Constraining the fundamental number of quantum degrees of freedom using gravity

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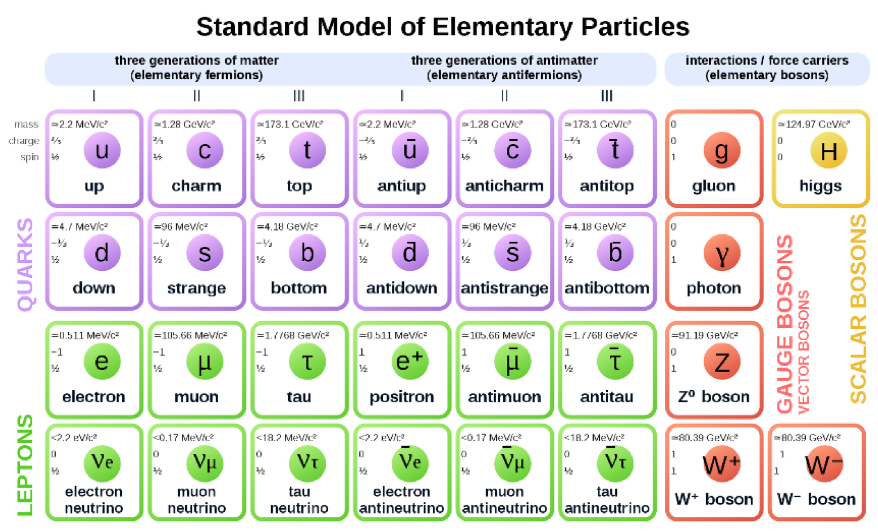
INTRODUCTION

- Question: How many fundamental particles are present in the universe?
- Approach:
  - Fundamental particles in the universe are quantization of fundamental fields.
  - Fundamental fields can be visualized as many interacting quantum DOF.
- Background: Probe gravitational effects in quantum systems in the low energy regime.
- Refined question: Can we devise an experiment in the low energy regime to constrain the number of quantum DOF?
- Theoretical framework: Gravitational redshift and gravitational decoherence due to time dilation.



