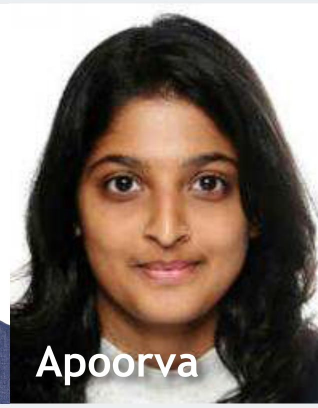
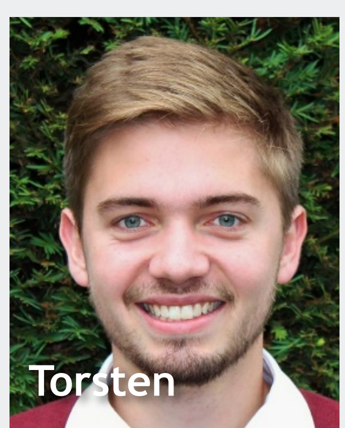
Synthetic
Quantum
Systems

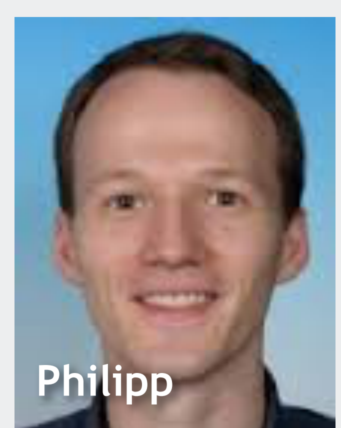
SynQS



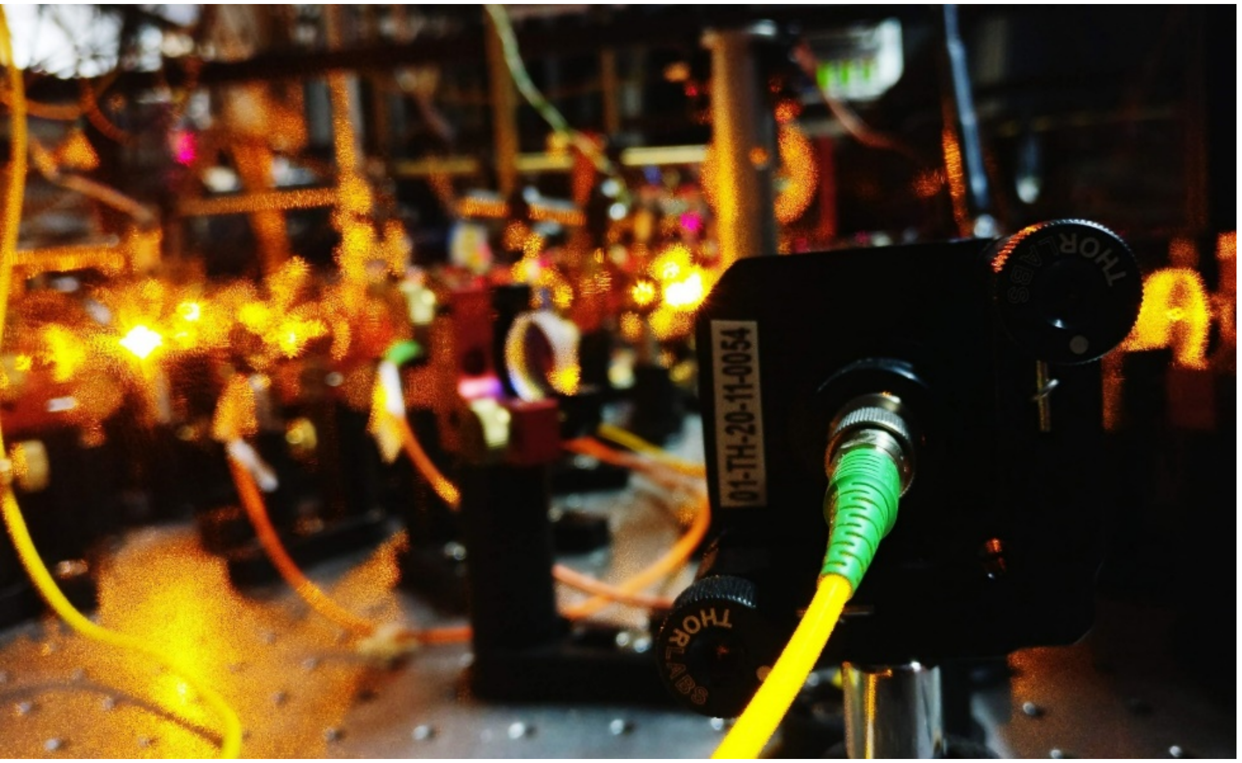
Engineering local U(1) symmetries

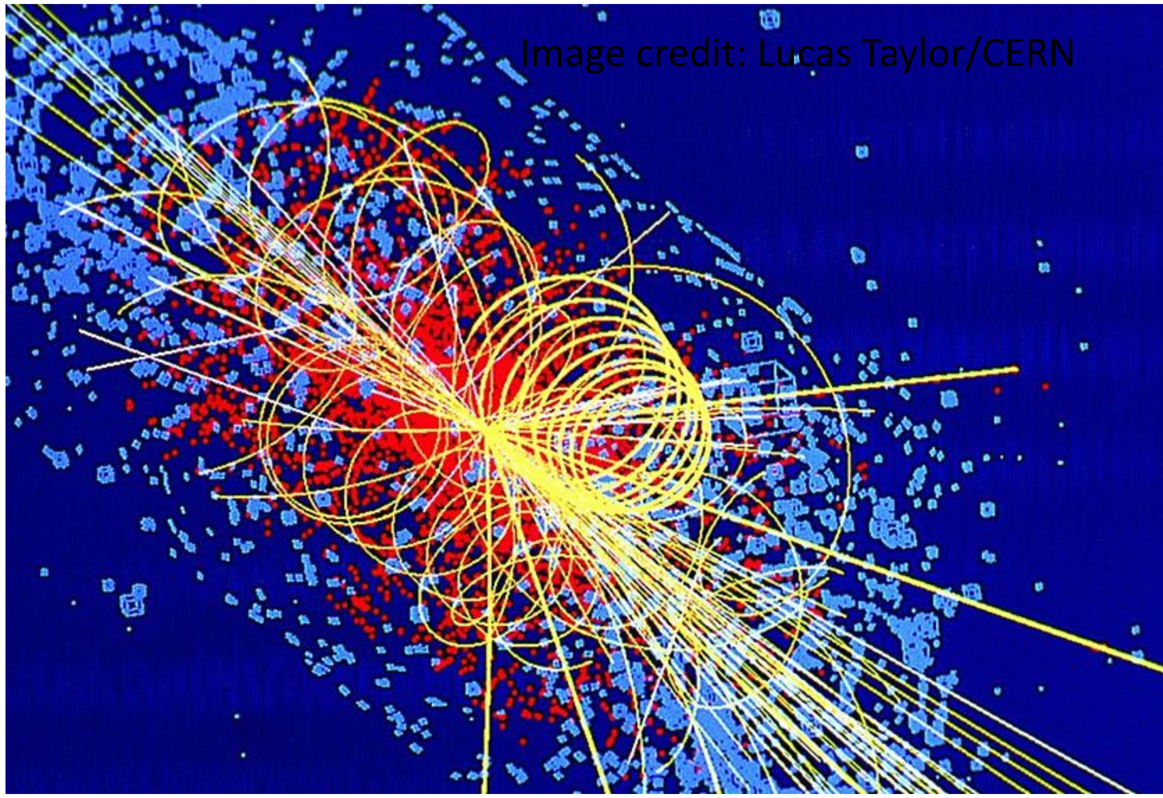
Fred Jendrzejewski
Universität Heidelberg, Germany

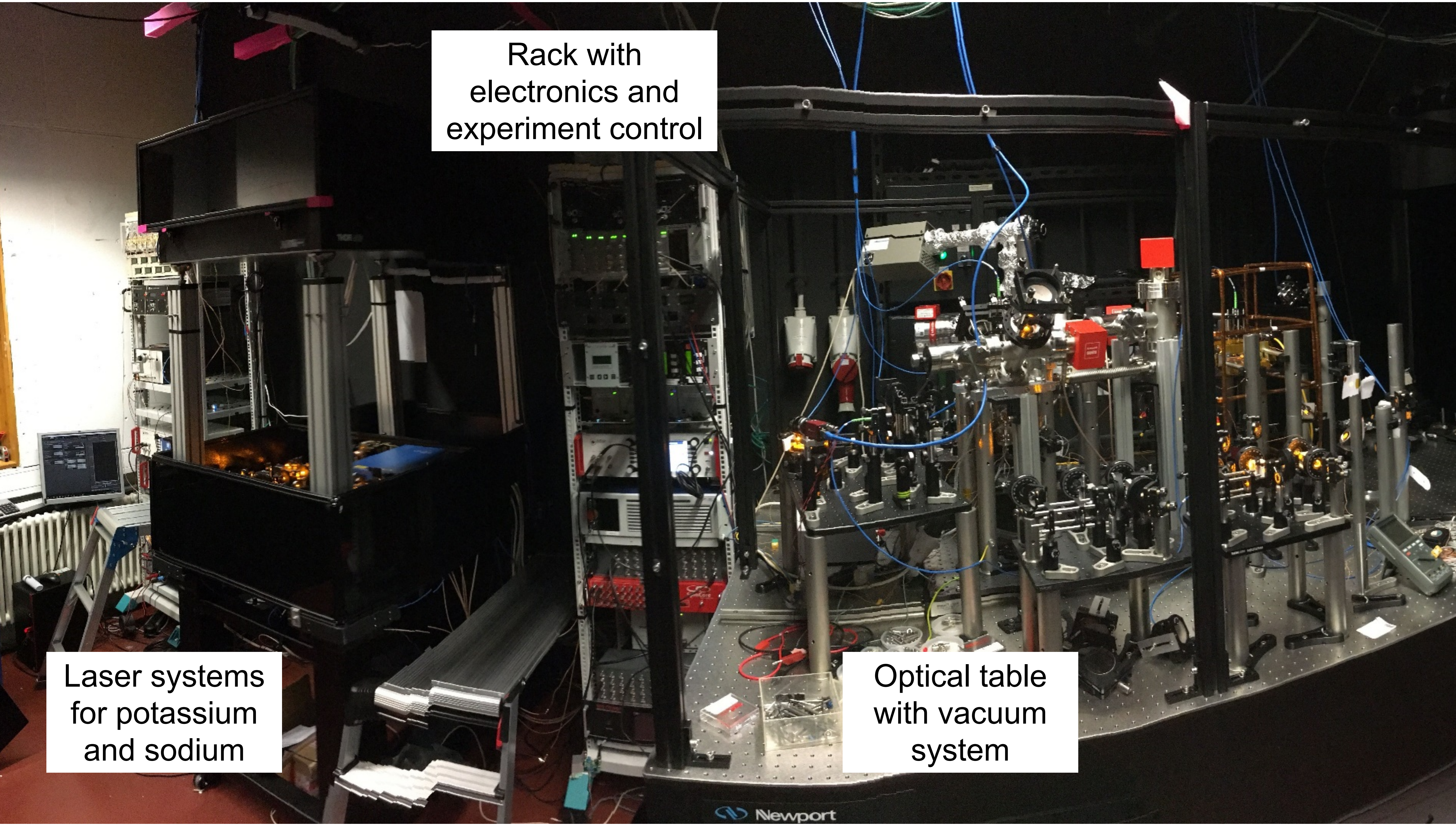




Could we use cold atoms to study high-energy physics?

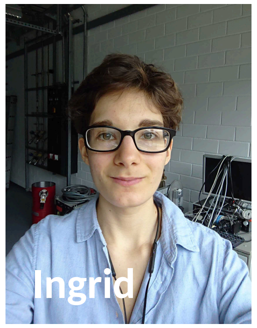





Rack with electronics and experiment control
Laser systems for potassium and sodium
Optical table with vacuum system
Newport


Lilo

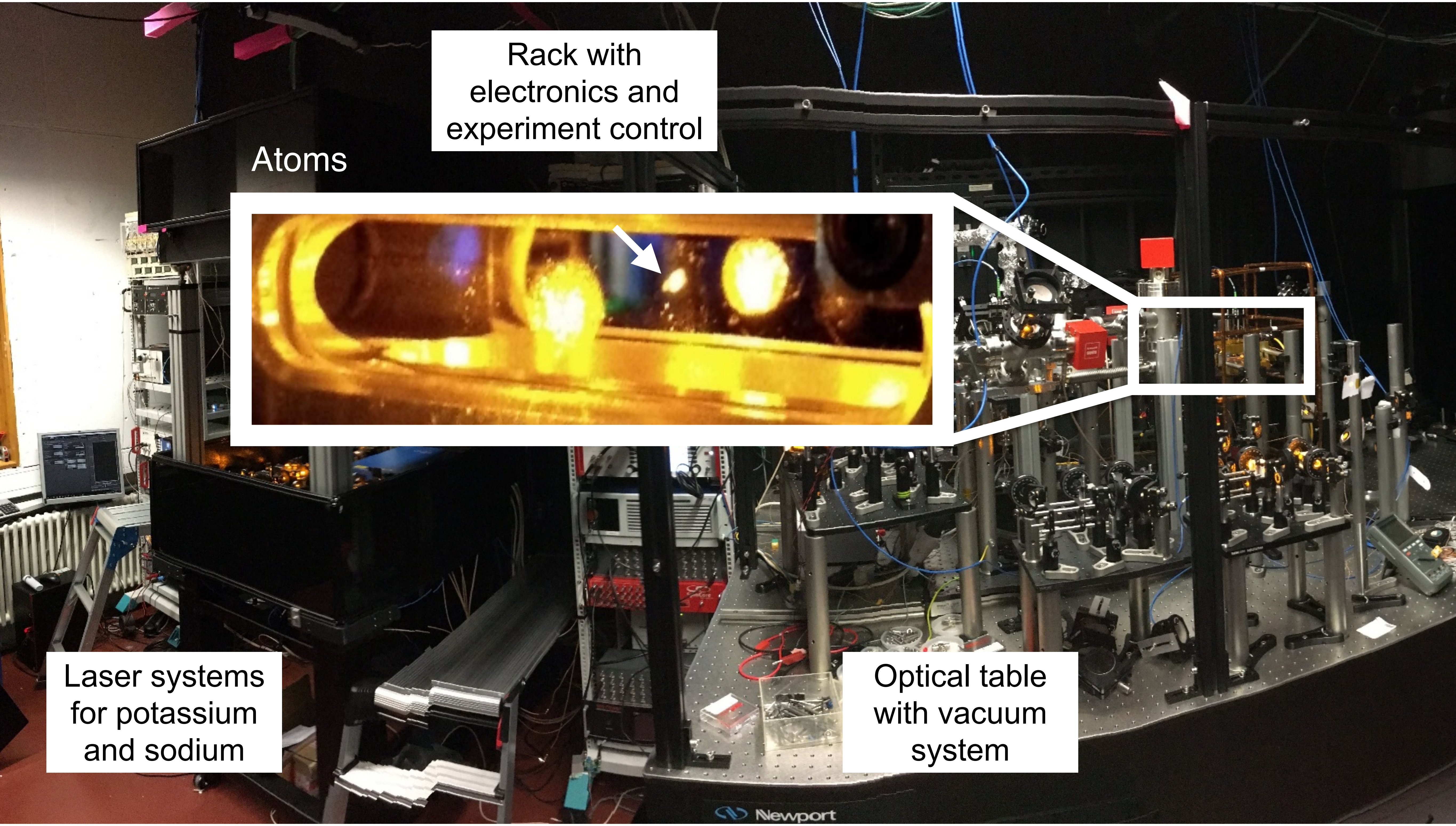
Jan

Hannes

Ingrid

Apoorva

Andy

Rohit


Rack with electronics and experiment control
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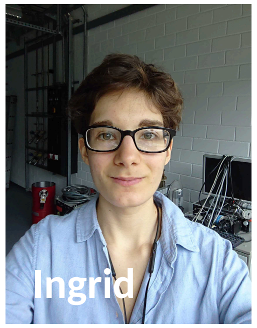
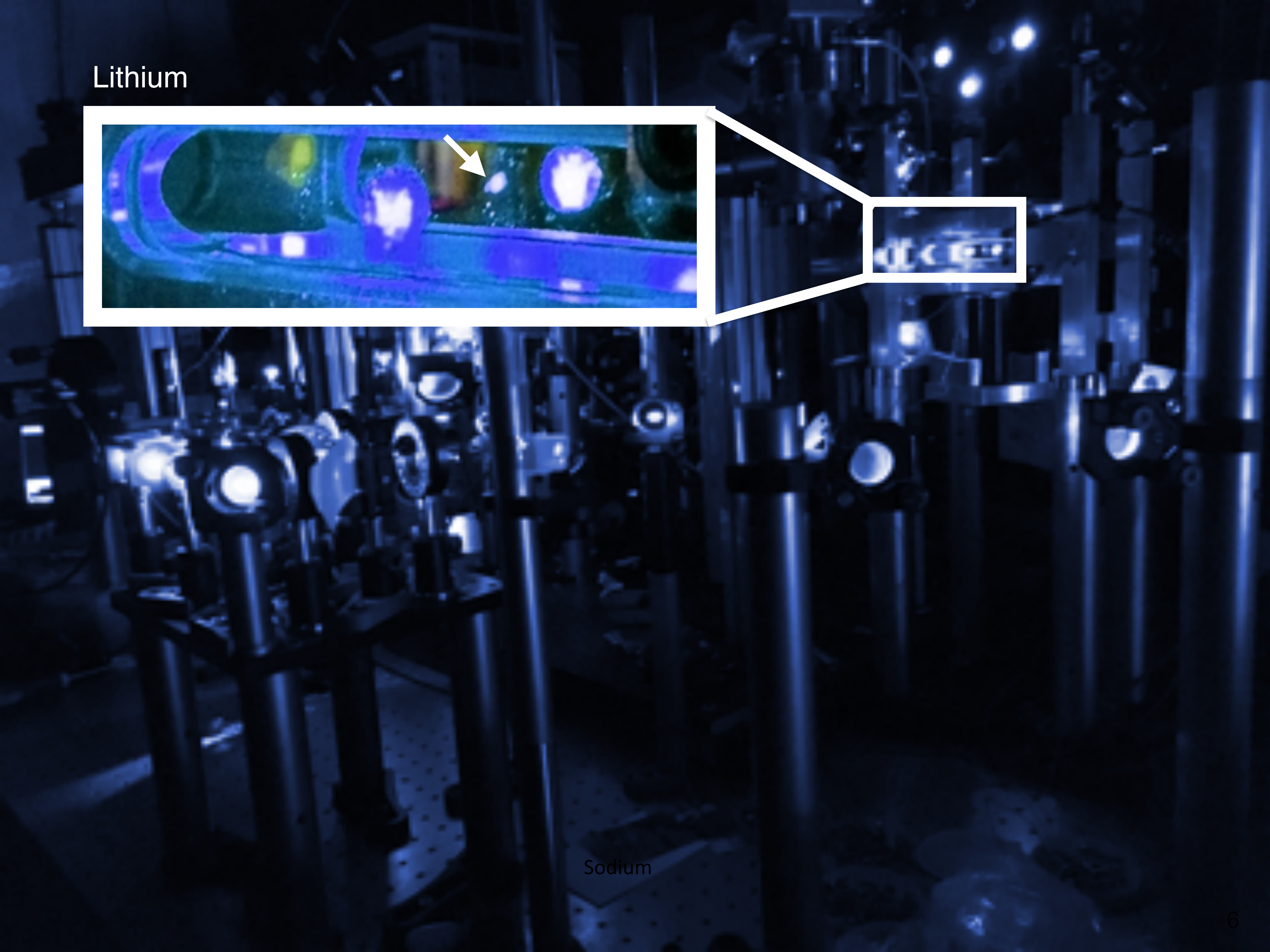

Ingrid

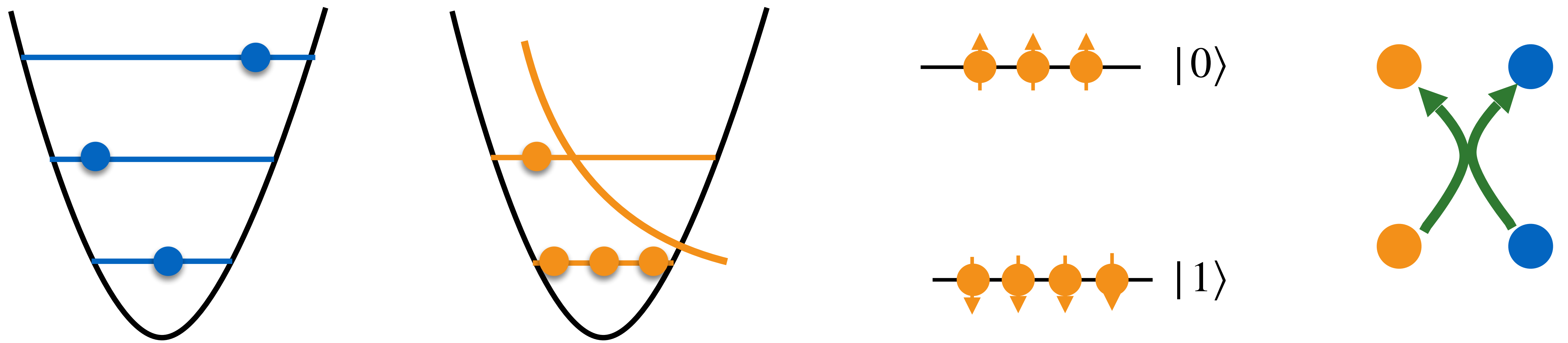
Apoorva

Andy

Rohit


Sodium
Sodium


Lithium
Sodium



$$\hat{H} = \int d^3\mathbf{x} \sum_{\alpha} \hat{\psi}^{\dagger}_{s,\alpha}(\mathbf{x}) \left[\frac{-\nabla^2_{\mathbf{x}}}{2m_s} + V_s(\mathbf{x}) + E_{s,\alpha}(B) \right] \hat{\psi}_{s,\alpha}(\mathbf{x}) + \frac{1}{2} \int d^3\mathbf{x} \sum_{\alpha,\beta} g^{s}_{\alpha\beta}\, \hat{\psi}^{\dagger}_{s,\alpha}(\mathbf{x}) \hat{\psi}^{\dagger}_{s,\beta}(\mathbf{x}) \hat{\psi}_{s,\beta}(\mathbf{x}) \hat{\psi}_{s,\alpha}(\mathbf{x})$$

$$+ \int d^3\mathbf{x} \sum_{\alpha,\beta} g^{Mix}_{\alpha\beta}\, \hat{\psi}^{\dagger}_{N,\alpha}(\mathbf{x}) \hat{\psi}^{\dagger}_{L,\beta}(\mathbf{x}) \hat{\psi}_{L,\beta}(\mathbf{x}) \hat{\psi}_{N,\alpha}(\mathbf{x})$$

All microscopic parameters known

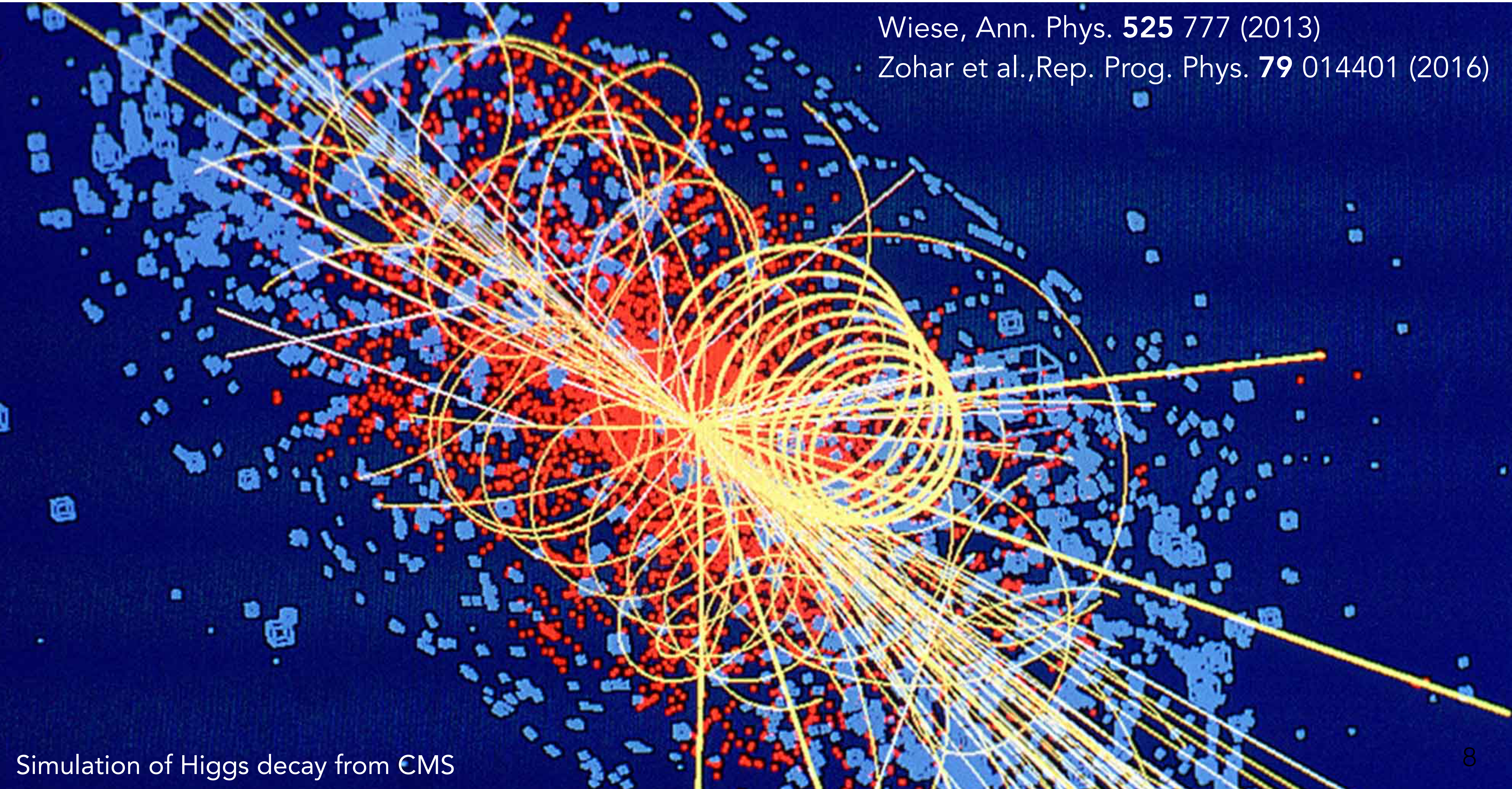
I. Bloch et al., Rev. Mod. Phys. **80**, 885 (2008).

$$\mathscr{L}_{QED} = \bar{\psi}\left(i\gamma^\mu D_\mu - m\right)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\mathscr{L}_{QCD} = \sum_{fi} \bar{\psi}^{fi}\left(i\gamma^\mu D_{\mu ij} - m_f\right)\psi^{fi} - \frac{1}{2g^2}Tr\left(G^{\mu\nu}G_{\mu\nu}\right)$$

