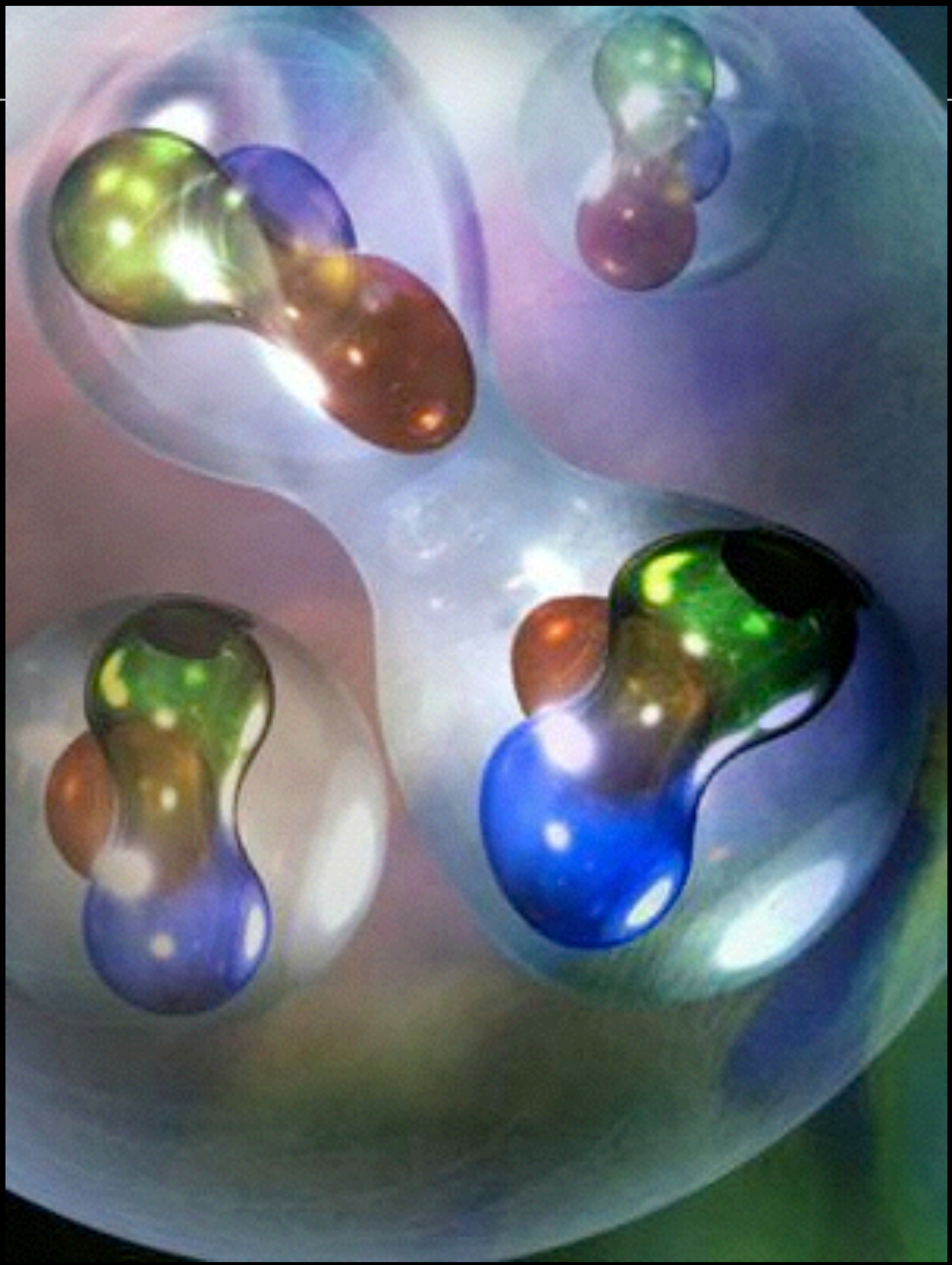
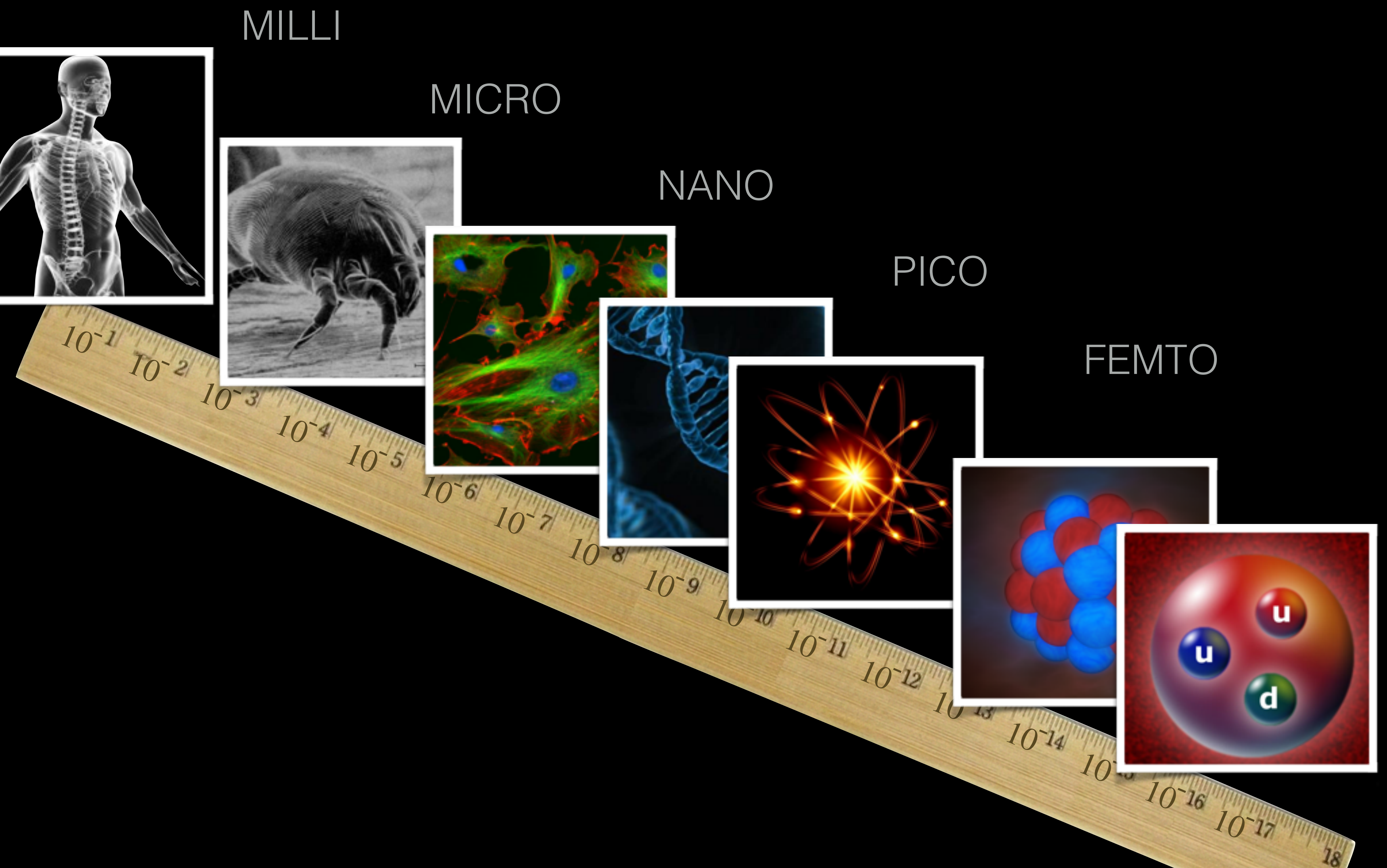


[image: © JLab]

The secret life of quarks

William Detmold, MIT

wdetmold@mit.edu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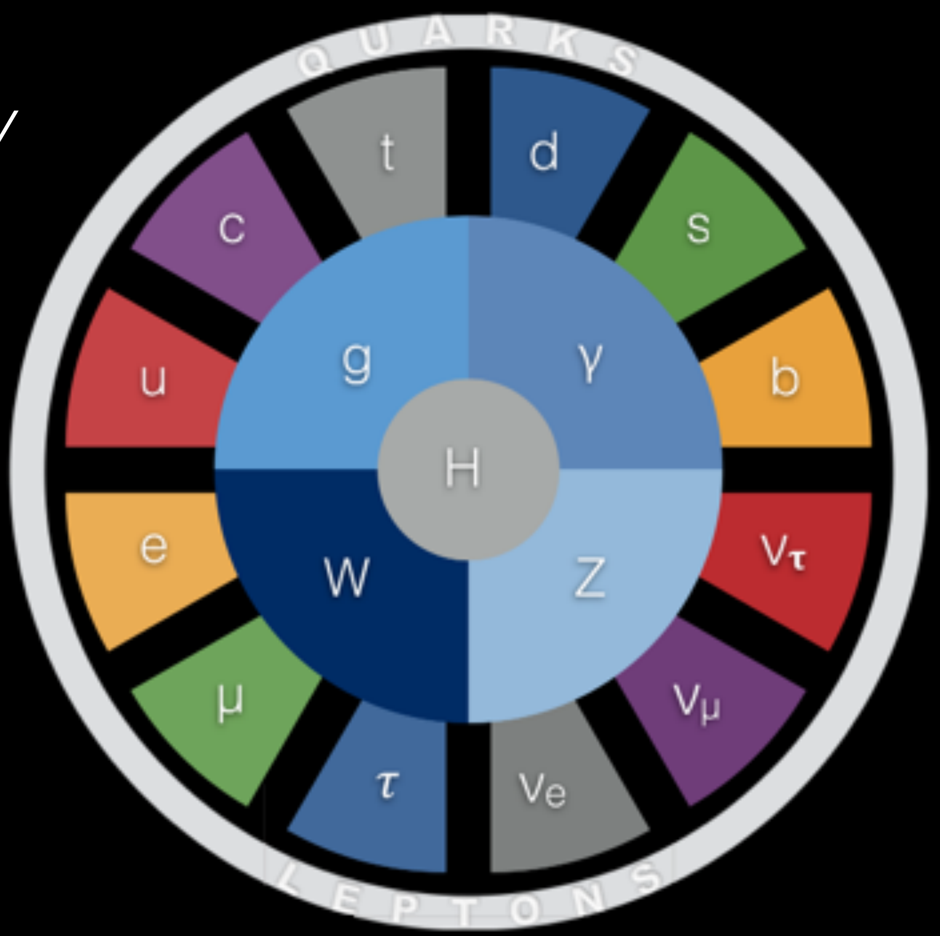
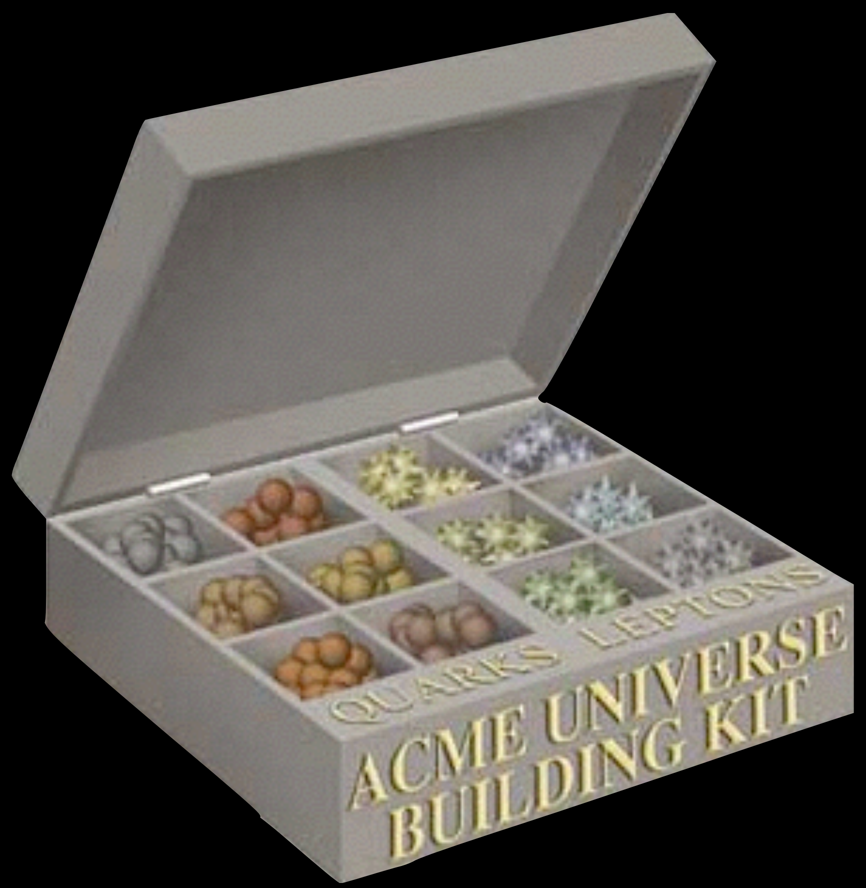
- The Standard Model is a *quantum field theory*
- Quantum chromodynamics (QCD) + Electroweak theory
- Particles:
  - (Anti-)quarks (up, down, strange…)
  - Leptons (electrons, neutrinos,...)
- Interact via the:
  - Electromagnetic force: photons
  - Weak force: W, Z particles
  - Strong force (QCD): gluons
- Higgs: mass for fundamental particles





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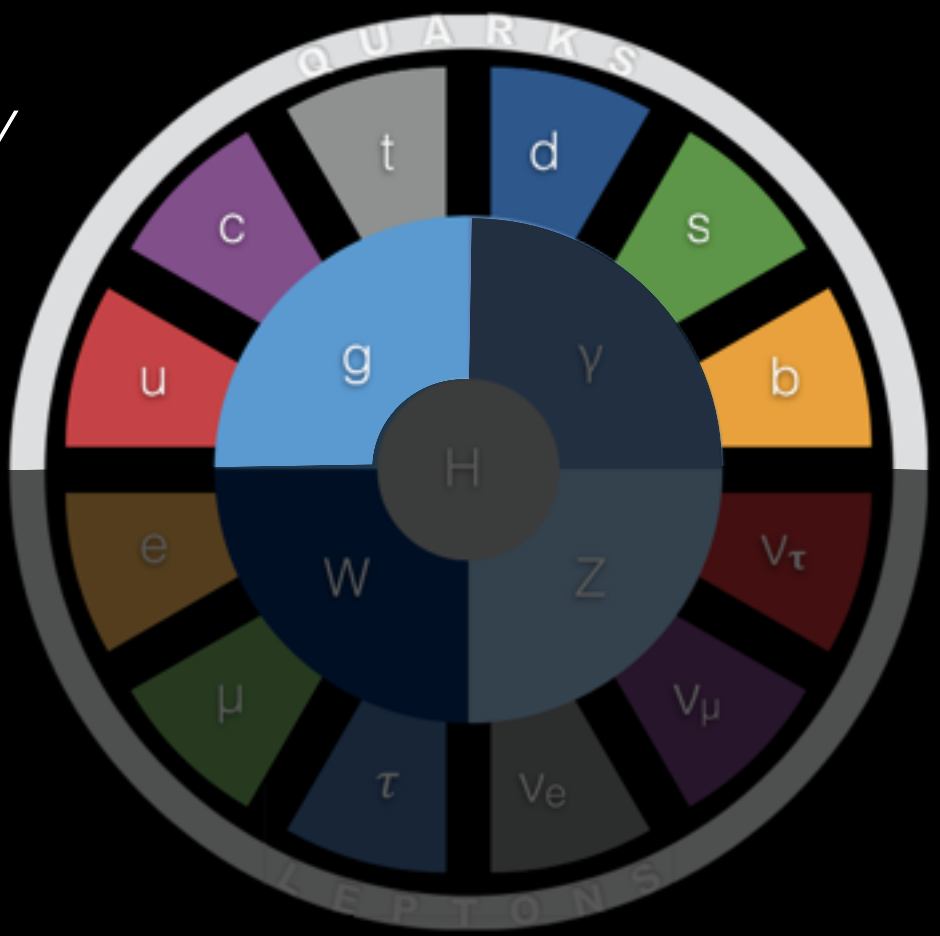
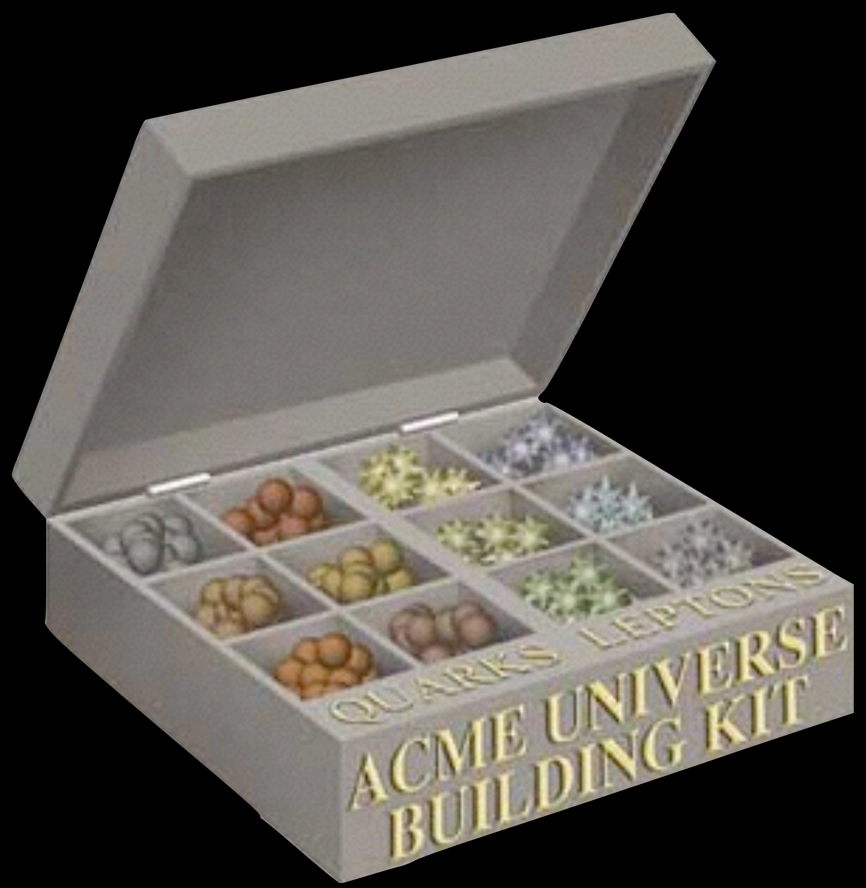
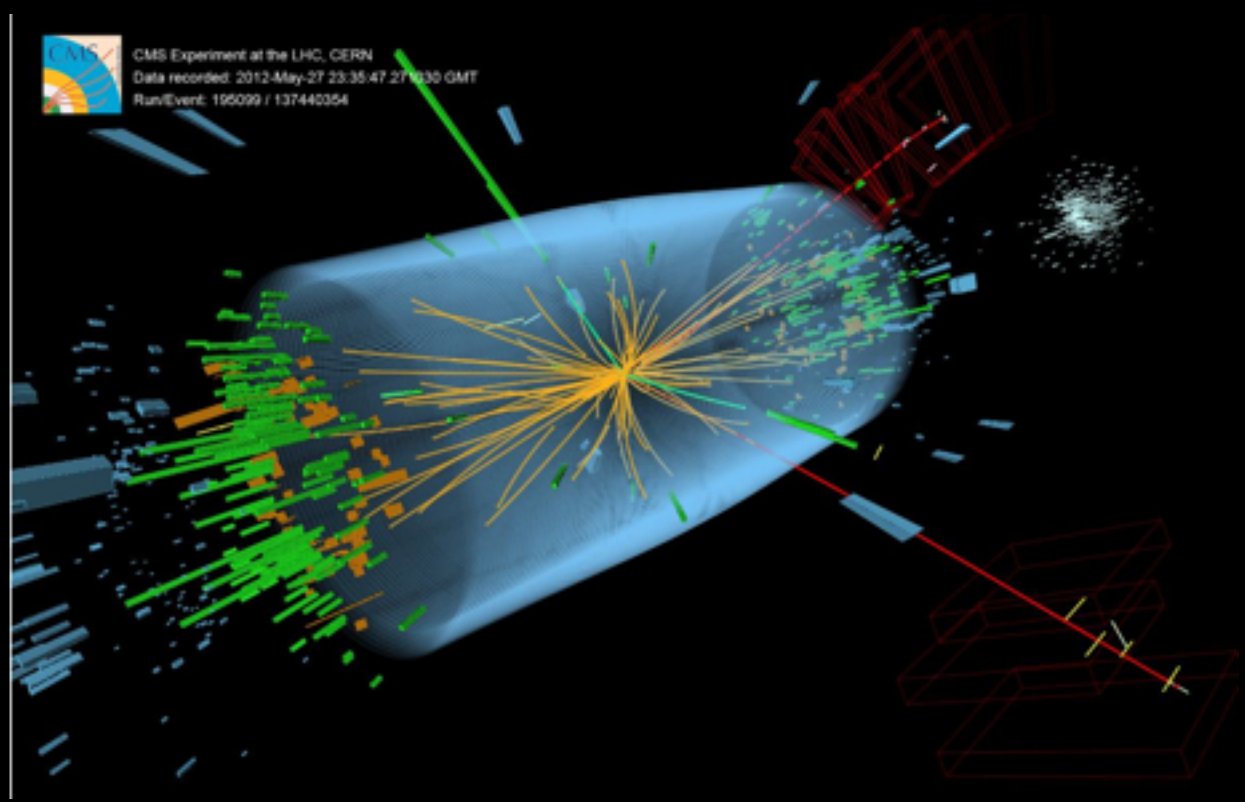
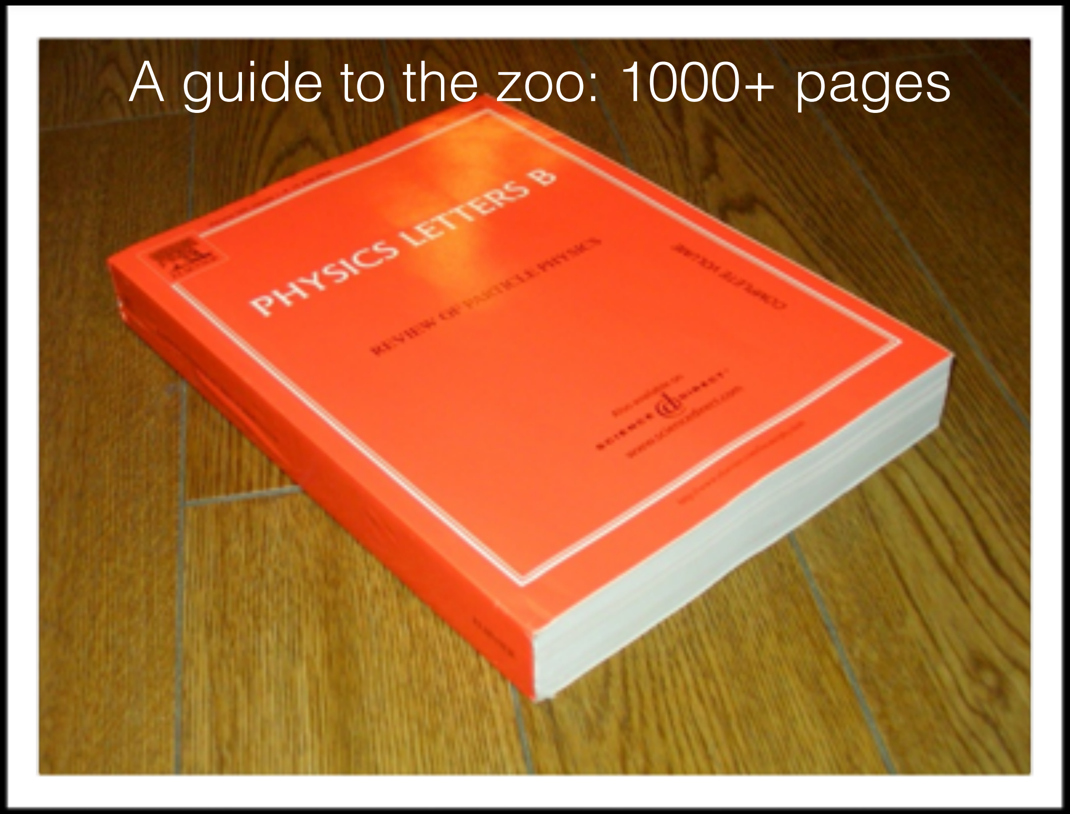


