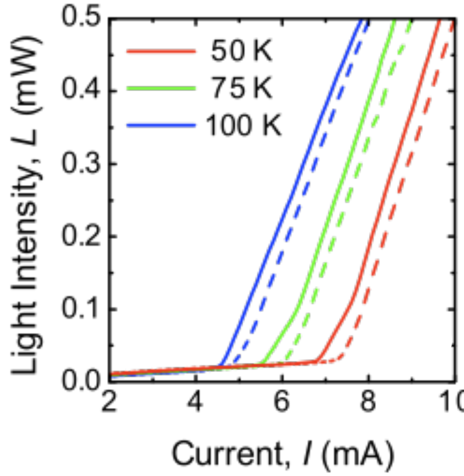


P. E. Faria Junior et al.,
PRB **92**, 075311 (2015)

Experiments: Spin Makes a Difference

Injected Spin-Polarized Carriers: Lasing Threshold Reduction

Electrical Spin Injection

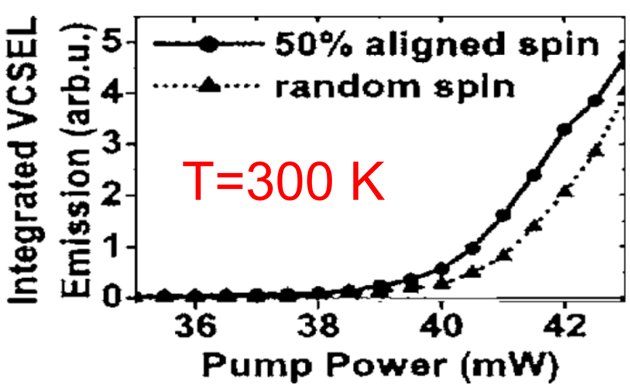


spin injection:
solid line (YES)
dashed (NO)

Fe-spin injector

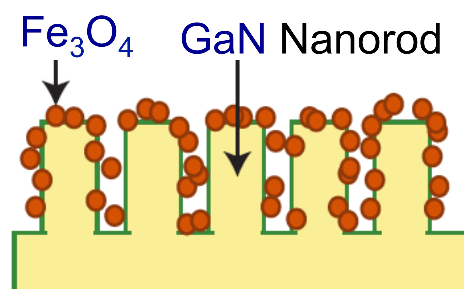
M. Holub et al., PRL 98, 146603 (2007)

Optical Spin Injection



J. Rudolph et al., APL 87, 241117 (2005)

Gain Region + Nanomagnets

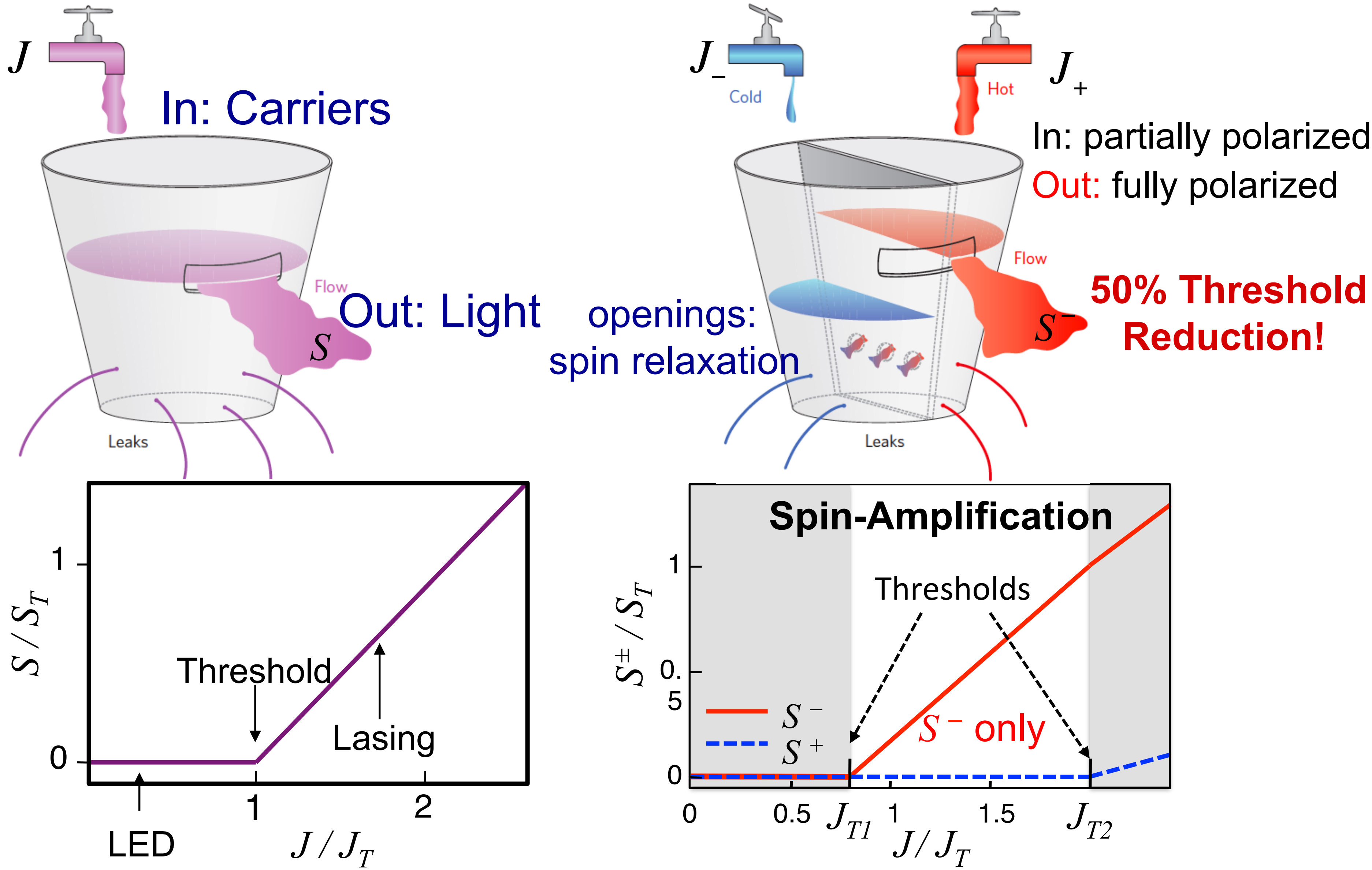


T=300 K

J.-Y Cheng et., Nat. Nanotech. 9, 845 (2014)

