Nuclear physics from QCD on supercomputers

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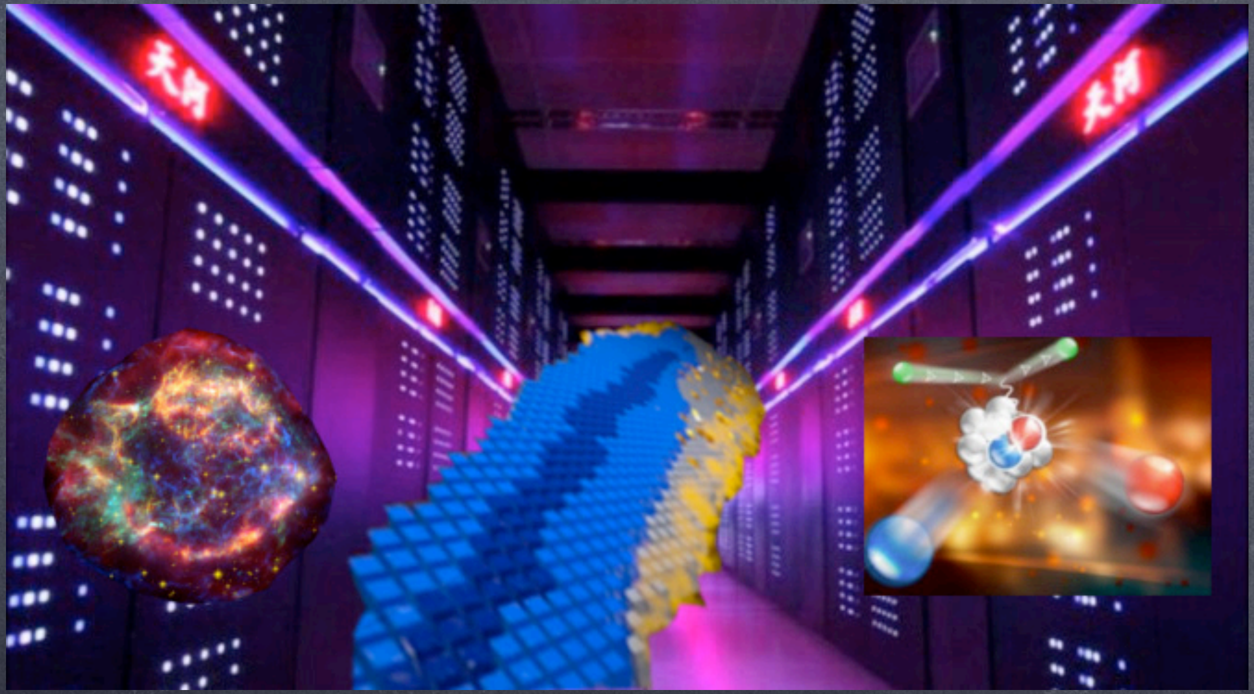
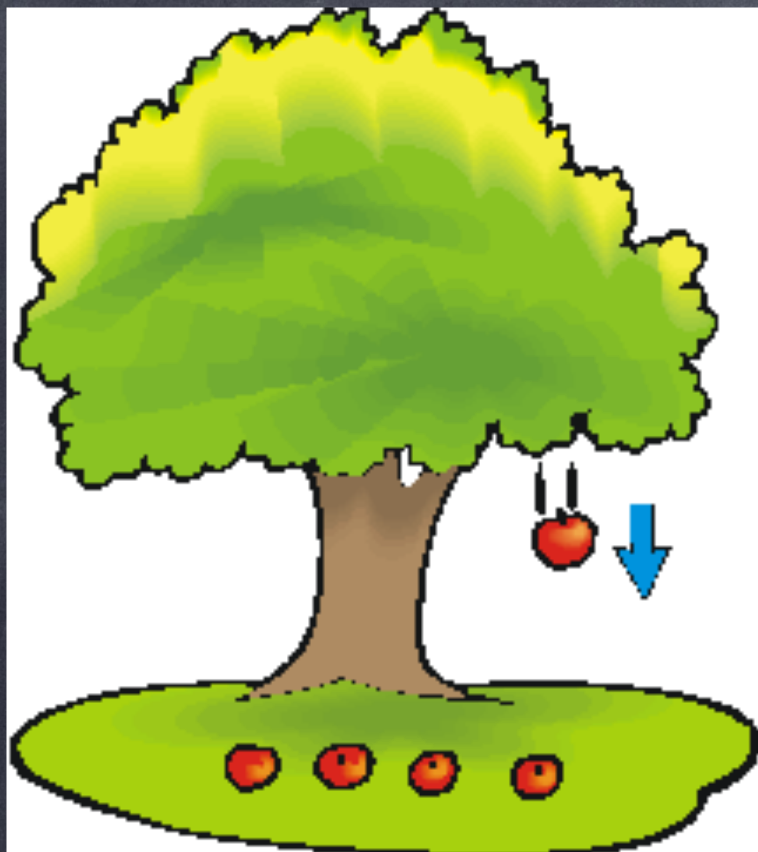


