Title: Ultracold Molecules: From Quantum Chemistry to Quantum Computing

Speakers: Alan Jamison

Series: Colloquium

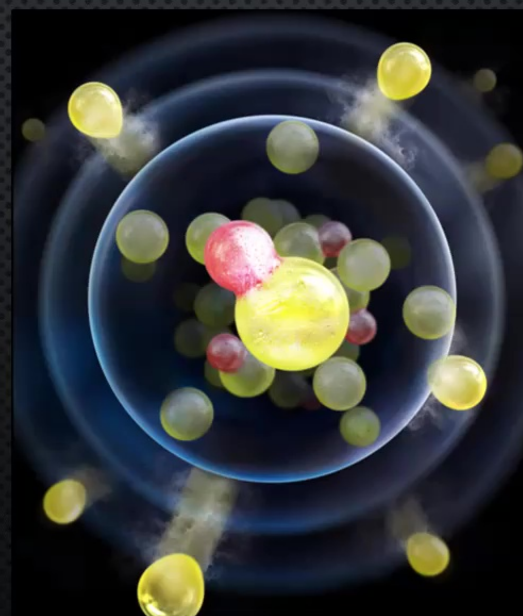
Date: May 06, 2020 - 2:00 PM

URL: http://pirsa.org/20050010

Abstract: Cooling atomic gases to ultracold temperatures revolutionized the field of atomic physics, connecting with and impacting many other areas in physics. Advances in producing ultracold molecules suggest similarly dramatic discoveries are on the horizon. First, I will review the physics of ultracold molecules, including our work bringing a new class of molecules to nanokelvin temperatures. Chemistry at these temperatures has a very different character than at room temperature. One striking effect is our recent result using spin states of reactants to control chemical reaction pathways. I will also describe how the strong electric dipole moments of ultracold molecules present an exciting new tool for quantum information and quantum computing.

ULTRACOLD MOLECULES

FROM QUANTUM CHEMISTRY TO QUANTUM COMPUTING



IQC Institute for Quantum Computing

ALAN JAMISON

UNIVERSITY OF WATERLOO | FACULTY OF SCIENCE Department of Physics and Astronomy

ULTRACOLD MOLECULES: WHY?

- ULTRACOLD ATOMS ARE GREAT

  … BUT

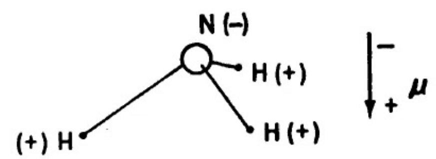
More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

…

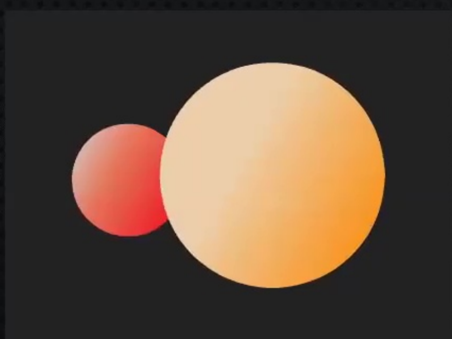
“is” a triangular pyramid

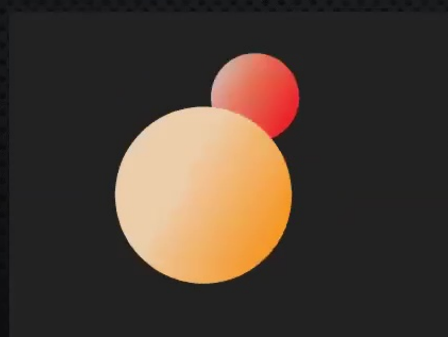


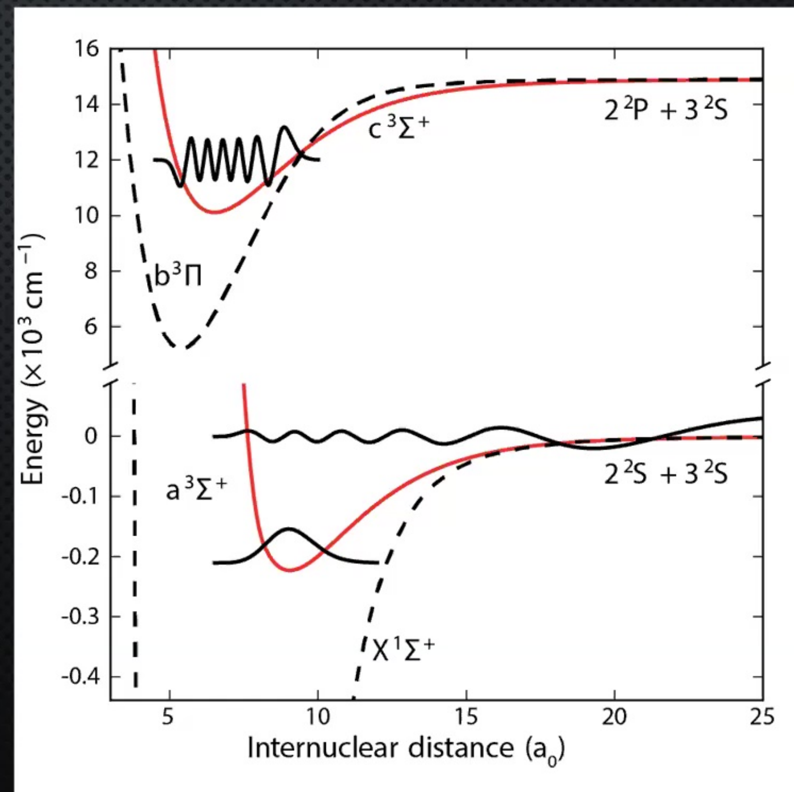
with the nitrogen negatively charged
and the hydrogens positively charged

MOLECULES: STRUCTURE

- STRUCTURAL HIERARCHY
  - ELECTRONIC (~10,000 K)
  - VIBRATIONAL (~1-100 K)
  - ROTATIONAL (~0.1-1K)
  - HYPERFINE (~1-100 μK)

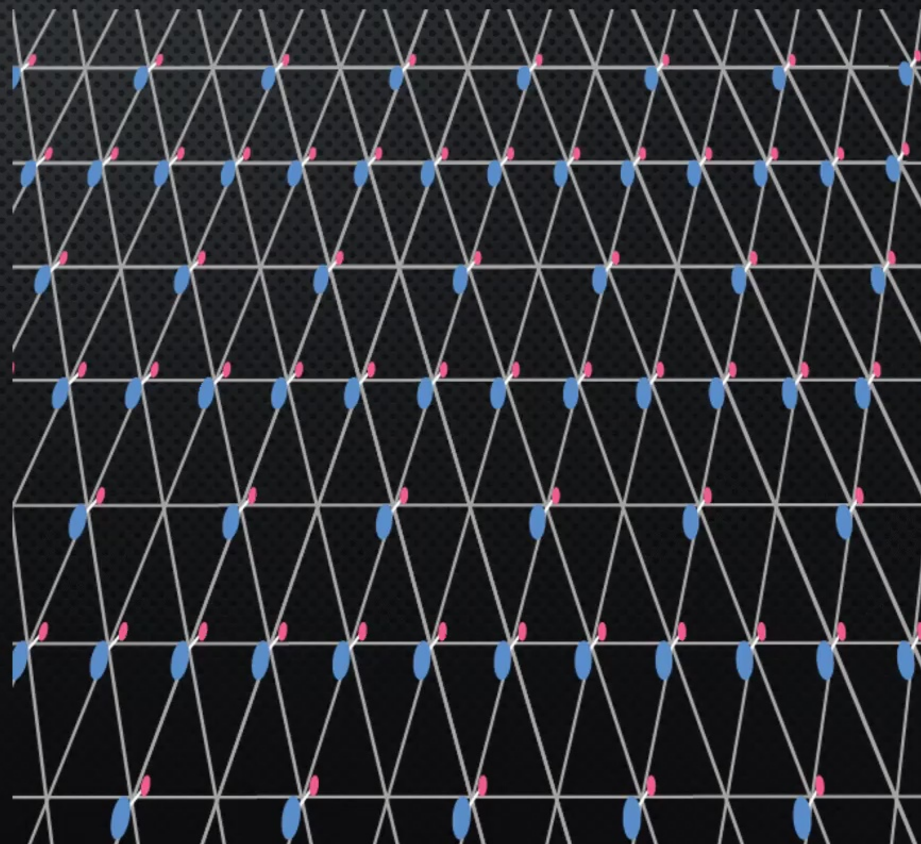






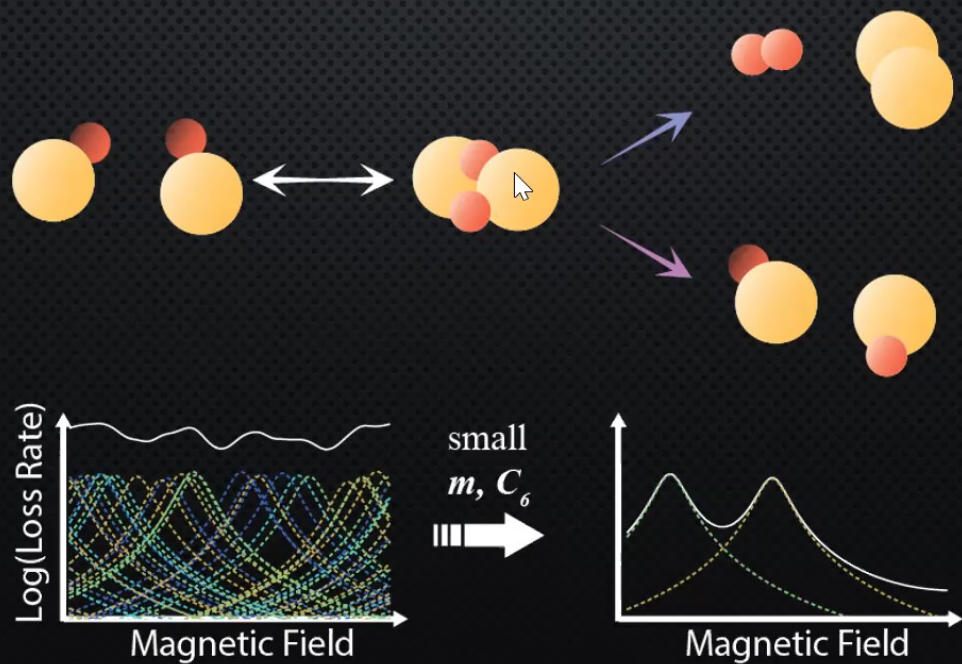
Molecules: Quantum AFM Simulation

- Structural Hierarchy
  - Electronic (~10,000 K)
  - Vibrational (~1-100 K)
  - Rotational (~0.1-1K)
  - Hyperfine (~1-100 μK)



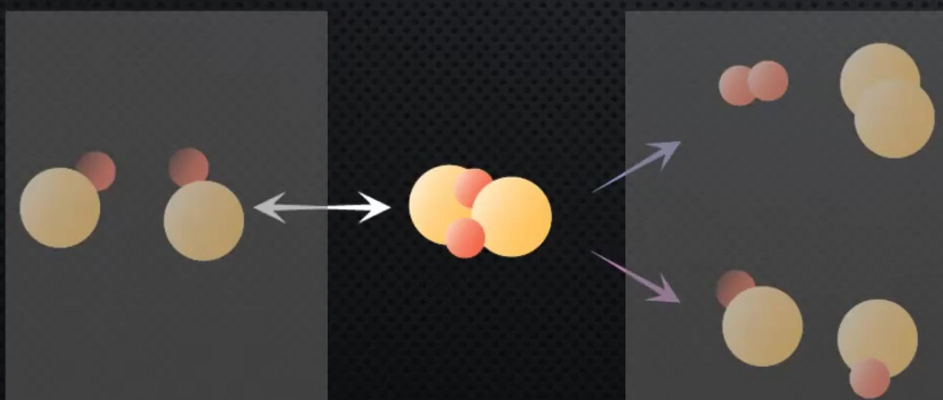
MOLECULES: QUANTUM CHEMISTRY

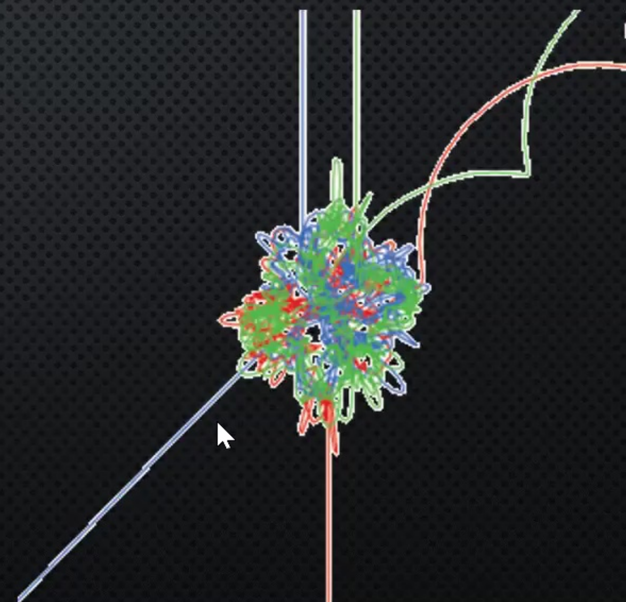
- CONTROL OF REACTIONS



MOLECULES: QUANTUM CHEMISTRY

- Control of Reactions
- Understanding collision Complex



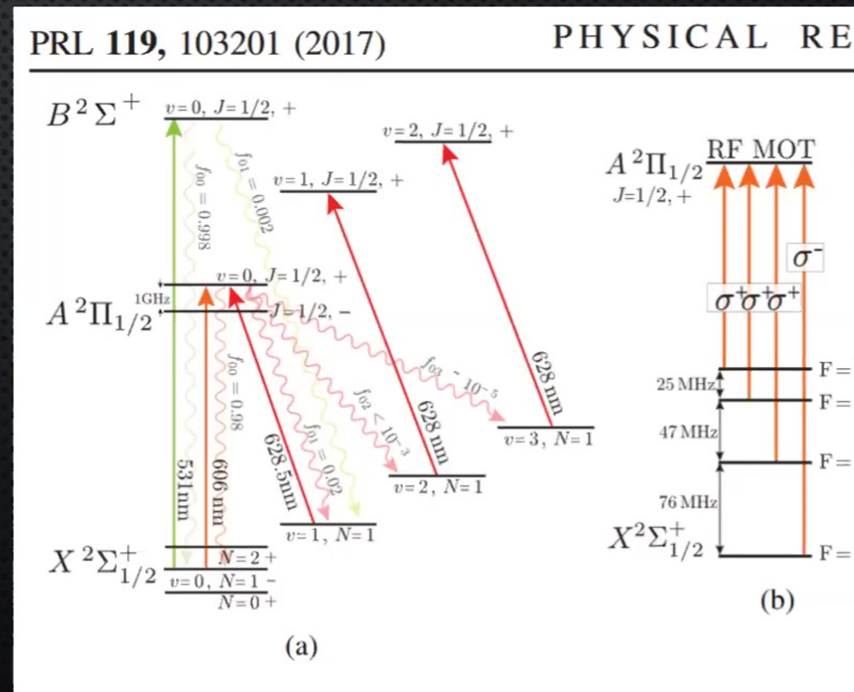


From J.F.E. Croft and J. Bohn
PRA 89, 012714

HOW TO MAKE MOLECULES ULTRACOLD

DIRECTLY COOLING MOLECULES?

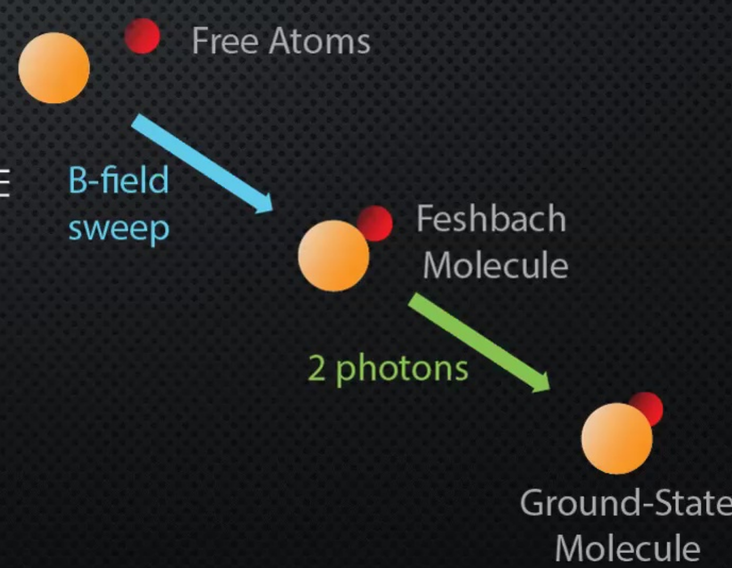
- **MUCH** EASIER TO LASER COOL ATOMS THAN MOLECULES
- TRY TO FIND THE MOST ATOM-LIKE MOLECULE POSSIBLE

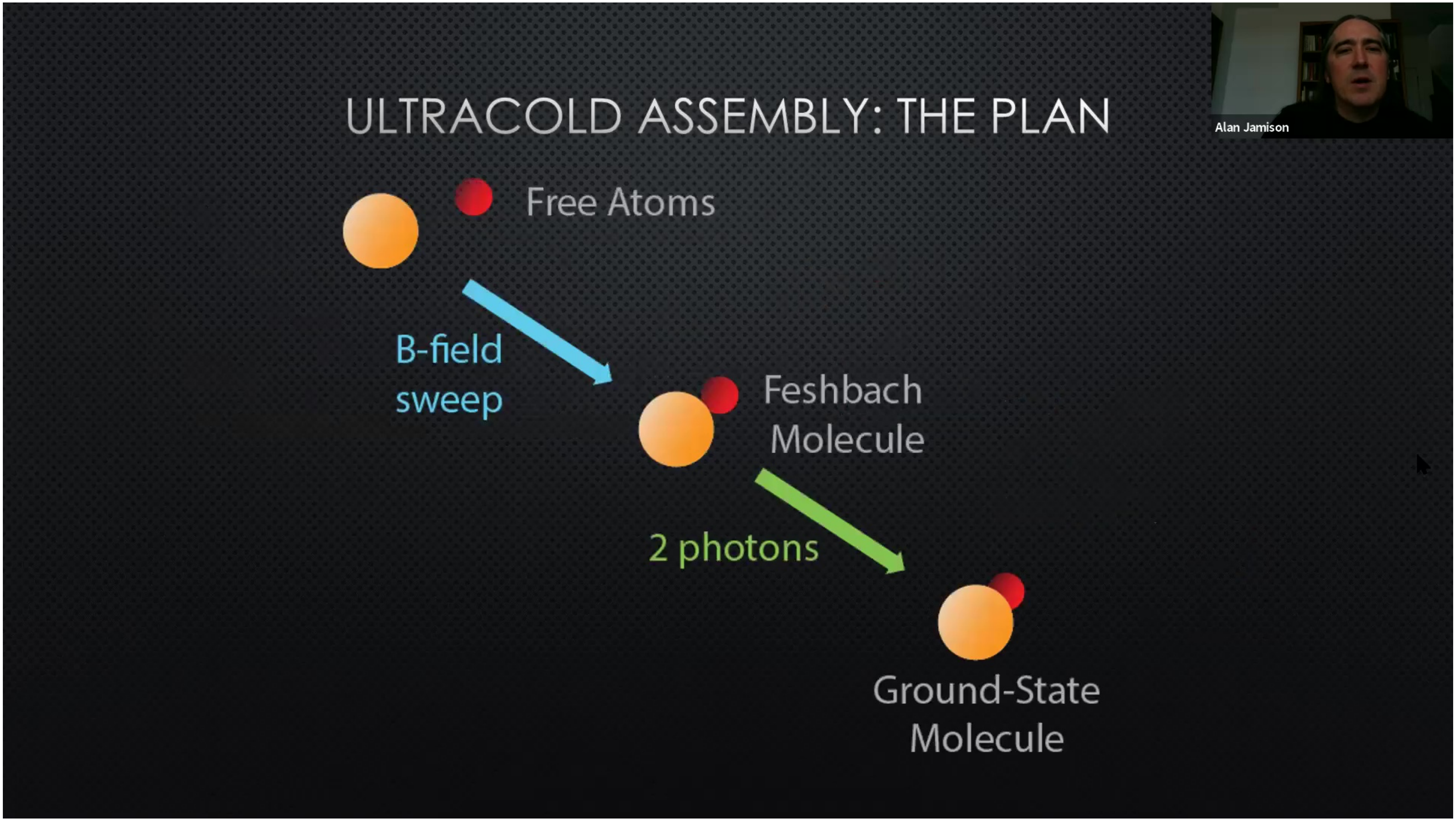


From Anderegg, et al. (2017)