Other work: S. Hallstein et al., PRB (1997), H. Ando et al., APL (1998); S. Hovel et al., APL (2008)

Bucket Model of Lasers



P. E. Faria Junior, I. Žutić, Nat. Nanotech. **9**, 750 (2014)
C. Gøthgen , R. Oszwałdowski, A. Petrou, I. Žutić, APL **93**, 042513 (2008)

Dynamic Operation of Spin-Lasers

Analogy: Harmonic Oscillator

$$J = J_+ + J_- \ , \ P_J = \frac{J_+ - J_-}{J_+ + J_-}$$

- **Amplitude Modulation (AM):**

$$J(t) = J_0 + \delta J \, cos(\omega t) \ \ \& \ \ P_J(t) = P_{J0}$$

- **Polarization Modulation (PM):**

$$J(t) = J_0 \ \& \ P_J(t) = P_{J0} + \delta P_J cos(\omega t)$$

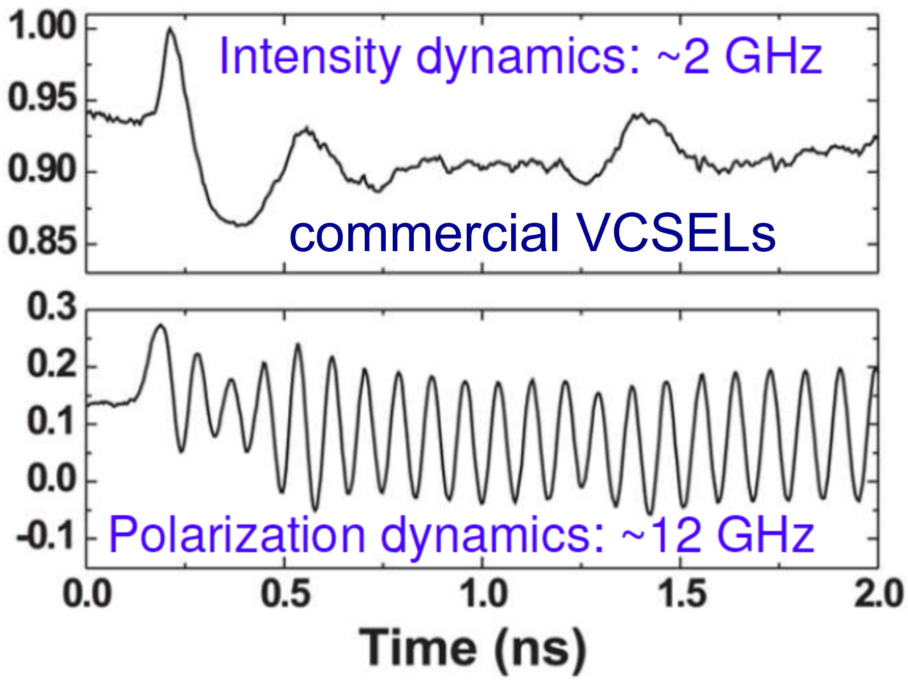
J_+ (Spin Up) - **Hot** Water

J_- (Spin Down) - **Cold** Water

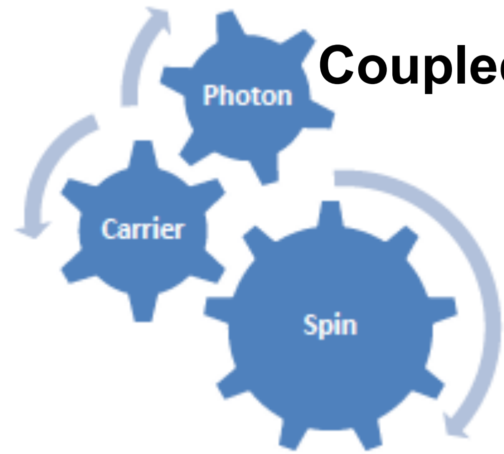
J. Lee et al., APL **97**, 041116 (2010)

Ultrafast Operation?

- **high-frequency: enhanced bandwidth & superior interconnects**



N. C. Gerhardt et al., APL **99**, 151107 (2011)
M. Li et al., APL **97**, 191114 (2010)



VCSELs: operate in one of two orthogonal linearly polarized modes (cavity anisotropy)

$\omega_{1,2} \approx \omega_0 \pm \gamma_P$ **Linear Birefringence**

$$\gamma_p \propto \omega\left[\varepsilon_r^x(\omega) - \varepsilon_r^y(\omega)\right]$$

Why Polarization Oscillations (PO)?