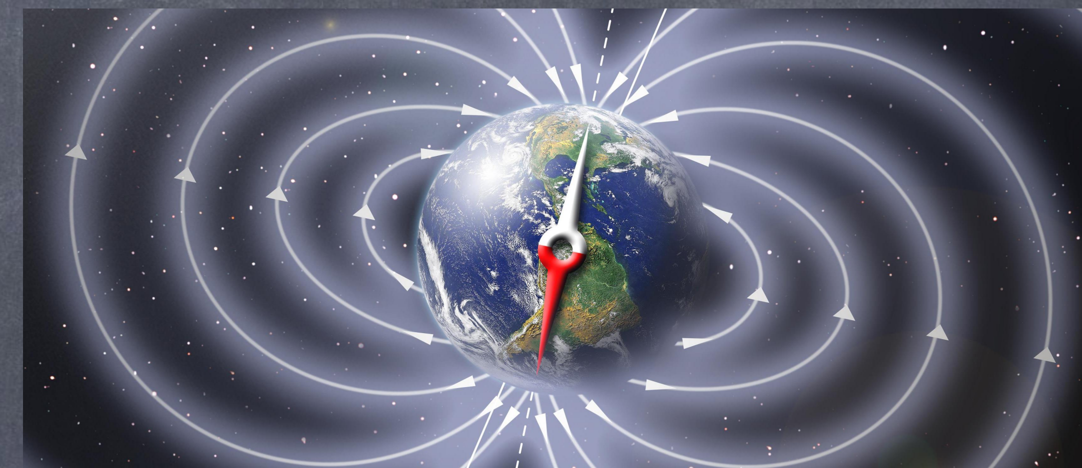
FRIB

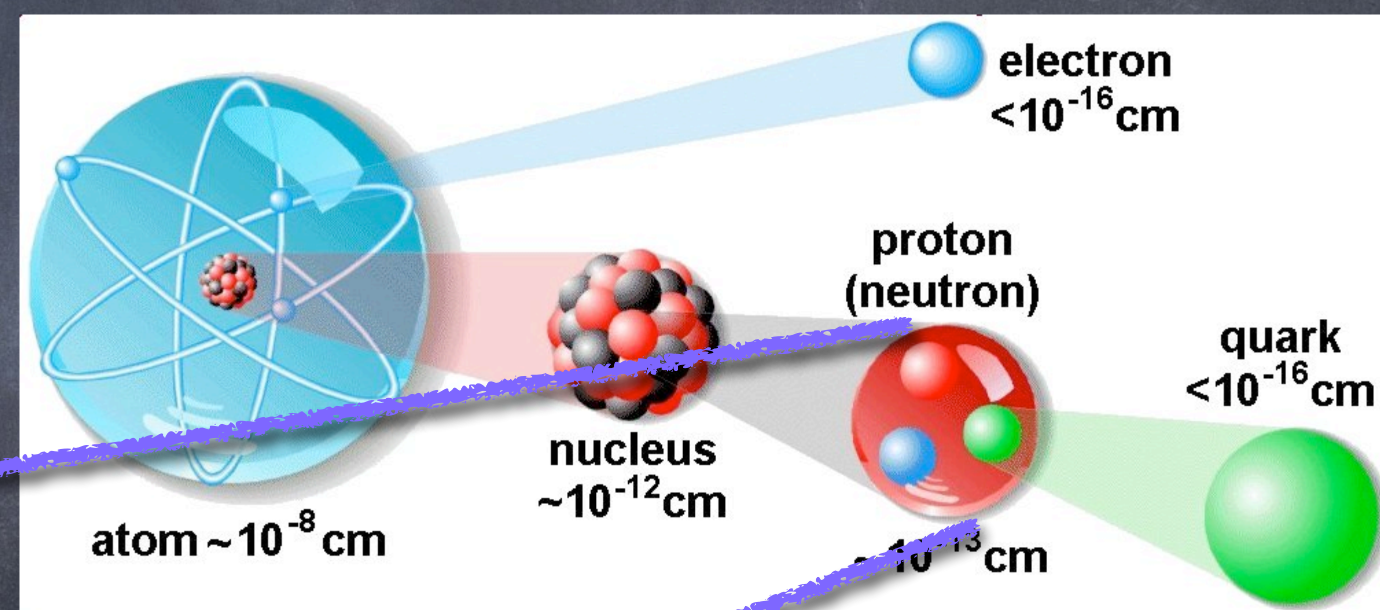
ICER

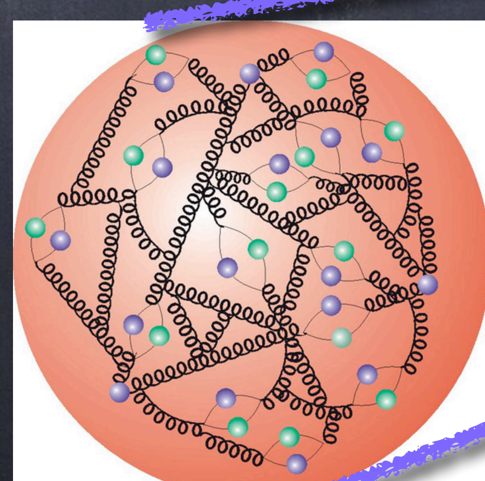
Michigan State University

Fundamental interactions

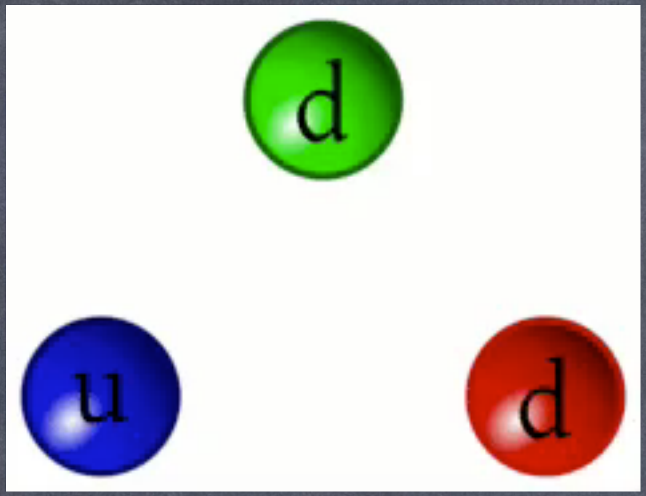


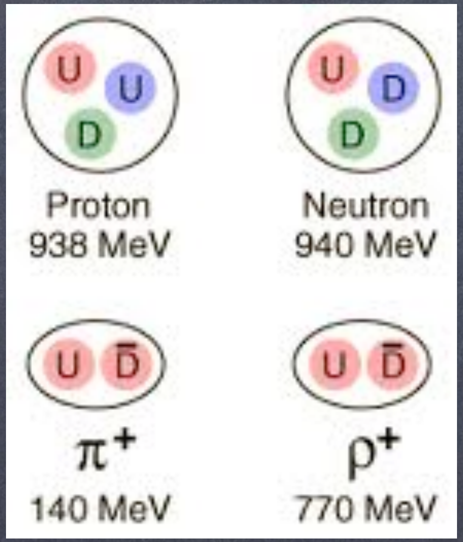




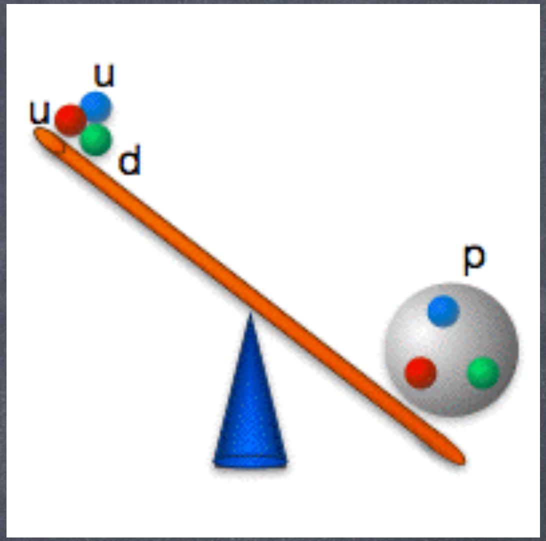


Quarks and gluons





$$E = mc^2$$



$$m_u \simeq 2 - 3 \text{ MeV}$$

$$m_d \simeq 4 - 5 \text{ MeV}$$

$$m_P = 938 \text{ MeV}$$

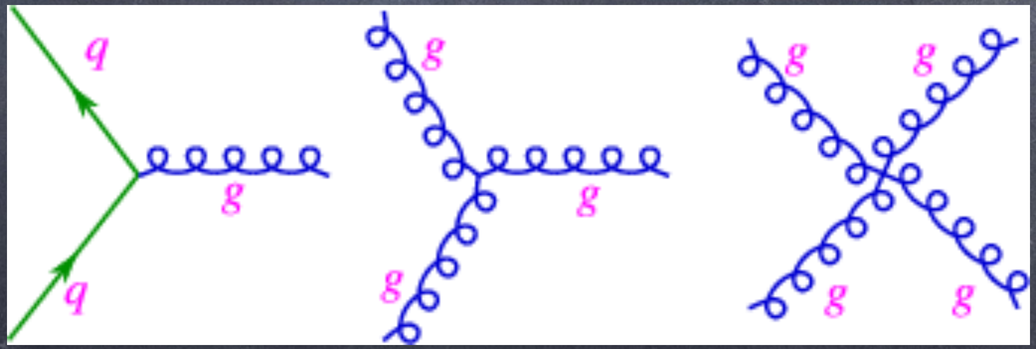
$$\lim_{m_u, m_d \to 0} m_P \simeq 900 \text{ MeV}$$