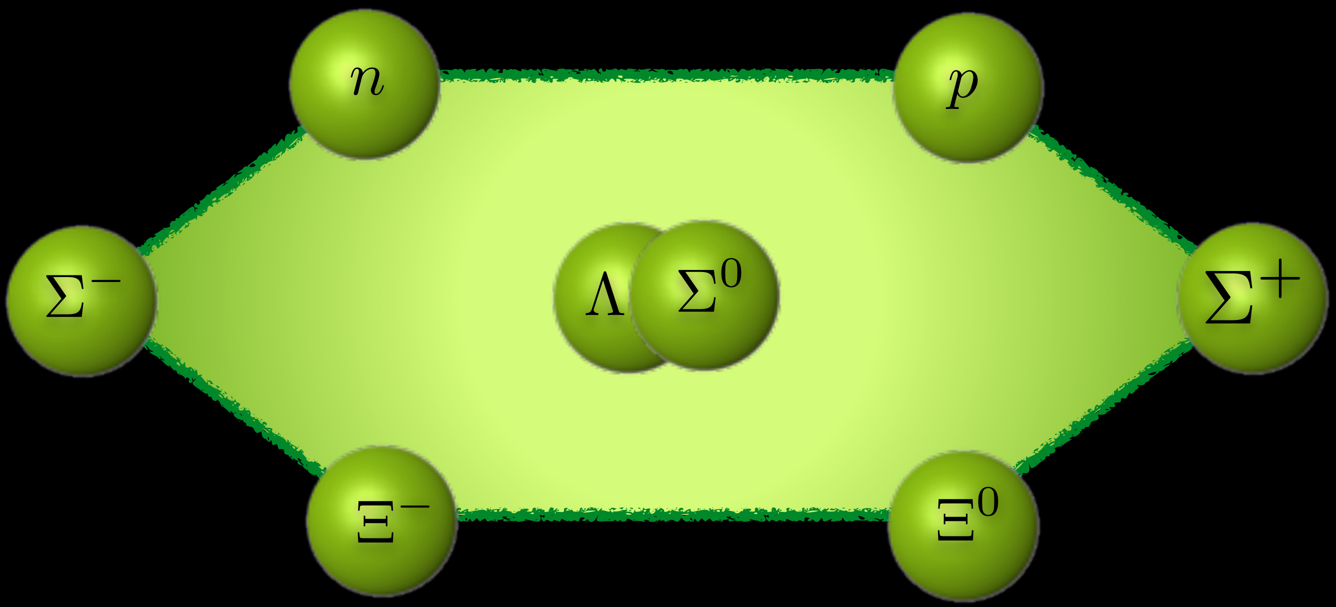


- *We never see quarks!*



- Observed particles are either leptons (electrons etc) or bound states of quarks and gluons
    - A zoo of particles!
- Classify in simple quark model
  [Gell-Mann "The Eightfold Way" 1960s]
    - Mesons: quark and antiquark
    - Baryons: three quarks
- Hyperons: baryons with strange quarks
    - Each row: very similar mass





$M_p = 1.672622 \times 10^{-27}$ kg
$M_n = 1.674929 \times 10^{-27}$ kg

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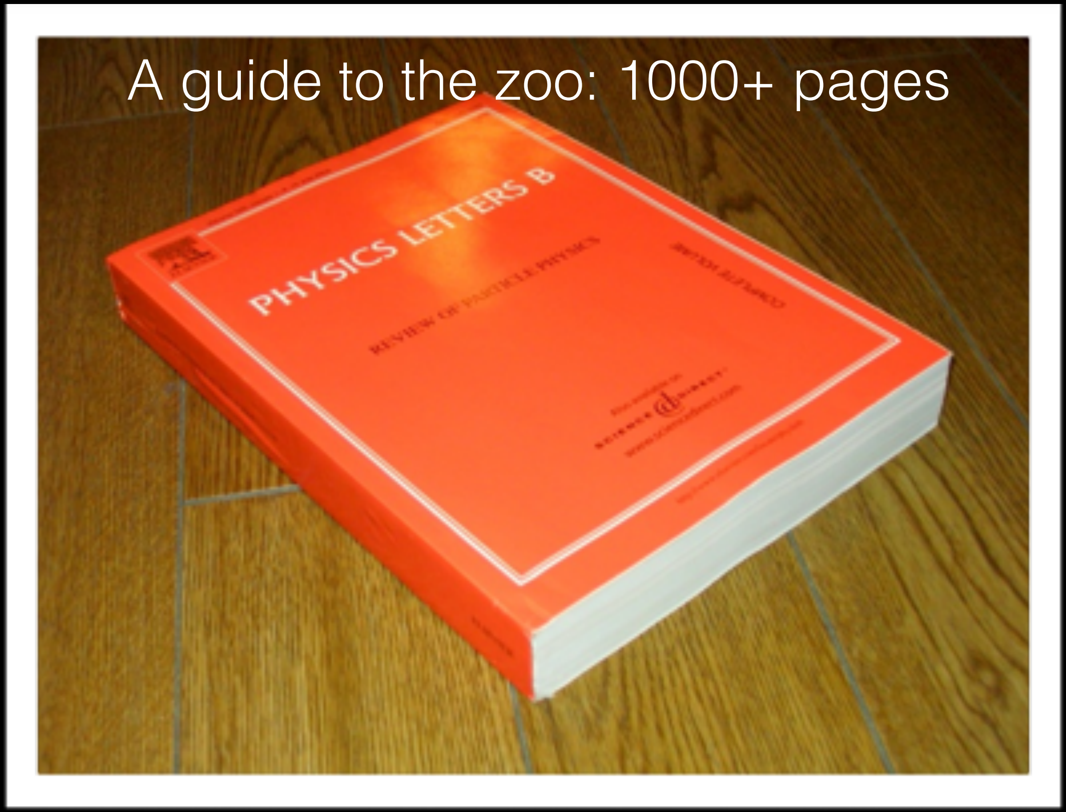
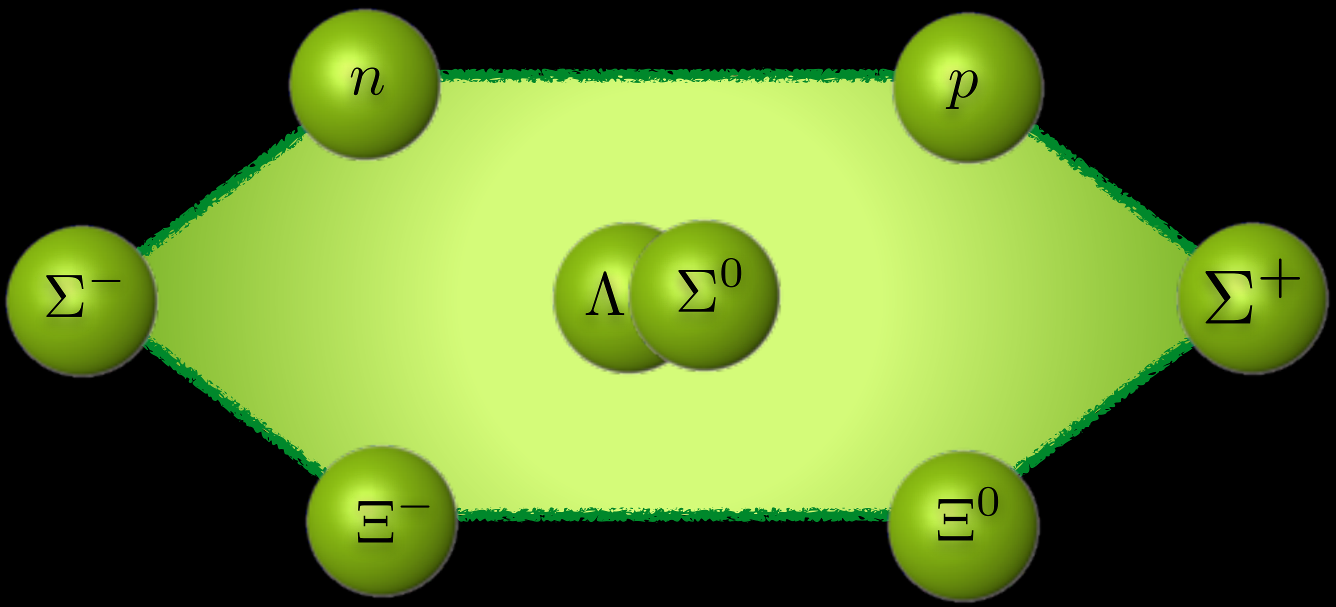
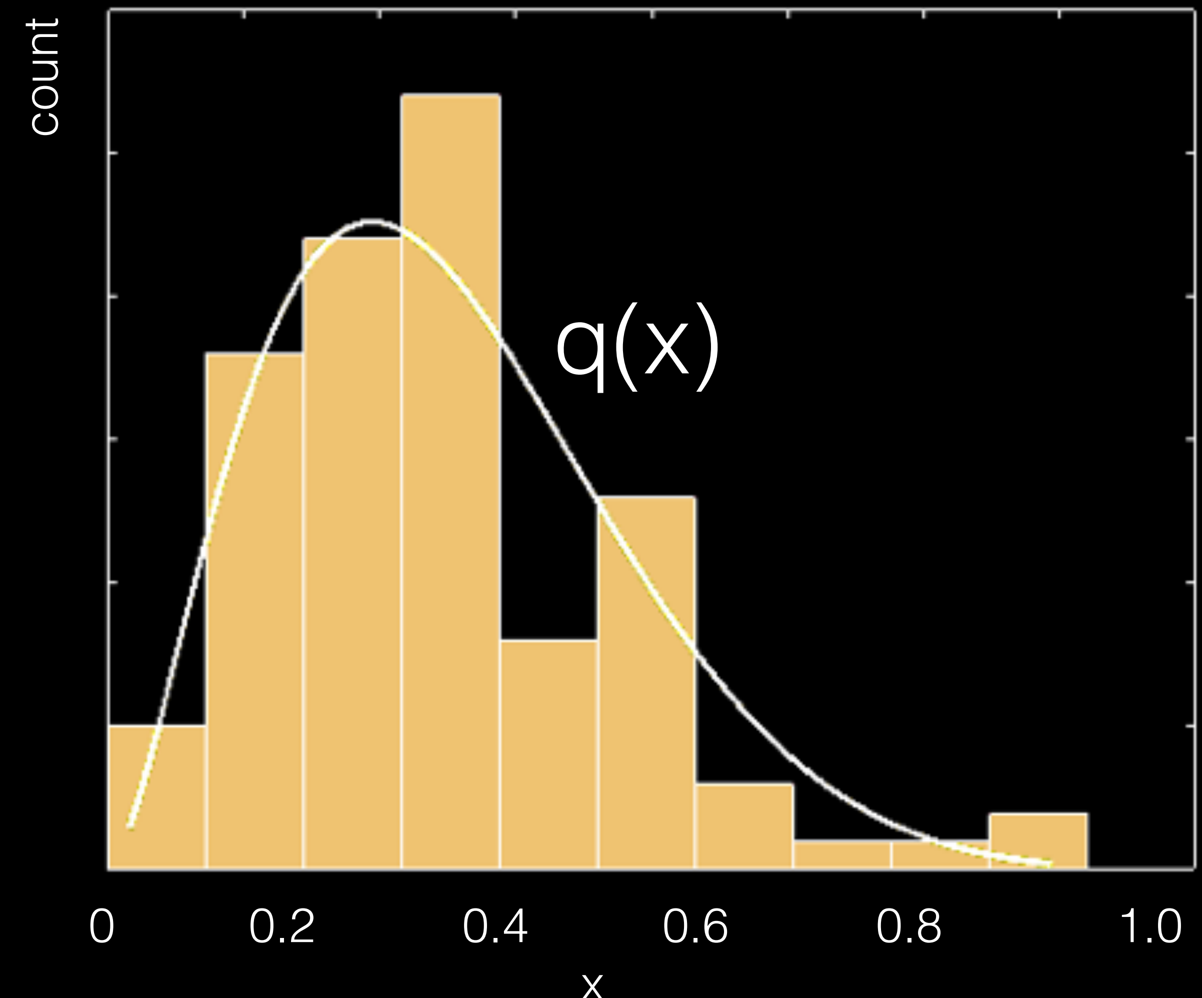
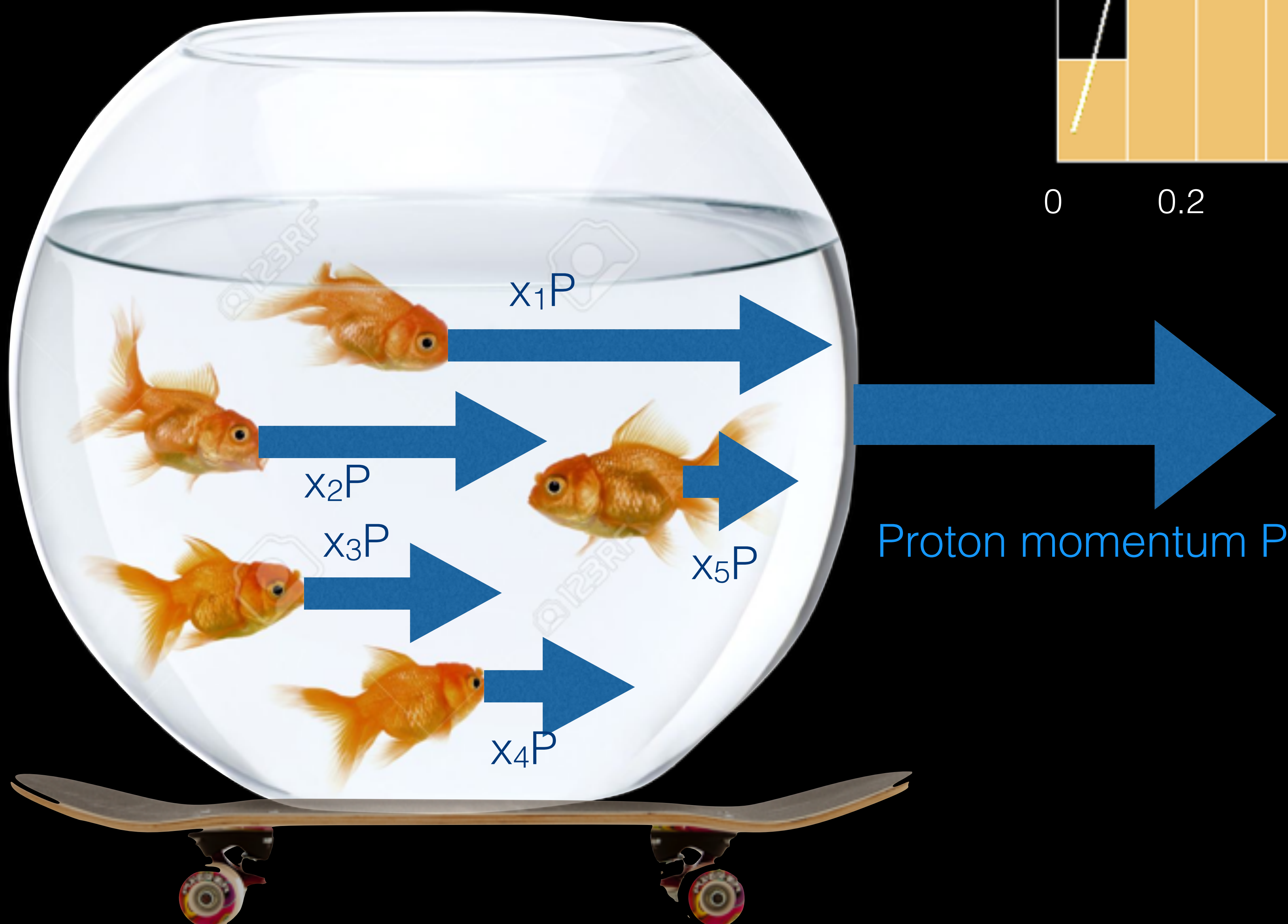




M_p=938.272046 MeV/c^2
M_n=939.565413 MeV/c^2

- What is a proton? Three quarks?
- Quark distribution functions:
  q(x) = prob. of finding a quark carrying a momentum fraction *x* in a proton





- What is a proton? Three quarks?
- Quark distribution functions:
  q(x) = prob. of finding a quark carrying a momentum fraction *x* in a proton
- How many quarks in a proton?