GRAVITATIONAL RED SHIFT IN EXTENDED QUANTUM SYSTEMS WITH INTERNAL DOF AND DECOHERENCE

MOTIVATION

Experimentally testable → Toy model for fields

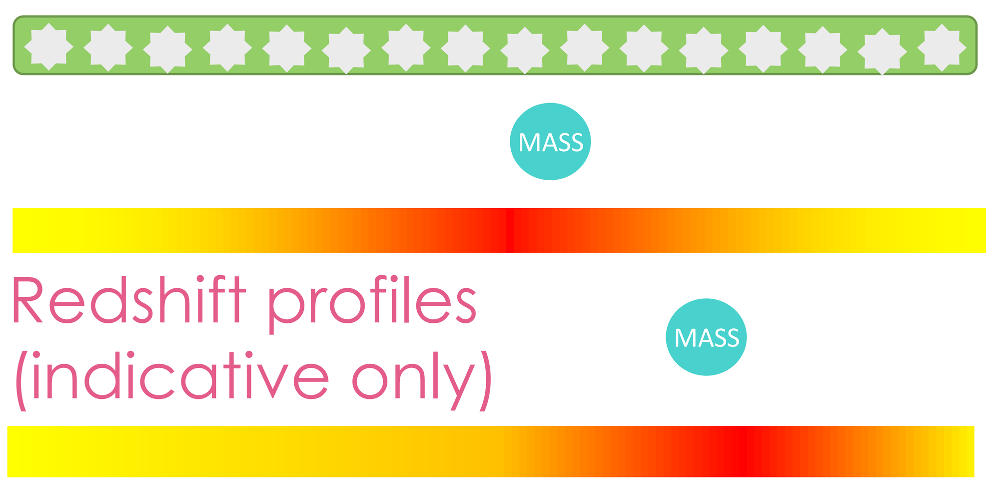
→ E.g. spin chain systems

Near term simulation on quantum hardware → Sum of Local Hamiltonians

$H_0 = \sum_{i=1}^{L} h_i$

(A) DIFFERENTIAL REDSHIFT

1D extended quantum system

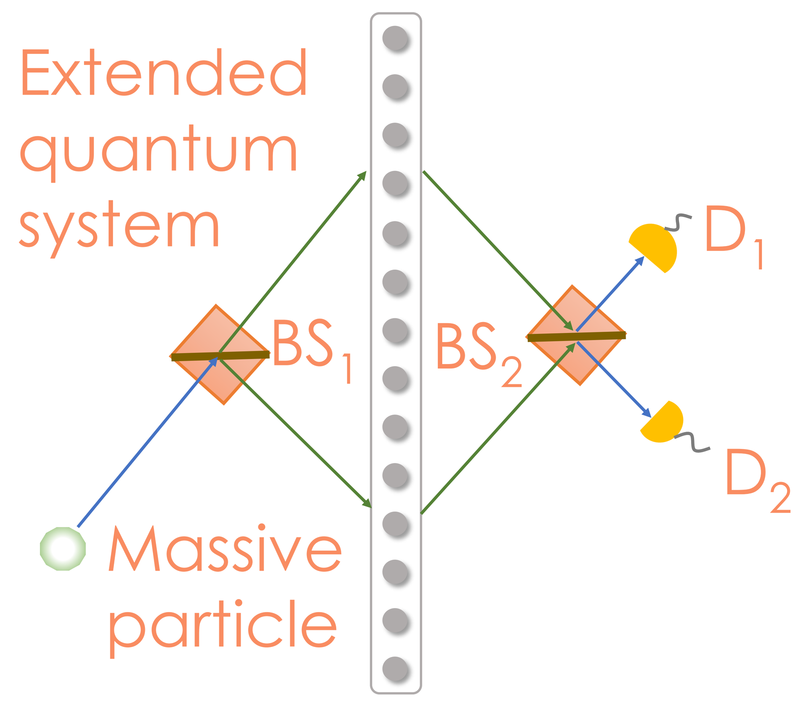


PARTS OF THE TOTAL HAMILTONIAN

$H = H_{cm} + H_0 + H_{int}$

H_{cm} = trivial $H_0 = \sum_{i=1}^{L} h_i$ $H_{int} = \sum_{i=1}^{L} h_i\,\phi(r_i)$

(B) GEDANKEN EXPERIMENT



- Scenario: Extended quantum system with internal DOF, with a massive particle nearby.
- Assumption: T = 0, massive particle is brought adiabatically near the system.
- (A) Total Hamiltonian (hence, the ground state) depends on the redshift profile - the relative position of mass from the spin chain.
- (B) If mass is prepared in a spatial superposition, the ground state of spin chain is entangled with the position of mass: $|\Psi\rangle = |R_1\rangle\,|GS\rangle_{R_1} + |R_2\rangle\,|GS\rangle_{R_2}$

Entangled state due to differential redshift

$M = |\langle GS_{R_2}|GS_{R_1}\rangle|$

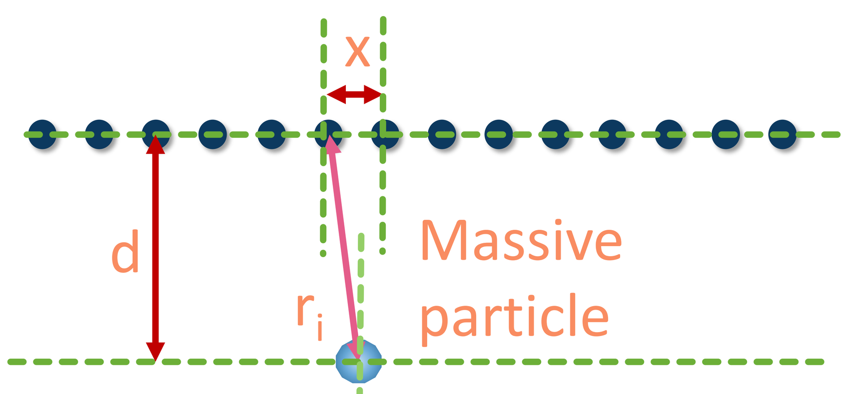
Visibility of path DOF

Decoherence ! ← Measure the COM in ± basis ← Trace out the internal DOF

- Inference: Low visibility → Low overlap b/w GS → High decoherence

DECOHERENCE IN SPATIAL SUPERPOSITION OF MASSIVE PARTICLE DUE TO SPIN CHAINS

MODELLING DIFFERENTIAL REDSHIFT IN SPIN CHAINS



Red shift factor :

$$\sqrt{-g_{00}} \approx \sqrt{1+2\phi(\vec{r_i})} \approx (1+\phi(\vec{r_i})) \quad \phi(\vec{r_i}) = -G\frac{M}{|\vec{r_i}|}$$

$$r_i = \sqrt{\left((k-i)+\frac{1}{2}\right)x^2 + d^2} \quad \forall i \in [1, L], \text{ for } \phi_i$$

$$r_i = \sqrt{(k-i)x^2 + d^2} \quad \forall i \in [1, L-1], \text{ for } \phi_{i,i+1}$$