$$1 \text{ MeV} = 1.783 \times 10^{-30} \text{Kg}$$

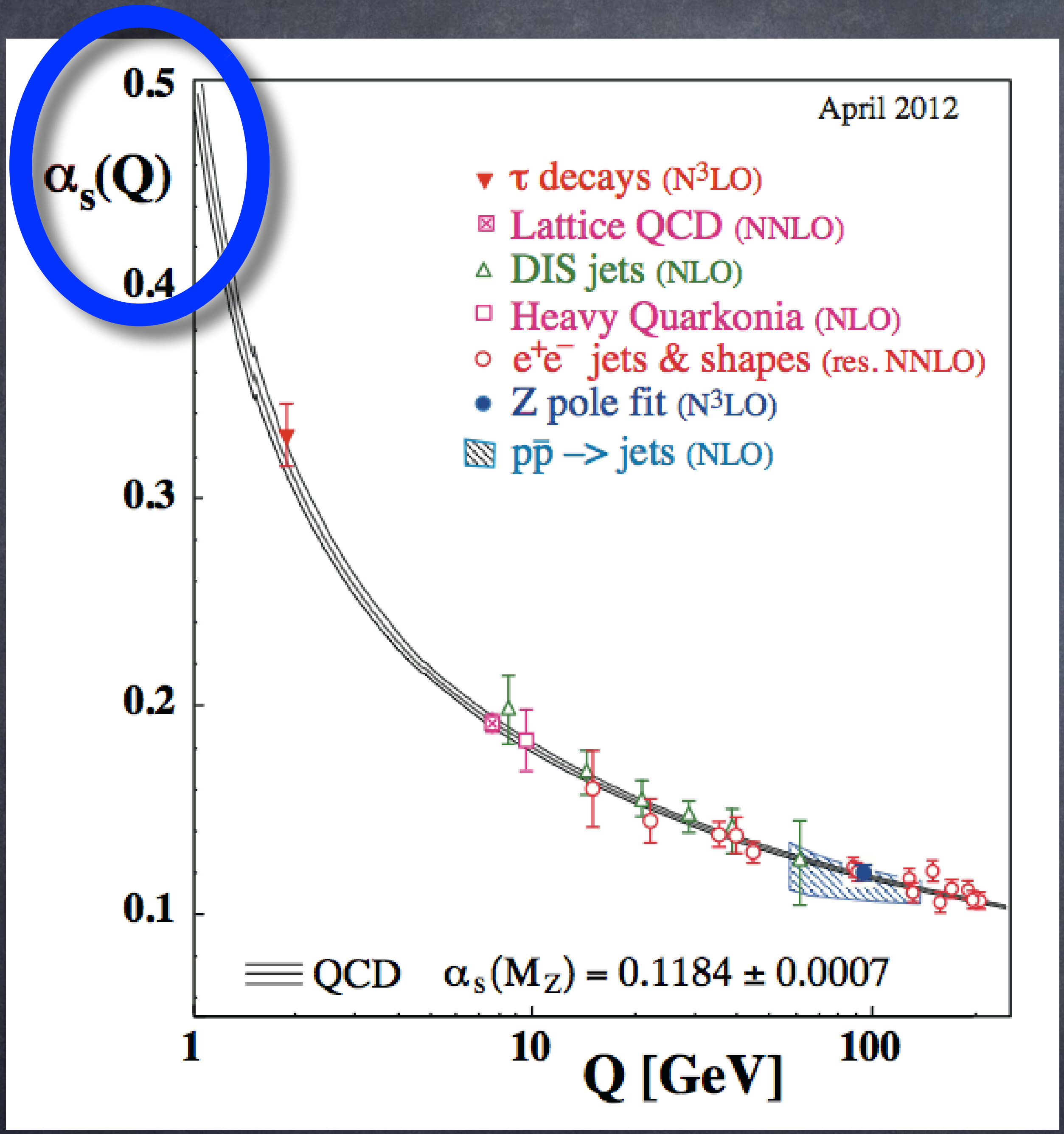
Quantum Chromodynamics (QCD)

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \sum_{f=u,d,s,\ldots} \overline{\psi}_f(x) \{ i\gamma^\mu [\partial_\mu + i g_s A^a_\mu T^a] - m_f \} \psi_f(x)$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f^{abc} A^b_\mu A^c_\nu$$



Gauge coupling



Bethke: 2012

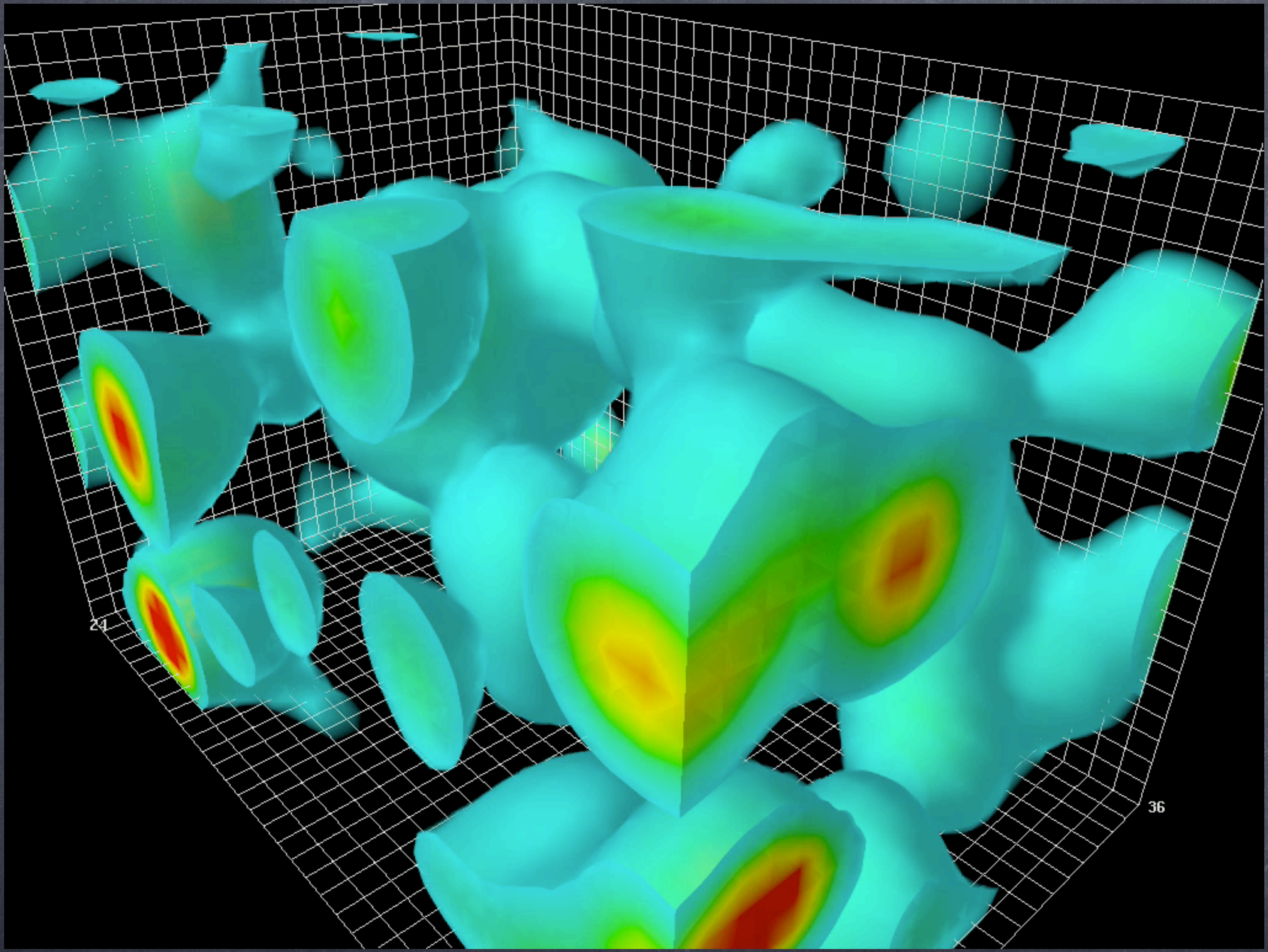
$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$\alpha_s\left(M_Z\right) = 0.1184 \pm 0.0007$$

$$\Lambda_{\mathrm{QCD}} = 213 \pm 8\ \mathrm{MeV}$$

The logarithmic decay of the coupling (asymptotic freedom) is observed in high-energy scattering experiments

