UW Quantum System Engineering Group

- People:
  - Joseph L. Garbini – *mechatronics & control*
  - John P. Jacky – *software engineering*
  - Doug Mounce – *program operations*
  - John A. Sidles – *QM and "utility infielder"*
  - Students: *Dorothy Caplow, Kristi Gibbs, Tom Kriewal, Tony Norman, Mark Peeples*
- Core expertise:
  - Quantum system engineering
- Research focus:
  - Quantum biomicroscopy
- Core funding and Affiliations:
  - NIH/BRSTP: (R01-RR08820-09)
  - NSF/ENG: MRE #0097544
  - DARPA/DSO: 3D Atomic Microscopy (MOSAIC)
  - IBM Almaden: MOSAIC-DSP subcontract
  - Center for AIDS Research (CFAR)

- Why Apply to Join the LSC?
  - GW interferometry and quantum microscopy share a set of common challenges in physics and engineering
  - Both our communities are embarked on a common adventure of scientific discovery
  - We at the UW are confident that LIGO is going to work!

We want to be part of something great.

UW LSC Membership Application
At: LIGO Hanford Laboratory
Date: November 11, 2003
Presenter: John Sidles

URL: http://courses.washington.edu/goodall/MRFM

Atomic Biomicroscopy: A Vision of a Great Generation

- 1959: Richard Feynman
  - *There's Plenty of Room at the Bottom*

I put this out as a challenge: Is there no way to make the electron microscope more powerful? … Make the microscope one hundred times more powerful, and many problems of biology would be made very much easier.

- 1946: John von Neumann to Norbert Weiner
  - Electron microscopy
  - Crystallography

There is no telling what really advanced electron microscopic techniques will do. In fact, I suspect that the main possi-bilities lie in that direction.

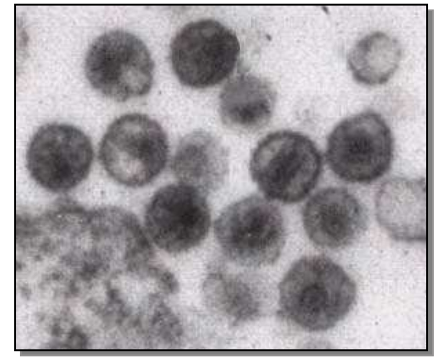
- 1946: Linus Pauling
  - Caltech system biology (proposal to Rockefeller Foundation)

It is appalling to consider how meager is our information about the composition and structure of proteins … Extremely important advances could be achieved if the effective resolving power of the electron microscope could be considerably improved.

Vast Scope and Frustrating Limits

- Electron microscopy
  - Henderson (1995):

> *Radiation damage … prevents the determination of the structure of a single biological macro-molecule at atomic resolution using any kind of microscopy. This is true whether neutrons, electrons, or x-rays are used as the illumination.*



HIV viruses

- NMR and crystallography
  - Trouble: insoluble proteins, variably translated,glyco-sylated, cross-linked, etc.
  - Result: the pipeline leaks ~95% of the input genes
  - And, what's all that RNA doing?

Christendat *et al.*

starting with	**1,871**	← genes
$\Downarrow\Downarrow\Downarrow$	1,200	
$\Downarrow\Downarrow$	424	
$\Downarrow$	180	
net structures obtained	**33**	← NMR spectra
	10	← crystals

New Tools from Physics: Breakthroughs 1980-2000

- Physics breakthroughs
  - Image with low energy quanta
  - Scanning probe microscopy
  - Quantum observation
    - Dynamics is Hamiltonian
    - Emergence is decoherent
- Engineering breakthroughs
  - Moore's Law really works!
    - Moore's scaling rule: "Design such that smaller works better."
  - Synoptic scientific literature
  - Global mechatronic infrastructure
- Biology breakthroughs
  - Genomics – succeeded
  - Proteomics – launched
  - System biology– envisioned

- Mansfield and Morris (and Damadian)

- Binnig and Rohrer

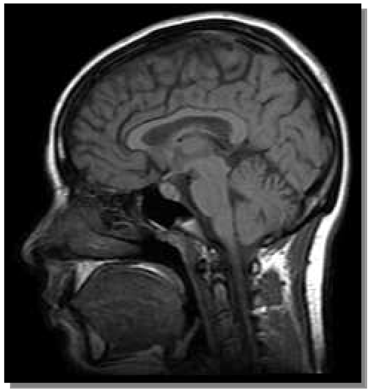
- Dehmelt, Leggett, Caves, Zurek, Braginsky …