Particle

Gauge field



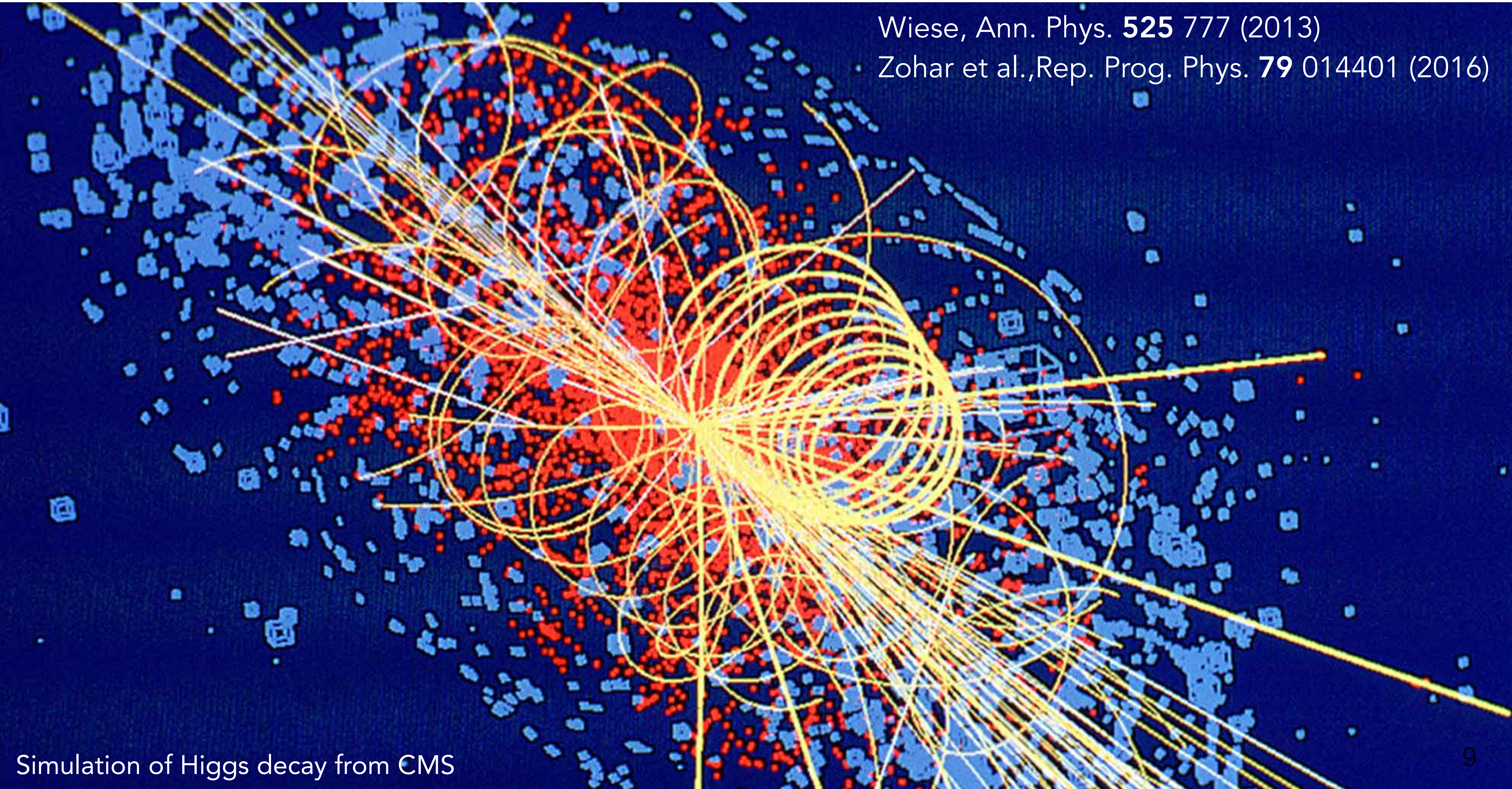
Wiese, Ann. Phys. **525** 777 (2013)
Zohar et al.,Rep. Prog. Phys. **79** 014401 (2016)

Simulation of Higgs decay from CMS

$$\mathscr{L}_{QED} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu} - m\right)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\mathscr{L}_{QCD} = \sum_{fi}\bar{\psi}^{fi}\left(i\gamma^{\mu}D_{\mu ij} - m_f\right)\psi^{fi} - \frac{1}{2g^2}Tr\left(G^{\mu\nu}G_{\mu\nu}\right)$$

Particle | **Gauge coupling** | Gauge field

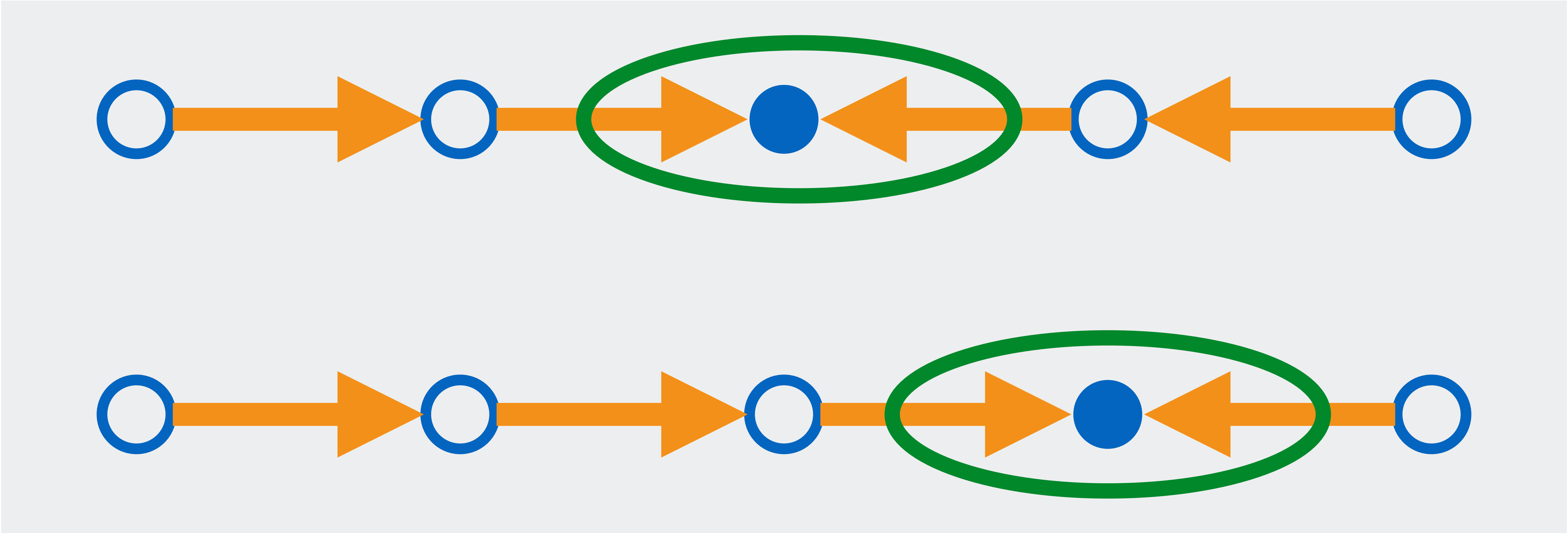


Wiese, Ann. Phys. **525** 777 (2013)

Zohar et al.,Rep. Prog. Phys. **79** 014401 (2016)

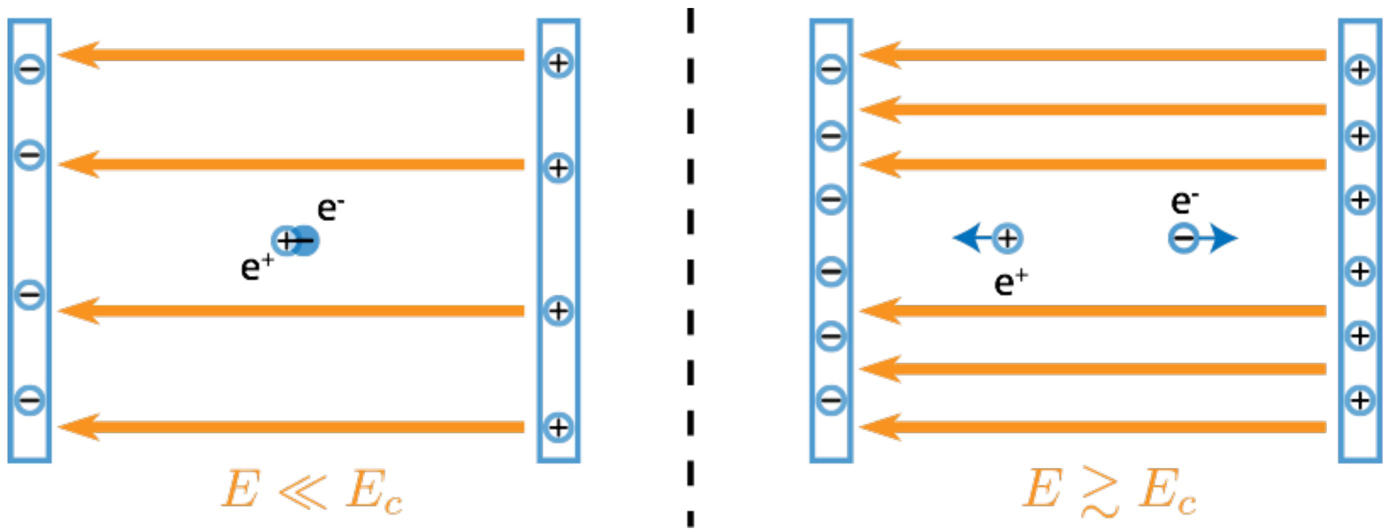
Simulation of Higgs decay from CMS

Conserved local charges = Conserved local gauge symmetry

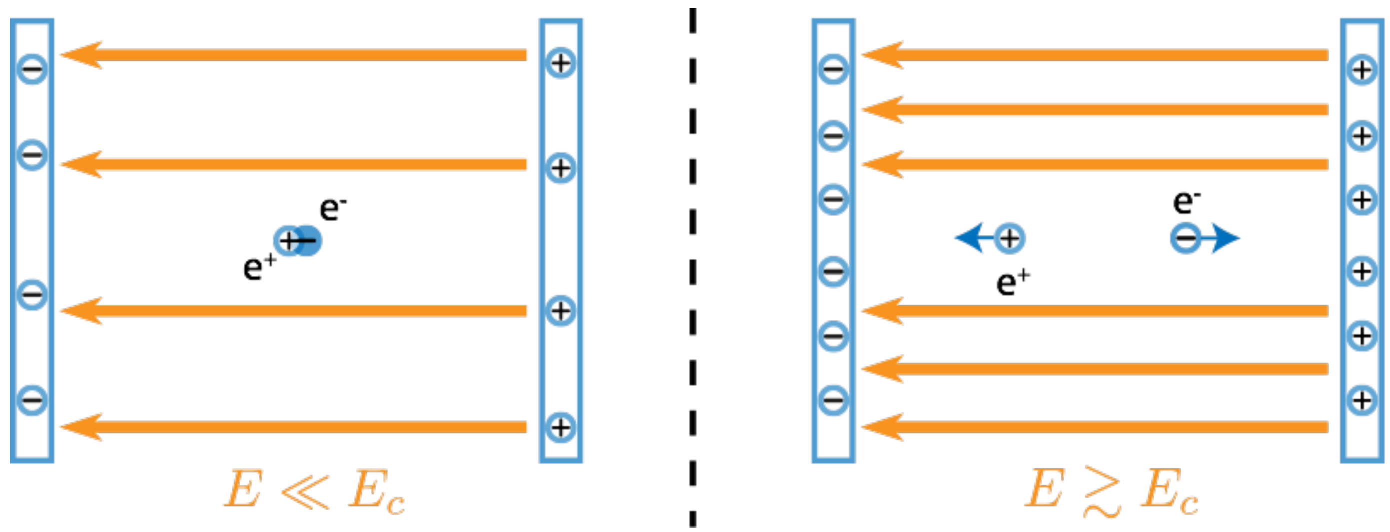


$$\mathrm{div}\ \mathbf{E}(\mathbf{r}) = e\rho(\mathbf{r})$$

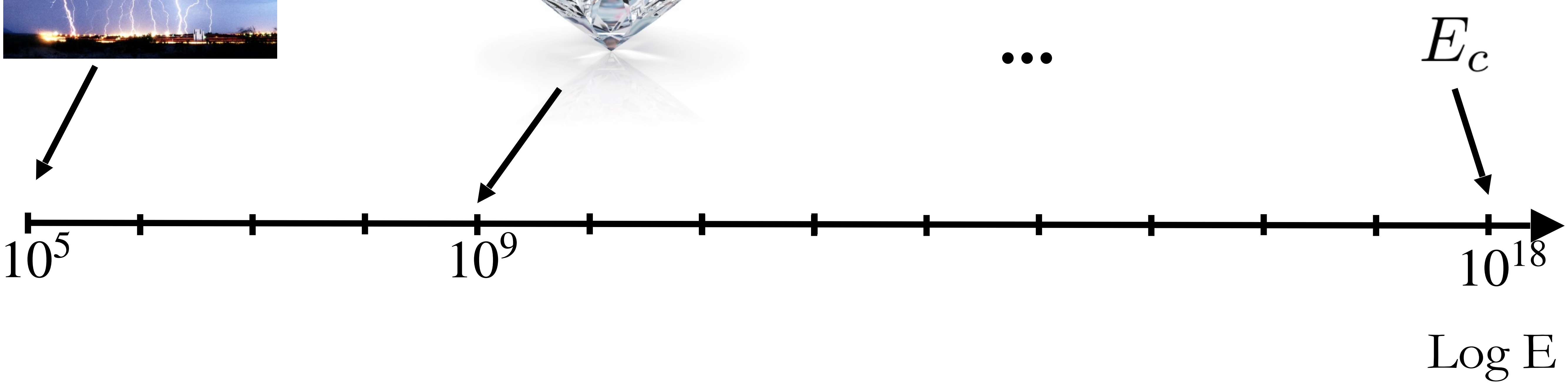
J. Schwinger, Phys. Rev. **714**, 16 (1951).



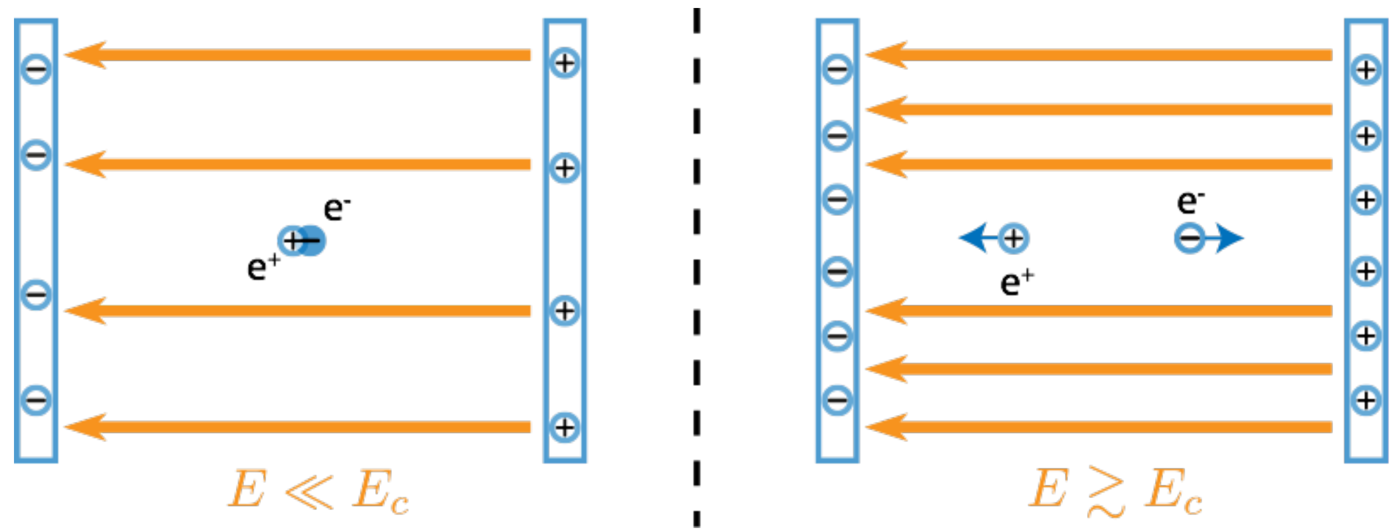
J. Schwinger, Phys. Rev. **714**, 16 (1951).



$$E_c = \frac{m_e^2 c^3}{\hbar q_e} \approx 10^{18} \mathrm{V/m}$$

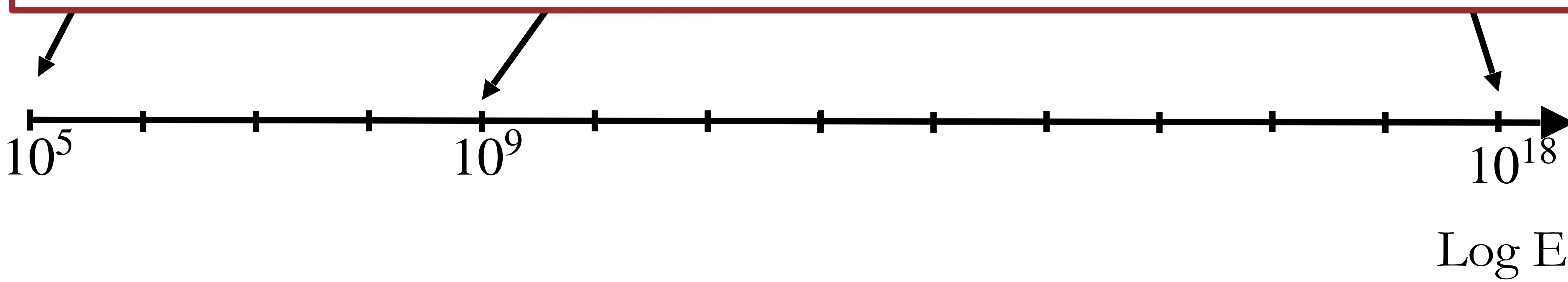


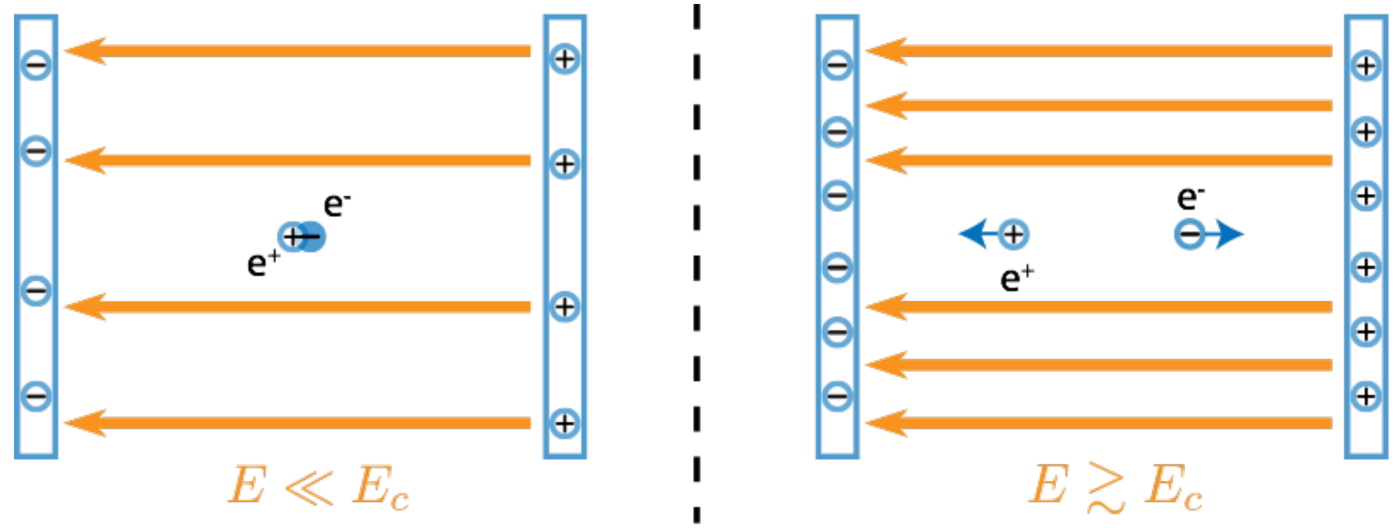
J. Schwinger, Phys. Rev. **714**, 16 (1951).



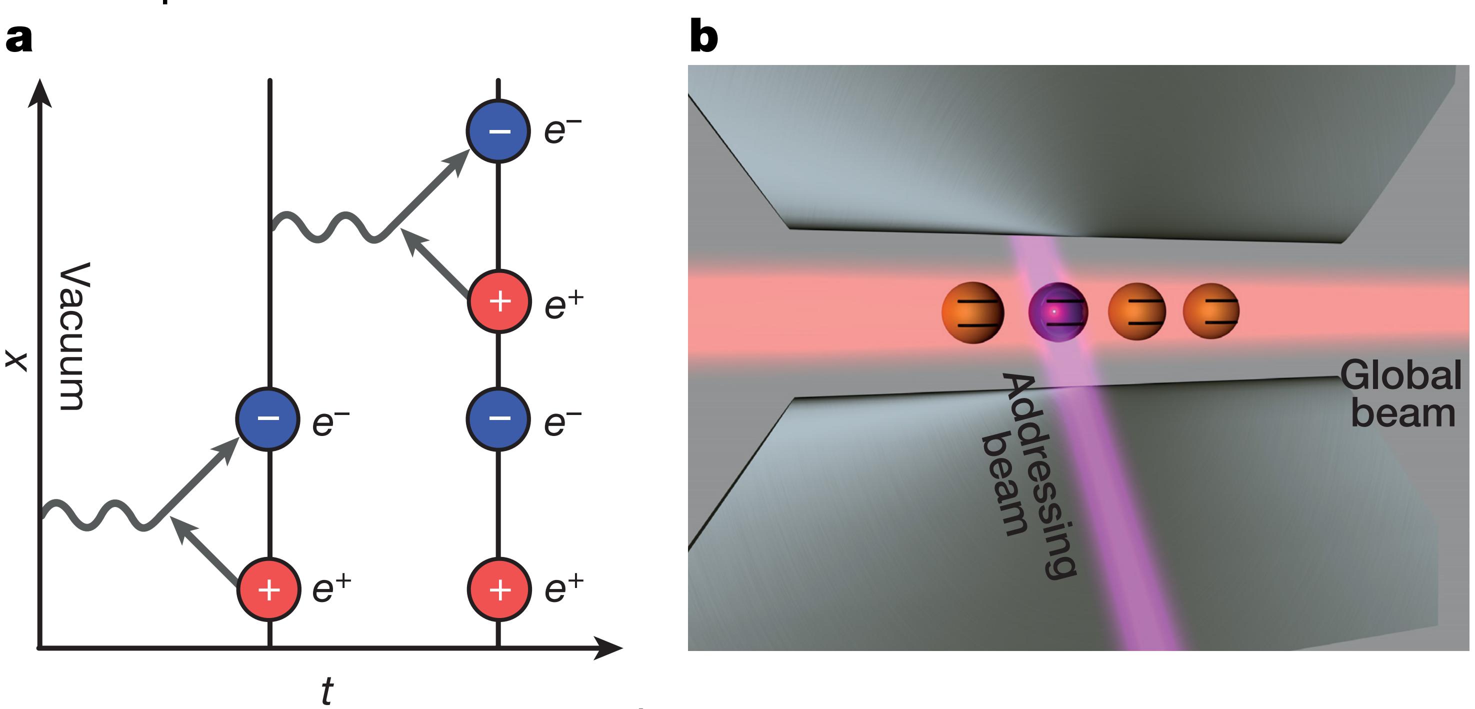
$$E_c = \frac{m_e^2 c^3}{\hbar q_e} \approx 10^{18} \mathrm{V/m}$$

Can we construct a quantum simulator ?