Birefringence: refraction index anisotropy considered **bad** in conventional lasers

Birefringence: $S^x \neq S^y$

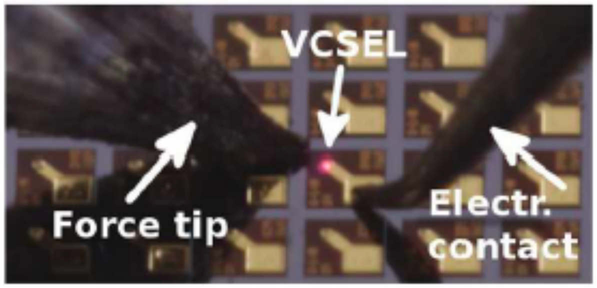
Spin: $S^+ \leftrightarrow S^-$ **Beating!**

Best Lasers: **Bandwidth ~50 GHz**

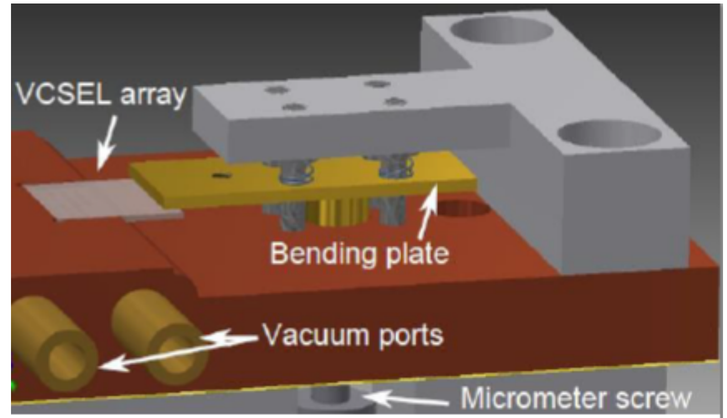
Experimental Support

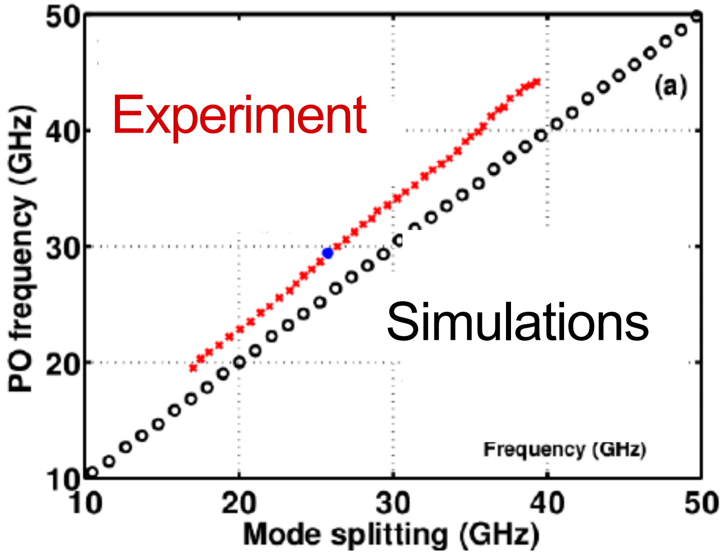
Plan: increase birefringence to increase the polarization oscillation (PO) freq.

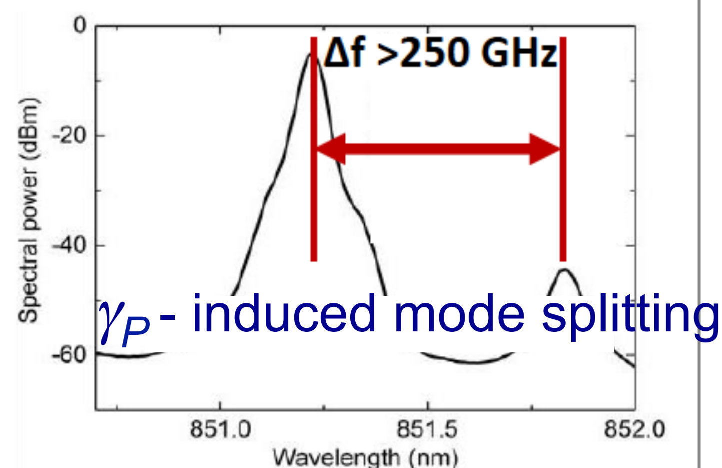
theory P. E. Faria Junior et al., PRB **92**, 075311 (2015)



Deformation (Strain)







T. Pusch et al., Elect. Lett. **51**, 1600 (2015)

Max. PO Frequency 44 GHz

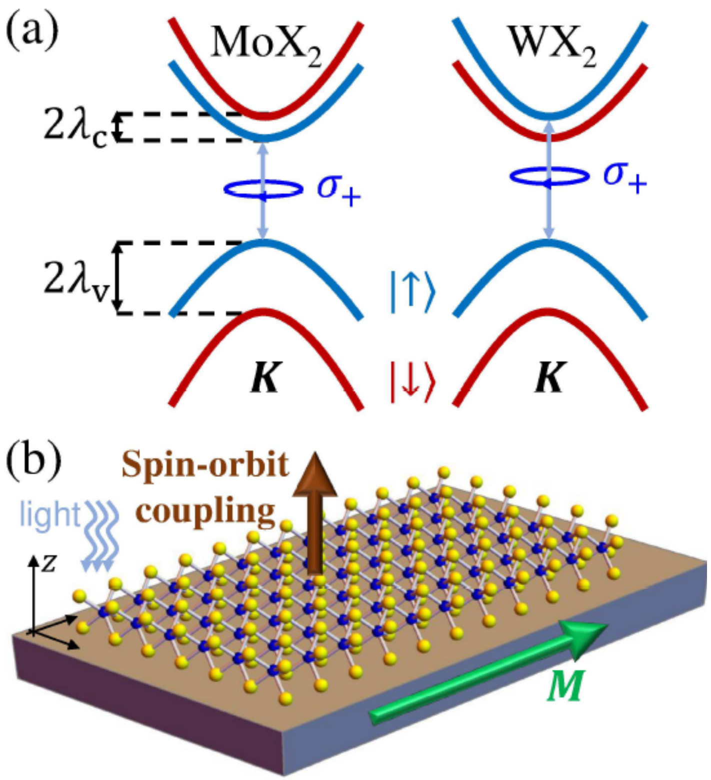
M. Lindemann et al., APL **108**, 042404 (2016)

Key: Mode Splitting $\xrightarrow{???}$ high freq.