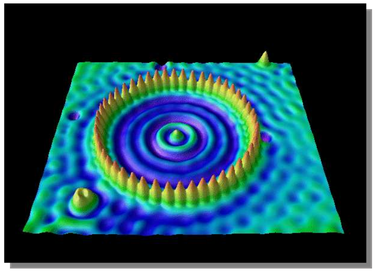
- Moore, Shockley, Brattain, Bardeen

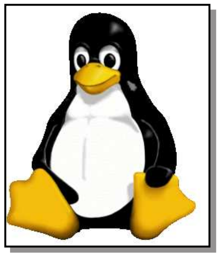
- Ginsparg, Varmus

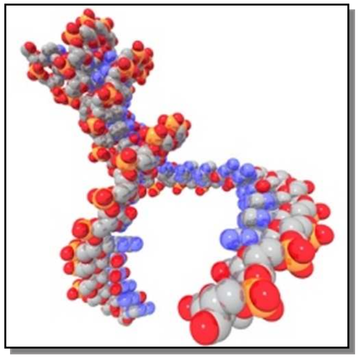
- Stallman, Torvalds

- Hood, Venter, Collins



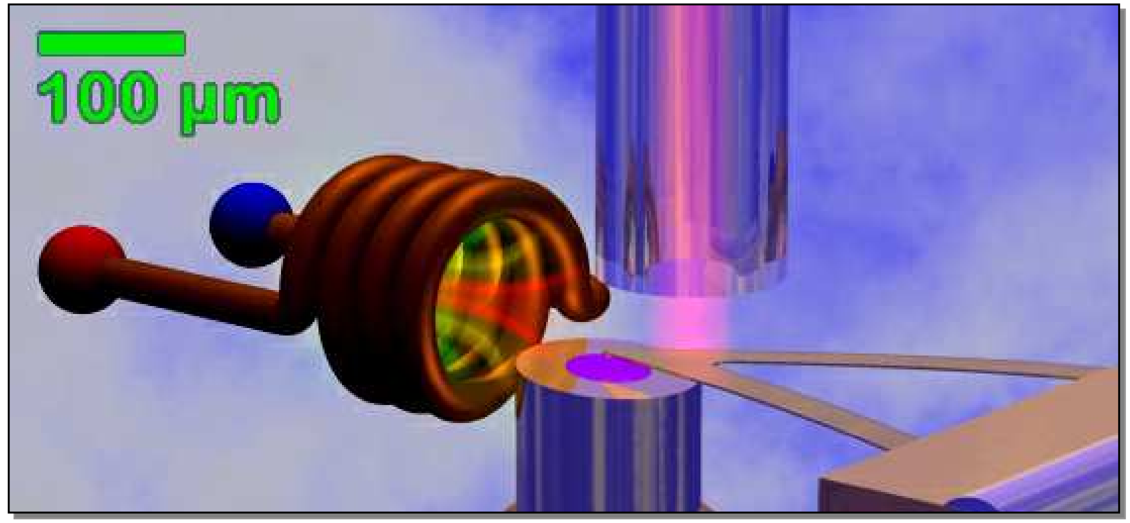


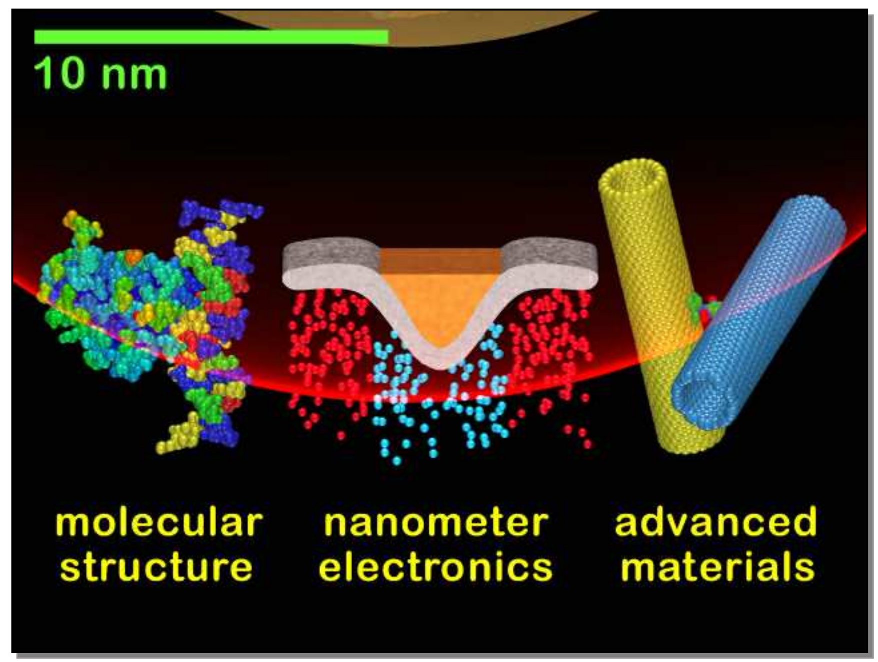


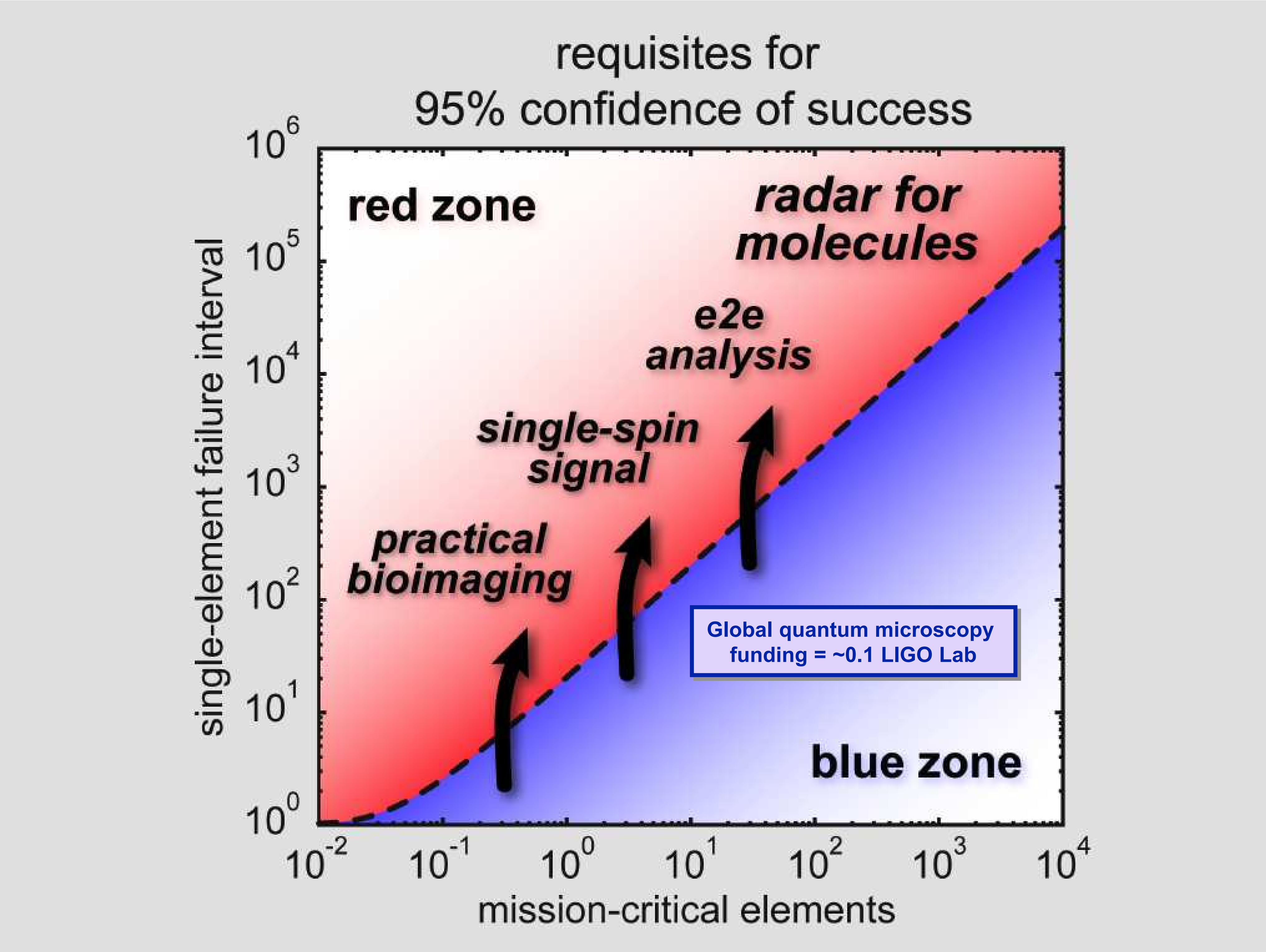


Key Elements of Magnetic Resonance Force Microscopy

- Force microscopy
  - For Moore scaling
    "Smaller works better"
- MRI imaging
  - Three-dimensional
  - Nondestructive
  - *In situ* imaging

