Collective Radiation of Coupled Atomic Dipoles and the Precise Measurement of Time

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Projects during PhD

- Study of Superradiance (OpEx 2012)
- Protected Subspace Method (PRL 2013)
- Superradiant Laser (OpEx 2014)
- Protected Subspace Method (PRA 2014)
- State Preparation (Sci. Rep. 2015)
- Optimized Clock Geometries (EPL 2016)
- Quantum Dot (PRB 2016)
- Quantum Dot pt. 2 (ongoing)
- Superradiance in optical fibers (ongoing)

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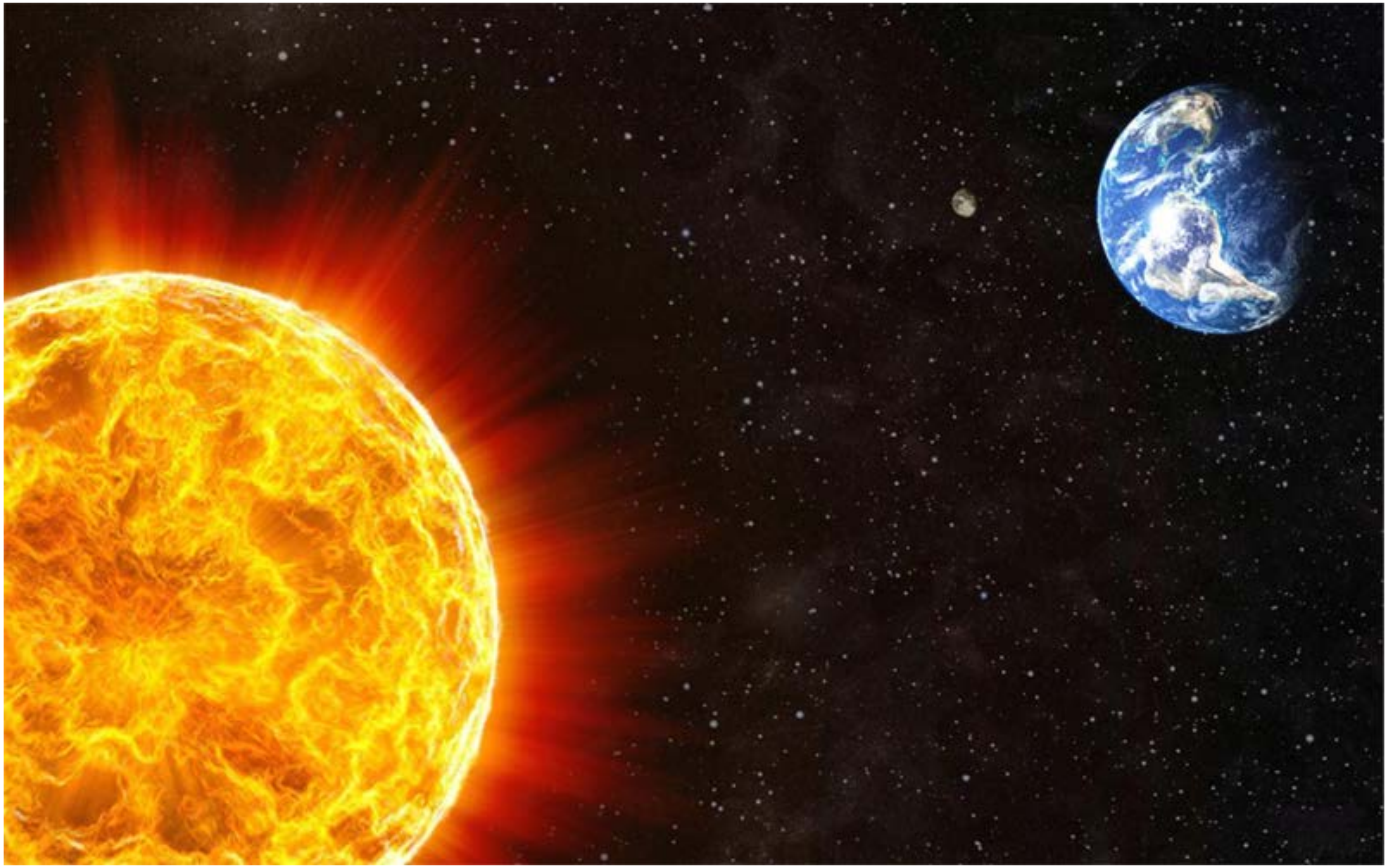
Outline

1. Atomic Clocks
2. Ramsey Procedure
3. Protected Subspace

1. Atomic Clocks

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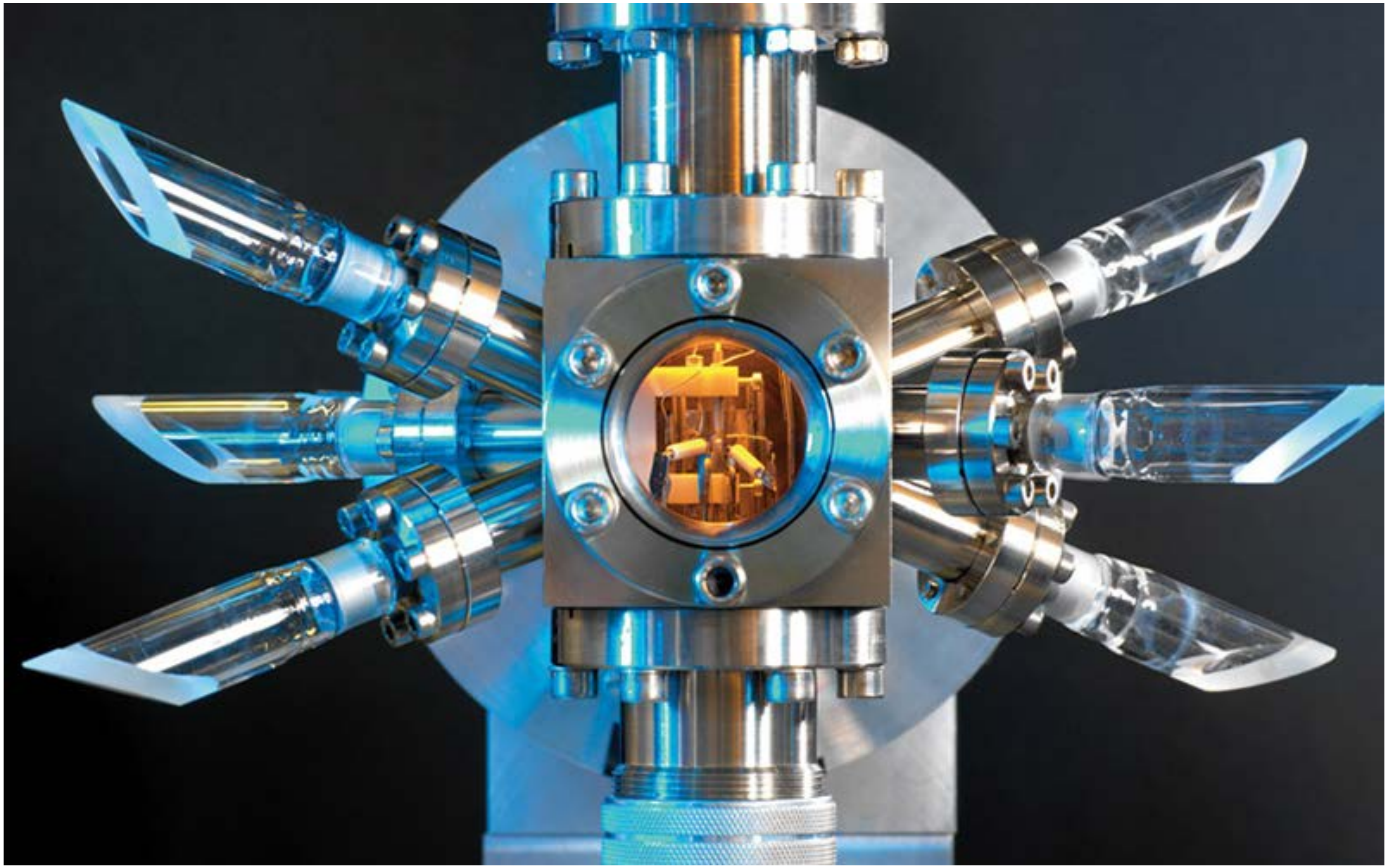
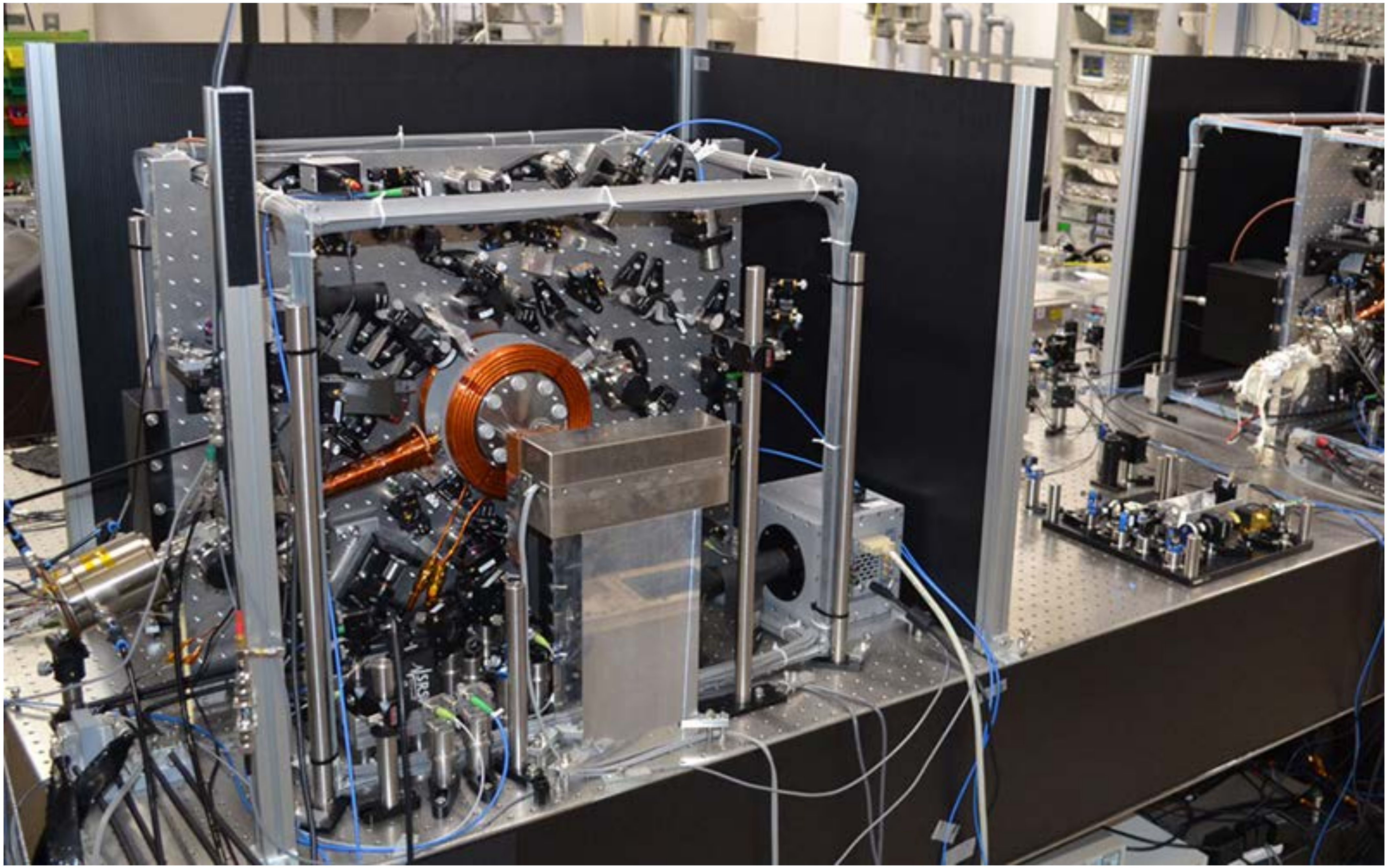
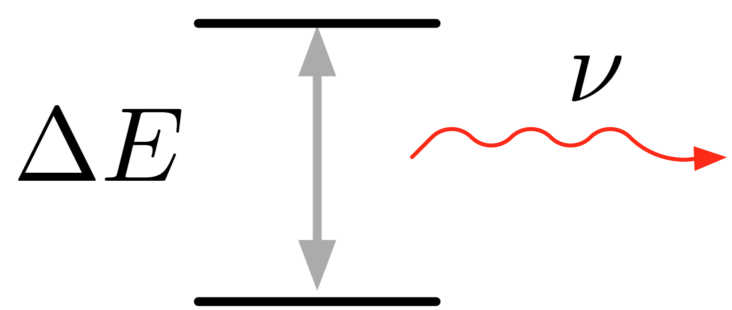