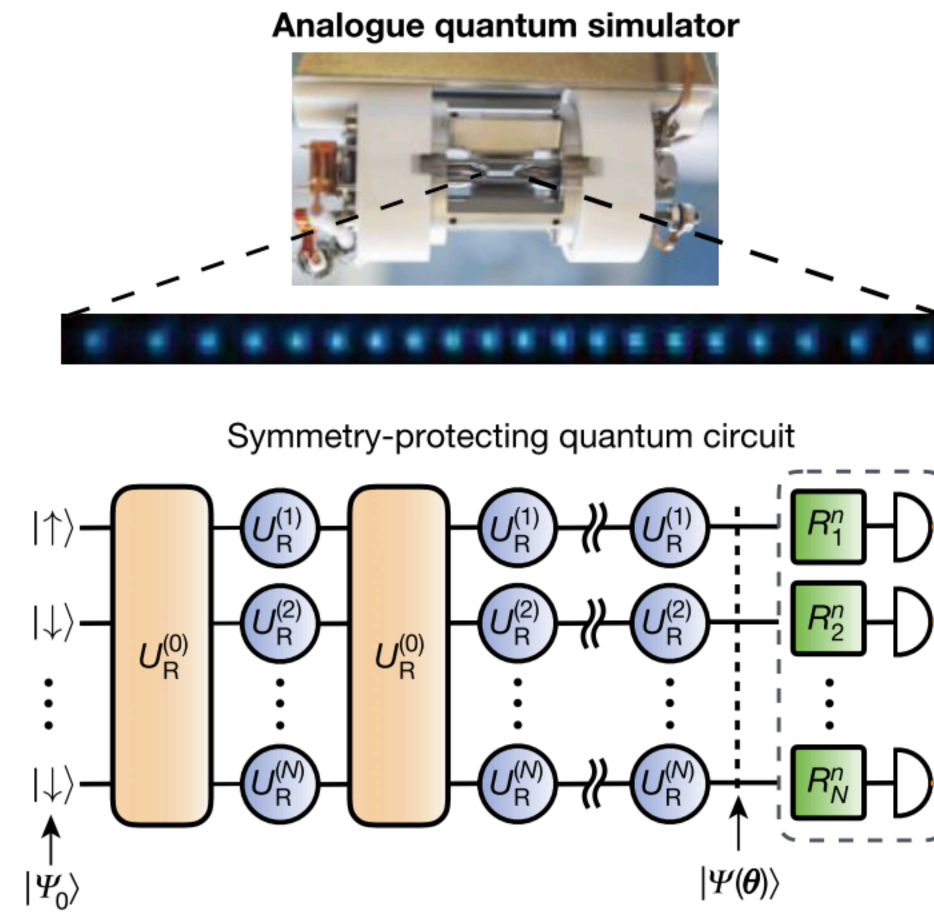




First digital
implementation with ions

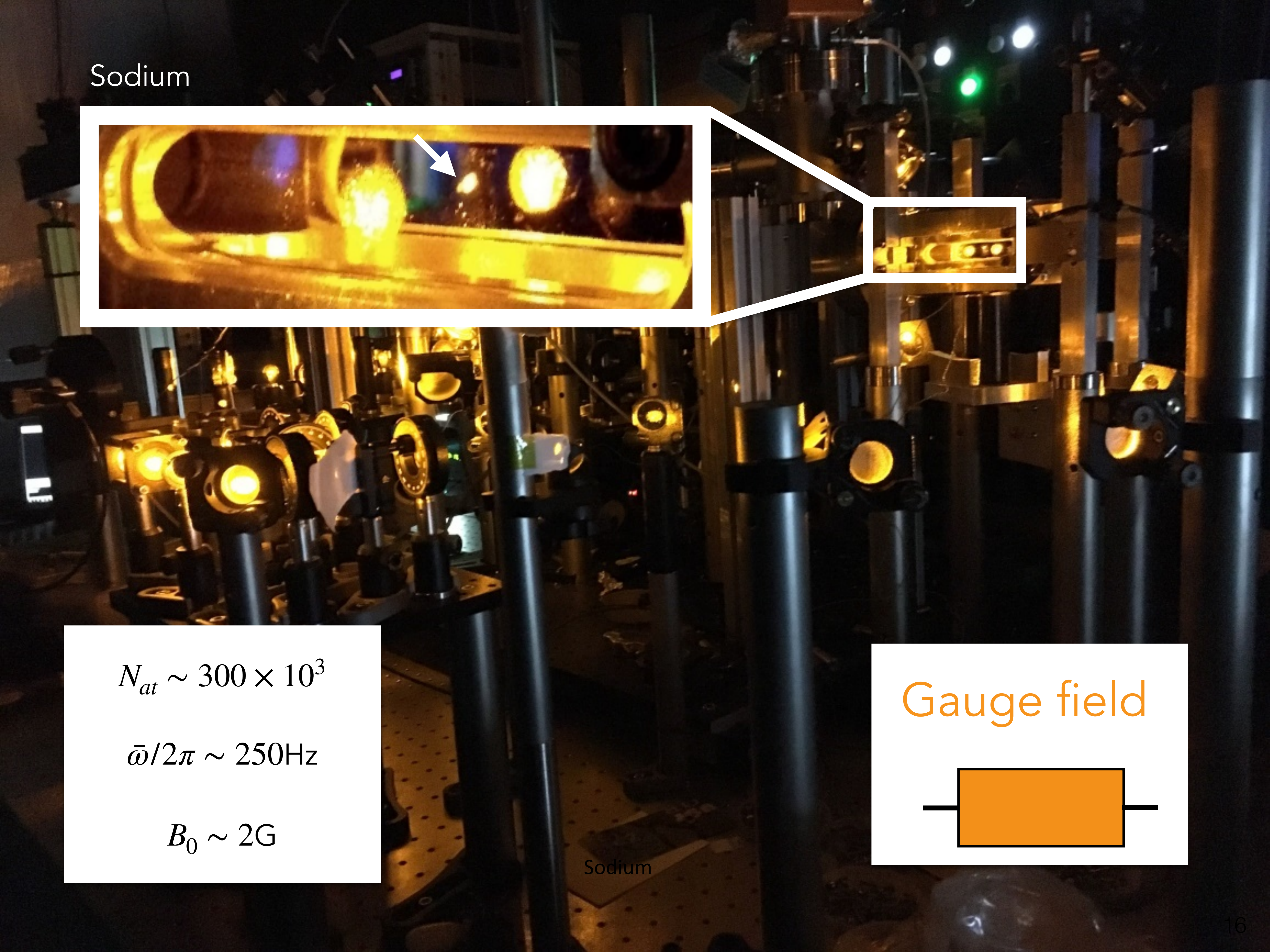


E. Martinez et al., Nature **534** 516 (2016).



C. Kokail et al., Nature **569**, 355 (2019).

Sodium



Sodium

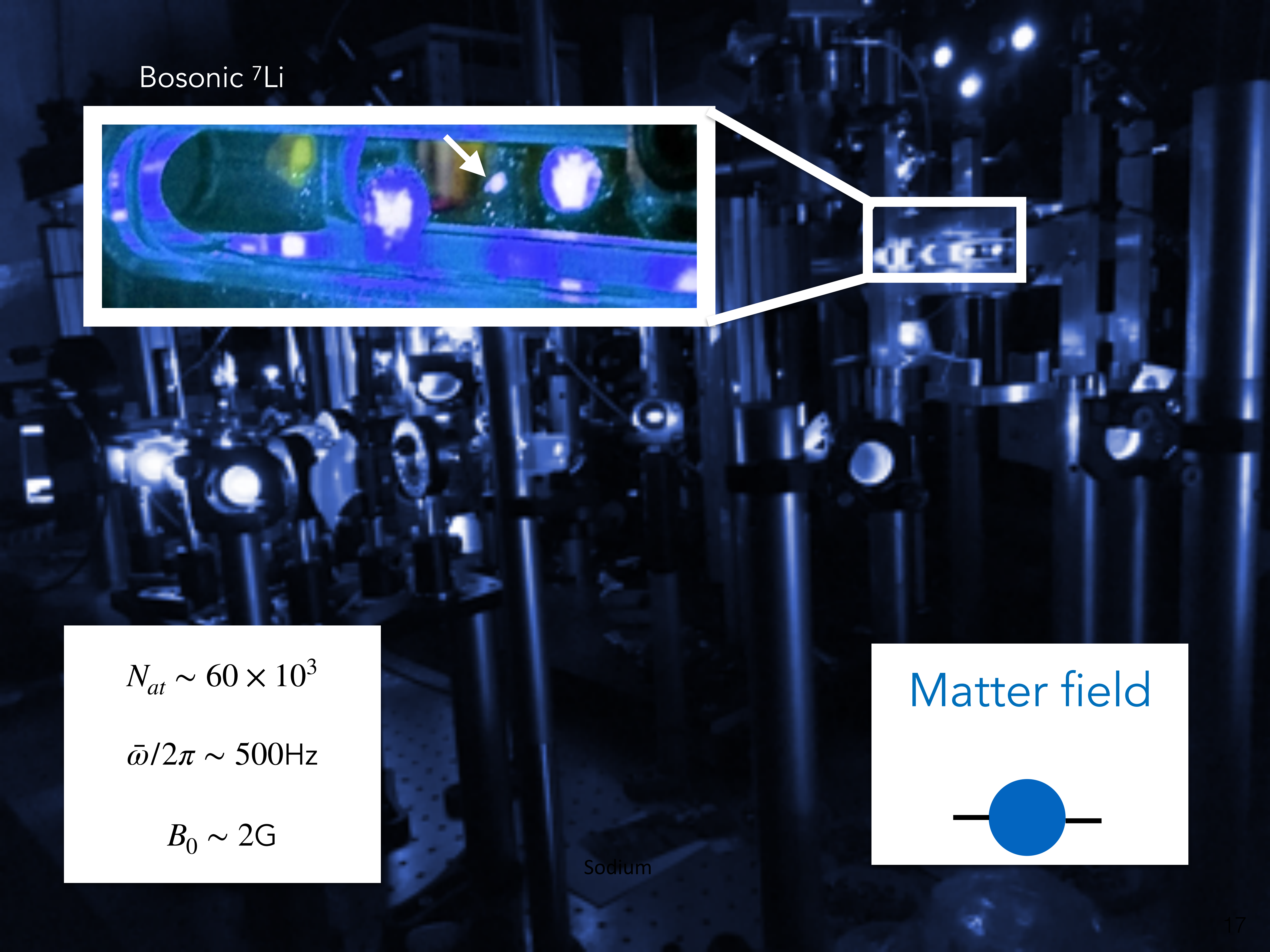
$N_{at} \sim 300 \times 10^3$

$\bar{\omega}/2\pi \sim 250\text{Hz}$

$B_0 \sim 2\text{G}$

Gauge field

Sodium



$N_{at} \sim 60 \times 10^3$

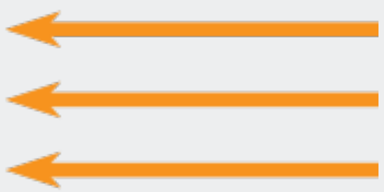
$\bar{\omega}/2\pi \sim 500\text{Hz}$

$B_0 \sim 2\text{G}$

Matter field

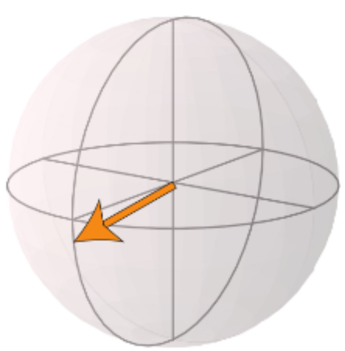
Gauge field

$$\hat{H}/\hbar = \chi L_z^2$$

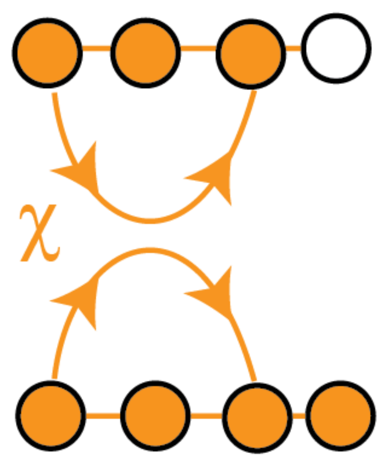


E

$|\uparrow\rangle = |1,0\rangle$



$|\downarrow\rangle = |1,1\rangle$



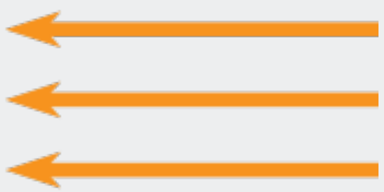
$N_{at} \sim 300 \times 10^3$

Mil et al. Science **367**, 1128 (2020)

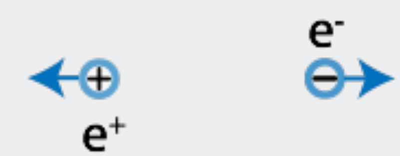
Gauge field

Matter field

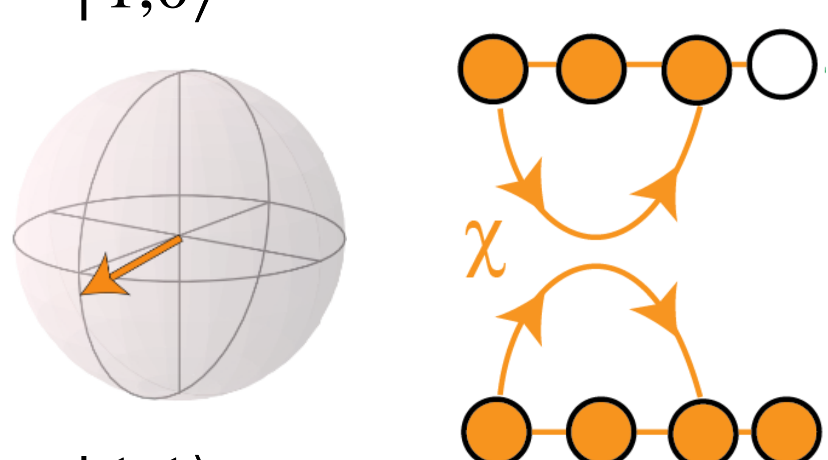
$$\hat{H}/\hbar = \chi L_z^2 + \frac{\Delta}{2}\left(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v\right)$$



E

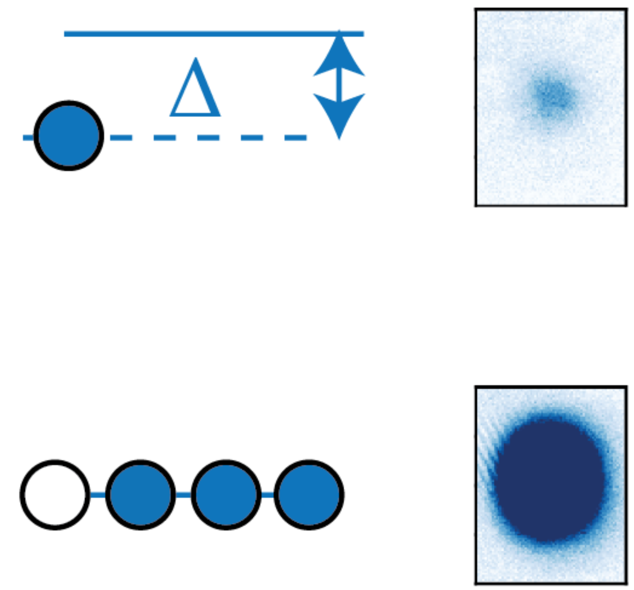


$|\uparrow\rangle = |1,0\rangle$



$|\downarrow\rangle = |1,1\rangle$

$N_{at} \sim 300 \times 10^3$



$|p\rangle = |1,0\rangle$

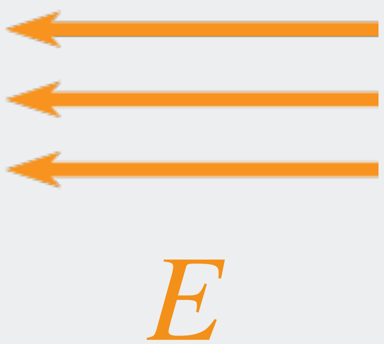
$|v\rangle = |1,1\rangle$

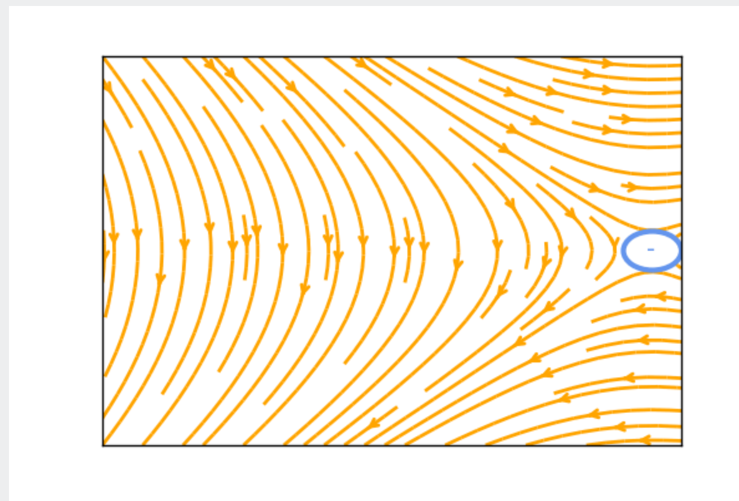
$N_{at} \sim 50 \times 10^3$

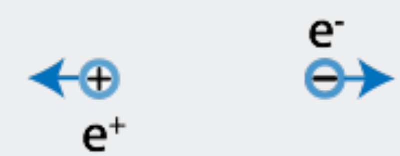
Mil et al. Science **367**, 1128 (2020)

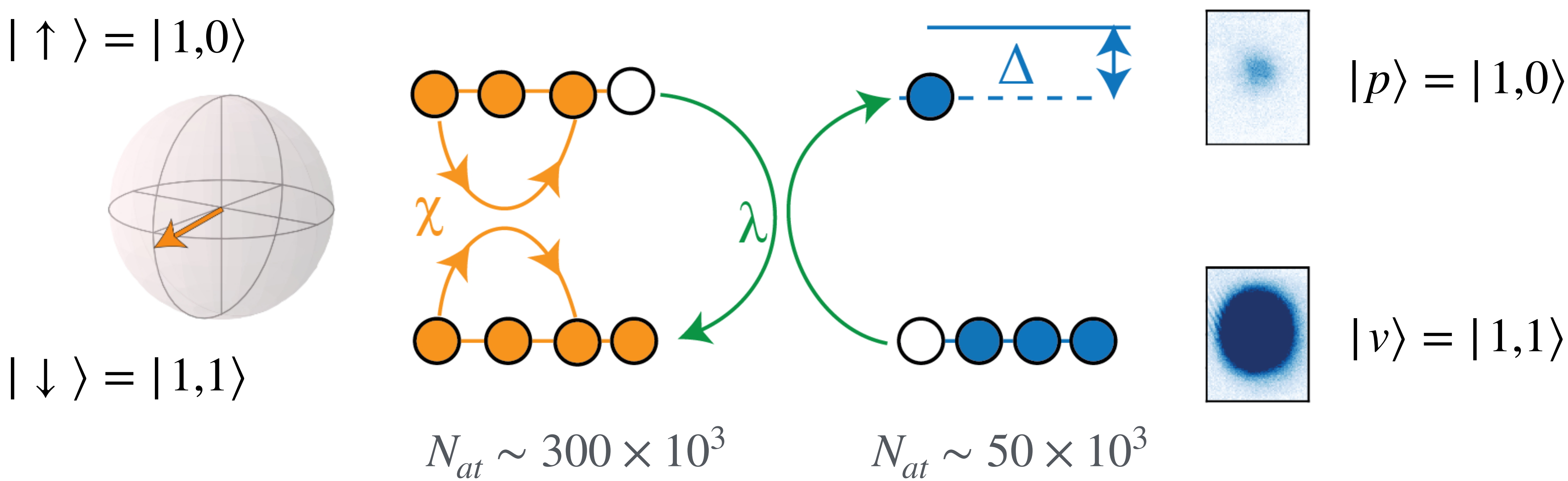
Gauge field | Gauge coupling | Matter field

$$\hat{H}/\hbar = \chi L_z^2 + \lambda\left(\hat{b}_p^\dagger \hat{L}_- \hat{b}_v + \hat{b}_v^\dagger \hat{L}_+ \hat{b}_p\right) + \frac{\Delta}{2}\left(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v\right)$$









Mil et al. Science **367**, 1128 (2020)

1.) Initialization

2.) Manipulation and evolution

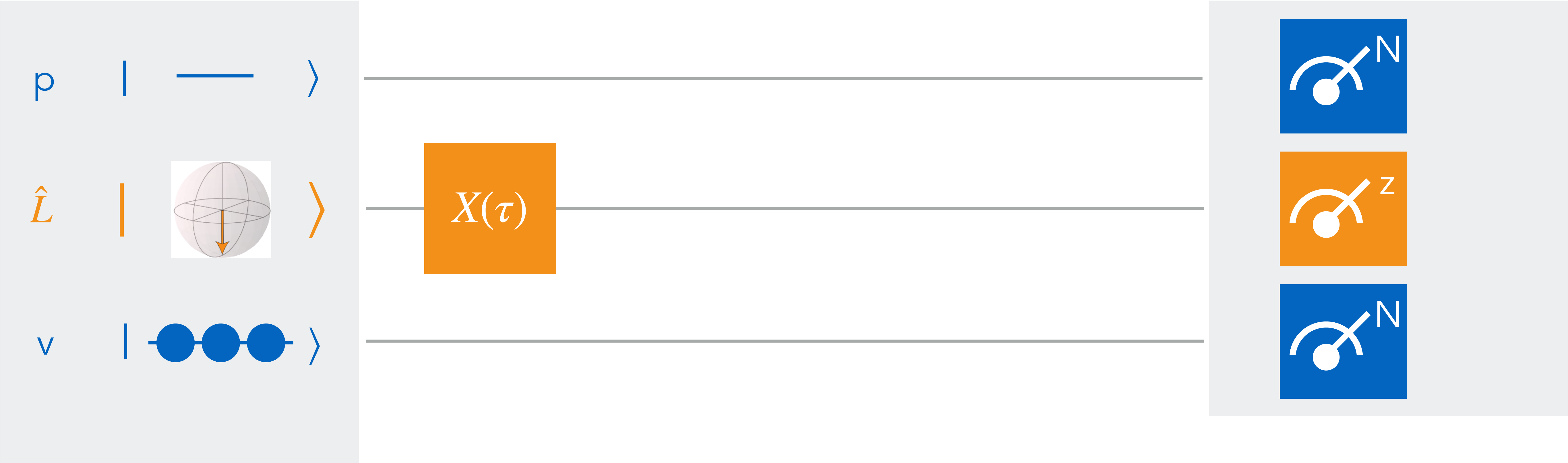
3.) Read-out

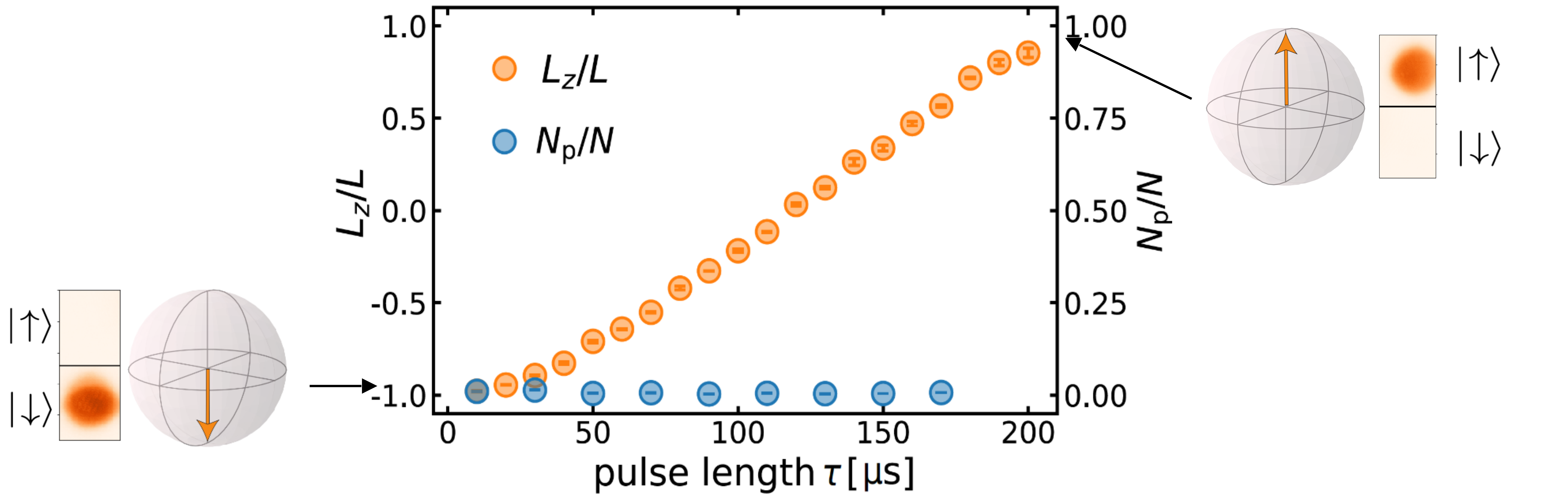
Mil et al. Science **367**, 1128 (2020)

