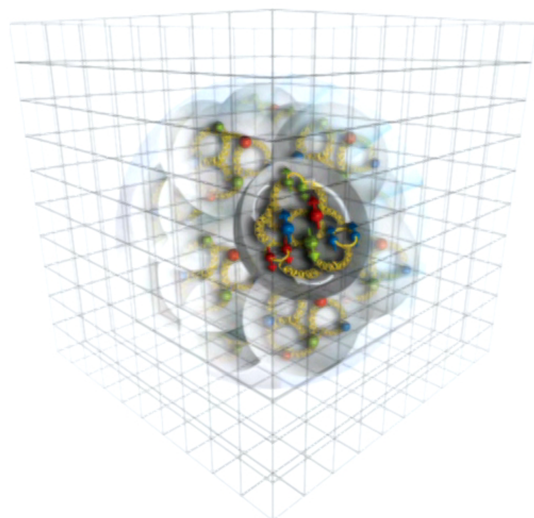
Title: Nuclear physics from the Standard Model

Date: Oct 17, 2018 02:00 PM

URL: http://pirsa.org/18100020

Abstract: <p>I will discuss the status and future of numerical lattice Quantum Chromodynamics (QCD) calculations for nuclear physics. With advances in supercomputing, we are beginning to quantitatively understand nuclear structure and interactions directly from the fundamental quark and gluon degrees of freedom of the Standard Model. Recent studies provide insight into the neutrino-nucleus interactions relevant to long-baseline neutrino experiments, double beta decay, and nuclear sigma terms needed for theory predictions of dark matter cross-sections at underground detectors. I will also address new work constraining `exotic glueâ€™ in nuclei, which will be measurable for the first time at a future electron-ion collider, and explain how machine learning tools are providing new possibilities in this field.</p>

Nuclear Physics from the Standard Model



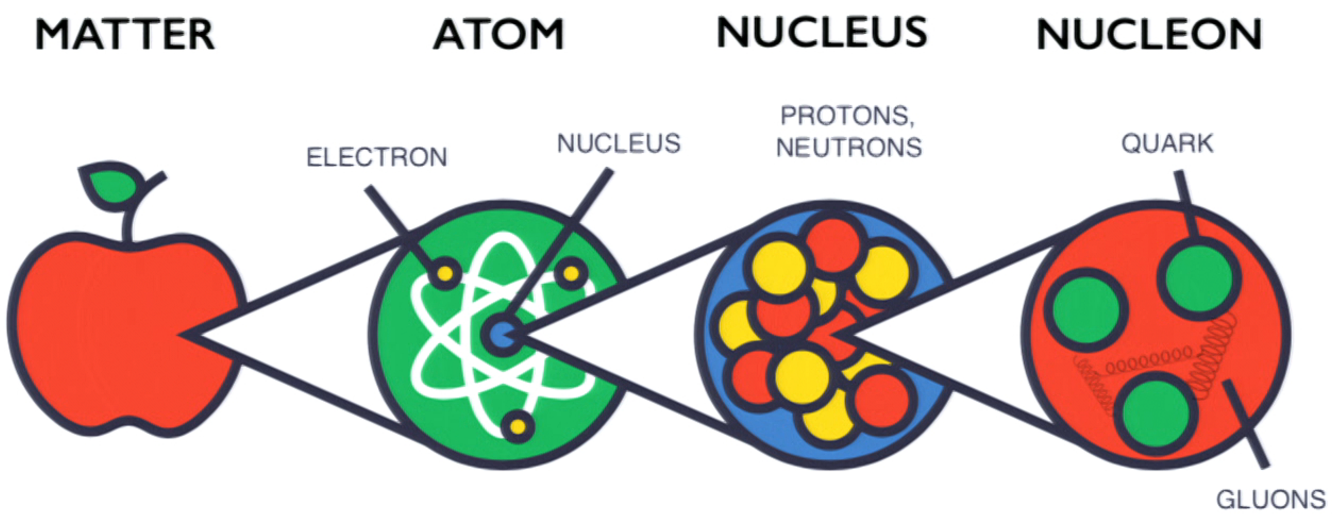
Phiala Shanahan

Massachusetts Institute of Technology

The structure of matter

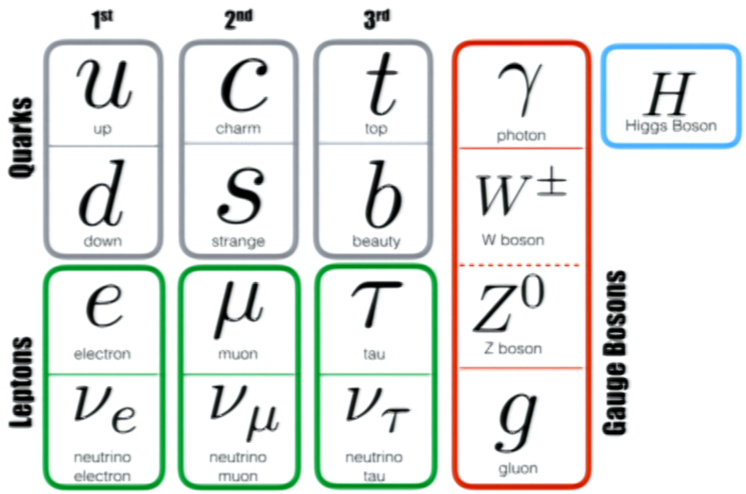
What is everything made of?

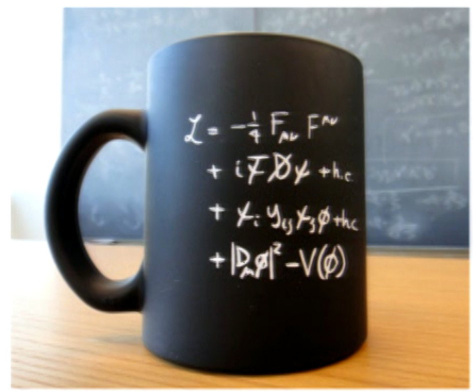
What laws describe the properties of matter?



The structure of matter

The Standard Model of nuclear and particle physics





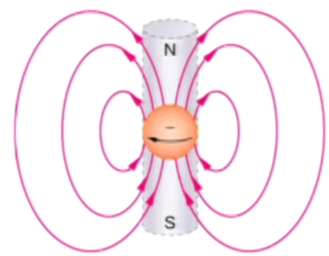
The structure of matter

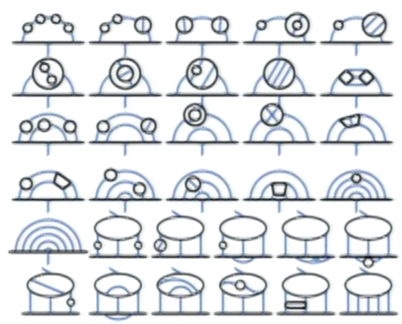
The Standard Model is successful

Magnetic moment of the electron:

(torque an electron feels in a magnetic field)

Most accurately verified prediction in the history of physics





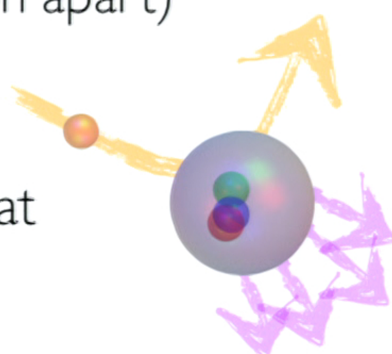
Theory	$a_e = 0.001159652181643(764)$
Exp.	$a_e = 0.00115965218073(28)$

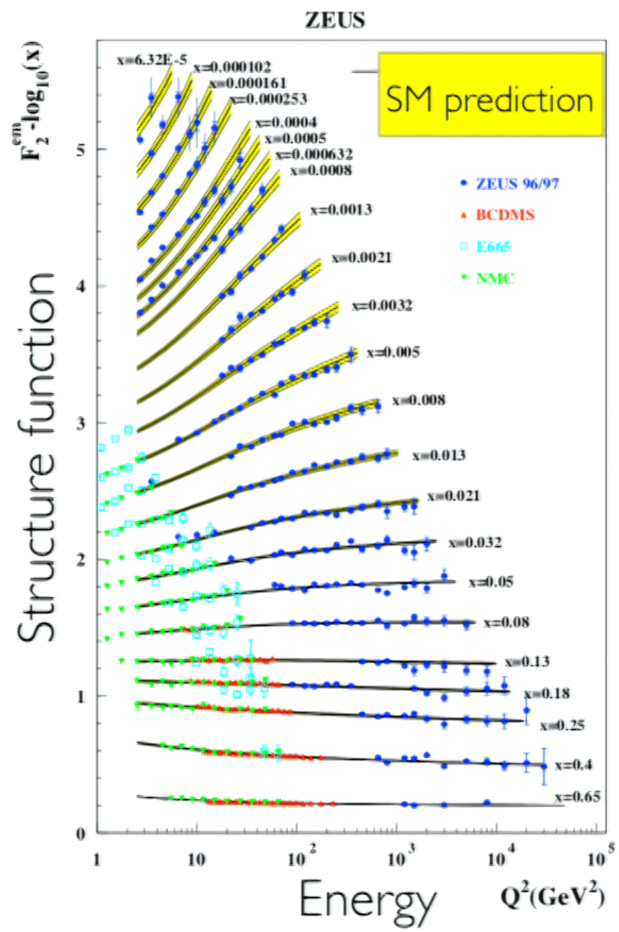
The structure of matter

The Standard Model is successful

Deep inelastic scattering of electron on proton (hits and breaks proton apart)