Atomic Clock

- Quantum physics: energies of electronic states are associated with frequencies

$$\Delta E = h\nu = \frac{h}{T}$$



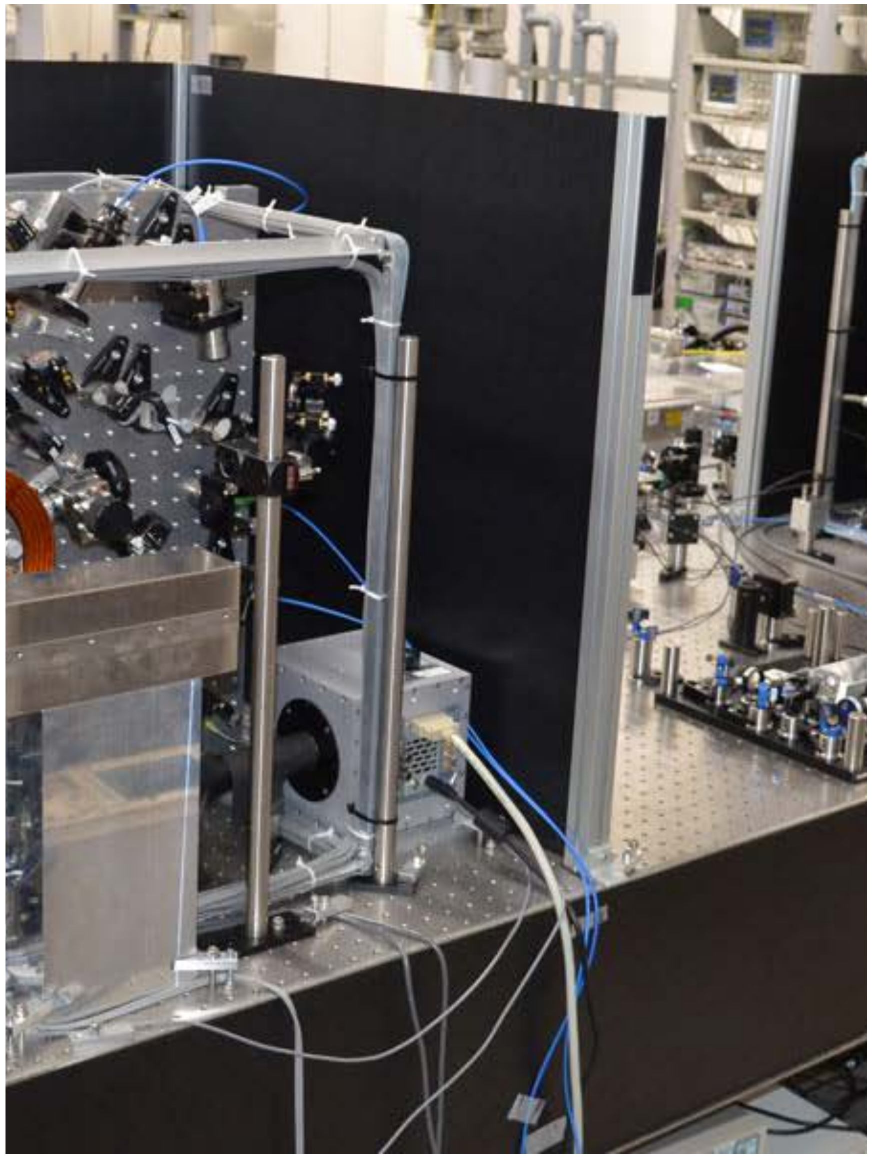
- Use the transition energy between two electronic levels as a time standard

Atomic Clock

Nowadays optical lattice atomic clocks

- Keep atoms trapped and isolated very long
- Minimizes collisions and shifts
- See gRT time difference at

