

CAN WE RELIABLY PREDICT NUCLEAR FORCES AND/OR NUCLEI FROM QCD?

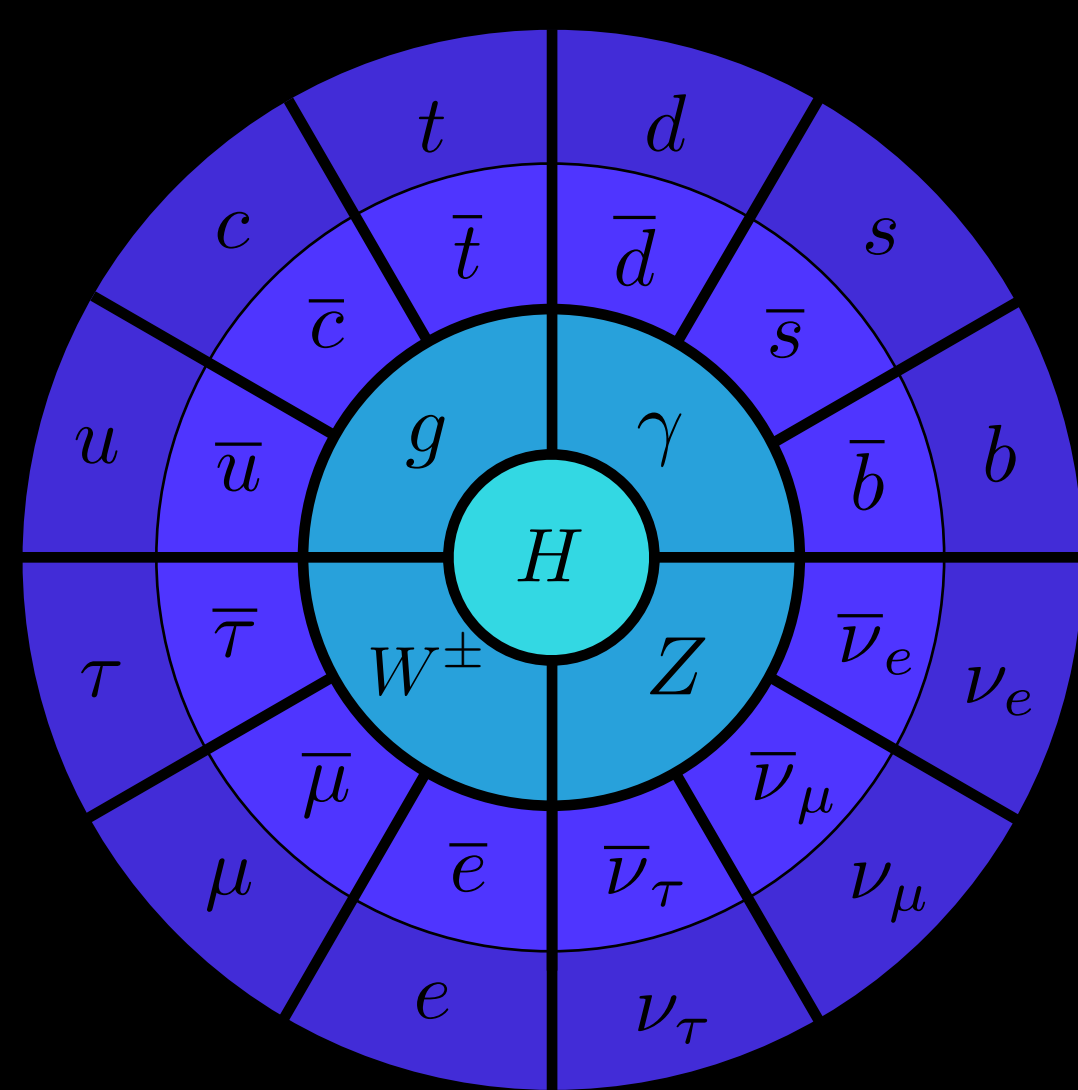
ZOHREH DAVOUDI

CENTER FOR THEORETICAL PHYSICS - MIT

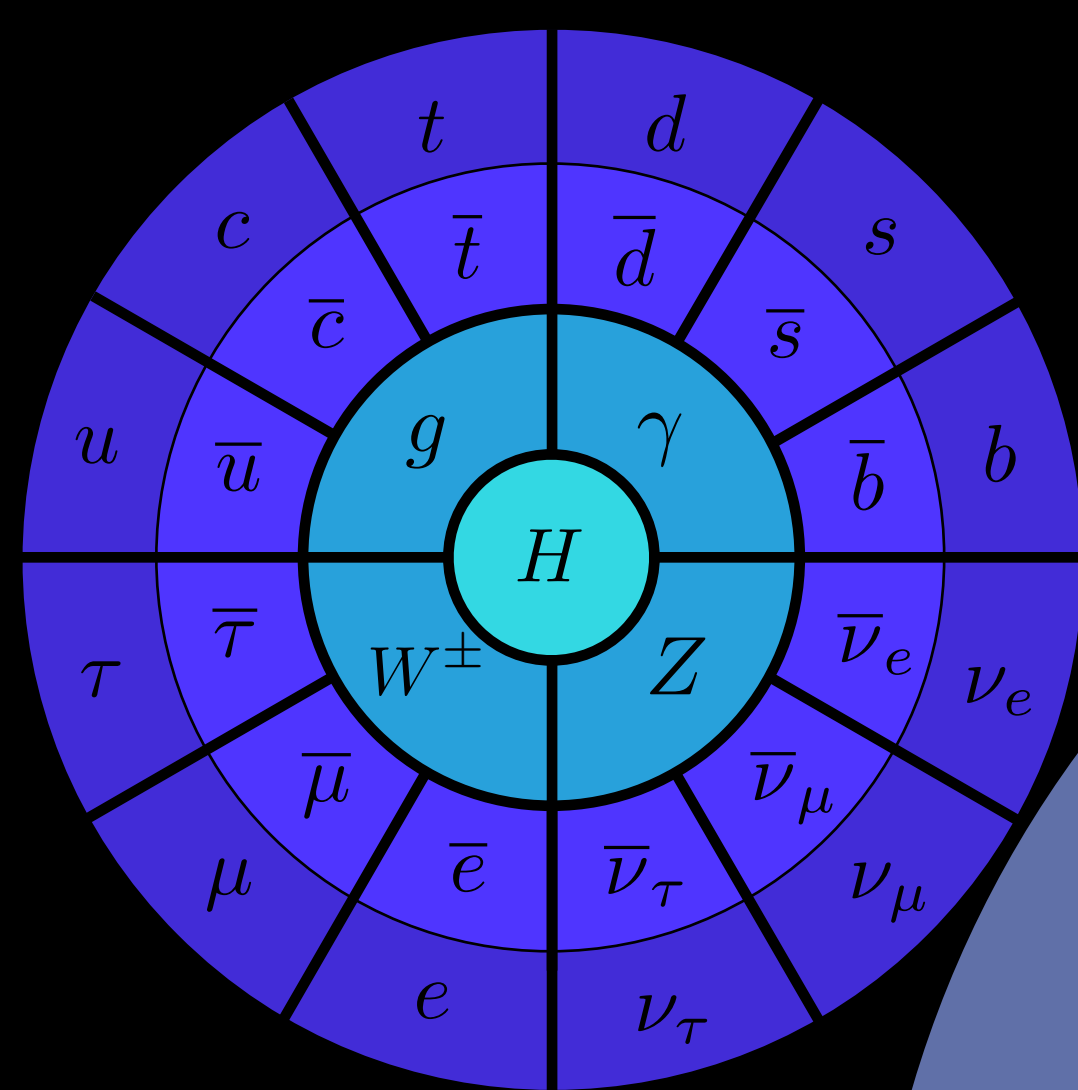
WORKSHOP ON:
THE TOWER OF THE EFFECTIVE FIELD THEORIES AND THE EMERGENCE
OF THE NUCLEAR PHENOMENA

CEA, SACLAY, FRANCE
JANUARY 2017

WHAT ARE THE UNDERLYING
RULES THAT GOVERN NATURE?