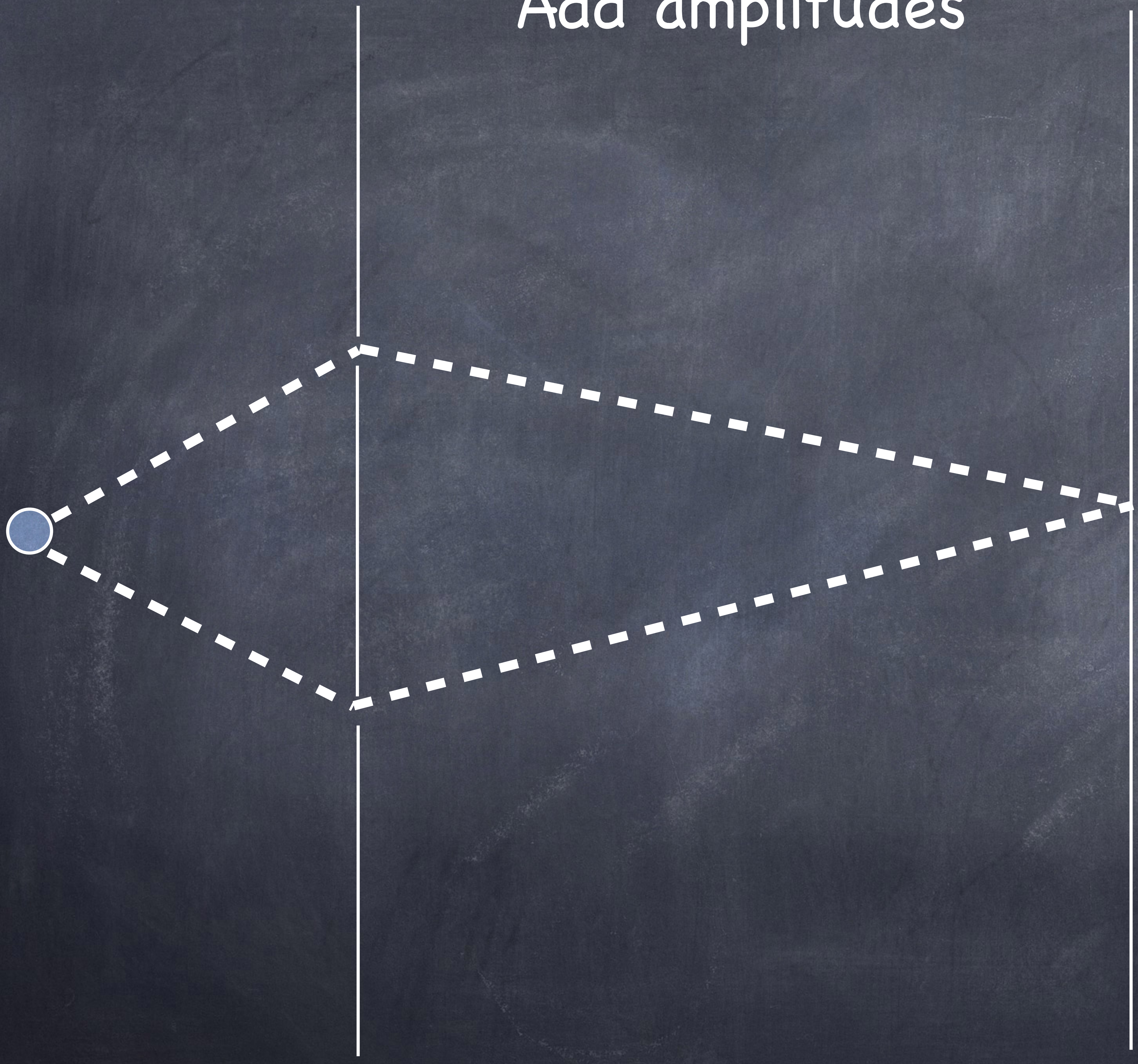
Quantum field theory



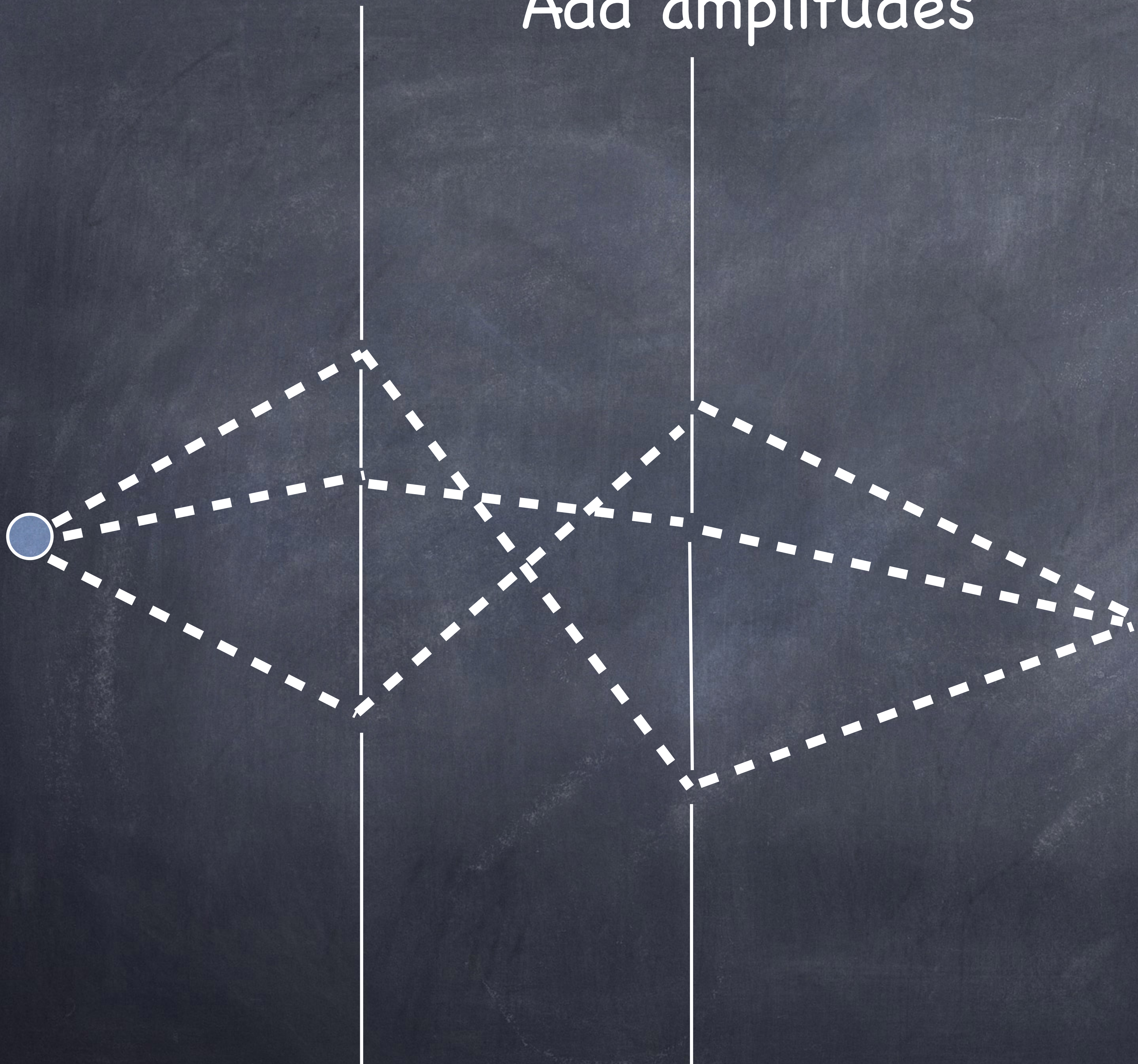
Leinweber:2003

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html

Add amplitudes



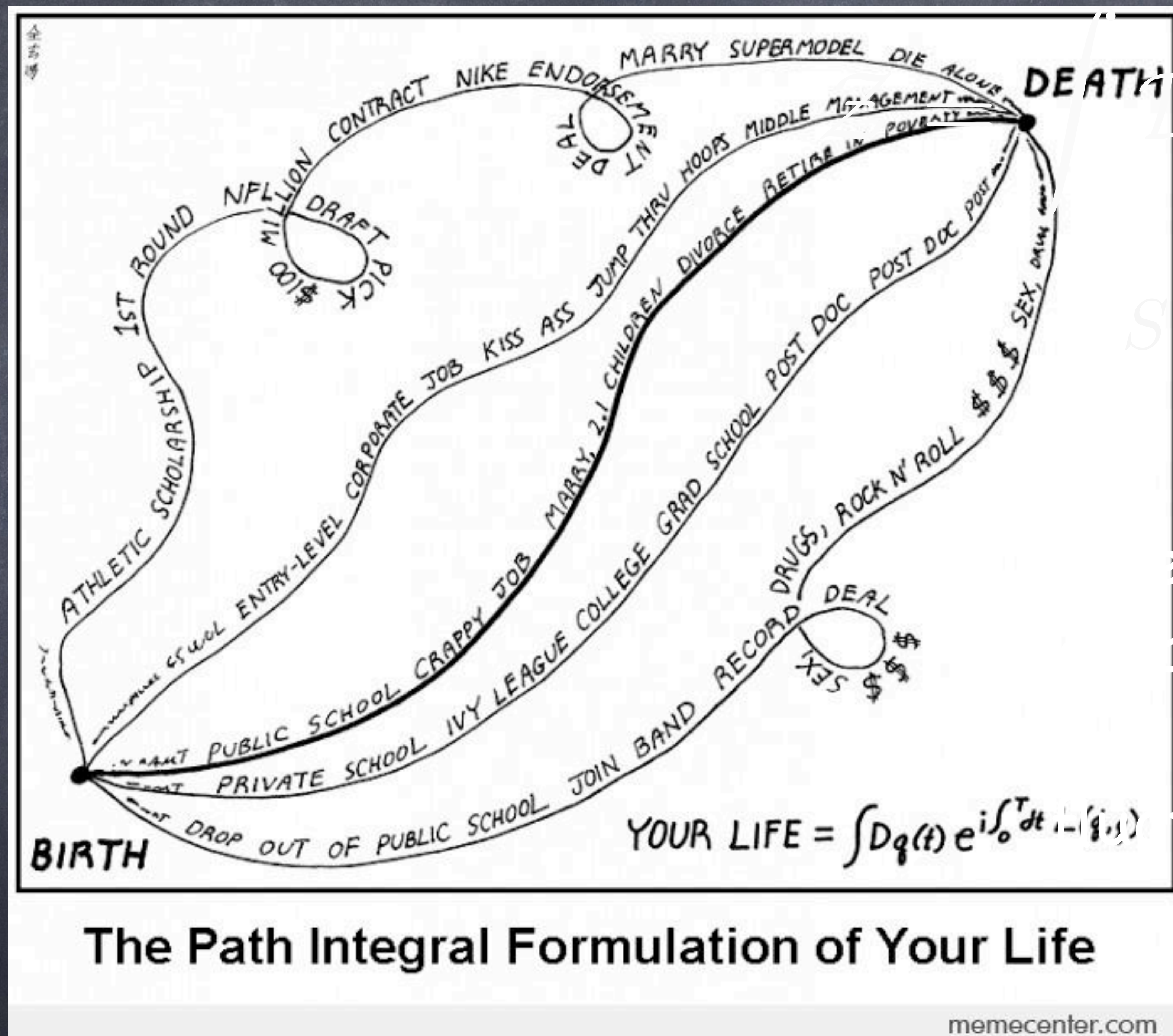
Add amplitudes



Add amplitudes

$$\mathcal{Z} = \int \mathcal{D}\left[\phi\right] \mathrm{e}^{\frac{i}{\hbar} S[\phi]}$$