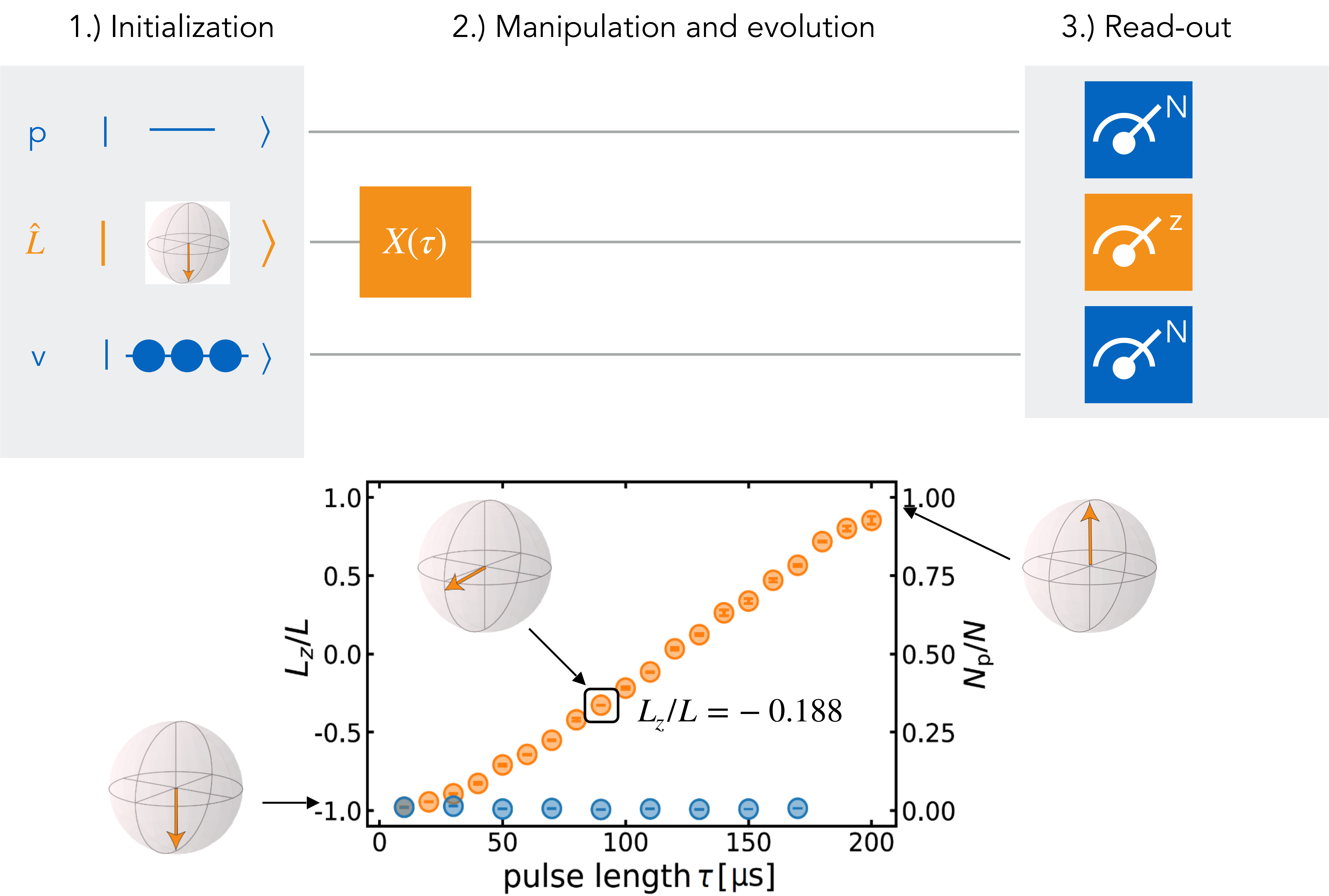
1.) Initialization

2.) Manipulation and evolution

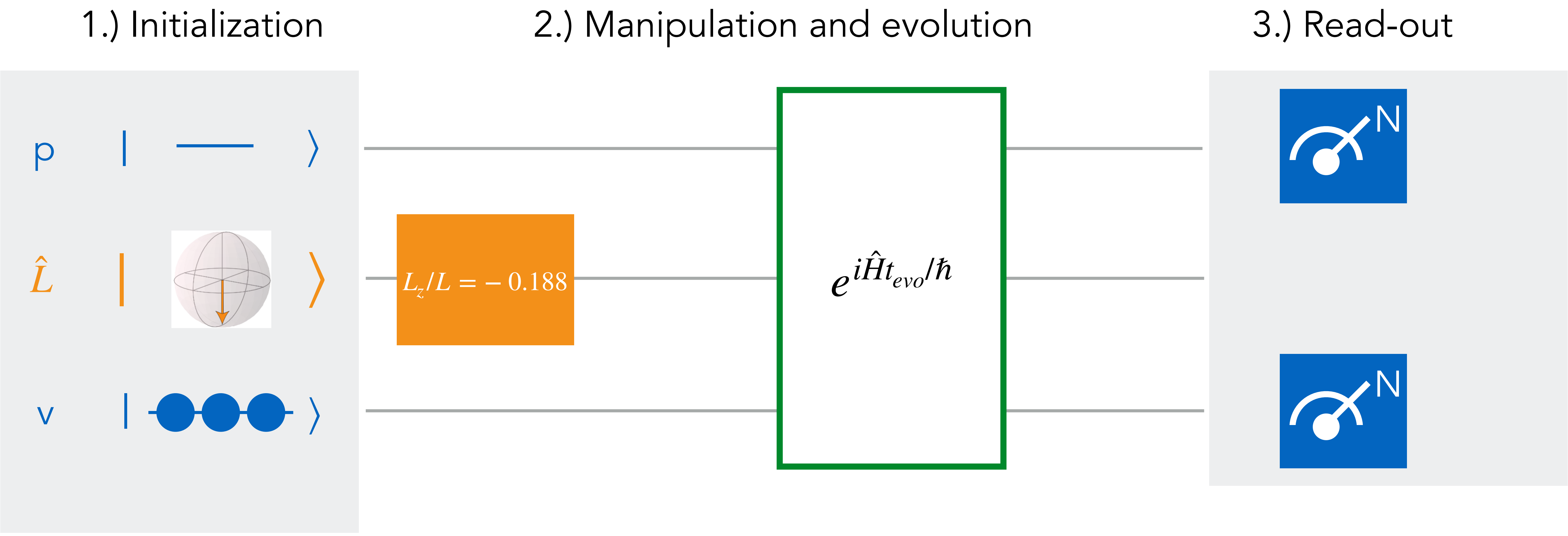
3.) Read-out

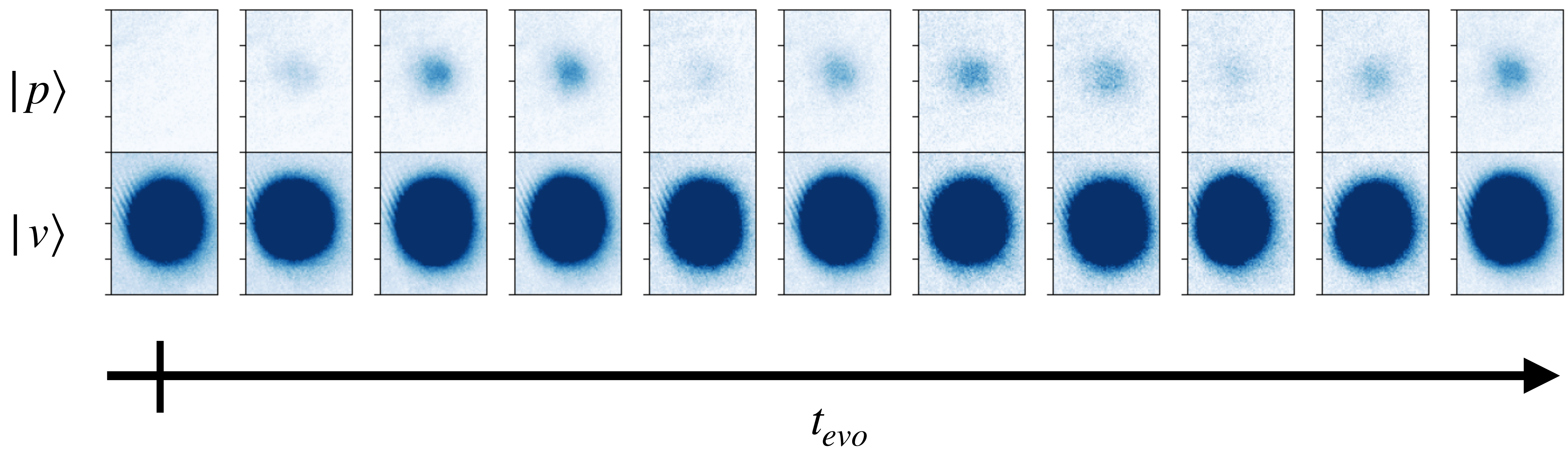


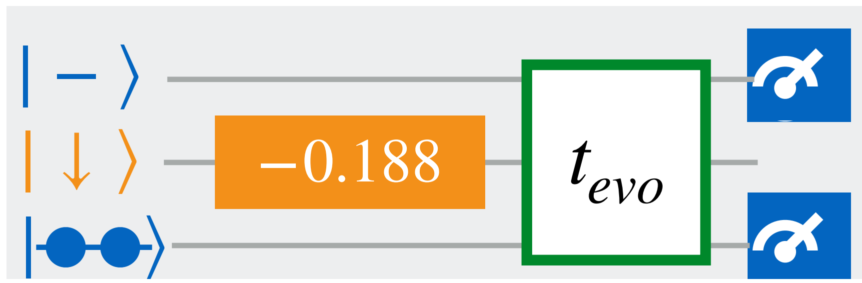


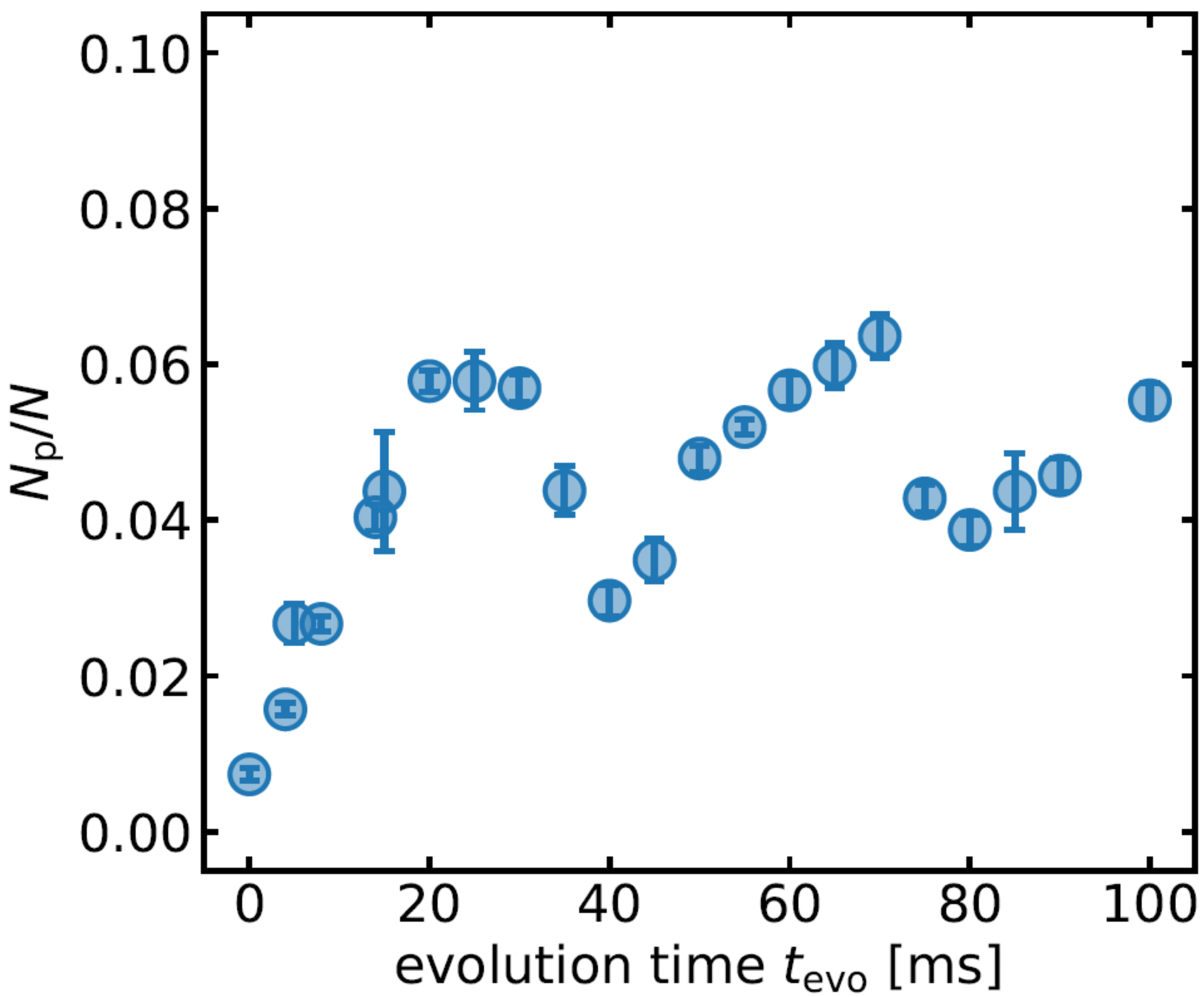


1.) Initialization
2.) Manipulation and evolution
3.) Read-out
p
$\hat{L}$
v
$X(\tau)$
N
z
N
1.0
0.5
0.0
-0.5
-1.0
L_z/L
1.00
0.75
0.50
0.25
0.00
N_p/N
$L_z/L = -0.188$
0
50
100
150
200
pulse length τ [μs]

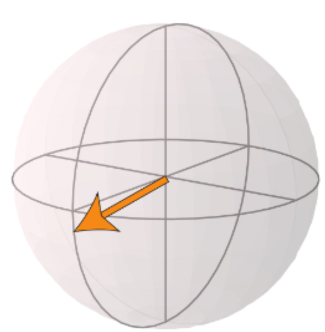

1.) Initialization
2.) Manipulation and evolution
3.) Read-out
p
$\hat{L}$
v
$L_z/L = -0.188$
$e^{i\hat{H}t_{evo}/\hbar}$
N
N


$|p\rangle$
$|v\rangle$
t_{evo}

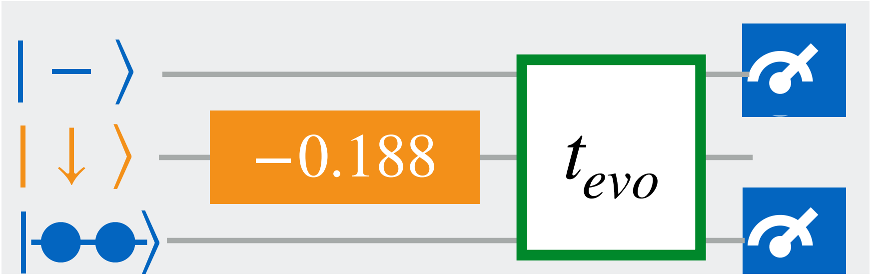

|−⟩
|↓⟩
−0.188
t_evo

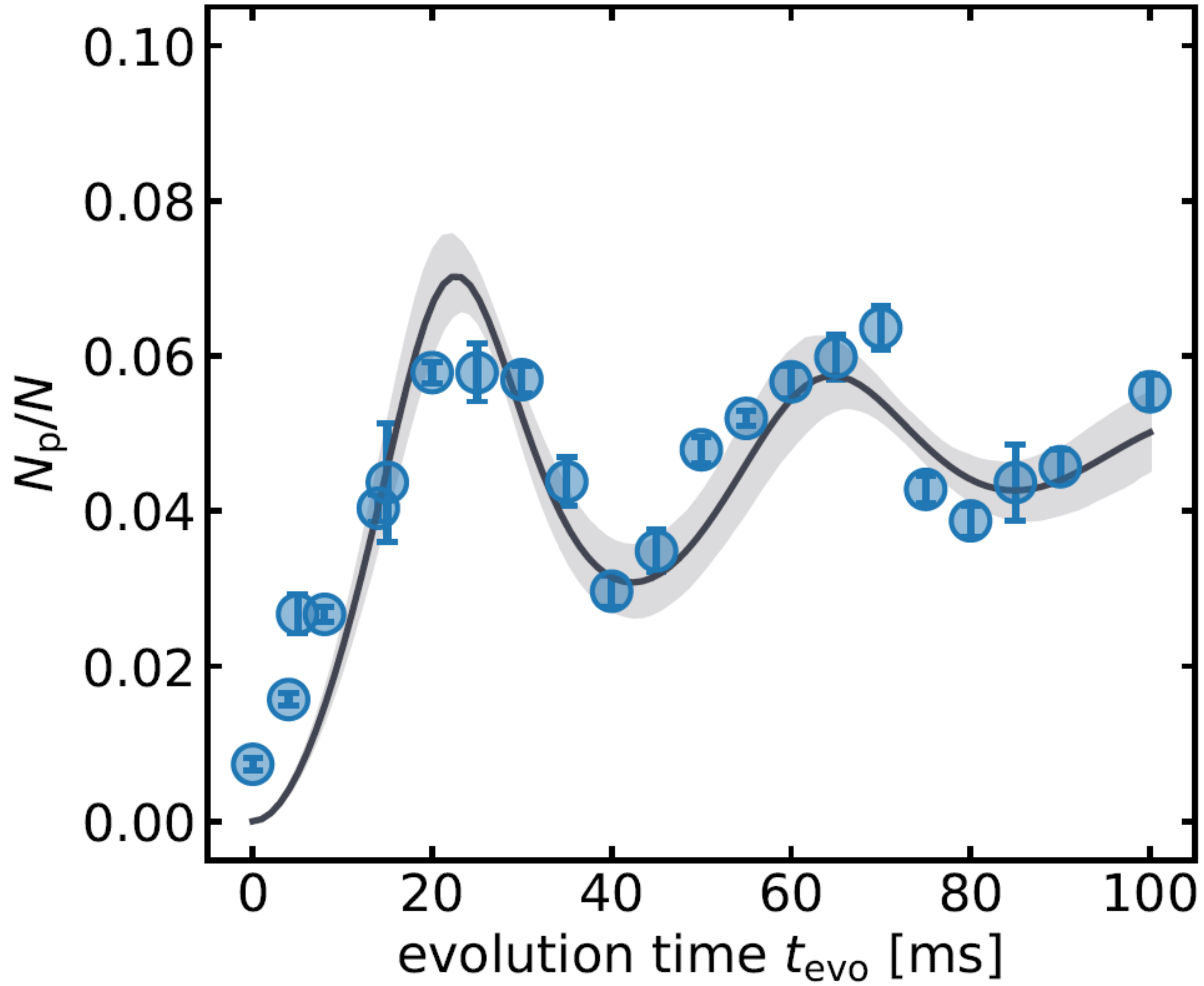

0.10
0.08
0.06
0.04
0.02
0.00
N_p/N
0
20
40
60
80
100
evolution time t_evo [ms]

L_z/L = -0.188

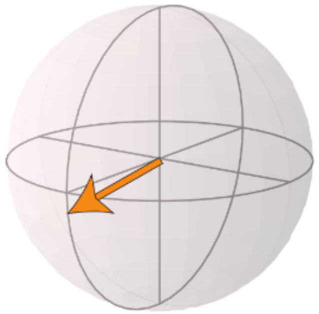


$$\hat{H}/\hbar = \chi \hat{L}_z^2 + \frac{\Delta}{2}\left(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v\right) + \lambda\left(b_v^\dagger \hat{L}_- \hat{b}_v + b_v^\dagger \hat{L}_+ \hat{b}_p\right)$$

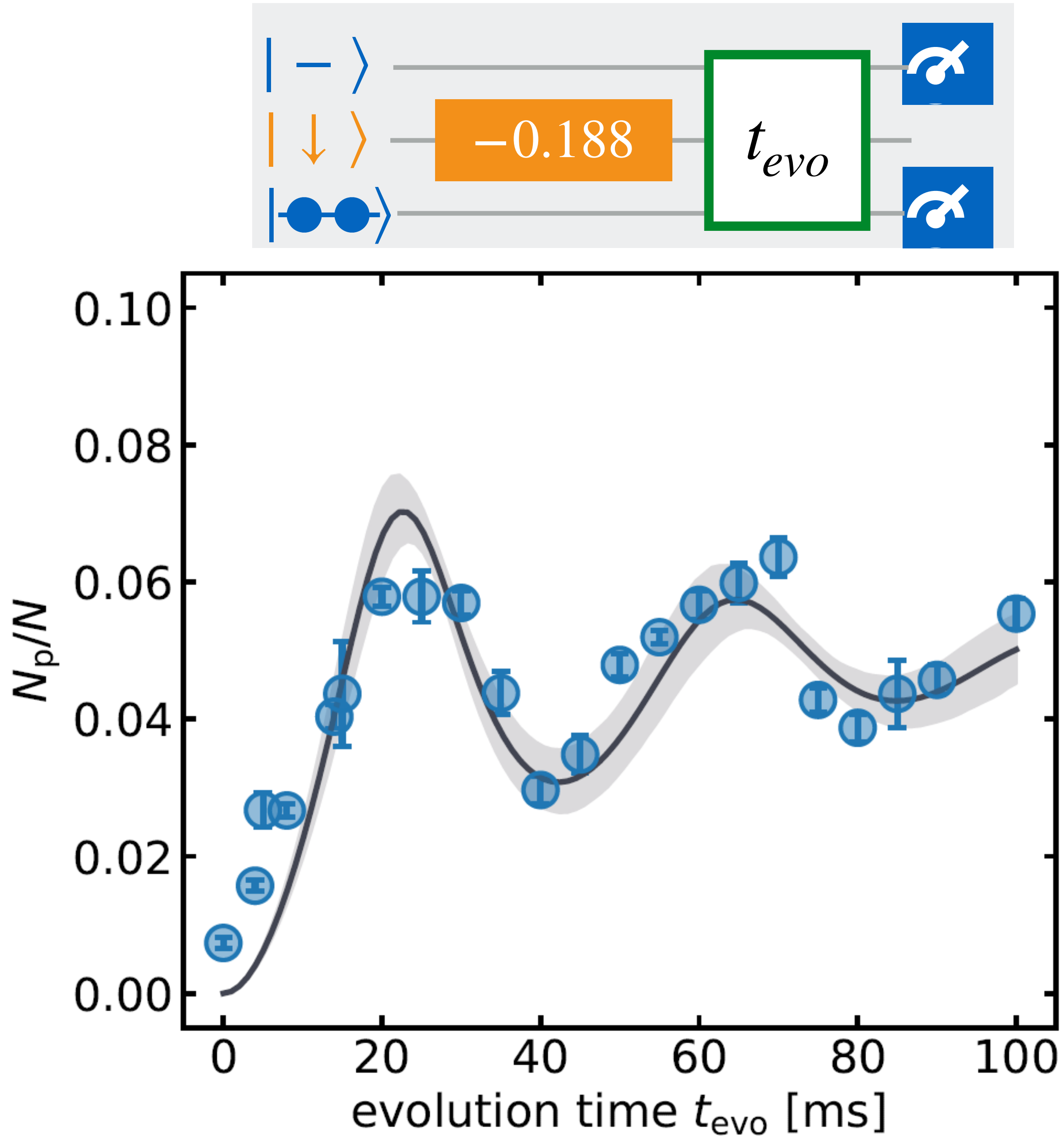


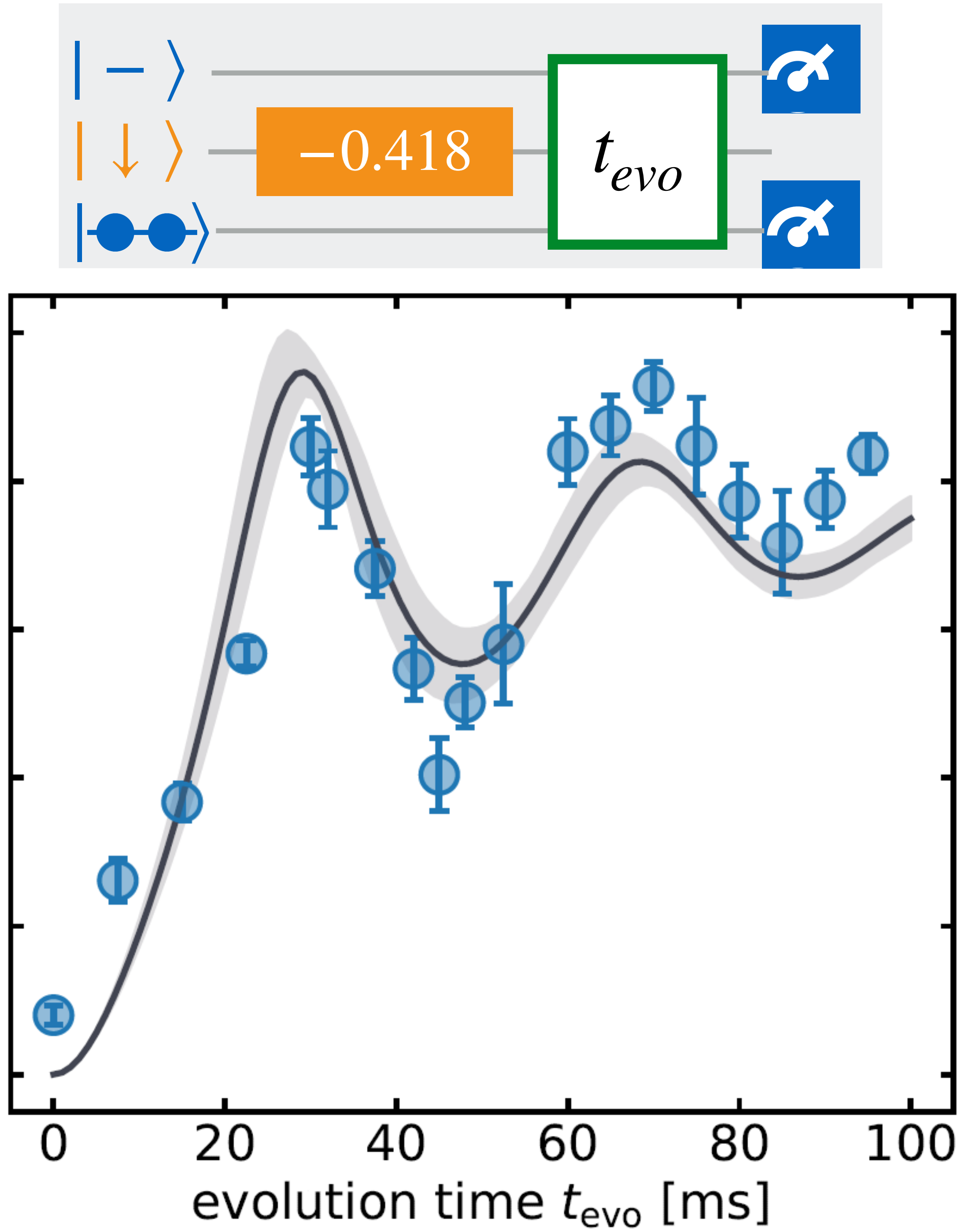


L_z/L = -0.188

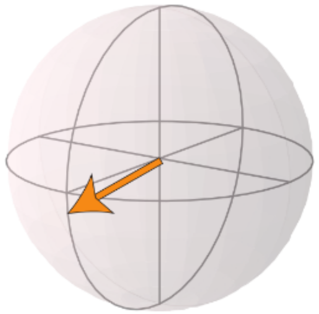


$$\hat{H}/\hbar = \chi \hat{L}_z^2 + \frac{\Delta}{2}\left(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v\right) + \lambda\left(b_v^\dagger \hat{L}_- \hat{b}_v + b_v^\dagger \hat{L}_+ \hat{b}_p\right)$$