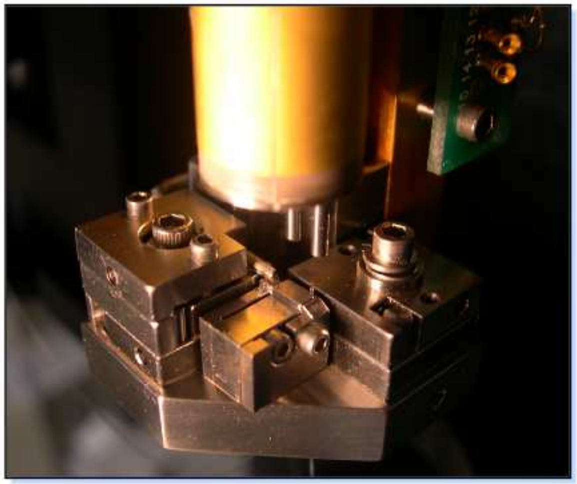






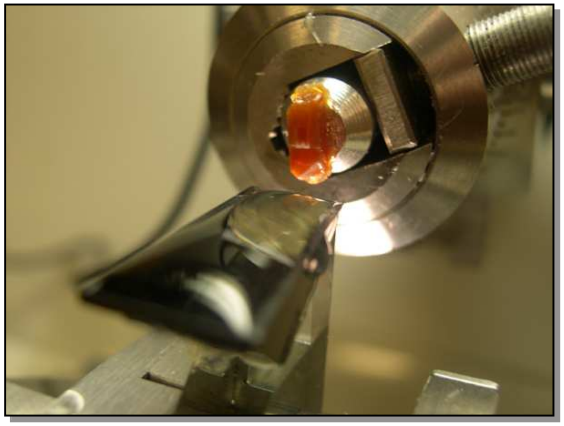
requisites for
95% confidence of success
single-element failure interval
mission-critical elements
red zone
radar for molecules
e2e analysis
single-spin signal
practical bioimaging
Global quantum microscopy funding = ~0.1 LIGO Lab
blue zone
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^{-2}
10^{-1}

Sample Preparation

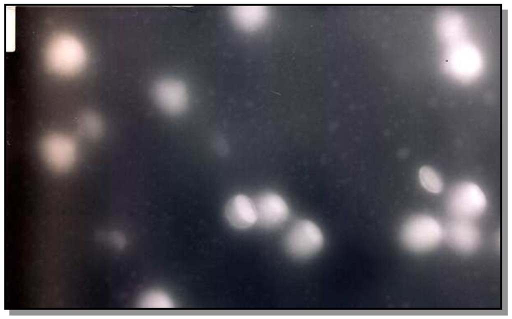


- Advanced MRFM scanner
  - Micrometer-scale volumes
  - Nanometer-scale voxels
  - Dimensionally stable over days
  - Status: ready