The path integral



The Path Integral Formulation of Your Life

$$\int \mathcal{D}[\phi]\, \mathrm{e}^{\frac{i}{\hbar}S[\phi]}$$

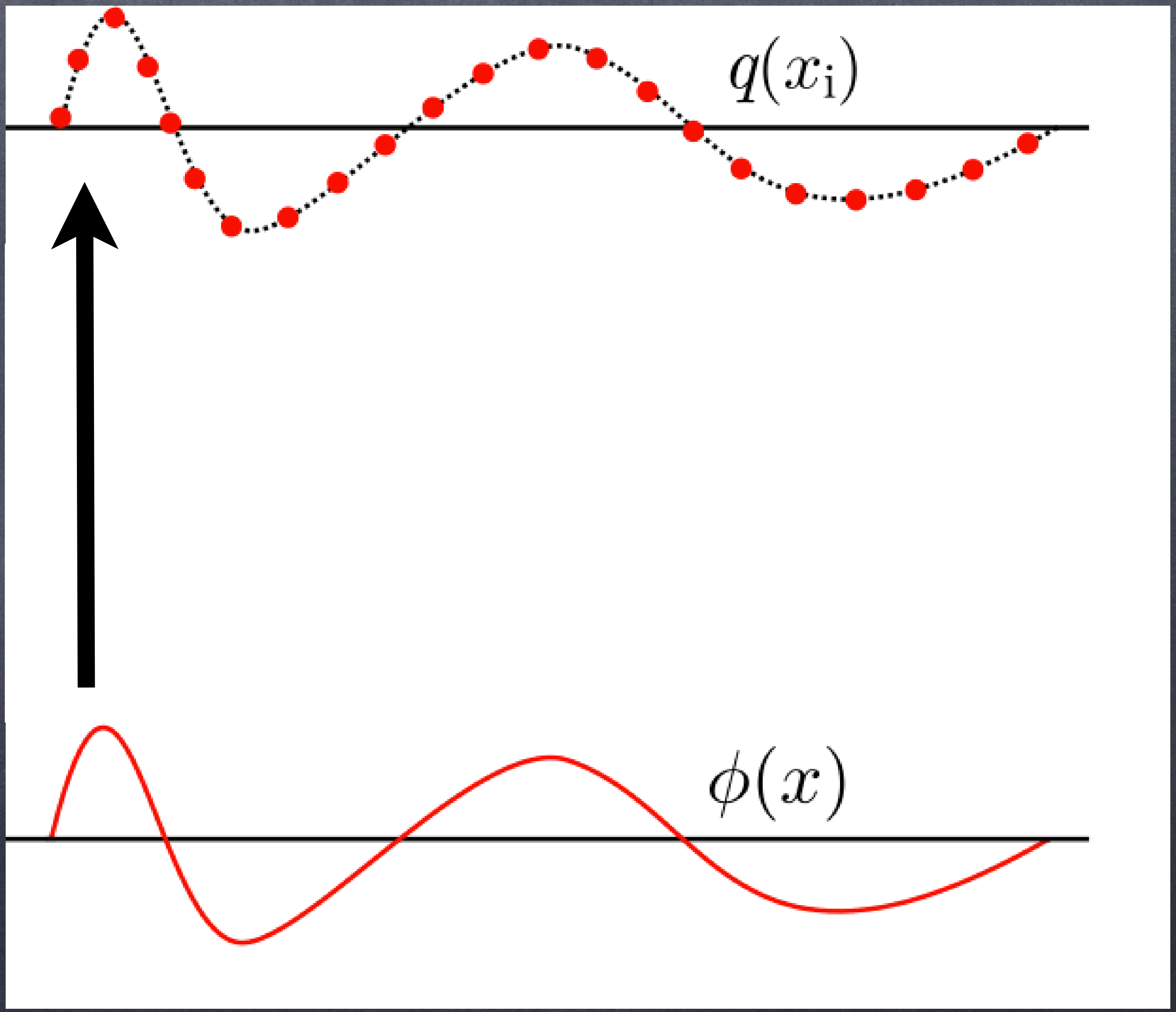
$$S = \int d^4x\, \mathcal{L}(x)$$

...rvable =
...tion values
...r these
...tuations

www.memecenter.com/fun/19500/The-Path-Integral-Formulation-of-Your-Life

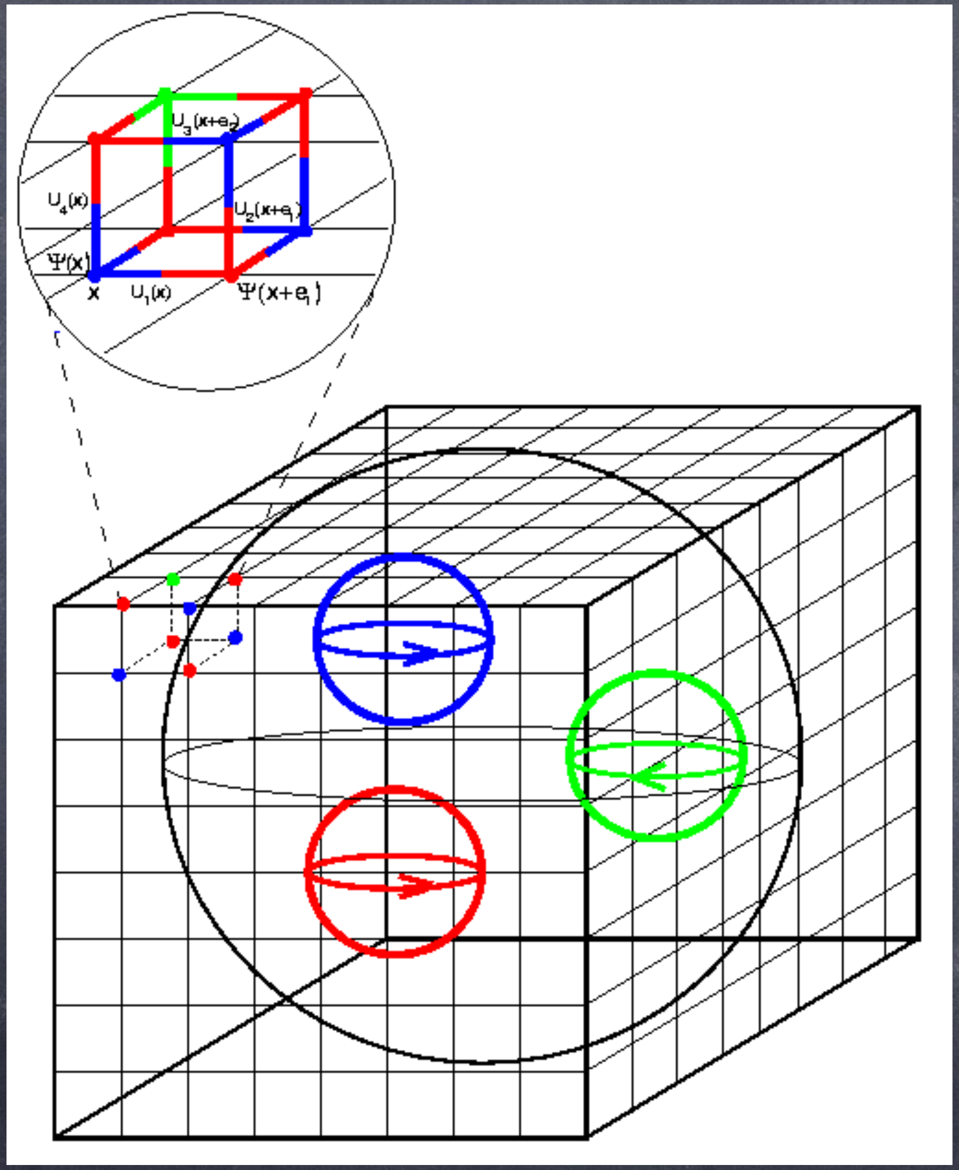
Be wise...discretise

Discretise space time
on finite lattice with
spacing a and finite size L



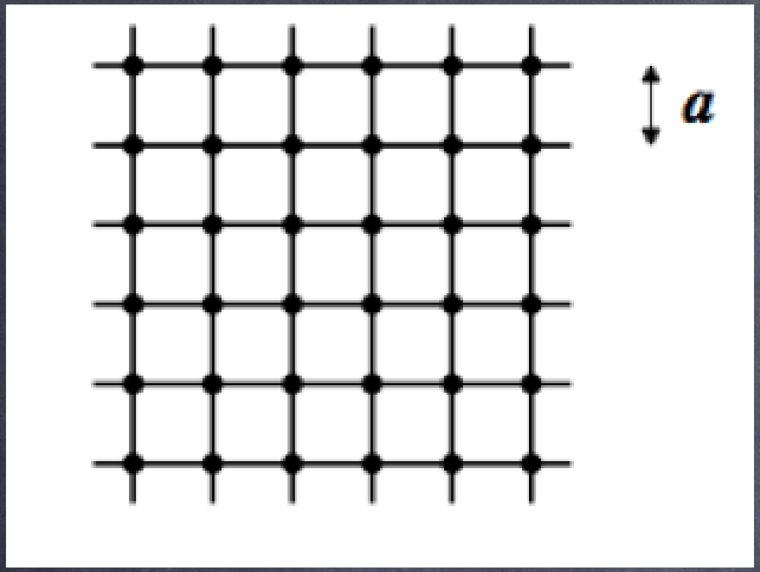
Lattice QCD

Be wise...discretize



QCD = Quantum Chromodynamics

Functional integral



$$\mathcal{D}\left[\phi\right] = \prod_{x_\mu} d\phi(x) = \prod_{x_\mu} d\phi_{x_\mu} \qquad x_\mu = a n_\mu$$