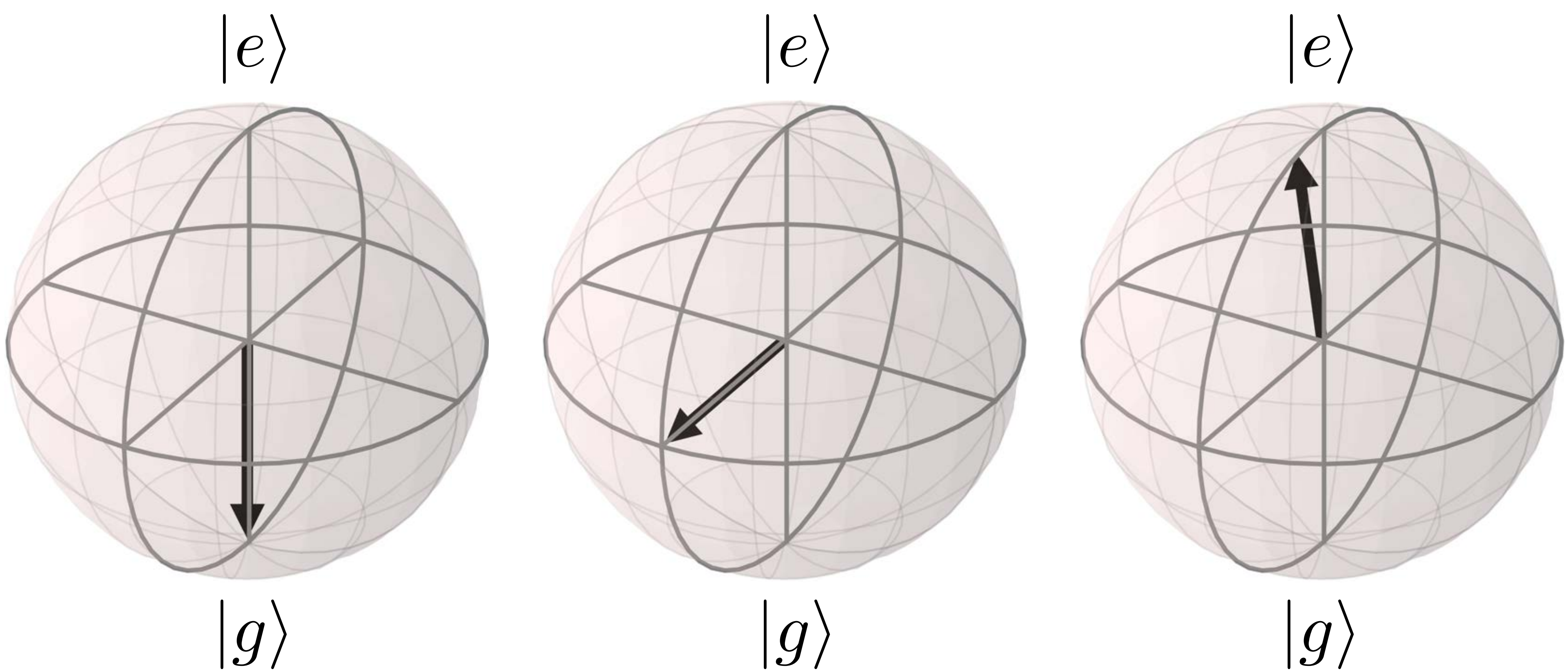
$$\Delta h = 1m$$

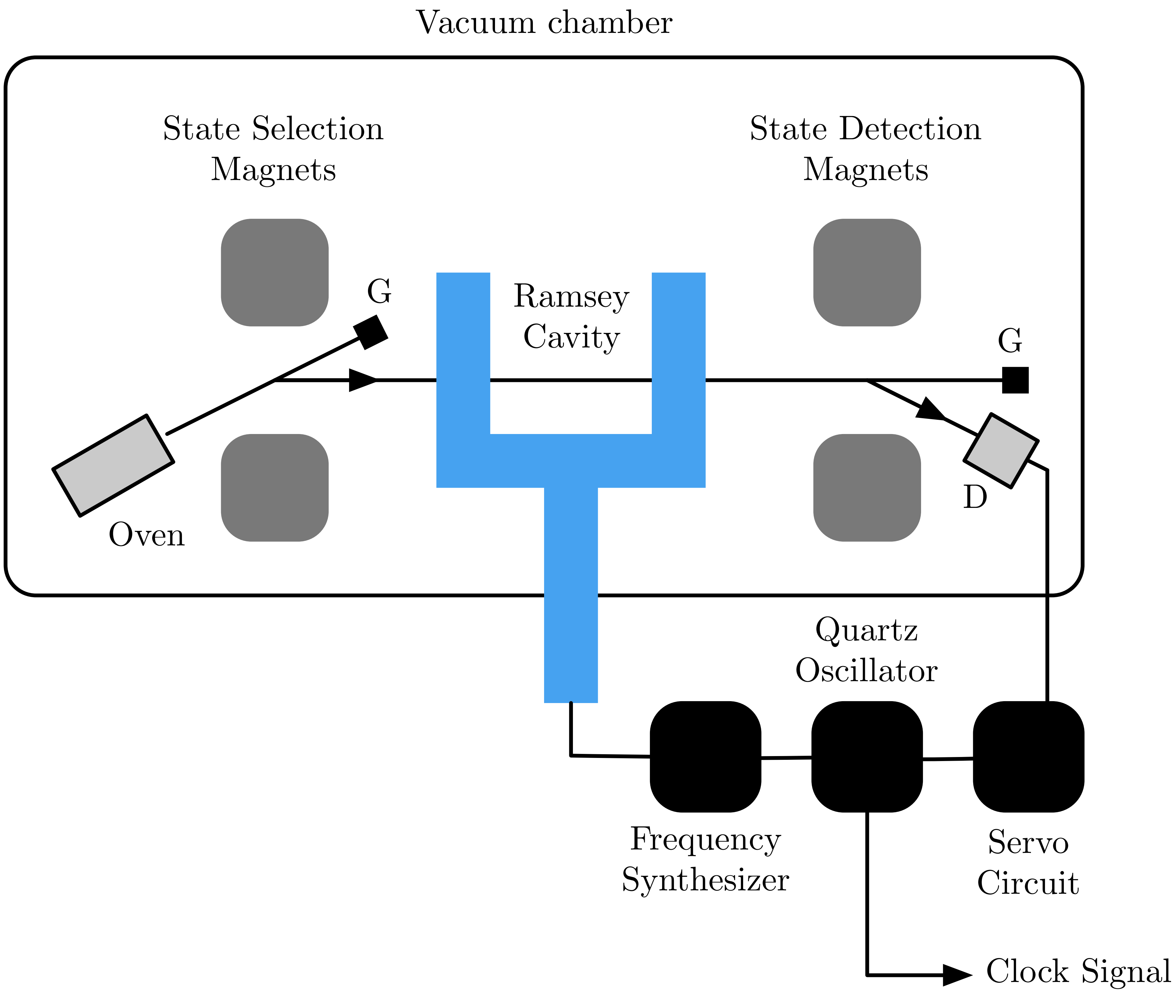


2. Ramsey Procedure

Ramsey Procedure

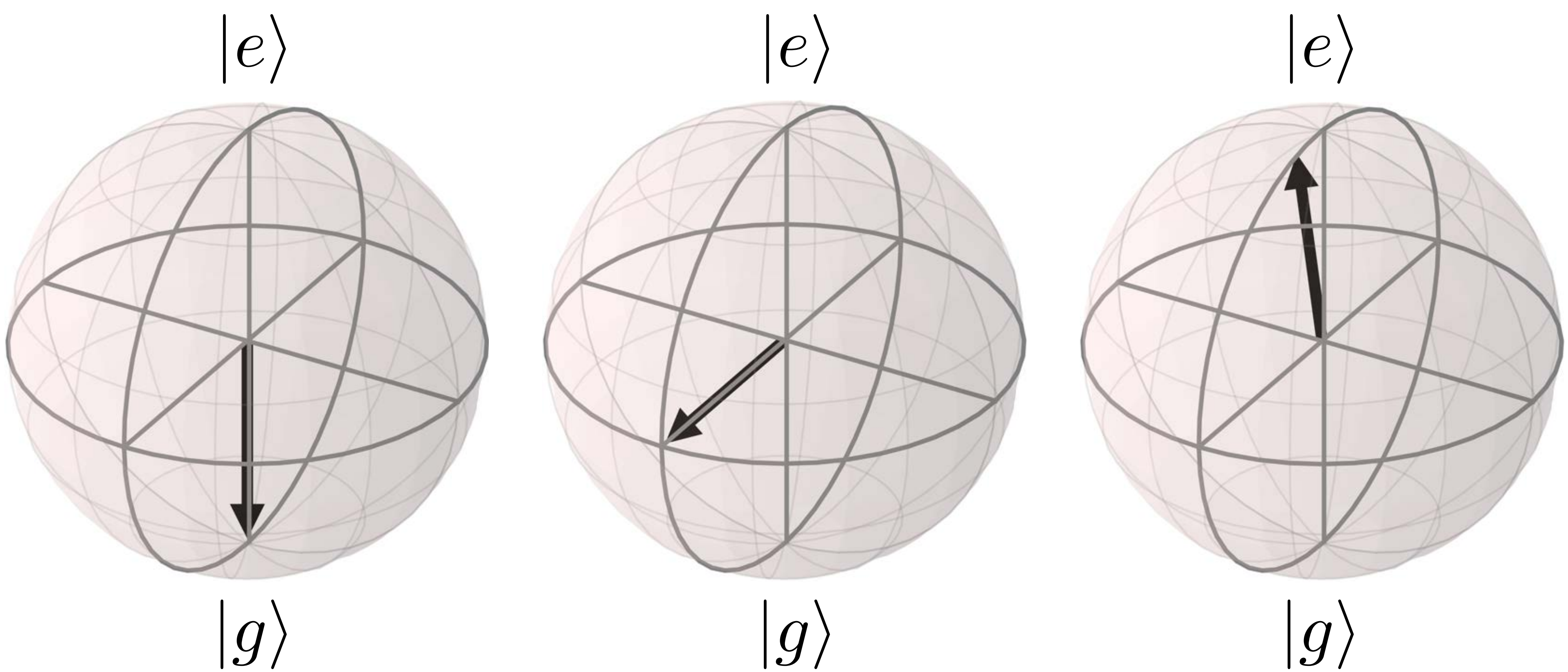
for one atom




Vacuum chamber
State Selection
Magnets
State Detection
Magnets
G
Ramsey
Cavity
G
D
Oven
Quartz
Oscillator
Frequency
Synthesizer
Servo
Circuit
Clock Signal