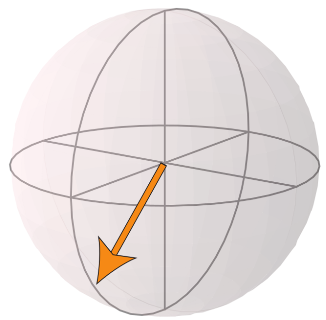


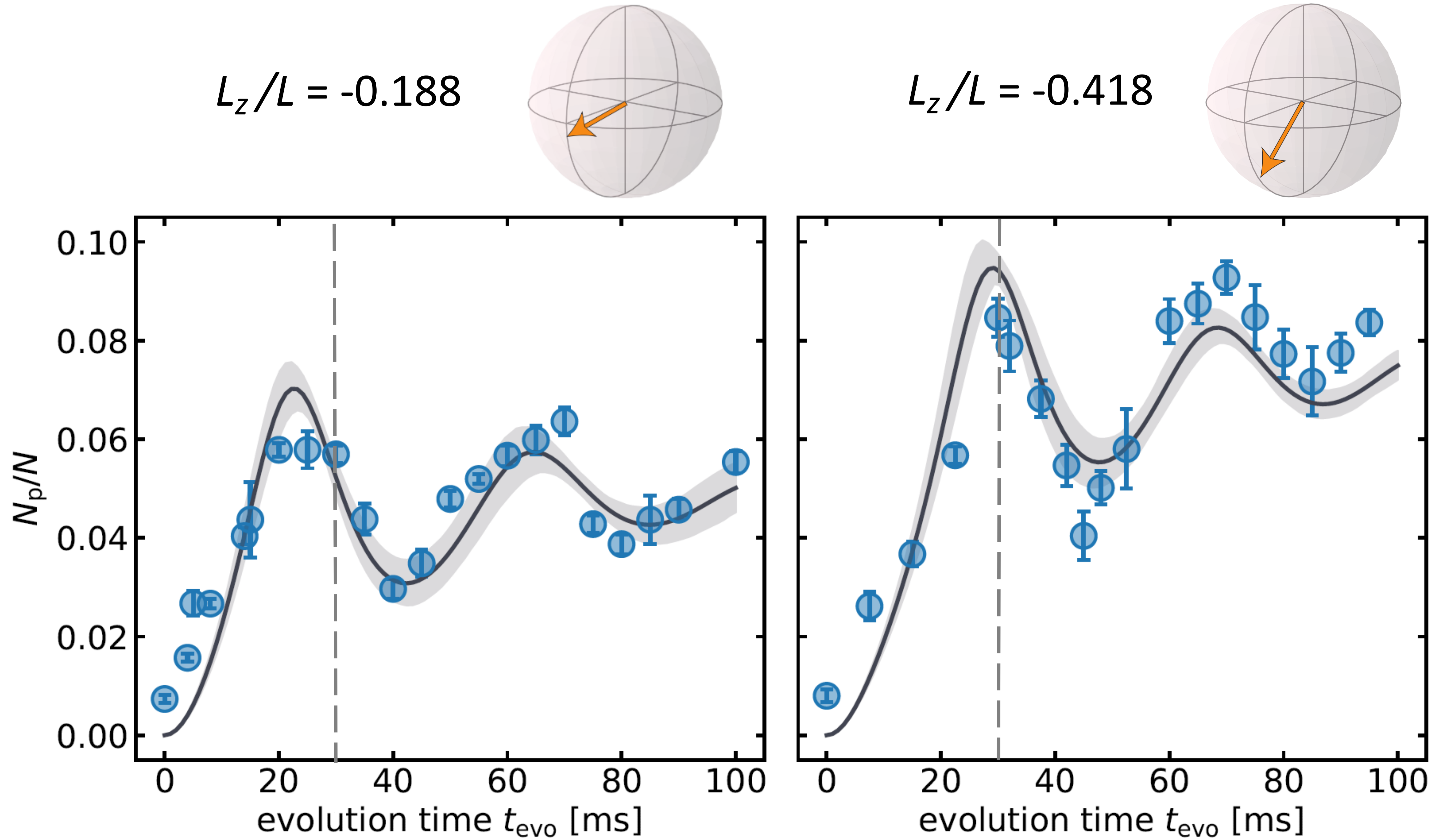


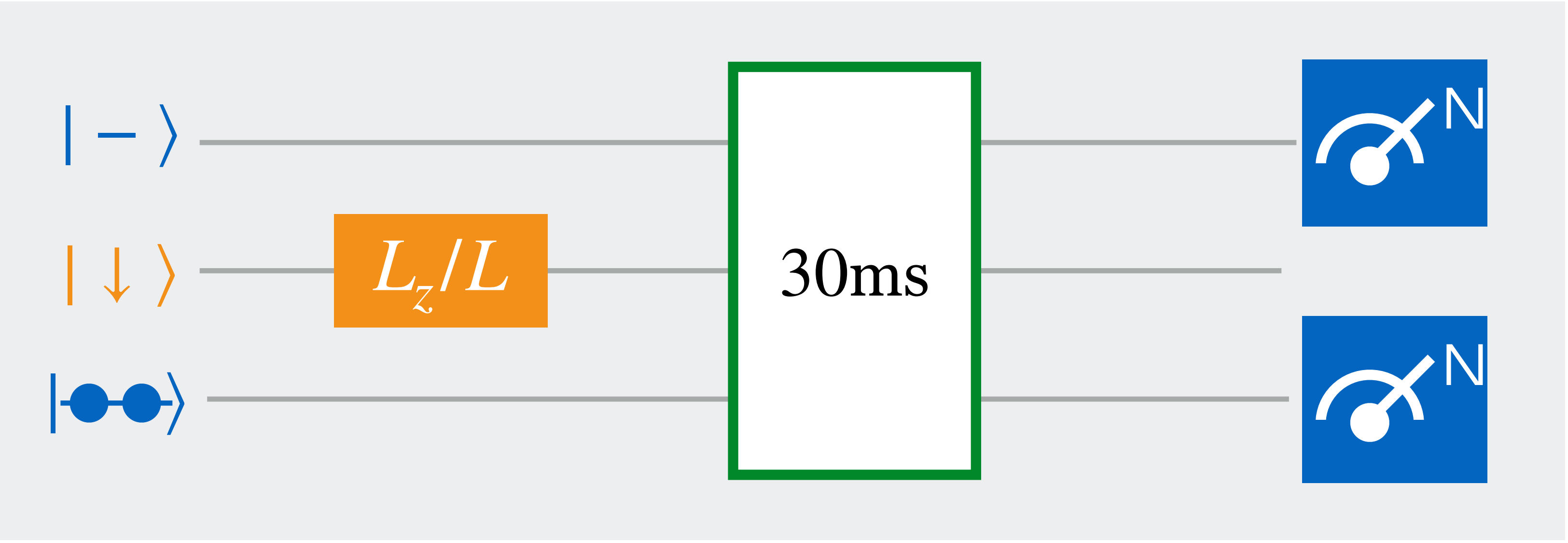
L_z/L = -0.188

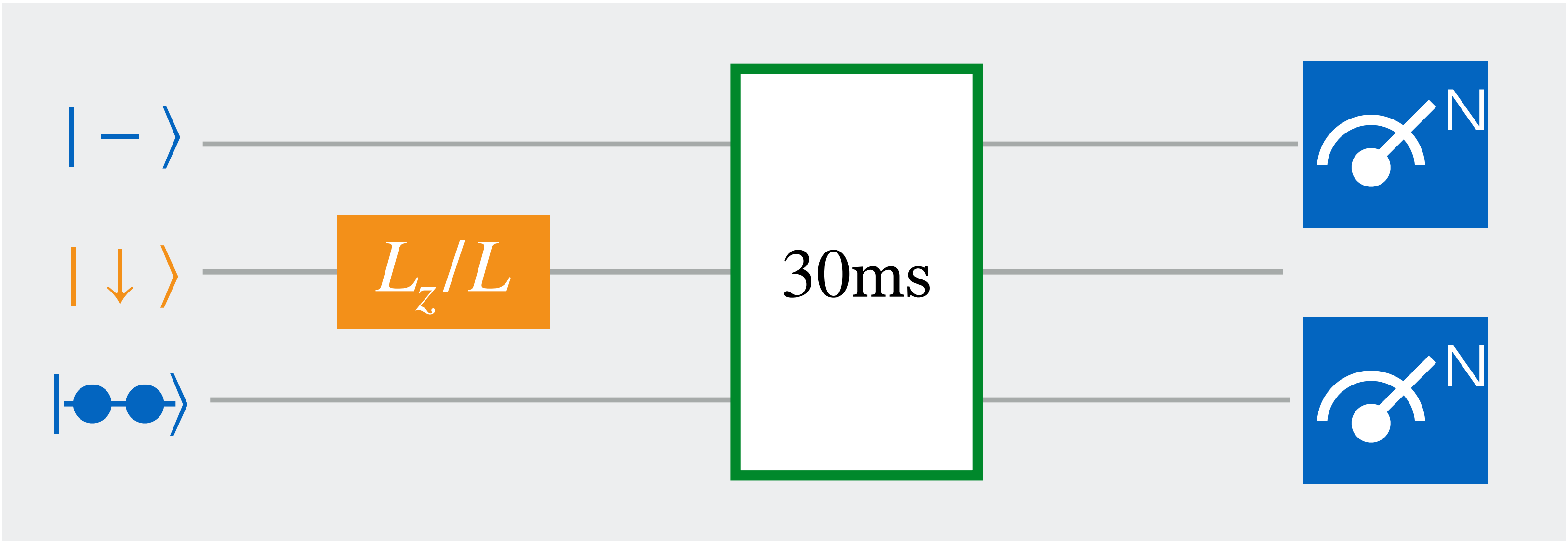


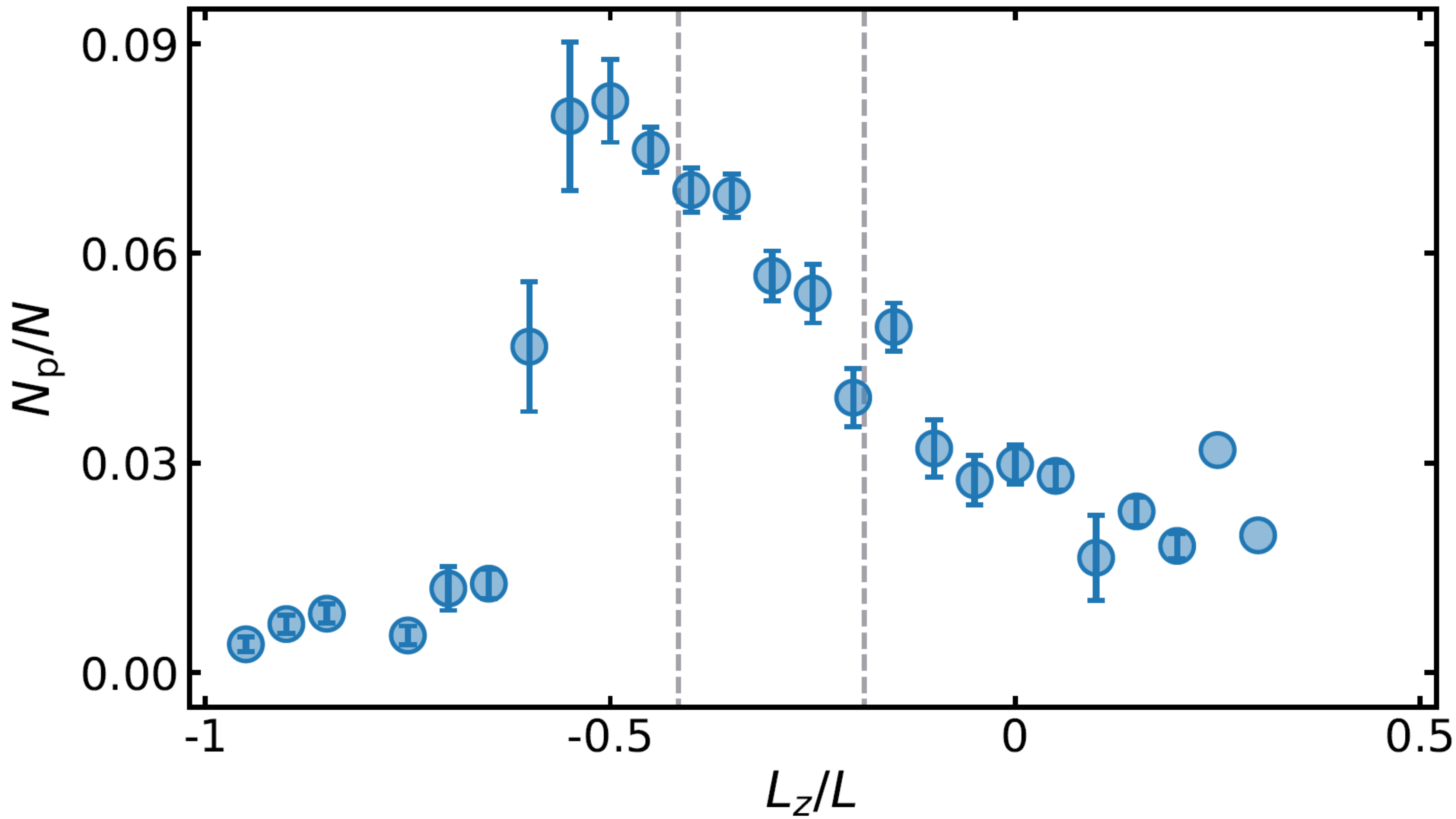
L_z/L = -0.418

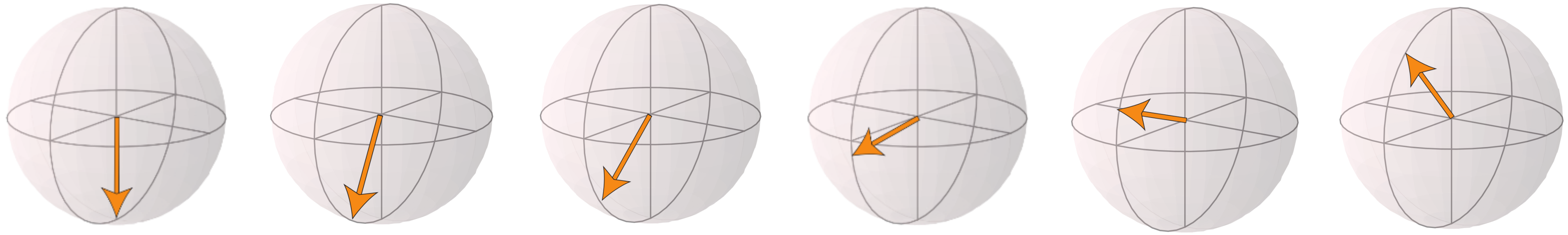


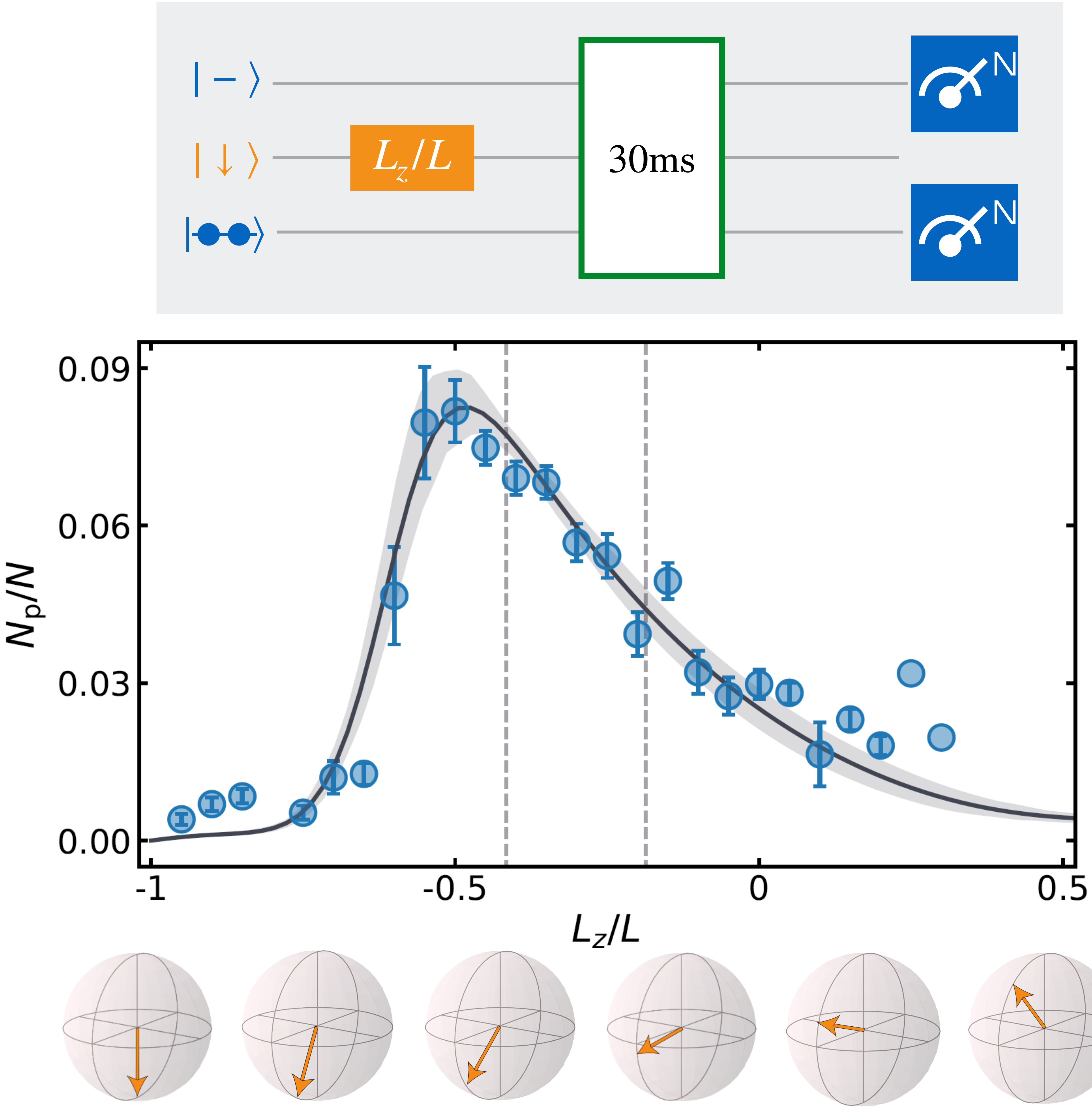

L_z/L = -0.188
L_z/L = -0.418
0.10
0.08
0.06
0.04
0.02
0.00
N_p/N
0 20 40 60 80 100
evolution time t_{evo} [ms]
0 20 40 60 80 100
evolution time t_{evo} [ms]

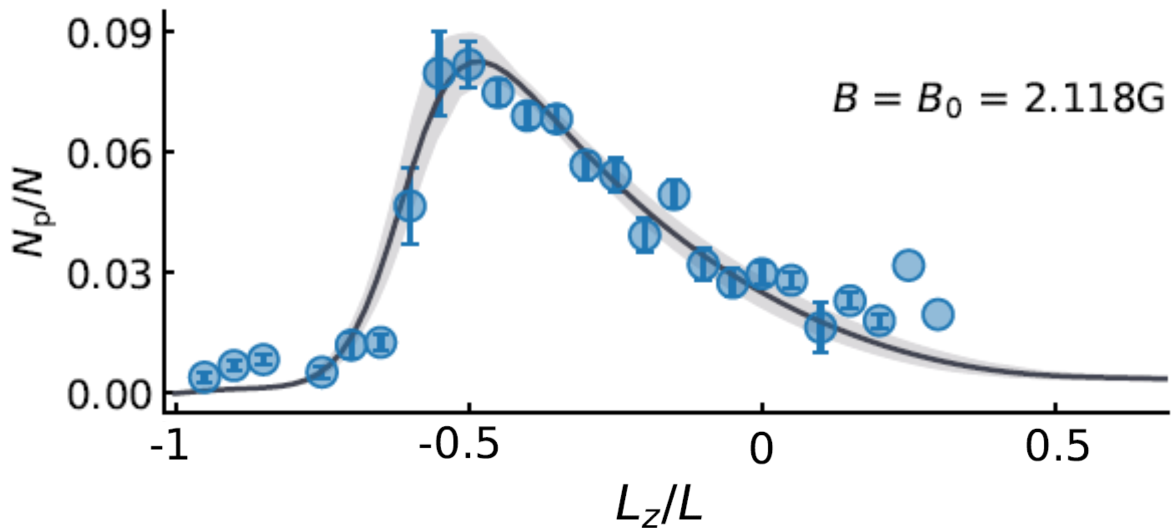

$|-\rangle$
$|\downarrow\rangle$
L_z/L
30ms
N
N

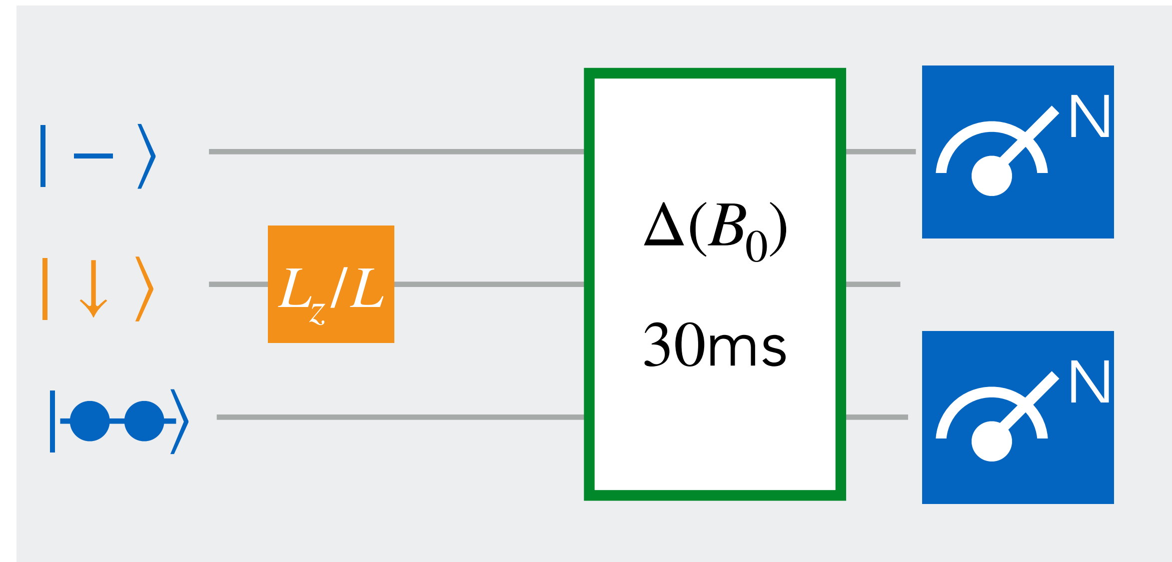

$|-\rangle$
$|\downarrow\rangle$
L_z/L
30ms
N
N

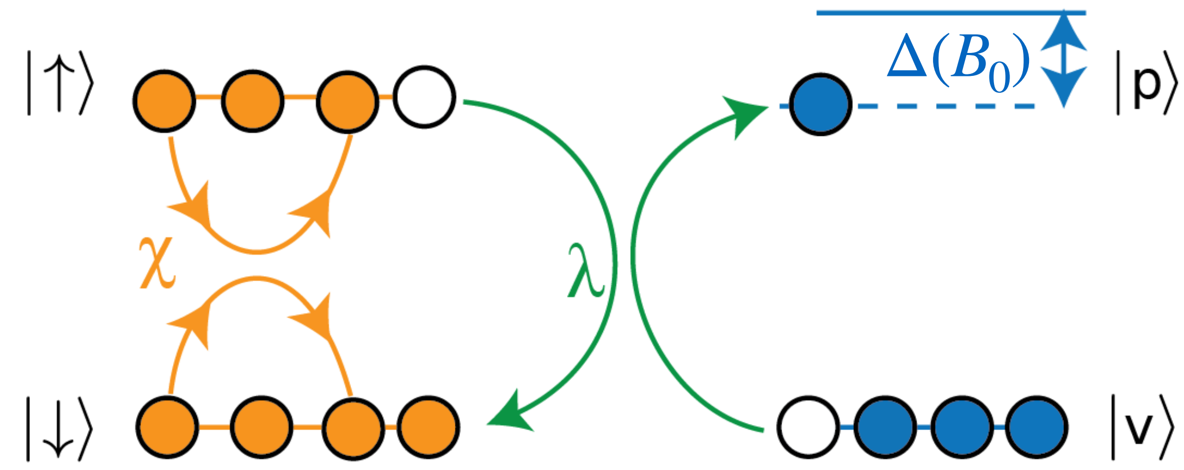

0.09
0.06
0.03
0.00
N_p/N
-1
-0.5
0
0.5
L_z/L

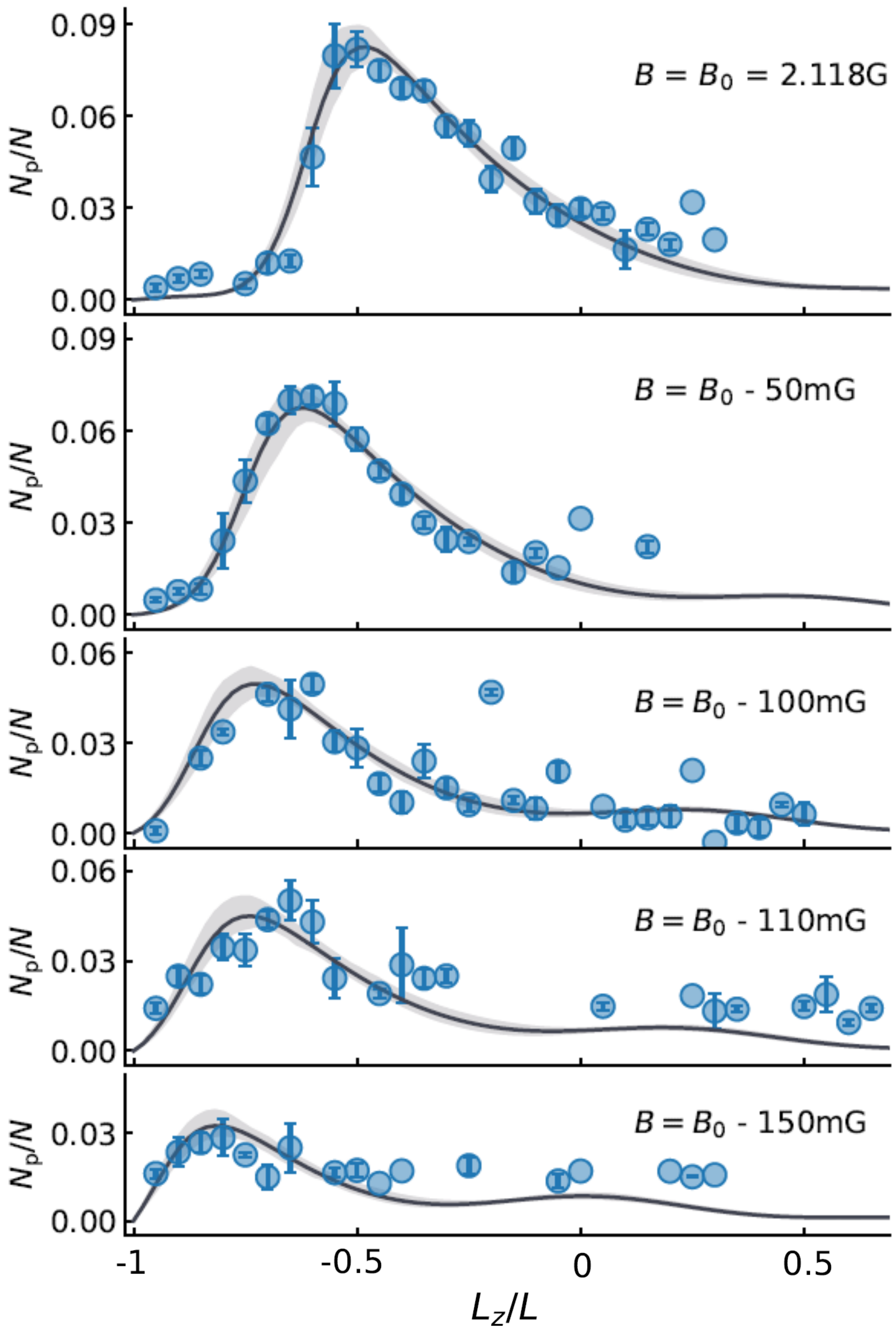



|−⟩
|↓⟩
|●●⟩
L_z/L
30ms
N
N
0.09
0.06
0.03
0.00
N_p/N
-1
-0.5
0
0.5
L_z/L

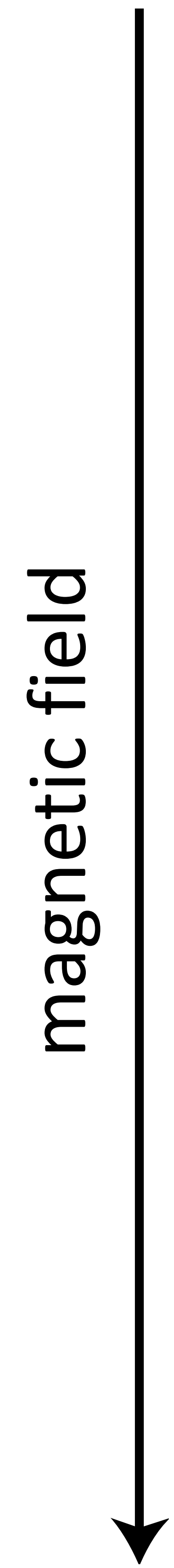

0.09
0.06
0.03
0.00
-1
-0.5
0
0.5
N_p/N
L_z/L
$B = B_0 = 2.118$G


$|-\rangle$
$|\downarrow\rangle$
L_z/L
$\Delta(B_0)$
30ms
N
N

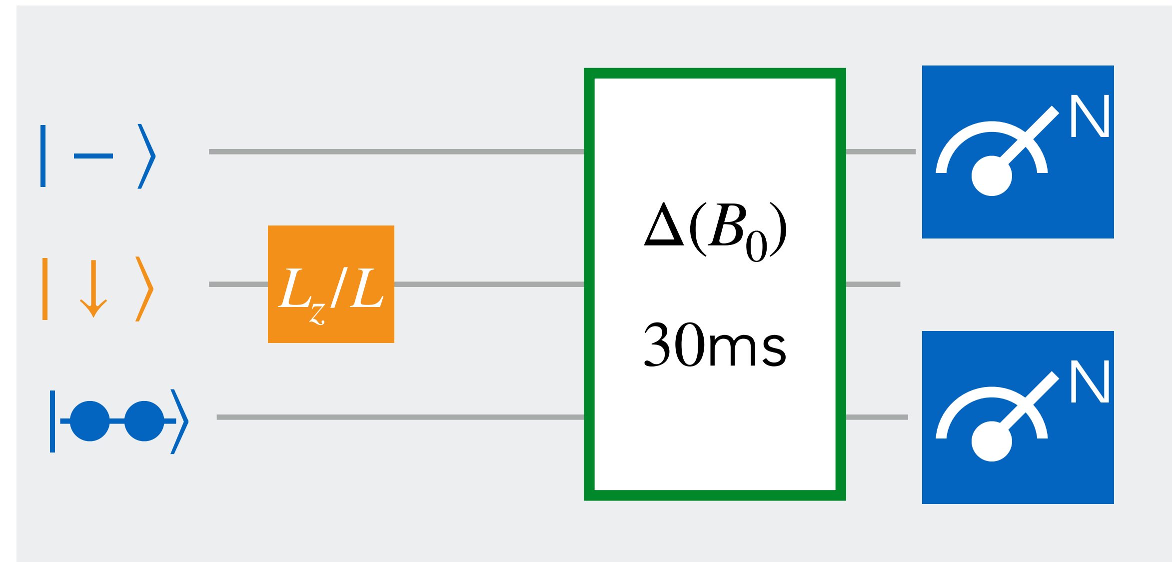

$|\uparrow\rangle$
$|\downarrow\rangle$
χ
λ
$\Delta(B_0)$
$|p\rangle$
$|v\rangle$