$$N_q = \int_0^1 q(x)dx$$

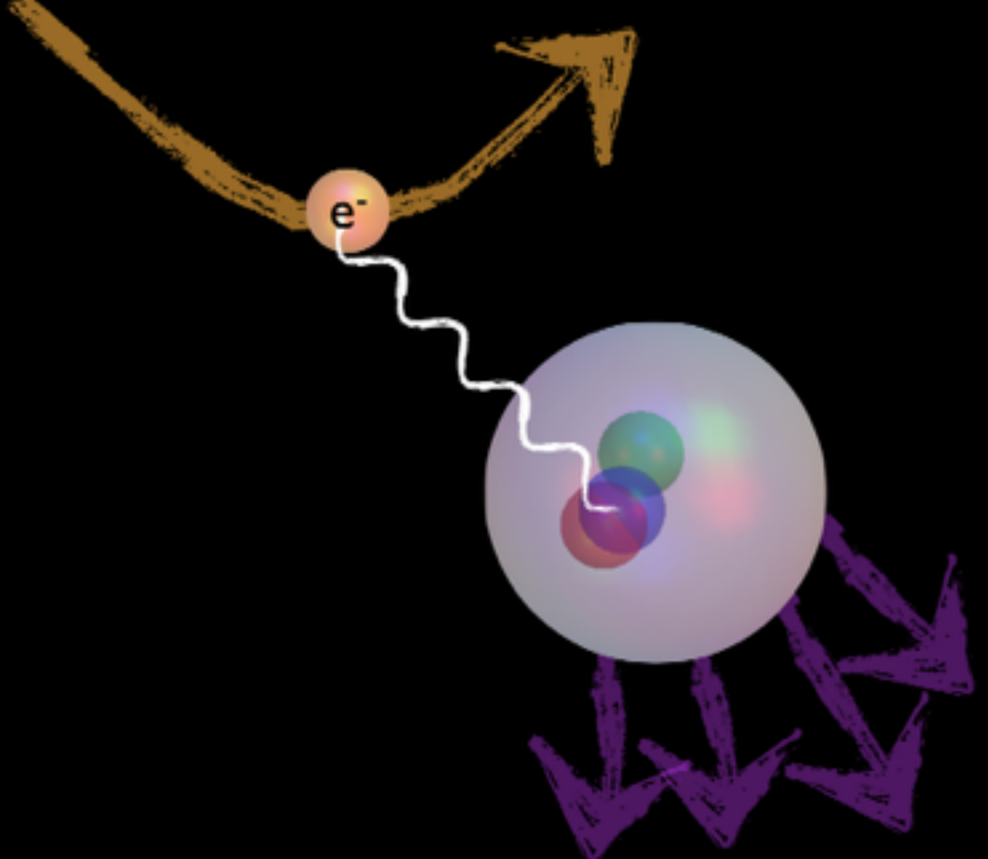
- *q(x)* extracted from deep inelastic scattering (DIS) experiments

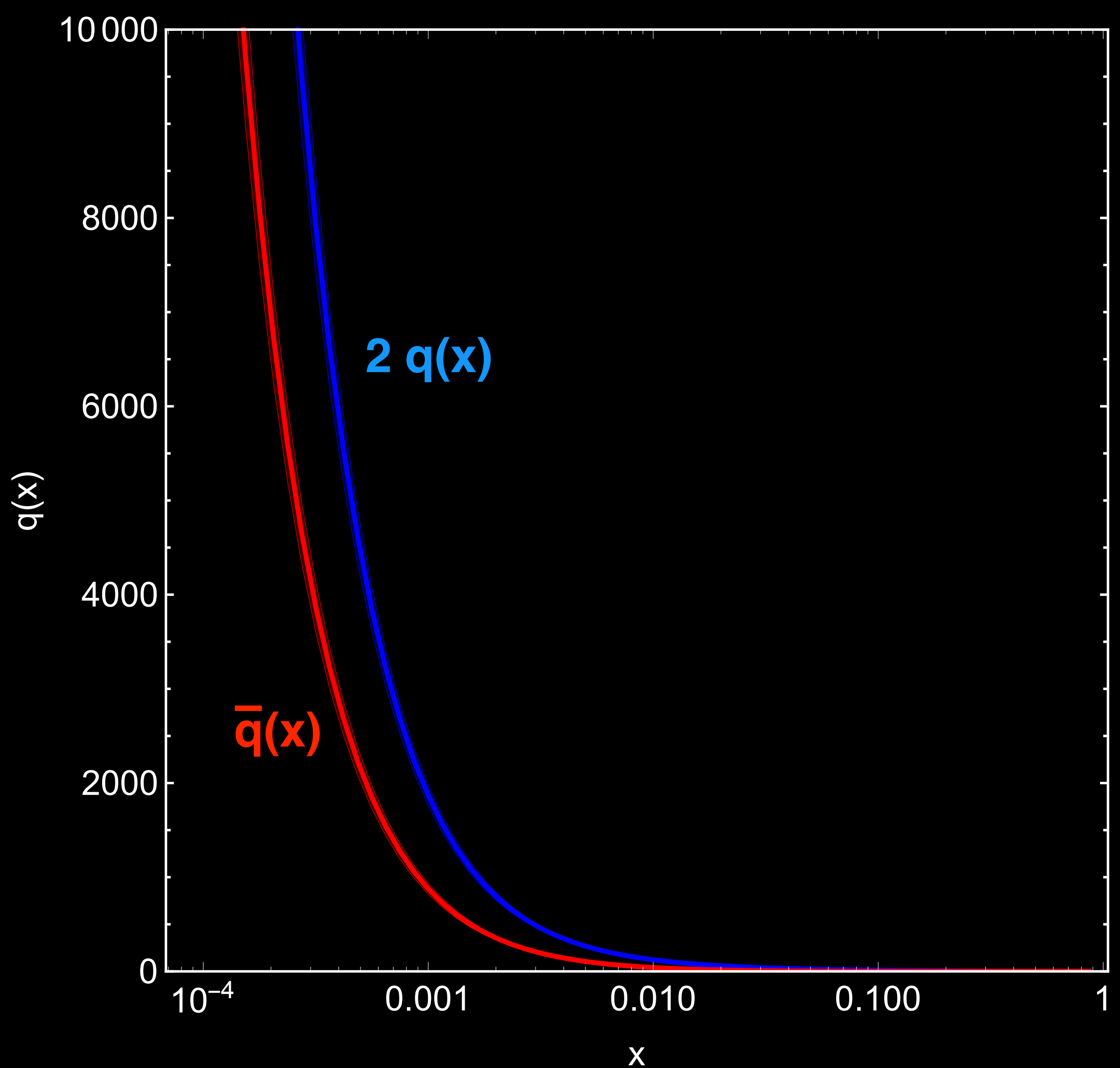
$$q(x) \sim x^{-1.2}(1-x)^3$$

- *So...*

$$N_q = \infty \qquad N_{\bar{q}} = \infty$$

there are infinitely many quarks in a proton!





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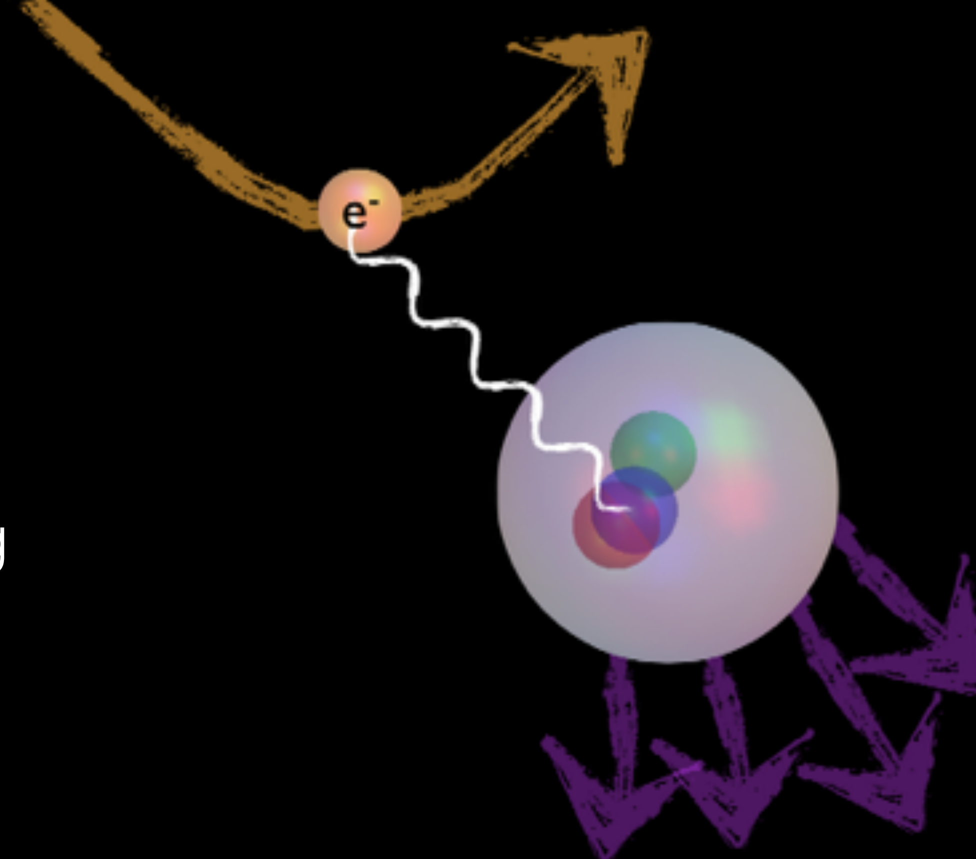
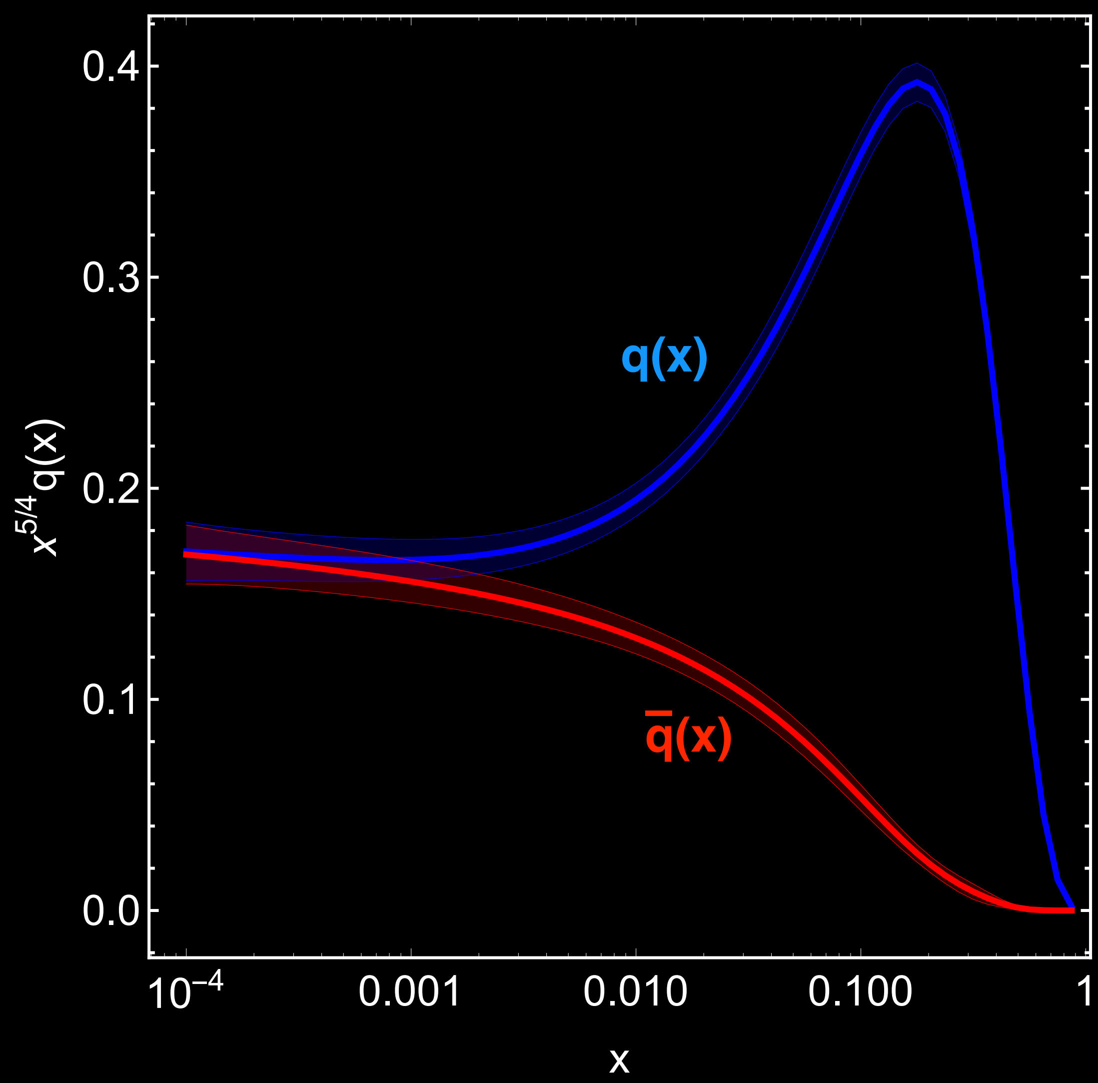
there are infinitely many quarks in a proton!