$$64 \times 64 \times 64 \times 64 = 2^{24}$$

$$\int dy_1 \; dy_2 \; \cdots dy_{2^{24}}$$

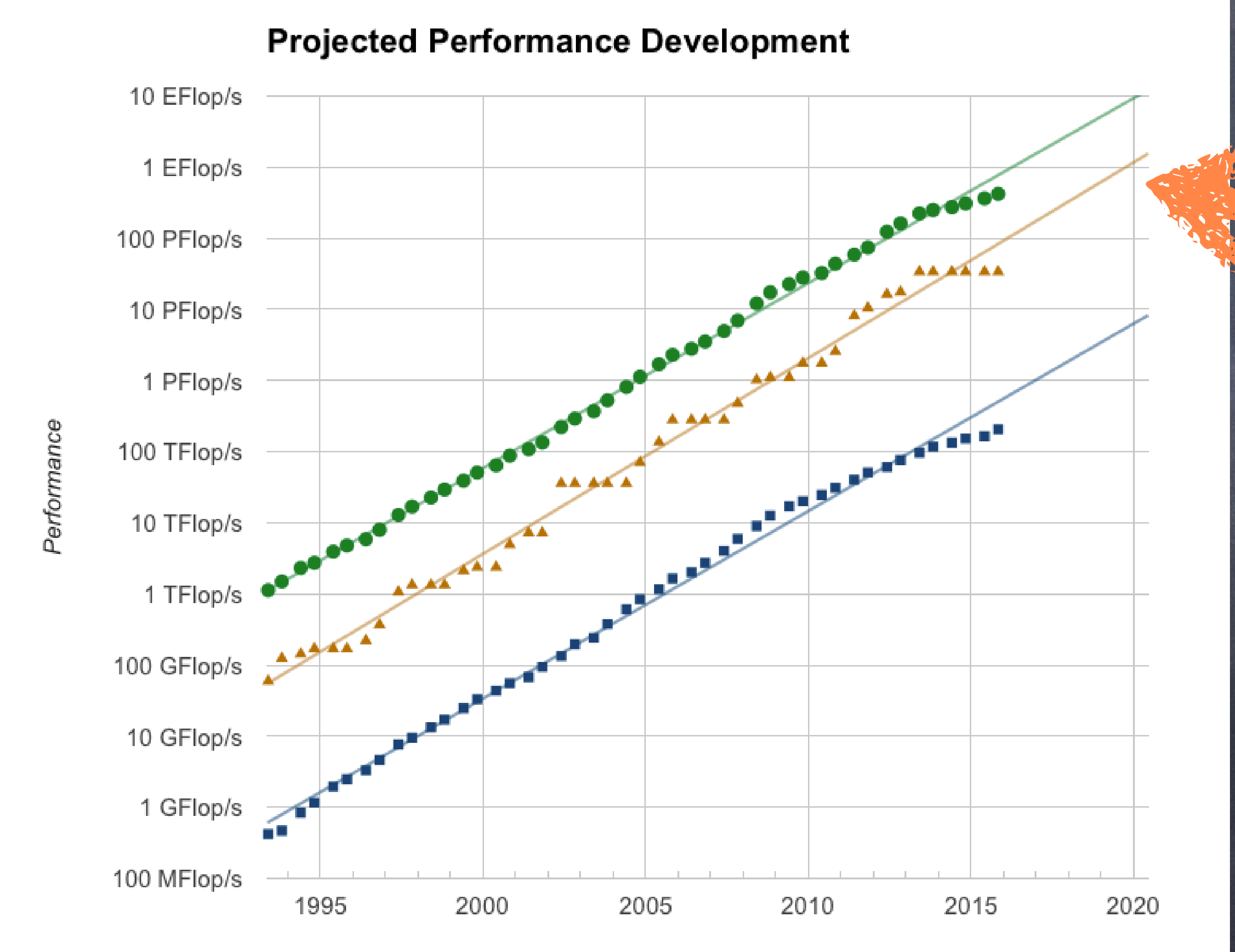
- Not factorizable. $n^{2^{24}}$ terms in the sums AAAARRRRRGGGGHHHH!!!!!
- Statistical approach => importance sampling

$$\{\phi_i\} \qquad \langle \mathcal{O} \rangle = \frac{1}{N_{\text{cf}}} \sum_{i=1}^{N_{\text{cf}}} \mathcal{O}\left[\phi_i\right] + O\left(\frac{1}{\sqrt{N_{\text{cf}}}}\right)$$

Hardware development

K. Wilson: "Lecture at Lattice 1989 Capri"

Lattice gauge theory could require a 10^8 increase in computer power AND spectacular algorithmic advances before useful interactions with experiment



Exascale in 2020 ?