Verification at many scales



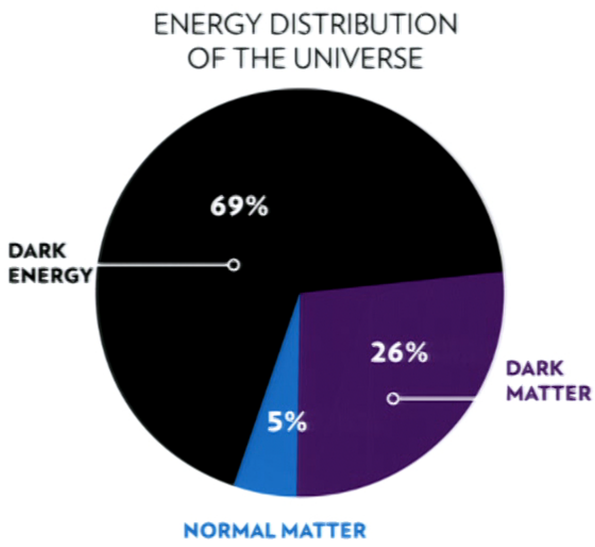


The structure of matter

BUT The Standard Model isn't everything

Example 1:

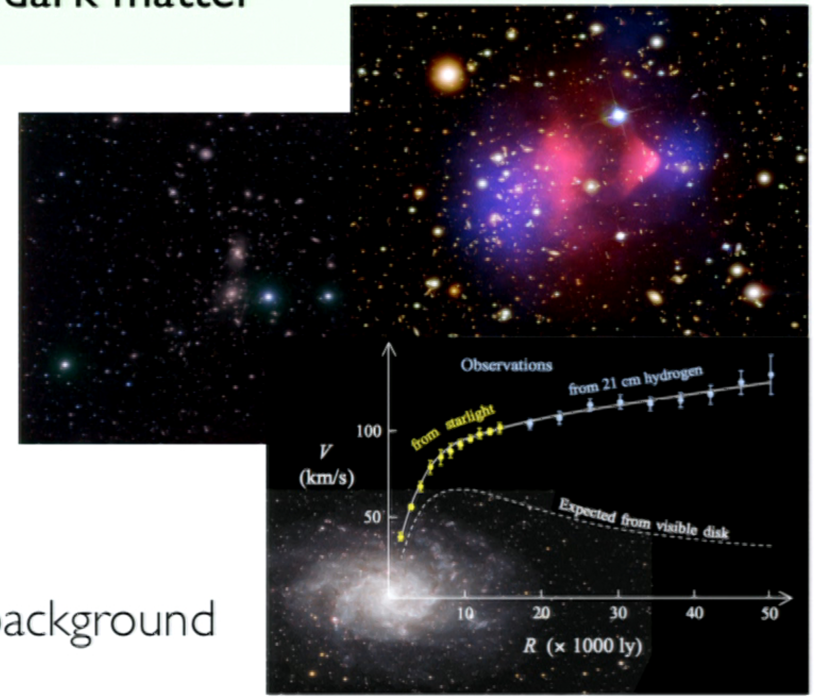
Despite the success of the Standard Model, most of the matter in the universe is something else!



Dark matter

Compelling evidence for dark matter

- Rotation curves
- Lensing
- Structure formation
- Cosmic microwave background



Neutrinos have mass

BUT The Standard Model isn't everything

Example 2:

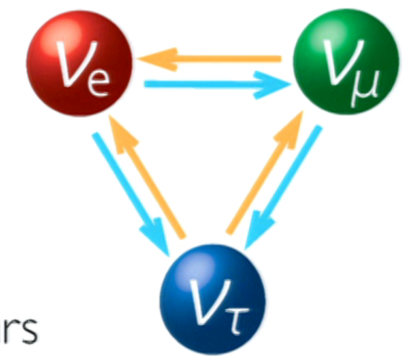
Standard Model

Neutrinos have zero mass

Observed

Neutrinos "oscillate" between flavours

→ Neutrinos have mass



Matter-antimatter asymmetry

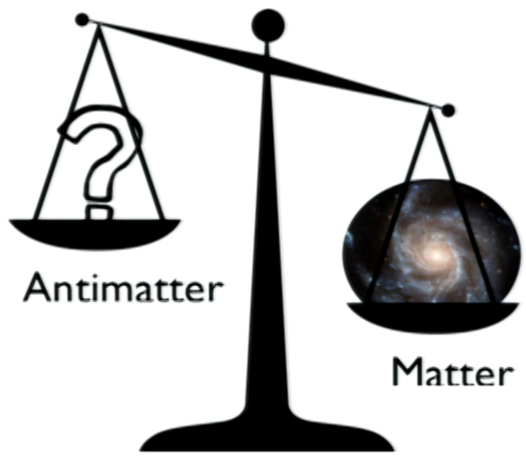
BUT The Standard Model isn't everything

Example 3:

Big Bang ➡ equal amounts of matter and antimatter

Standard model treats matter and antimatter (almost) the same

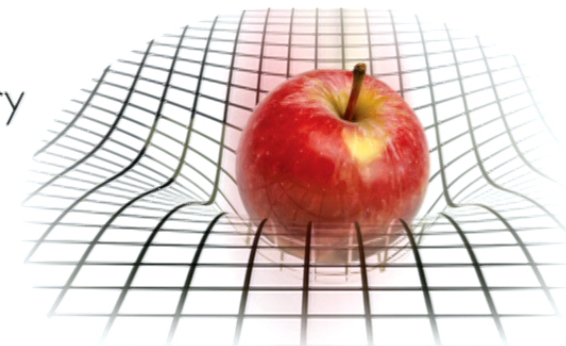
BUT Galaxies etc. all made of matter (not antimatter)



The structure of matter

BUT The Standard Model isn't everything

- Dark matter and dark energy
- Neutrino masses
- Matter–antimatter asymmetry
- Gravity
- Naturalness problems
- Tensions in B-meson decay
- …

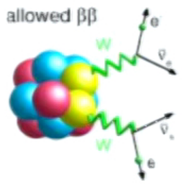


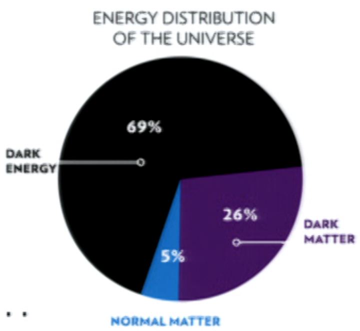
The search for new physics

Precise experiments seek new physics at the "Intensity Frontier"

- Sensitivity to probe the rarest Standard Model interactions
- Search for beyond—Standard-Model effects

- Dark matter direct detection
- Neutrino physics
- Charged lepton flavour violation, **ββ**-decay, proton decay, neutron-antineutron oscillations…

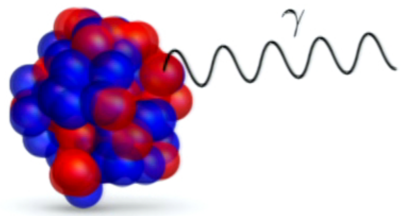




Matrix elements

Nuclear matrix elements:

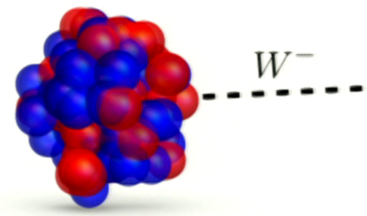
Describe interaction of nucleus with external probes



Electromagnetic current matrix element

$$\langle A | J_\mu^{\mathrm{EM}} | A \rangle$$

Encodes charge distribution in nucleus



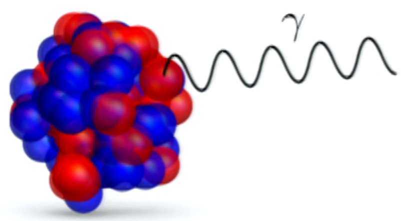
Weak current matrix element

$$\langle A | J_\mu^{W} | A \rangle$$

Describes nuclear structure as seen by weak probe

Matrix elements

Nuclear matrix elements:
Describe interaction of nucleus with external probes



Electromagnetic current matrix element

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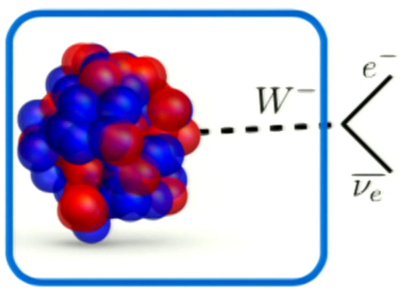


Weak current matrix element

$$\langle A | J_\mu^{W} | A \rangle$$

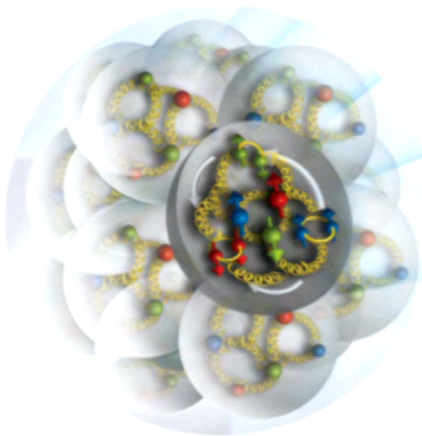
Encodes beta-decay rate

The structure of matter

Understand nuclear structure from the Standard Model

Emergence of complex structure in nature

Backgrounds and benchmarks for searches for new physics

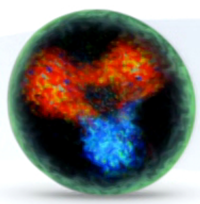


Strong interactions

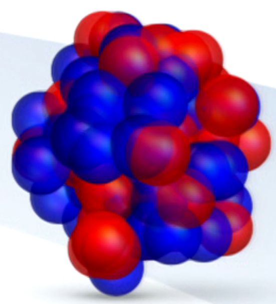
Study nuclear structure from the strong interactions

Quantum Chromodynamics (QCD)

Strongest of the four forces in nature

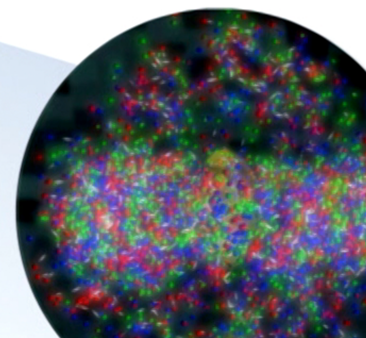


Binds quarks and gluons into protons, neutrons, pions etc.