Yes! PO freq. **> 120 GHz** preprint

Magnetic Proximity Effects: Converting Excitons

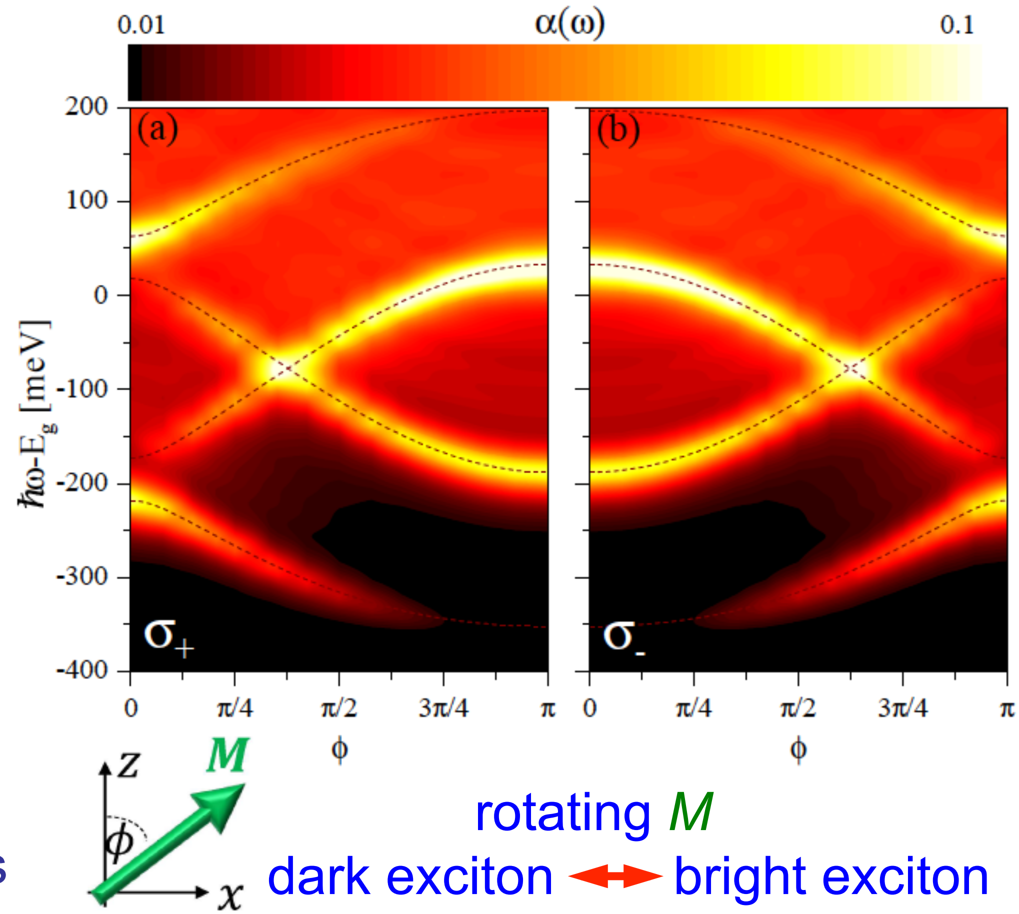
Spin-Valley Coupling in ML TMDs



rotating *M* in the substrate modifies spin-split conduction/valence bands

tightly-bound excitons > 100 meV !

Absorption Spectra: $MoTe_2/EuS$



rotating *M*

dark exciton ↔ bright exciton

Coulomb/many-body effects

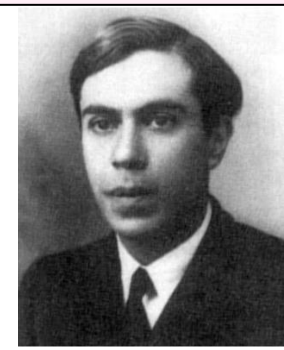
B. Scharf, G. Xu, A. Matos-Abiague, I. Žutić, 119, 127403 (2017)

Majorana Fermions in Solid State

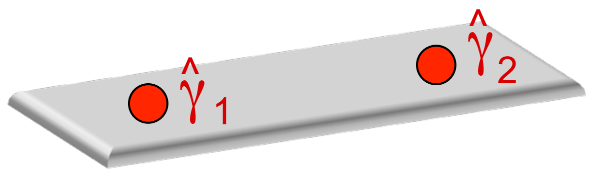
Majorana Fermion is its own Antiparticle $\hat{\gamma} = \hat{\gamma}^{+}$

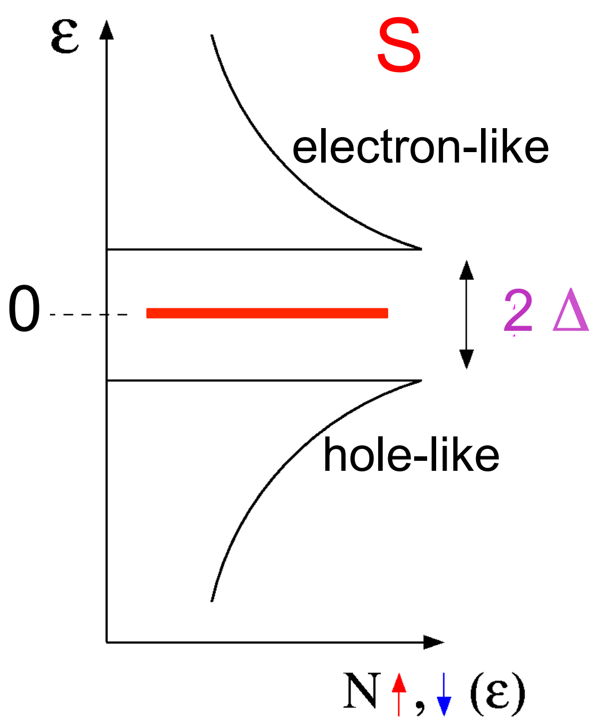
real solutions

1 Majorana = " Half " a usual Fermion $f = \hat{\gamma}_1 + i\,\hat{\gamma}_2^{+}$



E. Majorana
Nuovo Cimento 14, 171 (1937)





Majorana Bound States

- Zero energy pairs of degenerate states
- Protected by energy gap
- Chargeless
- Spinless
- Nonlocal – "fractionalized electron"