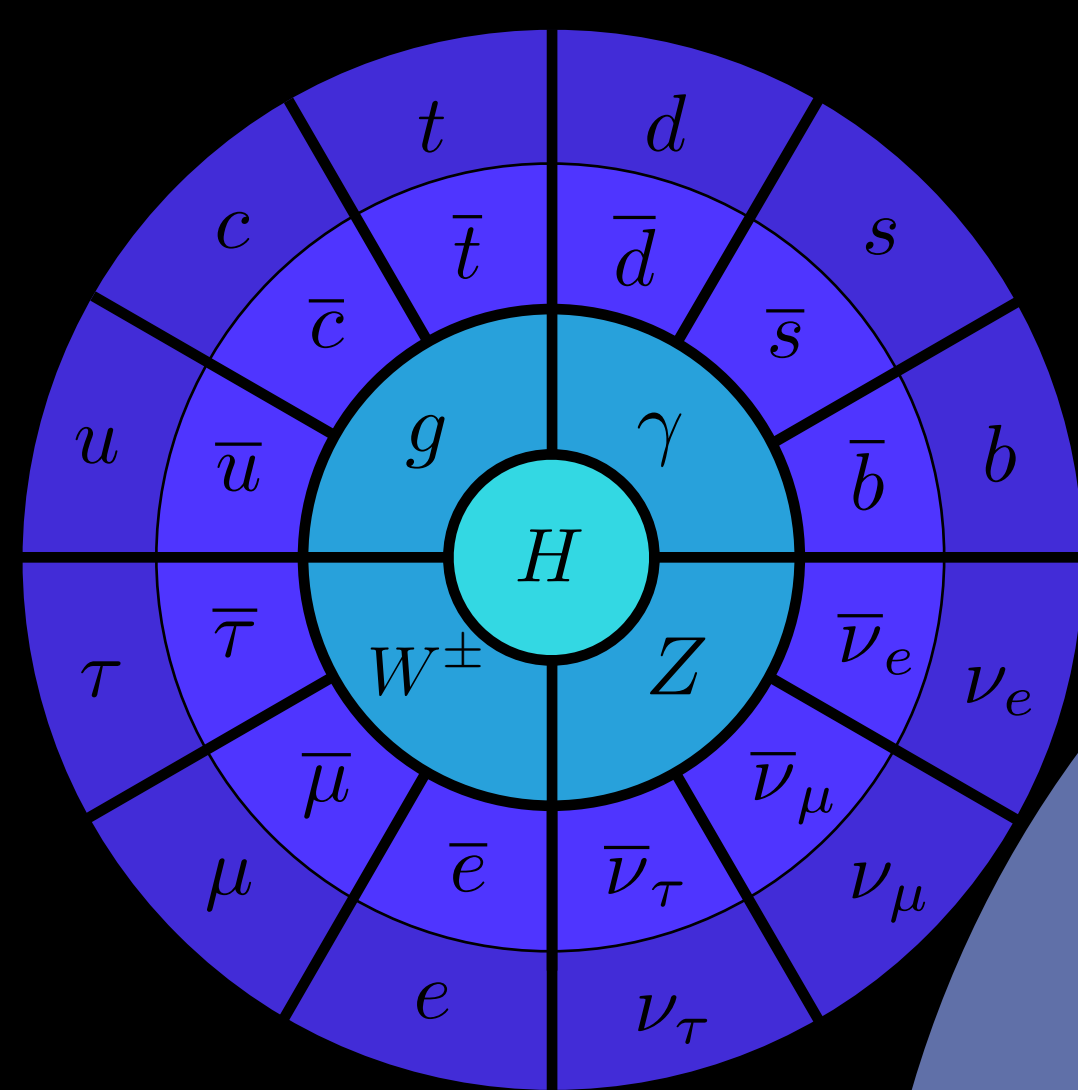


WHAT ARE THE UNDERLYING
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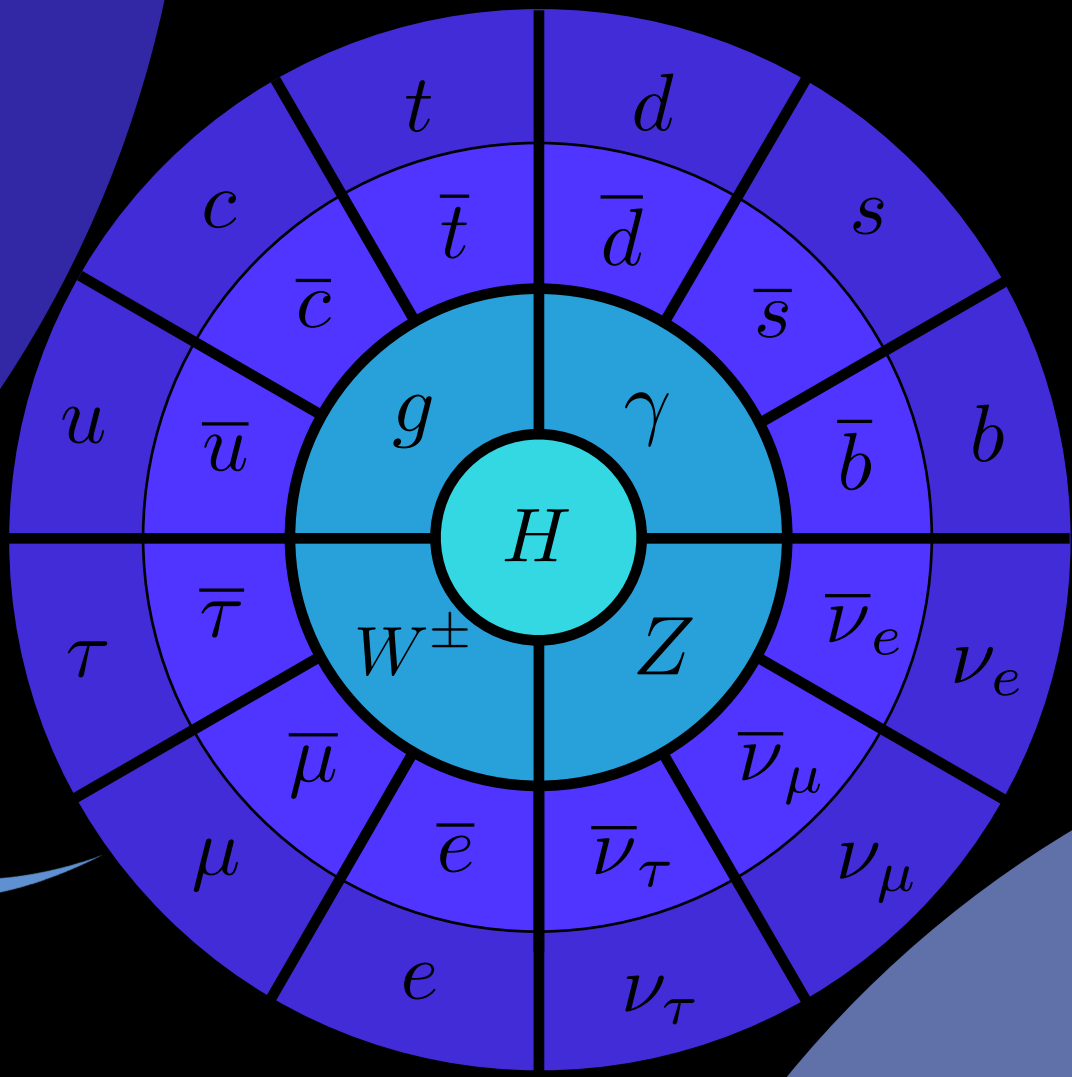


PARTICLE PHYSICS
AND COSMOLOGY

?

Q1) HOW DO COMPLEXITIES IN VISIBLE
UNIVERSE EMERGE FROM STANDARD MODEL?

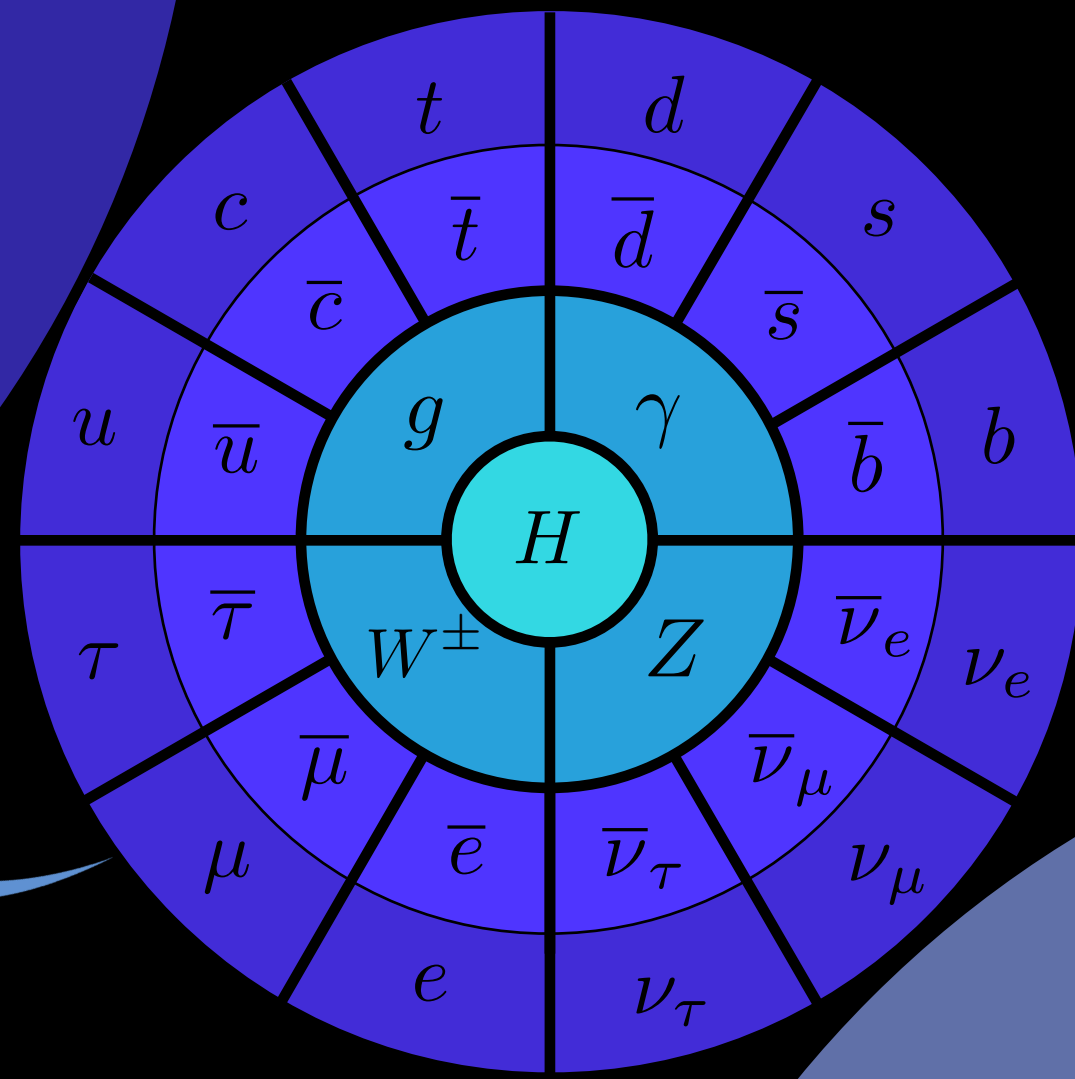
?