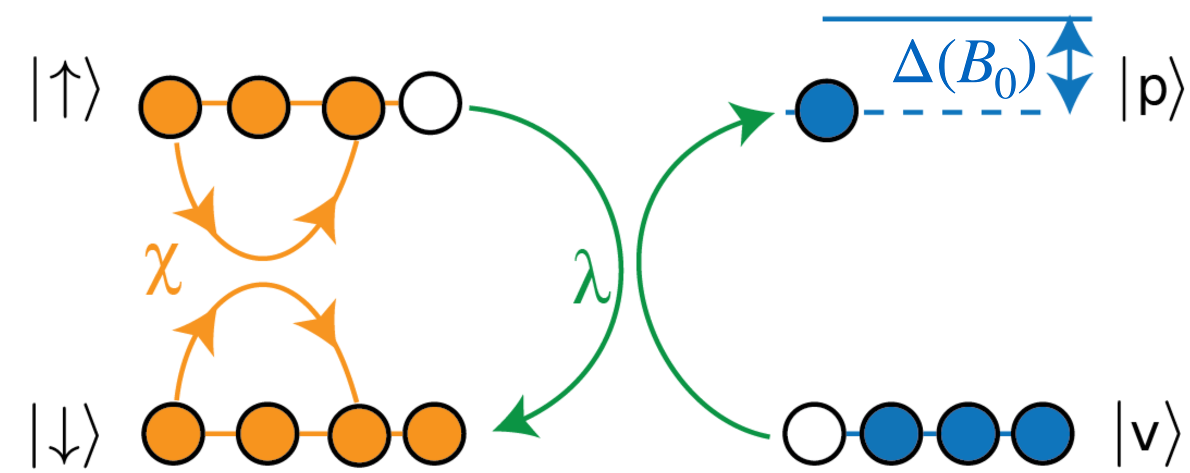
0.09
0.06
0.03
0.00
N_p/N
$B = B_0$ = 2.118G
$B = B_0$ - 50mG
$B = B_0$ - 100mG
$B = B_0$ - 110mG
$B = B_0$ - 150mG
-1
-0.5
0
0.5
L_z/L



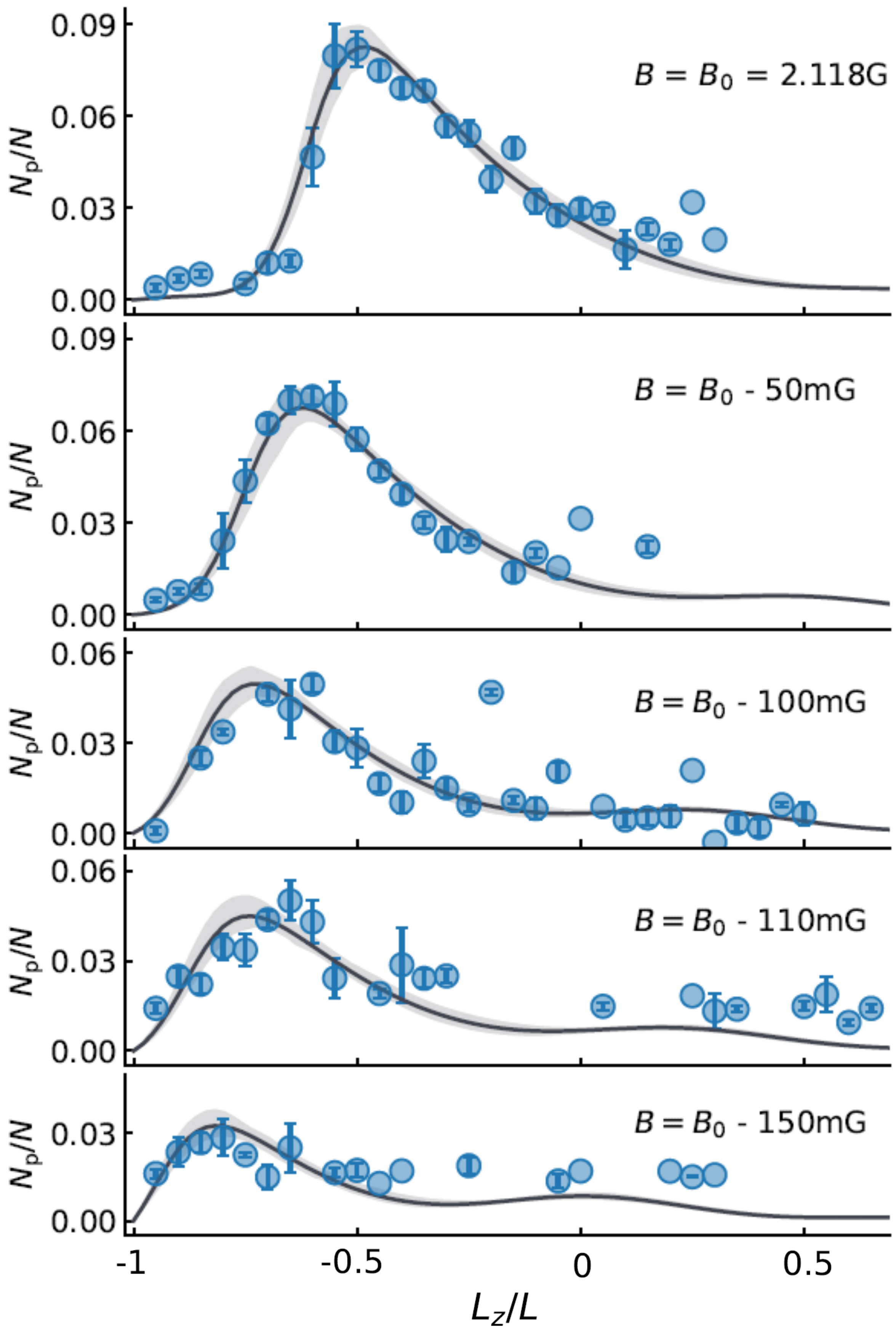
magnetic field

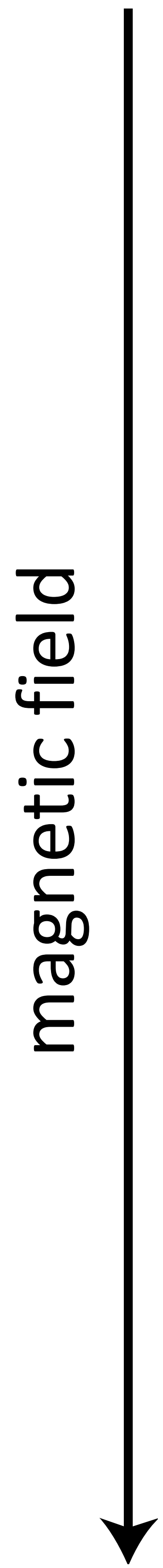


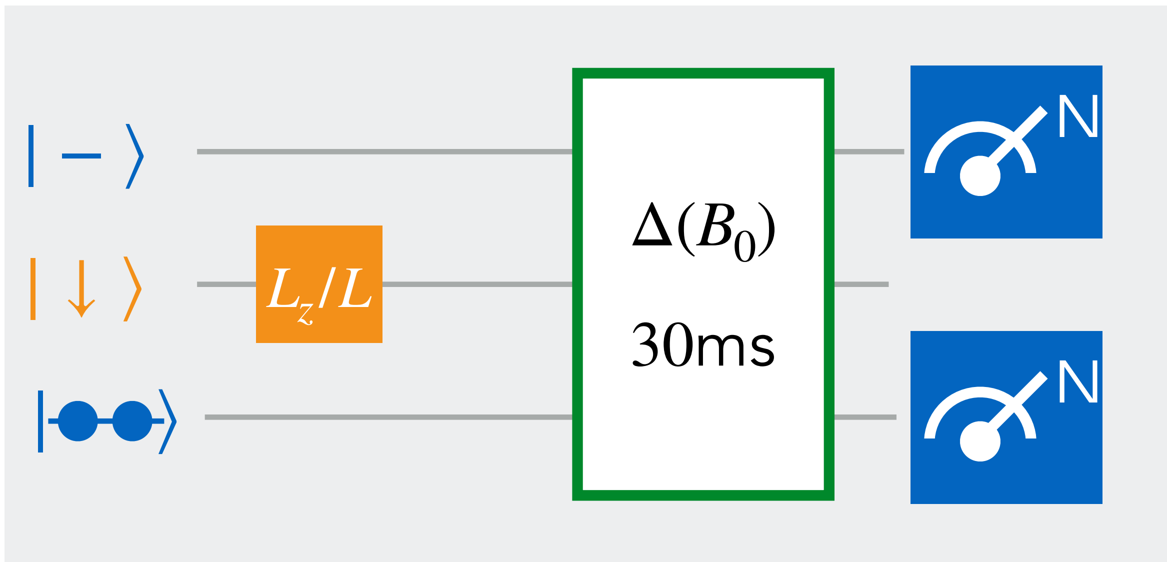
$|-\rangle$
$|\downarrow\rangle$
L_z/L
$\Delta(B_0)$
30ms
N
N

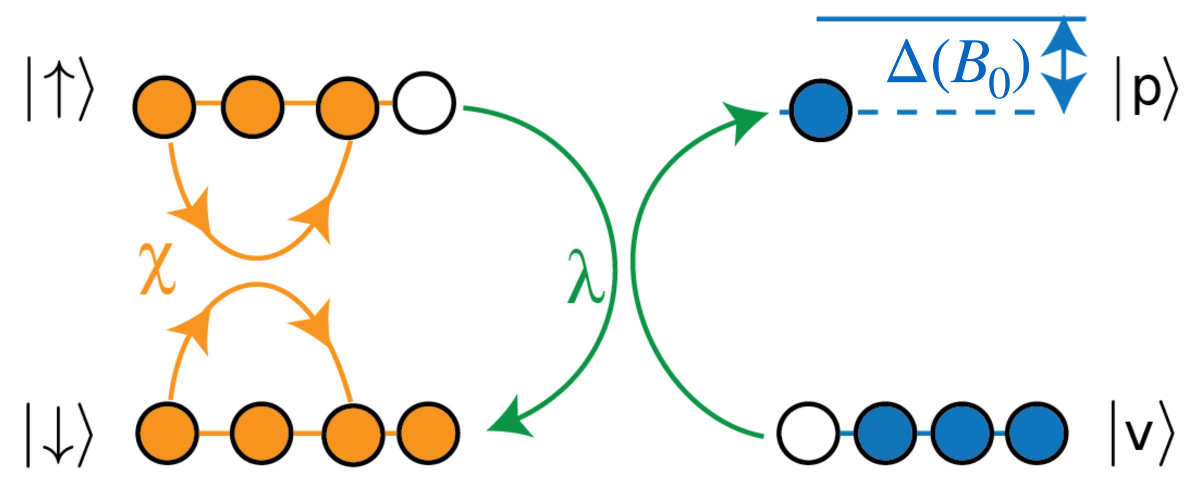


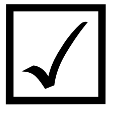
$|\uparrow\rangle$
$|\downarrow\rangle$
χ
λ
$\Delta(B_0)$
$|p\rangle$
$|v\rangle$

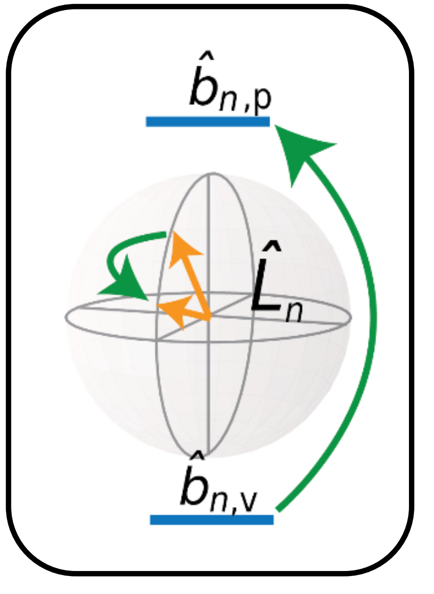




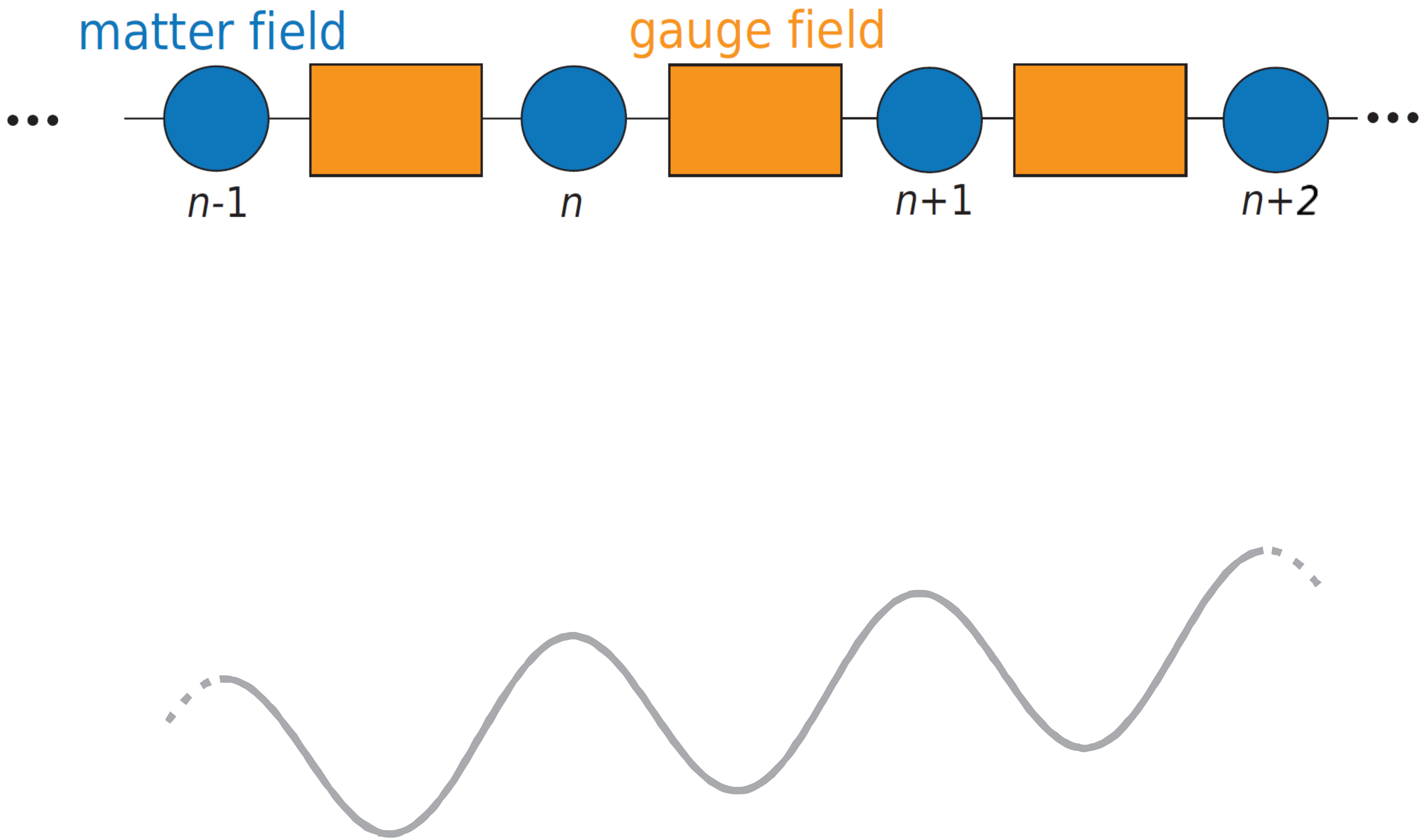






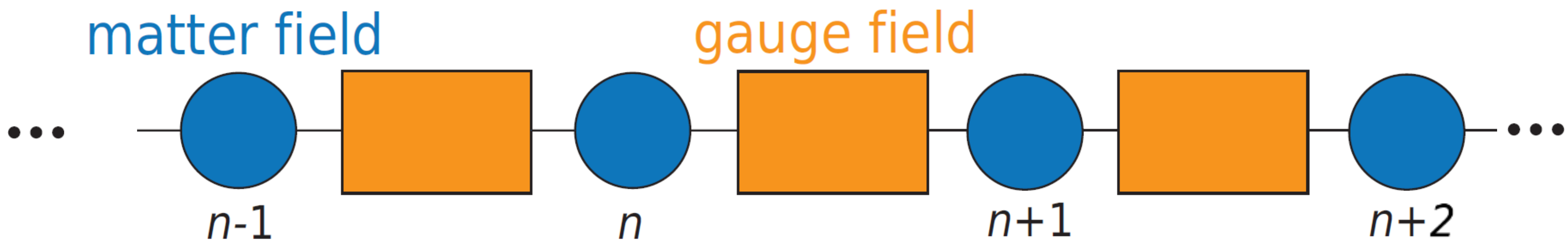


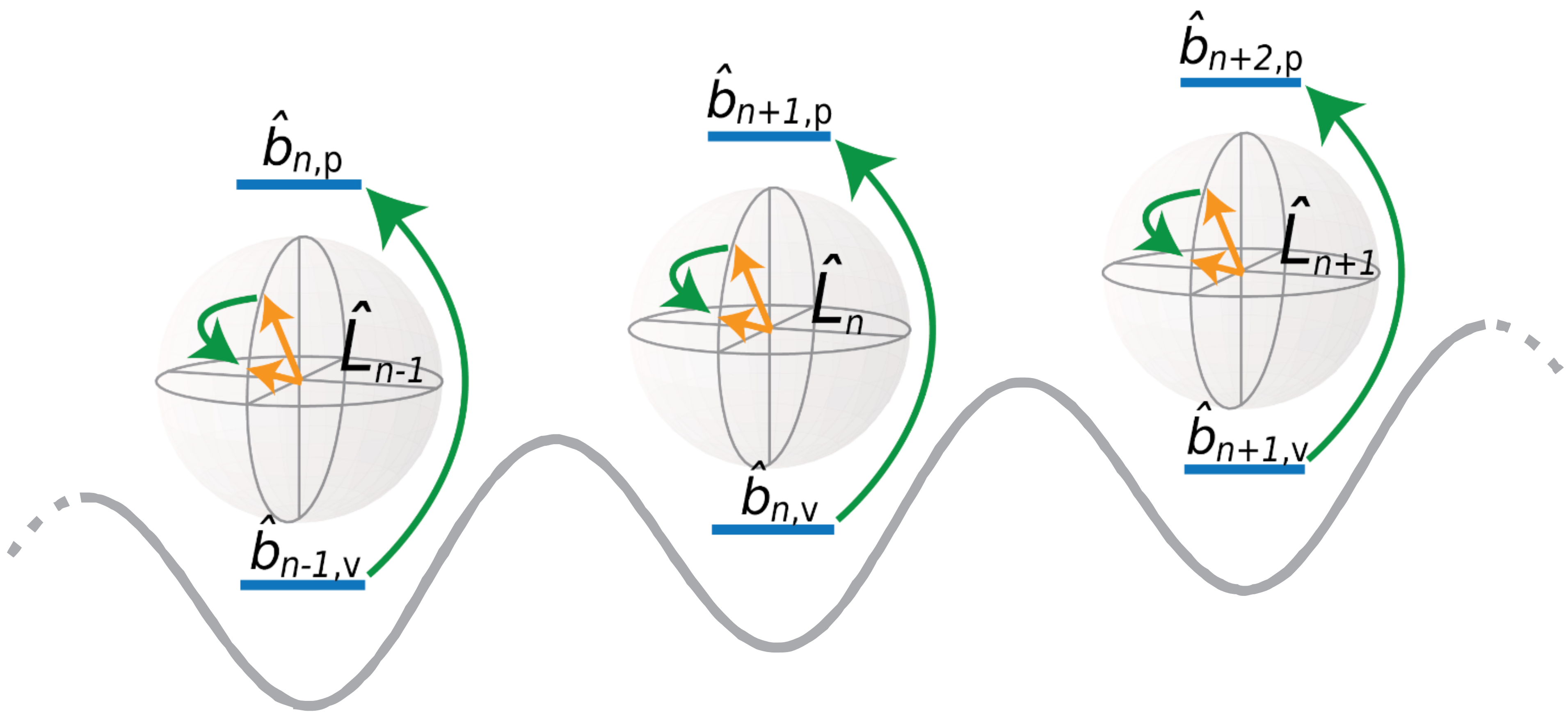
building block

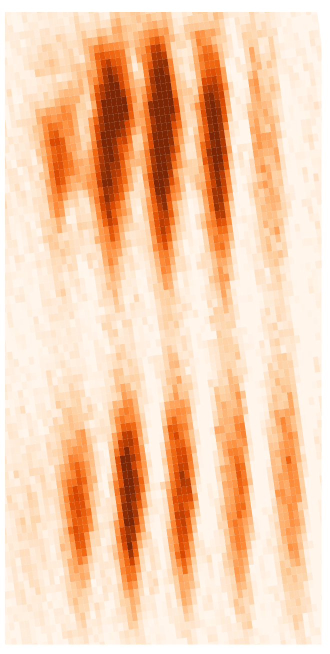


$$\hat{H} = \sum_n$$

Mil et al. Science **367**, 1128 (2020)

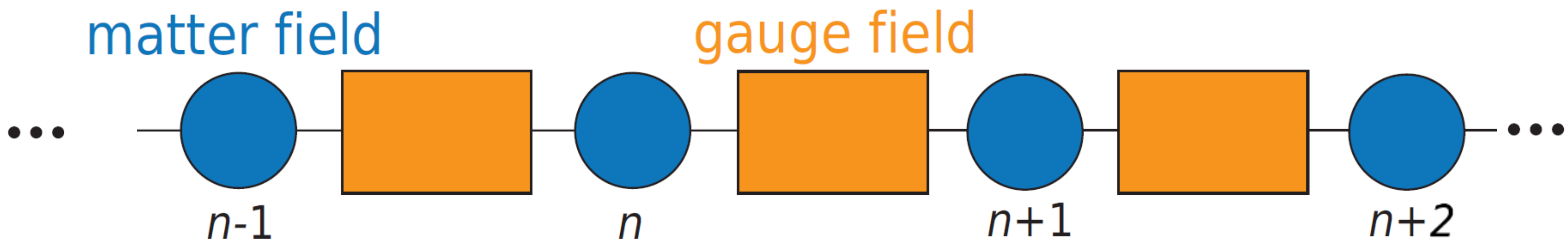


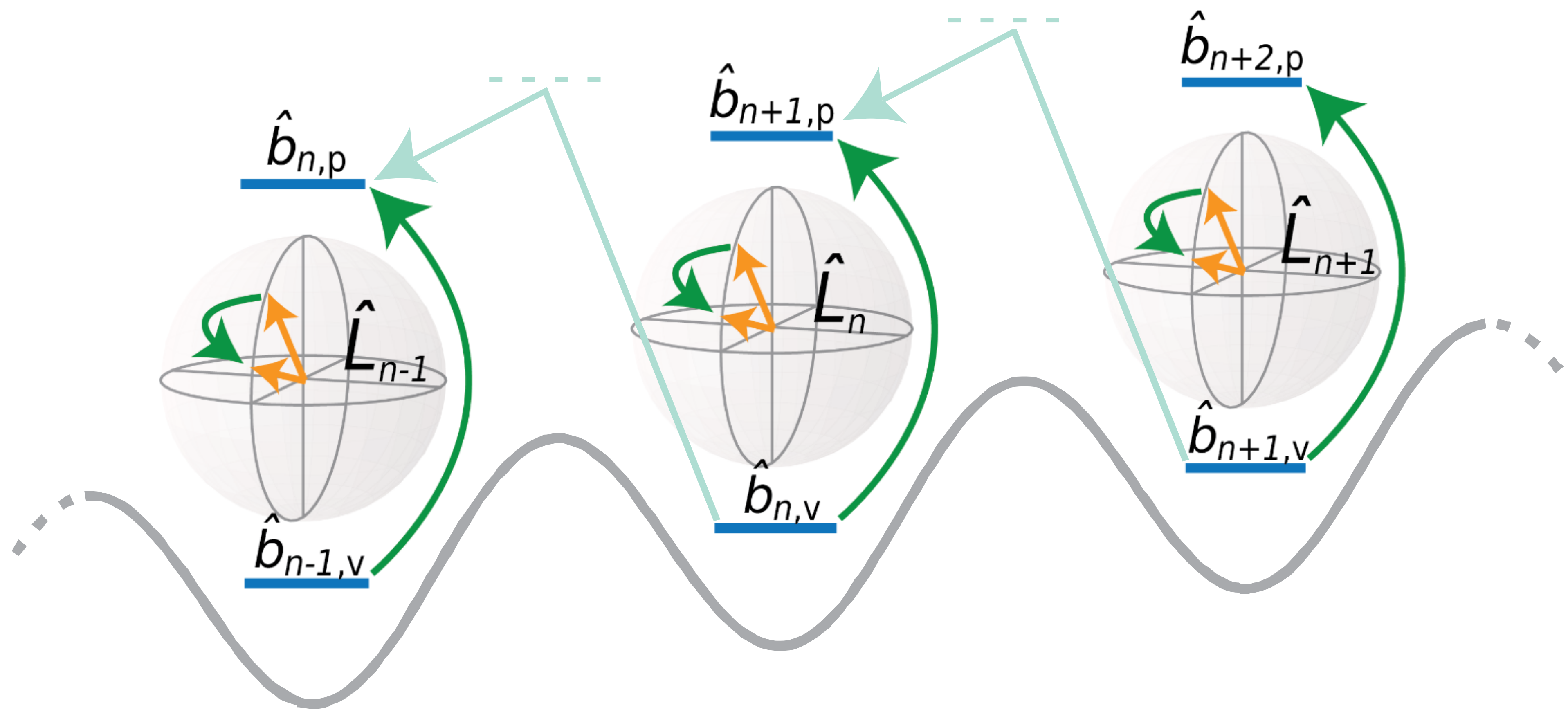


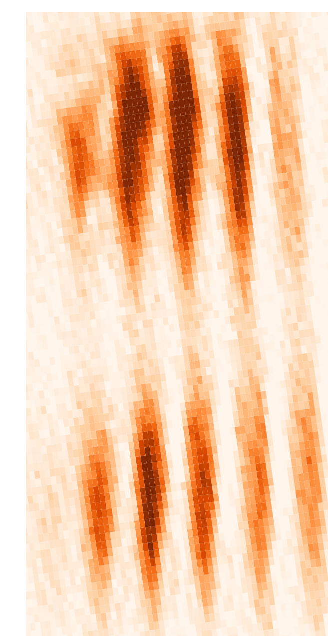


$$\hat{H} = \sum_n [\hat{H}_n$$

Mil et al. Science **367**, 1128 (2020)