- Microtome sample sections
  - Final sample dimensions
  - 100 x 100 x 20 microns
  - Status: ready



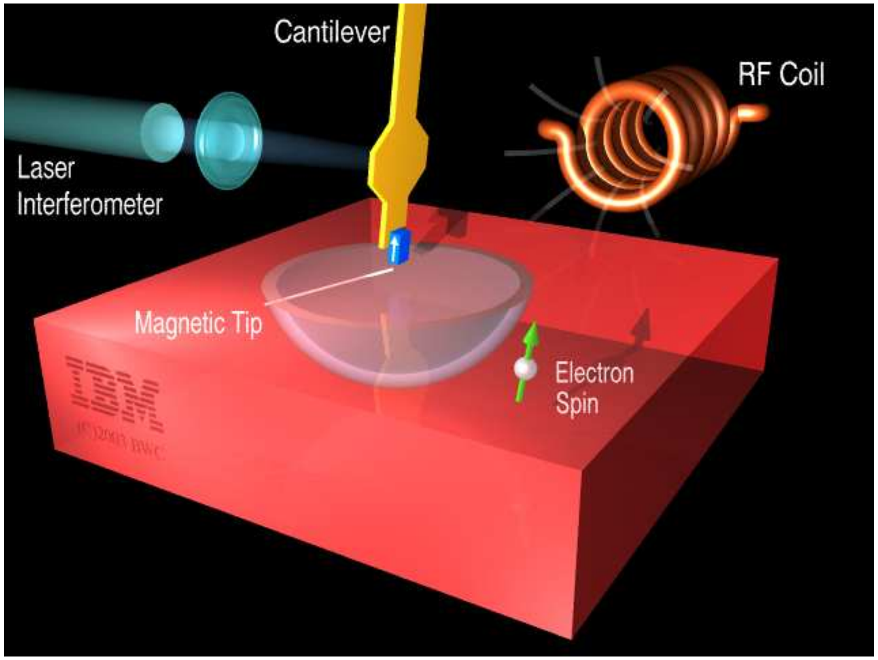
- Verification
  - Spin properties: ESR
  - Sphere distribution: TEM & SEM
  - Status: Ready
- Good-to-go on our Bioimaging Milestone
  - When it all works on the same day!
  - Status: trying!



Approaching Single-Spin MRFM

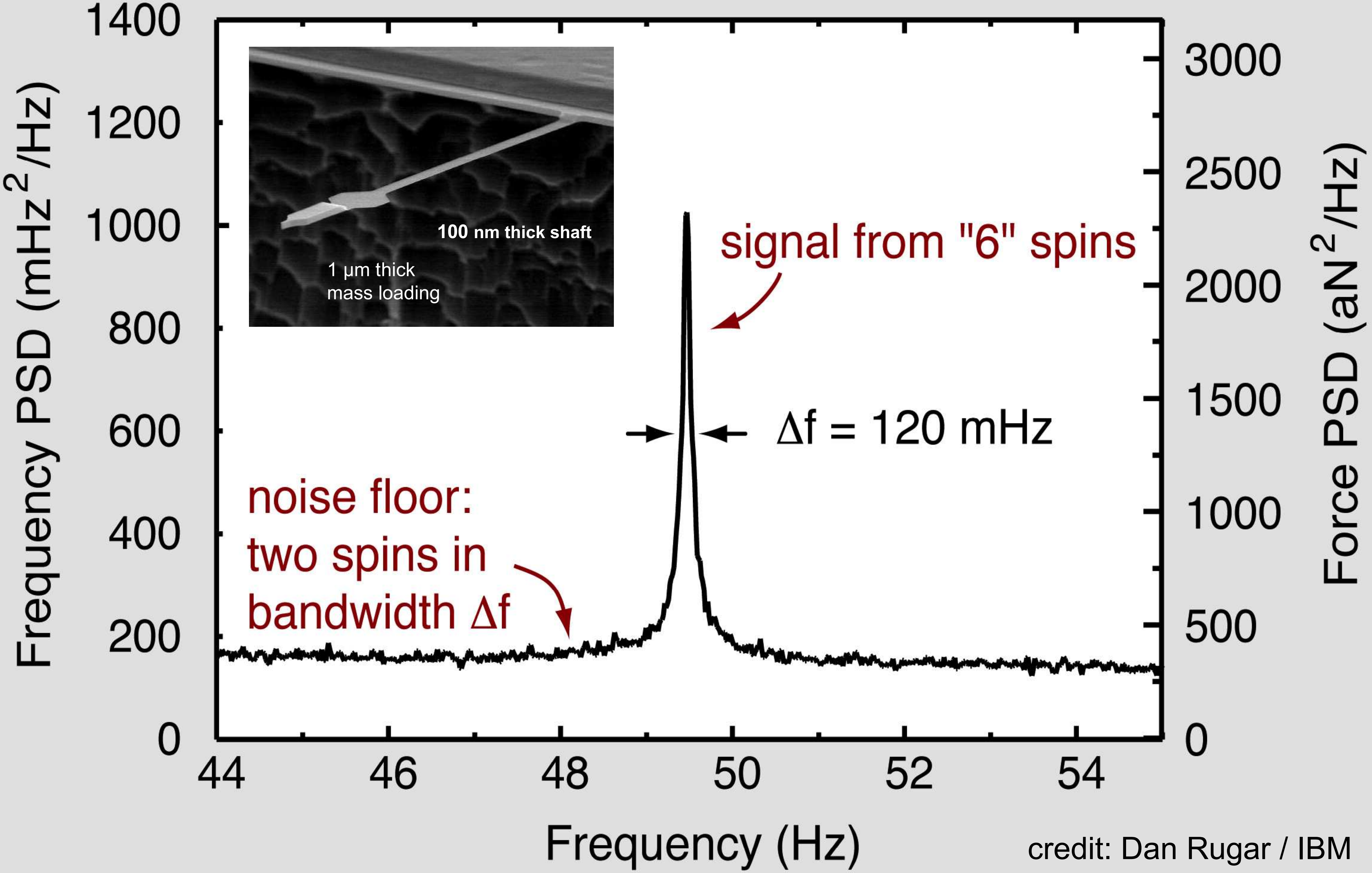
- Single-spin physics requires
  - Top-ranked physicists
  - A great working environment
  - Hard-nosed pragmatism
  - Commitment to a clear vision