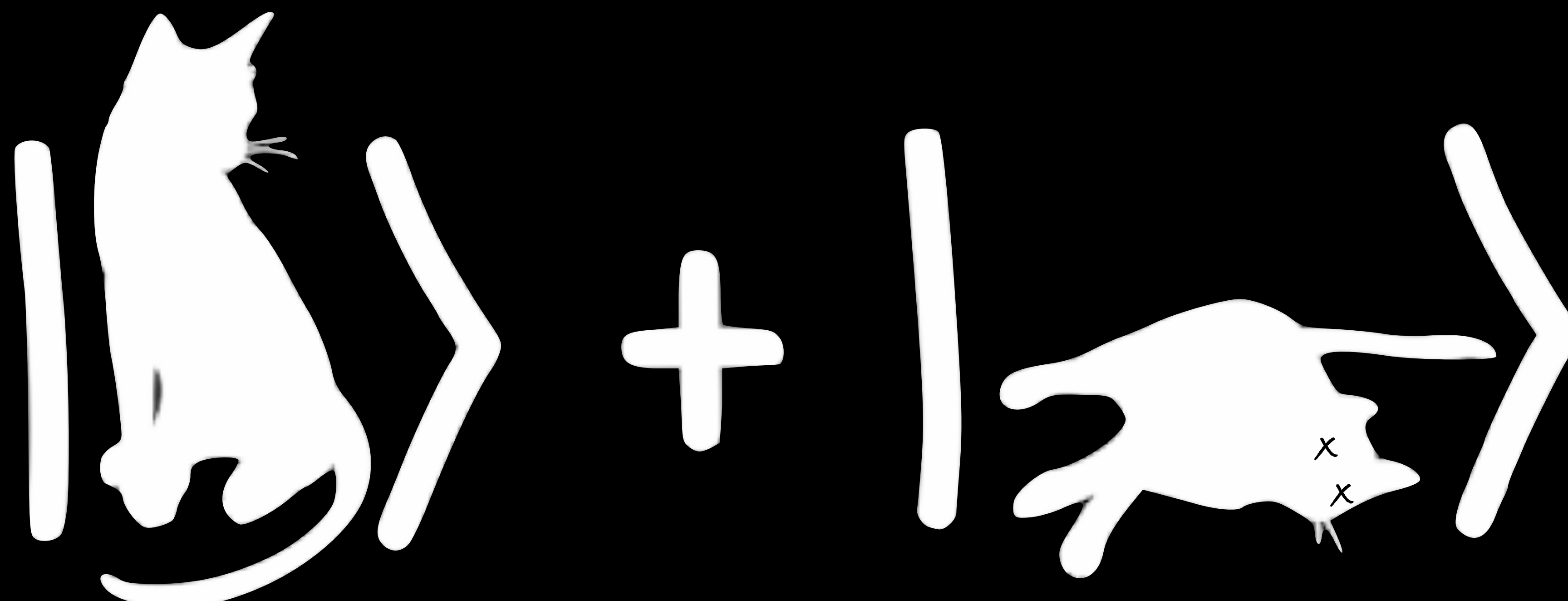
$$N_q - N_{\bar{q}} = 3$$

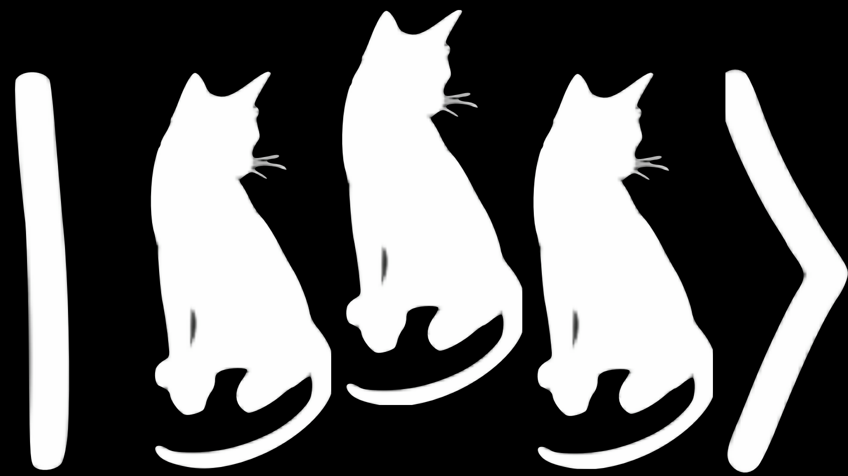




Schrödinger's cat

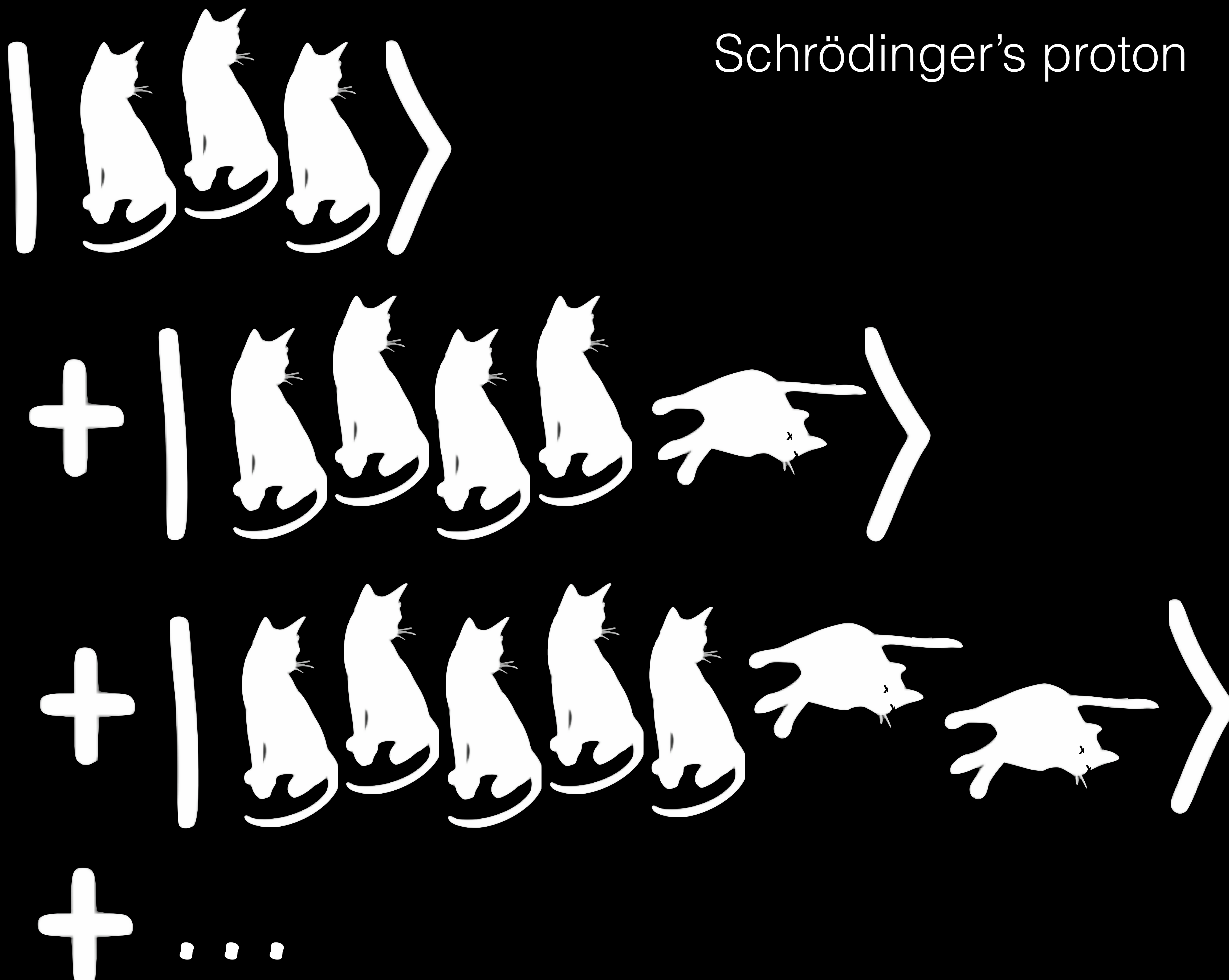
Schrödinger's cat



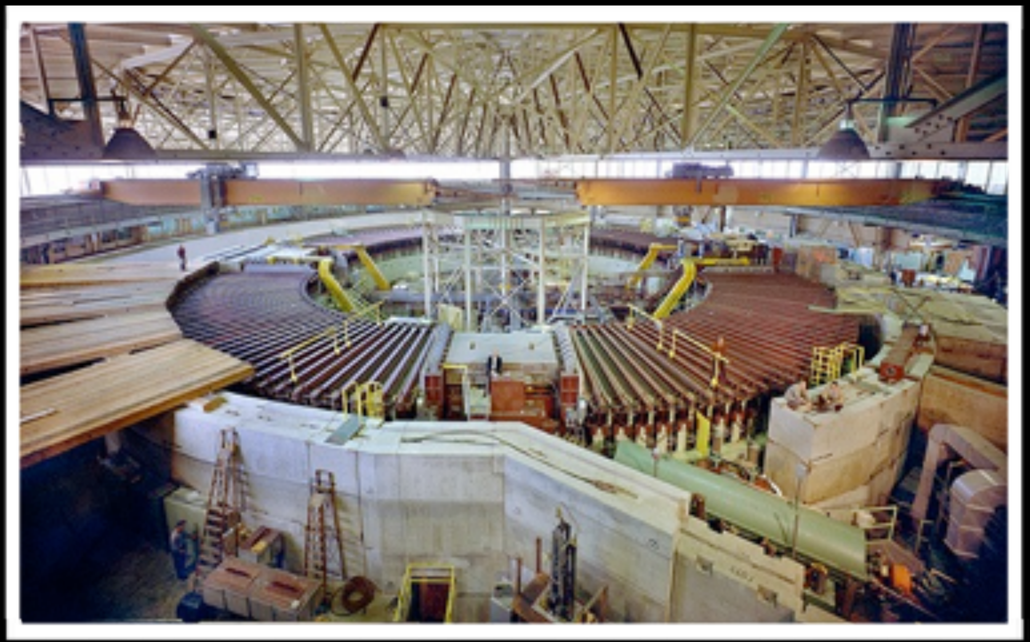


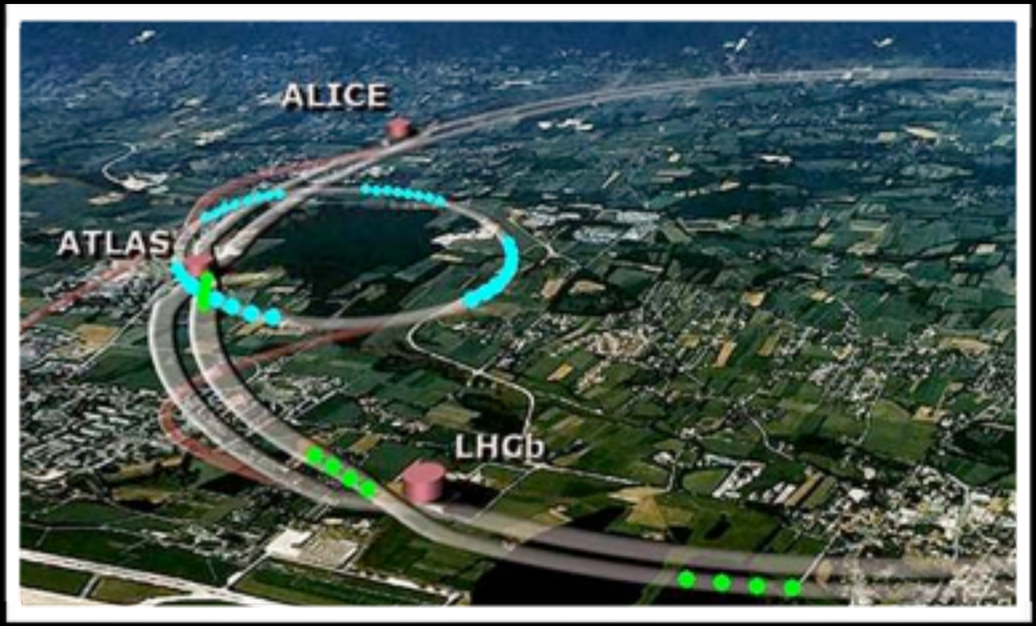
Schrödinger’s proton

Schrödinger's proton



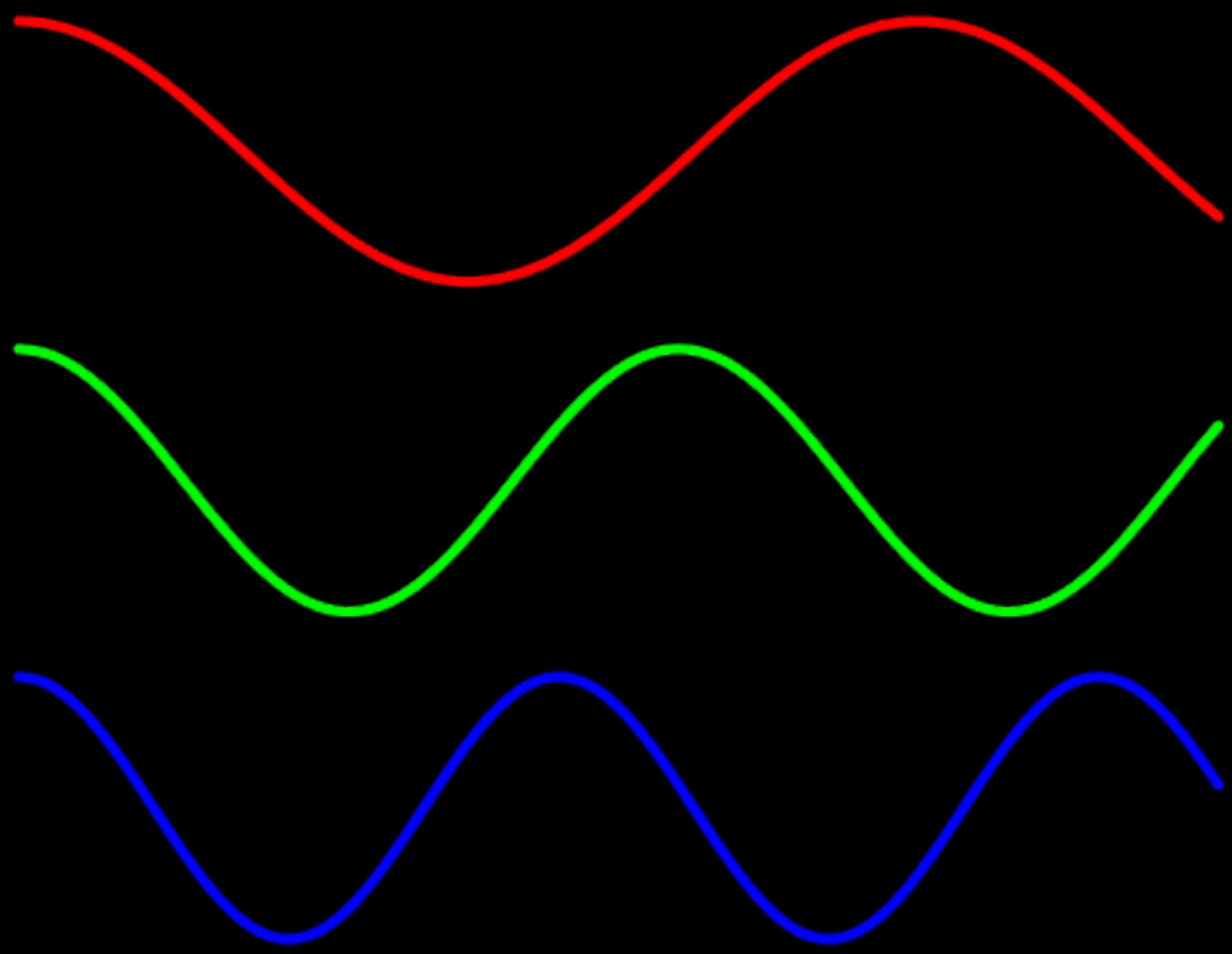
- What is a quark?
- It depends on how you look!
- Alice and Zac are experimenters
- Zac makes a particle accelerator and does DIS experiments
    - Zac sees a quark inside the proton
- Alice built a bigger accelerator with more energy
    - Alice looks at the same proton and sees a quark and two gluons





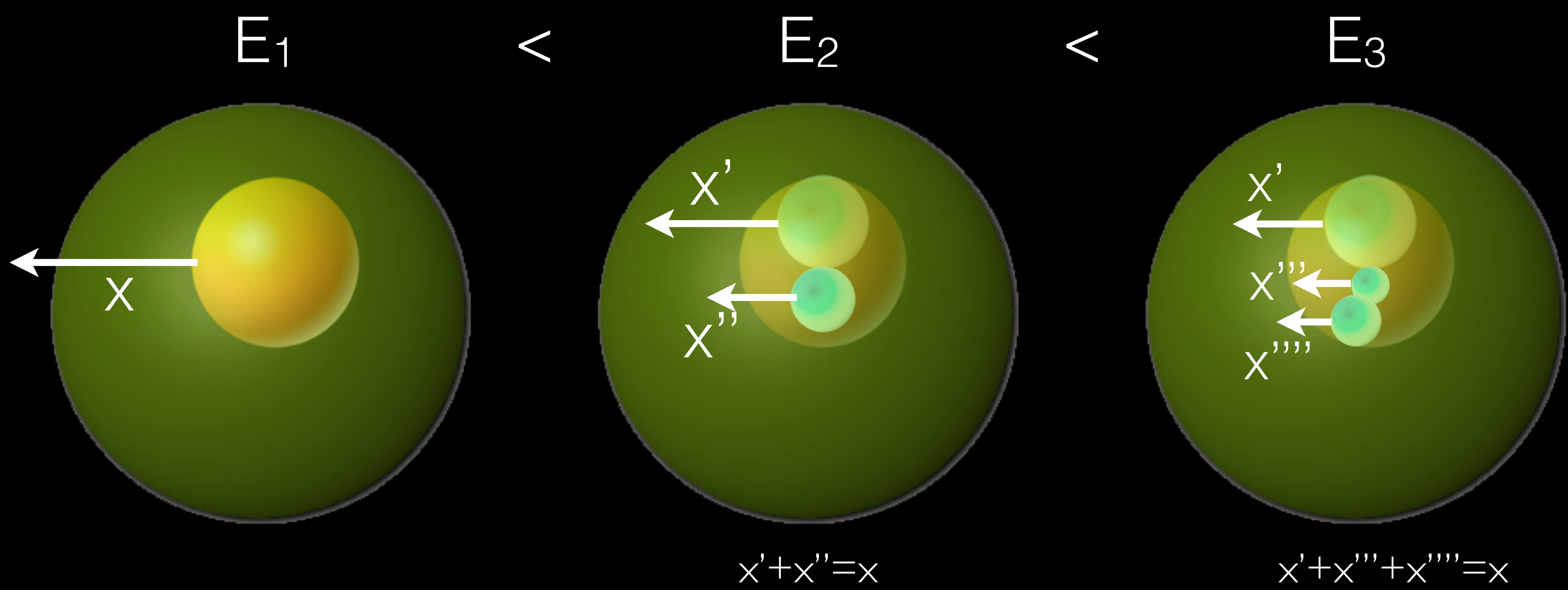
- The energy of the collision is the inverse of the resolution with which we probe the proton

$$E = \frac{hc}{\lambda}$$



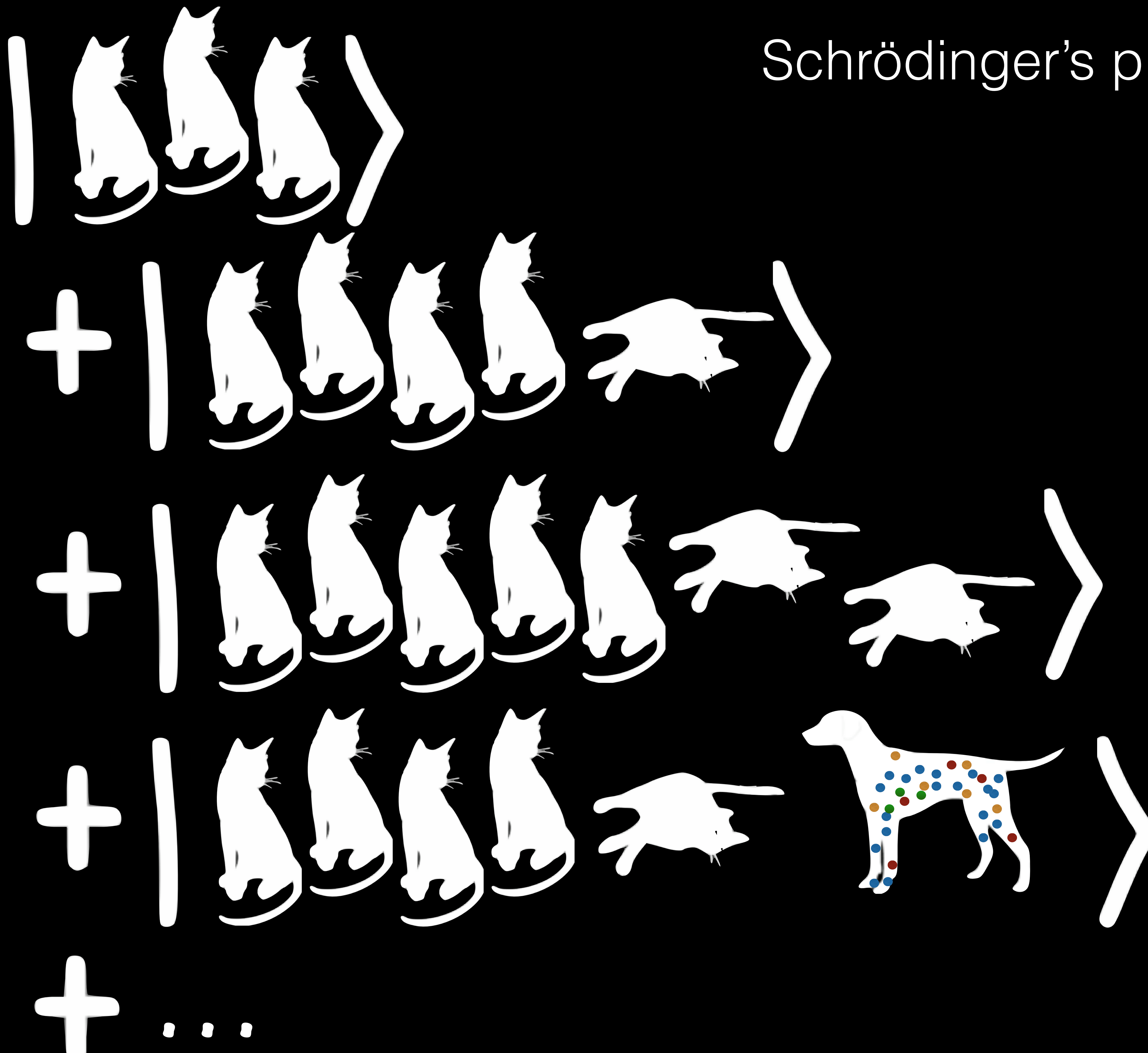
- The energy of the collision is the inverse of the resolution with which we probe the proton

- In QCD, as the scale changes, what is resolved changes



- *A quark at one resolution is something else at higher scales*

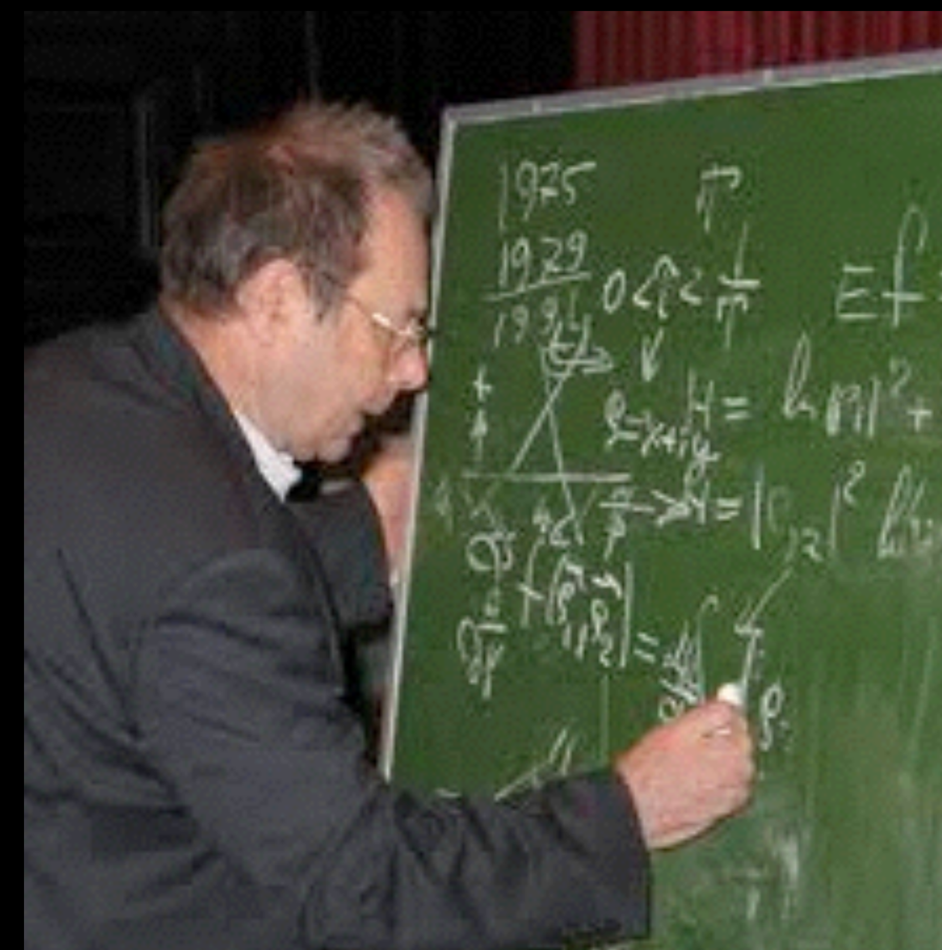
Schrödinger's proton



- QCD predicts this weird behaviour

- Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equations

$$q(x, E_1) \longrightarrow q(x, E_2) \longrightarrow q(x, E_3)$$



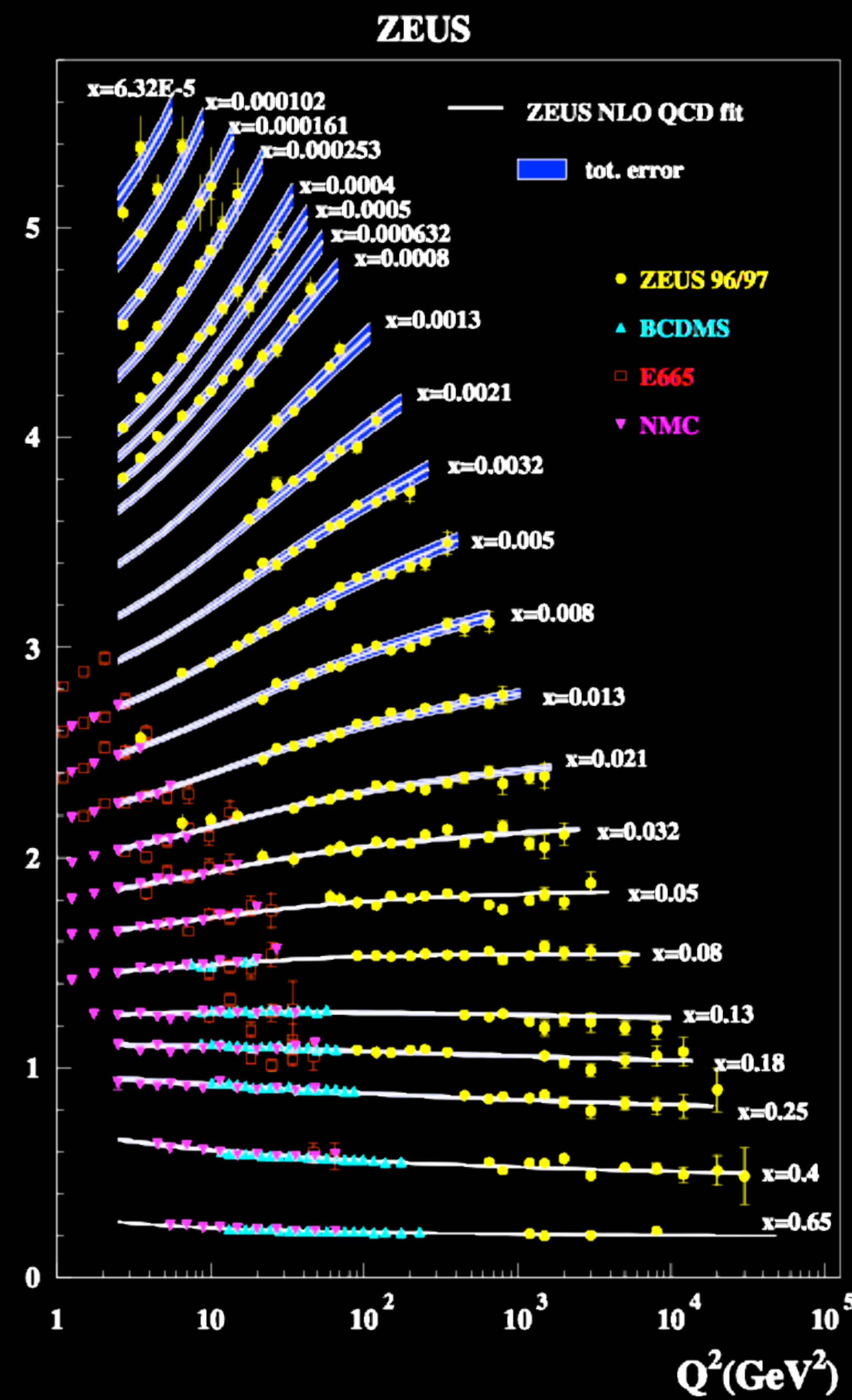
- QCD predicts this weird behaviour

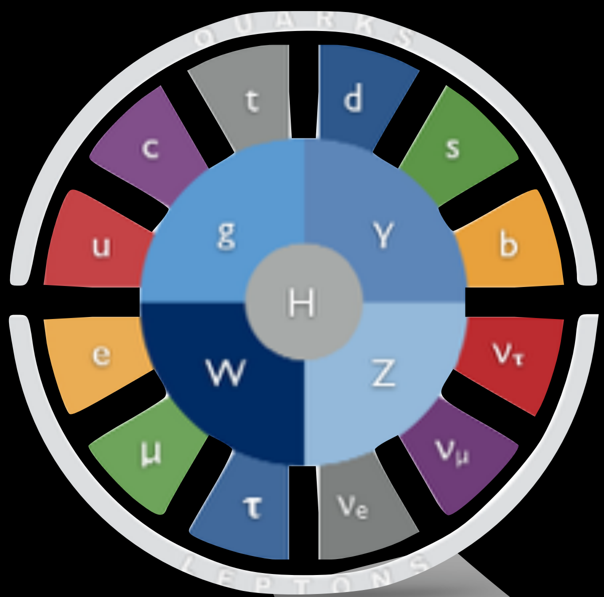
- Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equations