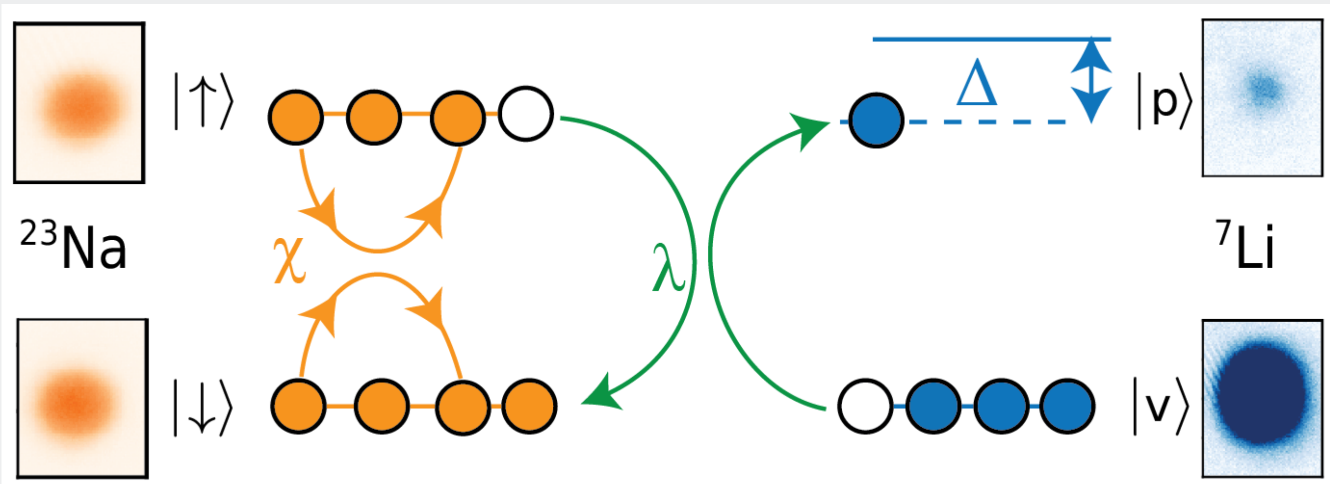




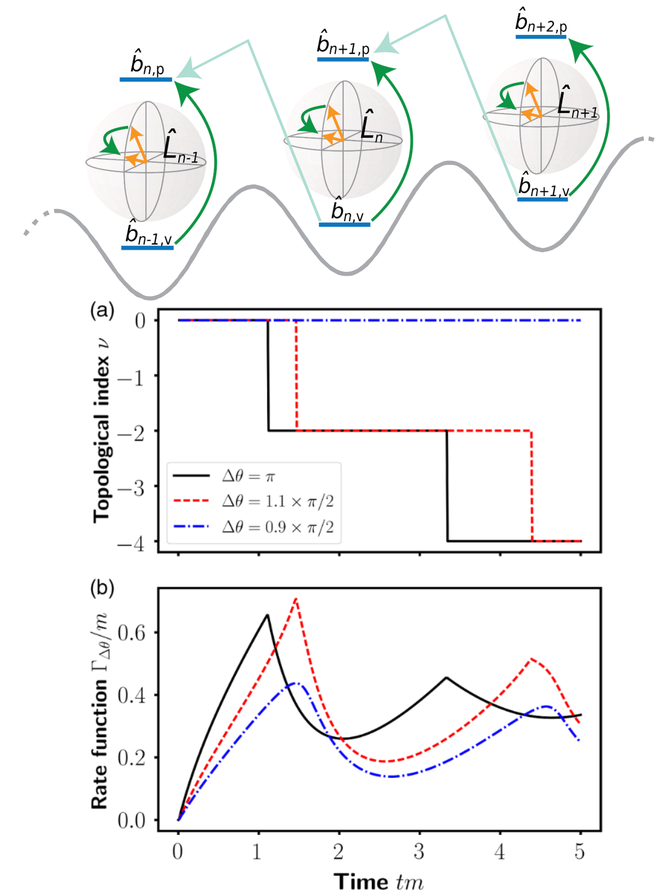
$$\hat{H} = \sum_n [\hat{H}_n + \hbar\Omega(\hat{b}^{\dagger}_{n,\mathrm{p}}\hat{b}_{n,\mathrm{v}} + \mathrm{h.c.})]$$

Mil et al. Science **367**, 1128 (2020)

$$\hat{H} = \chi \hat{L}_z^2 + \frac{\Delta}{2}\left(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v\right) + \lambda\left(b_v^\dagger \hat{L}_- \hat{b}_v + b_v^\dagger \hat{L}_+ \hat{b}_p\right)$$

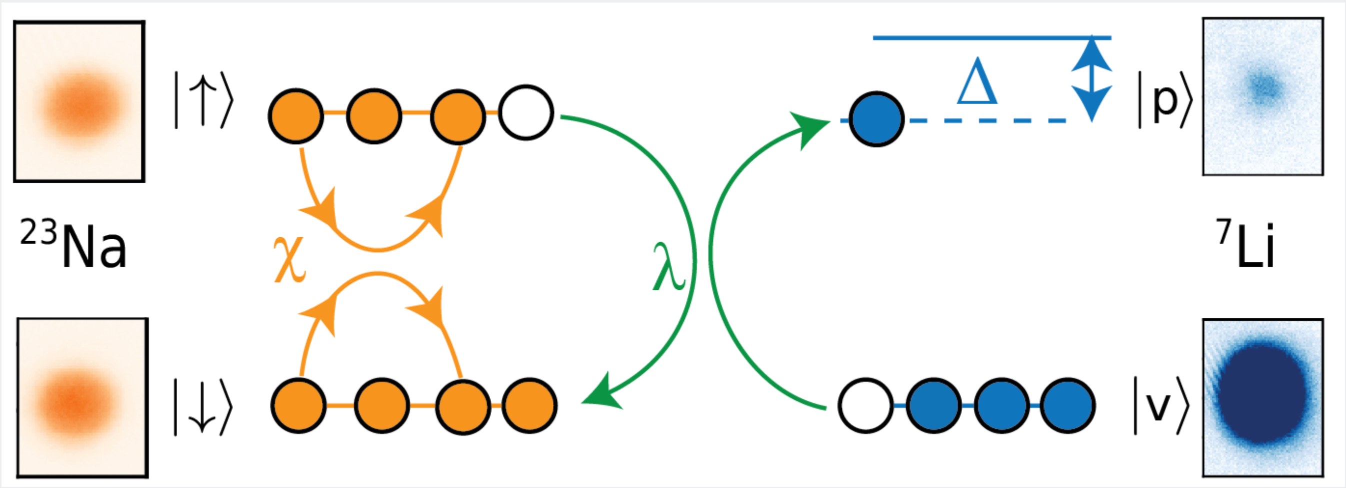


Mil *et al.*, Science **367**, 1128 (2020)

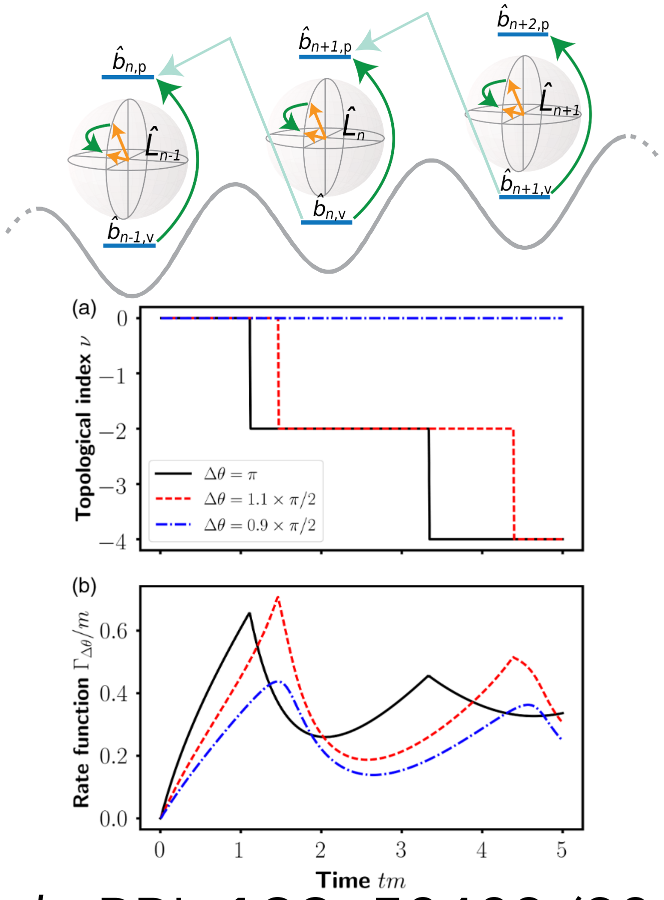


Zache *et al.*, PRL **122**, 50403 (2019)

$$\hat{H} = \chi \hat{L}_z^2 + \frac{\Delta}{2}\left(\hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v\right) + \lambda\left(b_v^\dagger \hat{L}_- \hat{b}_v + b_v^\dagger \hat{L}_+ \hat{b}_p\right)$$

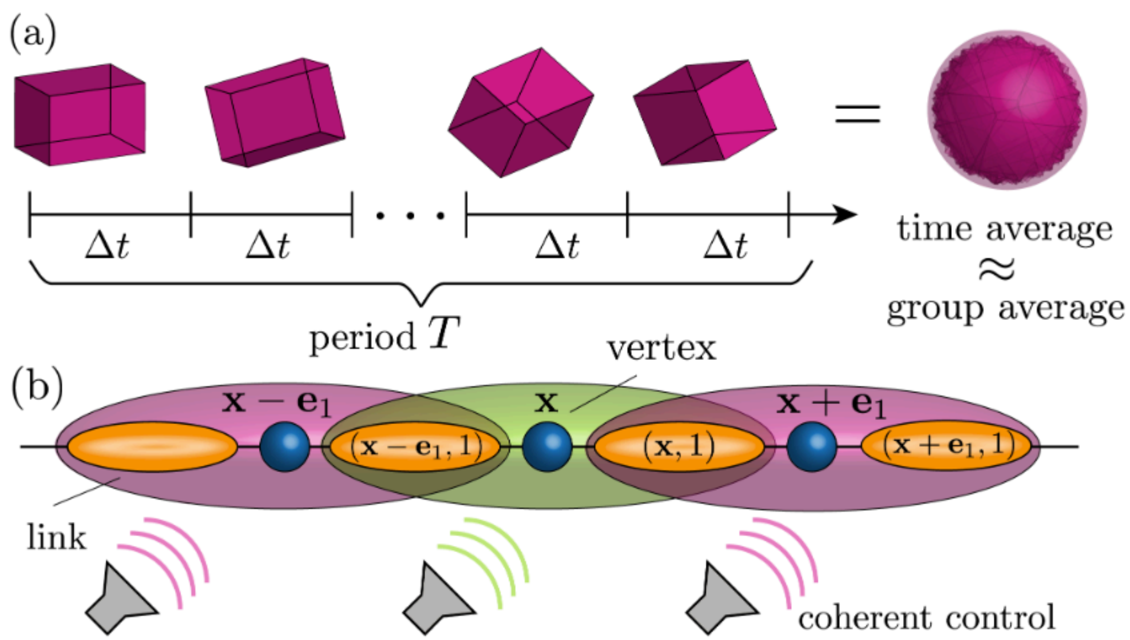


Mil *et al.*, Science **367**, 1128 (2020)



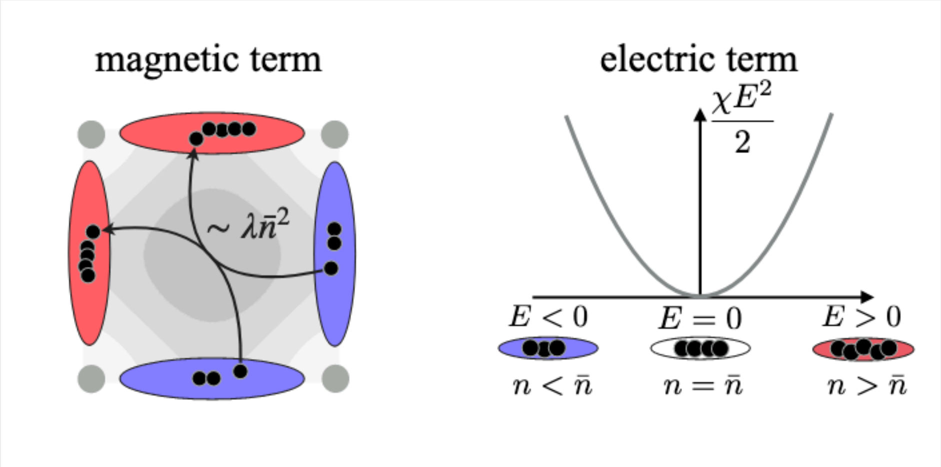
Zache *et al.*, PRL **122**, 50403 (2019)

Non-abelian gauge fields ?



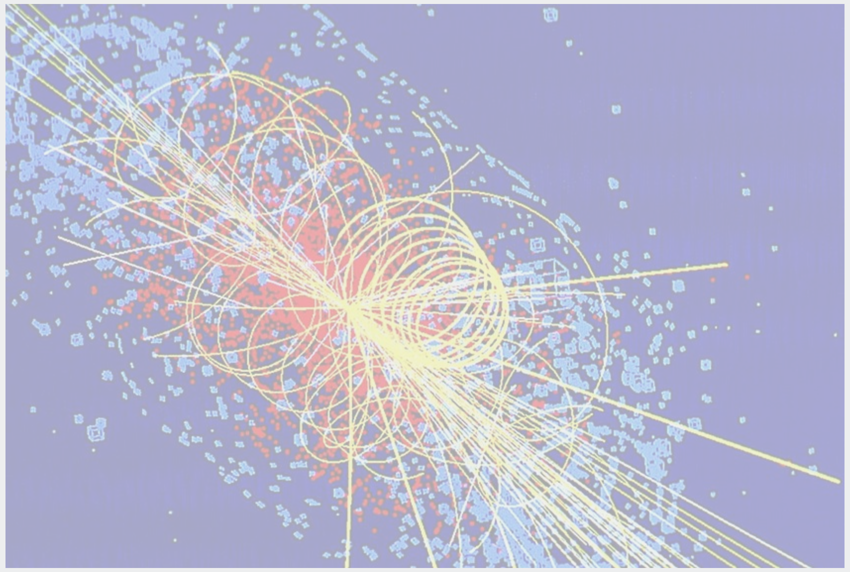
Kasper *et al.*, arXiv:2012.08620 (2020)

Higher dimensions ?

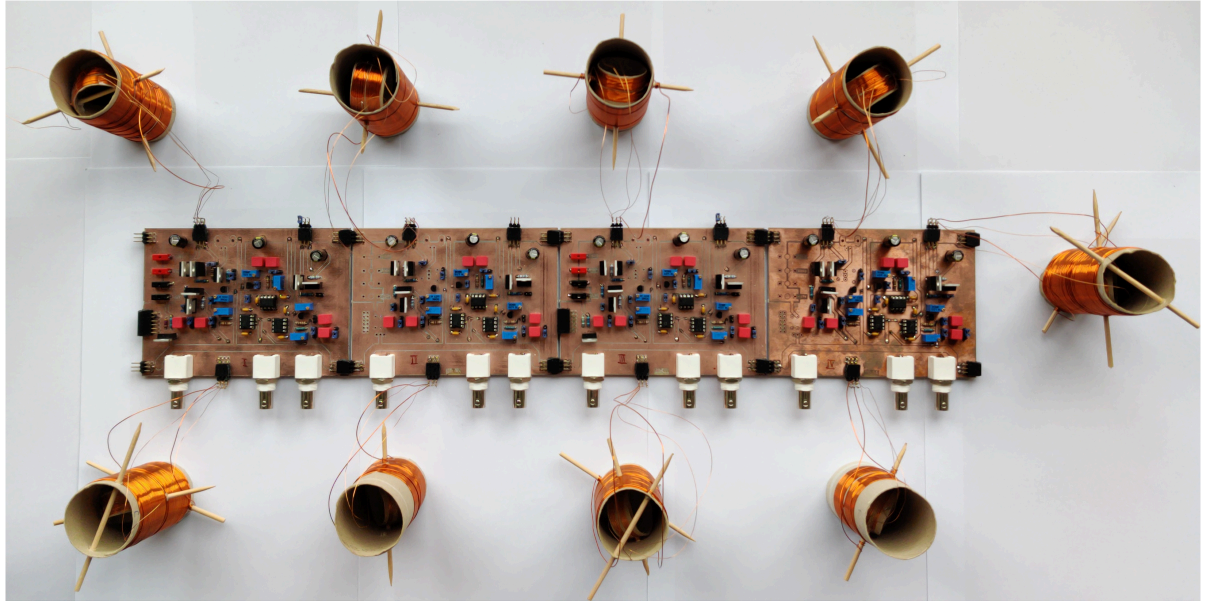


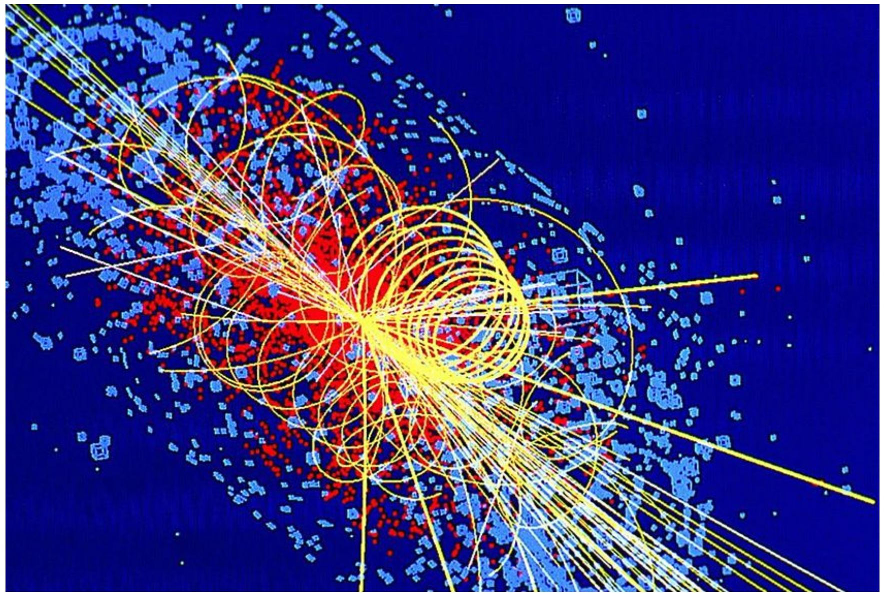
Ott *et al.*, arXiv:2012.10432 (2020)

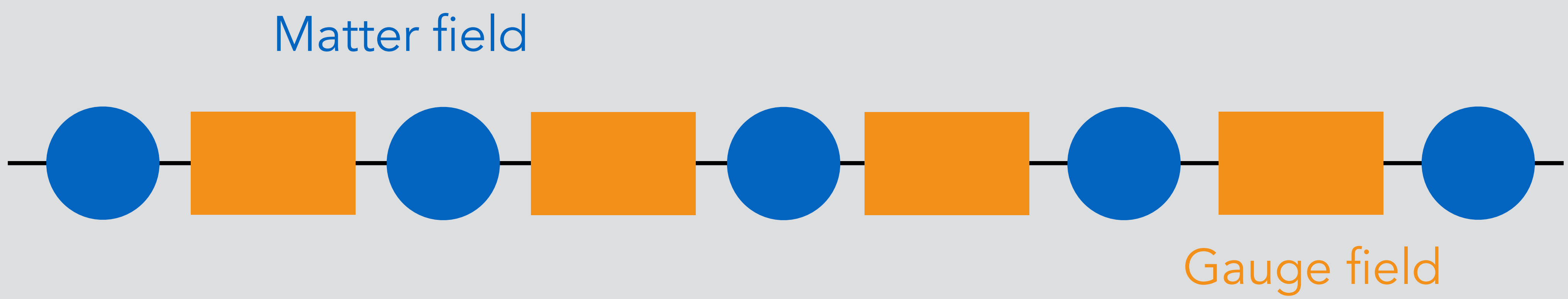
Could we use cold atoms to study high-energy physics?



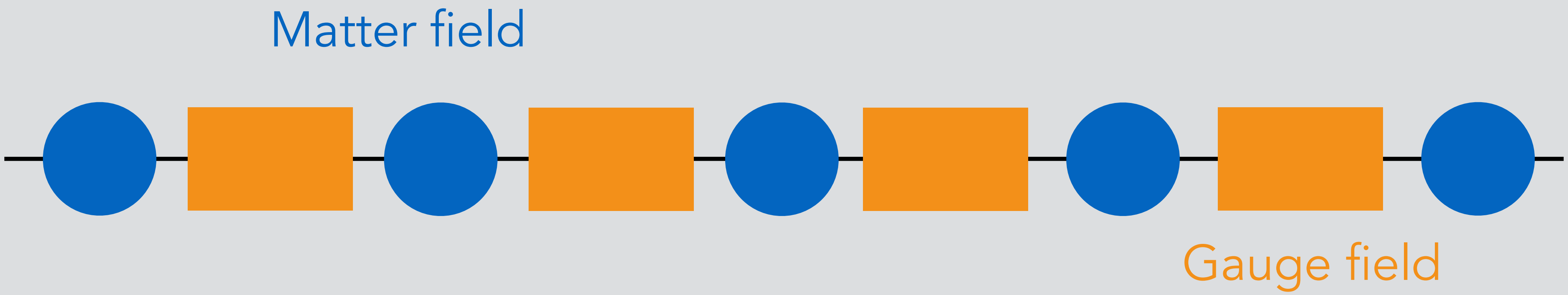
Could we use electric circuits to engineer local symmetries ?



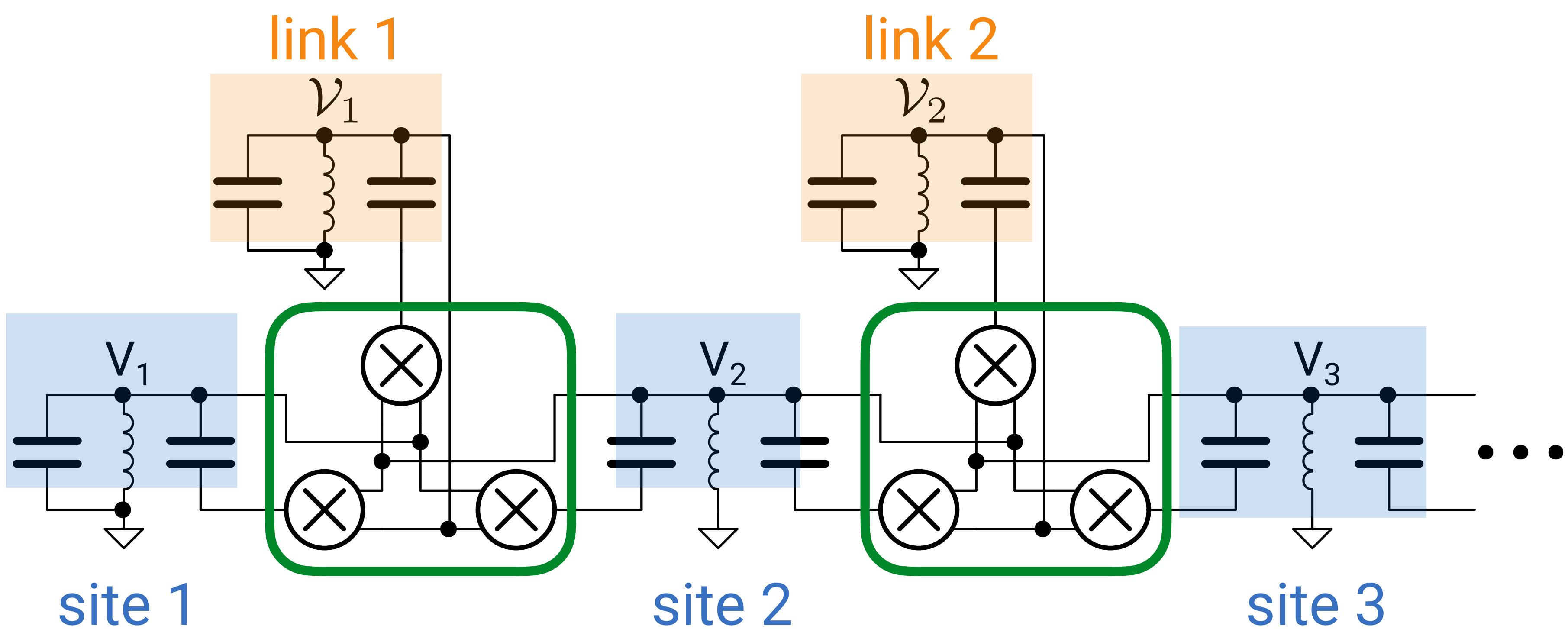


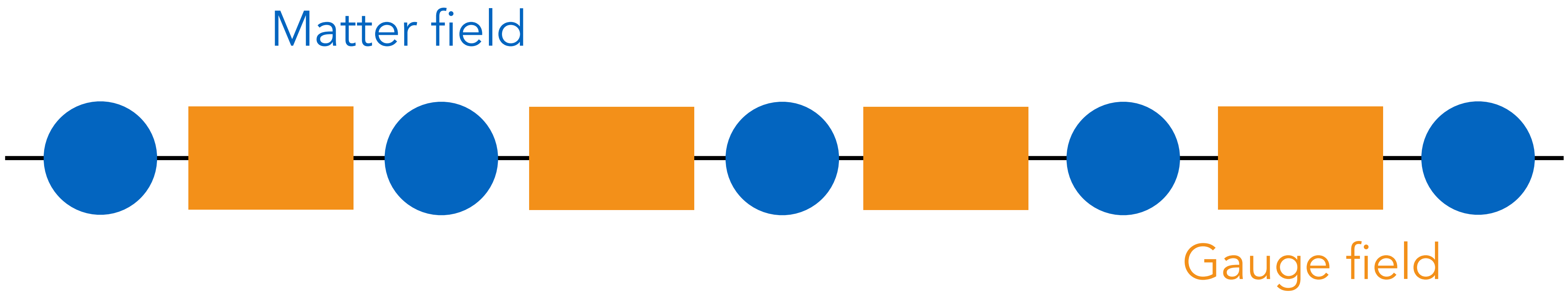


$$H = \frac{\Delta}{2}\sum_{x}(-1)^{x}a_x^{*}a_x + \Omega\sum_{x\ odd}(a_x^{*}b_x^{*}a_{x+1} + c.c.) + \Omega\sum_{x\ even}(a_x^{*}b_x a_{x+1} + c.c.)$$