10^7 increase in 25 years

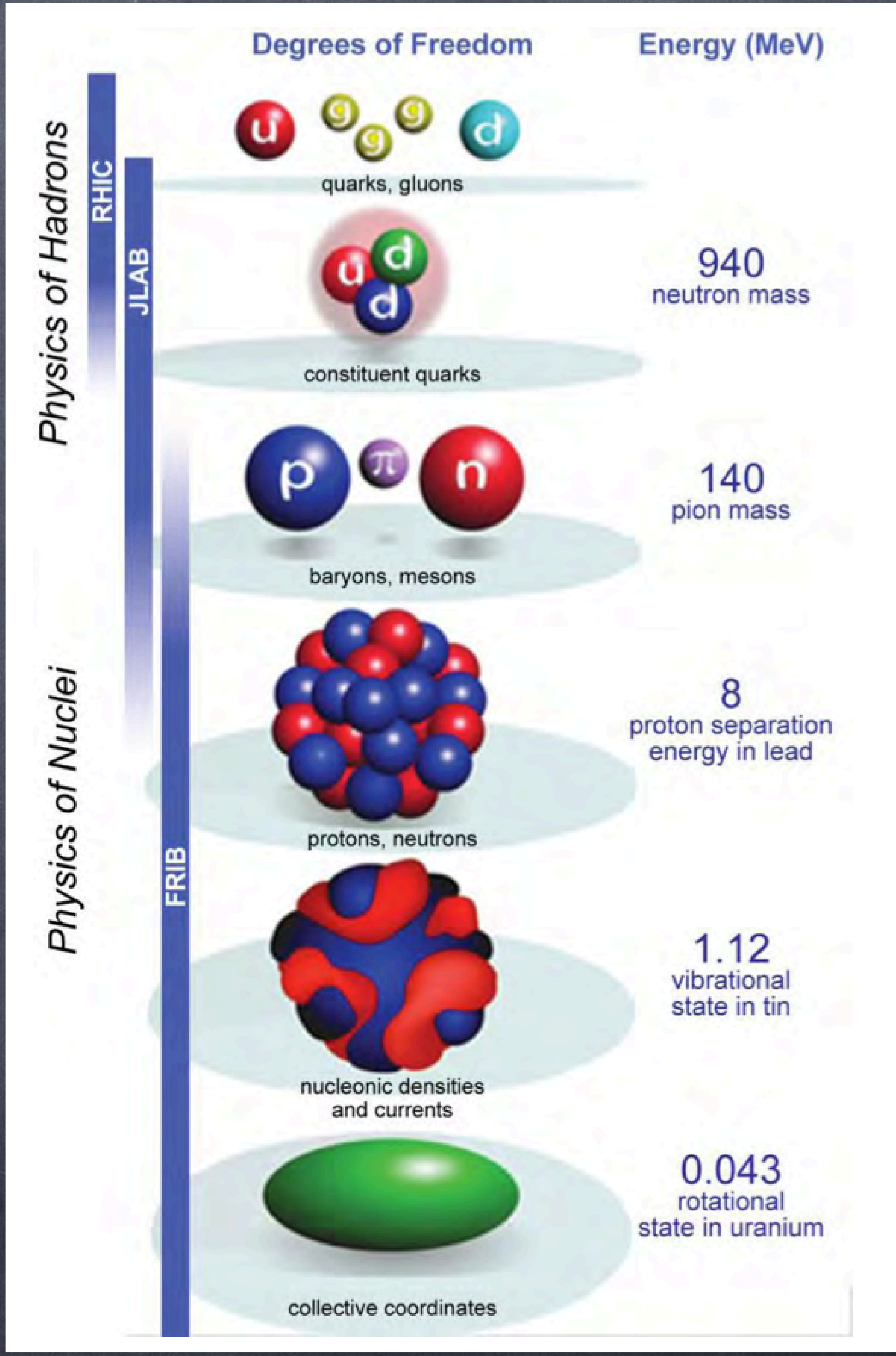
top500.org

From quarks to nuclei

Small number of parameters responsible for a plethora of phenomena

$$g_s, m_u, m_d, m_s, \cdots, e$$

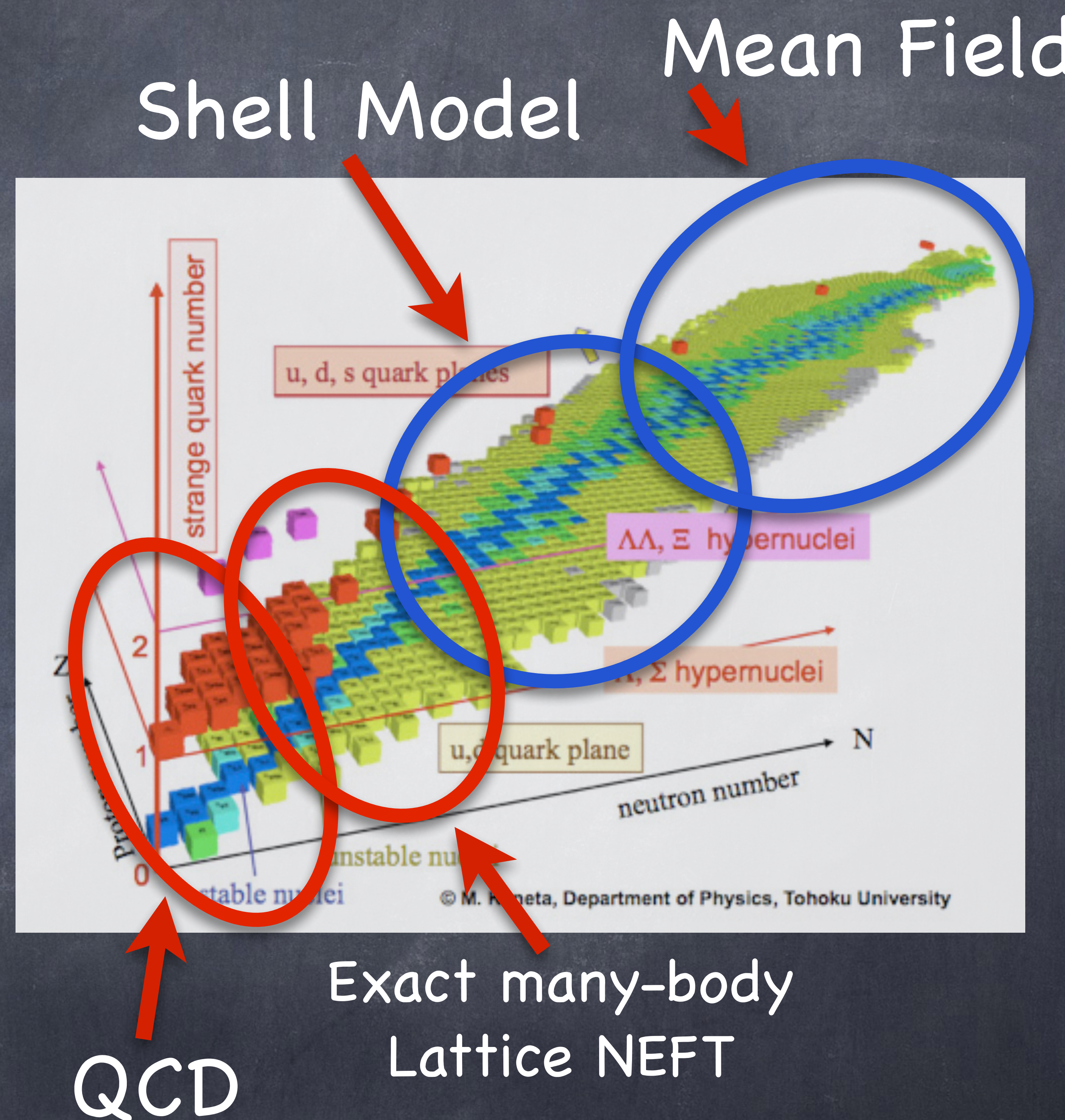
Low energy nuclear physics from
(lattice) QCD