Binds protons and neutrons into nuclei

Forms other types of exotic matter e.g., quark-gluon plasma



Strong interactions

Interaction strength depends on energy

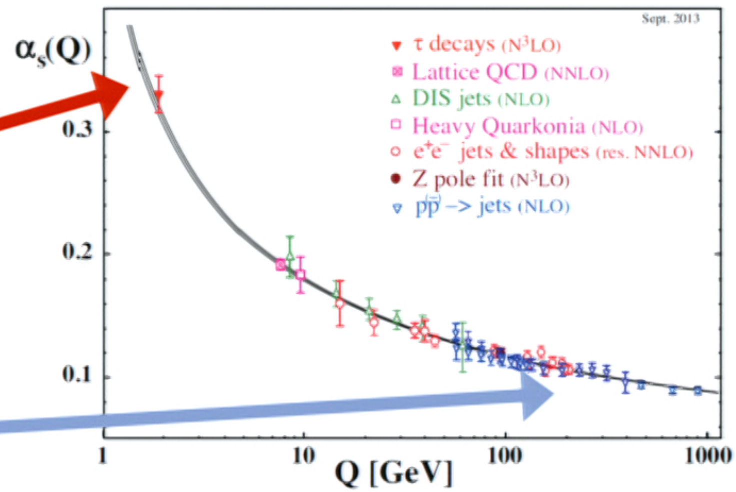
[Gross, Politzer, Wilczek, Nobel 2004]

Low-energy QCD is non-perturbative

Perturbation theory at high energies

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

Strong coupling

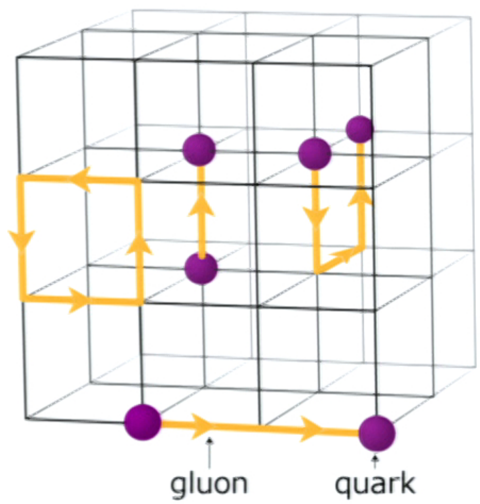


Energy

Lattice QCD

Numerical first-principles approach to non-perturbative QCD

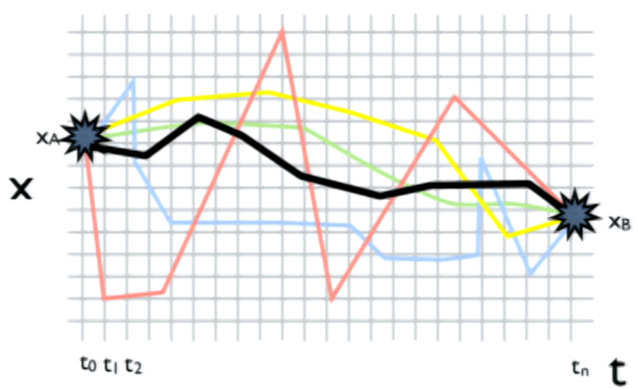
- Discretise equations of QCD onto space-time grid
- Calculate observables
- Take limit of vanishing discretisation afterwards



Lattice QCD

Numerical first-principles approach to non-perturbative QCD

- QCD equations ↔ integrals over the values of quark and gluon fields on each site/link (QCD path integral)
- $\sim 10^{10}$ variables



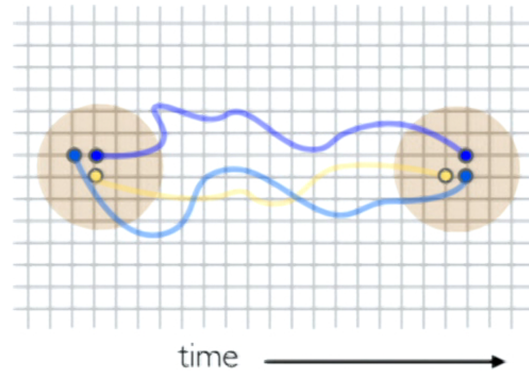
- Evaluate by importance sampling
- Paths near classical action dominate
- Calculate physics on a set (ensemble) of samples of the quark and gluon fields

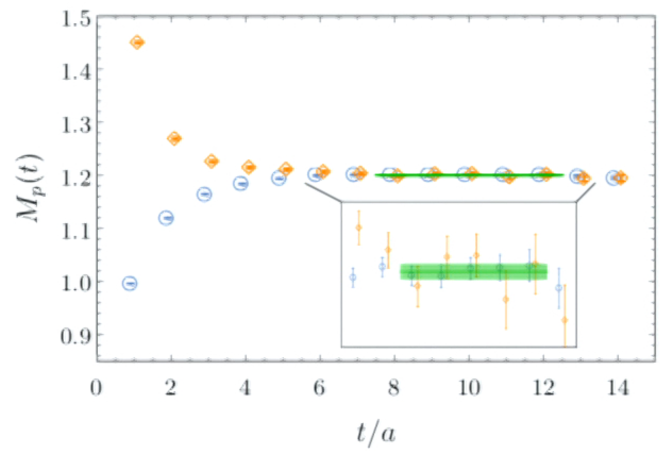
Lattice QCD

Calculate a nucleon mass

- Create three quarks, annihilate them far from source
- QCD path integral adds quark anti-quark pairs and gluons automatically
- Measure exponentially decaying correlation to extract mass

$$M(t) = \ln\left[\frac{C(t)}{C(t+1)}\right] \xrightarrow{t\to\infty} E_0$$

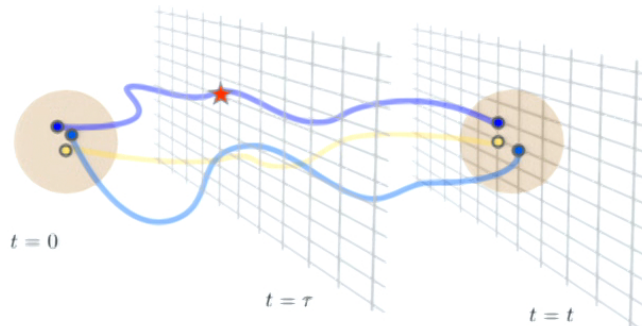




Lattice QCD matrix elements

Calculate matrix elements

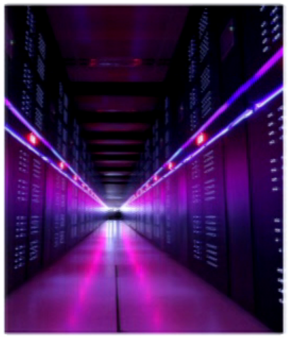
- Create three quarks (correct quantum numbers) at a source and annihilate the three quarks at sink far from source
- Insert operator at intermediate timeslice



- Remove time-dependence by dividing out with two-point correlators: $\frac{C_3(t,\tau,\vec{p'},\vec{q})}{C_2(t-\tau,p')C_2(\tau,p)} \xrightarrow{t\to\infty} \langle N(p')|\mathcal{O}(q)|N(p)\rangle$

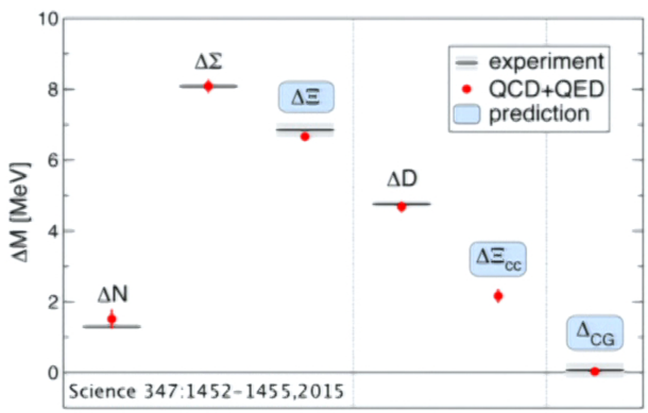
Lattice QCD

- Calculations use world's largest computers
- Many millions of CPU hours
- Specifically designed processors for QCD (QCDOC precursor of BlueGene computers)

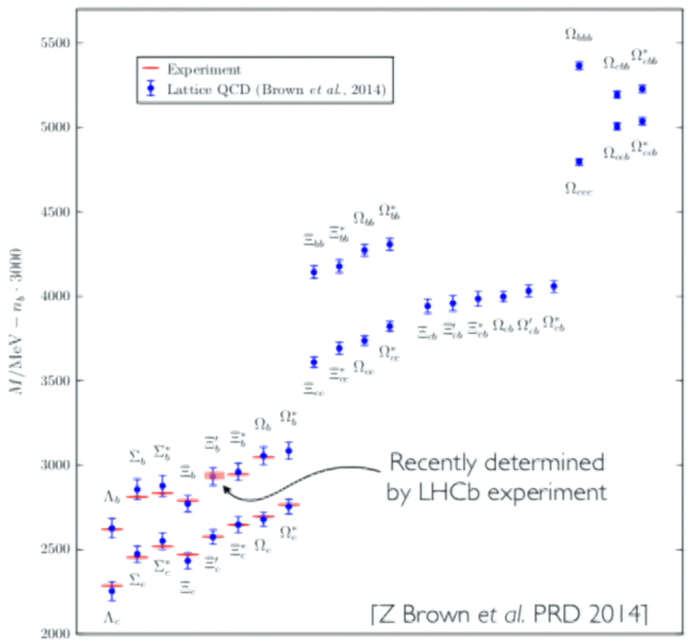


Lattice QCD works

- Ground state hadron spectrum reproduced
- p-n mass splitting reproduced
- ...