Q1) HOW DO COMPLEXITIES IN VISIBLE
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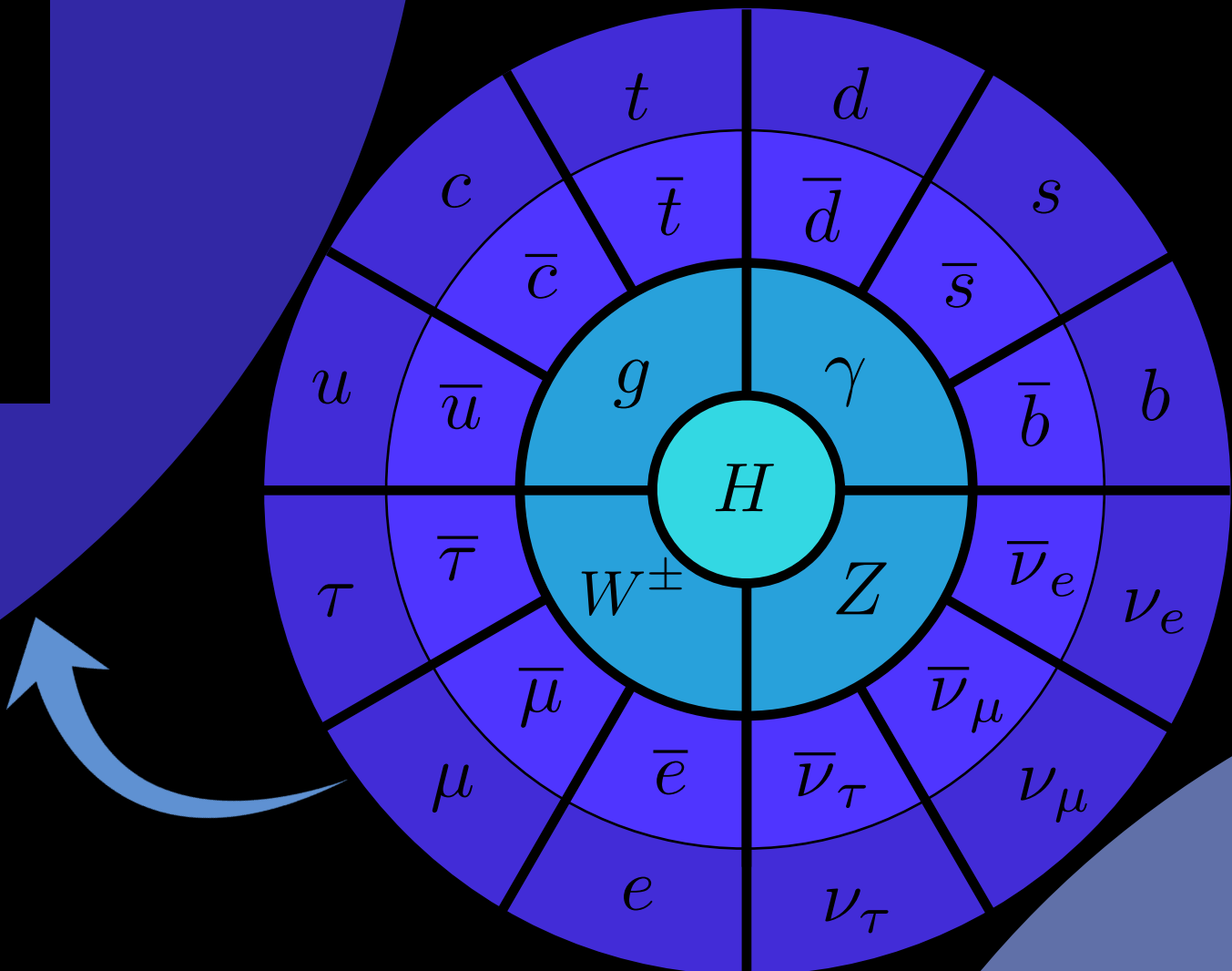
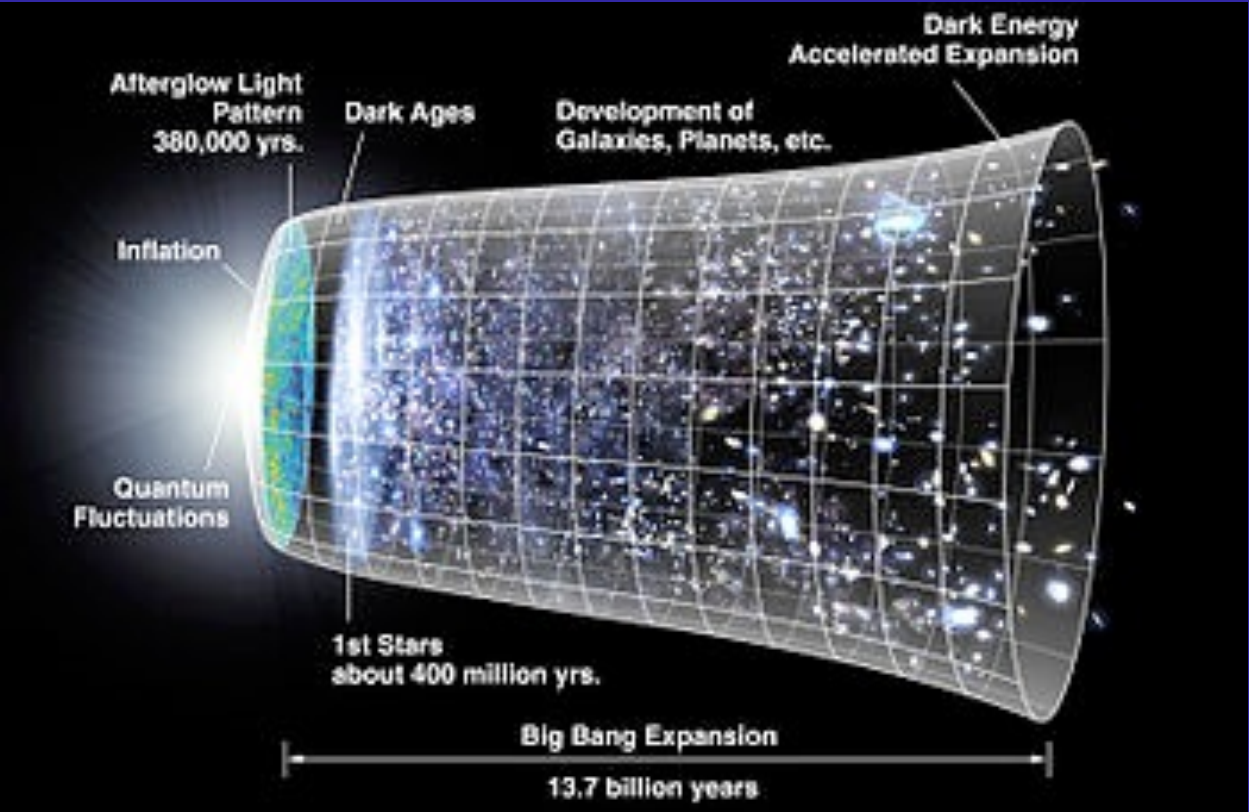
NUCLEAR PHYSICS

?



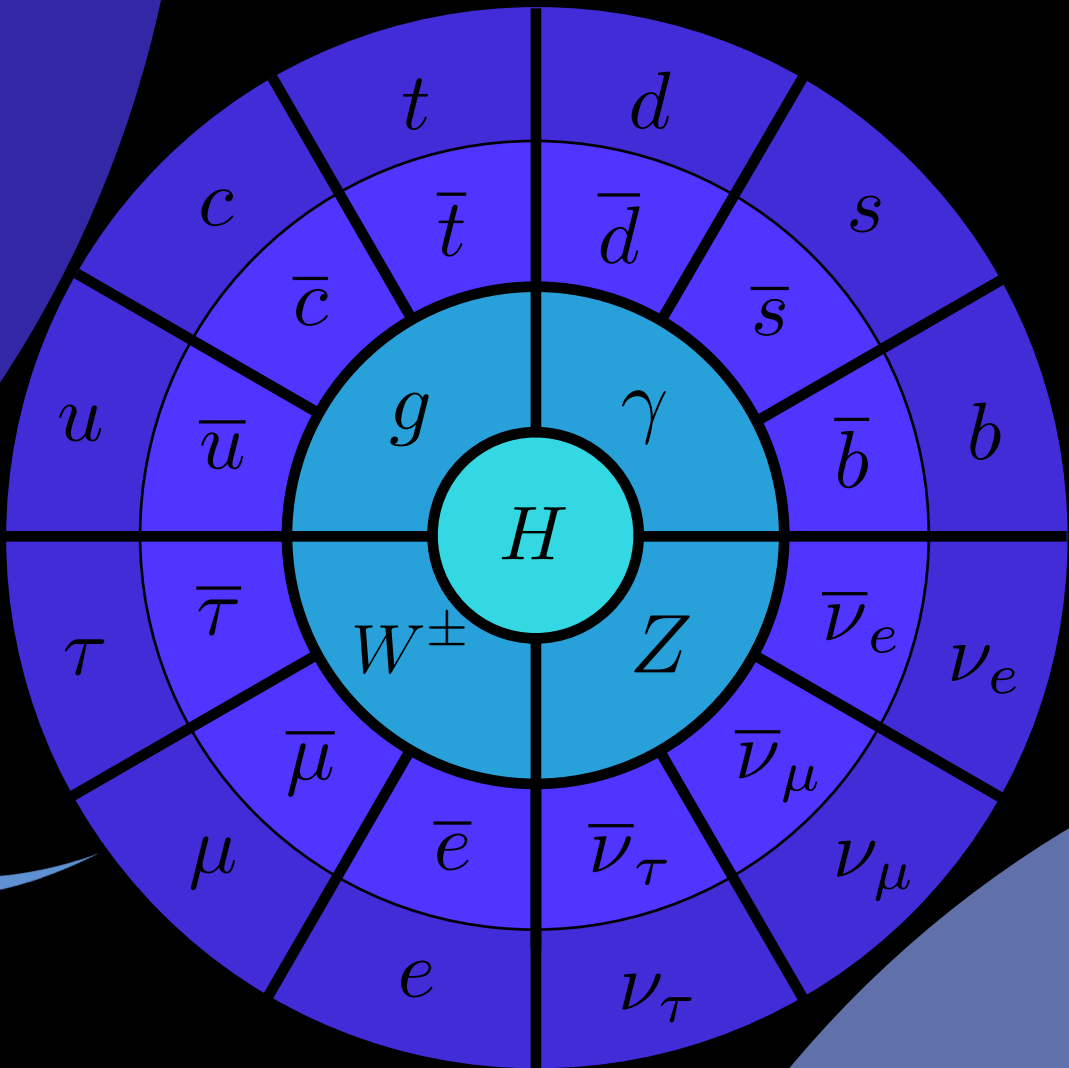
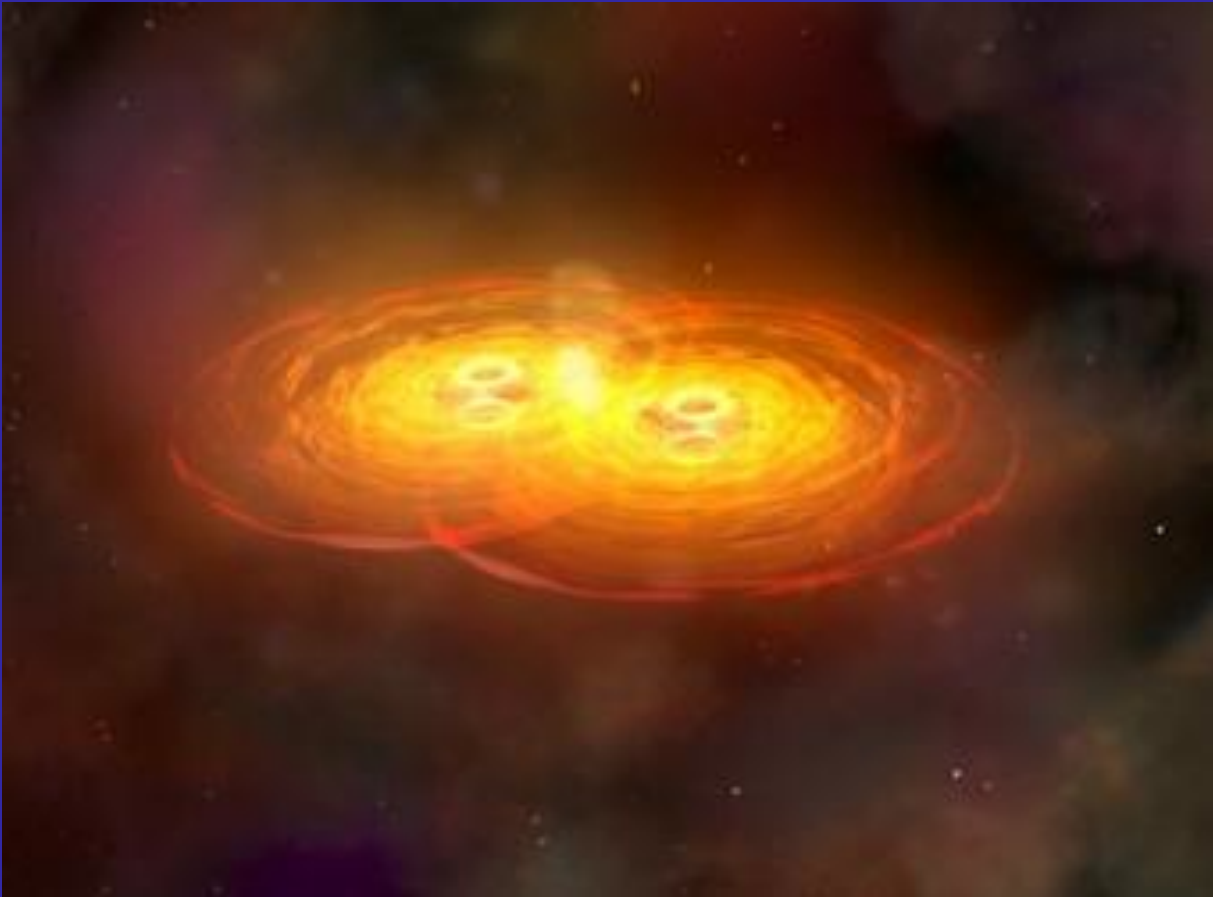
Q1) HOW DO COMPLEXITIES IN VISIBLE
UNIVERSE EMERGE FROM STANDARD MODEL?