$$q(x, E_1) \longrightarrow q(x, E_2) \longrightarrow q(x, E_3)$$

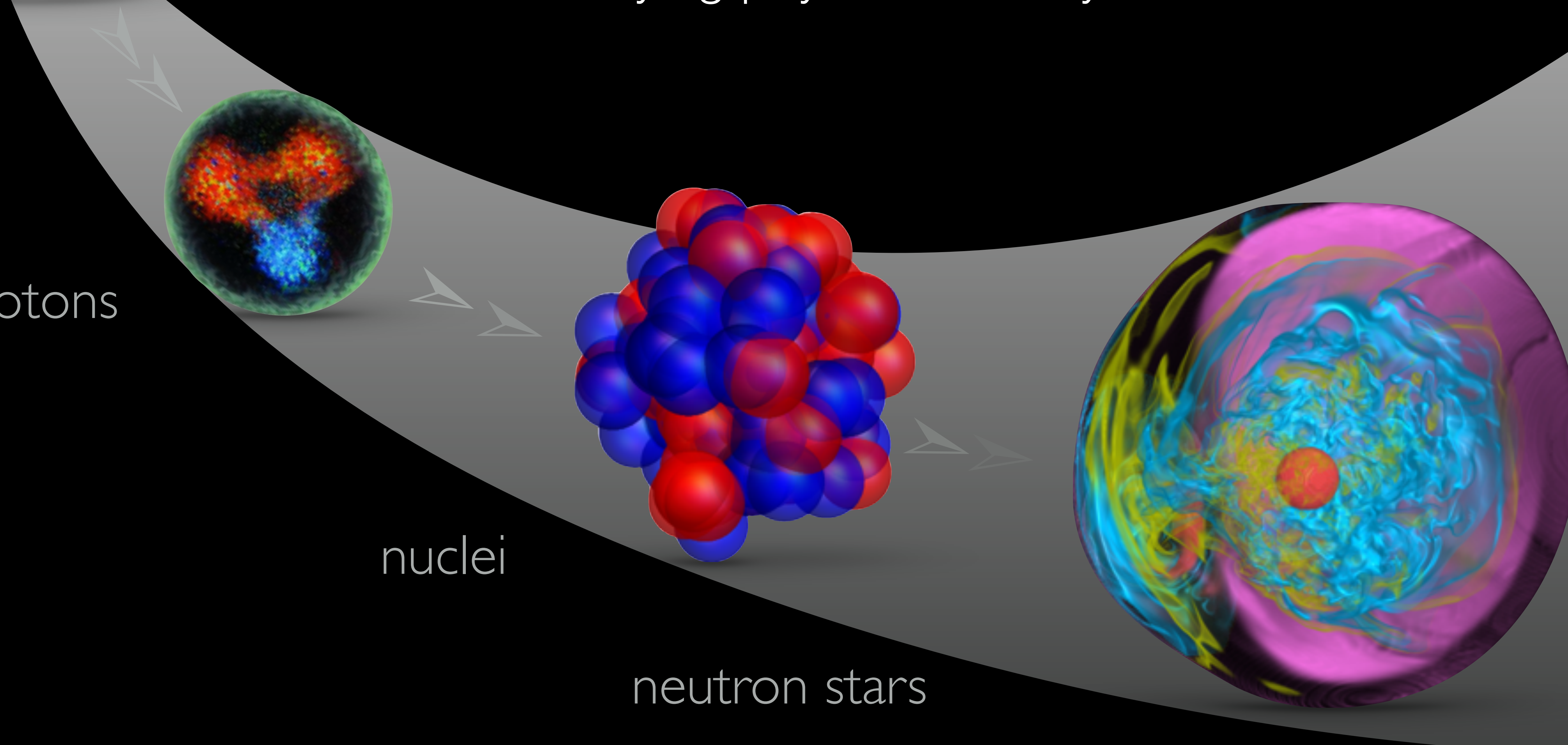
- Beautifully confirmed in many experiments (Q=**E**=scale)

- *Compelling evidence that QCD is the correct theory of the strong interaction*

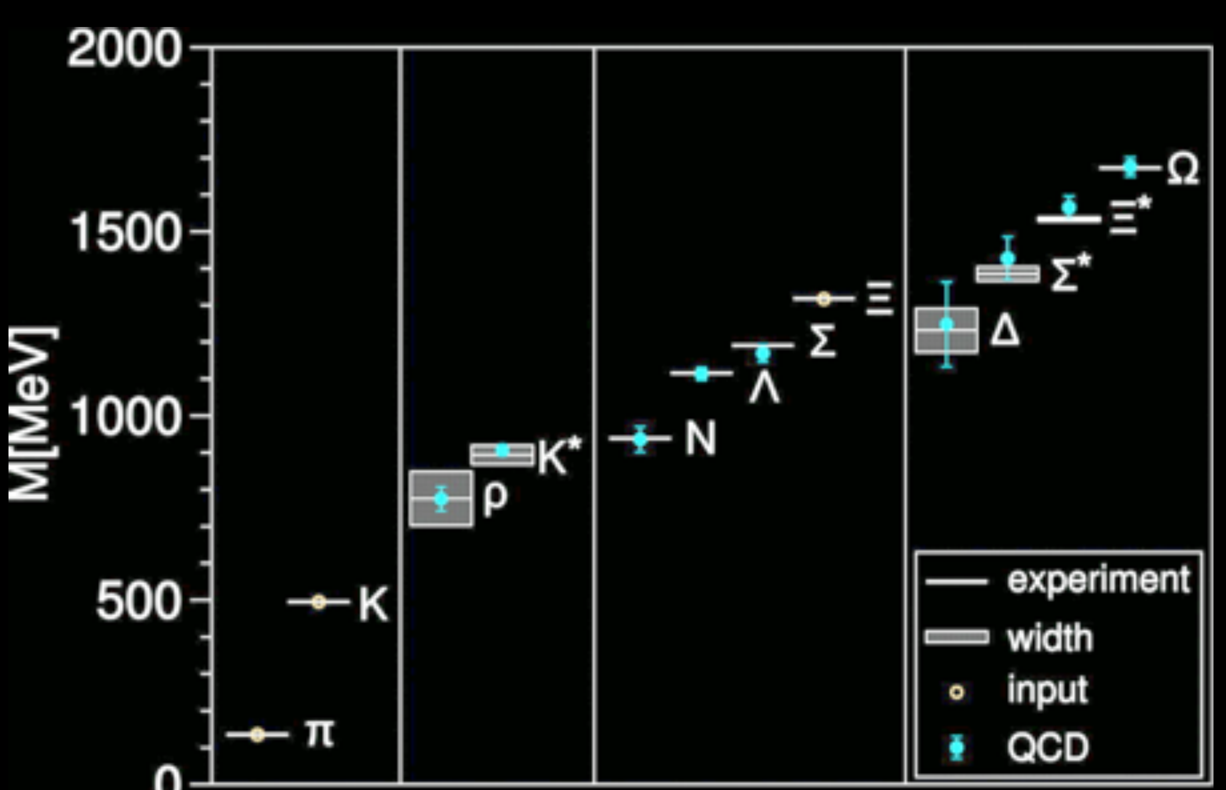




- QCD doesn’t just describe quarks in the proton
- Complexity of nuclear physics emerges from the Standard Model
- Same underlying physics at vastly different scales



- So what is the mass of the neutron?
- After 35 years of work, theoretical physicists finally know!
- Timeline
  - 1973: QCD discovered
  - 1974: "Lattice QCD"
  - 1979: first rudimentary attempts at calculations
  - 2008: first complete QCD calculation of M_n



Borsanyi et al, Science 322, 1224 (2008)

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  - 1932: Chadwick measures M_n
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The Existence of a Neutron.

By J. Chadwick, F.R.S.

(Received May 10, 1932.)

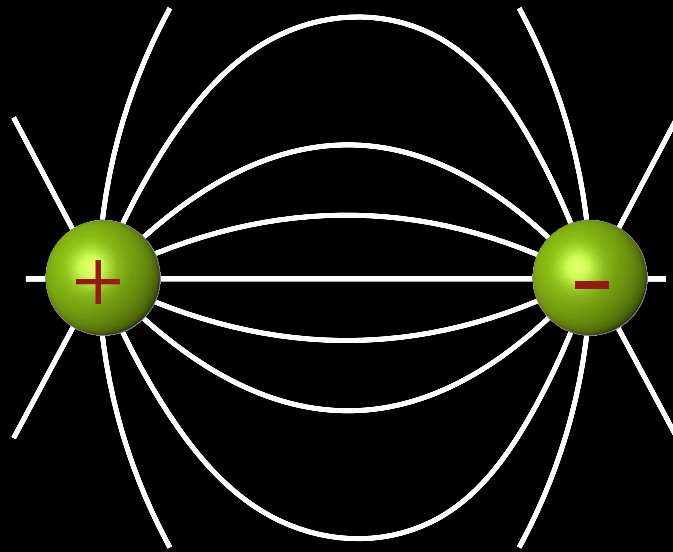
wn by Bothe and Becker* that some light elements when particles of polonium emit radiations which appear to be of The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Mme. Curie-Joliot† and by Webster‡ showed that the radiation excited in beryllium possessed a penetrating power distinctly greater than that of any γ-radiation yet found from the radioactive elements. In Webster's experiments the intensity of the radiation was measured both by means of the Geiger-Müller tube counter and in a high pressure ionisation chamber. He found that the beryllium radiation had an absorption coefficient in lead of about $0 \cdot 22$ cm.$^{-1}$ as measured under his experimental conditions. Making the necessary corrections for these conditions, and using the results of Gray and Tarrant to estimate the relative contributions of scattering, photoelectric absorption, and nuclear absorption in the absorption of such penetrating radiation, Webster concluded that the radiation had a quantum energy of about 7×10^6 electron volts. Similarly he found that the radiation from boron bombarded by α-particles of polonium consisted in part of a radiation rather more penetrating than that from beryllium, and he estimated the quantum energy of this component as about 10×10^6 electron volts. These conclusions agree quite well with the supposition that the radiations arise by the capture of the α-particle into the beryllium (or boron) nucleus and the emission of the surplus energy as a quantum of radiation.

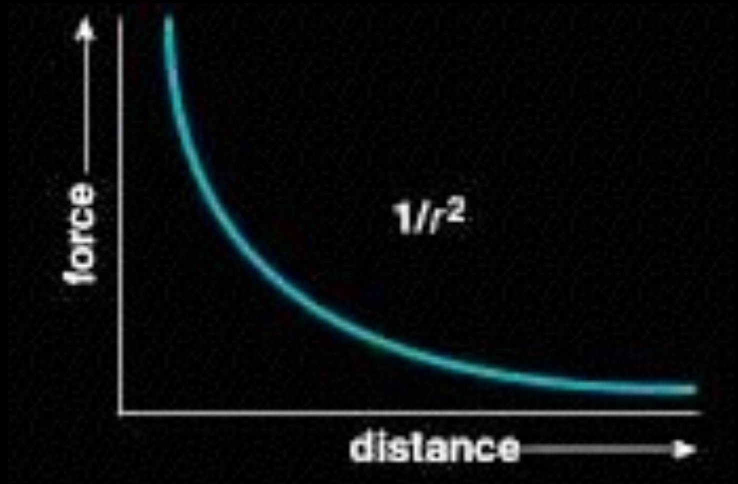
The radiations showed, however, certain peculiarities, and at my request the beryllium radiation was passed into an expansion chamber and several photographs were taken. No unexpected phenomena were observed though, as will be seen later, similar experiments have now revealed some rather striking events. The failure of these early experiments was partly due to the weakness of the available source of polonium, and partly to the experimental arrangement, which, as it now appears, was not very suitable.

* 'Z. Physik,' vol. 66, p. 289 (1930).
† I. Curie, 'C. R. Acad. Sci. Paris,' vol. 193, p. 1412 (1931).
‡ 'Proc. Roy. Soc.,' A, vol. 136, p. 428 (1932).

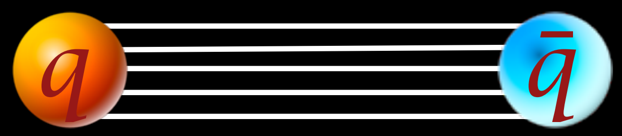
- Why was it so hard?
- QCD is the “strong force”: quarks and gluons interact strongly

- QED





- QCD

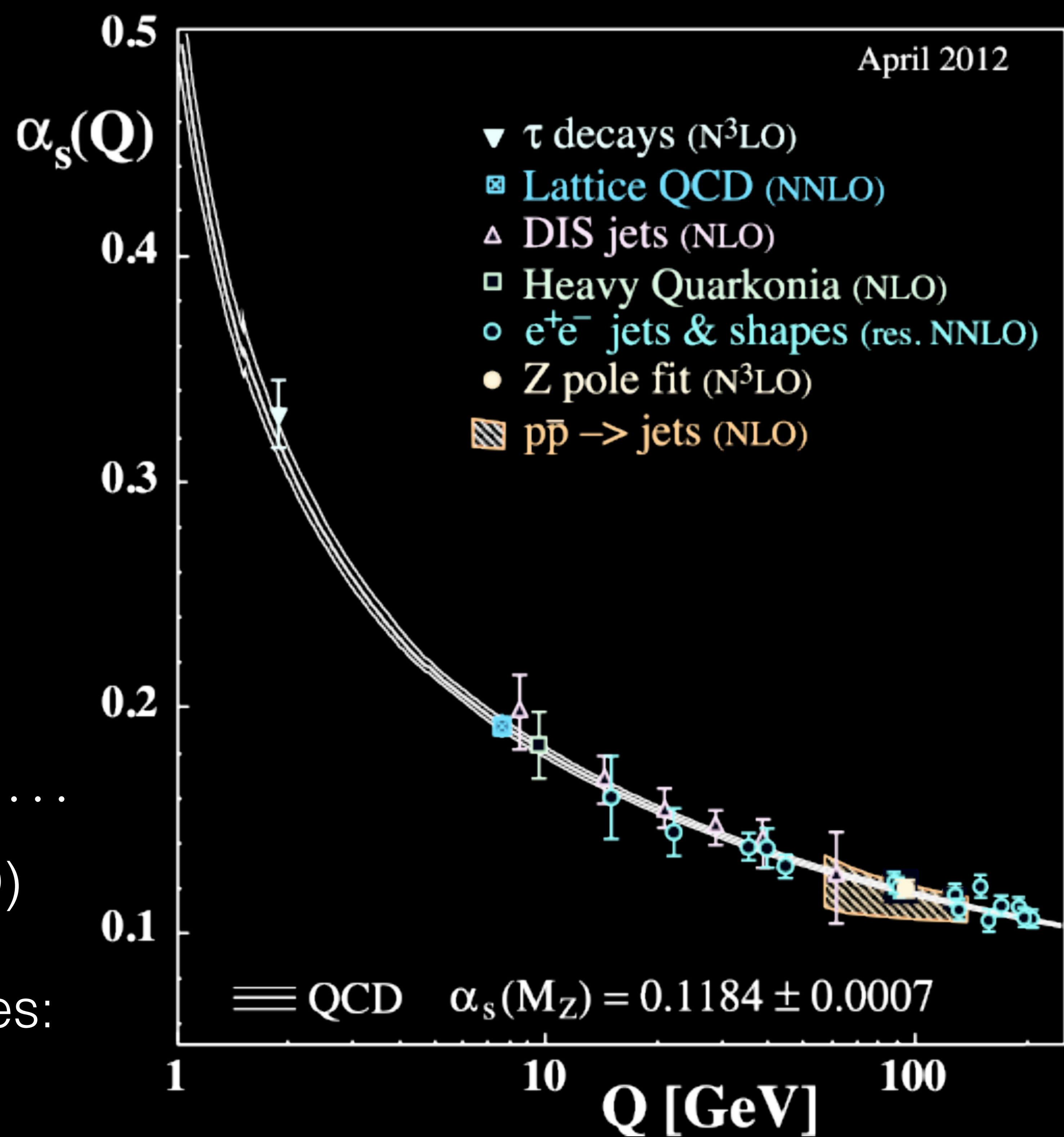


- Why was it so hard?
- QCD is the "strong force": quarks and gluons interact strongly
- Interaction strength depends on energy
- At high energy, can use perturbative expansion

$$\mathcal{O}_{\text{exact}} = \mathcal{O}_0 + \mathcal{O}_1 \alpha_s + \mathcal{O}_2 \alpha_s^2 + \ldots$$

(also works beautifully in QED)