Ramsey Procedure

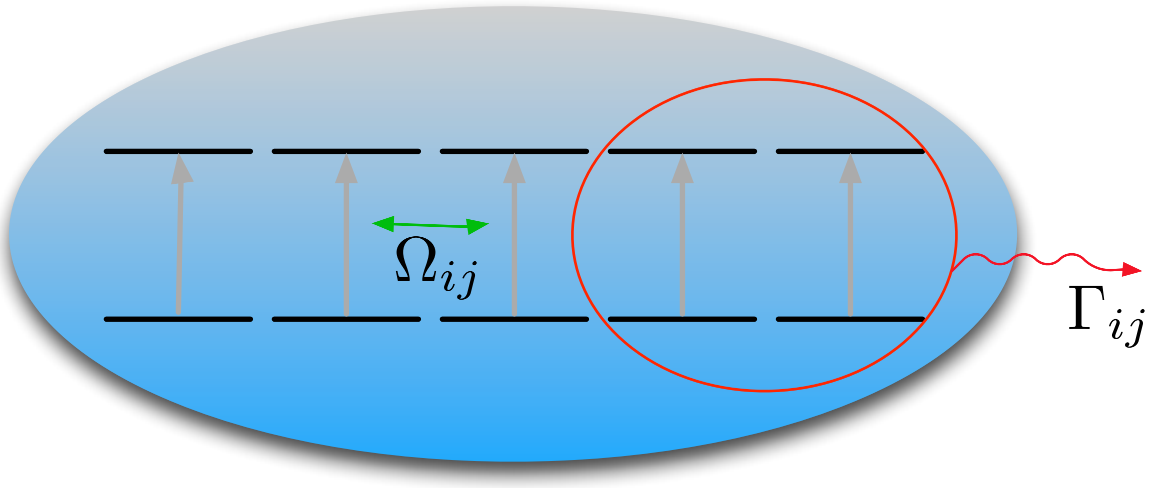
for one atom

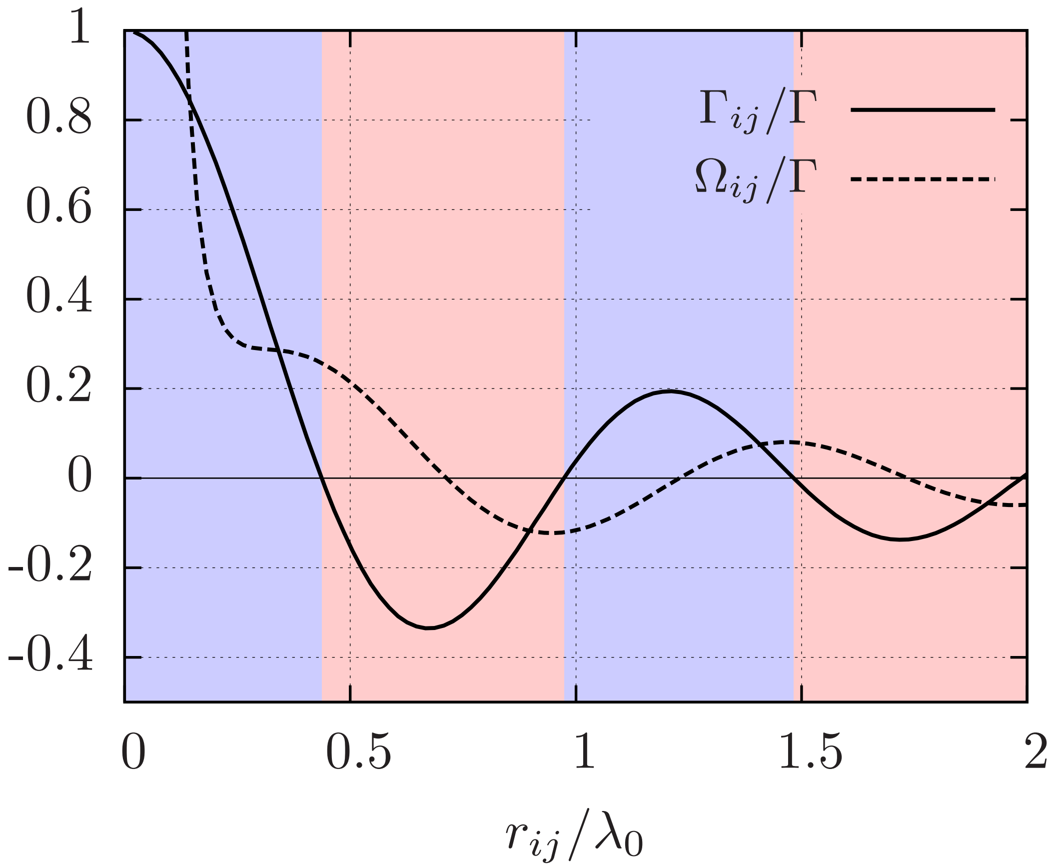


The signal for one atom is very weak and noisy.

→ Use many atoms (noise scales down)

Dipole - Dipole





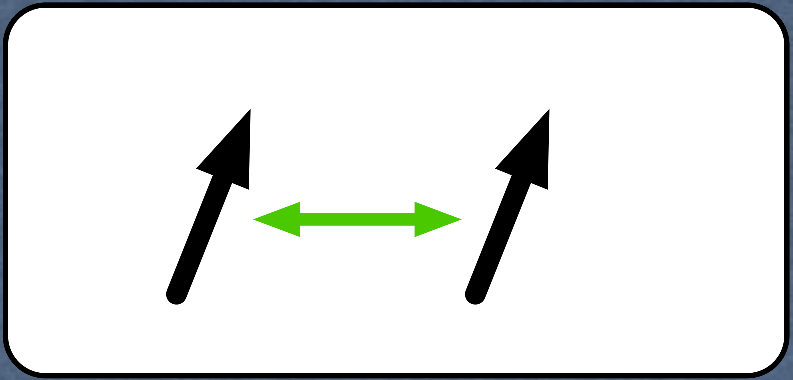
$$\frac{\partial \rho}{\partial t} = i[\rho, H] + \mathcal{L}[\rho]$$

$$H = \frac{\omega}{2}\sum_i \sigma_i^z + \sum_{i \neq j} \Omega_{ij}\, \sigma_i^+ \sigma_j^- \qquad \omega = \omega_0 - \omega_l$$

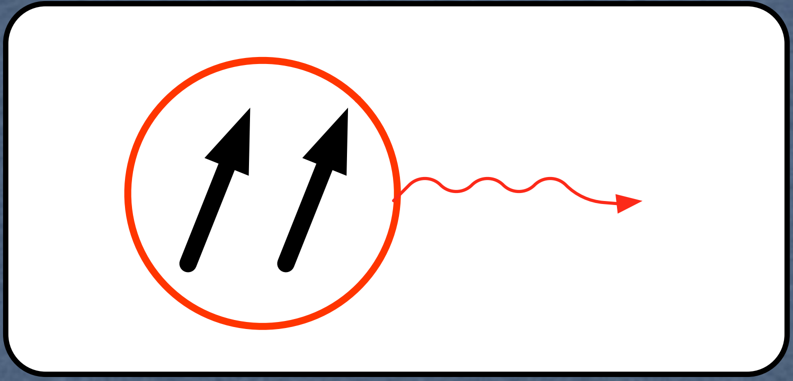
$$\mathcal{L}[\rho] = \frac{1}{2}\sum_{i,j} \Gamma_{ij}\left[2\sigma_i^- \rho\, \sigma_j^+ - \sigma_i^+ \sigma_j^- \rho - \rho\, \sigma_i^+ \sigma_j^-\right]$$

R. Lehmberg: Phys. Rev. A 2, 883 (1970); Z. Ficek et al.: Physics Reports 372, 369-443 (2002)

Dipole - Dipole



Atoms talk to each other and don't keep quiet.