FRIB Users Organization for the NSAC Long Range Plan Implementation Subcommittee

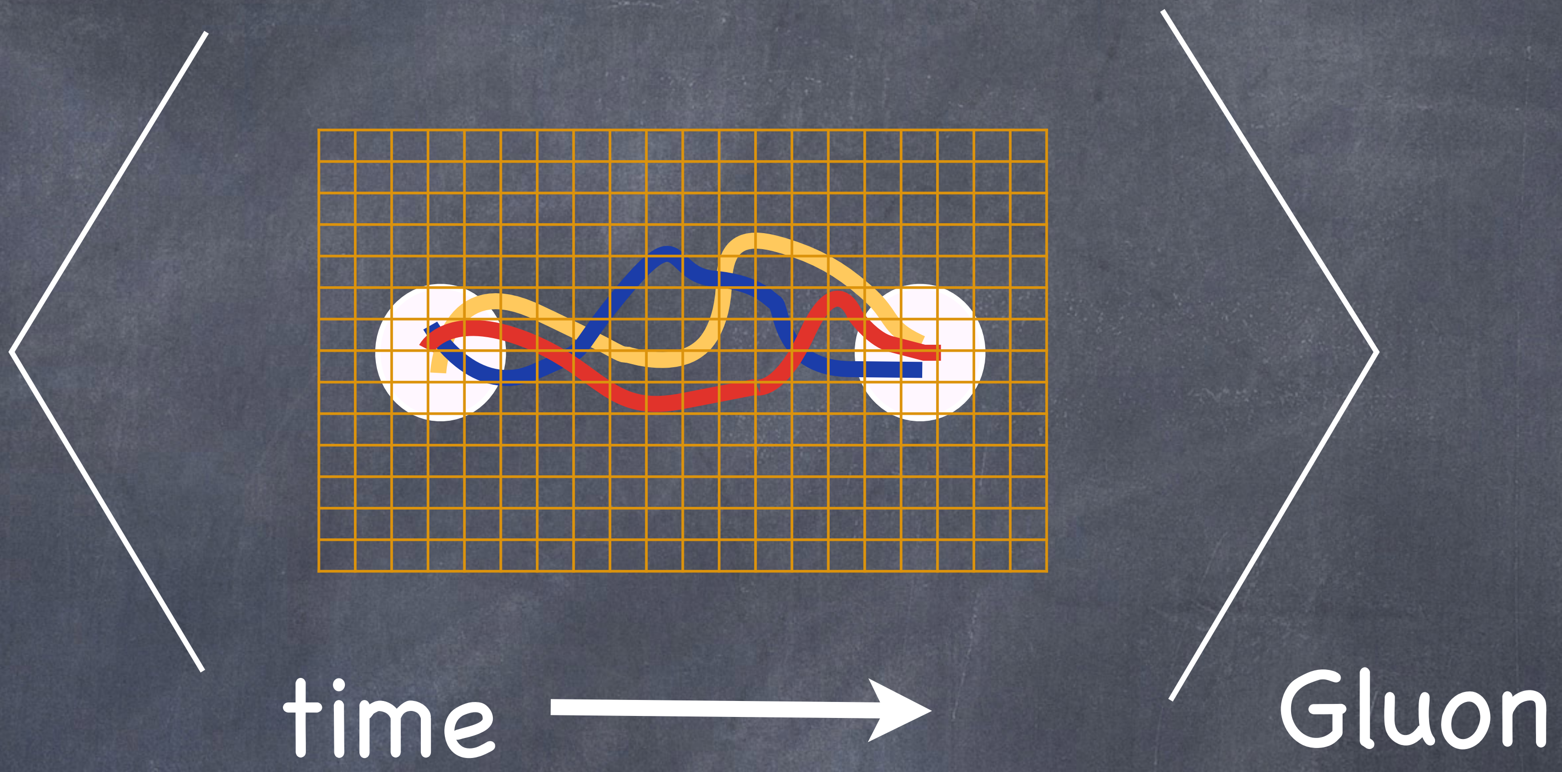
Tools for precision predictions

- Exploit effective degrees of freedom
- Quantitative matching between different methods
- QCD for light nuclei binding energies and matrix elements
- Match QCD and Nuclear Effective Field Theory methods



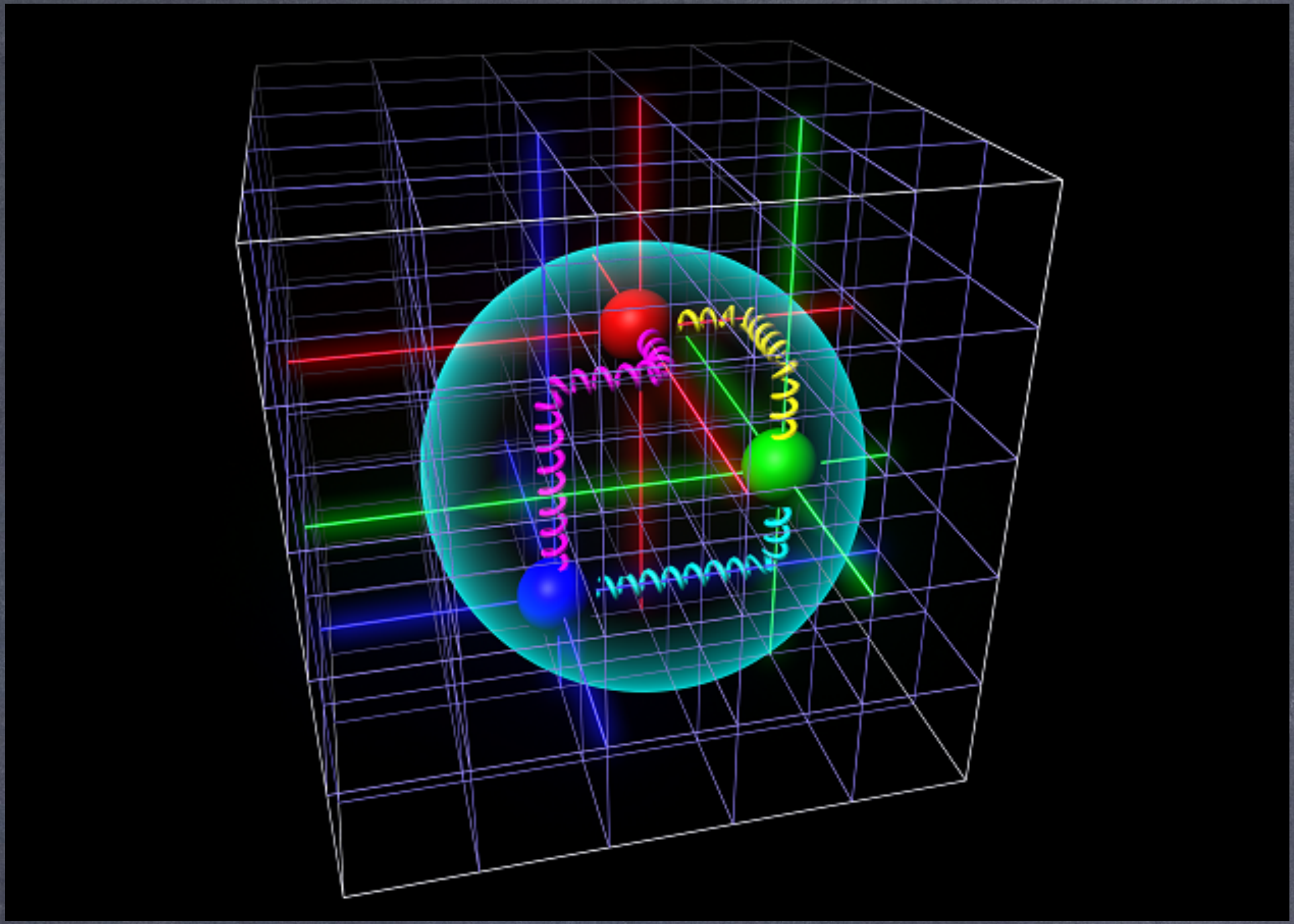
Hadron masses

- Create three quarks at source and annihilate three quarks at sink
- Ensembles add virtual gluons and quark loops
- Only correct quantum numbers propagate



$$C(t) = \sum_n Z_n \mathrm{e}^{-E_n t} \xrightarrow[t\to\infty]{} Z_0 \mathrm{e}^{-E_0 t}$$

Calculate proton mass



"There is no such thing as stupid questions"