Early universe and nucleosynthesis



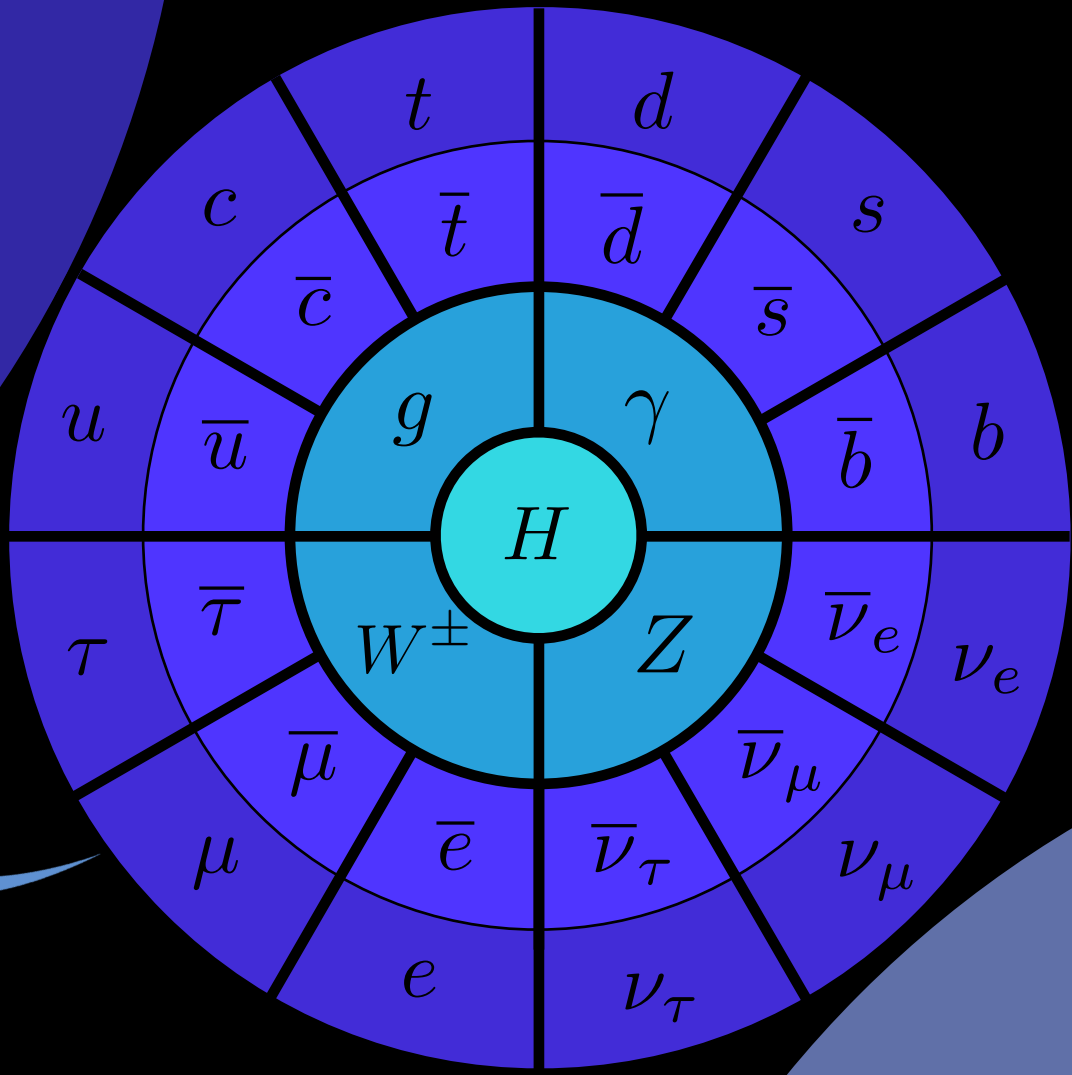
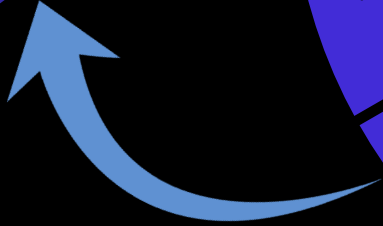
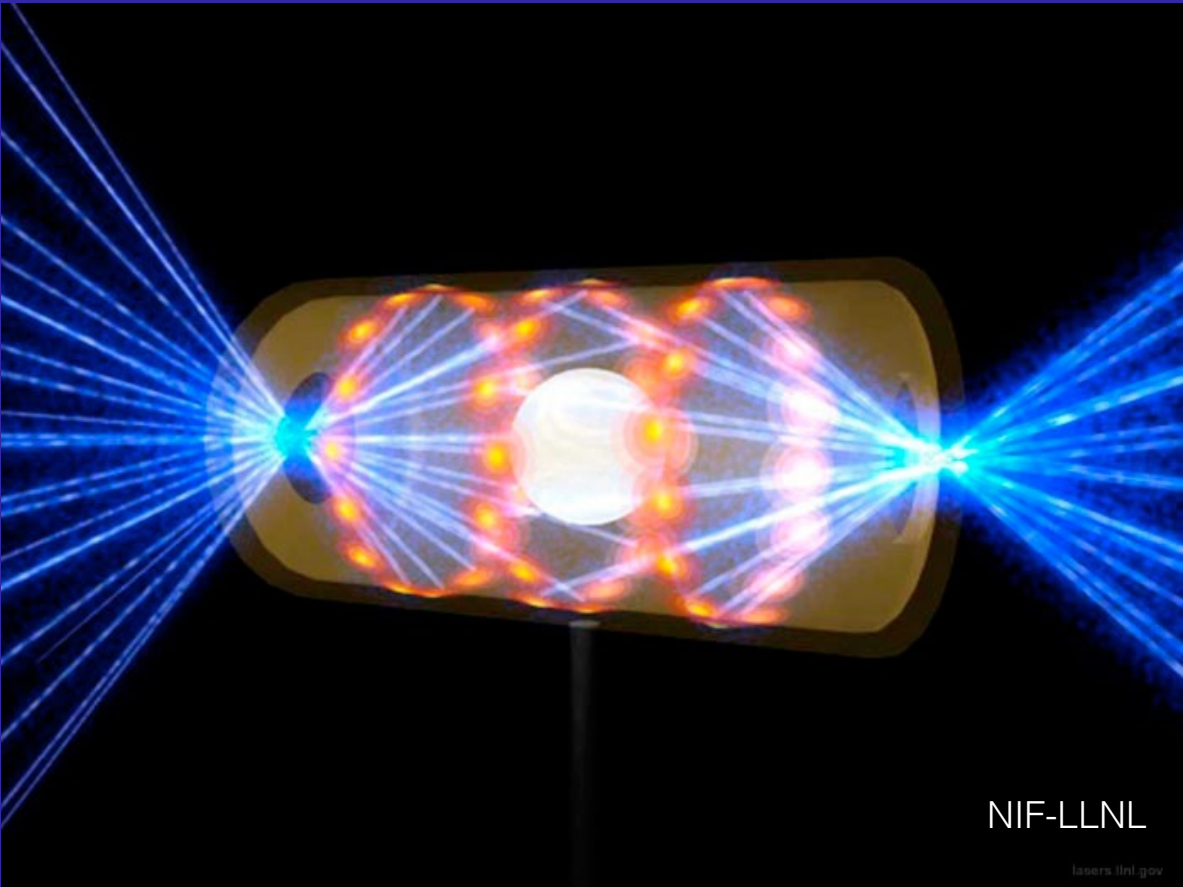
Q1) HOW DO COMPLEXITIES IN VISIBLE
UNIVERSE EMERGE FROM STANDARD MODEL?