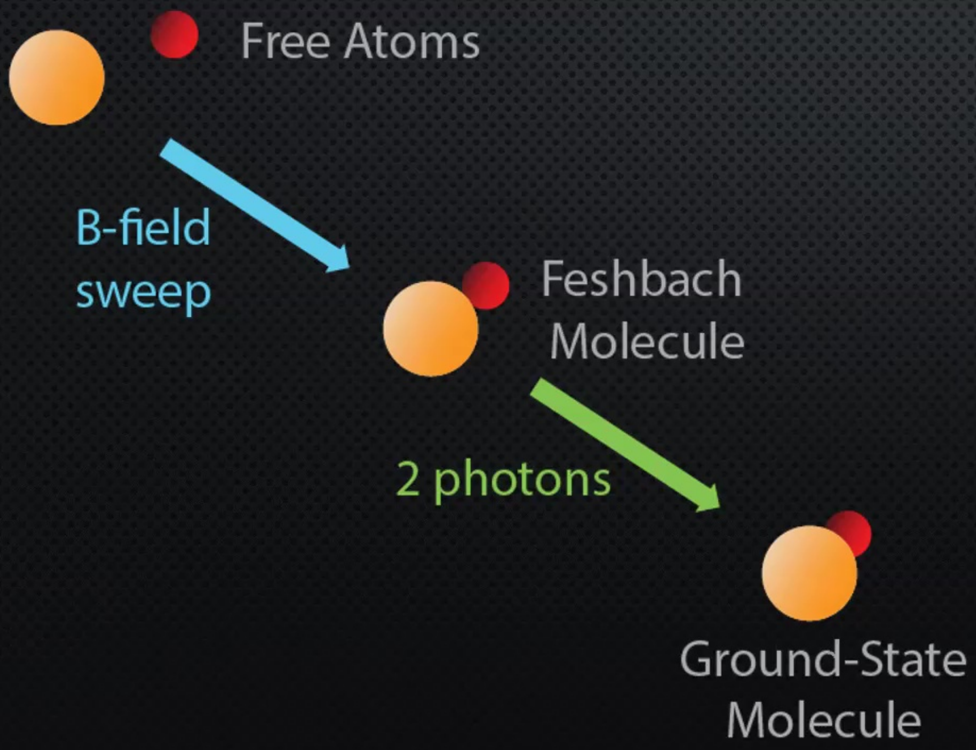
ULTRACOLD ASSEMBLY: THE PLAN

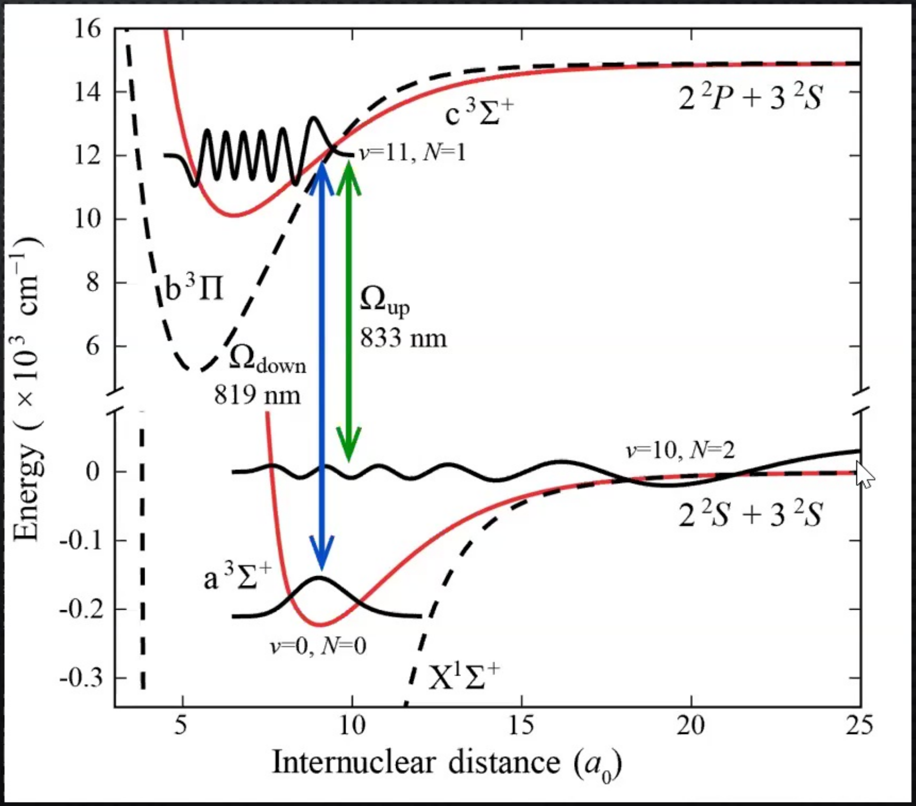
- MUCH EASIER TO LASER COOL ATOMS THAN MOLECULES
- … MOLECULES ARE MADE OF ATOMS!
- PATH ORIGINATED BY DEBBIE JIN AND JUN YE
  - NI, ET AL.; *SCIENCE*, 322, 231 (2008)



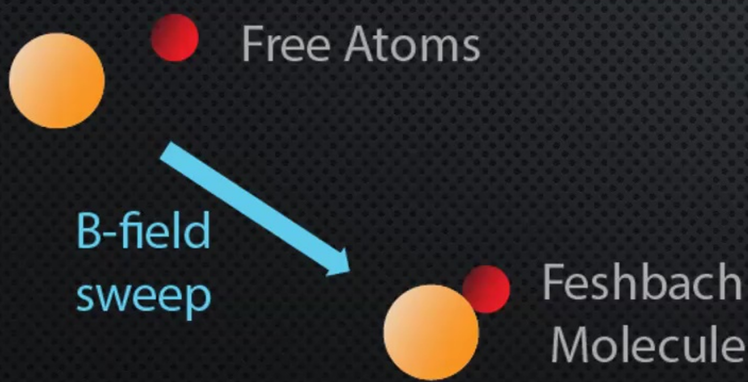

ULTRACOLD ASSEMBLY: THE PLAN
Free Atoms
B-field
sweep
Feshbach
Molecule
2 photons
Ground-State
Molecule
Alan Jamison