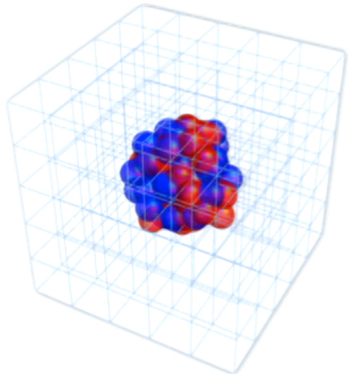
- Predictions for new states with controlled uncertainties

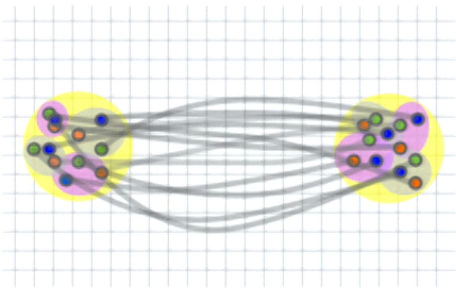


Nuclear physics from LQCD

Nuclei on the lattice

- Hard problem
  - Noise:
    Statistical uncertainty grows exponentially with number of nucleons
  - Complexity:
    Number of contractions grows factorially





Unphysical nuclei

- Nuclei with A<5
- QCD with unphysical quark masses

  $m_\pi \sim 800$ MeV, $m_N \sim 1{,}600$ MeV

  $m_\pi \sim 450$ MeV, $m_N \sim 1{,}200$ MeV

- Nuclear structure: magnetic moments, polarisabilities

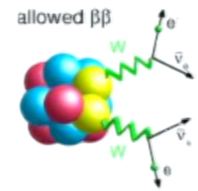
  [PRL **113**, 252001 (2014), PRD 92, 114502 (2015)]

- First nuclear reaction: np⟶dγ

  [PRL **115**, 132001 (2015)]

- Proton-proton fusion and tritium β-decay

  [PRL **119**, 062002 (2017)]

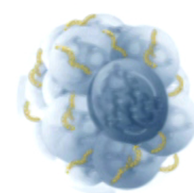


- Double β-decay

  [PRL **119**, 062003 (2017), PRD **96**, 054505 (2017)]

- Gluon structure of light nuclei

  [PRD **96** 094512 (2017)]

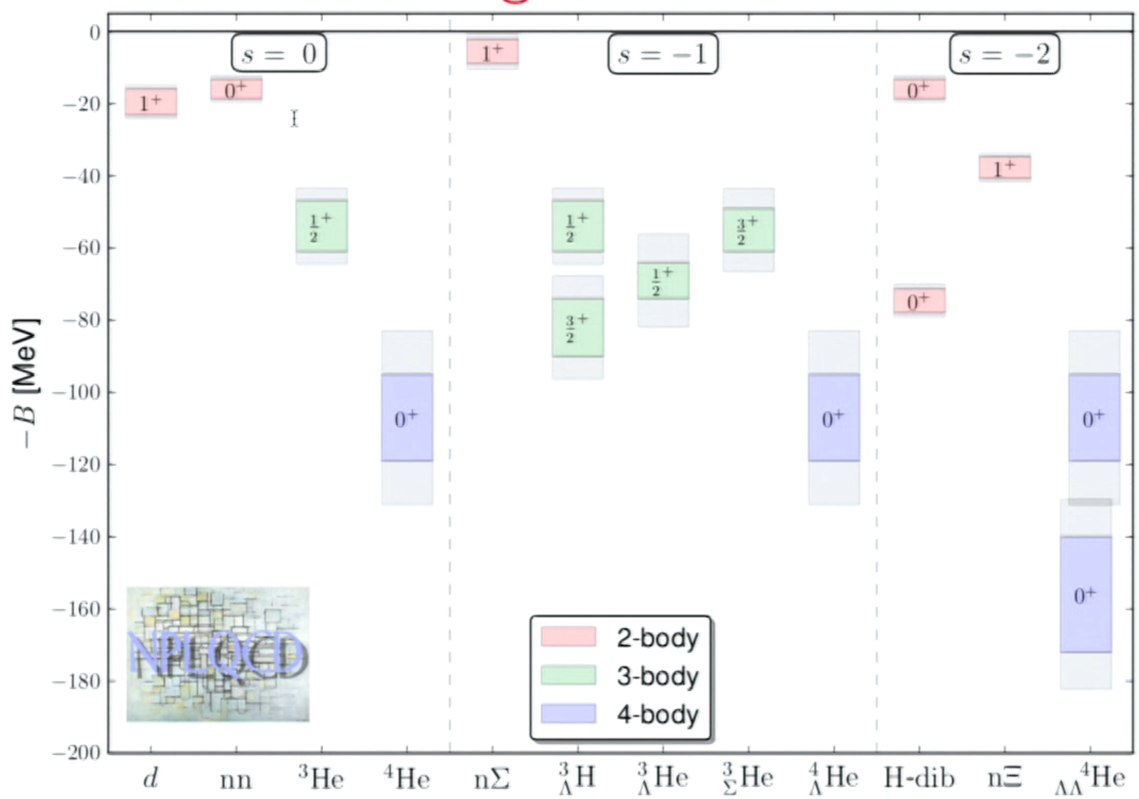


- Scalar, axial and tensor MEs

  [PRL **120** 152002 (2018)]

Spectrum of light nuclei

@ m_π = 800 MeV

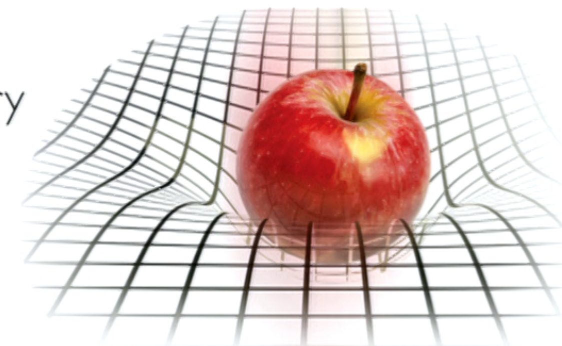


NPLQCD Phys.Rev. D87 (2013), 034506

The structure of matter

The Standard Model isn't everything

- Dark matter and dark energy
- Neutrino masses
- Matter–antimatter asymmetry
- Gravity
- Naturalness problems
- Tensions in B-meson decay
- …



Neutrino masses

Why are neutrinos so light?

- Popular class of theories: seesaw mechanism
- Requires additional (right-handed) sterile neutrinos and that neutrinos are their own antiparticles (Majorana particles)

- Diagonalise mass matrix
  → Super light particle (observed neutrino) and super heavy particle (mass~10^{15} m_{proton})

- Majorana neutrino
  → Lepton and baryon numbers can change
  → Possible explanation of matter-antimatter asymmetry

Neutrinos

Charged particles and antiparticles easy to distinguish

$$e^- \neq e^+$$

What about neutrinos?

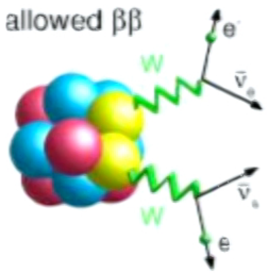
$$\nu \neq \overline{\nu}$$ "Dirac"

$$\nu = \overline{\nu}$$ "Majorana"

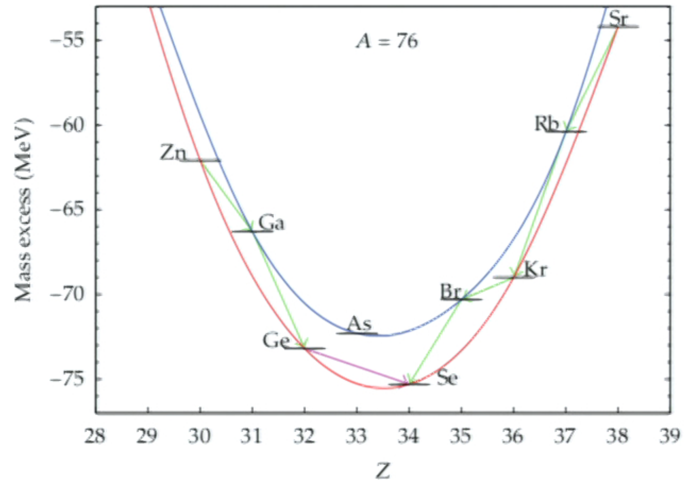
?