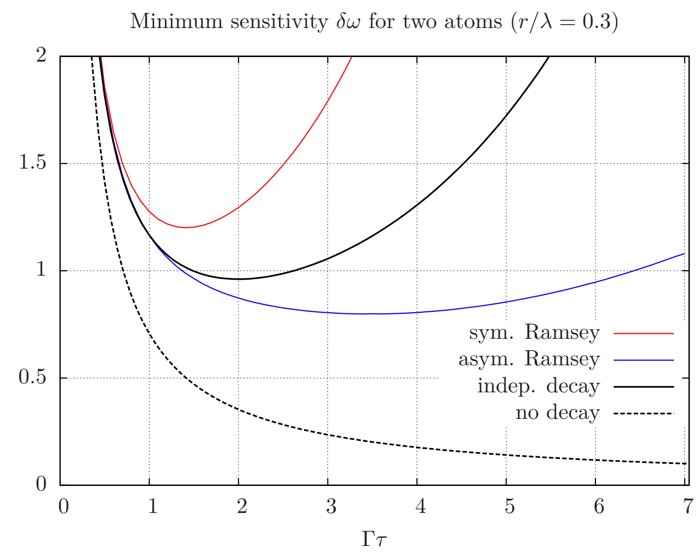


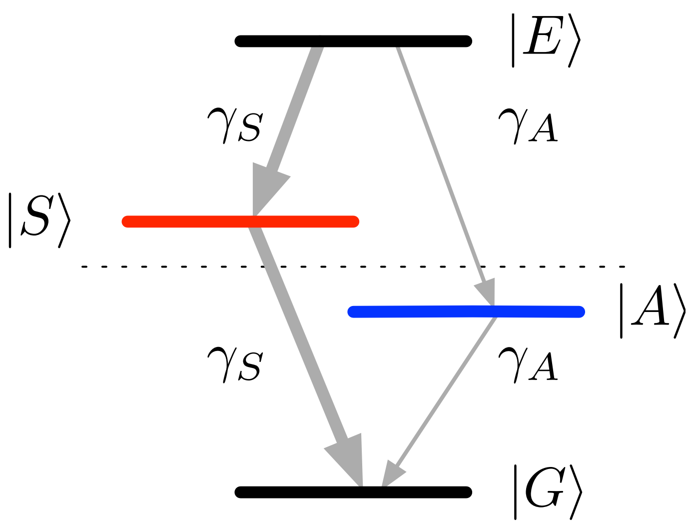
Atoms decay together and are lost.

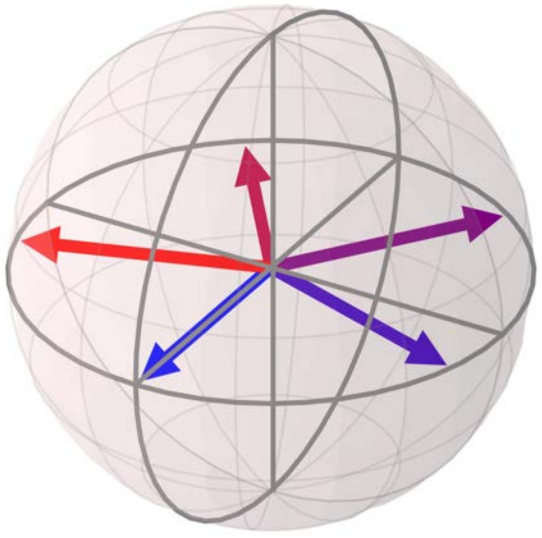
R. Lehmberg: Phys. Rev. A 2, 883 (1970); Z. Ficek et al.: Physics Reports 372, 369-443 (2002)

3. Protected Subspace

Protected Subspace



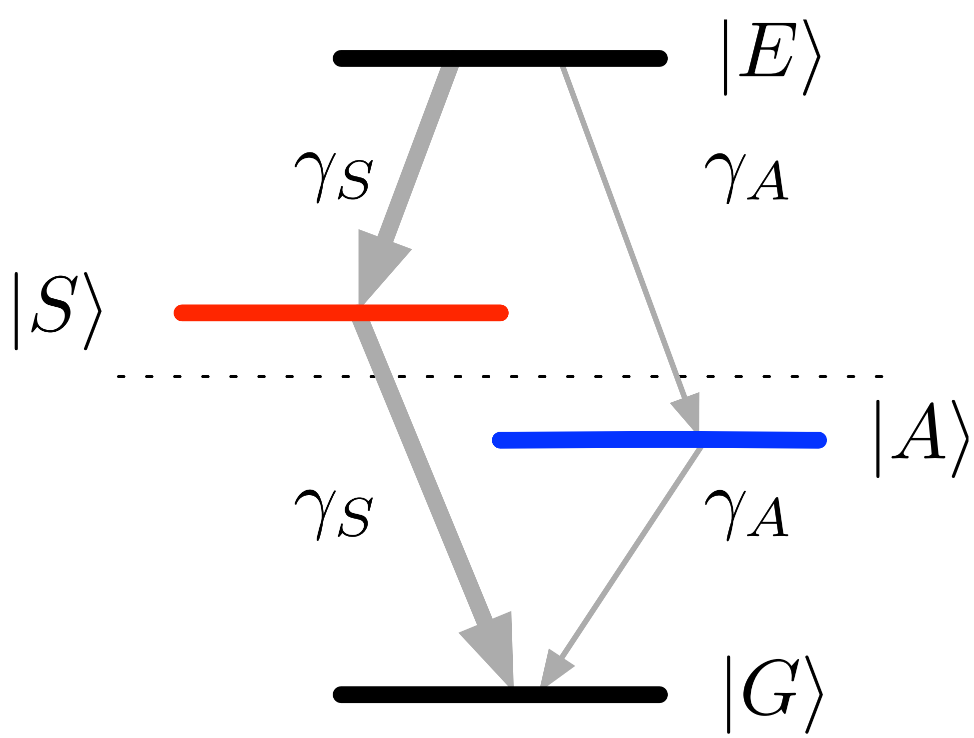




L. Ostermann, H. Ritsch, C. Genes: PRL 111 (2013); L. Ostermann, D. Plankensteiner, H. Ritsch, C. Genes: PRA 90 (2014); L. Ostermann, H.Zoubi, H. Ritsch: OpEx 20/28 (2012)

Two Atoms

Populate asymmetric state instead of symmetric one (minimize chatter)



$$\psi_0^{sym} = \frac{|g\rangle + |e\rangle}{\sqrt{2}} \otimes \frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

$$= \frac{1}{2}\Big(|G\rangle + \sqrt{2}\,|S\rangle + |E\rangle\Big)$$

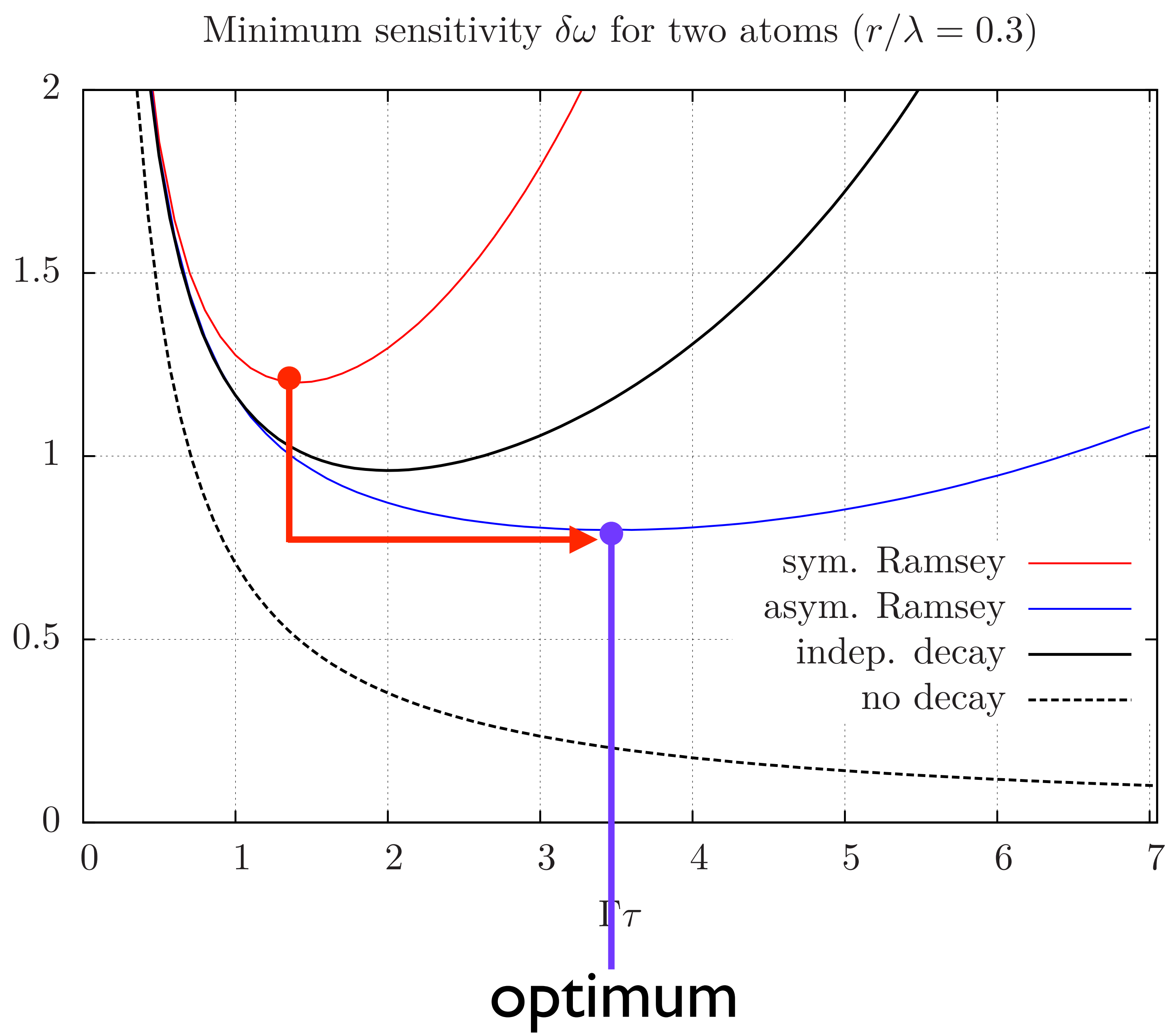
$$\psi_0^{asym} = \frac{|g\rangle + |e\rangle}{\sqrt{2}} \otimes \frac{|g\rangle - |e\rangle}{\sqrt{2}}$$