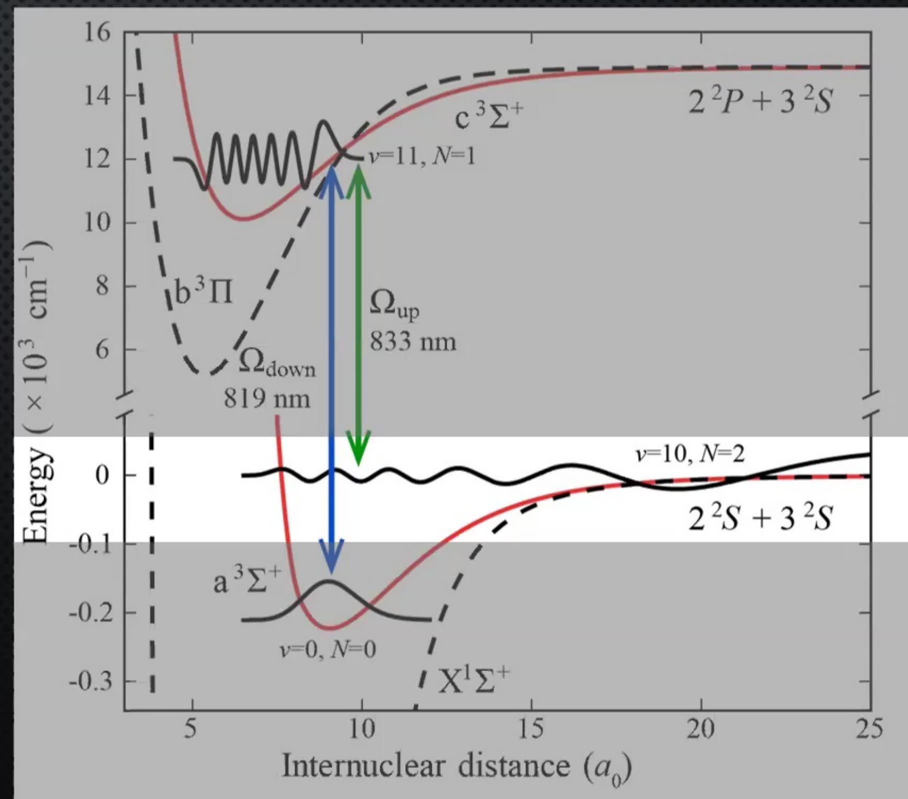
ULTRACOLD ASSEMBLY: THE PLAN

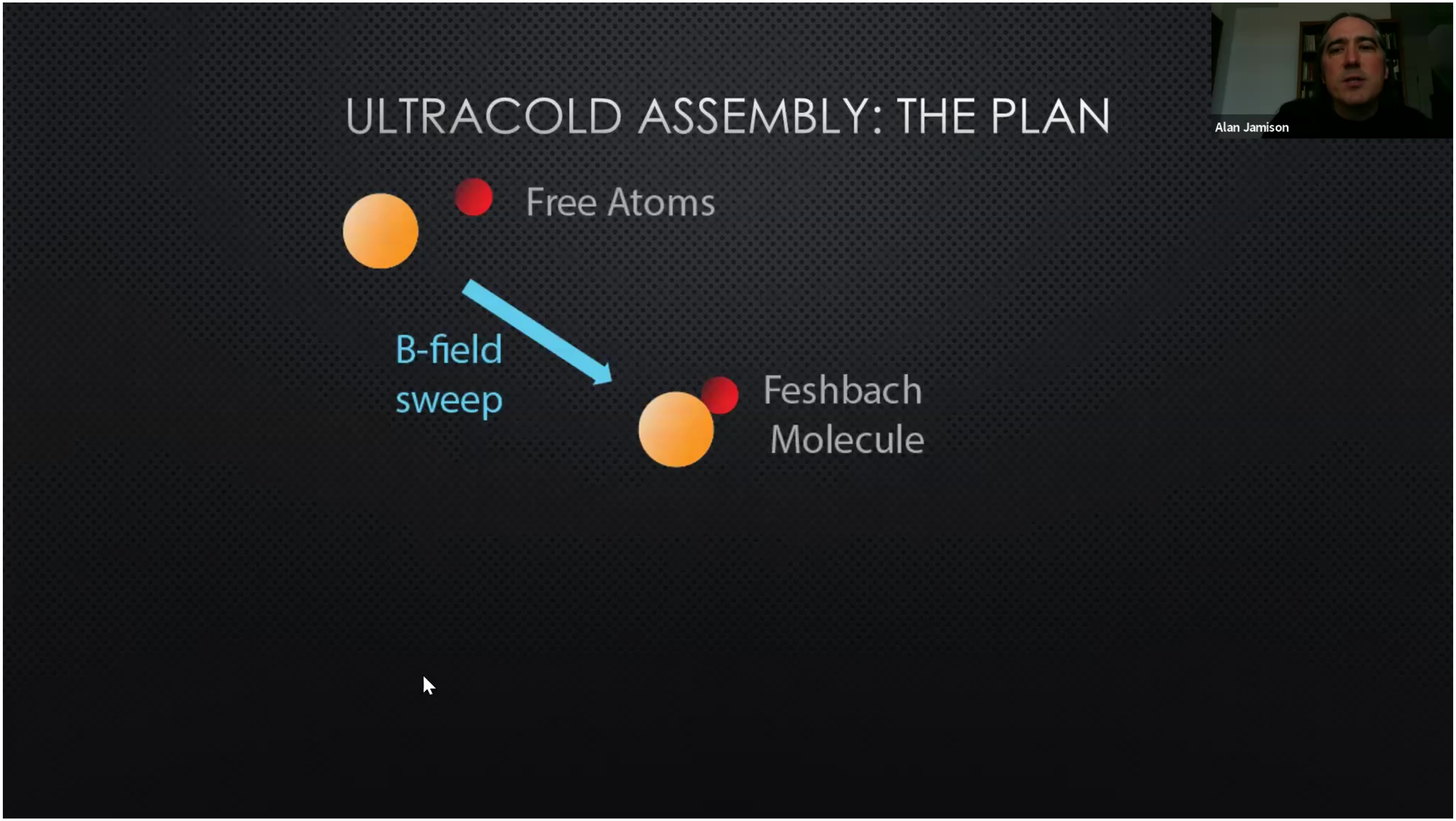


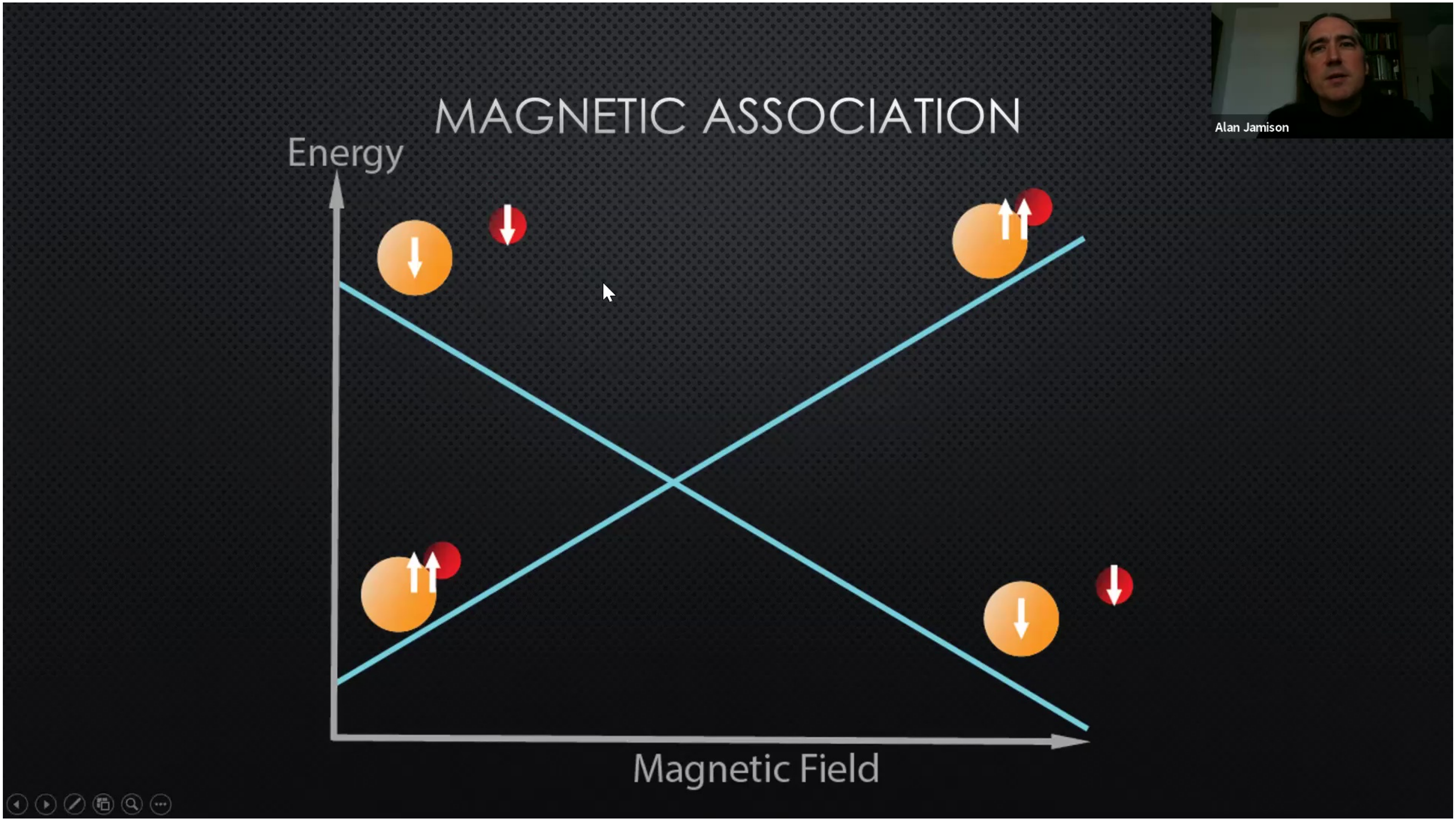


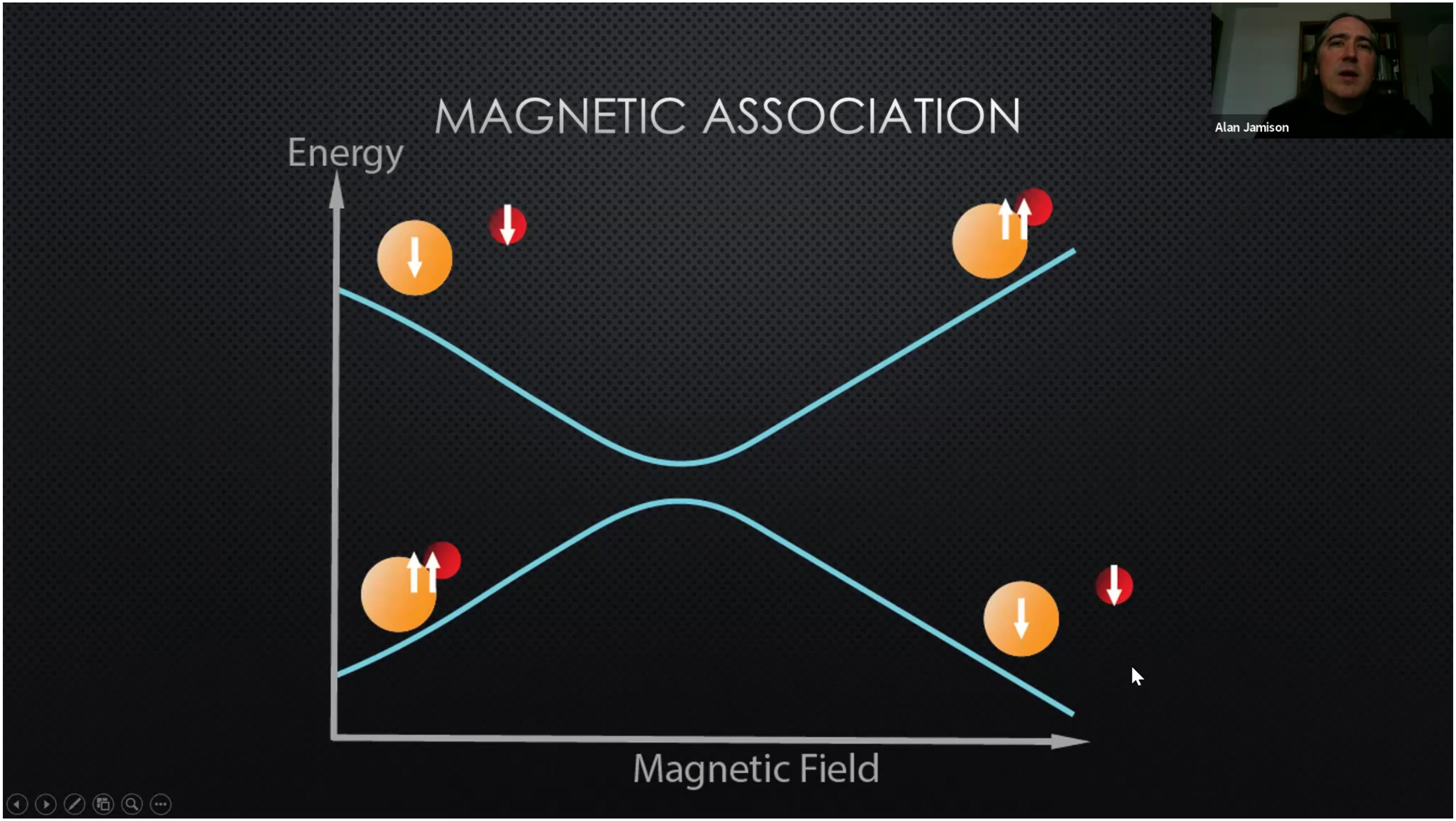
MAGNETIC ASSOCIATION





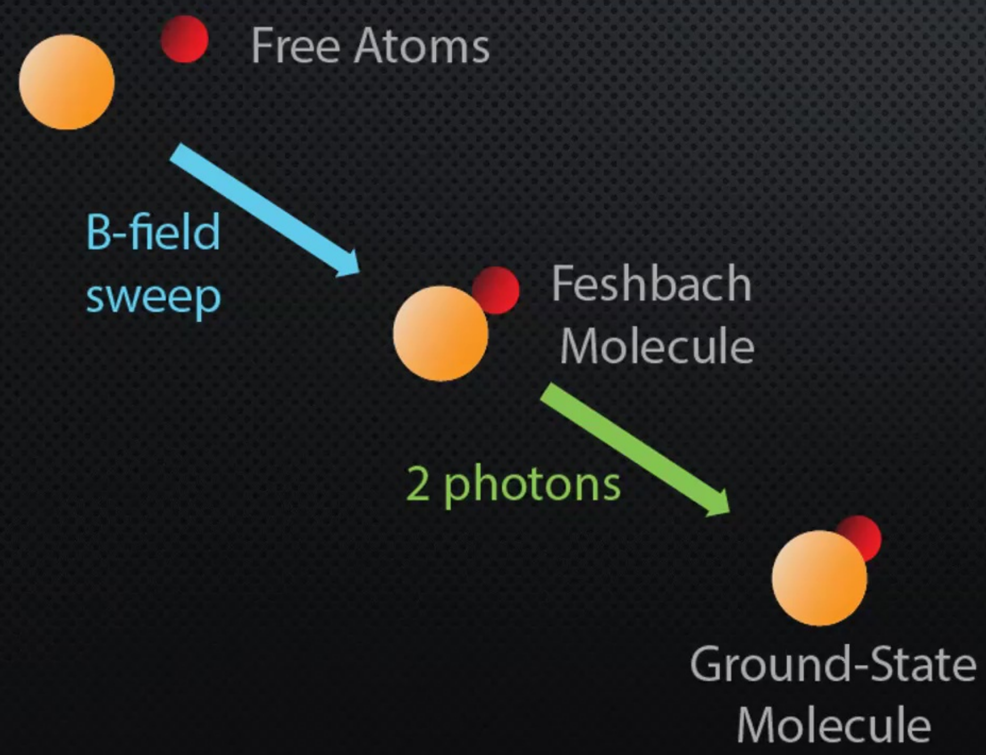

ULTRACOLD ASSEMBLY: THE PLAN
Free Atoms
B-field
sweep
Feshbach
Molecule
Alan Jamison

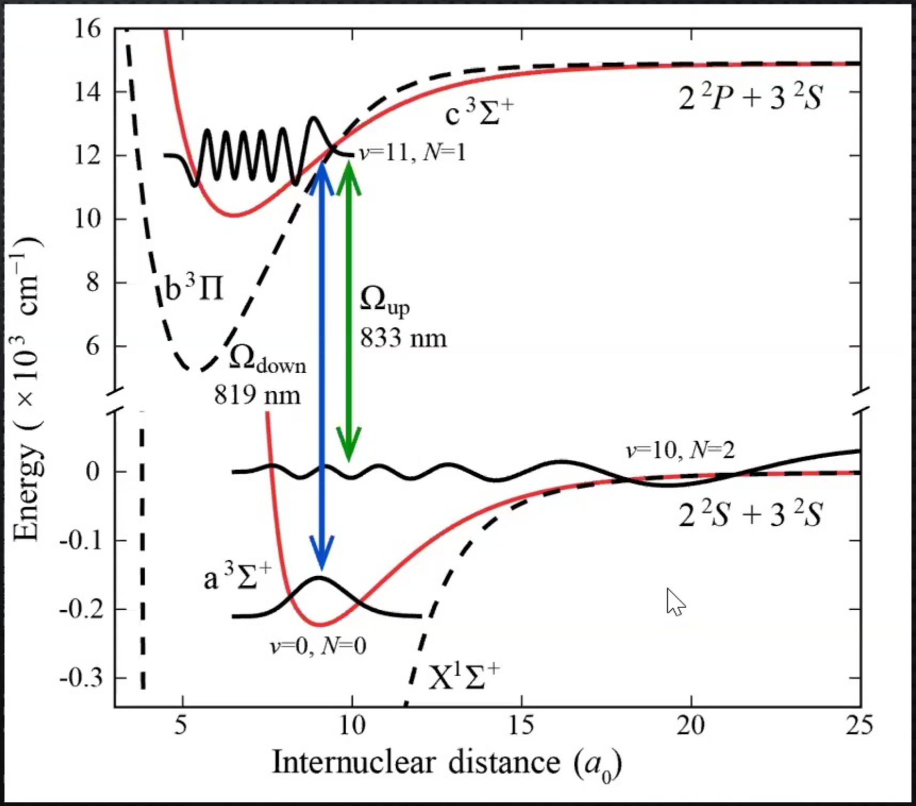

MAGNETIC ASSOCIATION
Alan Jamison
Energy
Magnetic Field



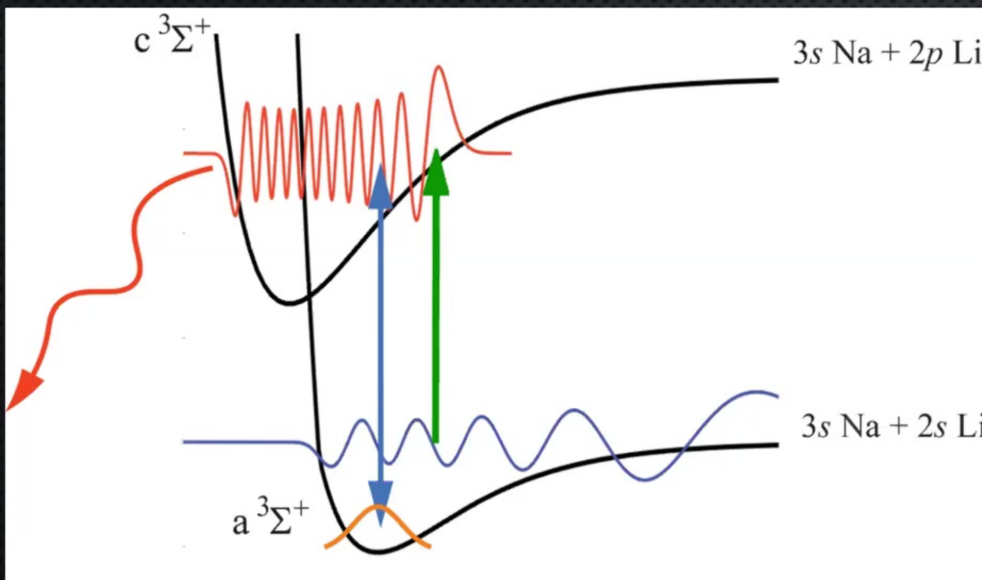
MAGNETIC ASSOCIATION
Energy
Magnetic Field
Alan Jamison