A. Y. Kitaev, Phys. Usp. 44, 131 (2001)

Fault-Tolerant Quantum Computing

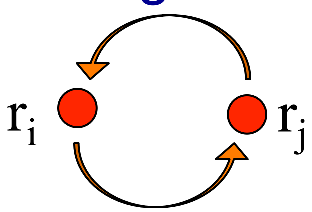
Quantum Bit: $a|0\rangle + b|1\rangle$

$|a|^2 + |b|^2 = 1$

superposition and entanglement

Talk: J. Freericks

Exchange Statistics



$$\Psi(\ldots, r_i, \ldots r_j, \ldots) = e^{i\phi}\Psi(\ldots, r_j, \ldots r_i, \ldots)$$

Bosons $\phi = 0$, Fermions $\phi = \pi$, Anyons $\phi \neq 0, \pi$

Majorana Fermions – Non-Abelian Statistics

Talk: H. Buljan

$$\Psi(\ldots, r_i, \ldots r_j, \ldots) = \hat{U}\Psi(\ldots, r_j, \ldots r_i, \ldots)$$

$$\hat{U} = e^{i\phi}$$ Non-Abelian Phase

Gate for Quantum Computing

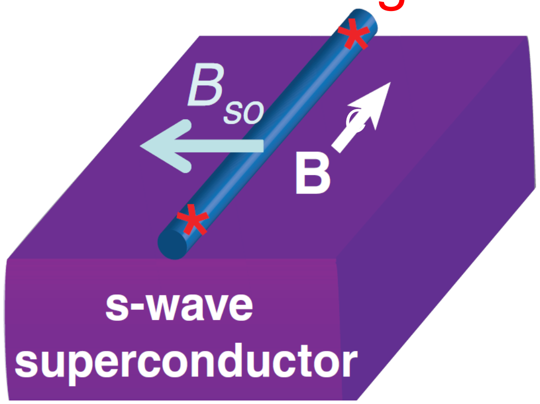
Majorana Bound States – degenerate states energetically protected from other states by an energy gap

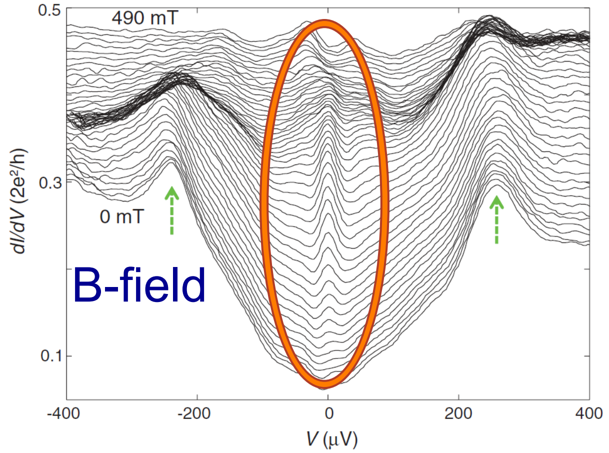
If we can exchange (“braid”) Majoranas we could implement gates for a fault-tolerant quantum computing

C. Nayak et al., Rev. Mod. Phys. 80, 1083 (2008)

Majorana Experiments: 1D Nanostructures

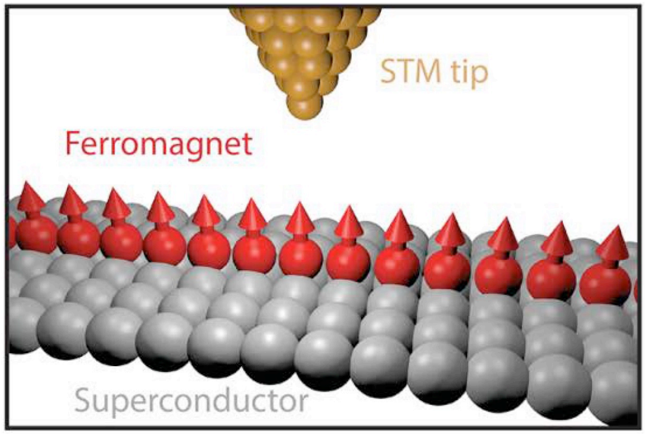
Semiconducting Wires





V. Mourik et al., Science 336, 1003 (2012)
L. P. Rokhinson et al., Nat. Phys. 8, 795 (2012)
M. T. Deng et al., Science 354, 1557 (2016),...

Atomic Magnetic Chains



S. Nadj-Perge, et al., Science 346, 602 (2014)
R. Pawlak, et al., NPJ QI 2,01635 (2016)

Ingredients?