Double β-decay

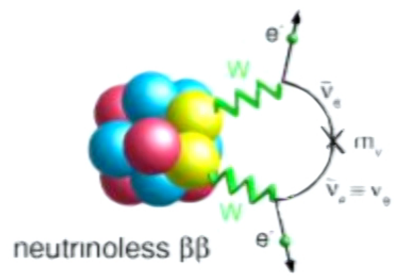
- Certain nuclei allow observable ββ decay



$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y



- If neutrinos are massive Majorana fermions 0νββ decay is possible

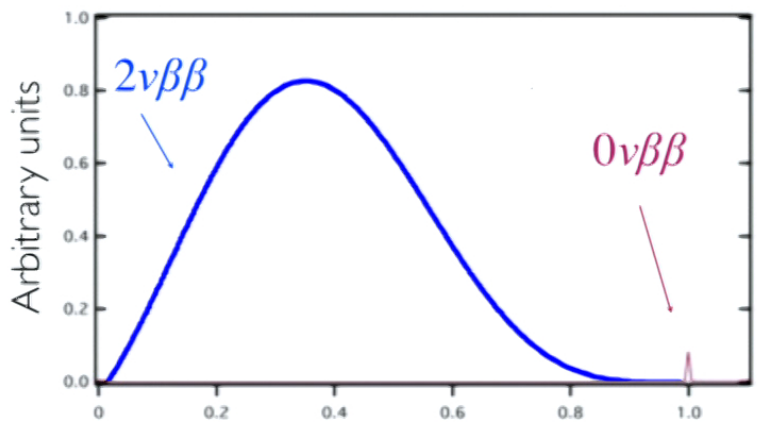


$T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y

Double β-decay

Most sensitive experiments using ^{76}Ge, ^{130}Te, and ^{136}Xe:

→ $T_{1/2} > 5\times10^{25}$ to 10^{26} years



(Summed β energy) / (Total decay process energy)

Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05

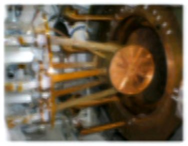
Background ~0.1 cnts/t-y
(next generation experiments)

Double β-decay

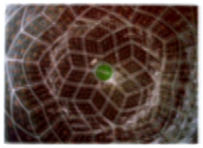
Major ton-scale experimental searches underway

CUORE

EXO200



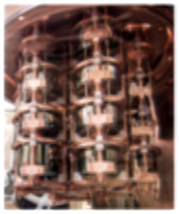
KamLAND Zen



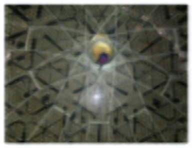
Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA



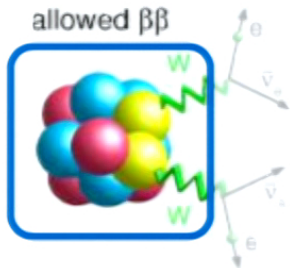
SNO+



J.F.Wilkerson (2017)

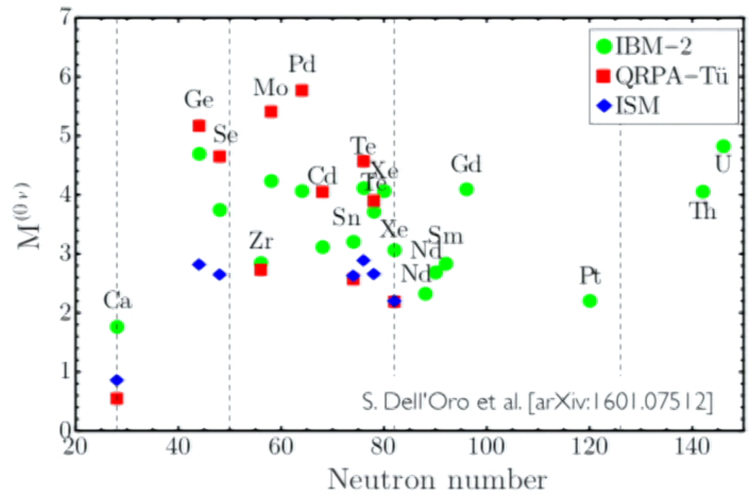
Double β-decay

Want to understand **2νββ** and **0νββ** decay from theory



Calculate two-current nuclear matrix elements
→ dictate half-life

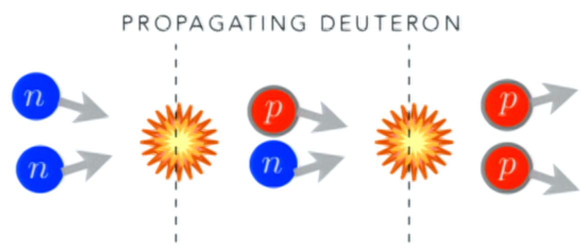
Model calculations have large uncertainties



Second order weak interactions

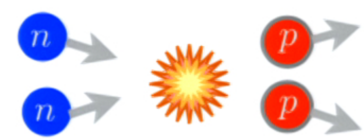
NPLQCD PRL **119**, 062003 (2017), PRD **96**, 054505 (2017)

Lattice QCD: Calculate nn→pp transition matrix element



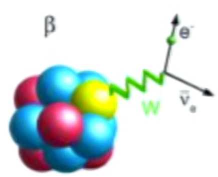
LONG-DISTANCE PIECE

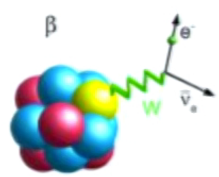
Two single-beta decays

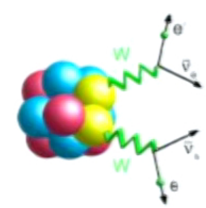


SHORT-DISTANCE PIECE

Two-body effect







Second order weak interactions

NPLQCD PRL **119**, 062003 (2017), PRD **96**, 054505 (2017)

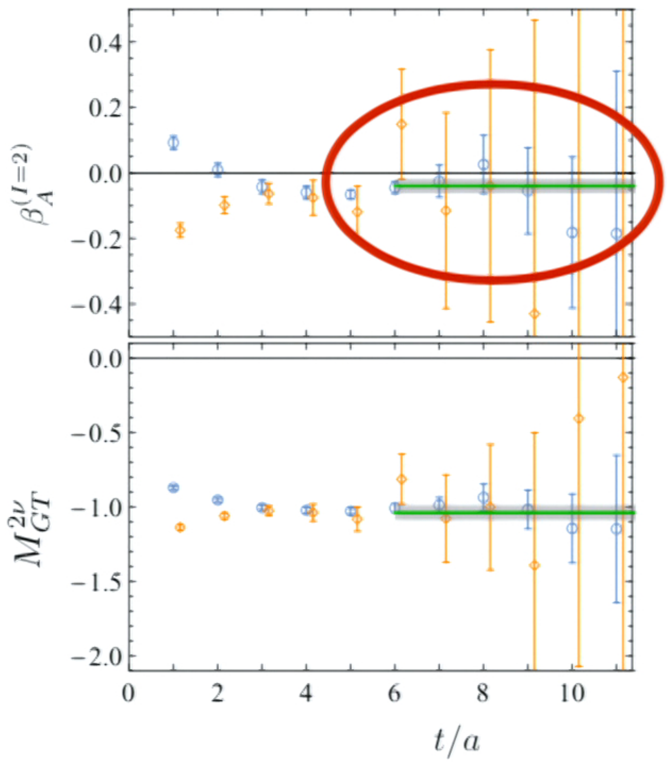
- Non-negligible deviation from long distance deuteron intermediate state contribution

Isotensor axial polarisability

$$M_{GT}^{2\nu} = -\frac{|M_{pp\to d}|^2}{E_{pp} - E_d} + \beta_A^{(I=2)}$$

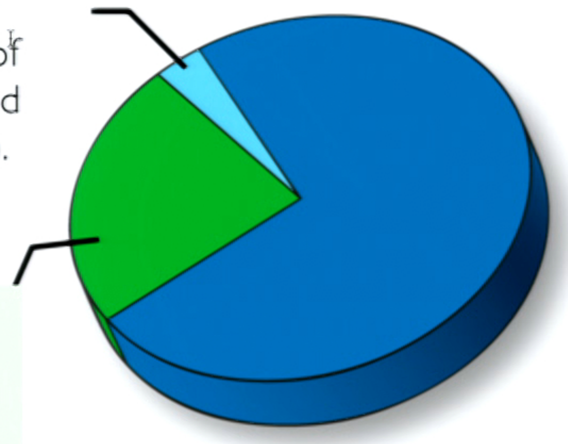
➡ Multi-body effects can't be neglected!

- TBD: connect to models / effective field theory for larger systems



Dark matter

5%
Normal matter
The building blocks of stars and planets (and everything on Earth).