… IBM



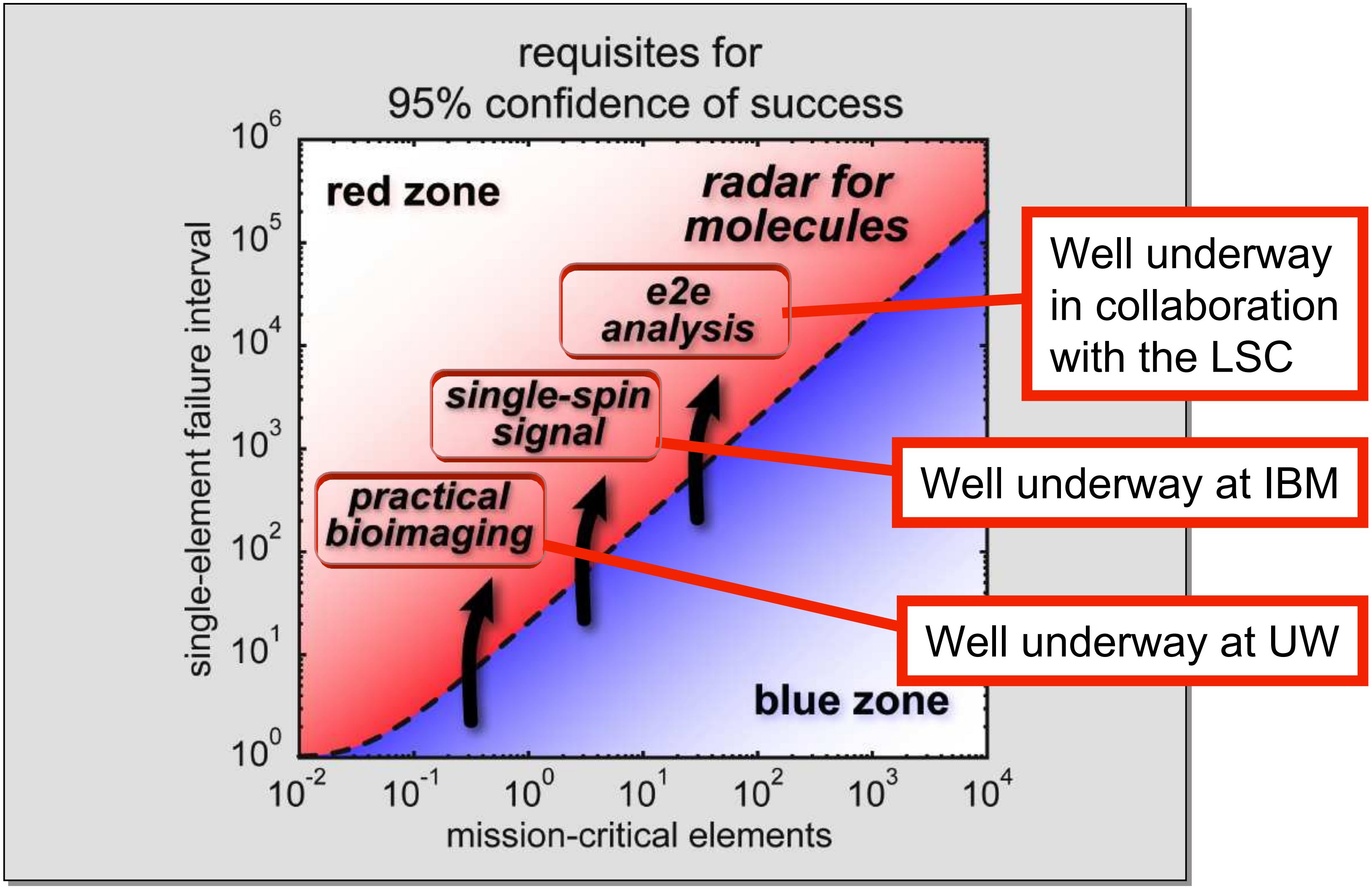
IBM Almaden's Dan Rugar (right) with DARPA sponsors Stu Wolf, Eric Eisenstadt, and Doug Cochran