- Proximity-Induced Superconductivity
- Strong Spin-Orbit Coupling
- Zeeman Splitting
- Topological Superconductivity "p-wave"

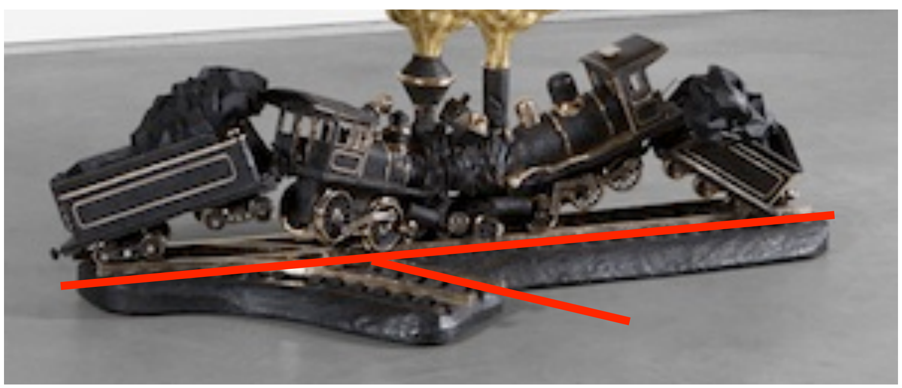
Topological Phases 2016 Nobel Prize in Physics

Challenge: Majorans can be **misdiagnosed** in Zero-Bias Conductance Peak
Braiding Needed!

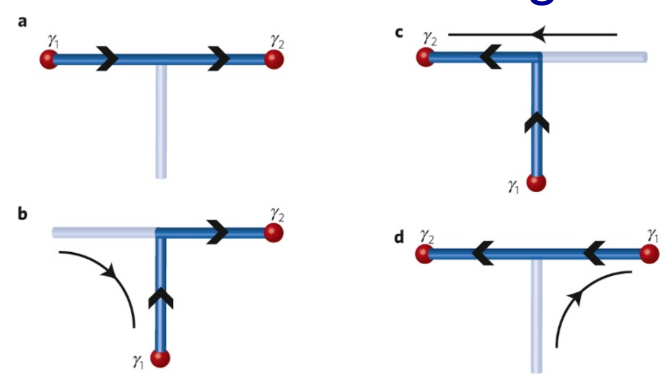
Limitations of 1D Systems

Particle Exchange and Braiding is a Problem in 1D

Partial Solution: T-junctions



Particle Exchange

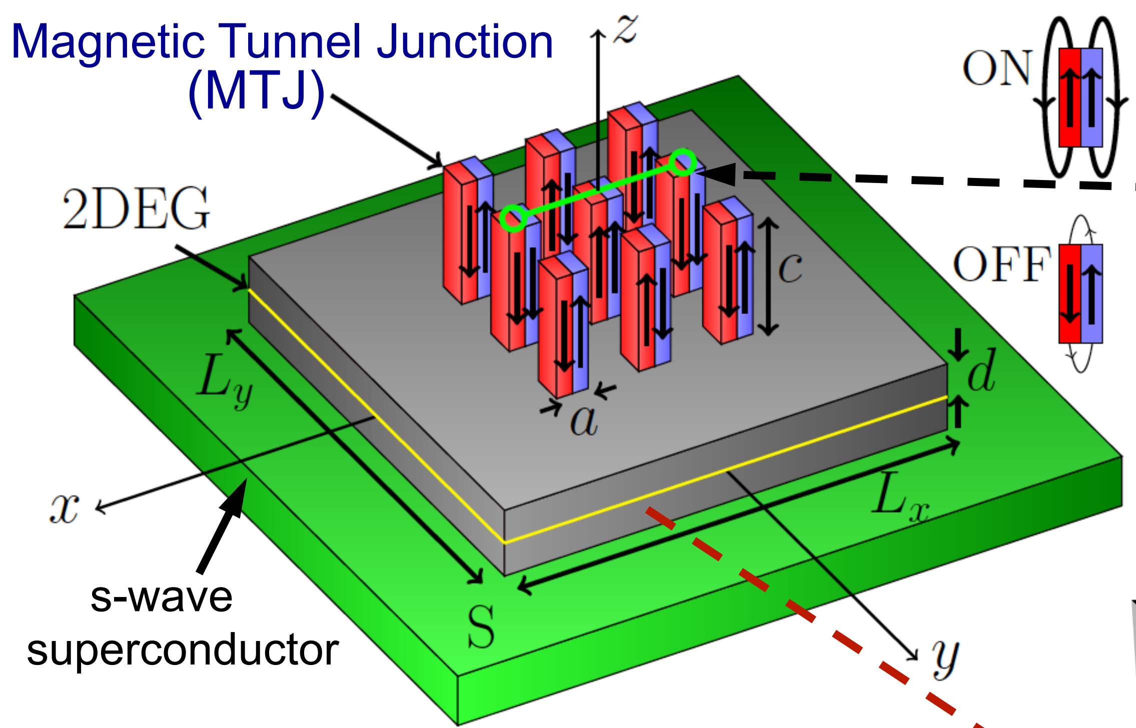


J. Alicea et al., Nat. Phys. 7, 412 (2011)

Complex wire networks are required for braiding

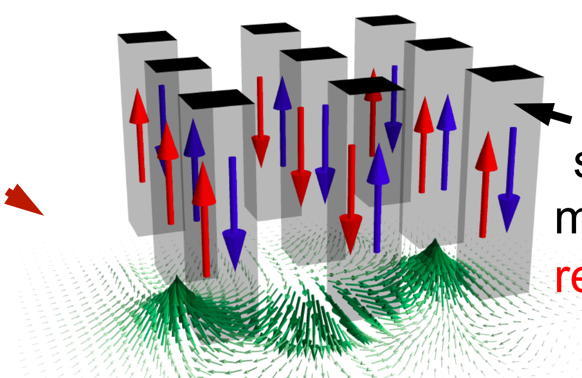
What about 2D?