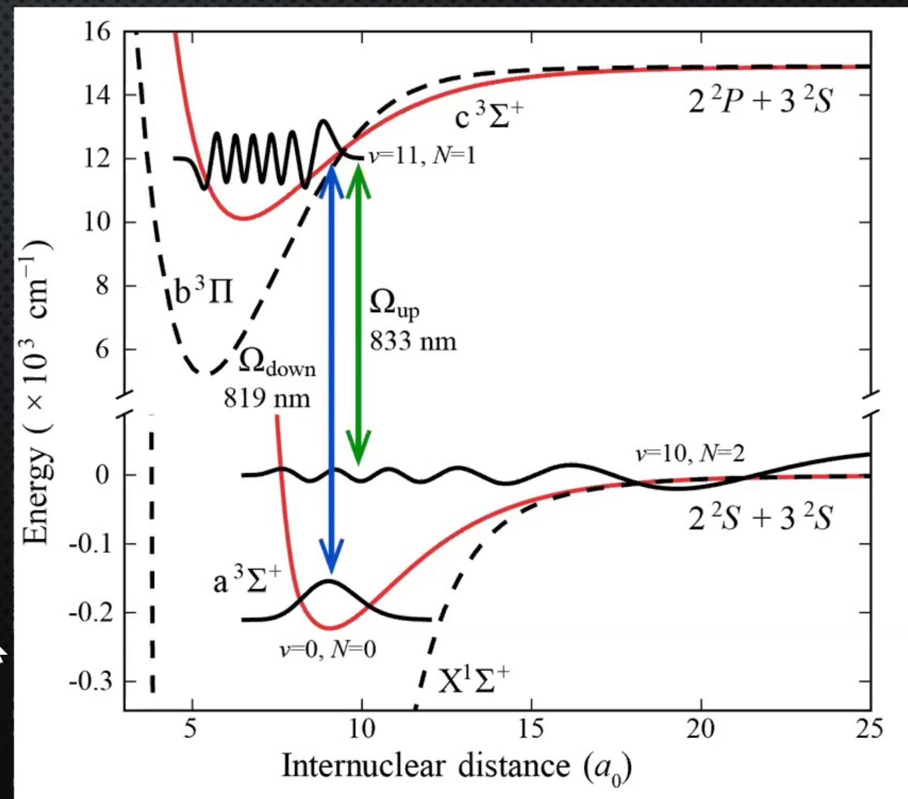
ULTRACOLD ASSEMBLY: THE PLAN





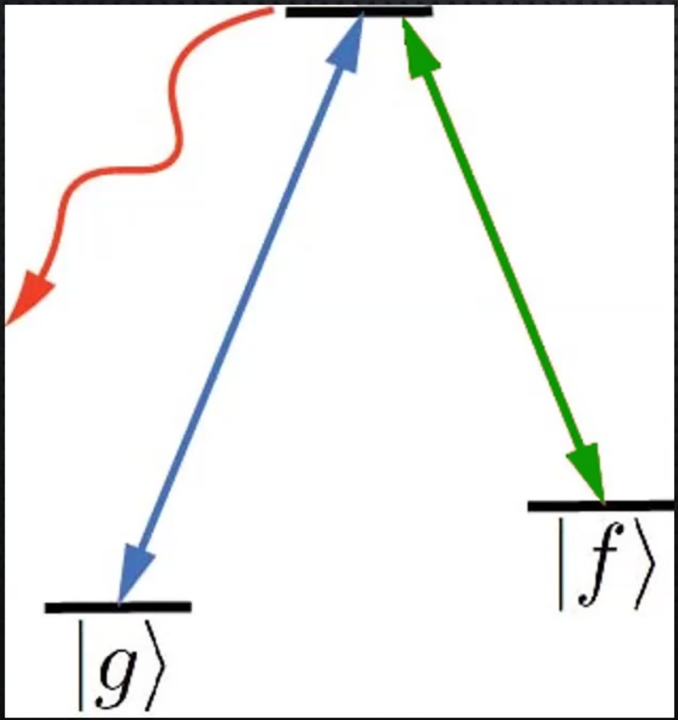
TWO-PHOTON TRANSFER

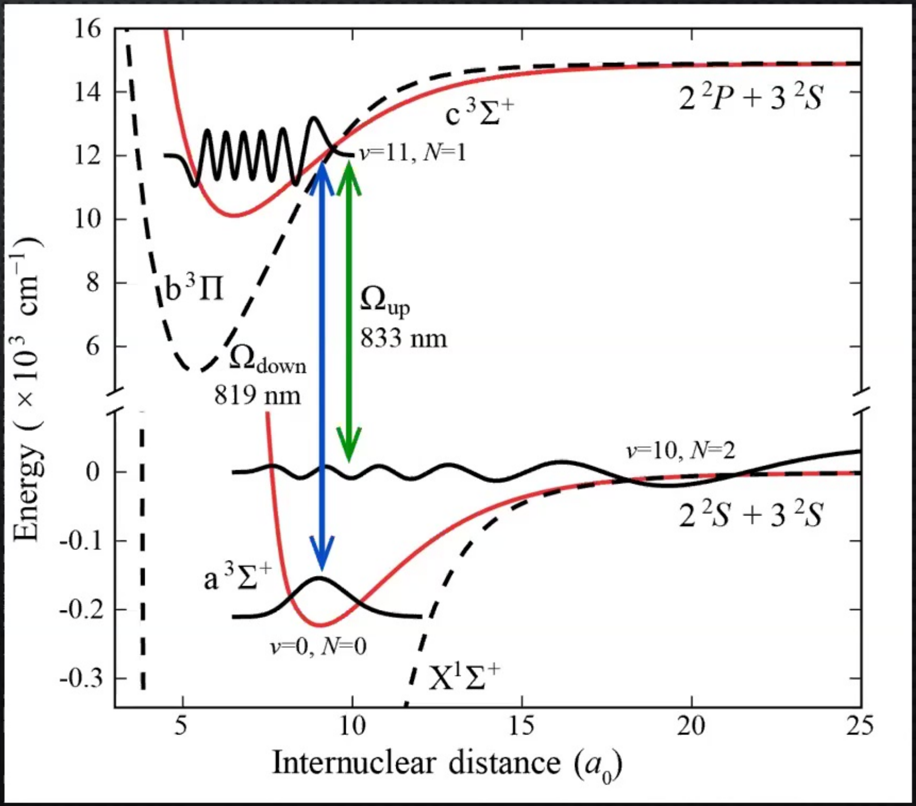




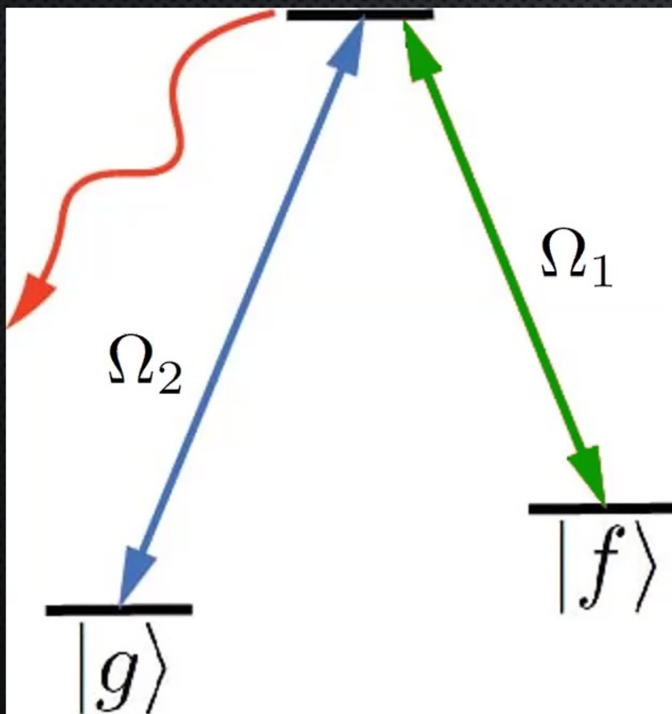
TWO-PHOTON TRANSFER

Alan Jamison



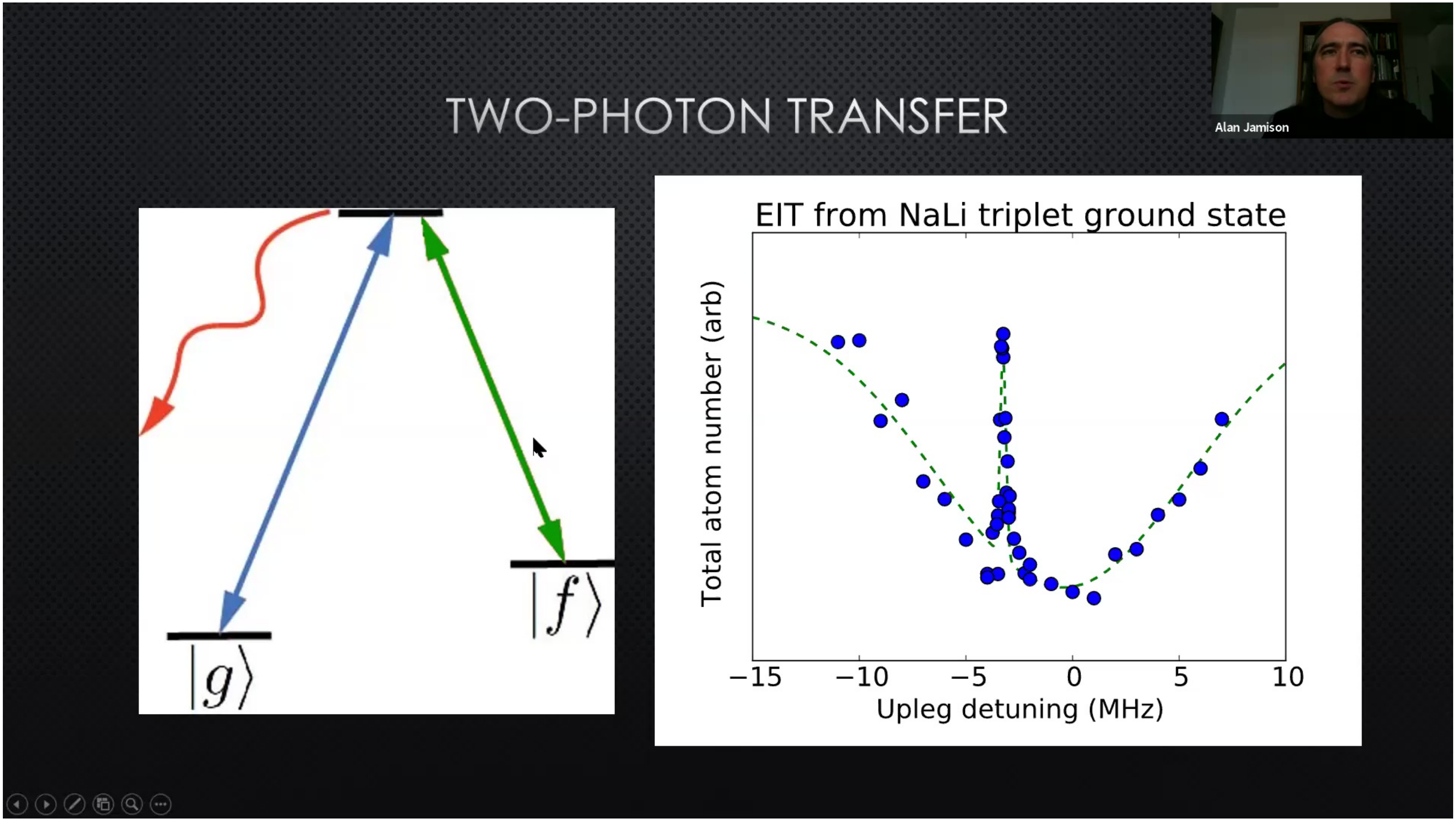


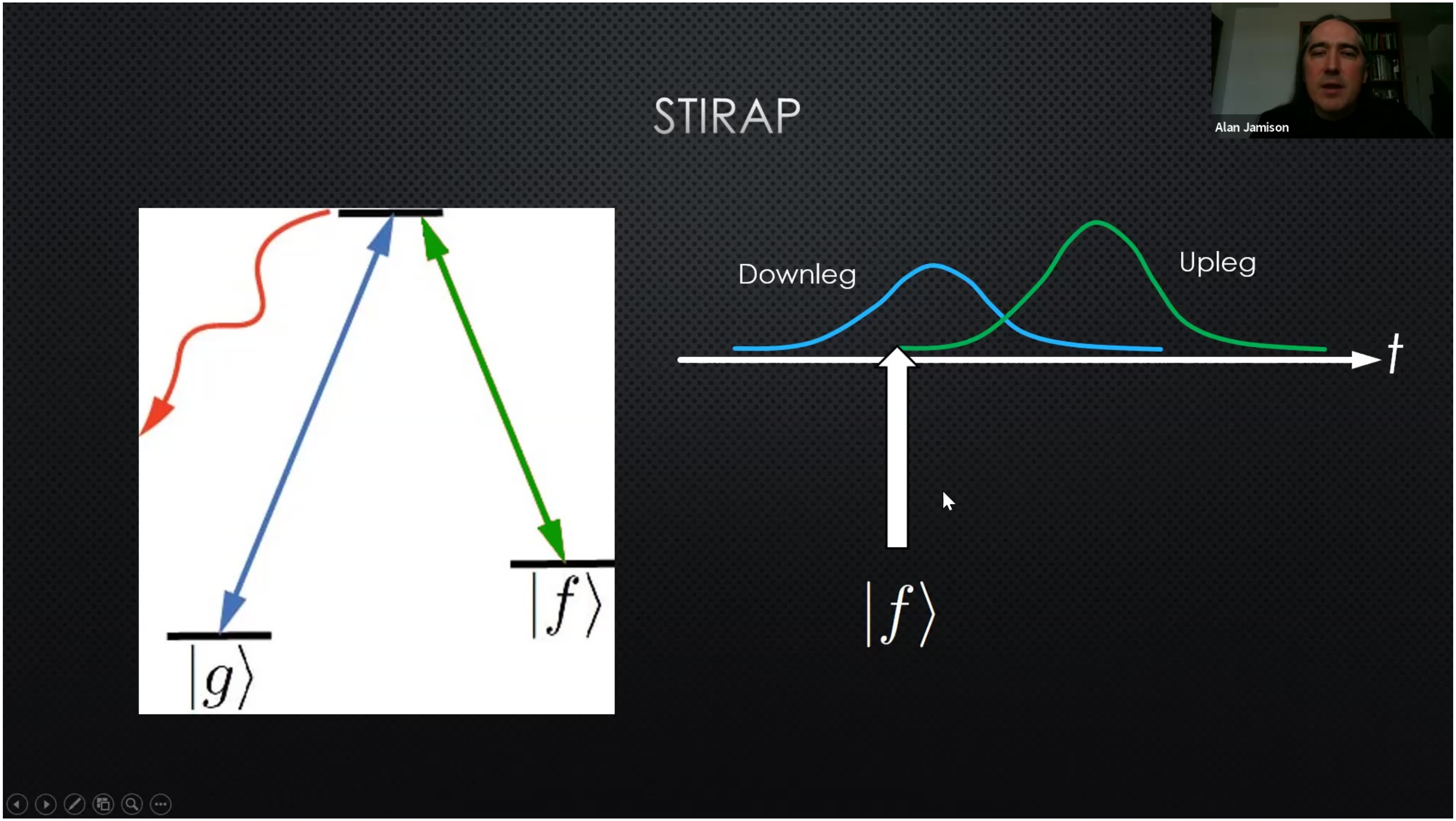
TWO-PHOTON TRANSFER

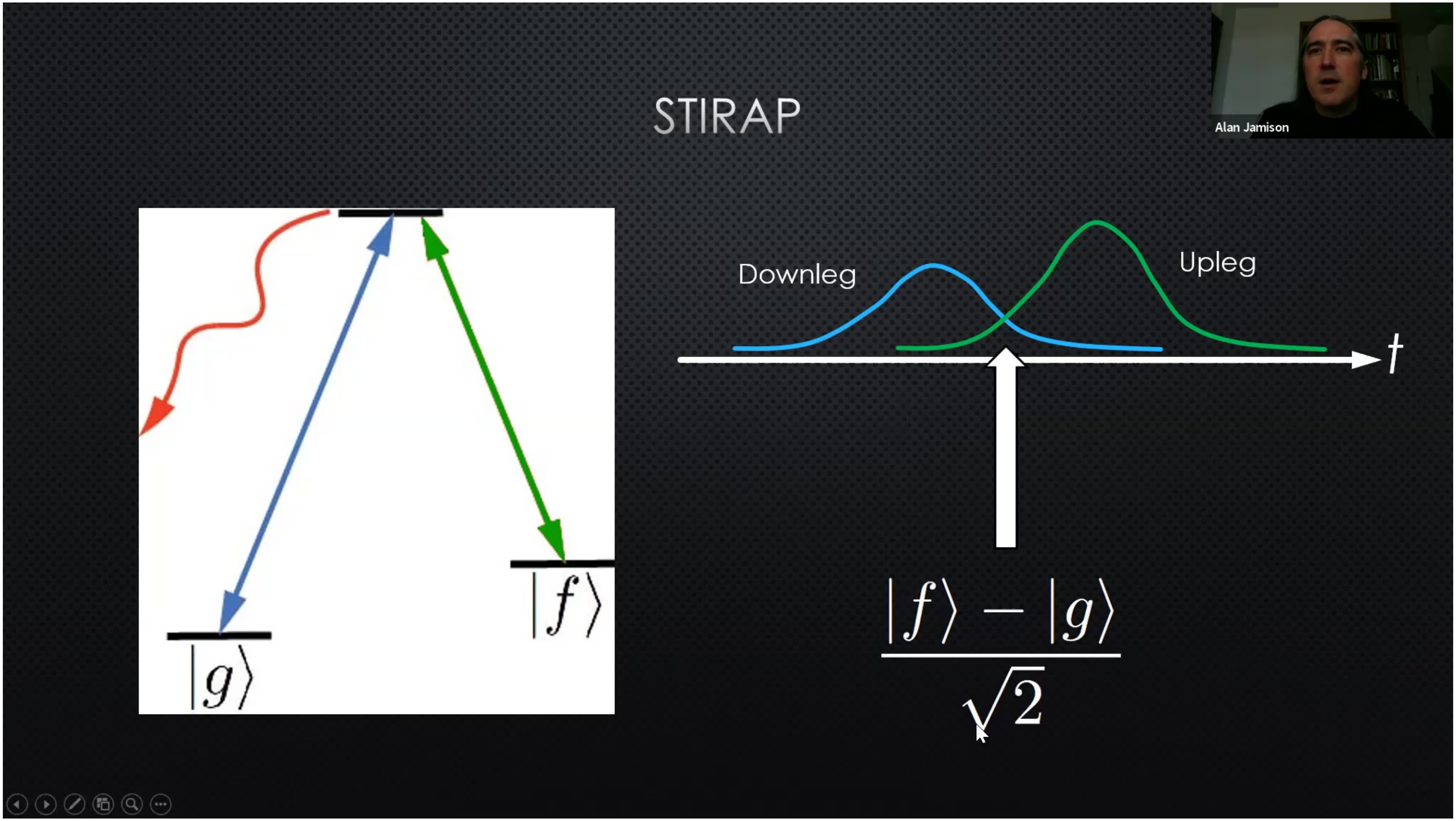


$$\begin{pmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & \Delta & \Omega_2 \\ 0 & \Omega_2 & 0 \end{pmatrix}$$

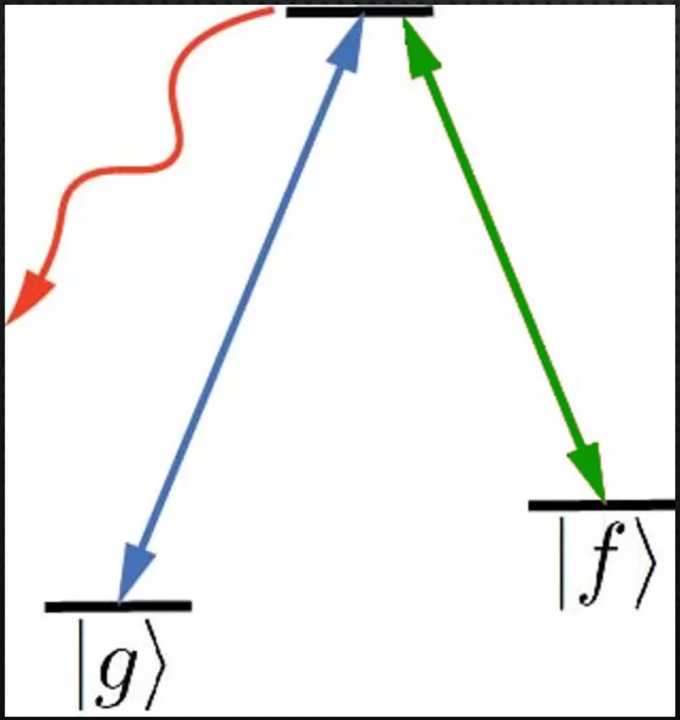
$$\frac{\Omega_2}{\sqrt{\Omega_1^2 + \Omega_2^2}}\,|f\rangle - \frac{\Omega_1}{\sqrt{\Omega_1^2 + \Omega_2^2}}\,|g\rangle$$

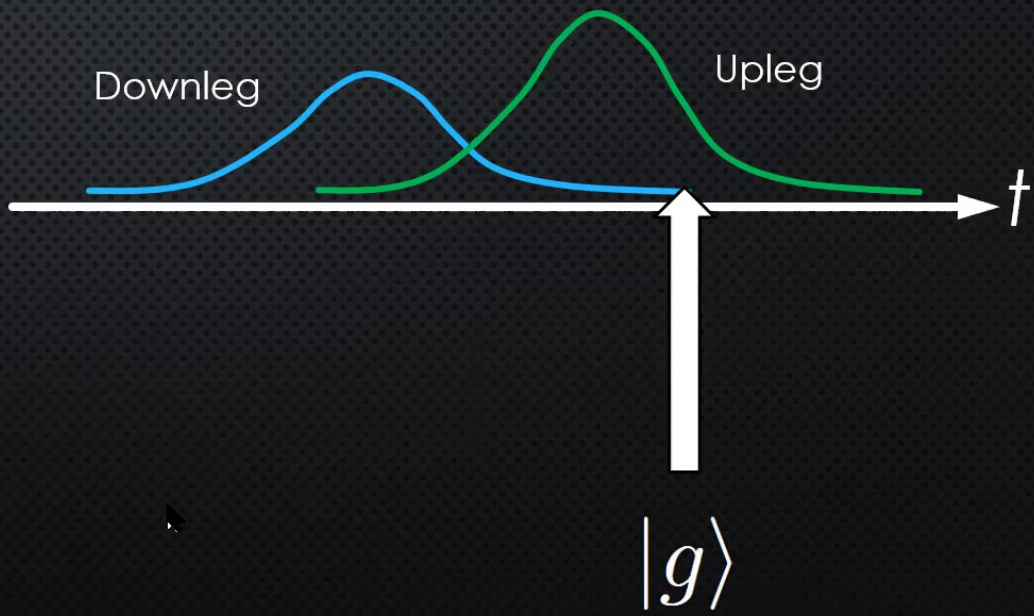

TWO-PHOTON TRANSFER
Alan Jamison
$|g\rangle$
$|f\rangle$
EIT from NaLi triplet ground state
Total atom number (arb)
Upleg detuning (MHz)
−15
−10
−5
0
5
10


STIRAP
Alan Jamison
$|g\rangle$
$|f\rangle$
Downleg
Upleg
t
$|f\rangle$

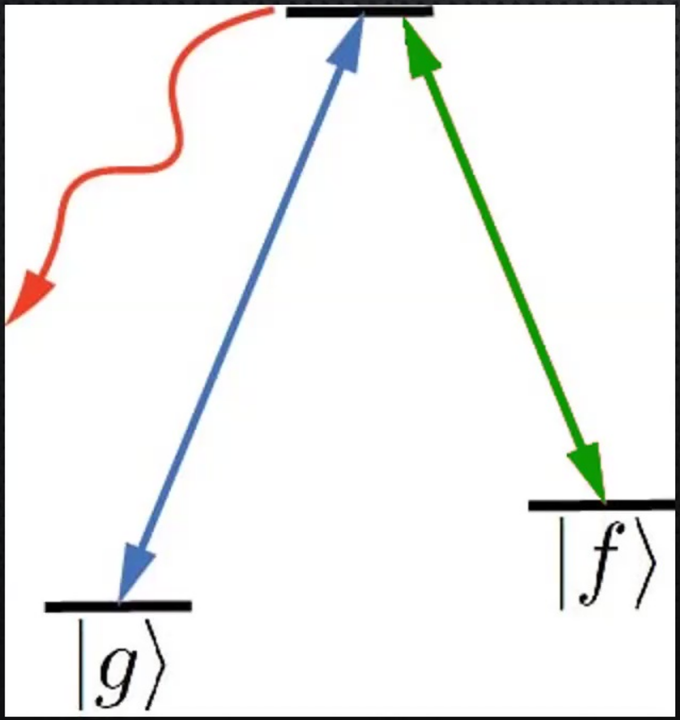

STIRAP
Alan Jamison
Downleg
Upleg
t
$\frac{|f\rangle - |g\rangle}{\sqrt{2}}$
$|g\rangle$
$|f\rangle$