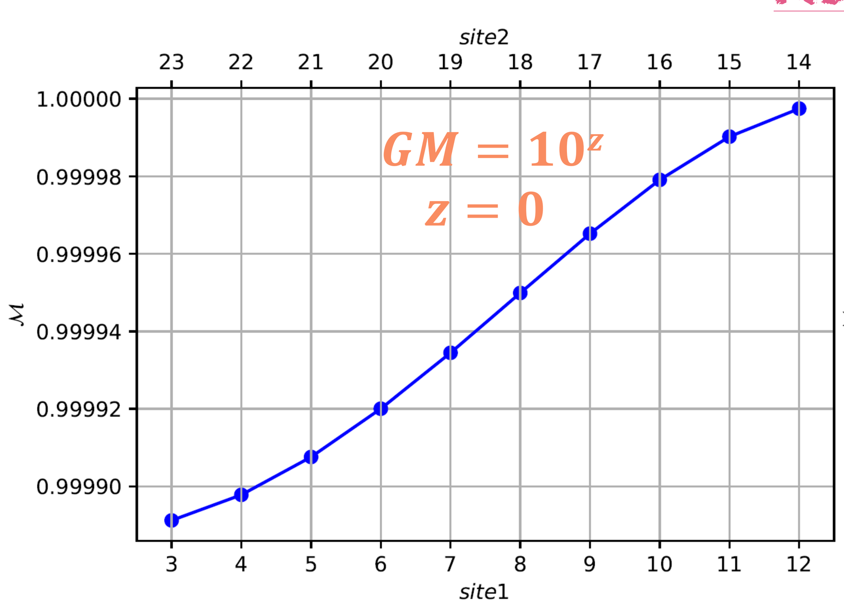
Original Hamiltonian :

$$H = J_x\sum_{i=1}^{L-1}\left(\hat{S}_i^x\hat{S}_{i+1}^x + \hat{S}_i^y\hat{S}_{i+1}^y\right) + J_z\sum_{i=1}^{L-1}\hat{S}_i^z\hat{S}_{i+1}^z - \sum_{i=1}^{L}B_i\hat{S}_i^z$$

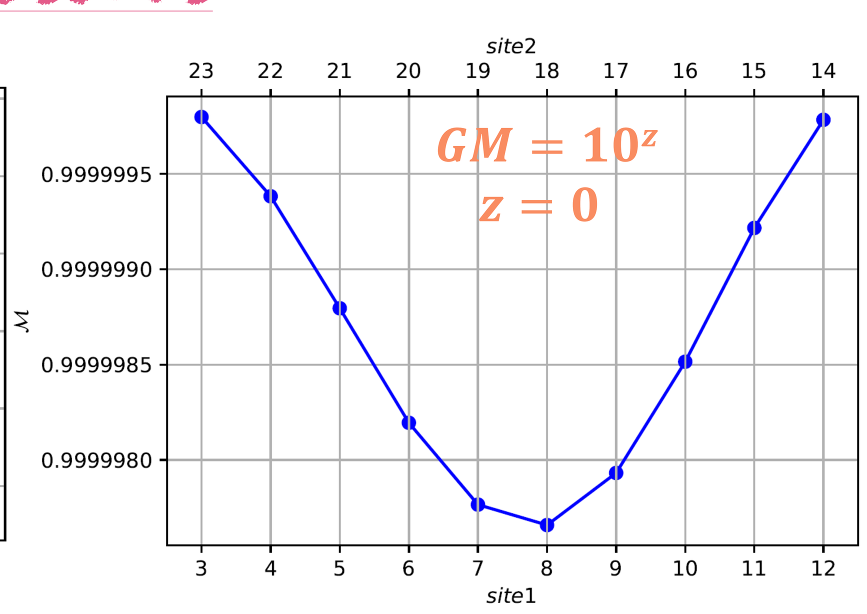
Red shifted Hamiltonian :