- At low energies/ long distances: out of luck



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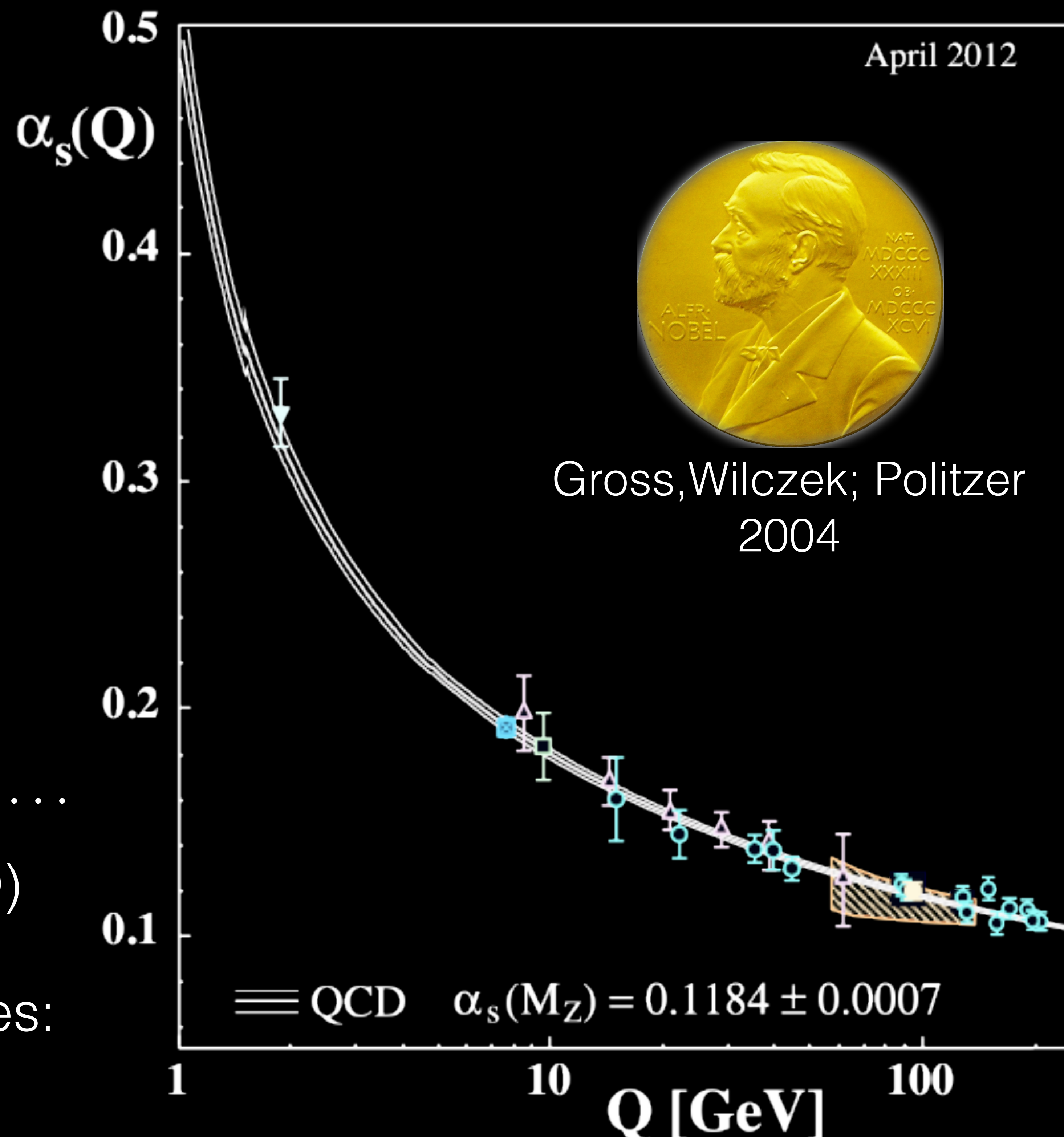
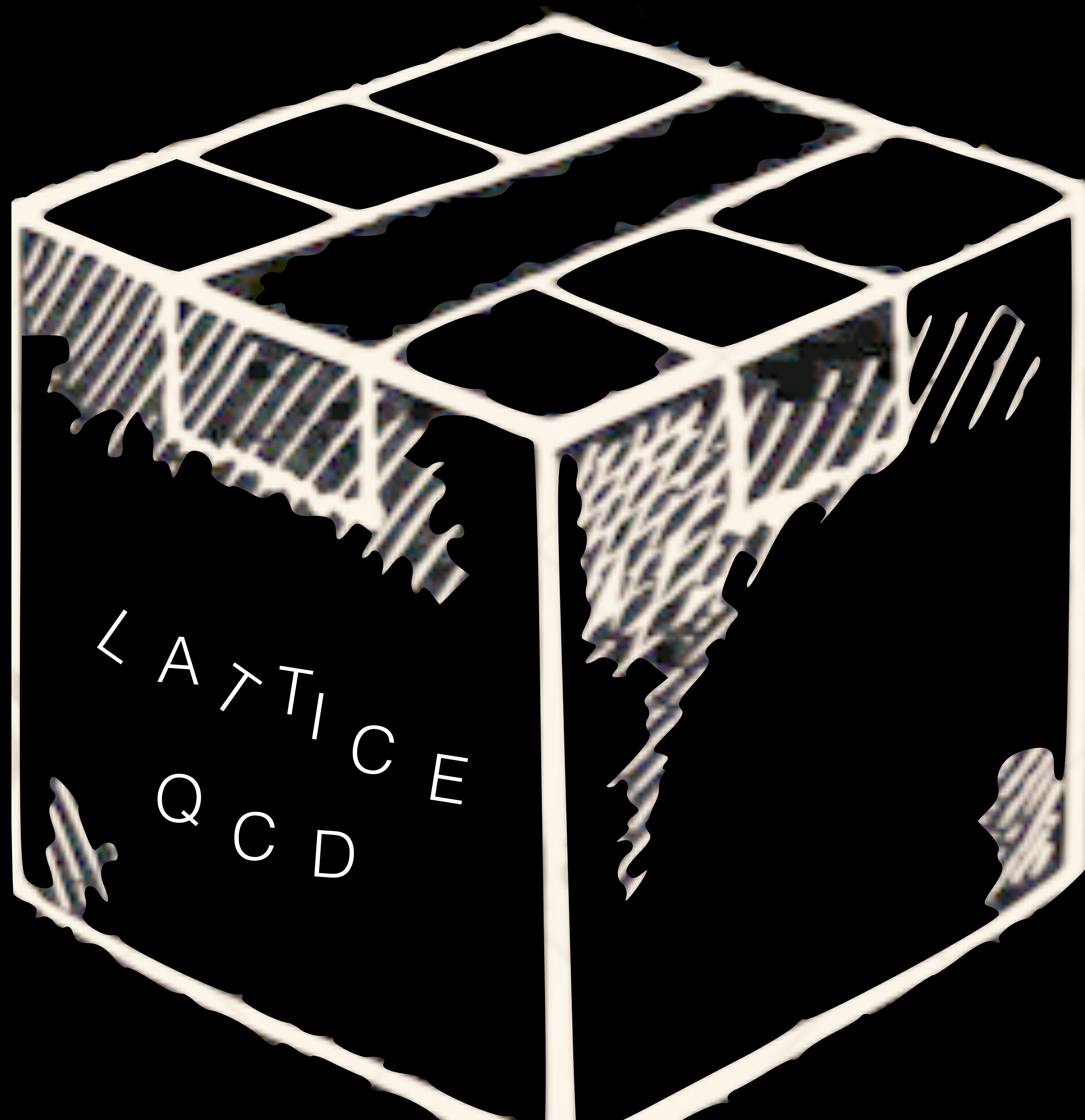
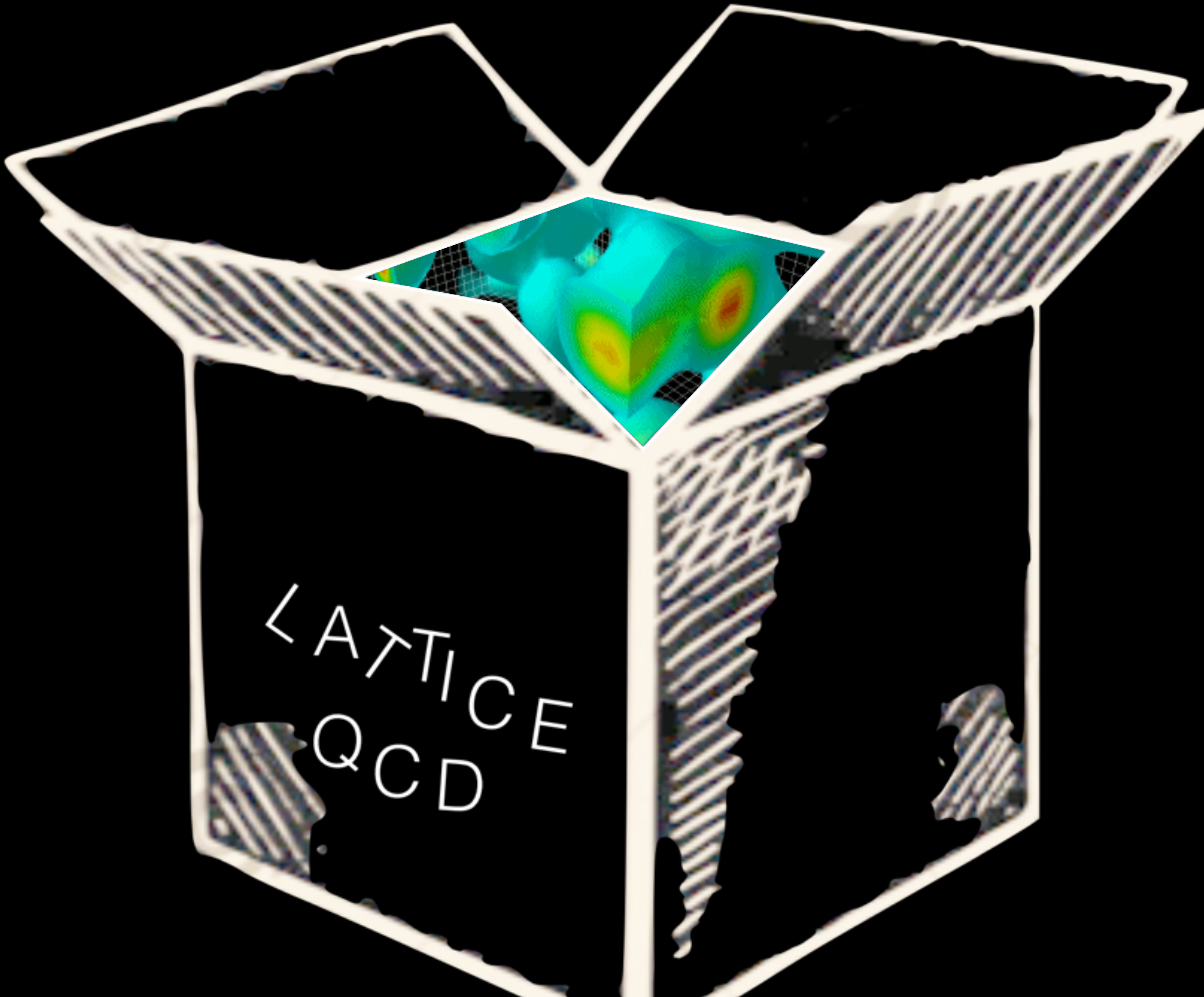
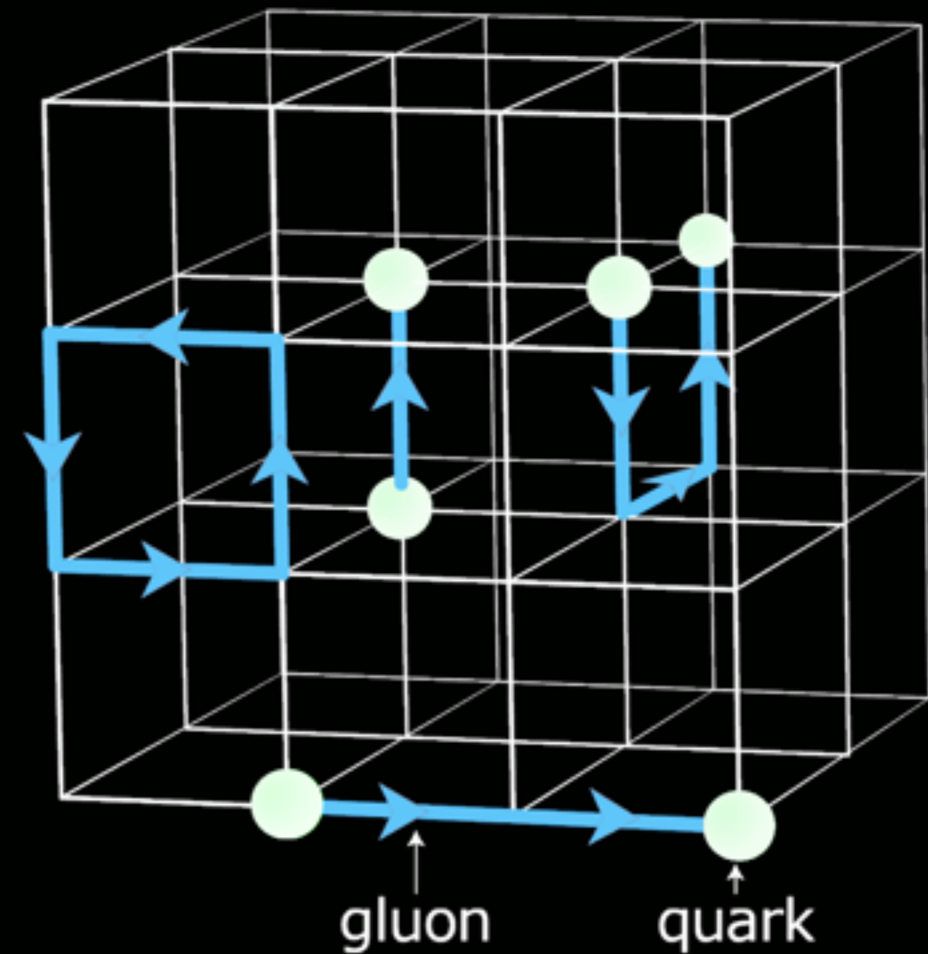
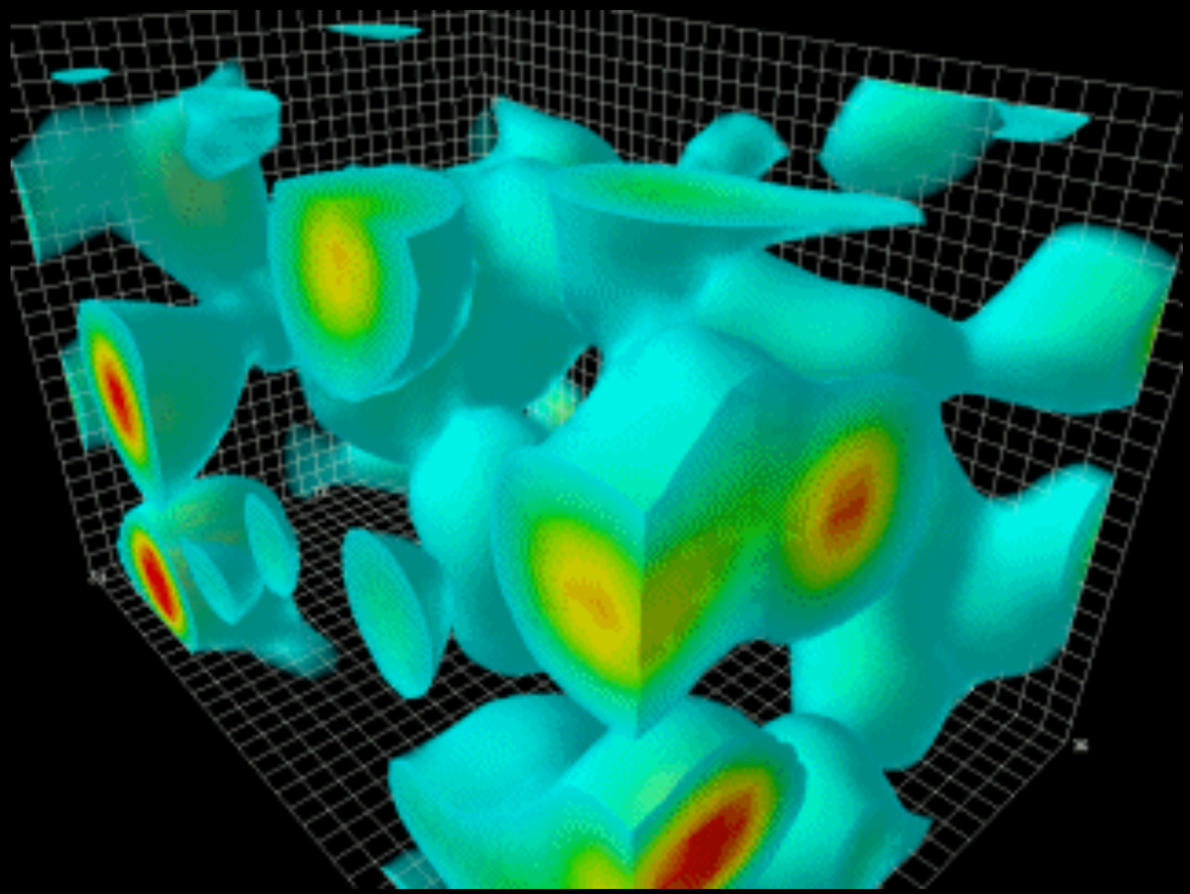



LATTICE
QCD


LATTICE
QCD

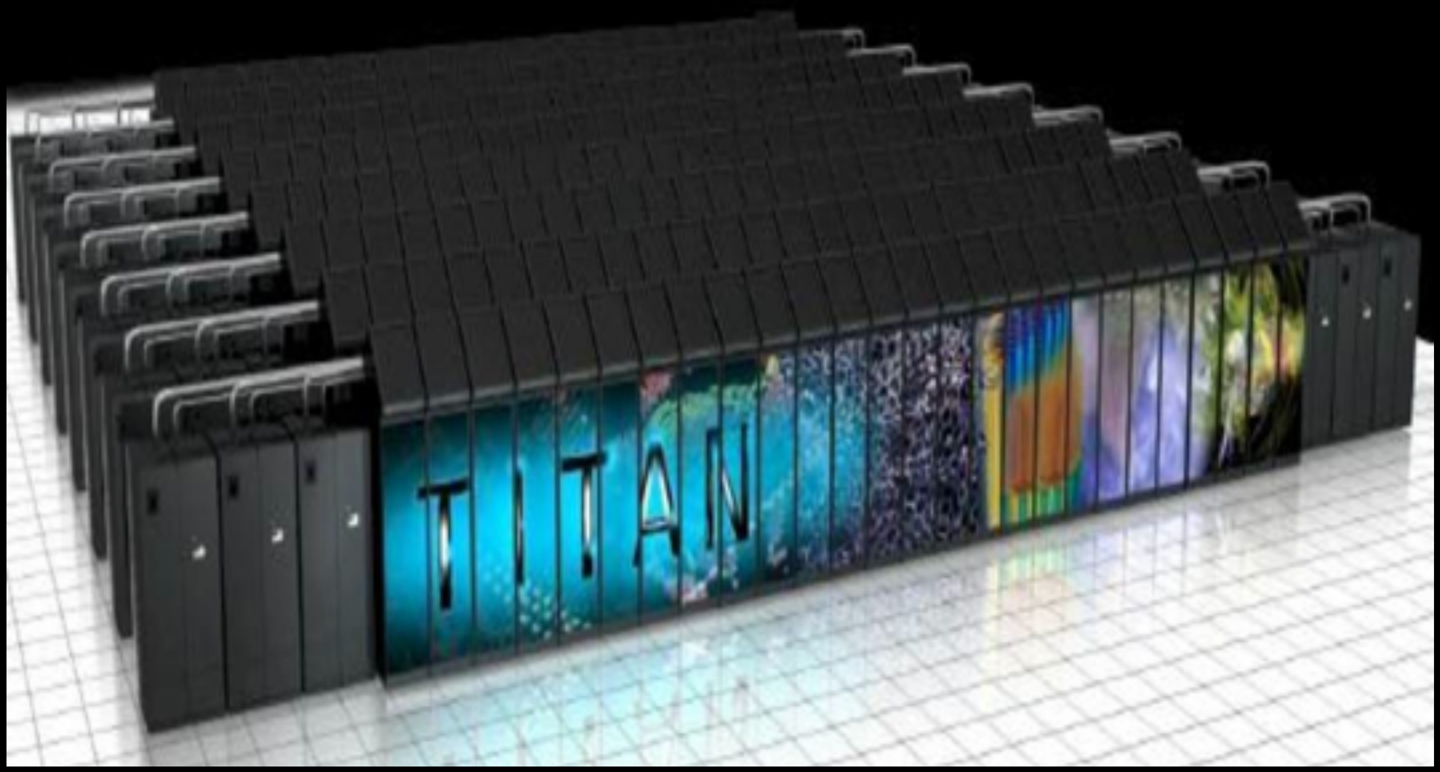
- Lattice QCD: tool to deal with quarks and gluons
  - Discretise system
  - Average over many representative configurations
  - Undo the harm done in previous steps

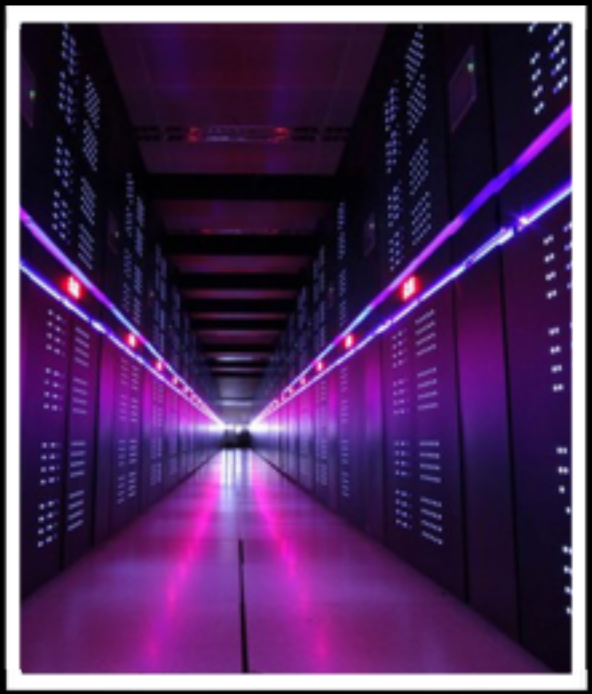




movie: D Leinweber, Adelaide

- Major algorithmic and computational challenge (30 years of R&D)
- World's largest computers
- 2015: lattice QCD used ~10^{10} CPU core hrs in US
  - 1,000,000 CPU cores running continuously!