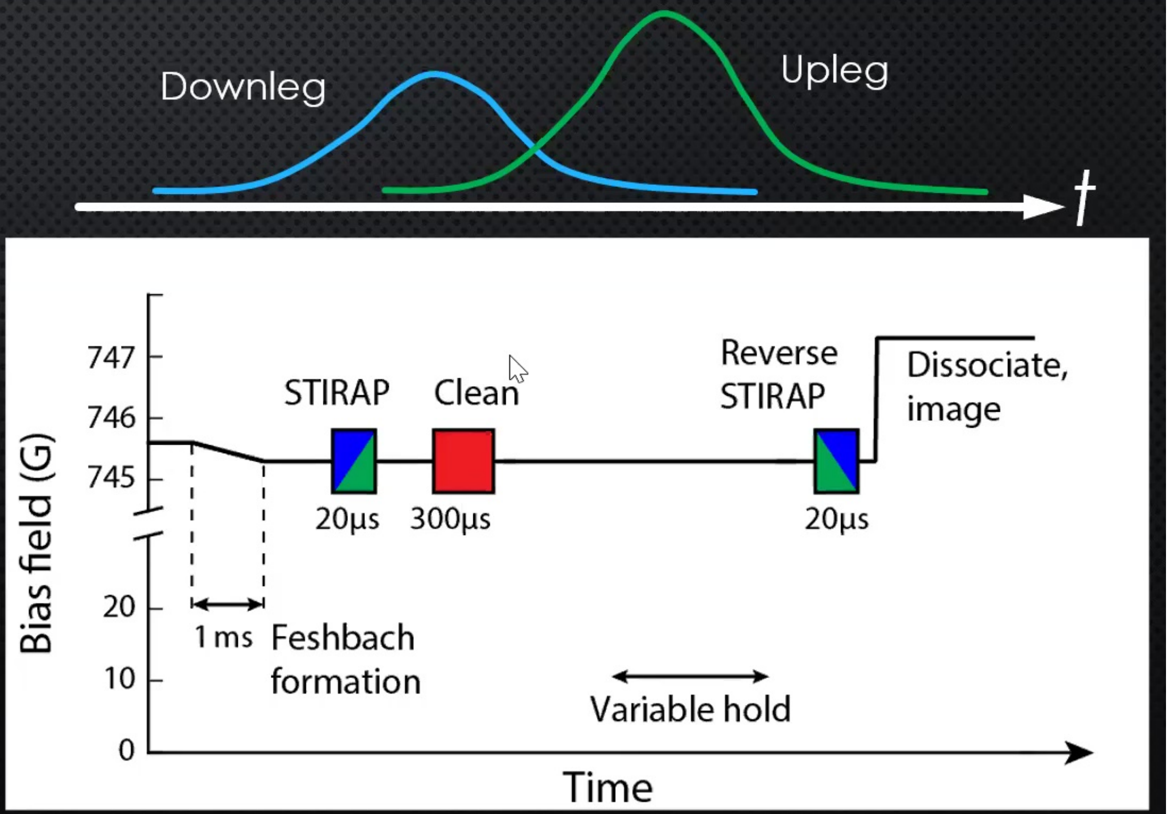
STIRAP



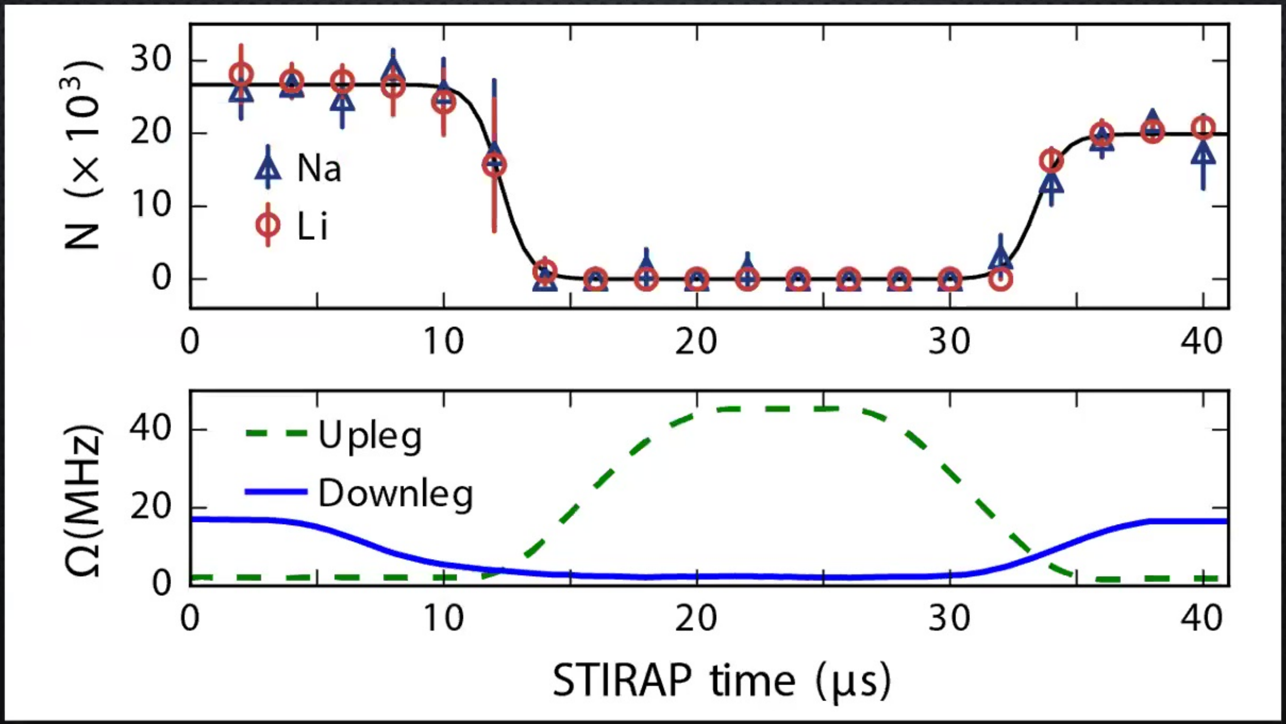


SEEING GROUND STATE MOLECULES





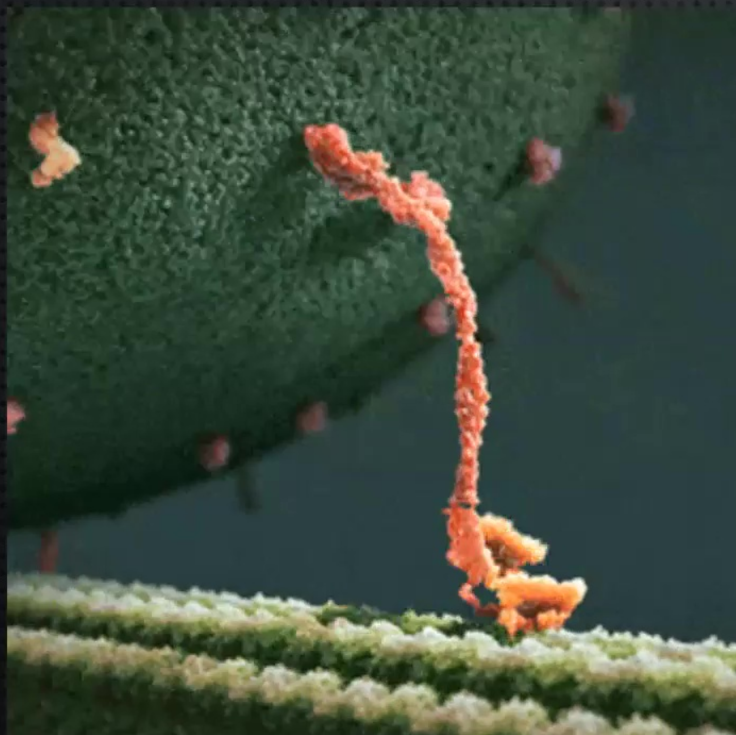
SEEING GROUND STATE MOLECULES

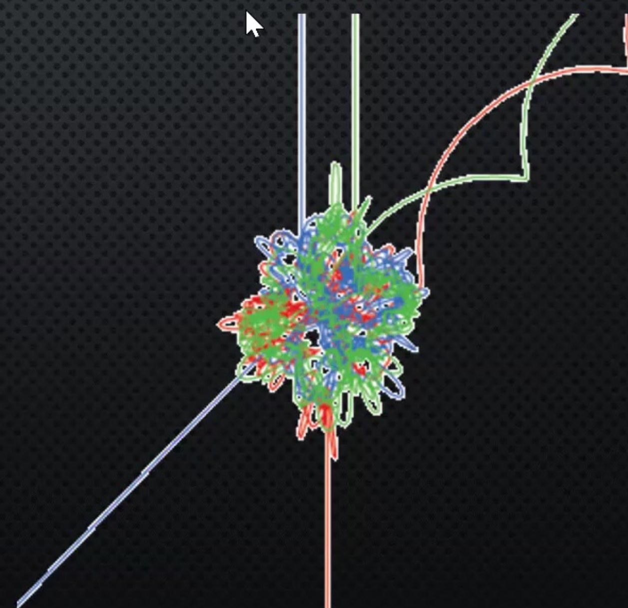


ULTRACOLD CHEMISTRY

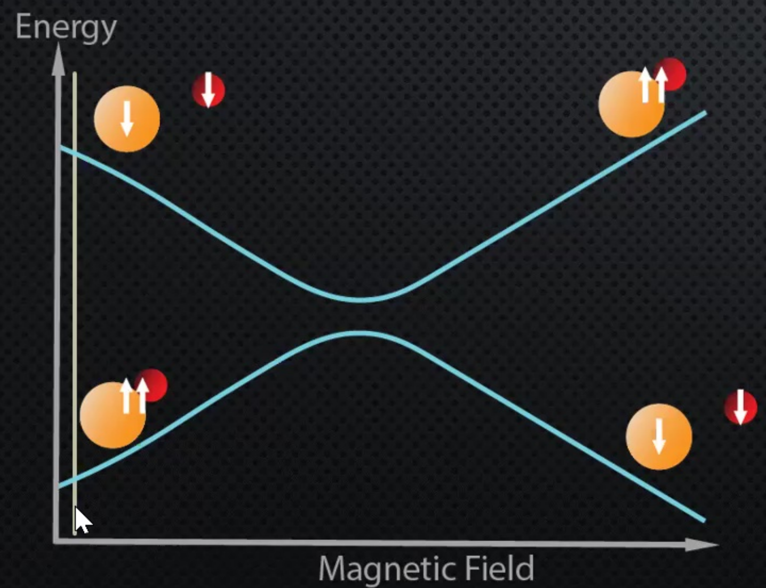
CHEMISTRY = SCATTERING

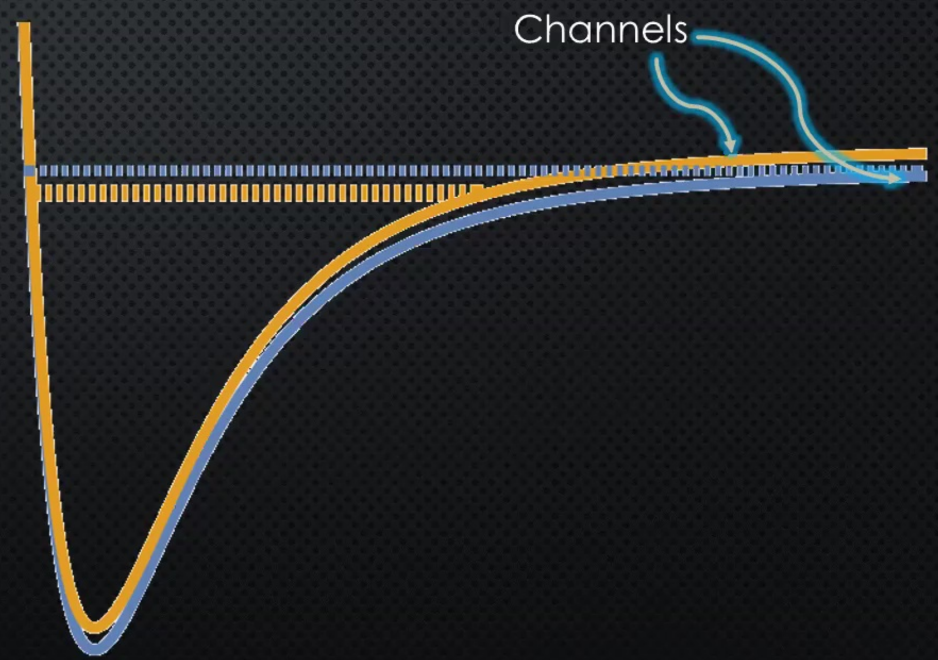
CHEMISTRY SCATTERING



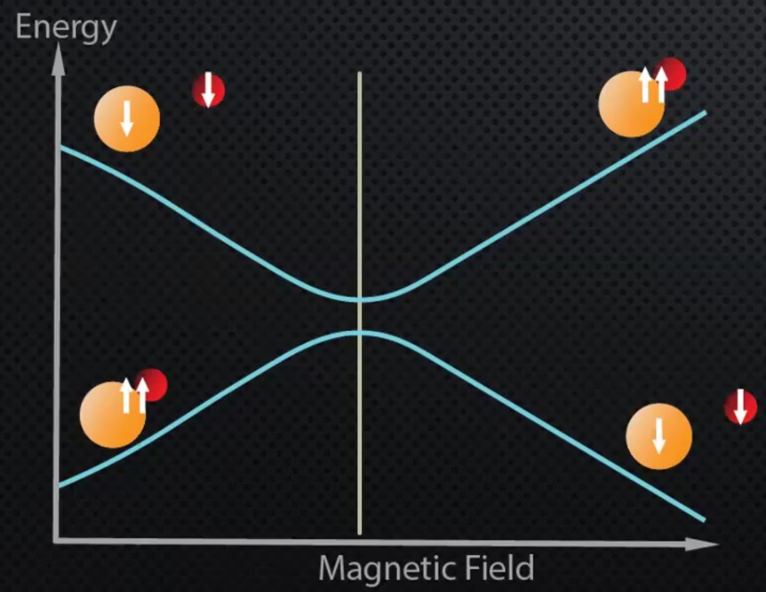


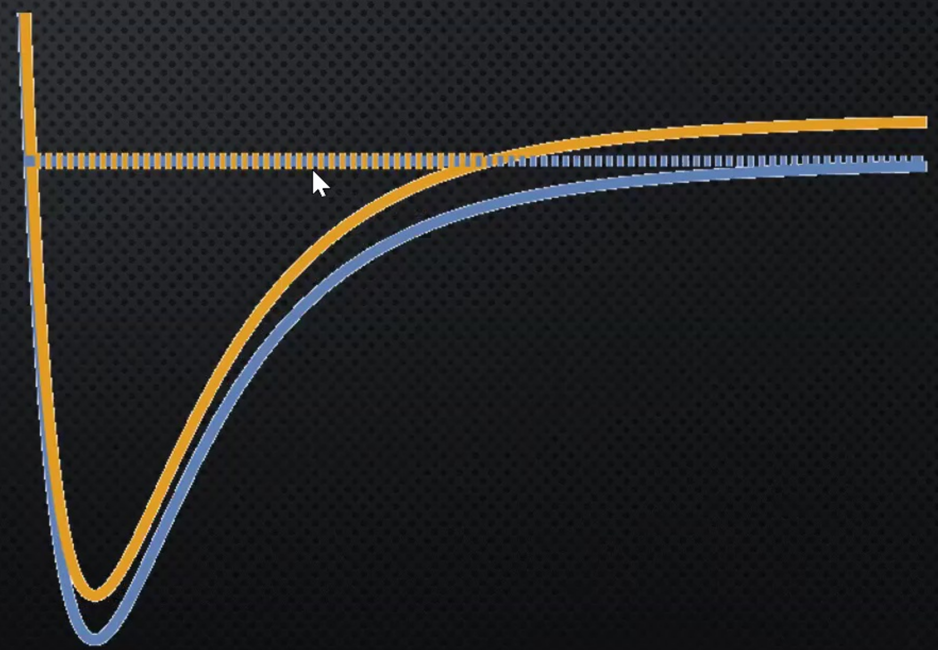
FESHBACH RESONANCE



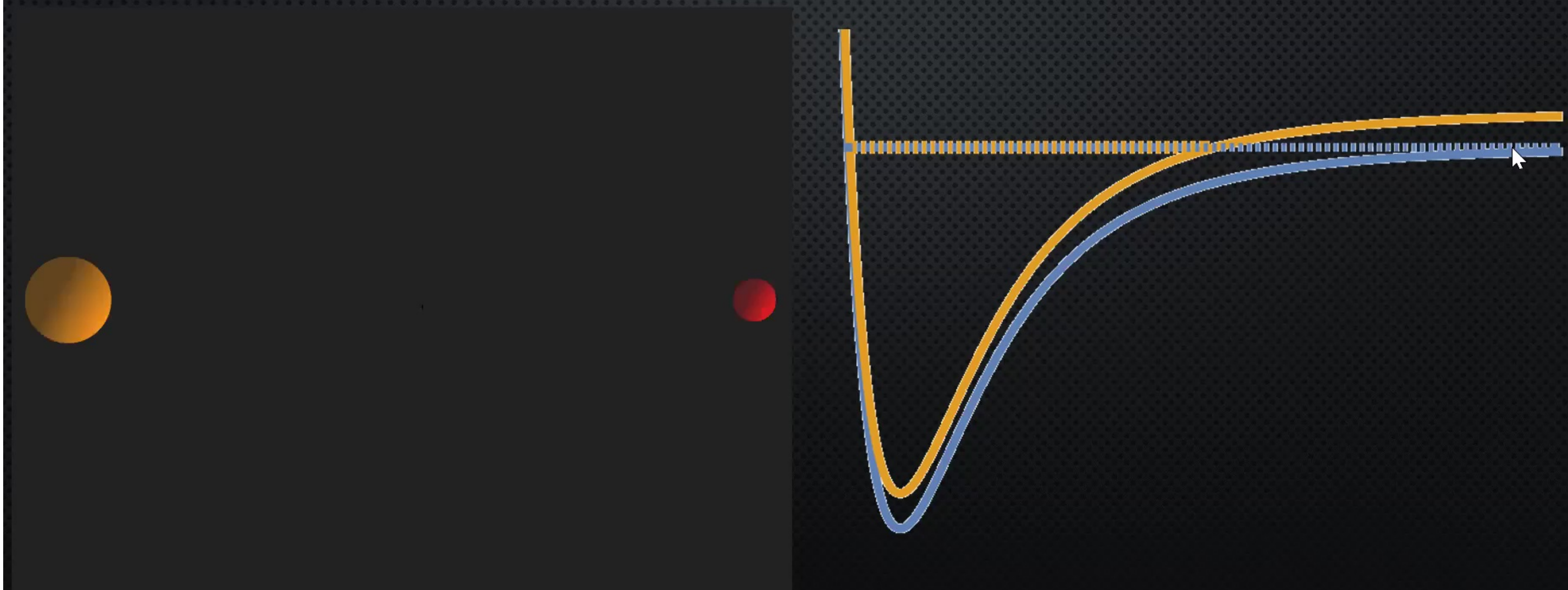


FESHBACH RESONANCE





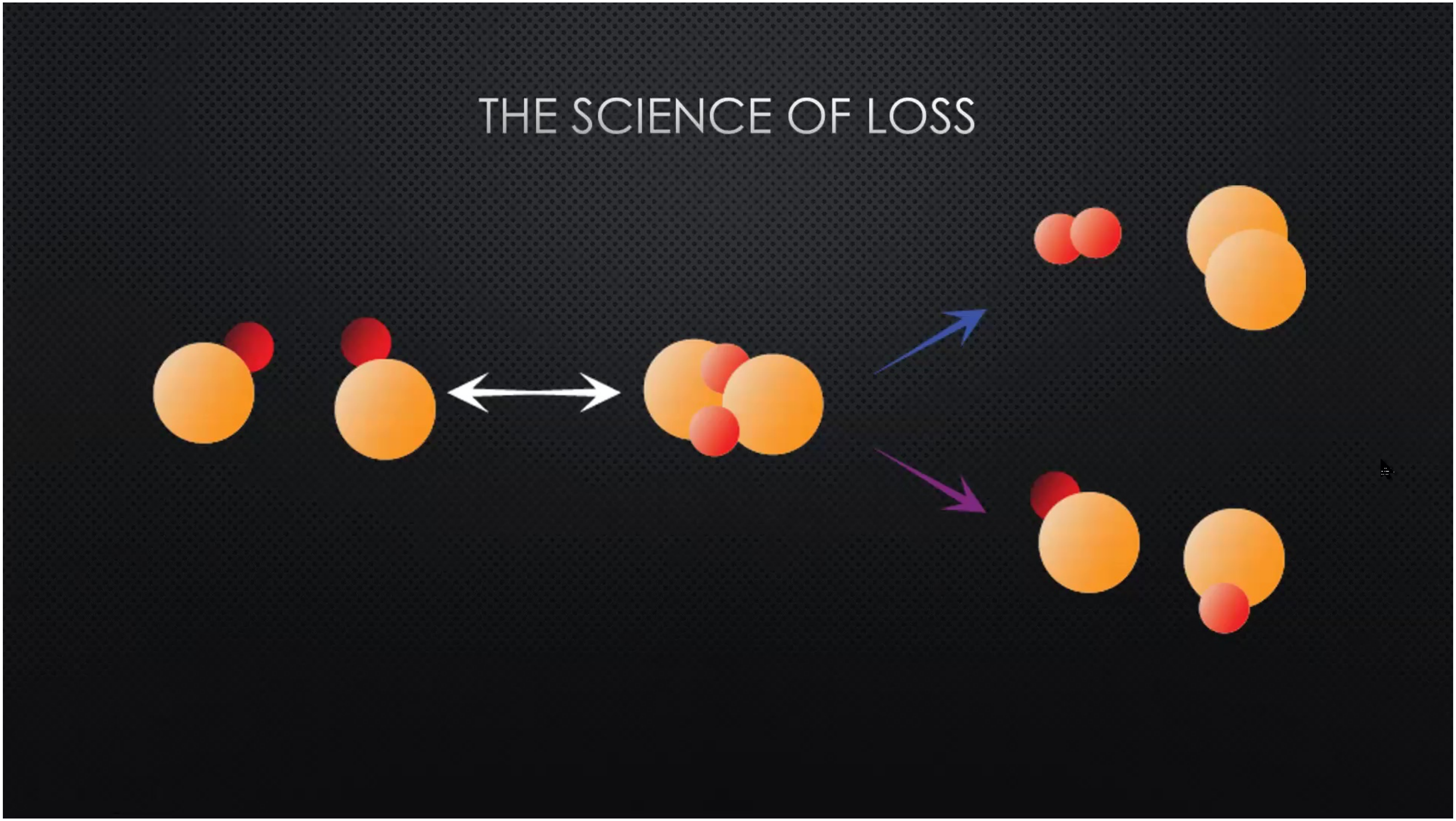
RESONANT SCATTERING

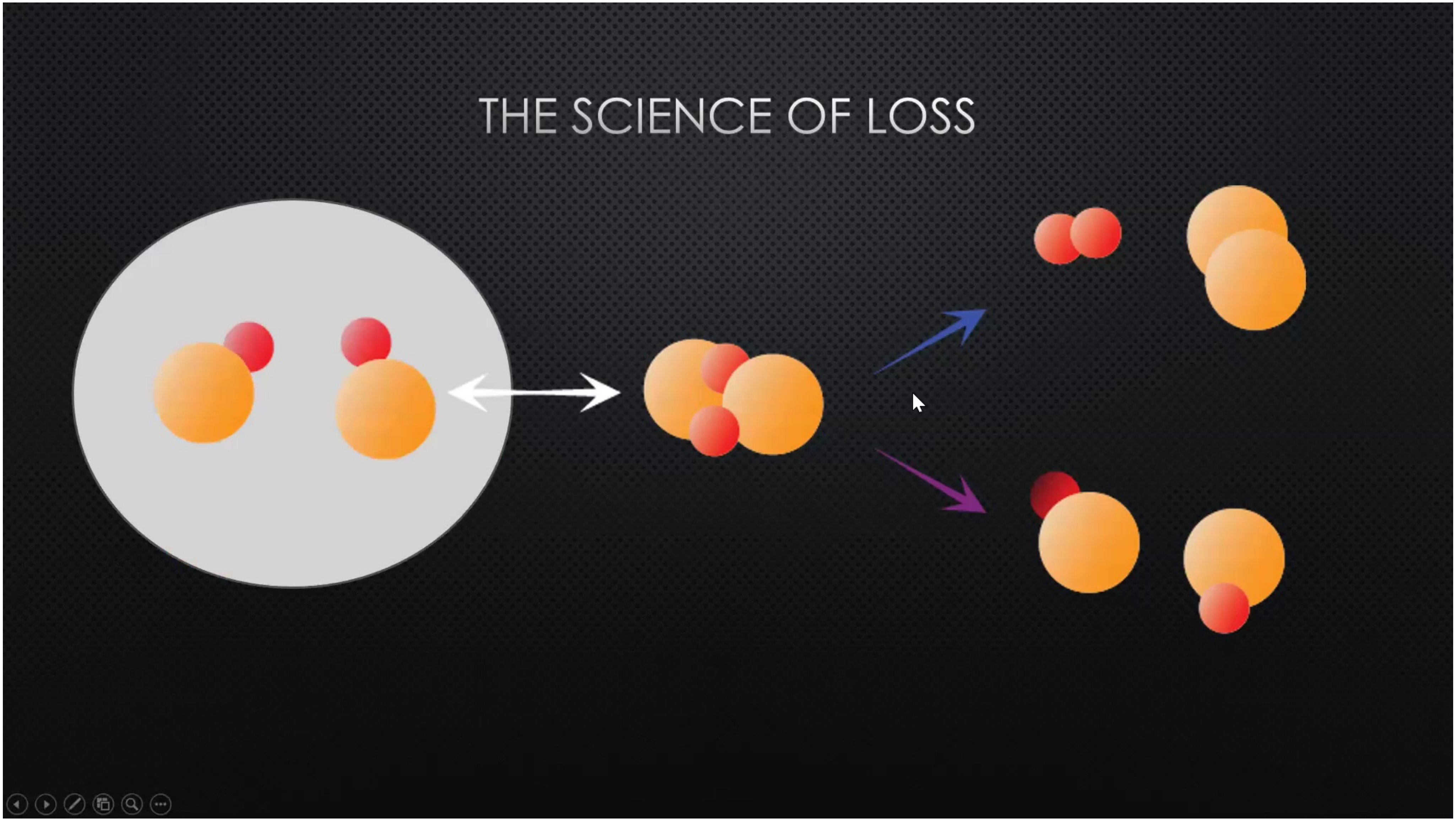


THE THREE-BODY PROBLEM

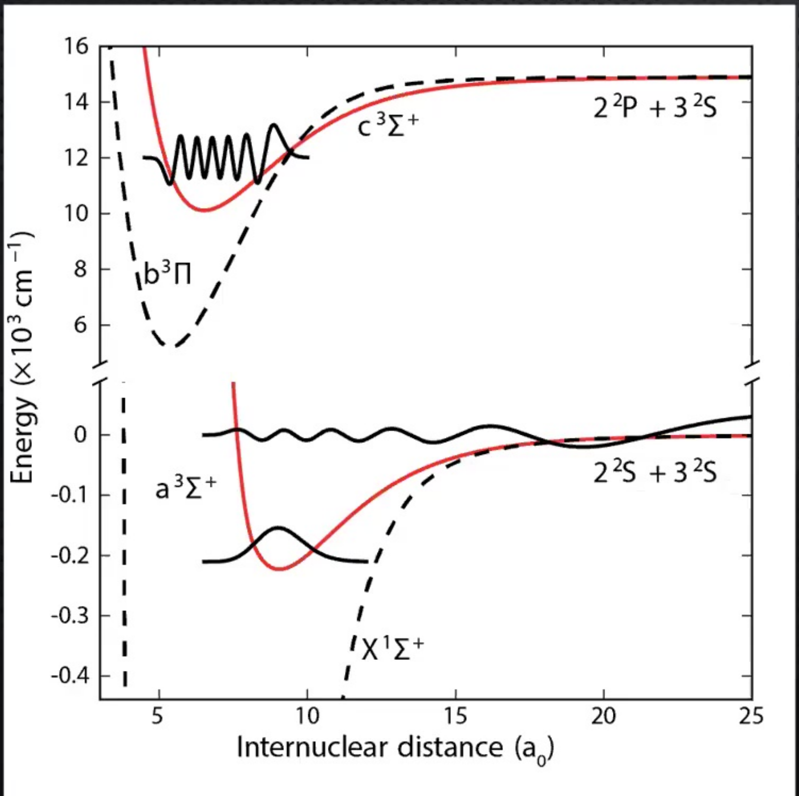
T = 1000K T = 100K T = 10K T = 1K

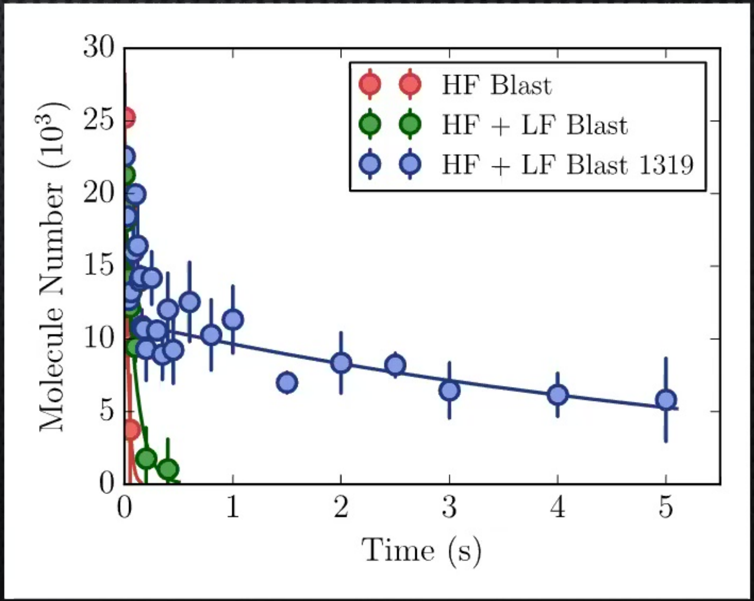
From J.F.E. Croft and J. Bohn
PRA 89, 012714 (2014)