New Platform for Majorana Bound States (MBS)



MTJs in hard drives, MRAM

Green line effective wire
with 2 MBS at its ends



single MTJ
magnetization:
red, blue

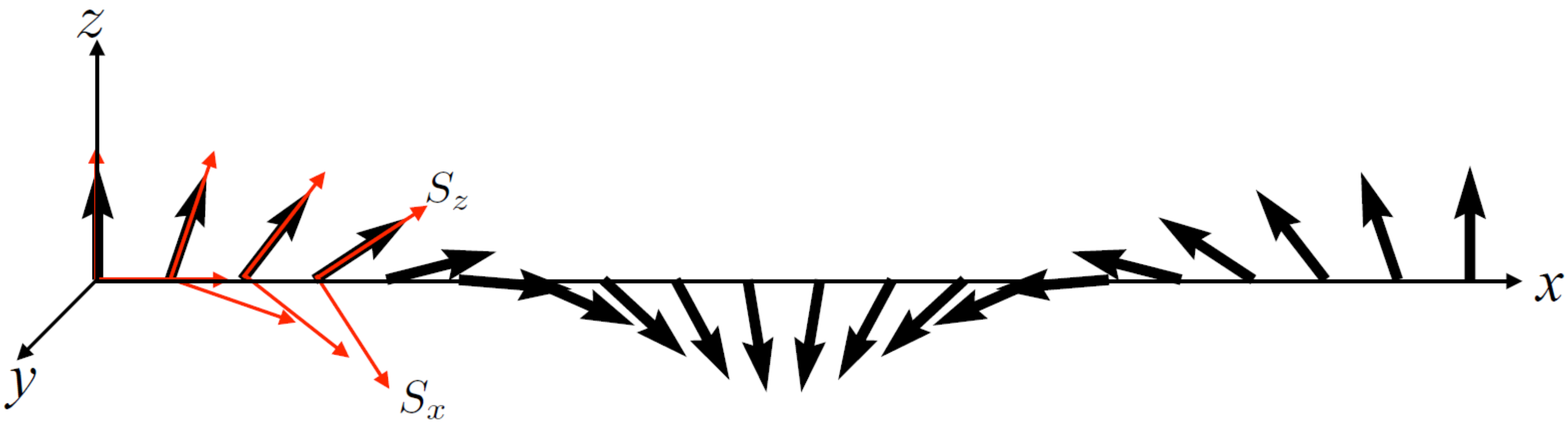
Two-dimensional electrons gas (2DEG) with

1. superconducting proximity
2. magnetic proximity (fringing fields)

magnetic textures (fringing fields)
to localize & braid MBS

G. Fatin, A. Matos-Abiague, B.Scharf, I. Žutić, PRL 117, 077002 (2016)

Magnetic Textures: Synthetic Spin-Orbit Coupling



$$\hat{H}_0 = \left(\frac{\hat{\boldsymbol{p}}^2}{2m^*} - \mu\right)\tau_z + \Delta\tau_x + \frac{g^*}{2}\mu_B \boldsymbol{B}(\boldsymbol{r})\cdot\boldsymbol{\sigma}$$

Bogoliubov-de Gennes Hamiltonian

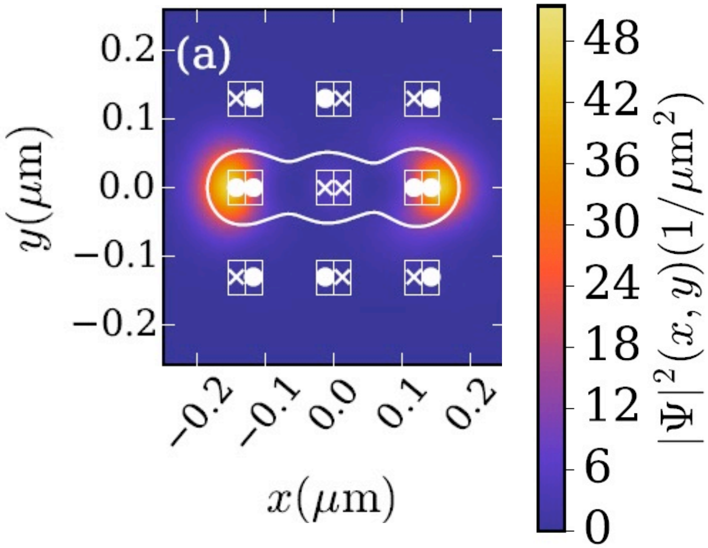
B-field is MTJ generated

$$\hat{H}_0 = \left[\frac{(\hat{\boldsymbol{p}} - e\mathcal{A}(\boldsymbol{r})\cdot\boldsymbol{\sigma})^2}{2m^*} - \mu\right]\tau_z + \Delta\tau_x + \frac{g^*}{2}\mu_B |\boldsymbol{B}(\boldsymbol{r})|\sigma_z$$

Non-Abelian field yields effective SOC

B. Braunecker et al., PRB **82**, 045127 (2010)
G. L. Fatin et al., PRL. **117**, 077002 (2016)

Effective Topolgical Wires, 3x3 MTJ Array



Magnetizations in
3x3 MTJ Array

● "up"

x "down"