$$= \frac{1}{2}\Big(|G\rangle + \sqrt{2}\,|A\rangle - |E\rangle\Big)$$

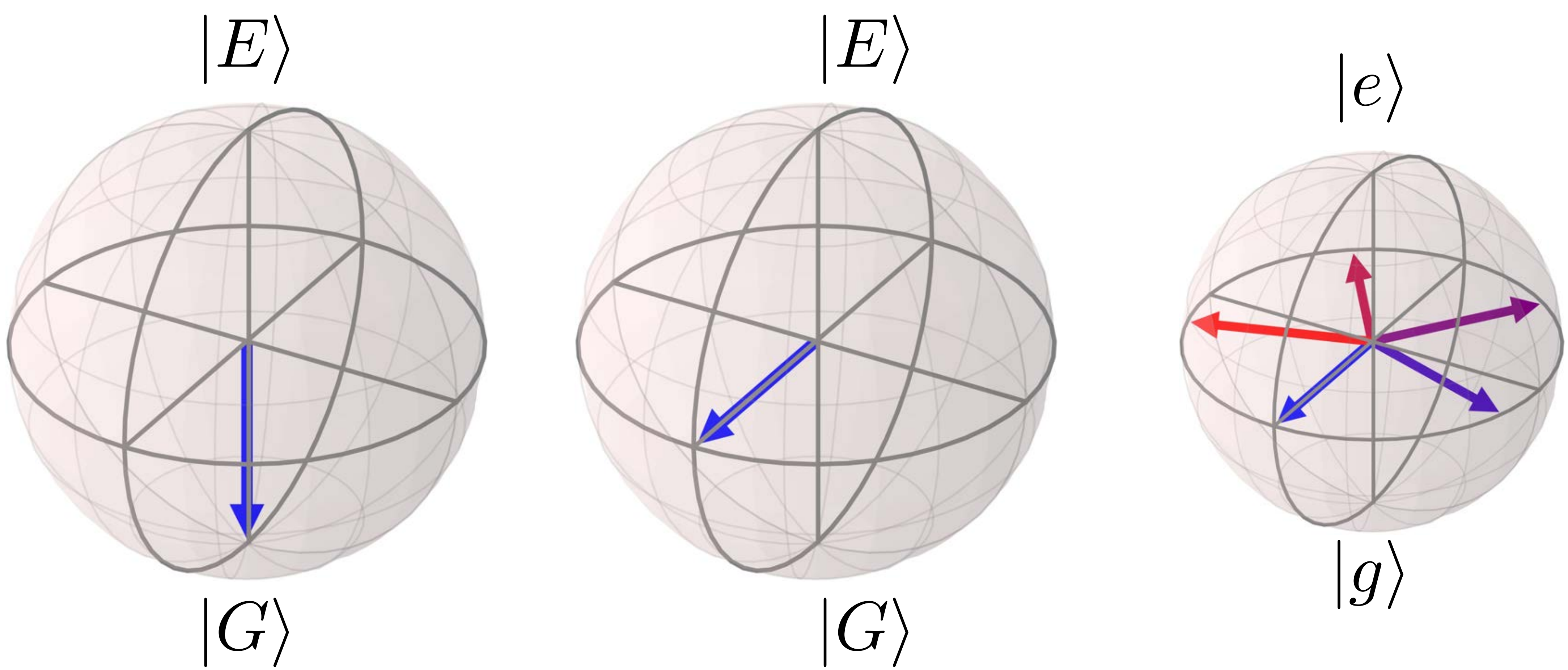
Minimum Sensitivity

$$S_z = \frac{1}{2}\sum_i \sigma_i^z$$

$$\delta\omega = \min_\omega \frac{\Delta S_z}{|\partial_\omega \langle S_z \rangle|}$$

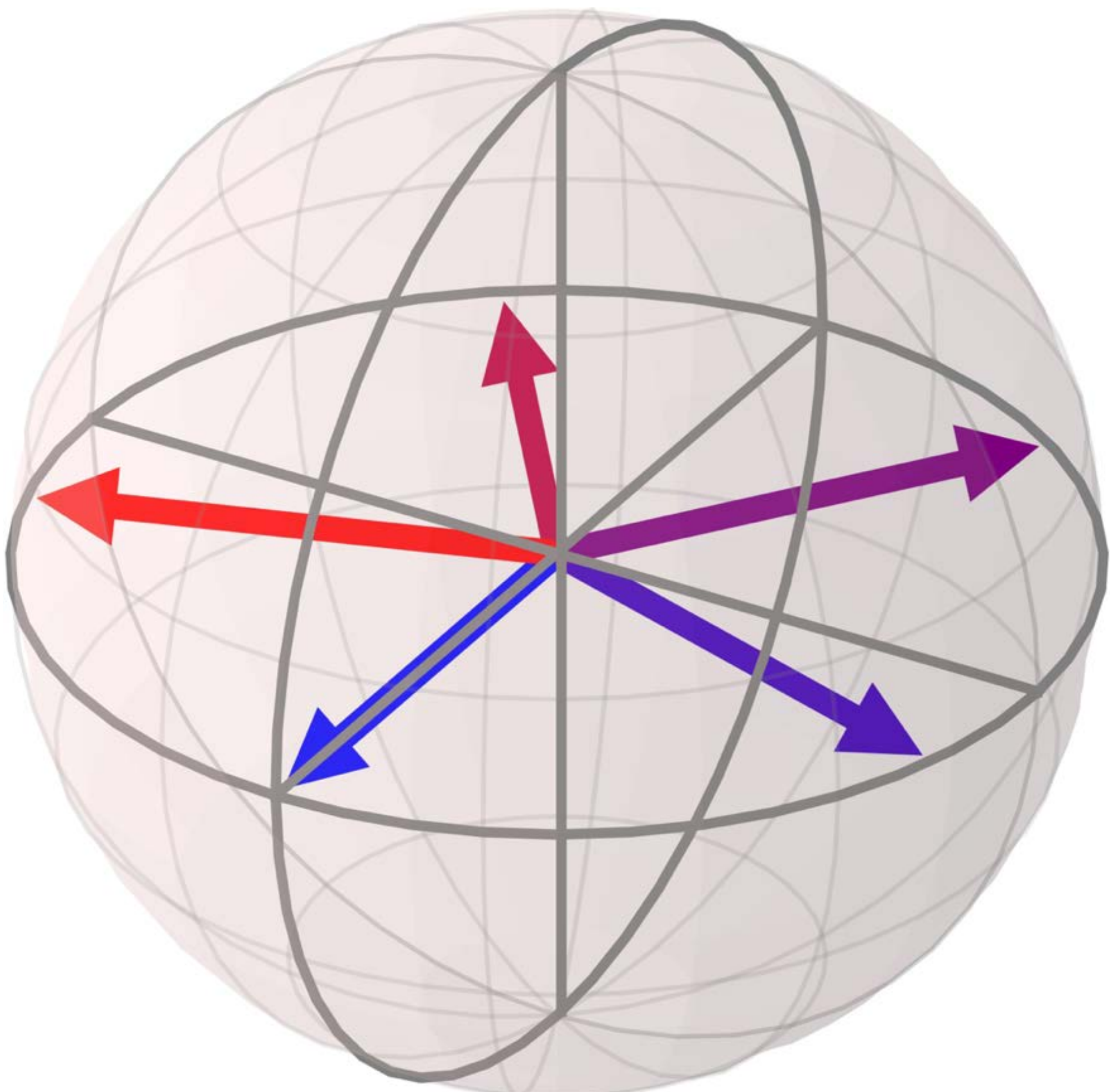


Initial State



$$\otimes_j \mathcal{R}_y^{(j)} \left[\frac{\pi}{2}\right] \qquad \otimes_j \mathcal{R}_z^{(j)} \left[\varphi_j^{(m)}\right]$$