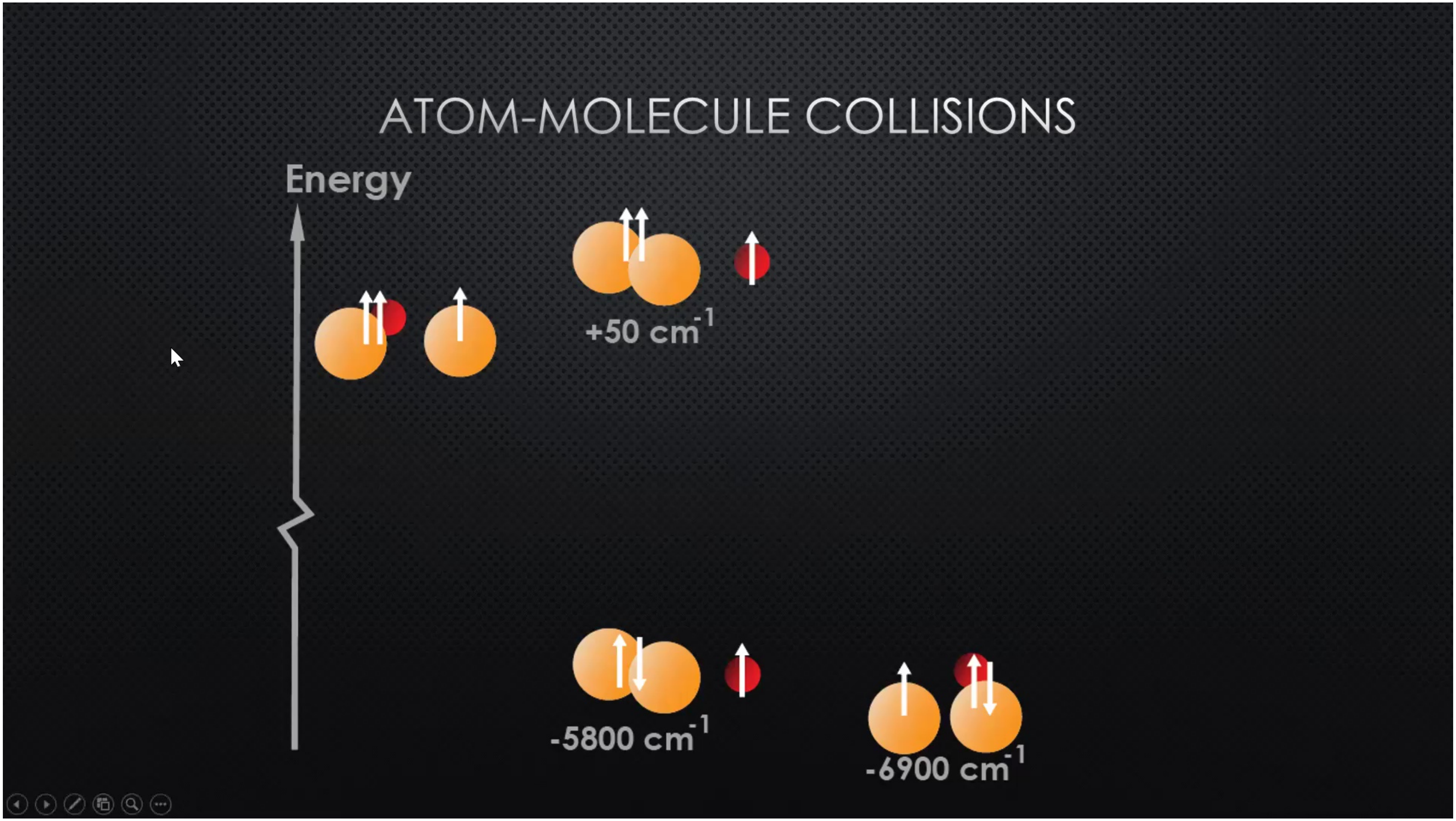

THE SCIENCE OF LOSS

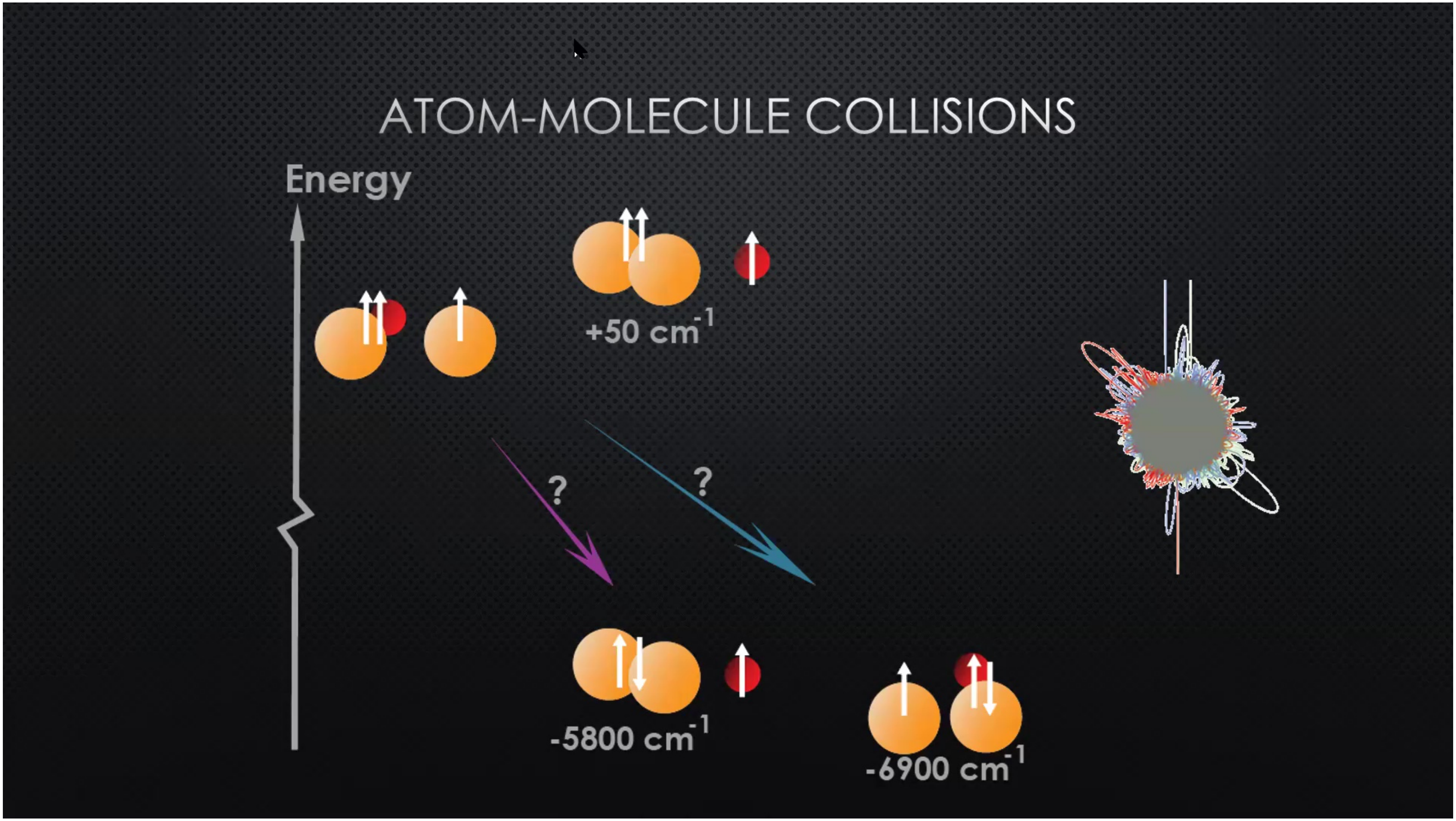

THE SCIENCE OF LOSS

LONG-LIVED NALI TRIPLET GROUND STATE MOLECULES

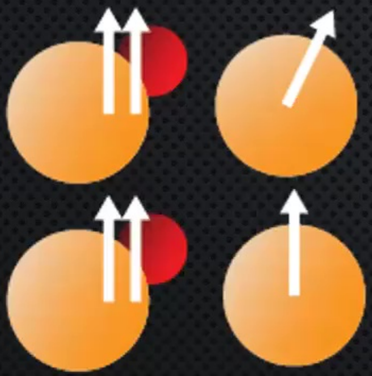


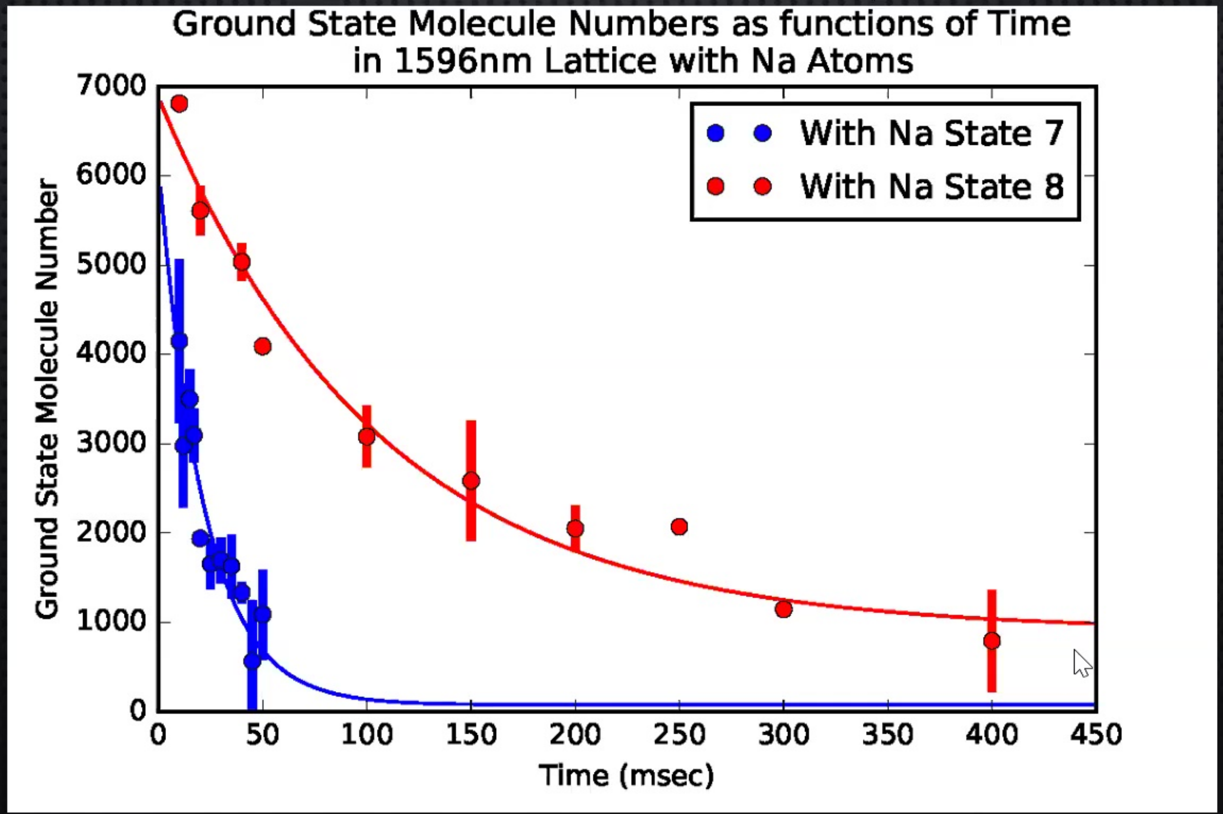


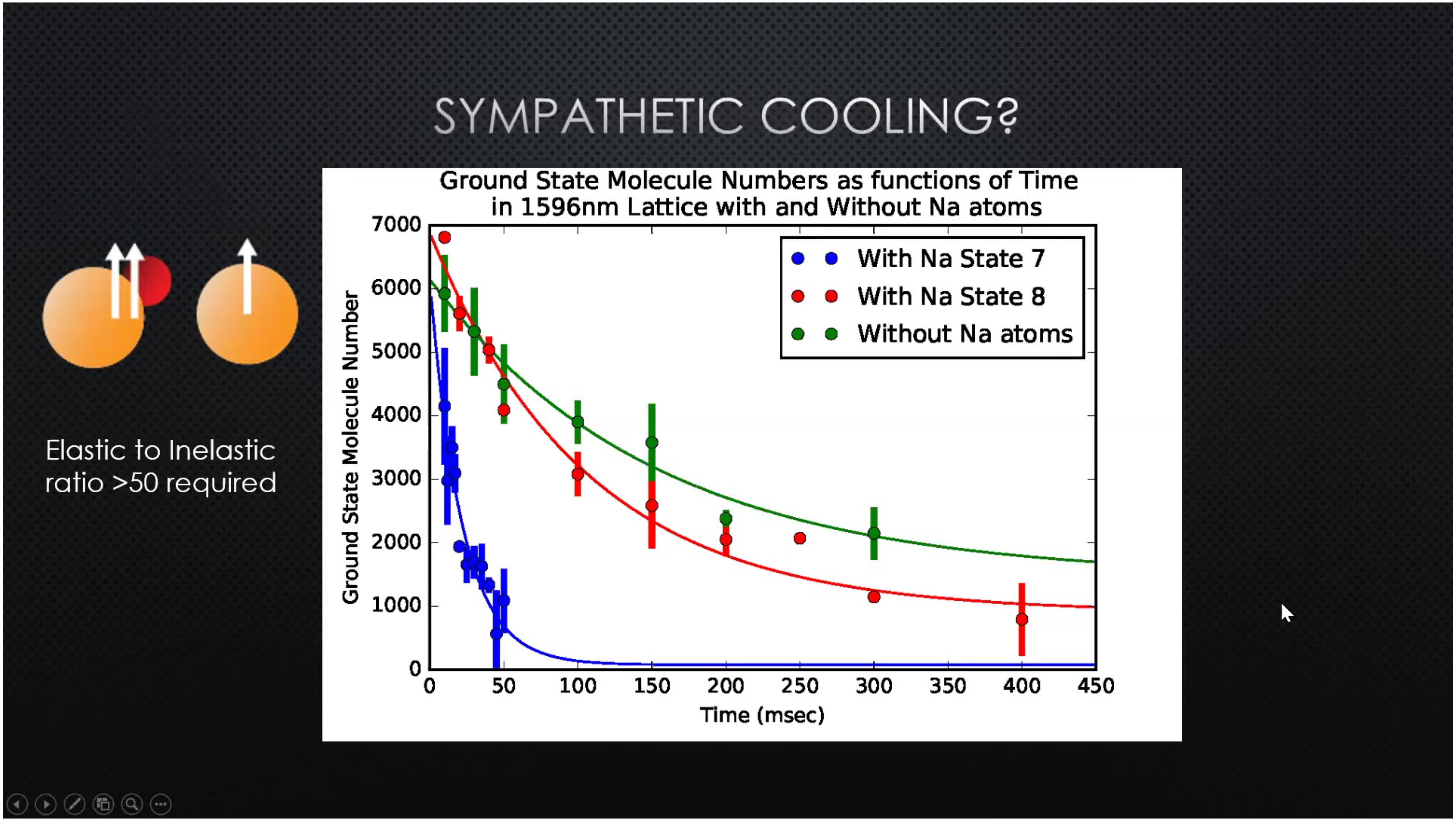

ATOM-MOLECULE COLLISIONS
Energy
+50 cm-1
-5800 cm-1
-6900 cm-1


ATOM-MOLECULE COLLISIONS
Energy
+50 cm-1
?
?
-5800 cm-1
-6900 cm-1

ATOM-MOLECULE COLLISIONS





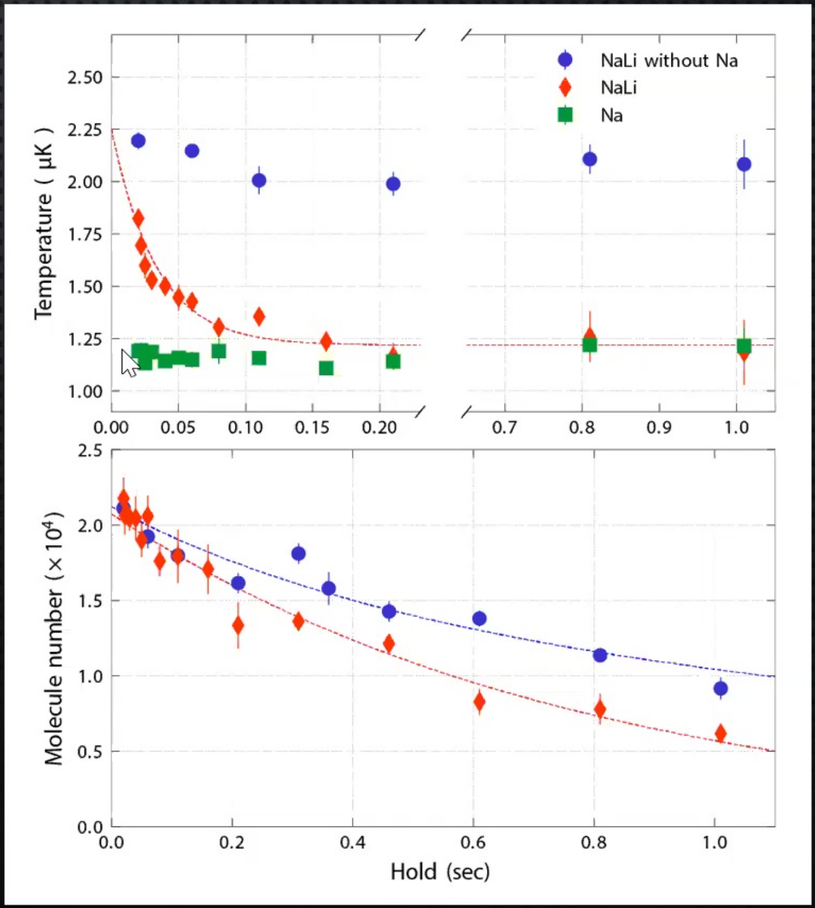

SYMPATHETIC COOLING?
Elastic to Inelastic ratio >50 required
Ground State Molecule Numbers as functions of Time in 1596nm Lattice with and Without Na atoms
Ground State Molecule Number
Time (msec)
With Na State 7
With Na State 8
Without Na atoms
0
1000
2000
3000
4000
5000
6000
7000
0
50
100
150
200
250
300
350
400
450

SYMPATHETIC COOLING

- COOLING TO DEGENERACY REQUIRES COLLISIONS
- COLLISIONAL COOLING OF MOLECULES NOT PREVIOUSLY SEEN BELOW 50MK
- ELASTIC TO INELASTIC RATIO >50

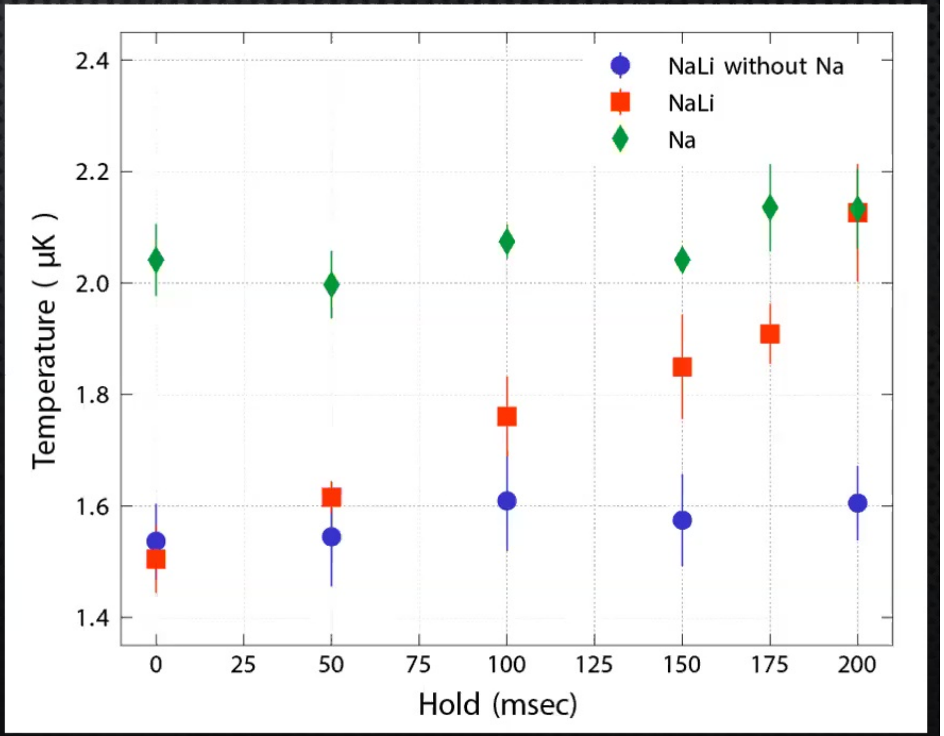
SYMPATHETIC COOLING

- COOLING TO DEGENERACY REQUIRES COLLISIONS