Dense matter - neutron stars



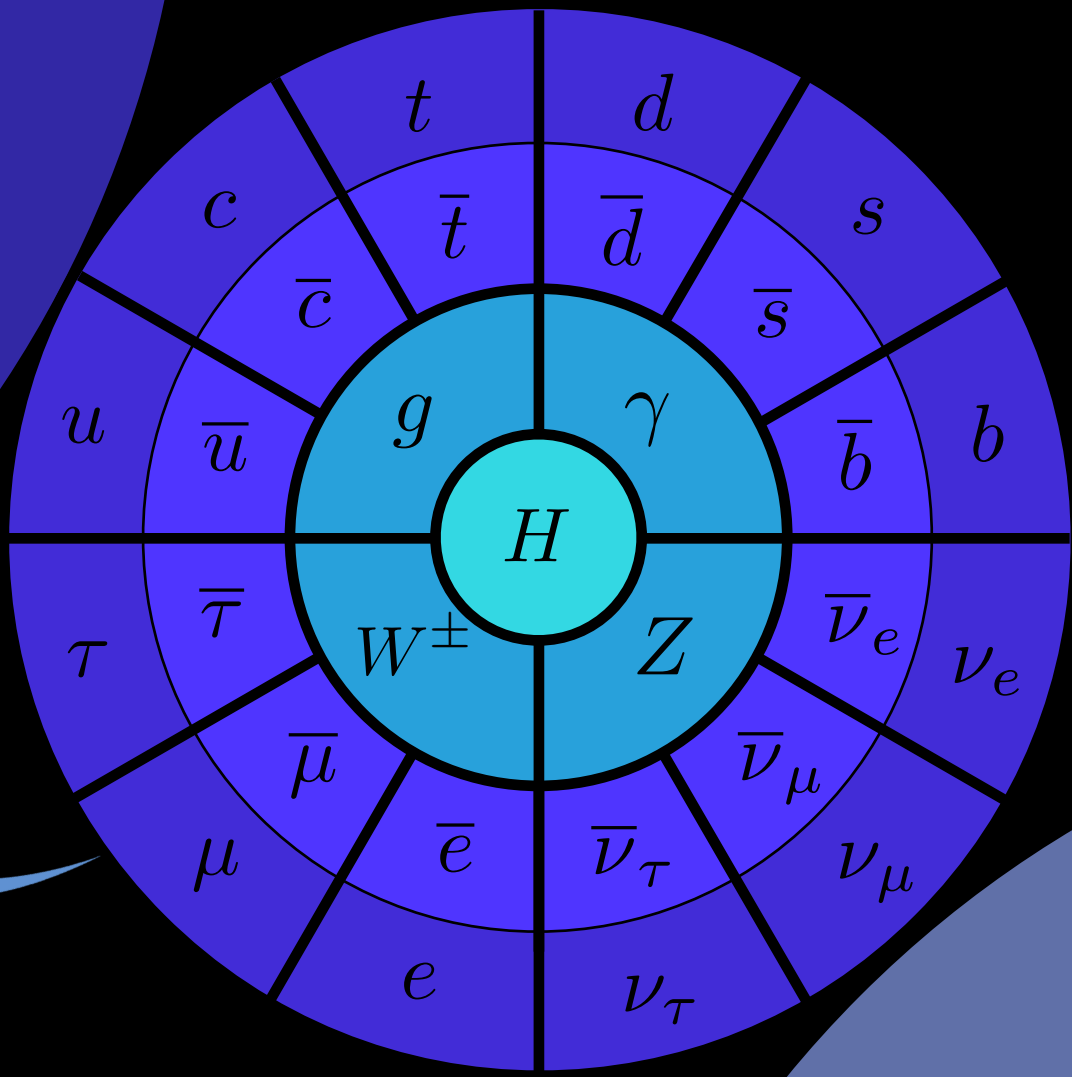
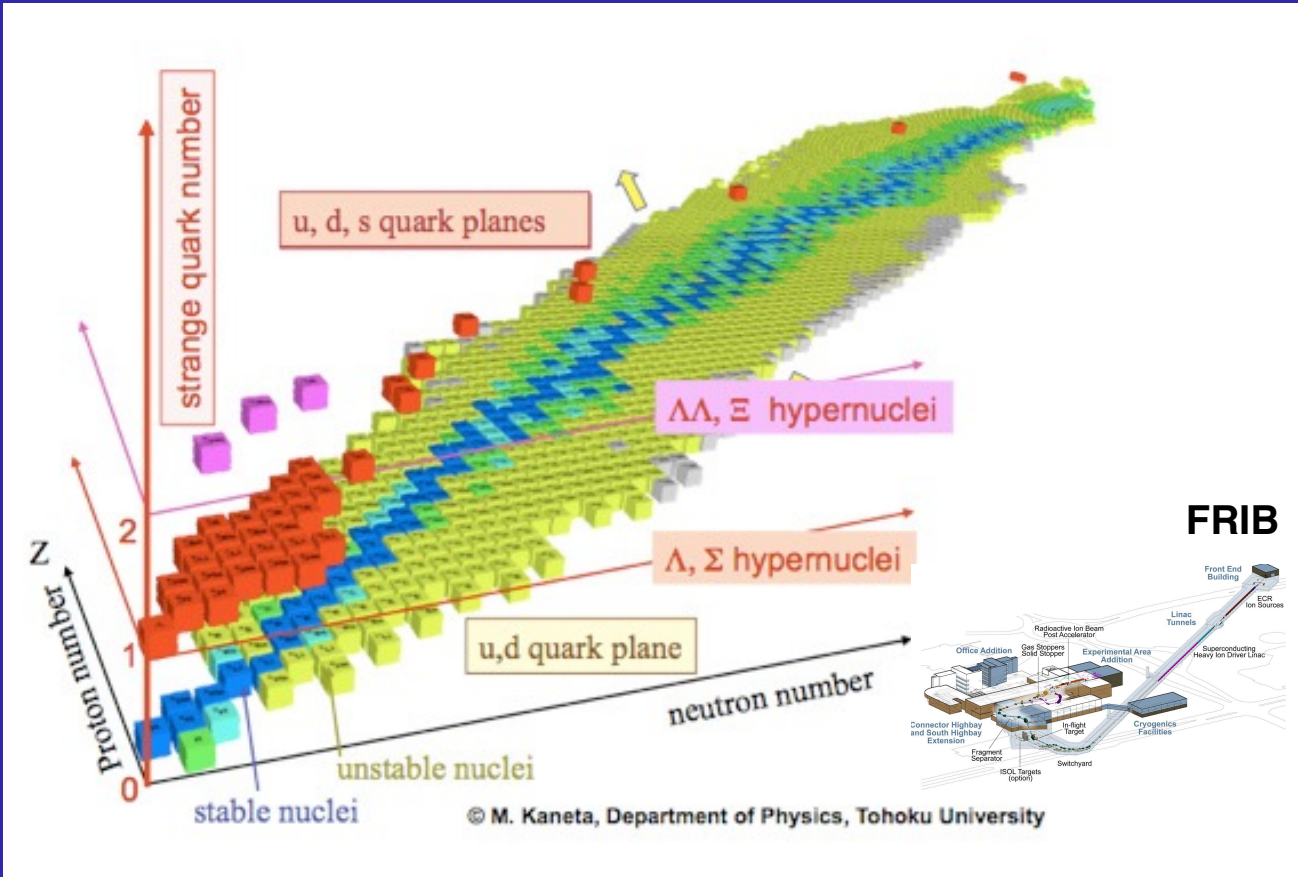
Q1) HOW DO COMPLEXITIES IN VISIBLE
UNIVERSE EMERGE FROM STANDARD MODEL?

Nuclear energy frontier



Q1) HOW DO COMPLEXITIES IN VISIBLE
UNIVERSE EMERGE FROM STANDARD MODEL?