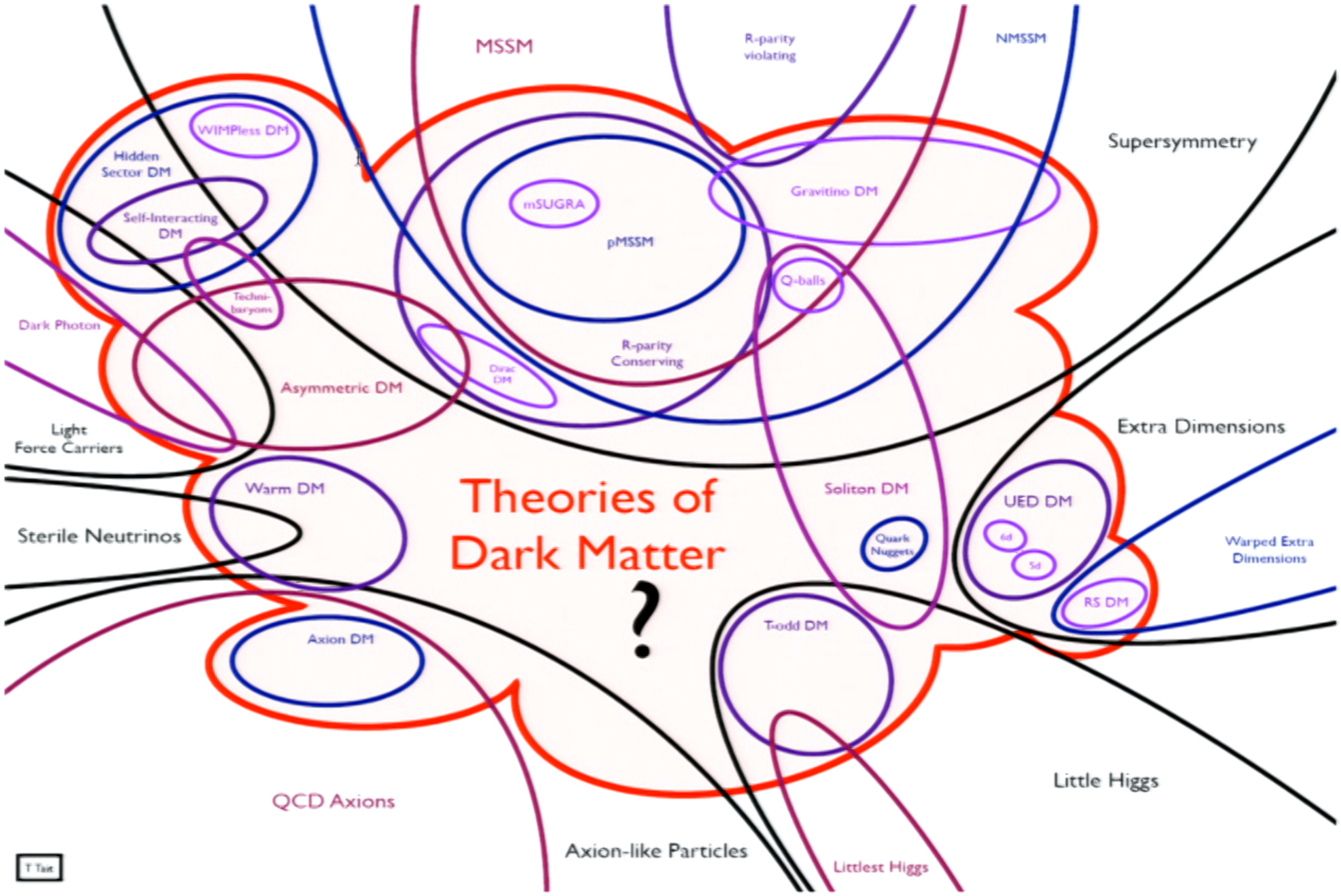


72 %
Dark energy
Something that we don't understand… but it's not matter.
-Responsible for the accelerating expansion of the universe

23 %
Dark matter
Matter that we don't understand.
-Doesn't emit or absorb light
-Interacts through gravity

Many models for dark matter!
BUT few constraints

Dark matter



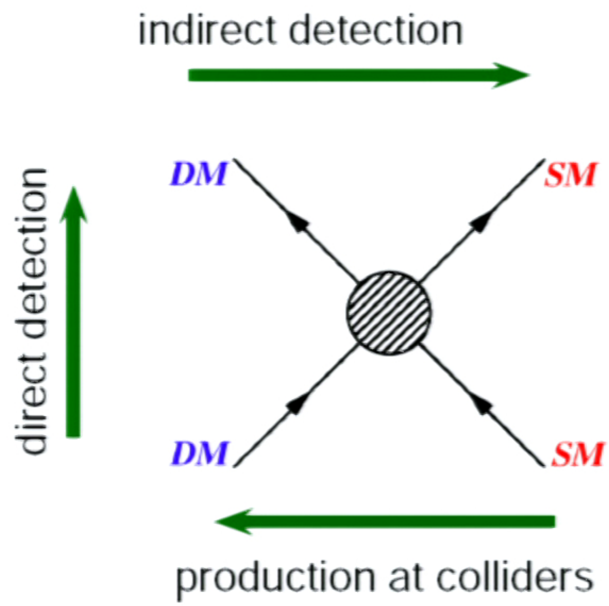
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Theories of Dark Matter
?
Warm DM
Sterile Neutrinos
Soliton DM
Quark Nuggets
UED DM
6d
5d
RS DM
Warped Extra Dimensions
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Dark matter

How do we find dark matter?

- Dark (does not interact with light)
- Interacts through gravity

WIMP
Weakly-interacting massive particles



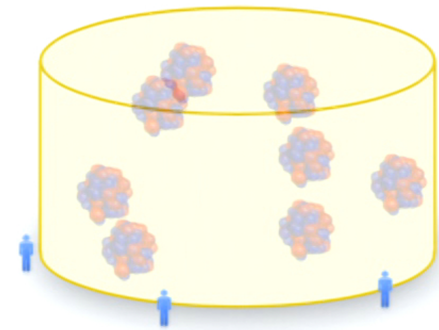
Dark matter

How do we find dark matter?