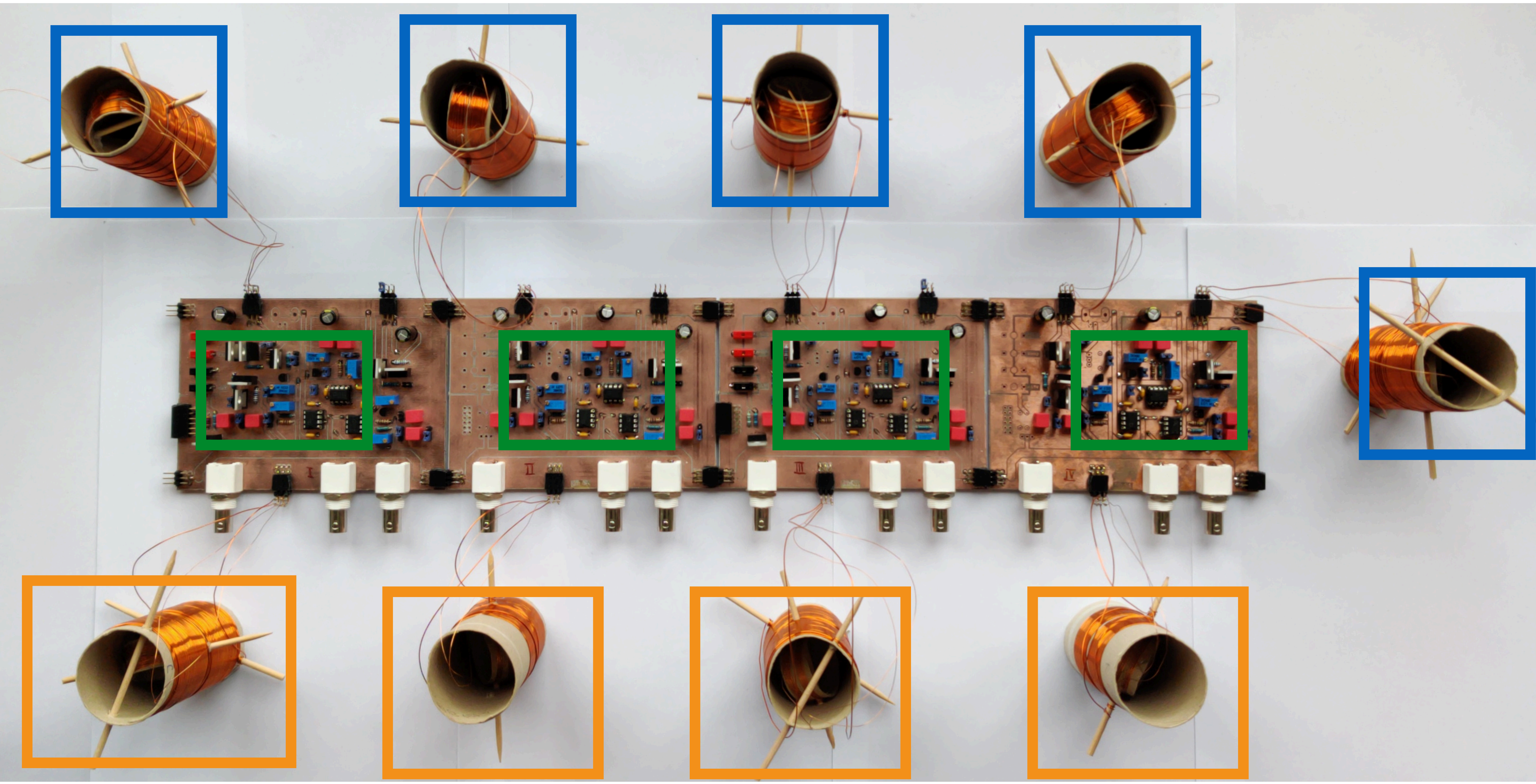


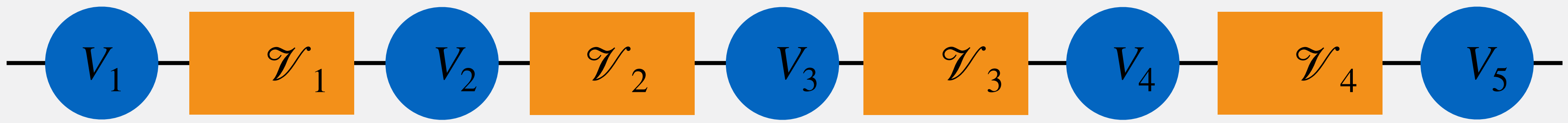
$$H = \frac{\Delta}{2} \sum_{x} (-1)^{x} a_x^{*} a_x + \Omega \sum_{x\ odd} (a_x^{*} b_x^{*} a_{x+1} + c.c.) + \Omega \sum_{x\ even} (a_x^{*} b_x a_{x+1} + c.c.)$$



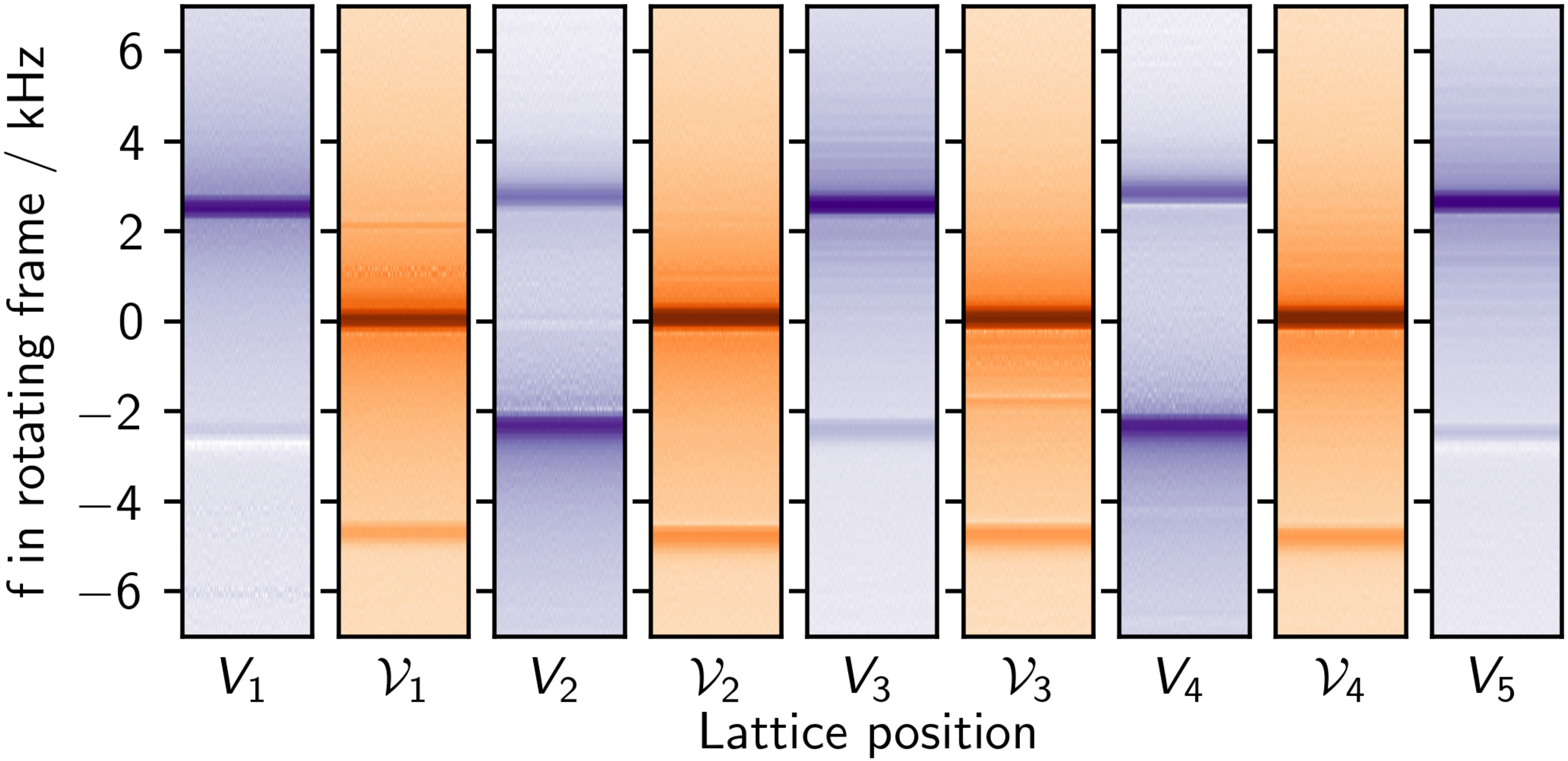

Matter field
Gauge field

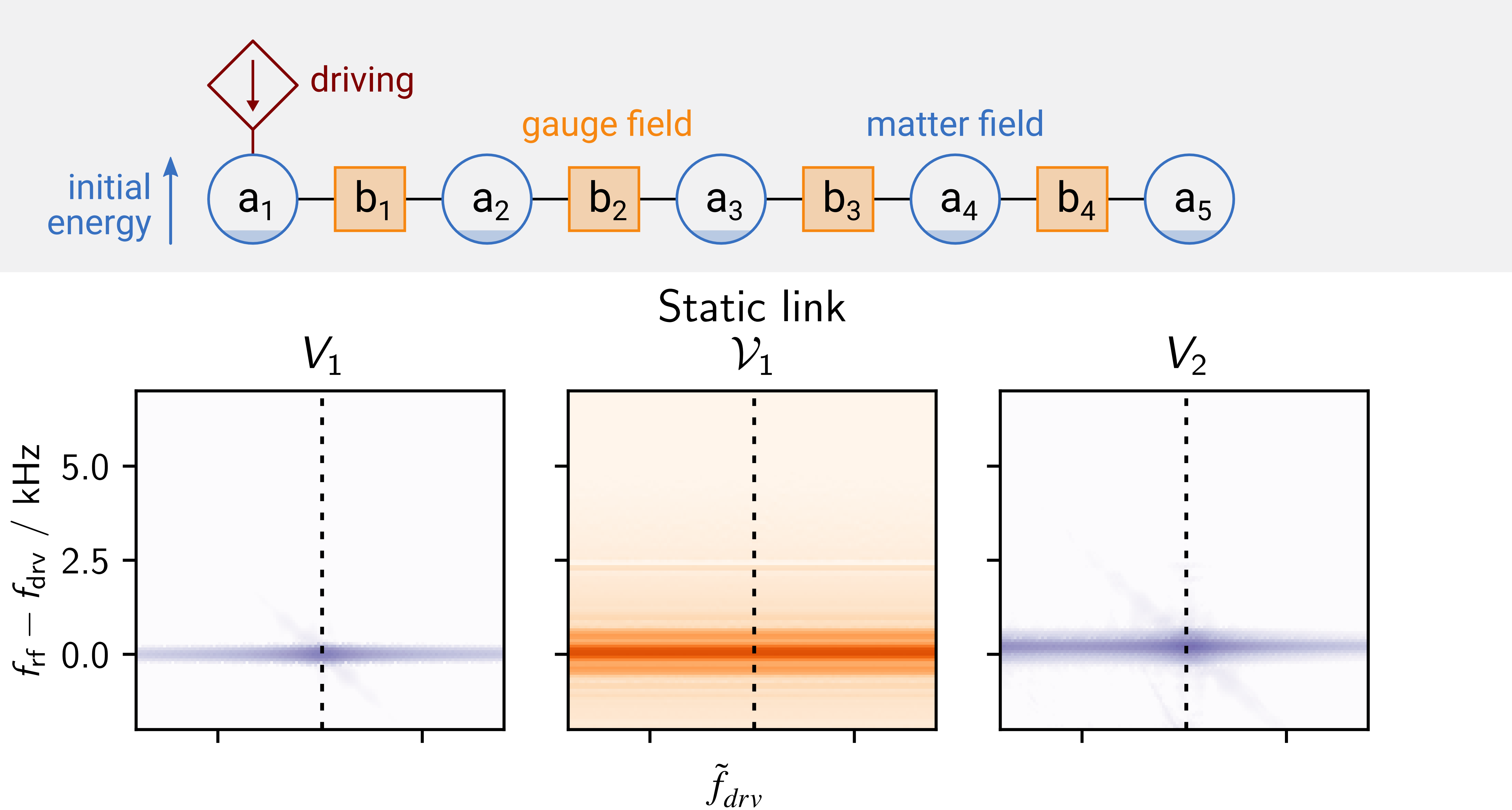

Hannes

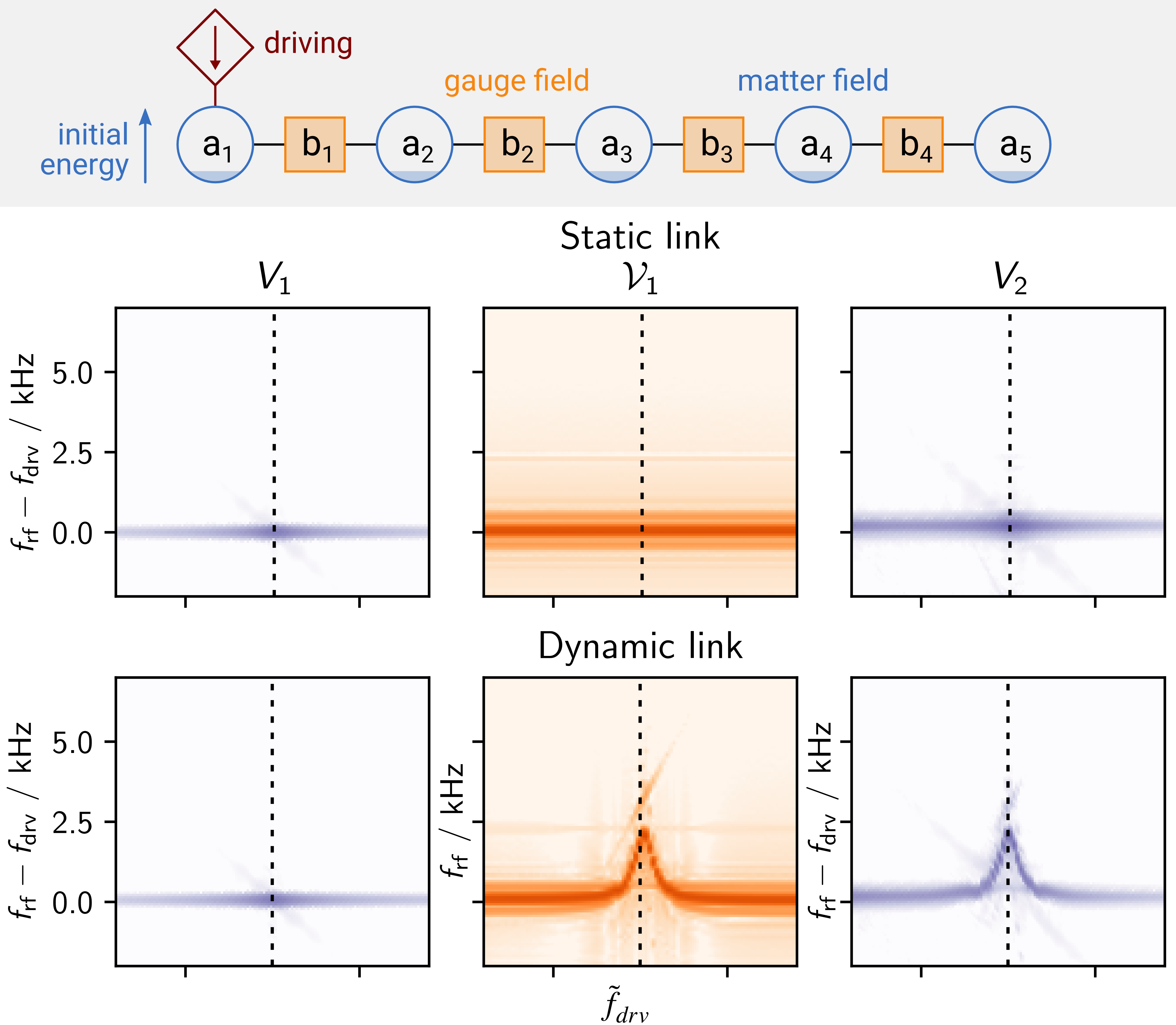




$$H = \frac{\Delta}{2} \sum_x (-1)^x a_x^* a_x + \Omega \sum_{x\ odd} (a_x^* b_x^* a_{x+1} + c.c.) + \Omega \sum_{x\ even} (a_x^* b_x a_{x+1} + c.c.)$$

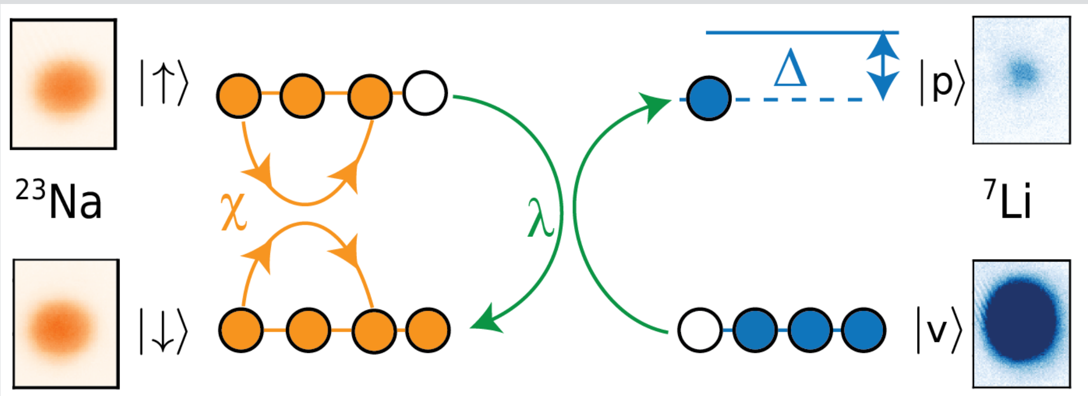


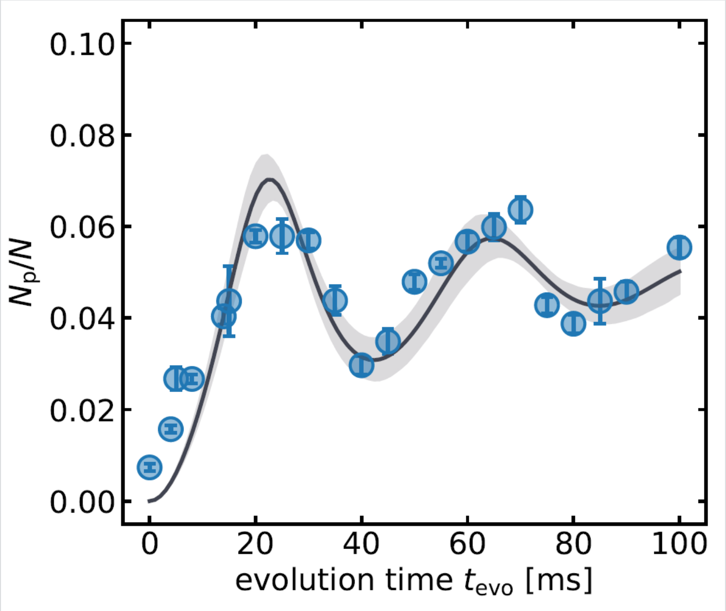

driving
gauge field
matter field
initial energy
a1
b1
a2
b2
a3
b3
a4
b4
a5
Static link
V_1
$\mathcal{V}_1$
V_2
$f_{rf} - f_{drv}$ / kHz
5.0
2.5
0.0
$\tilde{f}_{drv}$



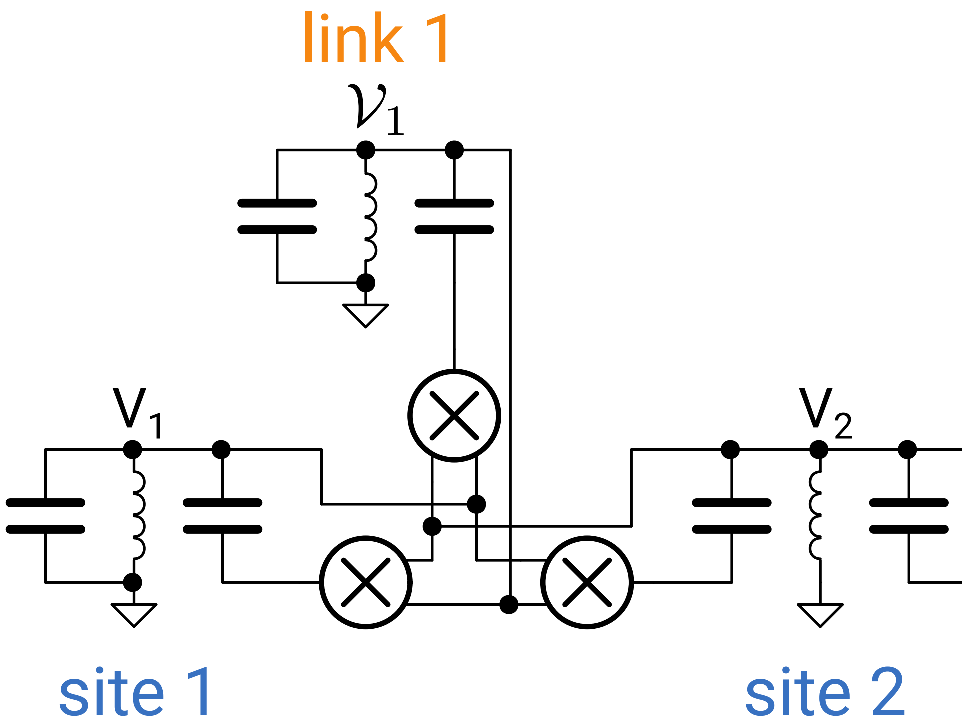
driving
gauge field
matter field
initial energy
a1 b1 a2 b2 a3 b3 a4 b4 a5
Static link
V1
𝒱1
V2
f_rf − f_drv / kHz
5.0
2.5
0.0
Dynamic link
f_rf / kHz
f̃_drv

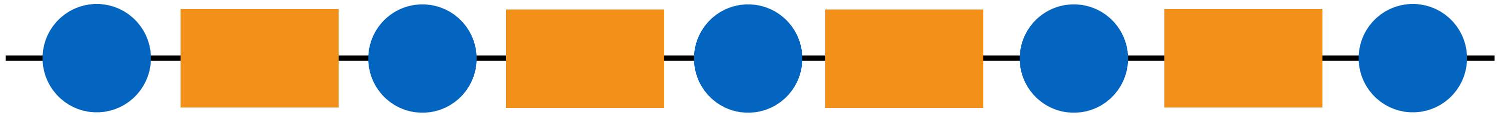
Building block with atomic mixtures realized

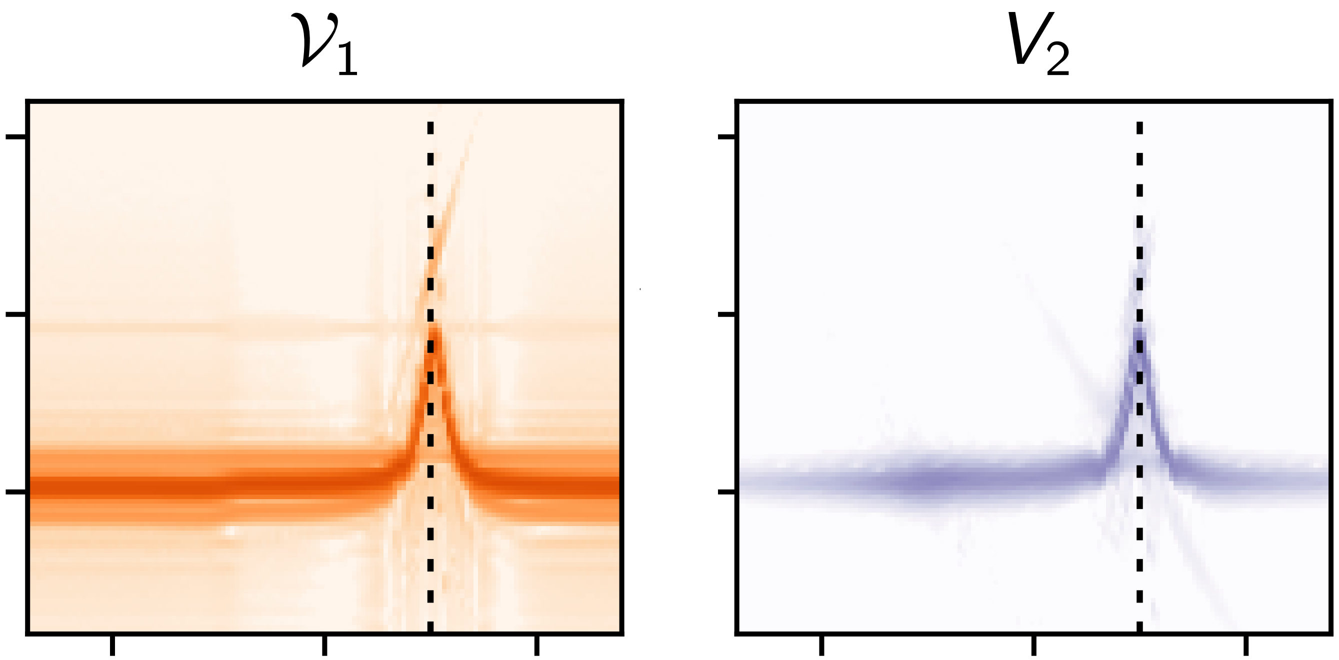




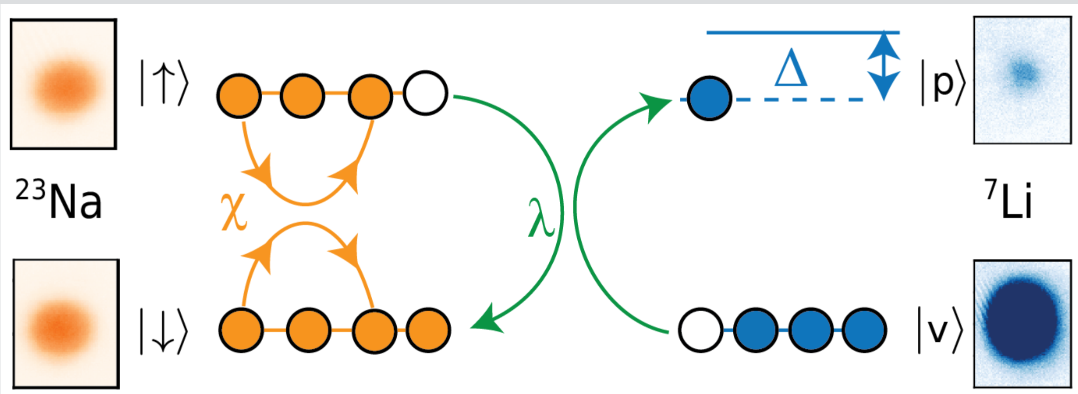
1D Lattice in classical electric circuits realized

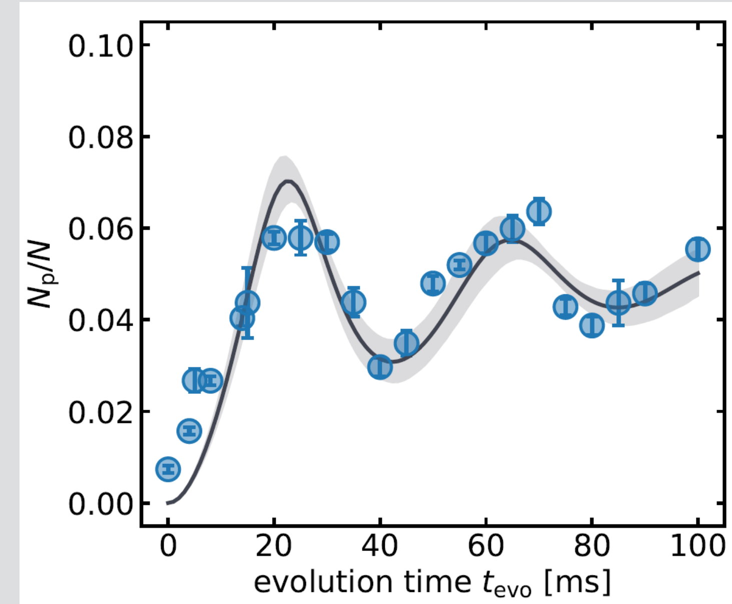






Building block with atomic mixtures realized





Thank you for your attention

1D Lattice in classical el