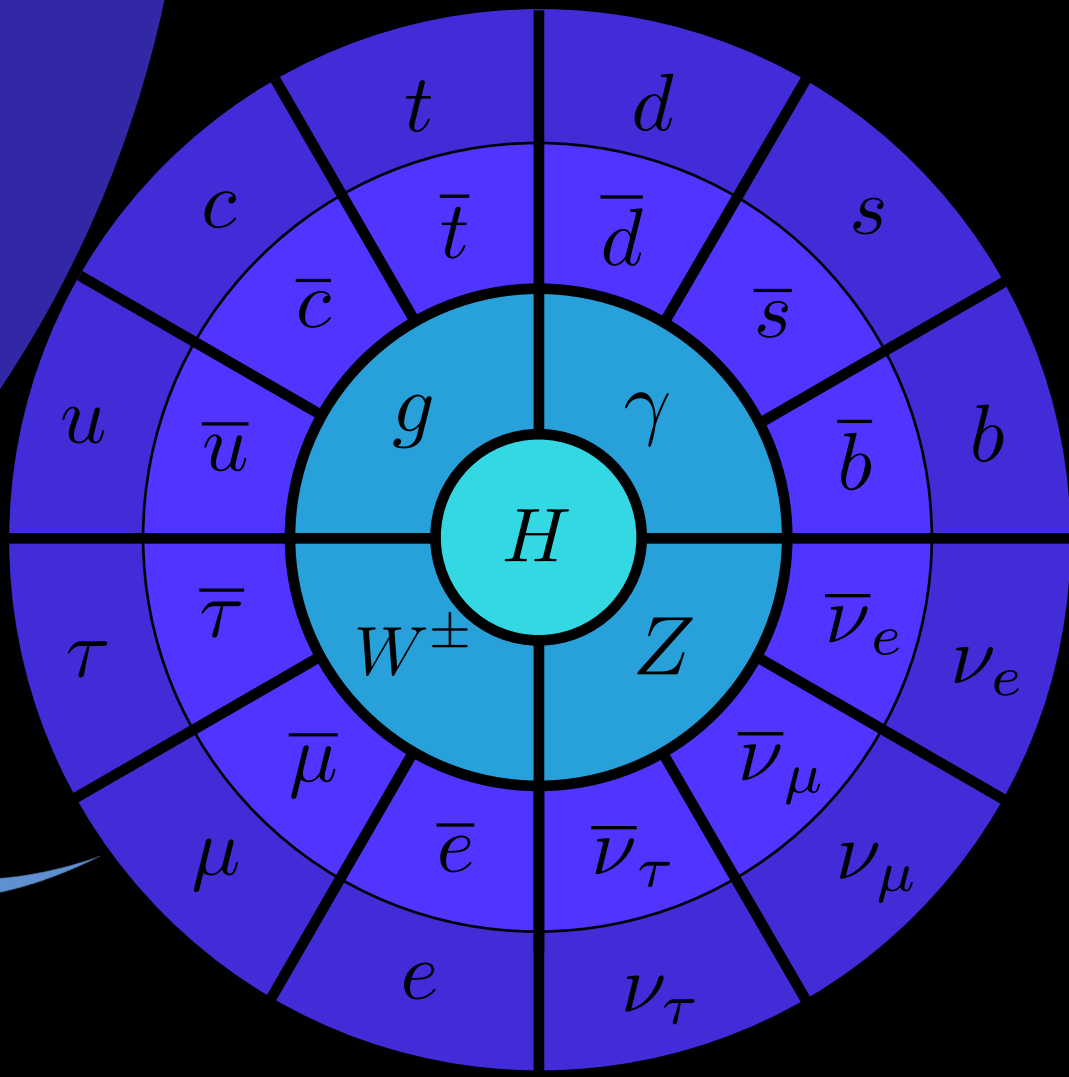
Exotic nuclei



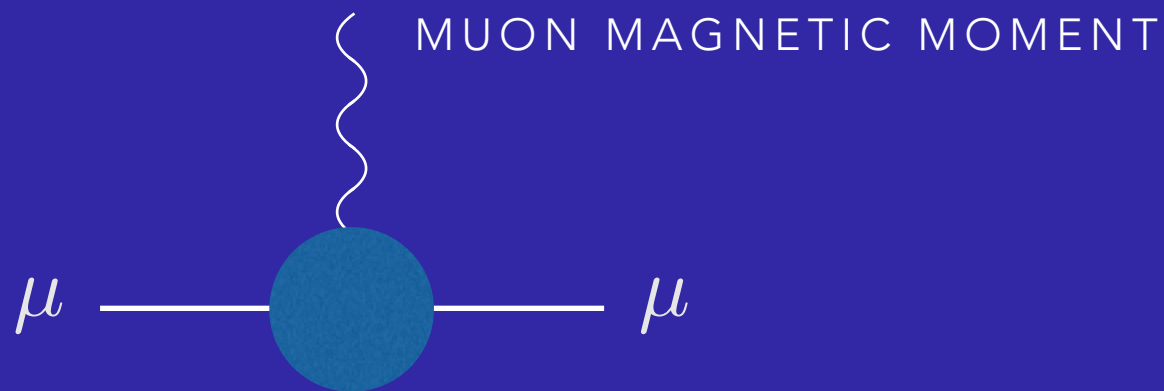
Q2) WHAT DOES IT TELL US ABOUT THE UNKNOWN PHYSICS BEYOND STANDARD MODEL?

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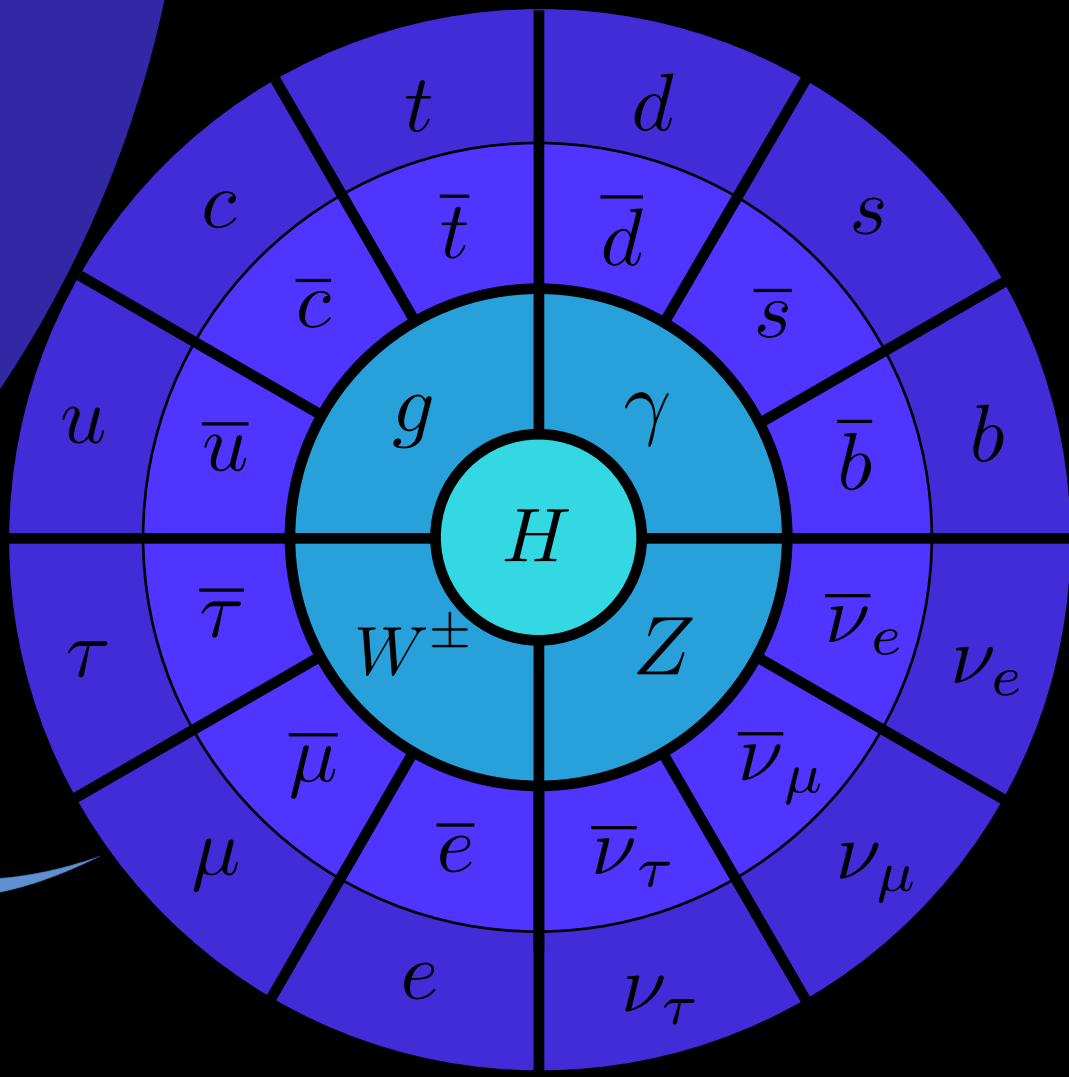


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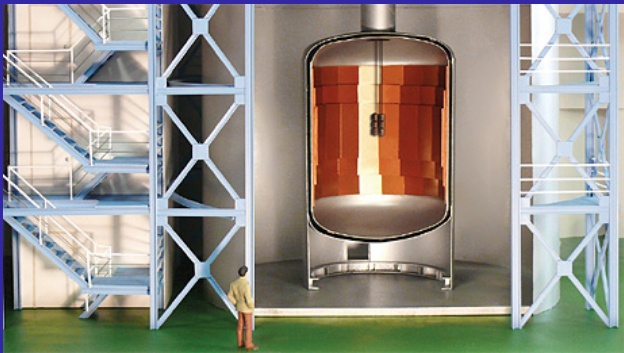
FERMILAB

?



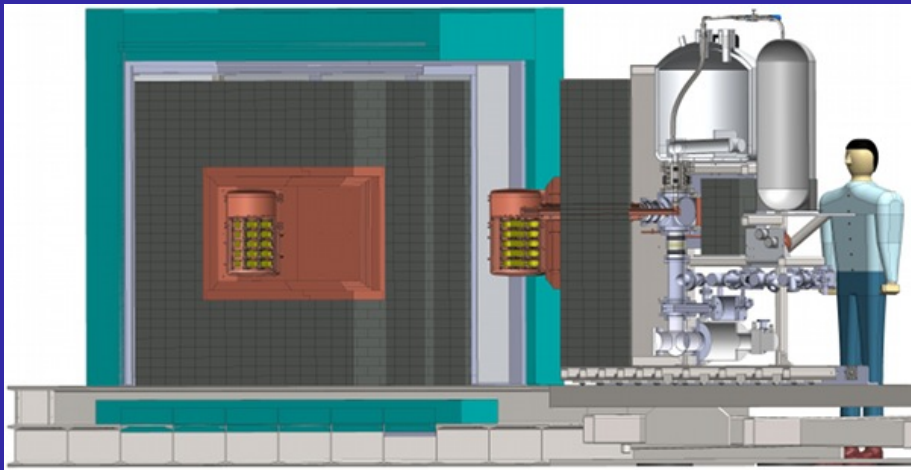
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GERDA