Probability density
for MBS

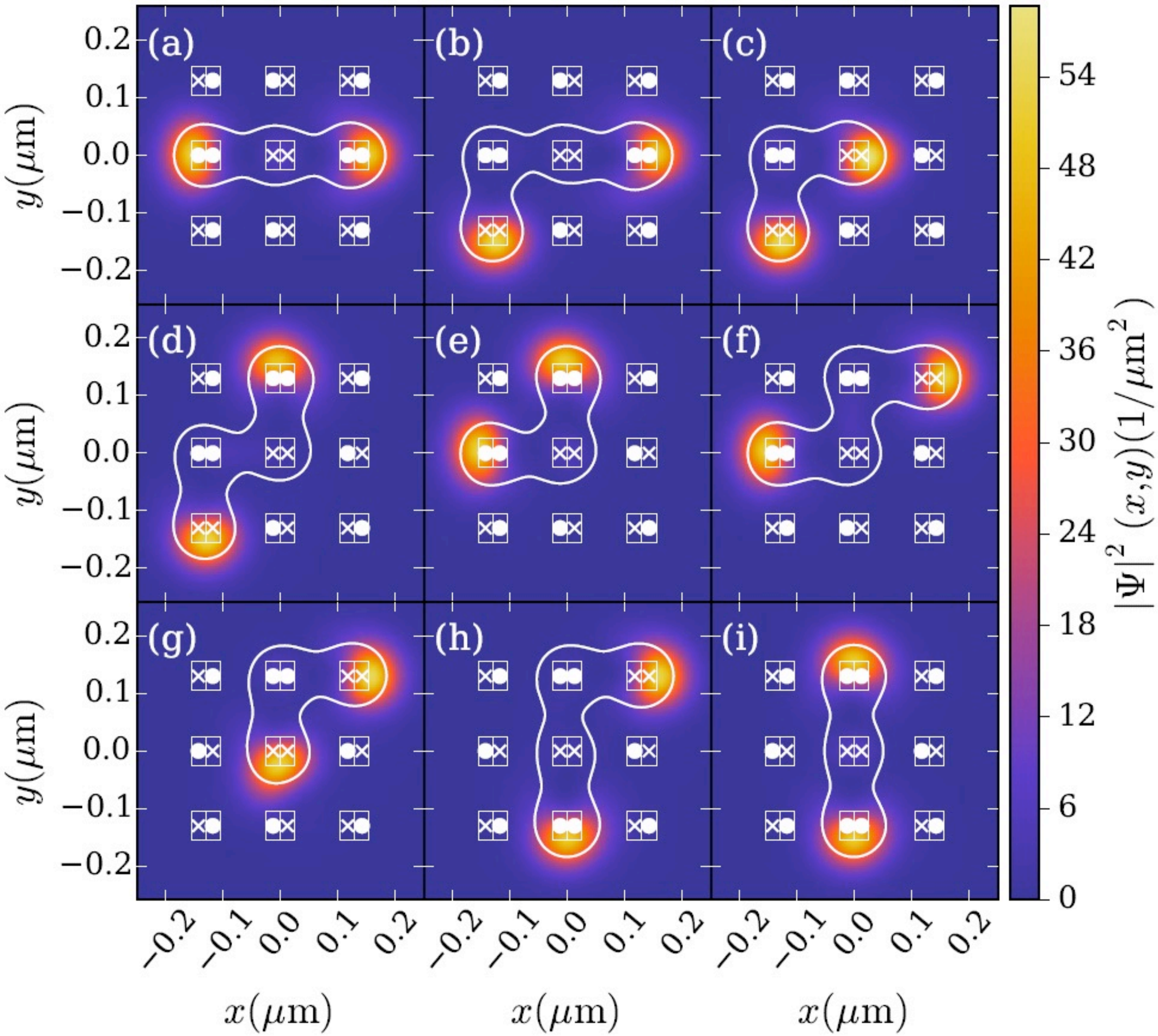
Topological Condition ("wire contours")

$$\left|\frac{g^*\mu_B \boldsymbol{B}(\boldsymbol{r})}{2}\right|^2 = \Delta^2 + \left[\mu - \frac{\hbar^2}{8m^*}\sum_{i=1}^{2}\frac{\partial_i \boldsymbol{B}(\boldsymbol{r}) \cdot \partial_i \boldsymbol{B}(\boldsymbol{r})}{|\boldsymbol{B}(\boldsymbol{r})|^2}\right]^2$$

Generalize M. Kjaergaard et al., PRB (2012), Y. Oreg et al., PRL (2010)

G. Fatin, A. Matos-Abiague, B.Scharf, I. Žutić, PRL 117, 077002 (2016)

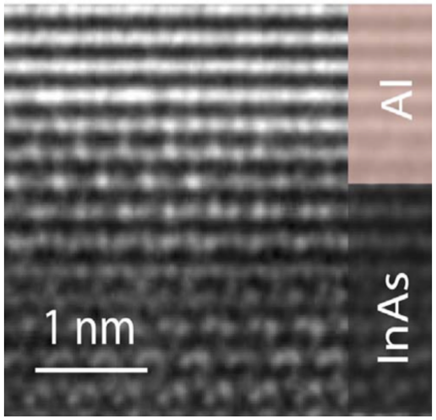
Effective Topolgical Wires, 3x3 MTJ Array



Suitable for Braiding & Non-Abelian Statistics

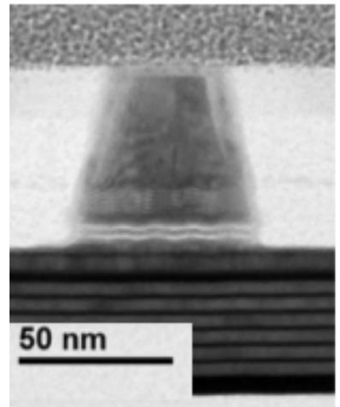
Towards Experimental Realization

High-Quality 2D Epitaxial Growth
Robust Proximity Effects



Magnetic Nanopillars from MRAM
Tunable Magnetic Textures

New York University
J. Shabani & A. D. Kent



A. Matos-Abiague et al., Solid State Commun. 262, 1 (2017); J. Shabani et al., PRB 93, 155402 (2016)

Individual elements demonstrated, but the challenge is putting things together

Conclusions and Outlook

- Teaching Spin Valves New Tricks
  also: C. Betthausen et al., Science 337, 324 (2012)

- Proximity Spin Switching

- Graphene Spin Logic to avoid "von Neumann bottleneck"

- Spin Lasers could outperform Conventional Lasers

- Coulomb Interactions in Magnetic Proximity

- Novel 2D platform to realize Majorana Bound States and investigate their non-Abelian statistics through braiding