- COLLISIONAL COOLING OF MOLECULES NOT PREVIOUSLY SEEN BELOW 50MK
- ELASTIC TO INELASTIC RATIO … 300 !



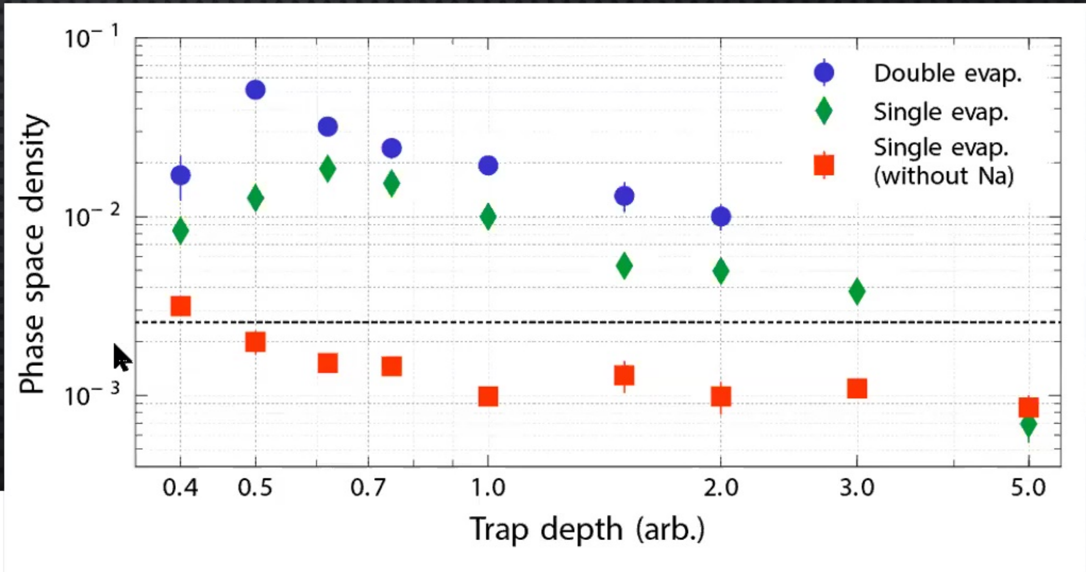
IS IT REAL?

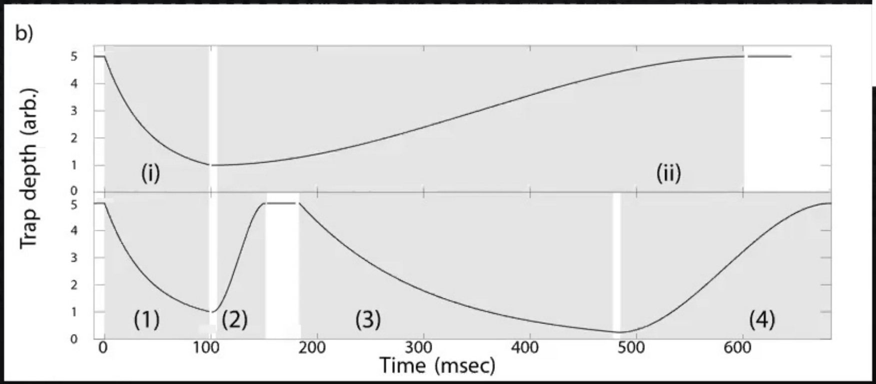
- ✓ SYMPATHETIC COOLING
- SYMPATHETIC … HEATING?
  - MODULATE TRAP AT NA FREQUENCY
  - SELECTIVELY HEAT NA, MOLECULES FOLLOW LATER



IT'S REAL

- ✓ Sympathetic cooling
- ✓ Sympathetic heating
- ✓ PSD Increase 20x

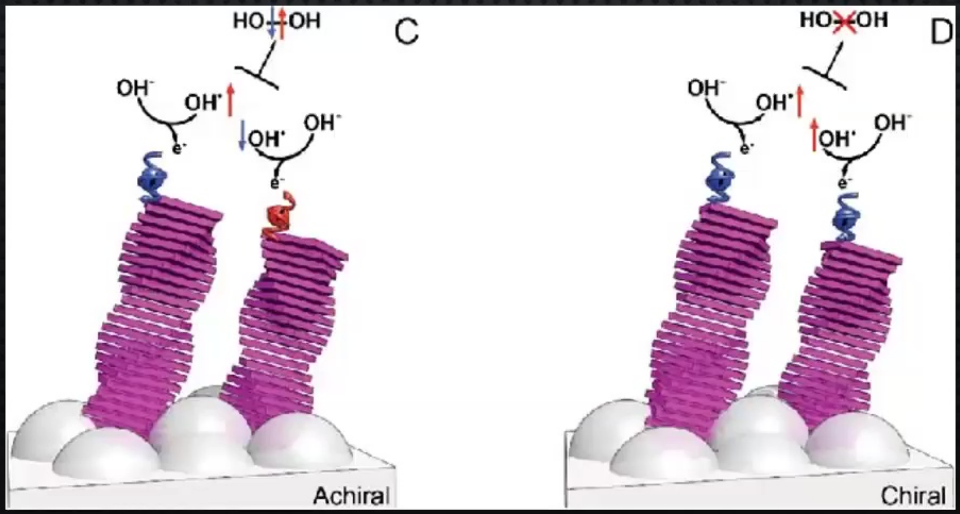




More details:
Collisional cooling of ultracold molecules
H. Son, J.J. Park, W. Ketterle, and **A.O. Jamison**
Nature **580**, 197 (2020)

QUANTUM CHEMISTRY

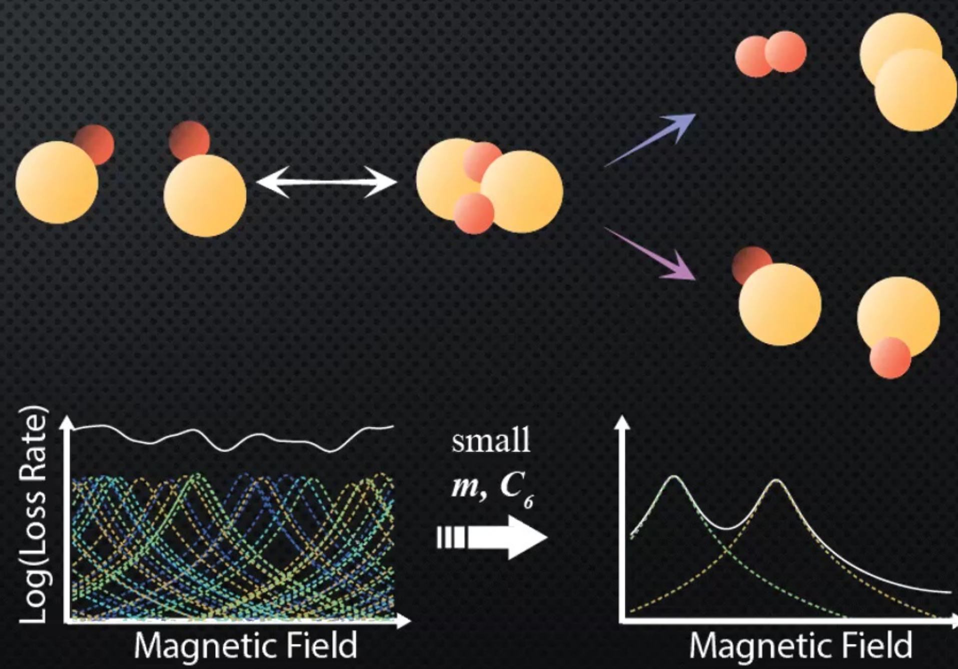
- Collision Complex Dynamics
  - Spin-Controlled Chemistry



from Mtangi et al., J. Am. Chem. Soc. 139, 2794 (2017)

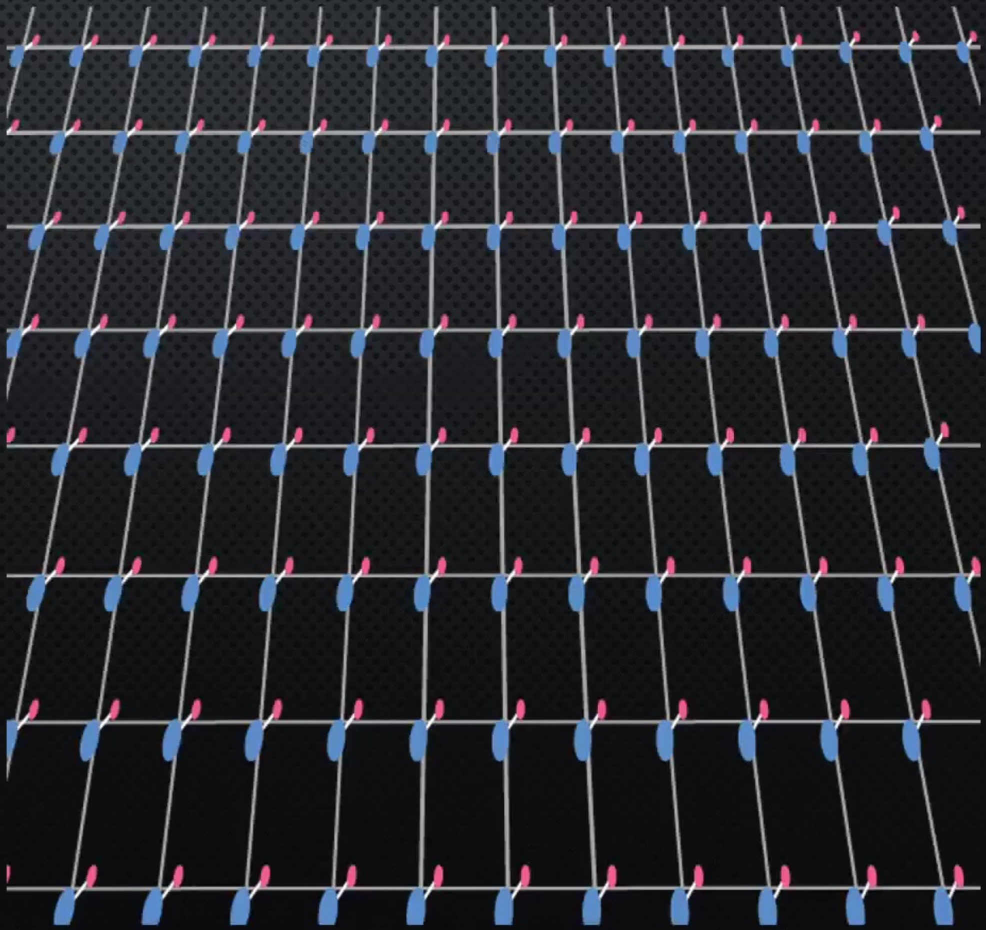
QUANTUM CHEMISTRY

- Collision Complex Dynamics
  - Spin-Controlled Chemistry
  - Atom/Molecule Feshbach Resonances?



MOLECULAR COMPUTERS

QUANTUM COMPUTING



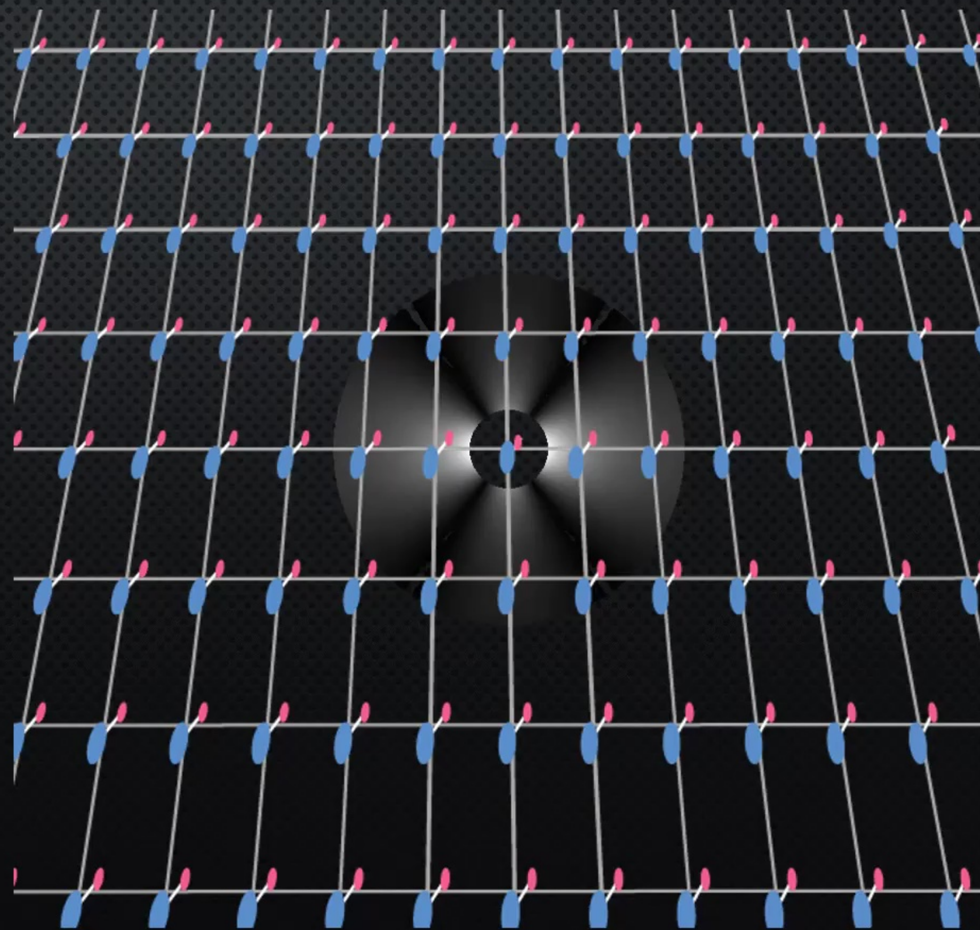
Figures of Merit

Coherence time: 10s
Number of qubits: 10^3-10^4
Single qubit gate time: 1-10μs
Two-qubit gate time: ??