- Dark (does not interact with light)
- Interacts through gravity

WIMP
Weakly-interacting massive particles

Direct detection
Wait for DM to hit us



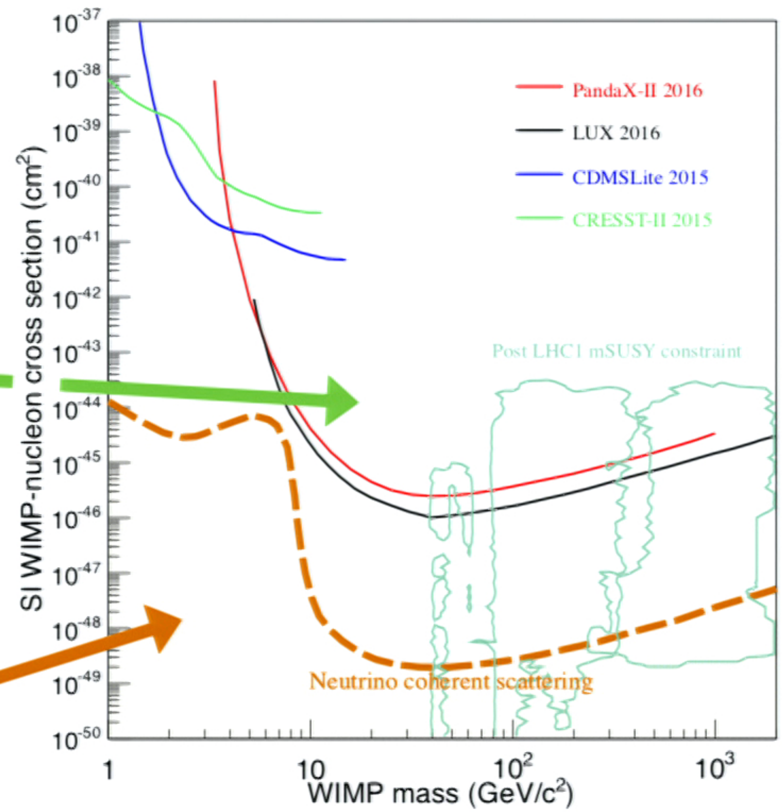
Detection rate depends on

- Dark matter properties
- Probability for interaction with nucleus

Dark matter direct detection

Limits on WIMP-nucleon interaction from direct detection experiments

Ruled out above the solid lines



Background

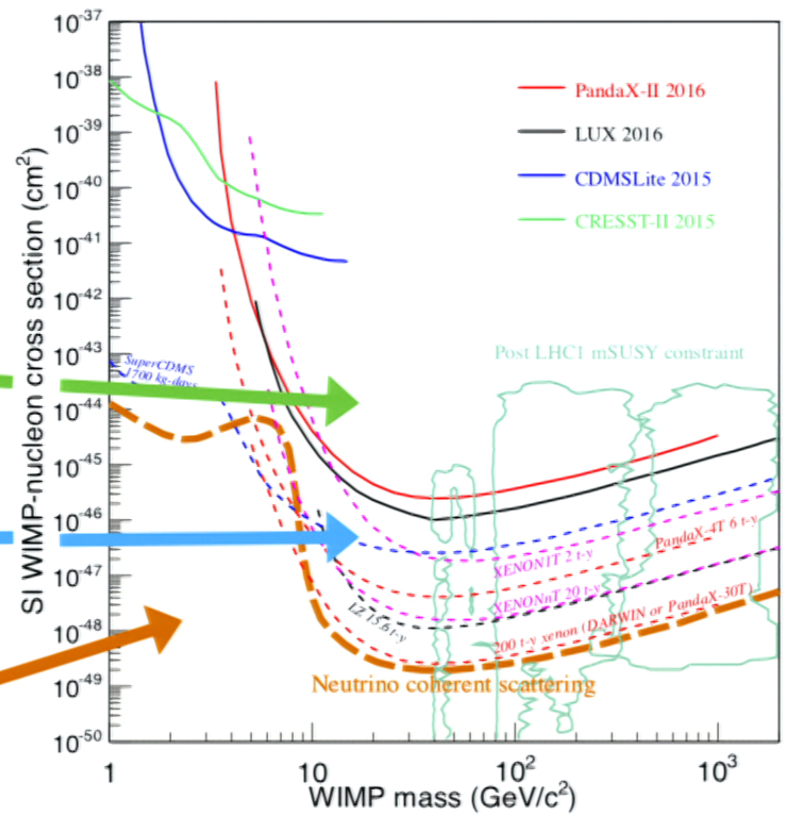
Dark matter direct detection

Limits on WIMP-nucleon interaction from direct detection experiments

Ruled out above the solid lines

Projected limits from future experiments

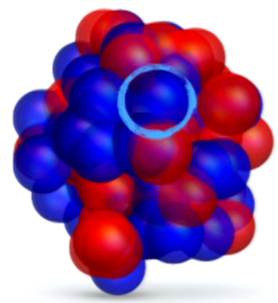
Background



Dark matter

Determine interaction cross-section (with nucleus) for a given dark matter model

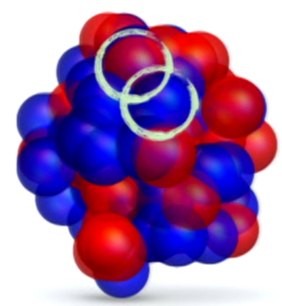
- Born approximation – interacts with a single nucleon



$$\sigma \sim |A \langle N|DM|N\rangle|^2$$

known from LQCD

- Interacts non-trivially with multiple nucleons

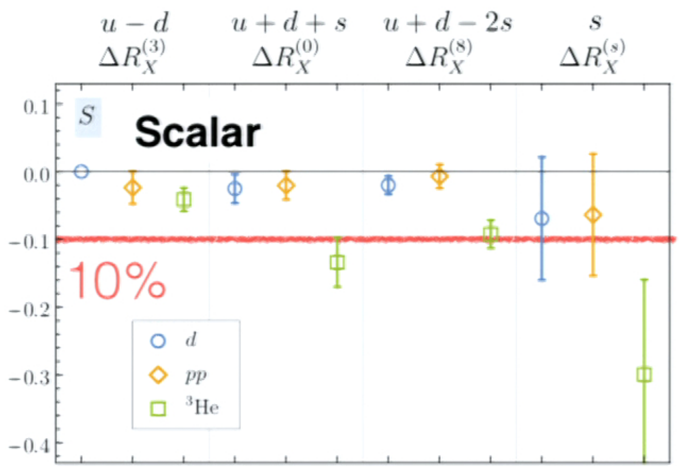


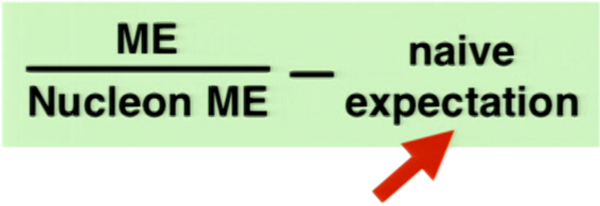
$$\sigma \sim |A \langle N|DM|N\rangle + \alpha \langle NN|DM|NN\rangle + \ldots|^2$$

poorly known!

Scalar matrix elements

- Spin-independent scattering of many WIMP candidates governed by scalar matrix elements
- Lattice QCD calculation shows 10% nuclear effects!

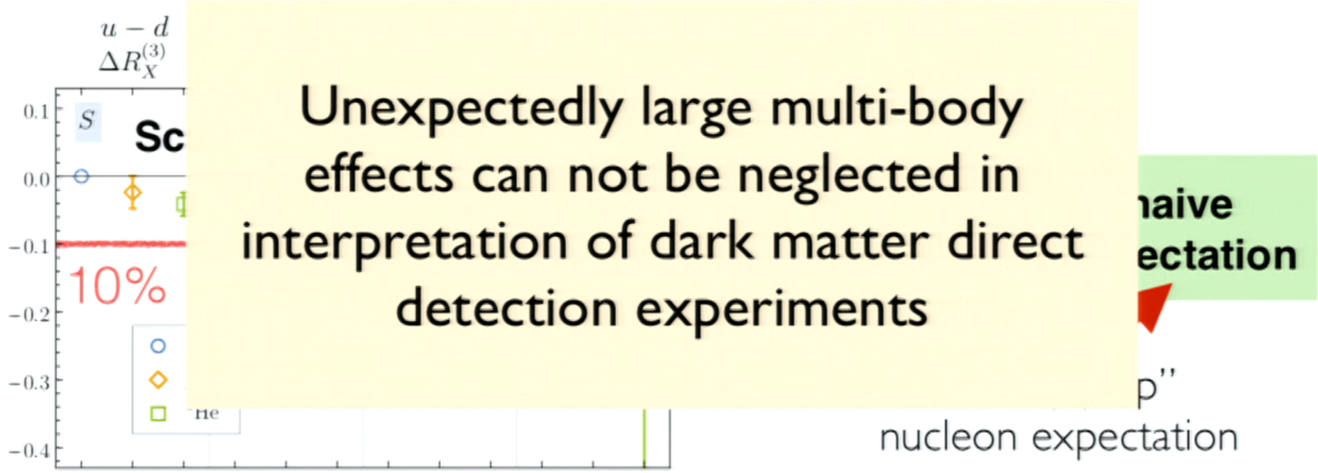




"Multiply up"
nucleon expectation

Scalar matrix elements

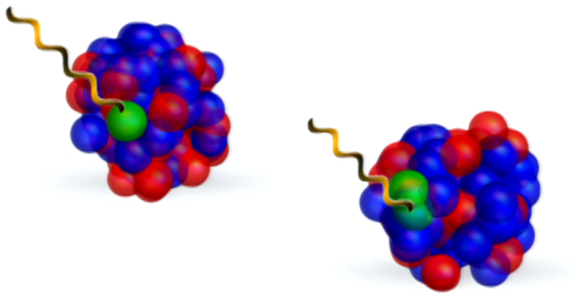
- Spin-independent scattering of many WIMP candidates governed by scalar matrix elements
- Lattice QCD calculation shows 10% nuclear effects!



Unexpectedly large multi-body effects can not be neglected in interpretation of dark matter direct detection experiments

Larger nuclei

- What about larger (phenomenologically-relevant) nuclei?
- Nuclear effective field theory:
  - 1-body currents are dominant
  - 2-body currents are sub-leading *but non-negligible*



- Determine one body contributions from single nucleon
- Determine few-body contributions from A=2,3,4...
- Match effective theory and many body methods to lattice results to make predictions for larger nuclei

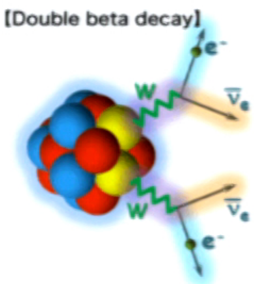
Pushing the boundaries

First-principles nuclear physics beyond A=4

How finely tuned is the emergence of nuclear structure in nature?

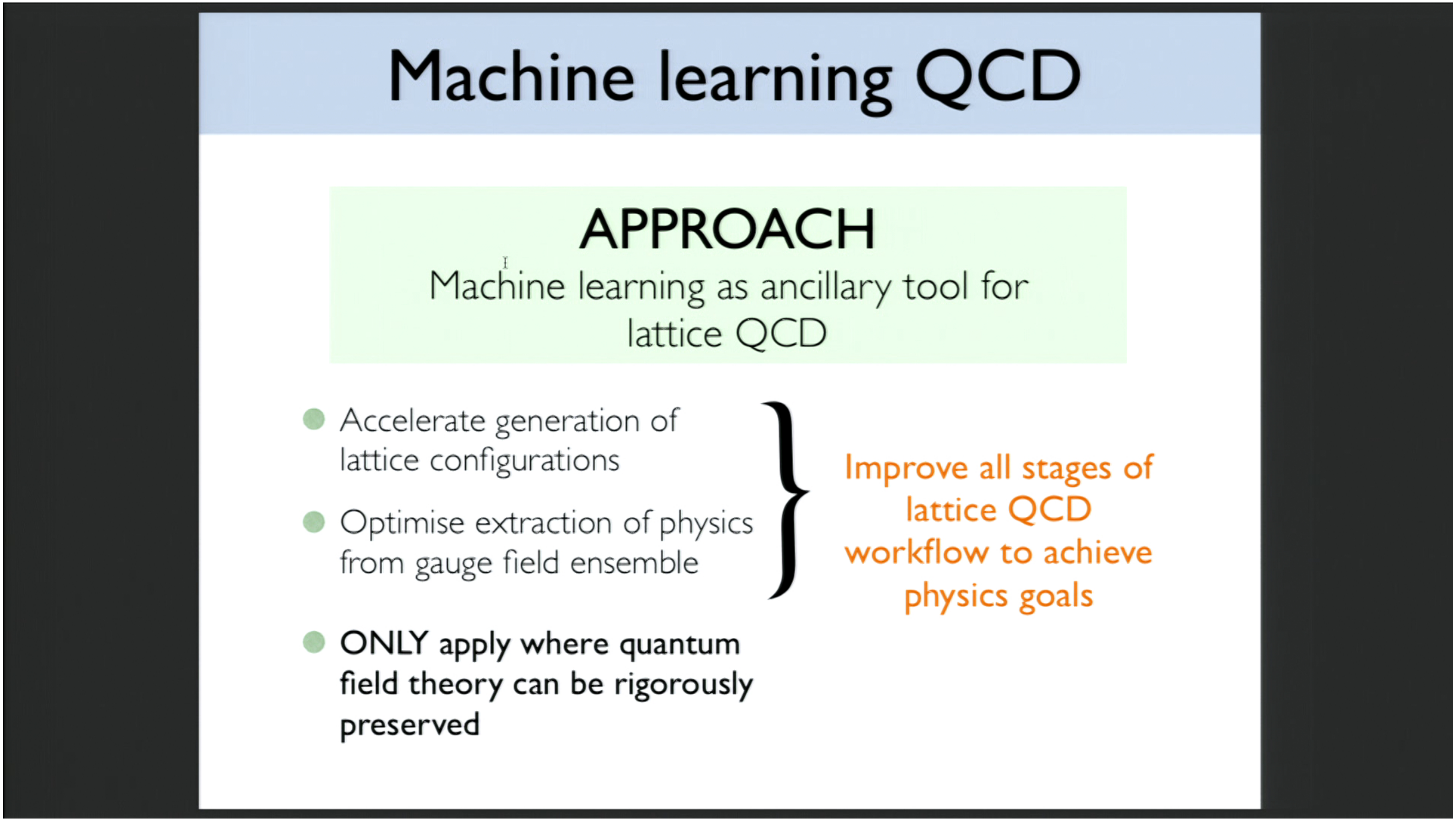
Interpretation of intensity-frontier experiments