Initial State

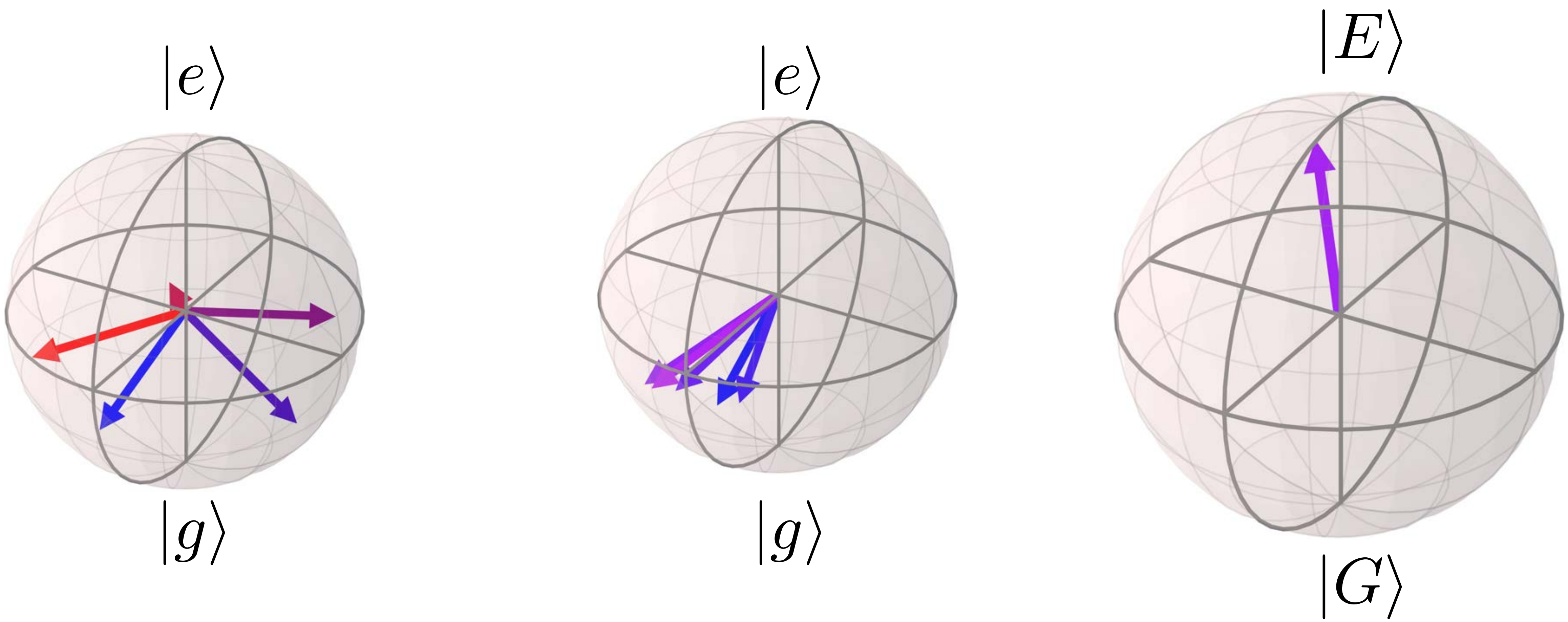


Phase-separate the atoms to keep them quiet

…free evolution…

$$\frac{\partial \rho}{\partial t} = i[\rho, H] + \mathcal{L}[\rho]$$

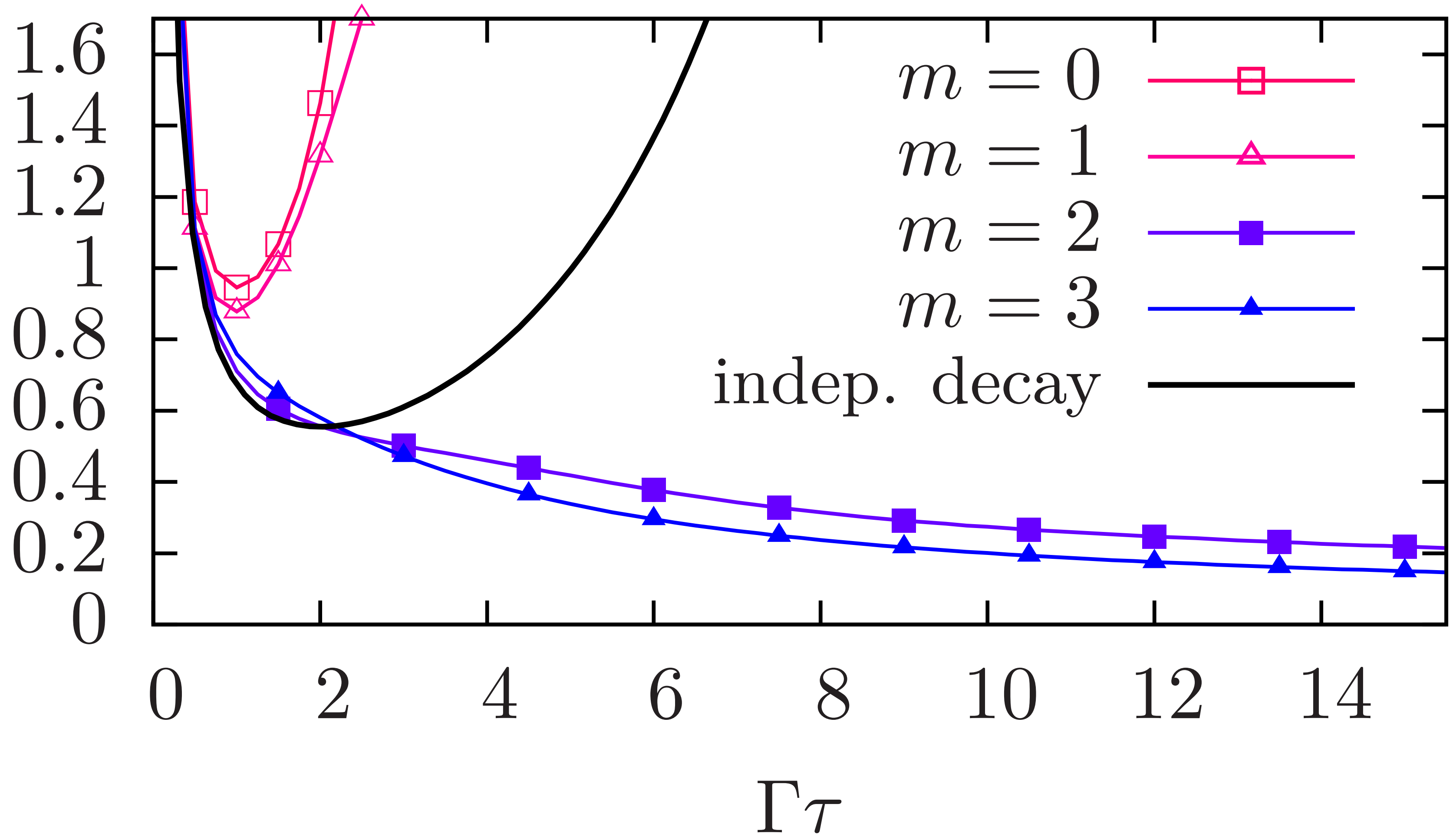
Spread Reversal



$$\otimes_j \mathcal{R}_z^{(j)}\left[-\varphi_j^{(m)}\right] \qquad \otimes_j \mathcal{R}_y^{(j)}\left[\frac{\pi}{2}\right]$$

Larger Systems

$\delta\omega$ for a chain of six atoms ($a/\lambda_0 = 0.2$)