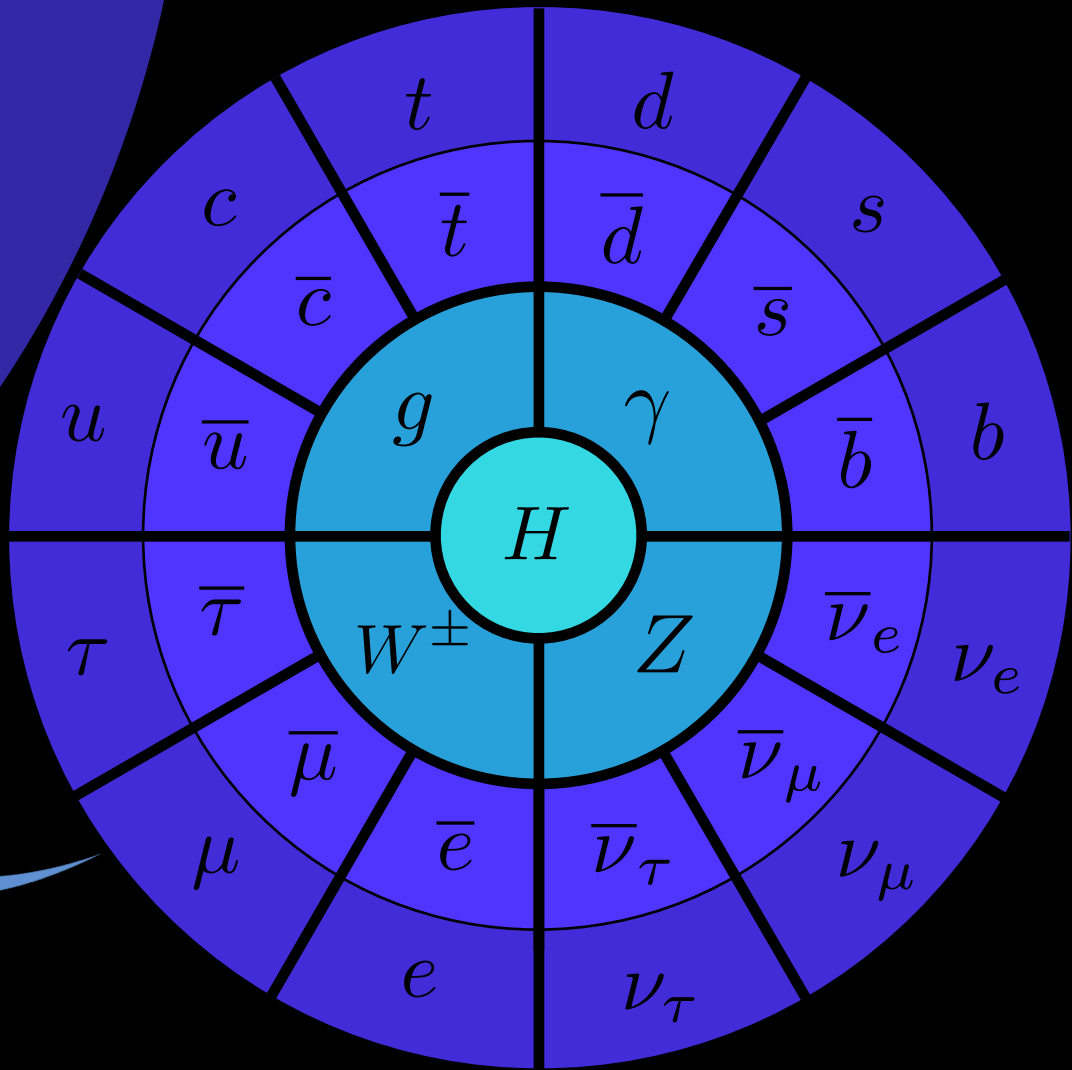


^{76}Ge

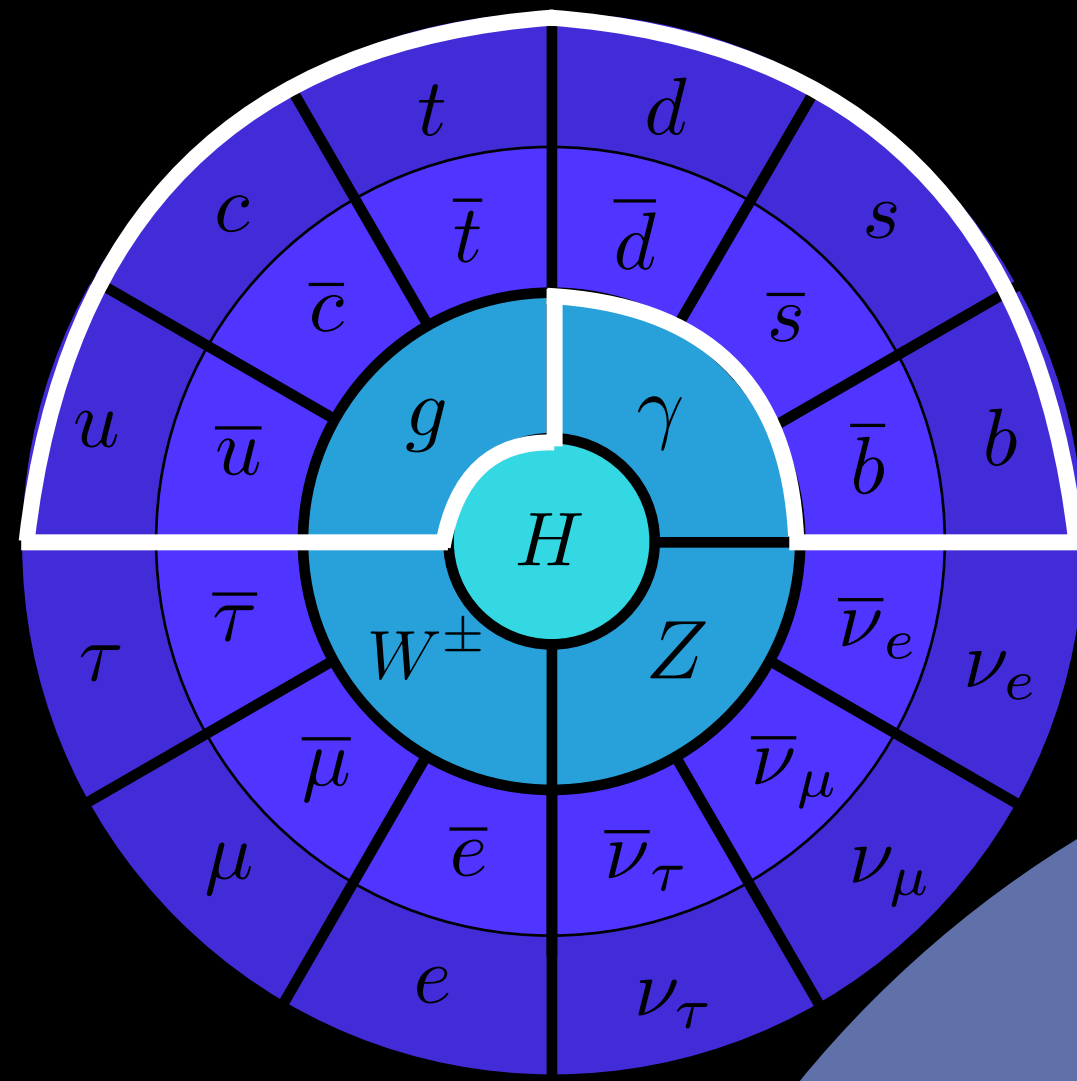
MAJORANA



?



QUANTUM CHROMODYNAMICS



NON-PERTURBATIVE PHENOMENA
IN THE STRONG SECTOR

TO BEST ANSWER THE QUESTION OF THIS TALK:

I WILL PRESENT AN EXAMPLE OF HOW LATTICE QCD AND EFFECTIVE FIELD THEORY
COME TOGETHER TO ADDRESS A NUCLEAR PHYSICS PROBLEM WITH GREAT
PHENOMENOLOGICAL IMPORTANCE



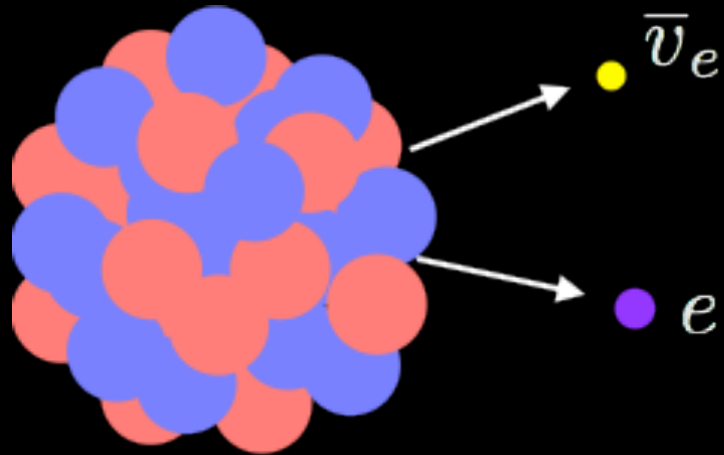
NEUTRINOLESS DOUBLE-BETA DECAY

- IS LEPTON NUMBER CONSERVED?
- WHAT IS THE NATURE OF NEUTRINO MASS?
- WHAT NEW PHYSICS BEYOND SM IS SIGNIFIED BY THE OBSERVATION OF A LEPTON-NUMBER VIOLATING PROCESS?

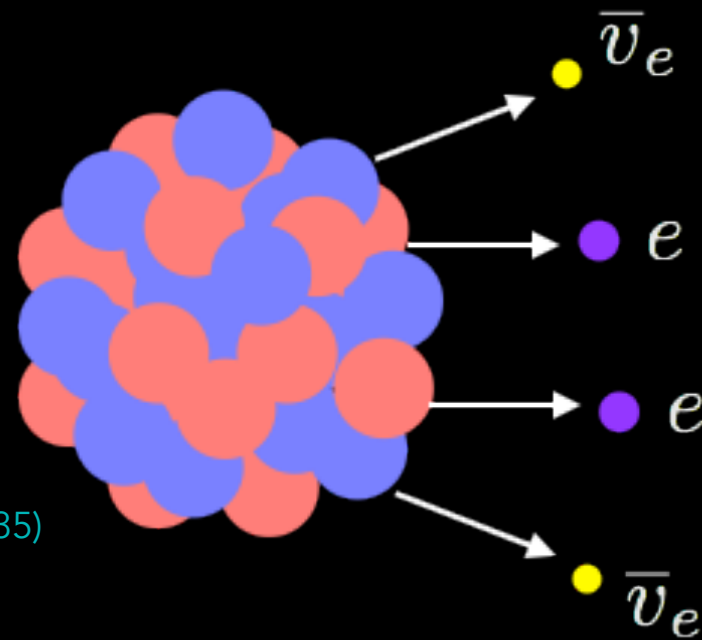
INITIAL STEPS...

- 1) Single-beta decay from lattice QCD: NPLQCD collaboration, arXiv:1610.04545 [hep-lat].
- 2) Double-beta decay from lattice QCD: NPLQCD collaboration, arXiv:1701.03456 [hep-lat].
- 3) Double-beta decay from lattice QCD (more details): NPLQCD collaboration, arXiv:1701.???? [hep-lat].
- 4) EFT for 2ν and 0ν double-beta decay: ZD and William Detmold, in preparation.