Approaching Single-Spin MRFM at IBM



credit: Dan Rugar / IBM

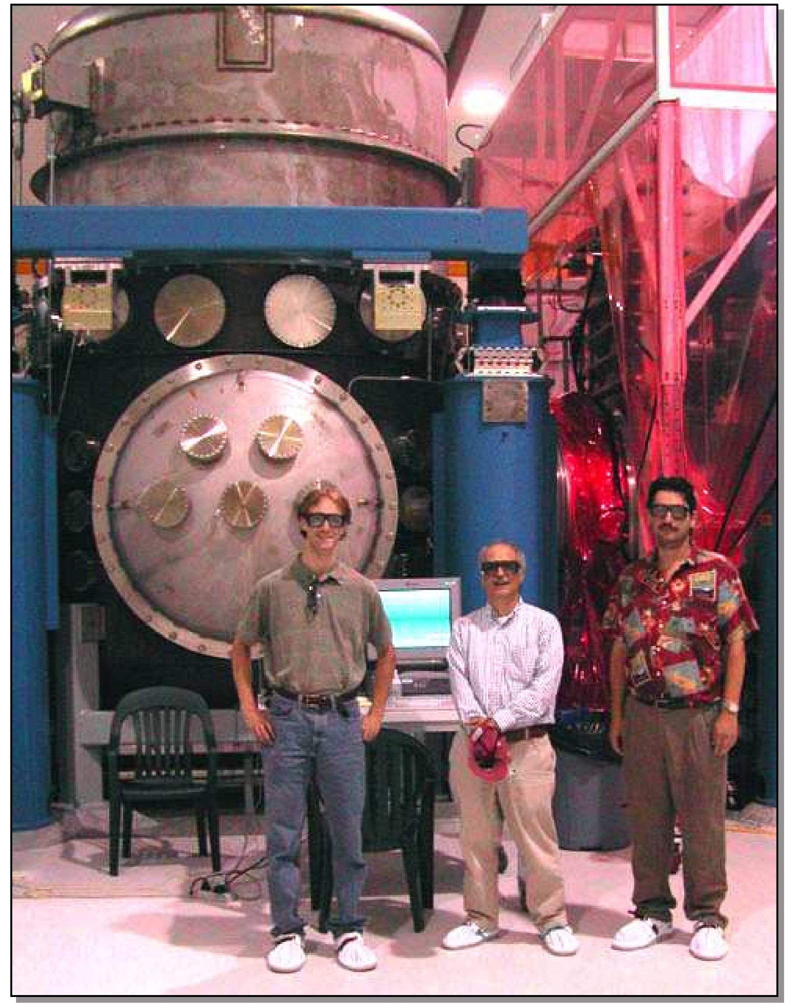
RADAR For Molecules: Challenges in the Red Zone



We see an opportunity: tackle these challenges together

LIGO / LSC: Deep in the Red Zone

- Gravity-wave (GW) interferometry:
  a multibillion-dollar red zone community
  - LIGO, VIRGO, GEO 600,
    TAMA 300, ACIGA, and LISA
- LIGO Scientific Collaboration (LSC)
  - UW formally applying to join the LSC
  - The UW's role will be e2e analysis
    - GW interferometry <u>and</u>
    - Quantum microscopy



Optical Torques in Suspended Fabry-Perot Interferometers

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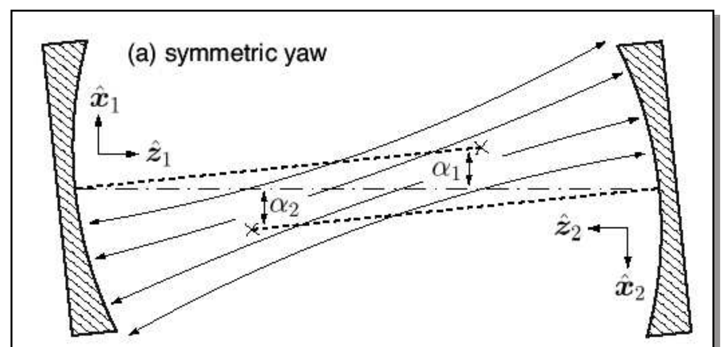
Seattle, Washington, 98195, USA

Daniel Sigg†
LIGO Hanford Observatory
P.O. Box 159
Richland, WA 99352, USA

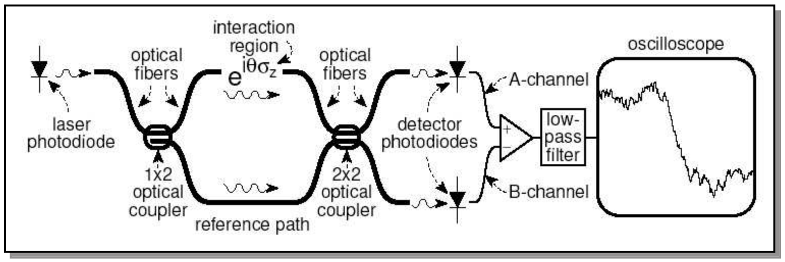
(Dated: October 14, 2003)



- Red zone payoff: LSC's review process
  - We'll be "going to school" to learn
    red zone culture and discipline