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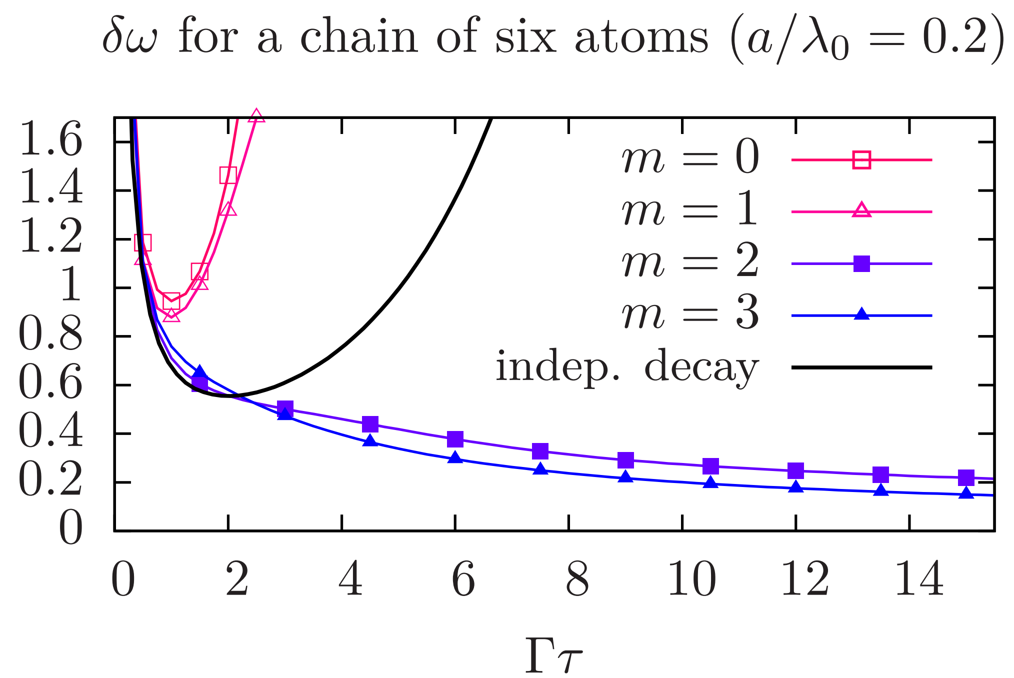
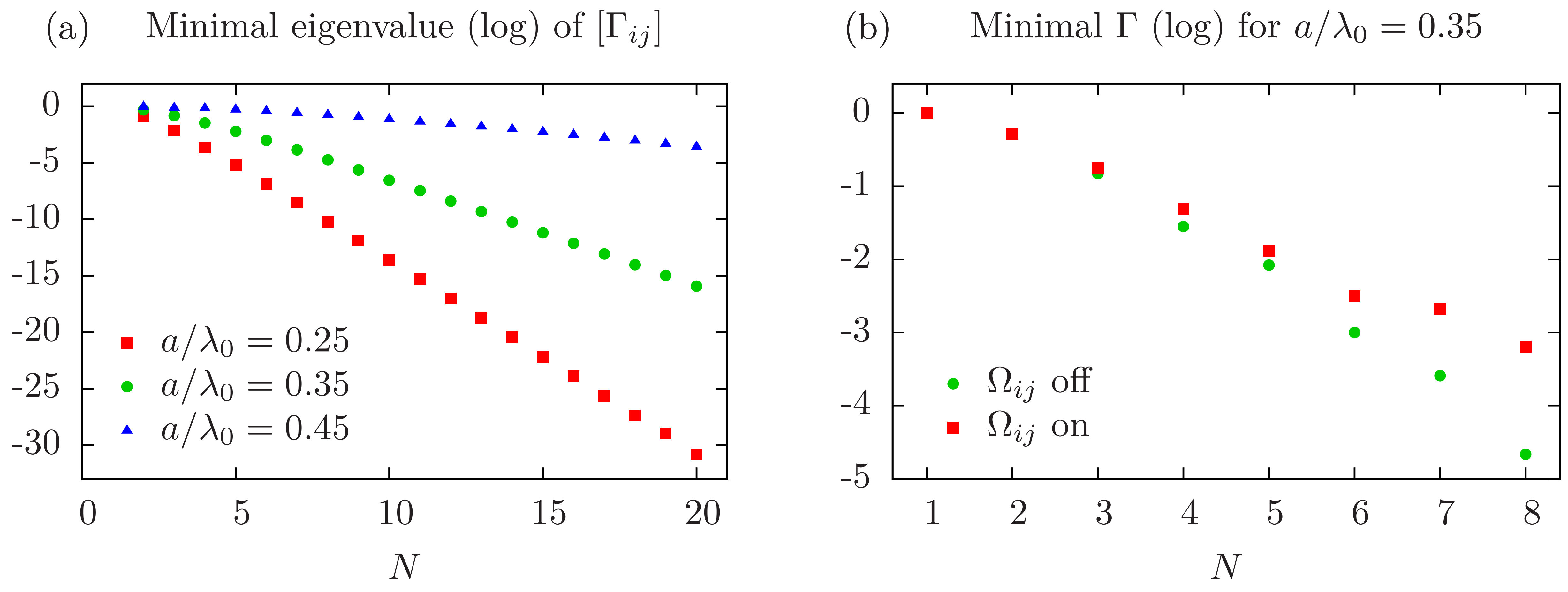


$$\mathcal{R}_1^{(m)} = \bigotimes \mathcal{R}_z^{(j)} \left[\varphi_j^{(m)}\right] \cdot \mathcal{R}_y^{(j)} \left[\frac{\pi}{2}\right]$$

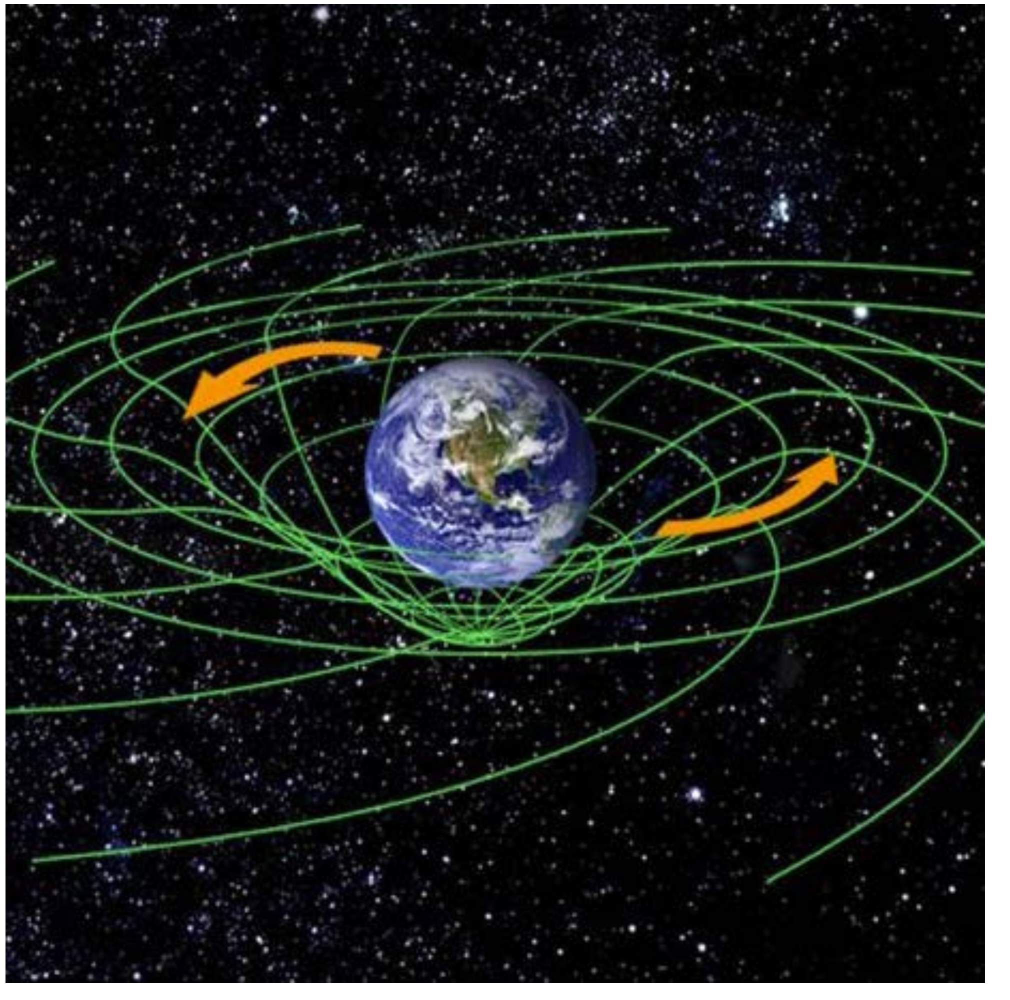
$$\varphi_j^{(m)} = 2\pi m \, \frac{j-1}{N}$$

Scaling Laws



Why?

- Fundamental Physics
- Communication
- Navigation



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