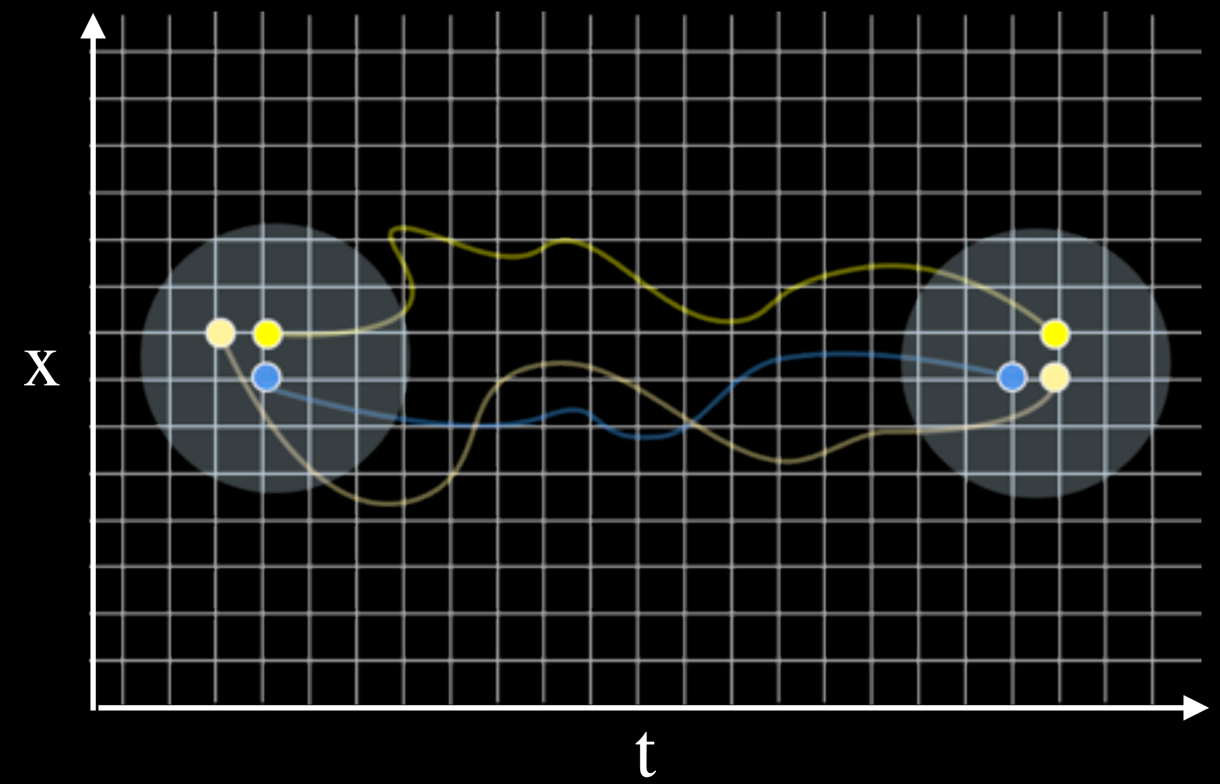


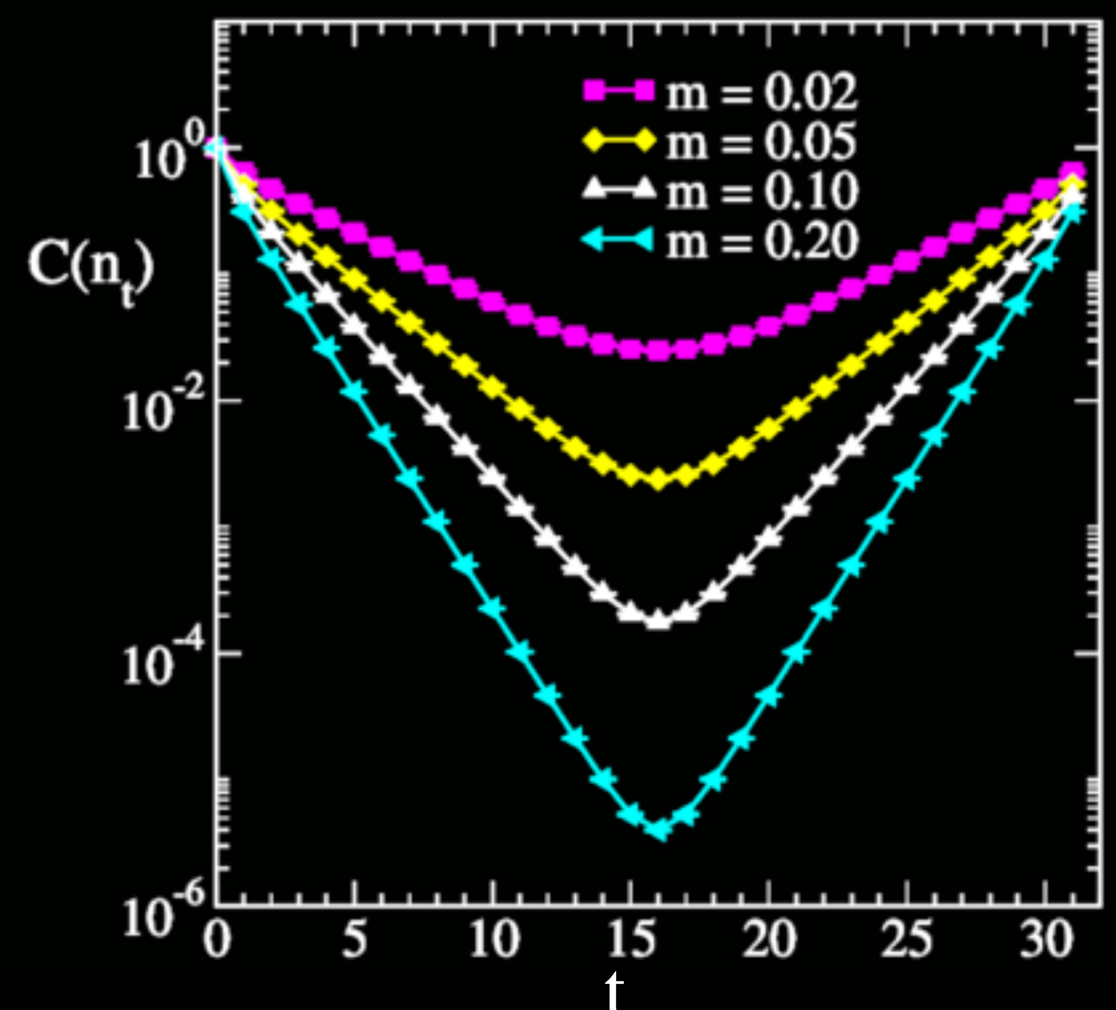


- How do we calculate a mass?
- An analogy with rock dropping

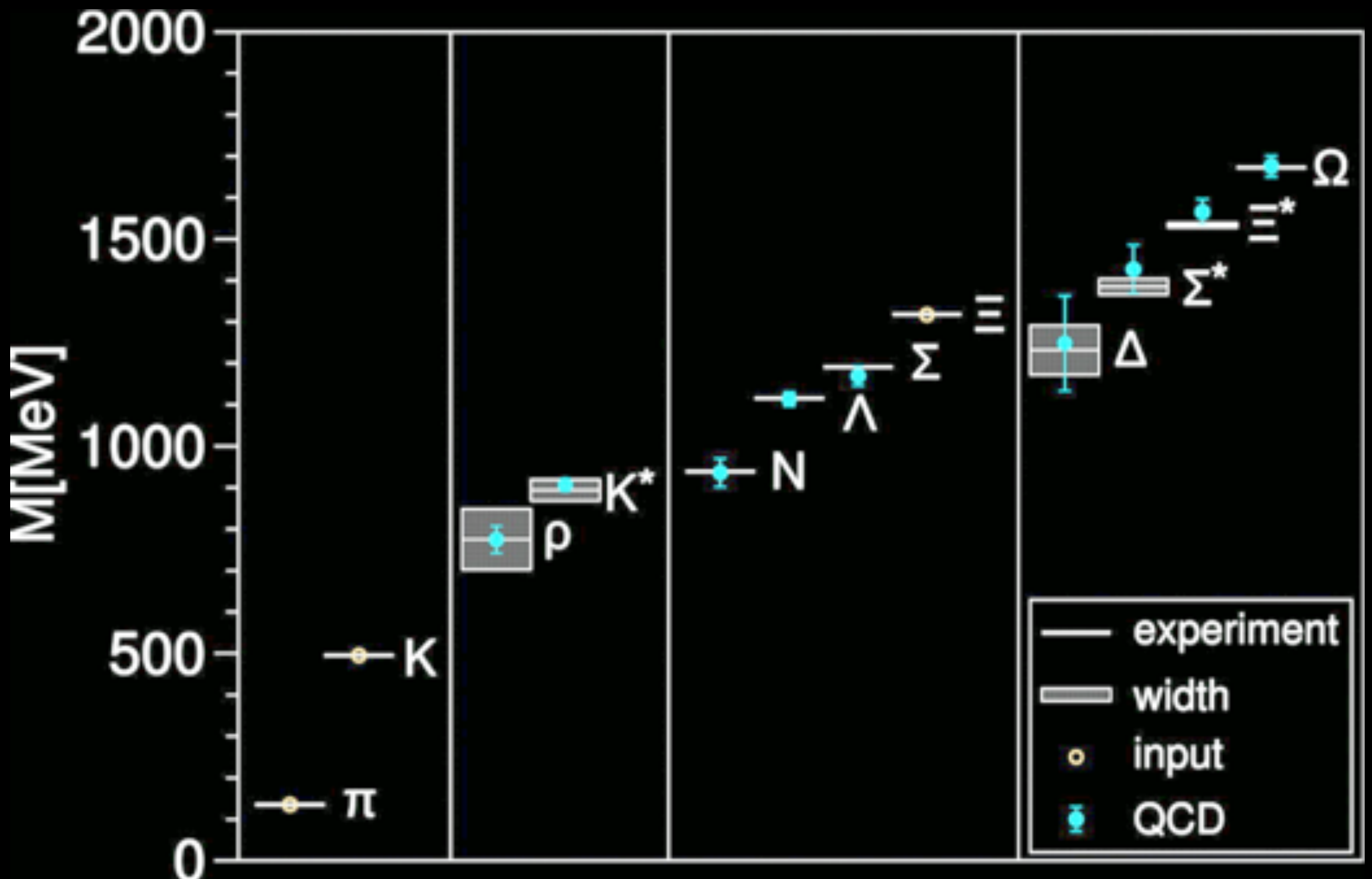
- Response of water surface determined by size of rock

- Create three quarks at a point and annihilate them far from source
- QCD adds all the quark anti-quark pairs and gluons automatically
- Measure exponentially decaying correlation to extract mass





- So what is the mass of the neutron?
- After 30 years (and lots of computers!), theoretical physicists finally know!



- *Verifies QCD as theory of strong interactions when they are strong!*

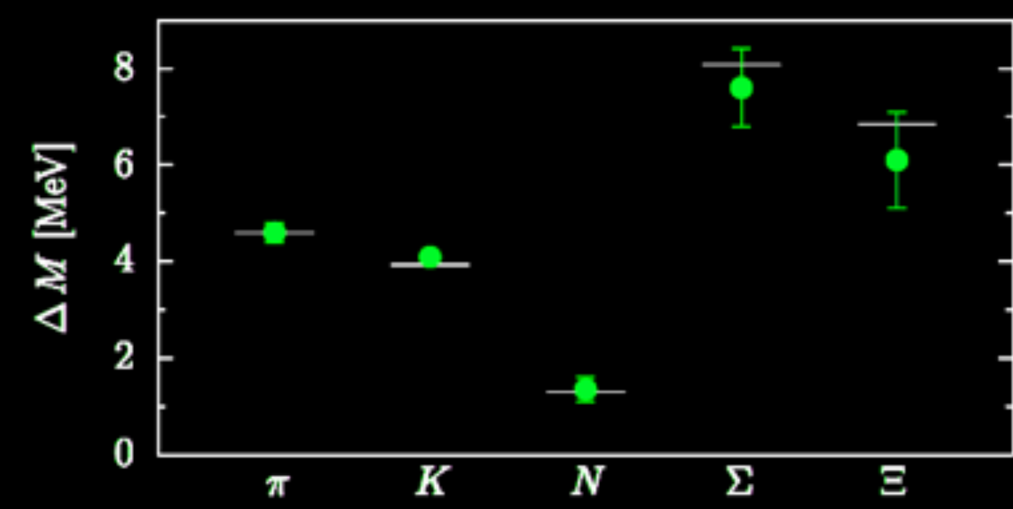
[Borsanyi et al, Science 322, 1224 (2008)]

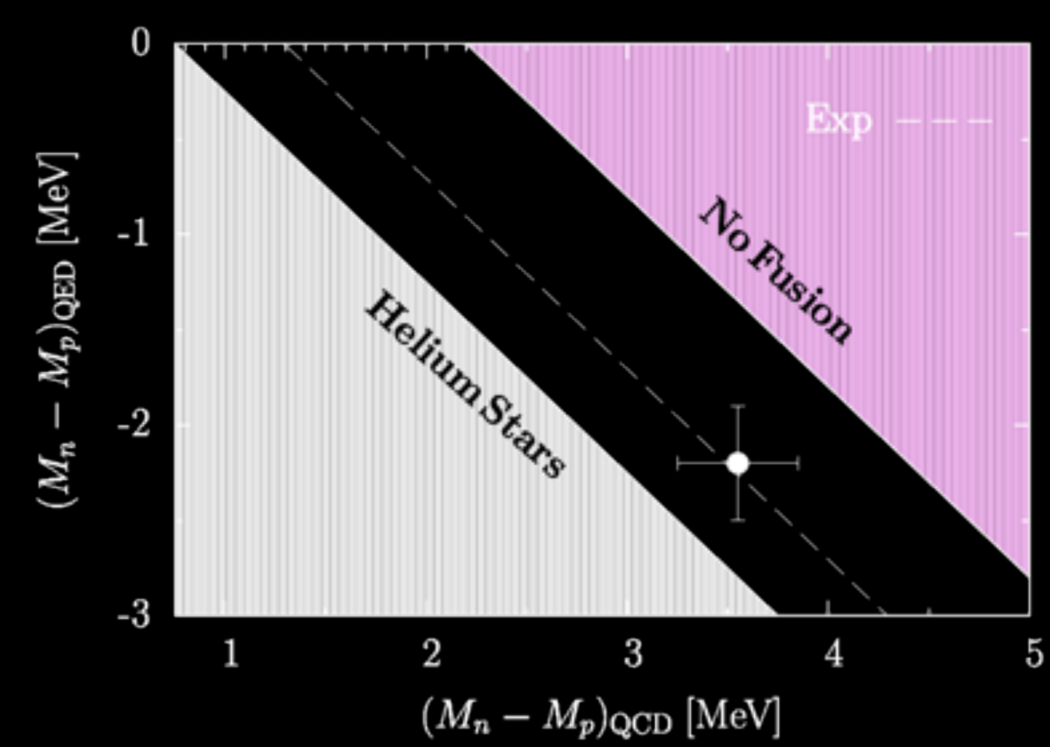
QCD ✅

- Proton(uud) neutron(udd) masses

  M_p=938.272046 MeV/c^2
  M_n=939.565413 MeV/c^2

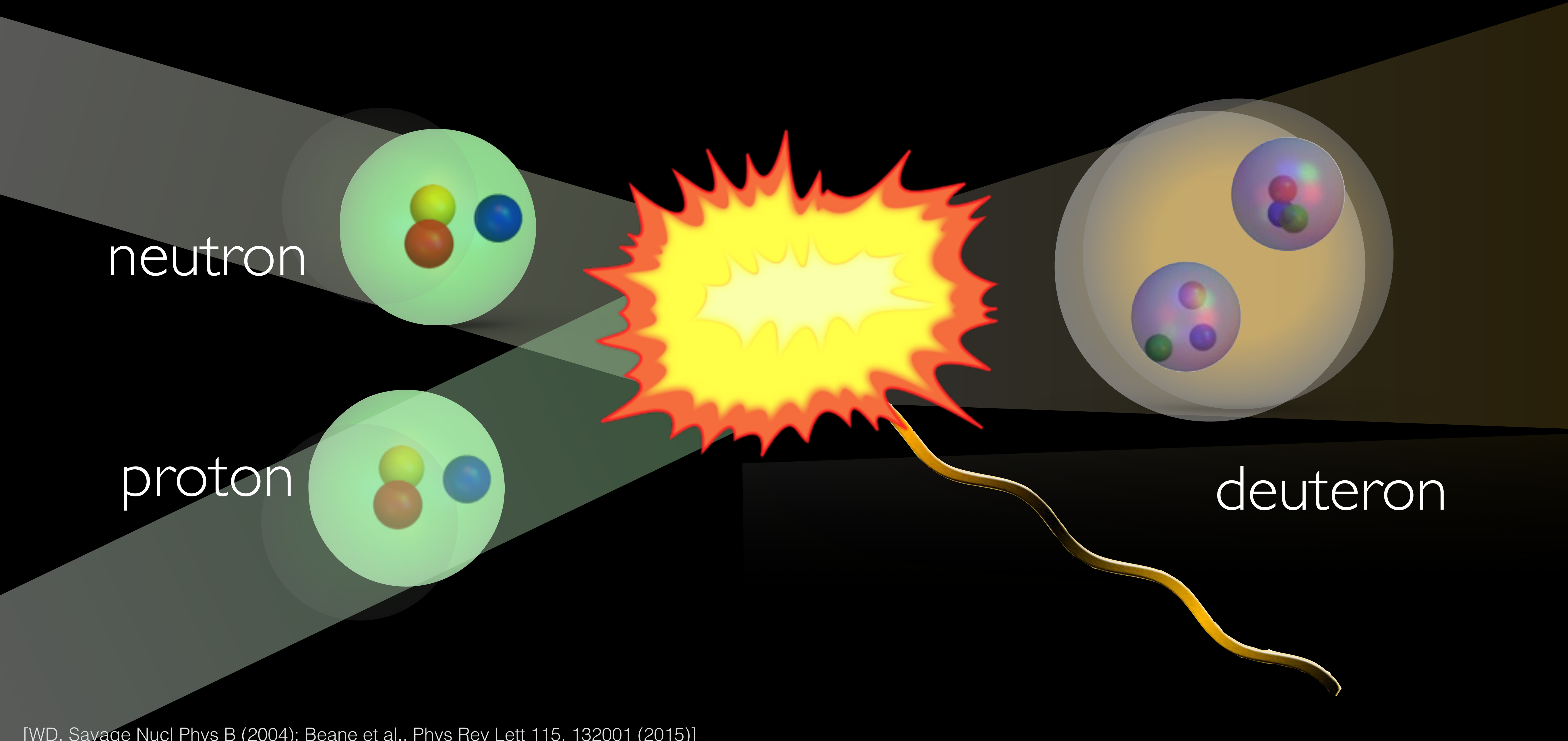
- Splitting
  - $m_u < m_d$
  - Electromagnetism
- Disentangle in LQCD+QED
- Consequences for existence of the universe as we know it





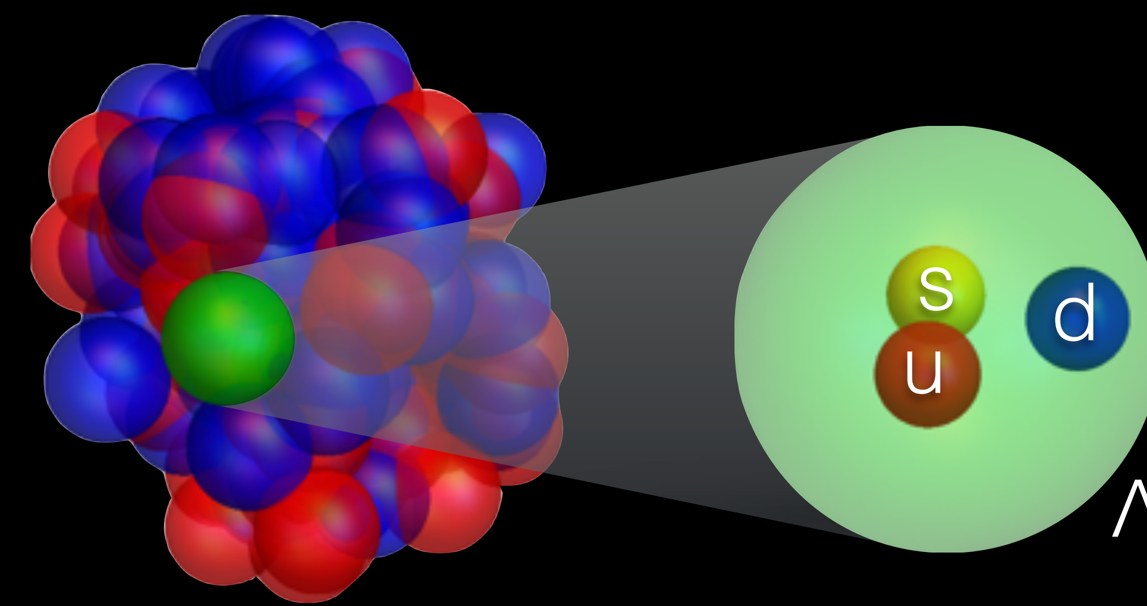
[Borsanyi *et al*, Science 347 (2015) 1452, Horsley *et al*, arXiv:1508.06401]