- Axial form factors of Argon A=40
  DUNE long-baseline neutrino expt.
- Double-beta decay rates of Calcium A=48
- Scalar matrix elements in A=131
  XENON1T dark matter direct detection search



Double beta decay
which emits anti-neutrinos

Exponentially harder problem → Need exponentially improved algorithms


Machine learning QCD
APPROACH
Machine learning as ancillary tool for lattice QCD
Accelerate generation of lattice configurations
Optimise extraction of physics from gauge field ensemble
ONLY apply where quantum field theory can be rigorously preserved
Improve all stages of lattice QCD workflow to achieve physics goals

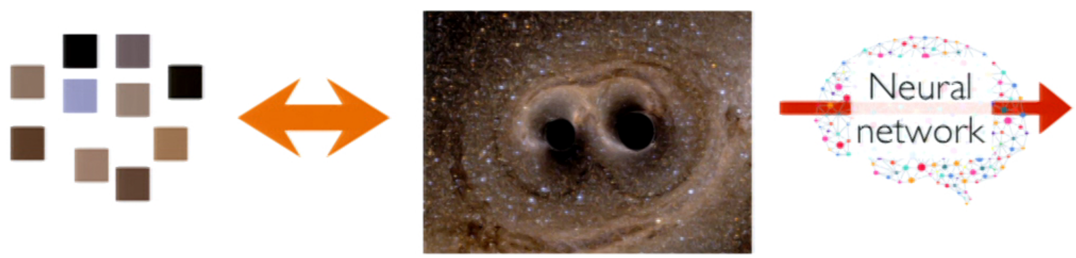
Machine learning QCD

Neural networks excel on problems where

Basic data unit has little meaning ↔ Combination of units is meaningful

Image recognition

Pixel | Image | Label



"Colliding black holes"

Machine learning QCD

Neural networks excel on problems where

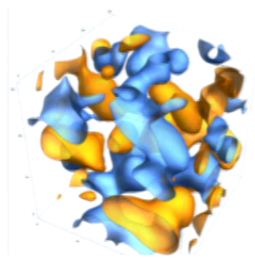
Basic data unit has little meaning ⟷ Combination of units is meaningful

Parameter identification

Element of a colour matrix at one discrete space-time point

0 6 7 3 5 6 2 8 4 1

Ensemble of lattice QCD gauge field configurations



Label

Parameters of action

Machine learning QCD

CIFAR benchmark image set for machine learning

- 32 × 32 pixels × 3 cols ≃3000 numbers
- 60000 samples
- Each image has meaning
- Local structures are important
- Translation-invariance within frame

Ensemble of lattice QCD gauge fields

- $64^3 \times 128 \times 4 \times N_c^2 \times 2$ $\simeq 10^9$ numbers
- ~1000 samples
- Ensemble of gauge fields has meaning
- Long-distance correlations are important
- Gauge and translation-invariant with periodic boundaries

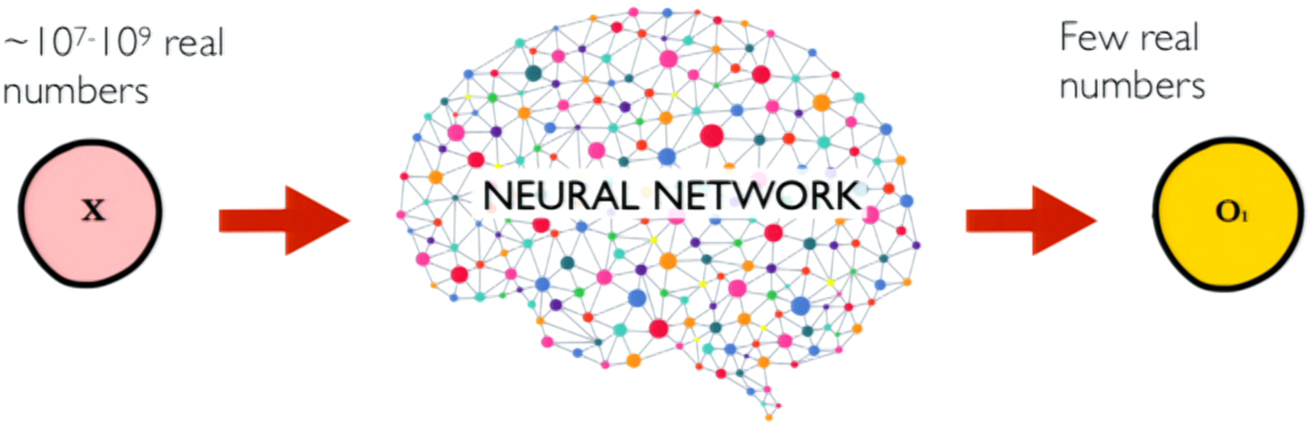
Regression by neural network

Lattice QCD gauge field

~10^7-10^9 real numbers

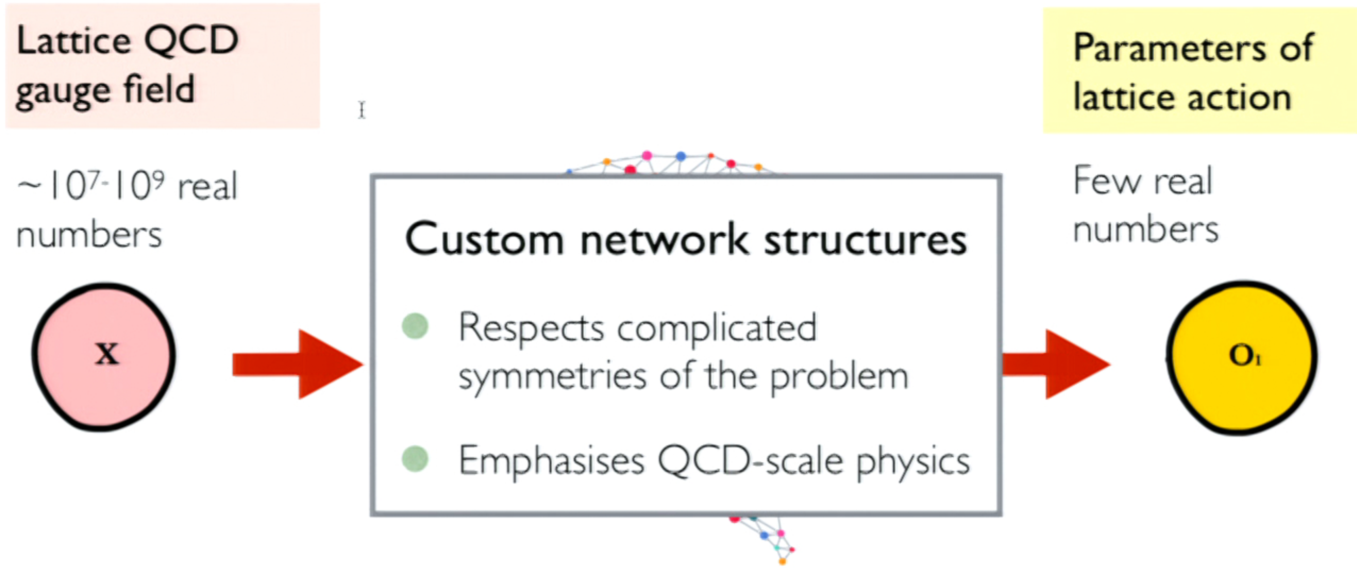
Parameters of lattice action

Few real numbers



- **Complete:** uses all the information encoded in the gauge fields (rather than a calculated (affordable) subset of relevant physics parameters)
- **Instant:** once trained over a parameter range

Regression by neural network



- **Complete:** uses all the information encoded in the gauge fields (rather than a calculated (affordable) subset of relevant physics parameters)
- **Instant:** once trained over a parameter range

Nuclear physics from QCD

- **Nuclei can be studied directly from QCD**
- Current state-of-the-art: significant systematics but phenomenologically interesting at current precision
- Nuclear matrix elements important to experimental programs and new physics searches e.g,
  - Electron-Ion Collider
  - **Double-beta decay**
  - **Dark matter direct detection**