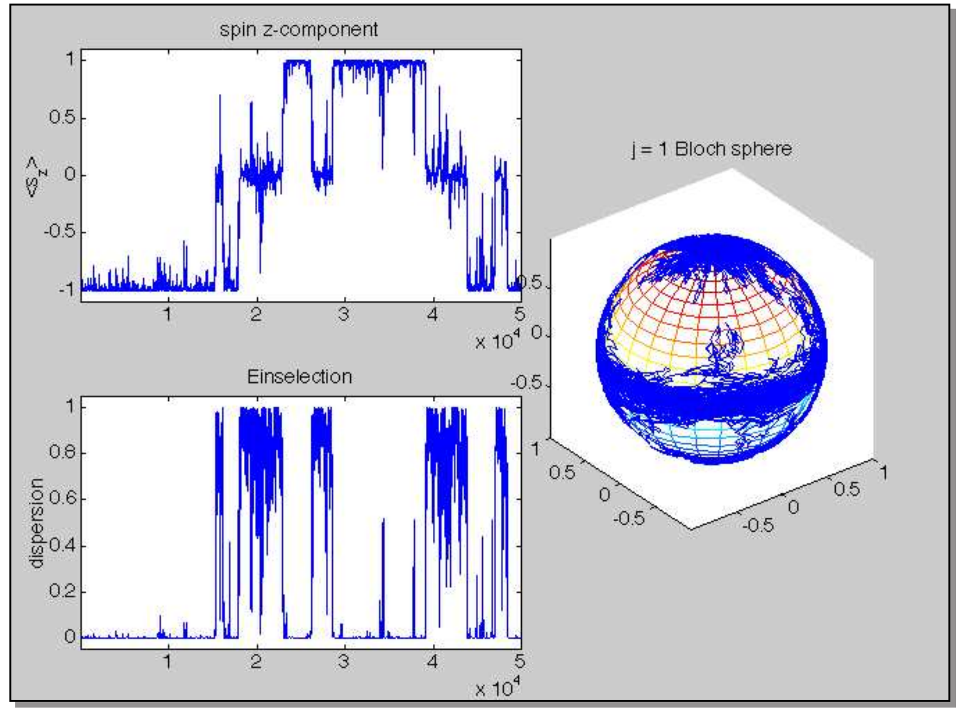
Spinometers I: Basics

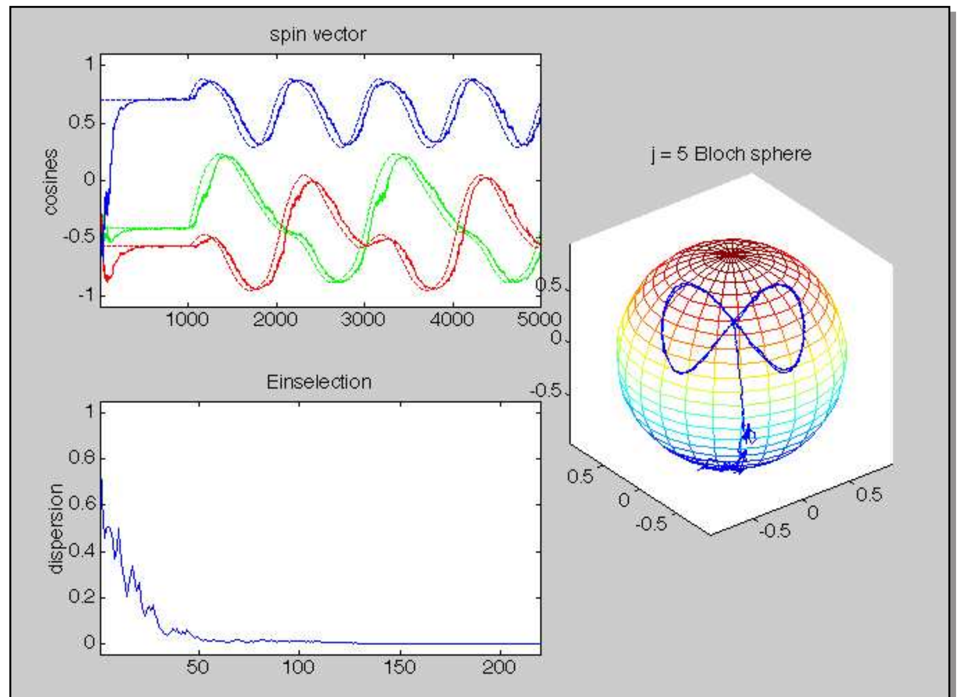
- Spinometers are “finite elements” for e2e simulation and analysis
  - Useful in GW interferometry: backaction, control, and noise
  - Useful in quantum microscopy: backaction, control, and noise



- Spinometers respect orthodoxy:
  - Perelomov, Gardiner, Mensky, Zurek, Braginsky, Thorne, Caves, Feynman
- Spinometer capabilities:
  - Heat baths, spring noise, oscillators, feedback control
- Closed-form design rules:
  - Encompassing many important design cases

NEW





Spinometers II:
Practical Design Rules for Quantum System Engineering

- Spinometers saturate the SQL
  - Consistent with quantum orthodoxy
- Spinometer measurement and process noise are perfectly correlated (Ito)
  - Linear: invisible! Nonlinear: Stern-Gerlach
- Spinometer control loops are heat baths
  - Including cryptographic equivalence
- Control loops einselect coherent states
  - Explains why classical physics works so well
- Lessons for OSCAR
  - Semiclassical SNR should be achieved
- What's next for spinometry
  - Joining the Center for AIDS Research (CFAR)
- **Green-light for MOSAIC Phase II**
  - And Blue Zone fun

standard quantum limit (SQL).

$$S_{q_N q_N} S_{f_N f_N} = (\hbar/2)^2\,,$$
$$S_{q_N f_N} = i\,(S_{q_N q_N} S_{f_N f_N})^{1/2} = i\hbar/2$$

closed-loop force noise PSD

$$S^{\mathrm{total}}_{f_N f_N} = \frac{2m\omega_0}{Q}\;\hbar\omega_0 \coth\left(\frac{\hbar\omega_0}{k_B T}\right)$$