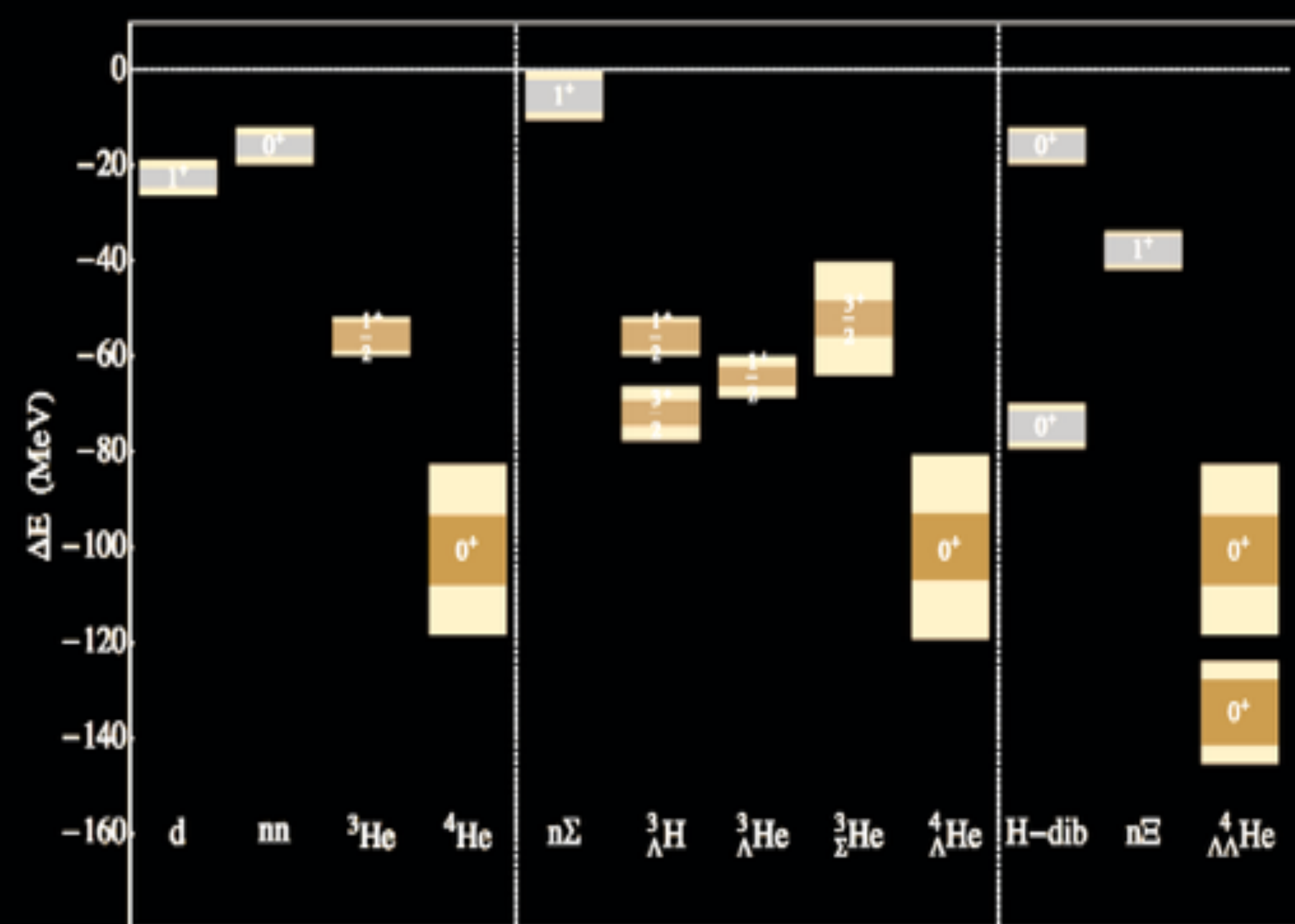
- Big Bang Nucleosynthesis
  - np→dγ : critical process in formation of first nuclei in the universe
  - Recent LQCD calculation: first QCD nuclear reaction!



[WD, Savage Nucl Phys B (2004); Beane et al., Phys Rev Lett 115, 132001 (2015)]

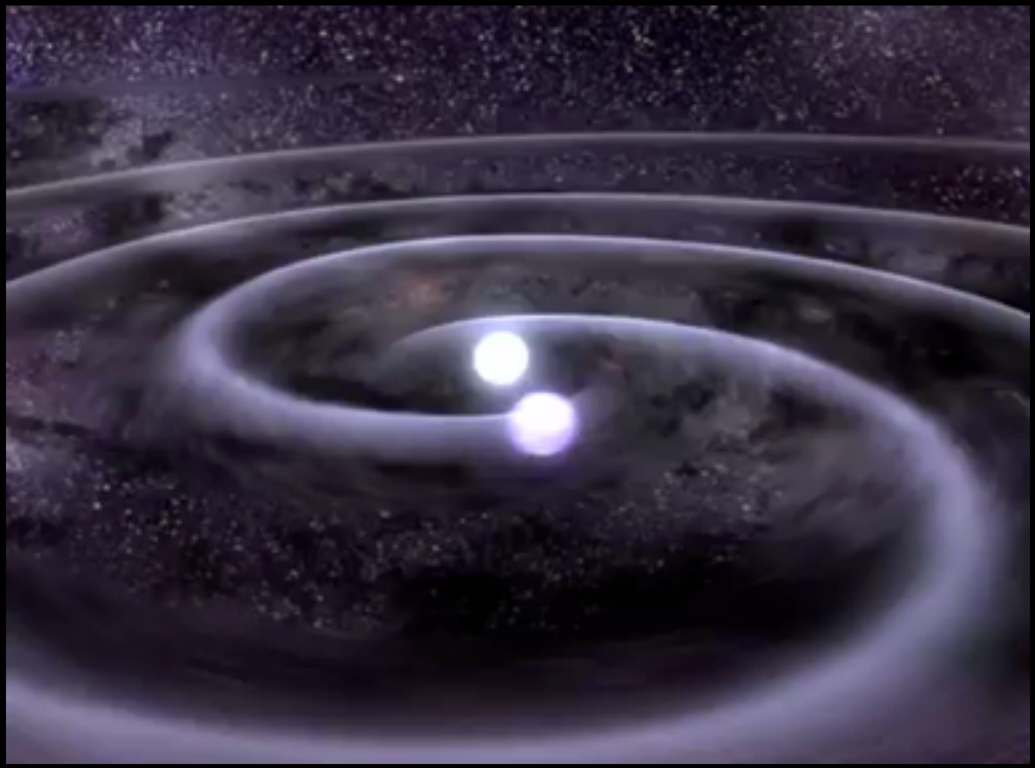
- Exotic states
- Hypernuclei
  - Nuclei with a strange baryon
  - A new periodic table: $^{4}He_{\Lambda}$, $^{7}Li_{\Lambda}$, …
  - Difficult for experiment
- Pentaquarks: recently observed by LHCb
- Study in LQCD
  - Computational limitations ⇒ still some caveats

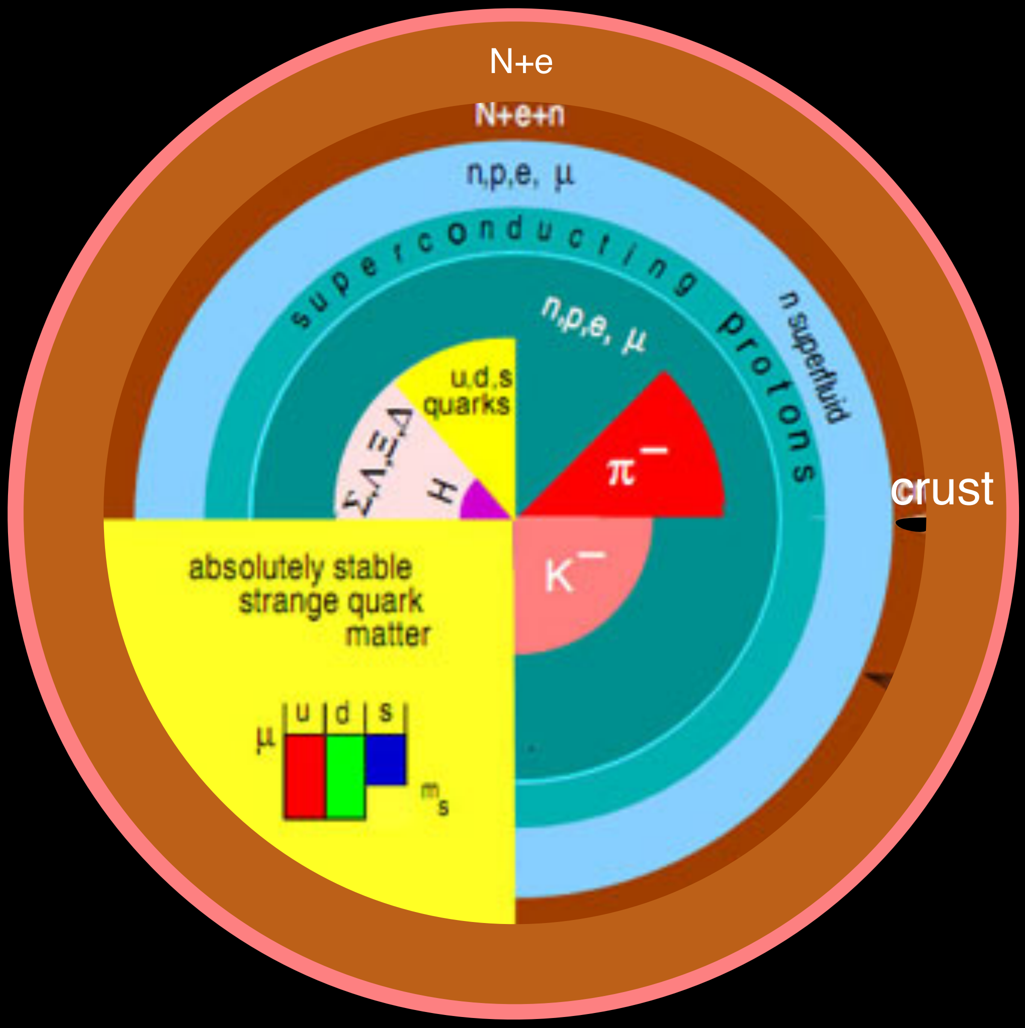




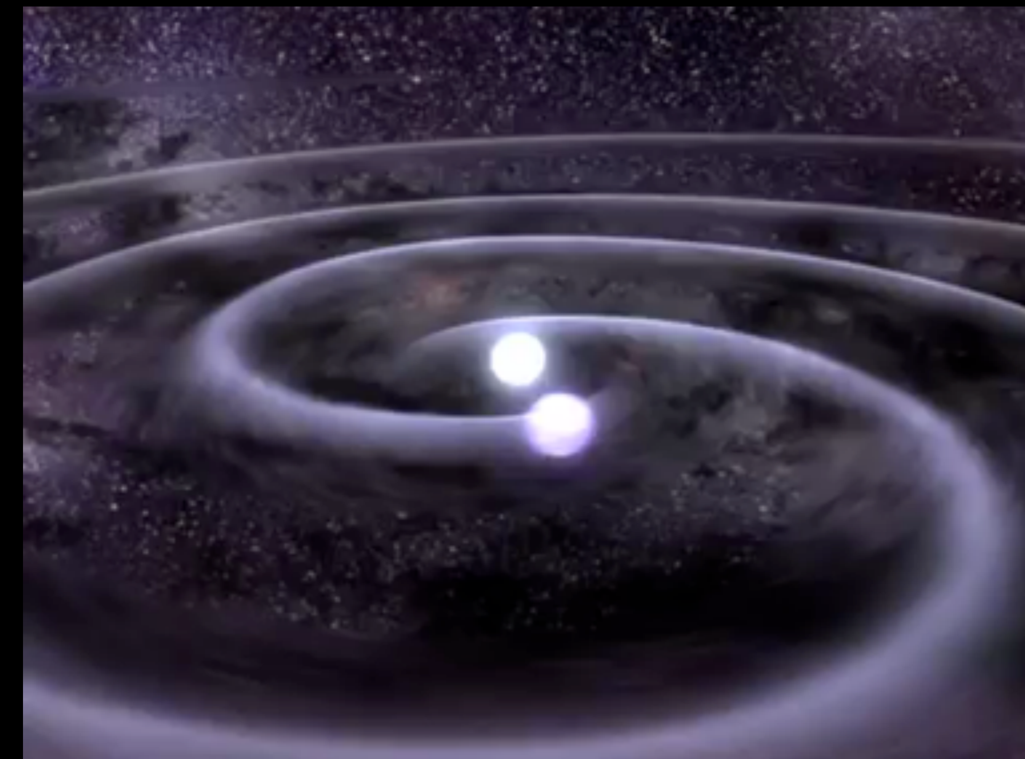
{Beane et al, [PRD 87 (2013), 034506]}

- What is the origin of the heavy elements?
  - Binary NS-NS or NS-BH mergers?
- Depends on NS interior
  - Equation of State: Energy vs Pressure
  - QCD interactions

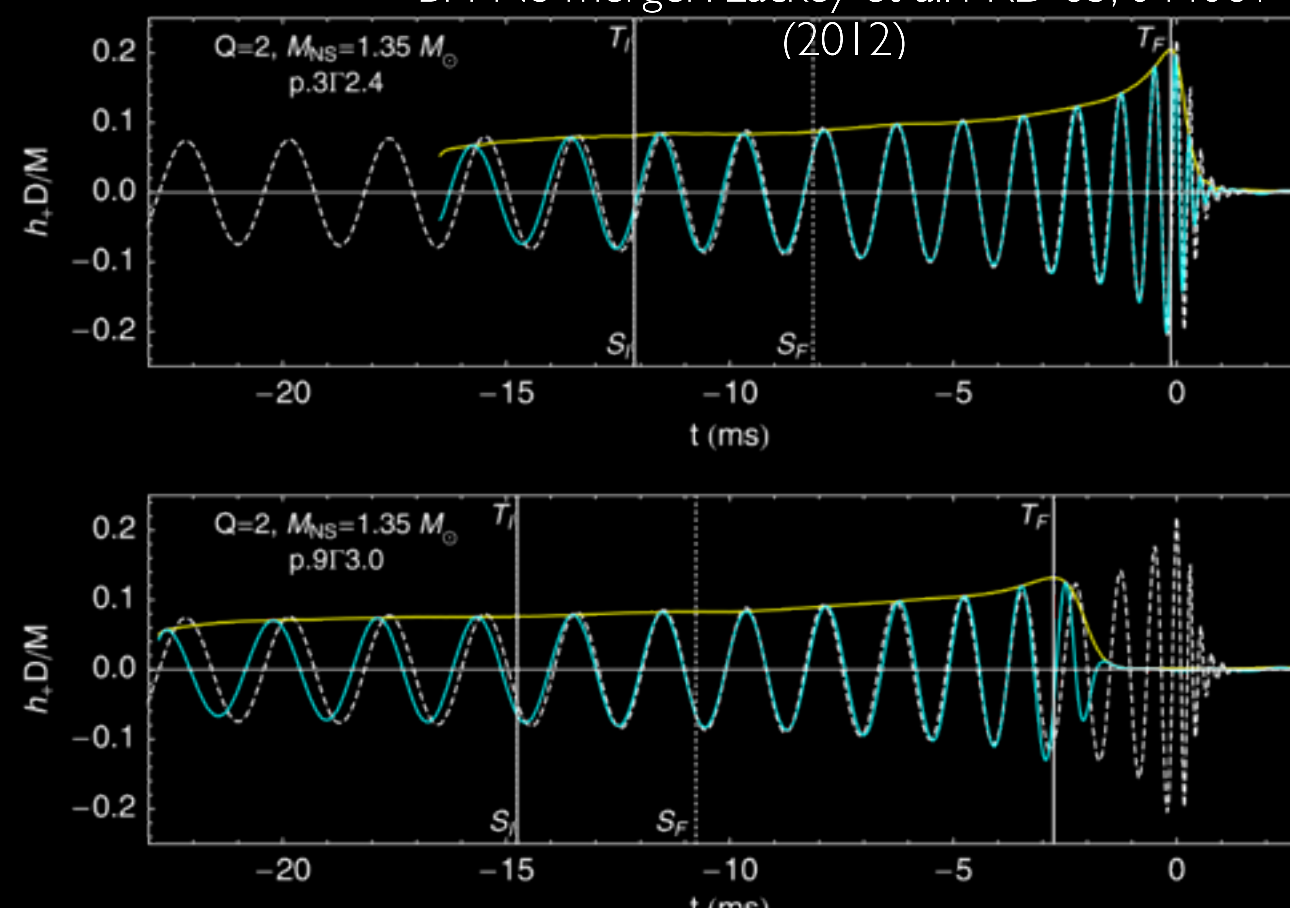


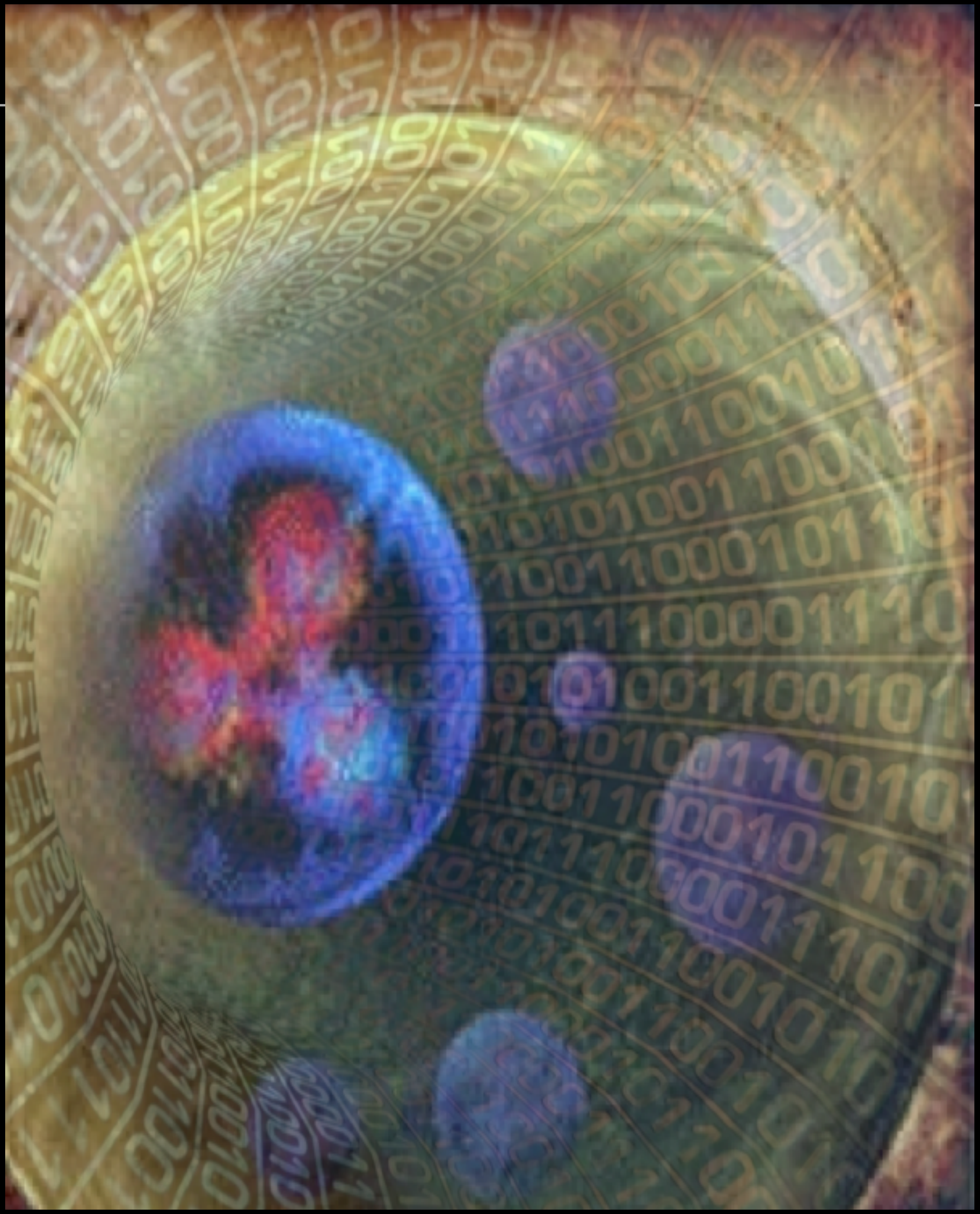


- What is the origin of the heavy elements?
  - Binary NS-NS or NS-BH mergers?
- Depends on NS interior
  - Equation of State: Energy vs Pressure
  - QCD interactions
- Measurable in gravitational wave ringdown!



BH-NS merger: Lackey et al. PRD 85, 044061 (2012)





The secret life of quarks

- Quarks (QCD) are vital to our understanding of nature
- Quarks are never seen and live in a weird quantum world
- Quantitative control of QCD in all regimes
  - Many new research directions