$$H = J_x\sum_{i=1}^{L-1}(1+\phi_{i,i+1})\left(\hat{S}_i^x\hat{S}_{i+1}^x + \hat{S}_i^y\hat{S}_{i+1}^y\right) + J_z\sum_{i=1}^{L-1}(1+\phi_{i,i+1})\hat{S}_i^z\hat{S}_{i+1}^z - \sum_{i=1}^{L}(1+\phi_i)B_i\hat{S}_i^z$$

RESULTS



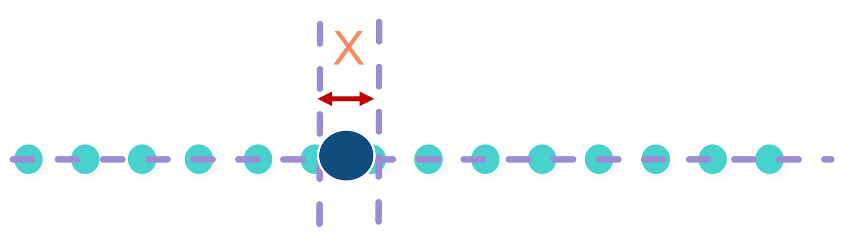
XXZ chain : $J_x = J_z = B = 1$



XX chain : $J_x = 1, J_z = B = 0$

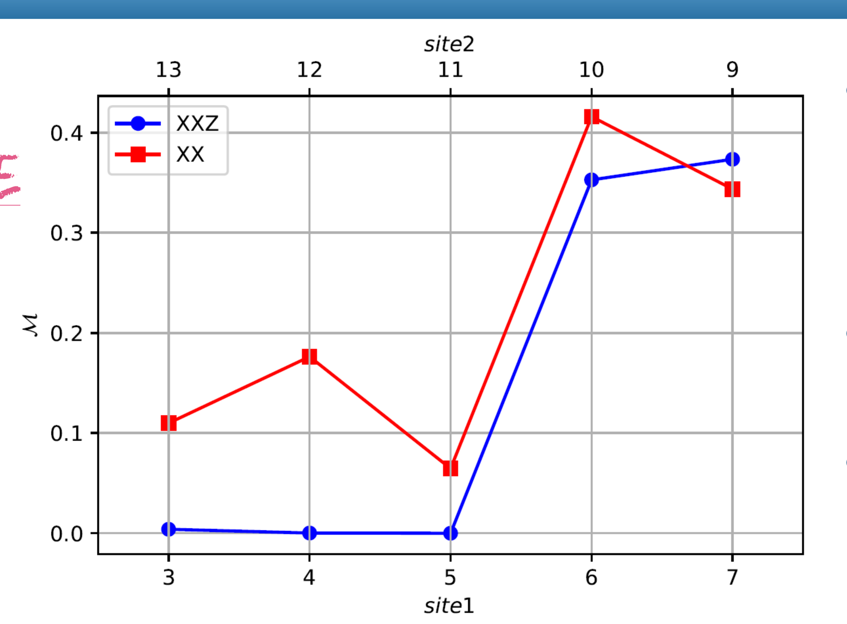
CONSTRAINING THE NUMBER OF QUANTUM DOF

LIMITING CASE WITH SCHWARZCHILD BLACK HOLE



Red shift factor : $\sqrt{-g_{00}} = \sqrt{1 - \frac{r_s}{2r_i}}$

$r_i = |(k-i+1/2)|r_s$



REFERENCES

[1] Pikovski I., Zych M., Costa F., and Brukner C., *Universal decoherence due to gravitational time dilation*, Nature Physics, 11, 668 (2015).

- N number of spin chains lying at the same relative position wrt. the massive particle.
- Each contributes equally to the decoherence : $M^N \to 0$.
- Limit α arbitrarily close to 0, defined by the limit of experimental observation. $M^N \to e^{-\alpha}$, $N = -\alpha/\ln(M)$

FOR BH: **$N = 2$ for $\alpha = 2$**

FOR FINITE MASS : **$N = 10000$ for $\alpha = 2$, in $z = 0$, XXZ**