SNR for OSCAR energy filter

$$\mathrm{SNR} = \frac{32}{\pi^4}\left(\frac{f^2_{\mathrm{spin}}}{S^{\mathrm{total}}_{f_N f_N}}\right)^2 T_{\mathrm{mod}}\, T_{\mathrm{av}}$$

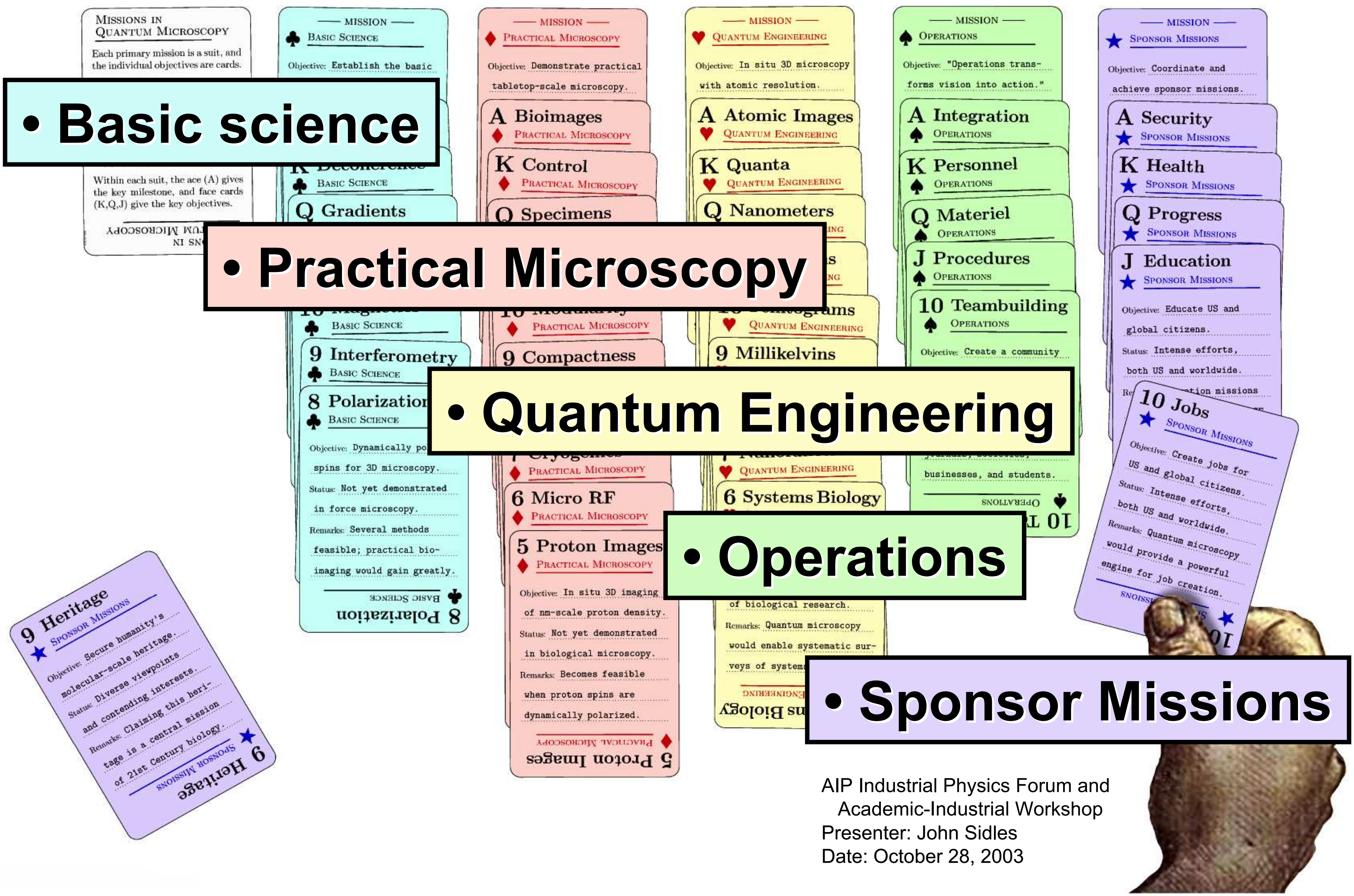
postulated diffusion equations for $\delta_Z(t)$

$$\dot{\delta}_Z(t) = -D\,\boldsymbol{\nabla}\cdot \boldsymbol{j}_Z(\boldsymbol{x},t)$$

$$P(\beta\hat{\boldsymbol{n}}, j) = \frac{2\sinh(\beta/2)Q(\beta\hat{\boldsymbol{\nu}}, j+1/2)Q(-\beta\hat{\boldsymbol{\nu}}, j+1/2)}{Q(-\beta\hat{\boldsymbol{n}}, j+1)\big(Q(-\beta\hat{\boldsymbol{\nu}}, j+1/2) - Q(\beta\hat{\boldsymbol{\nu}}, j+1/2)\big)}$$

UW Quantum System Engineering Group

3D Quantum Biomicroscopy



- Basic science
- Practical Microscopy
- Quantum Engineering
- Operations
- Sponsor Missions

AIP Industrial Physics Forum and Academic-Industrial Workshop
Presenter: John Sidles
Date: October 28, 2003

Looking to the Future …

For us, failure is not an option, and ignorance will not be our excuse.

We must see, we will see.