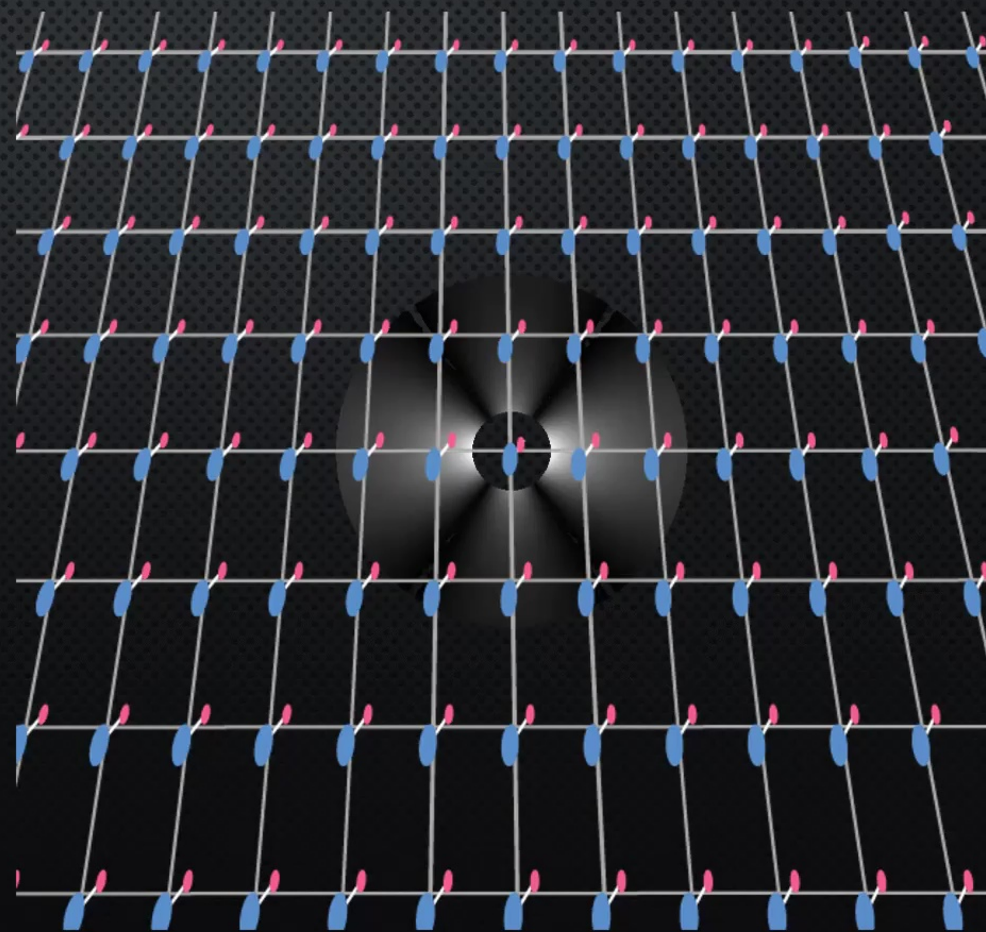
QUANTUM COMPUTING

Figures of Merit

Coherence time: 10s
Number of qubits: 10^3-10^4
Single qubit gate time: 1-10μs
Two-qubit gate time: 100μs

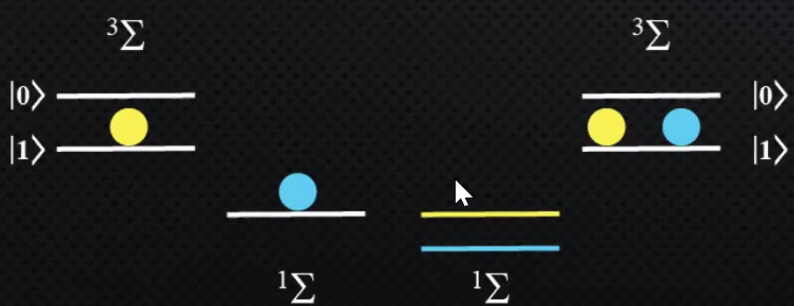


QUANTUM COMPUTING



Figures of Merit

Coherence time: 10s
Number of qubits: 10^3-10^4
Single qubit gate time: 1-10μs
Two-qubit gate time: 100μs



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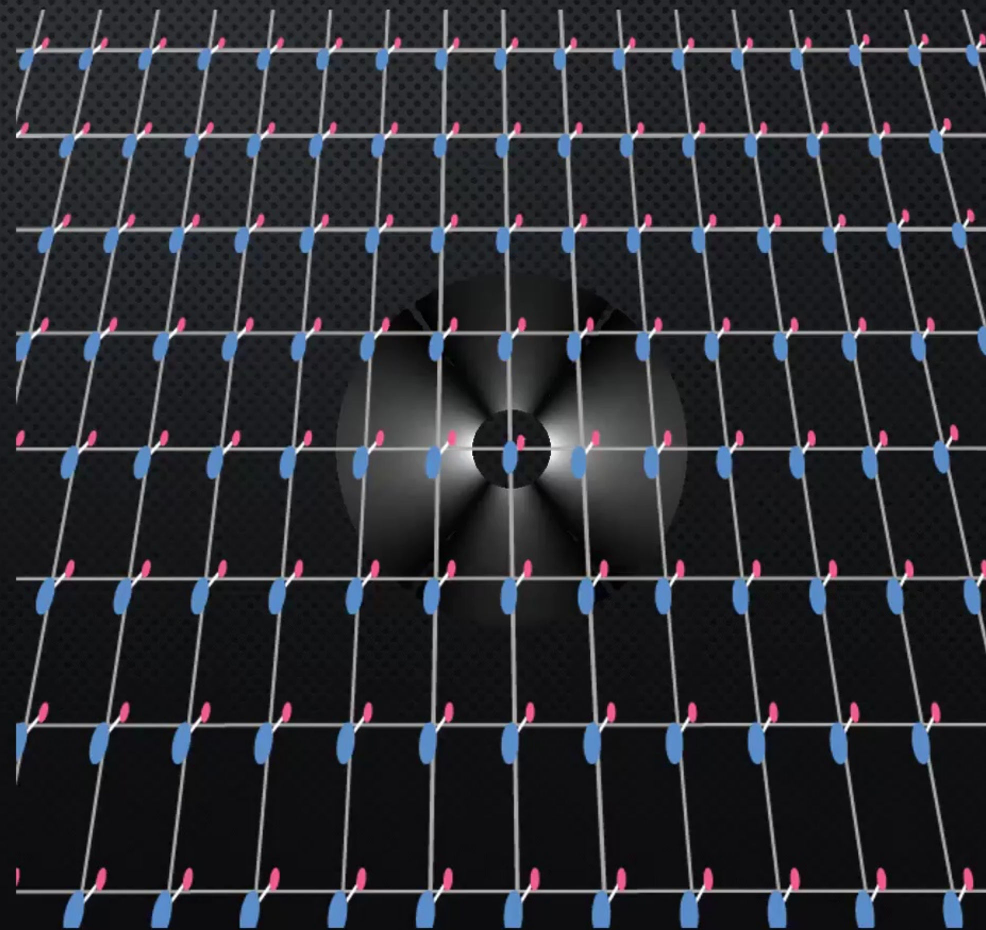

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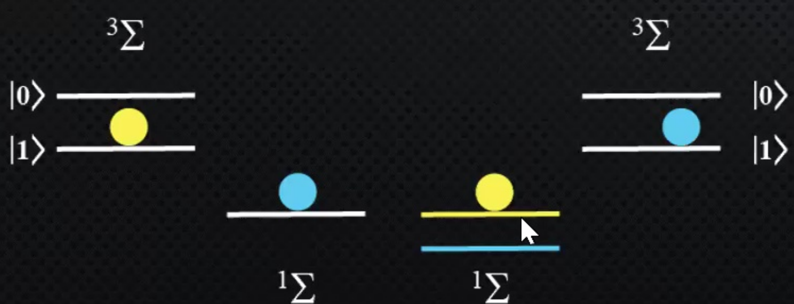

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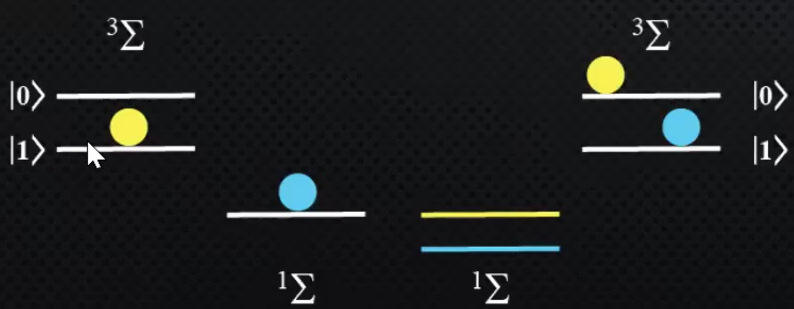

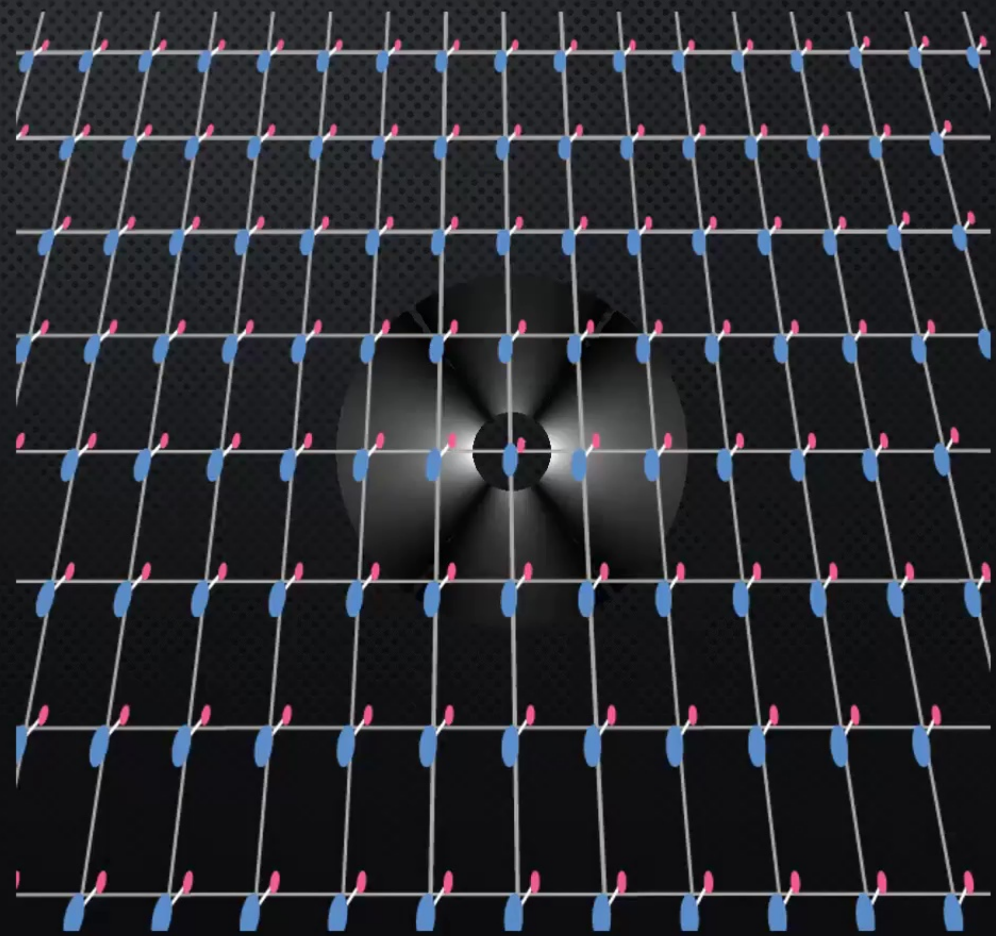

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Figures of Merit

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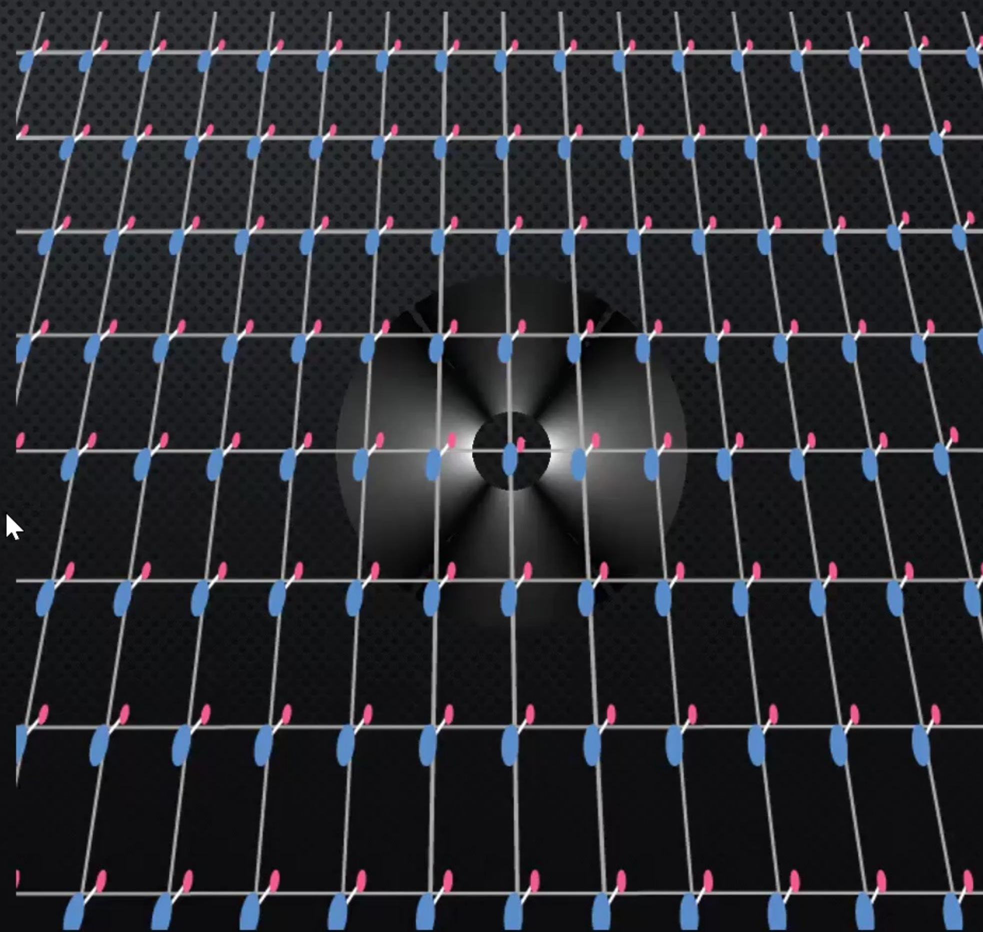

QUANTUM COMPUTING

<u>Figures of Merit</u>

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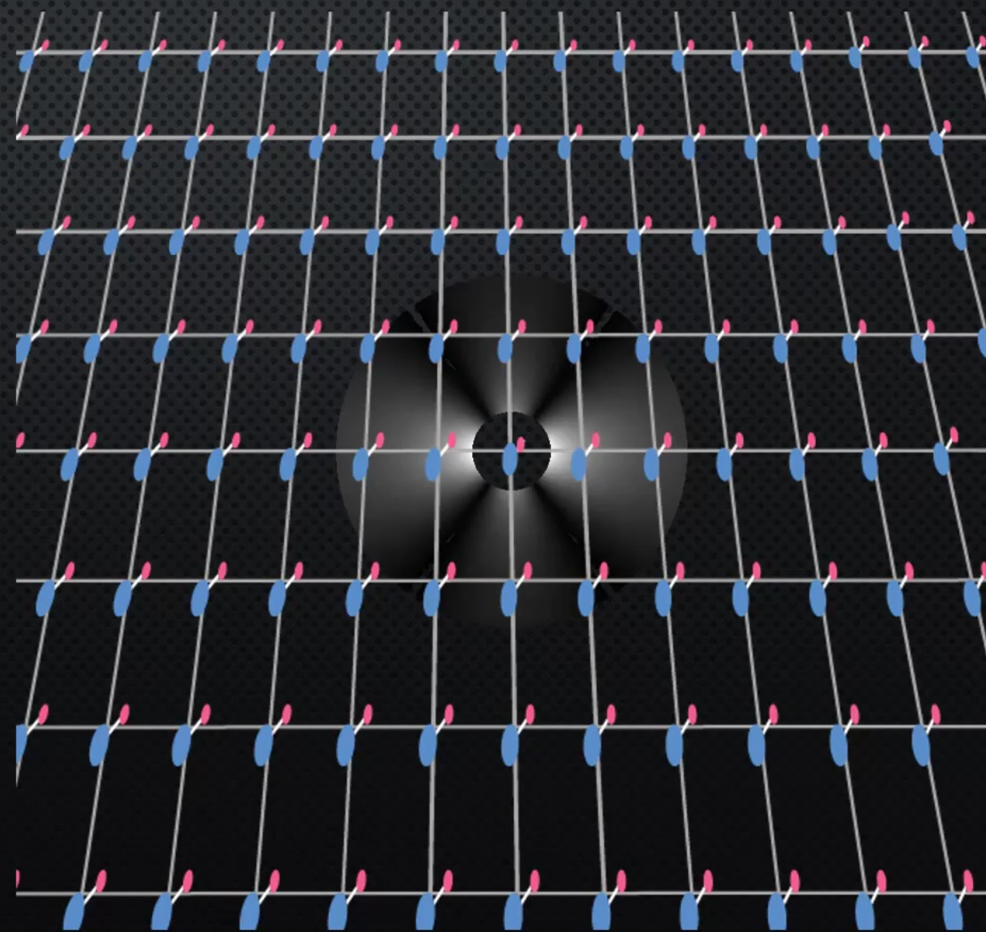

QUANTUM COMPUTING @ WATERLOO

- New group at University of Waterloo Physics+IQC
- Looking for Post docs and Grad Students!

THE TEAM

Hyungmok
Son

Juliana
Park

Wolfgang
Ketterle