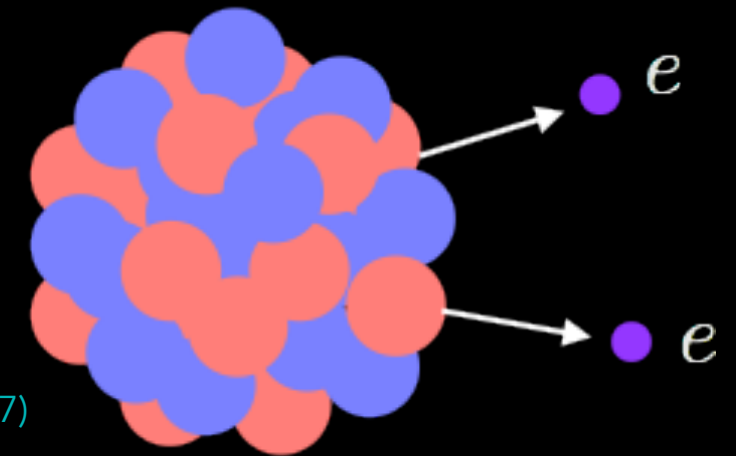
0V DOUBLE BETA DECAY AND BIG QUESTIONS



Eugene Wigner, Goeppert-Mayer (1935)

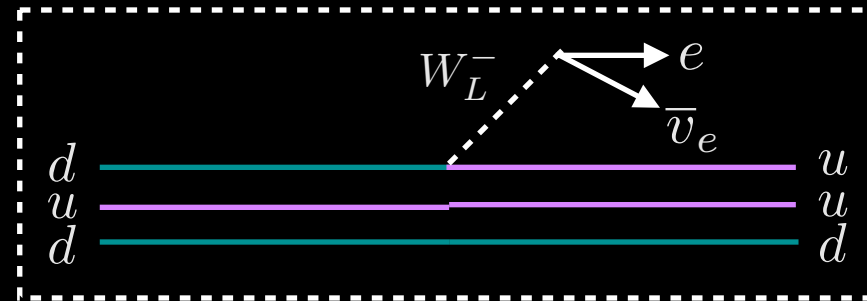


Giulio Racah (1937)
Furry (1939)
Primakoff (1952)

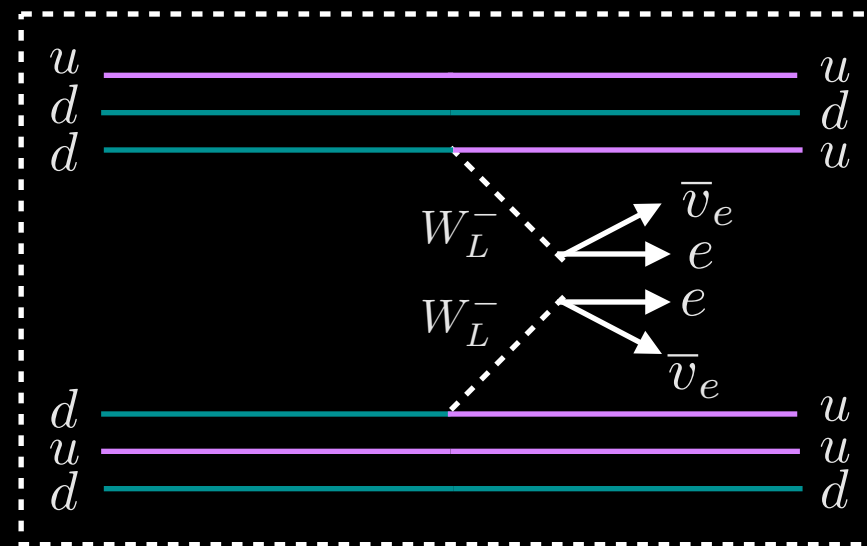


0V DOUBLE BETA DECAY AS A PROBE OF NEW PHYSICS

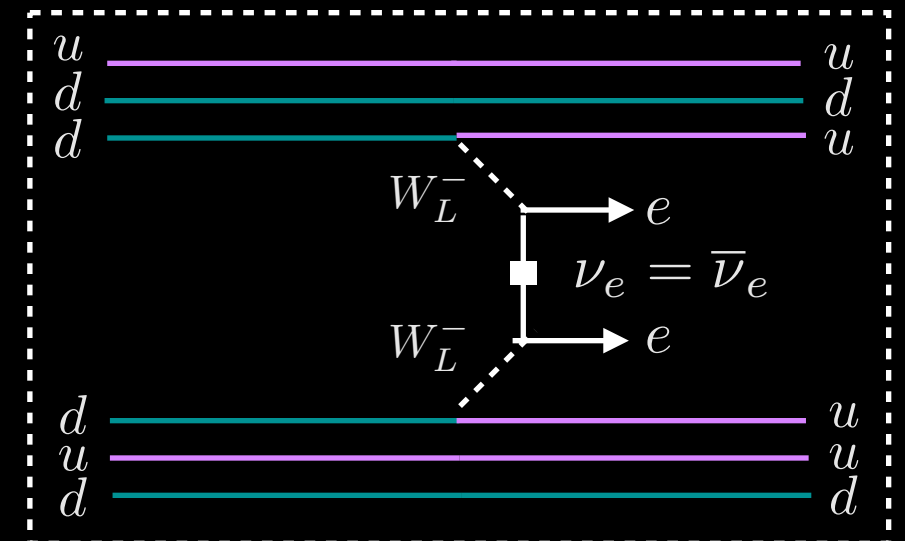
BETA DECAY:



DOUBLE-BETA DECAY:



NEUTRINOLESS DOUBLE-BETA DECAY:

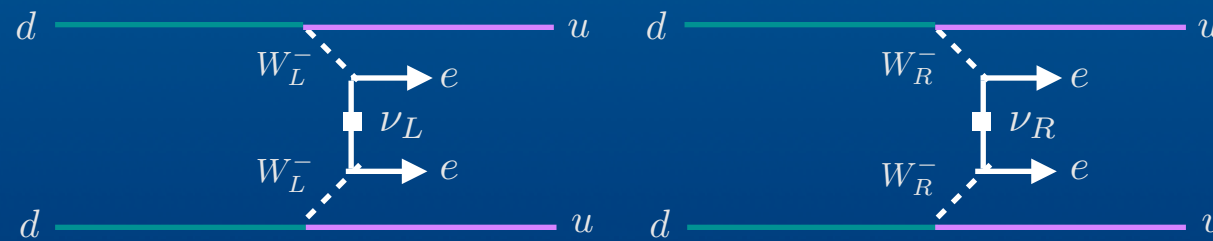


HOW TO CONNECT AN OBSERVED RATE IN
NUCLEI TO THE FUNDAMENTAL THEORY?

BOTTOM-UP APPROACH: MATCHING THE HIGH SCALE TO LOW SCALE

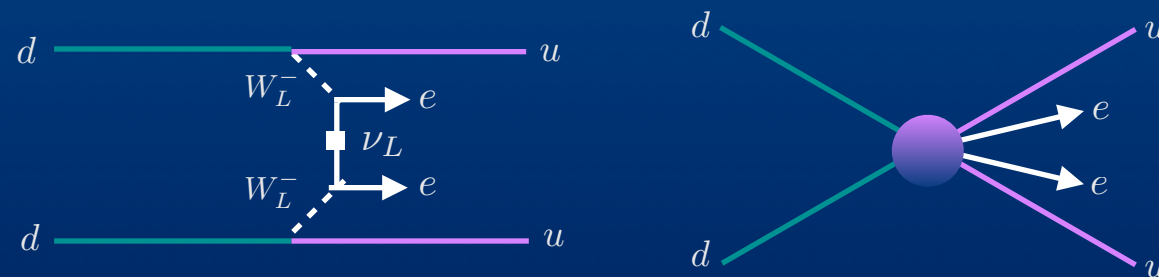
$\Lambda > \text{TeV}$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



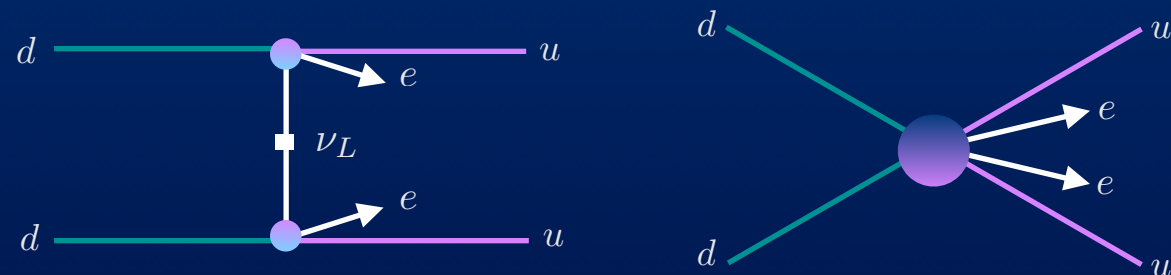
$\Lambda \sim 10^2 \text{ GeV}$

RUN IT DOWN TO BELOW THE EW SYMMETRY BREAKING SCALE:



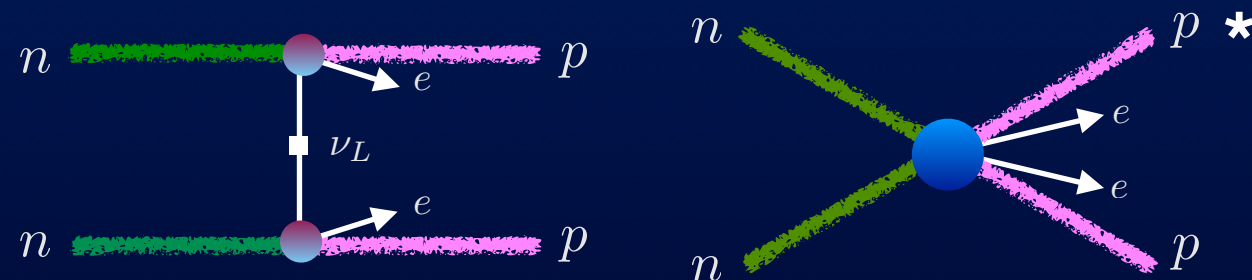
$\Lambda \sim 2 \text{ GeV}$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



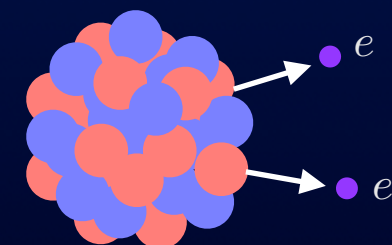
$\Lambda < \text{GeV}$

RUN IT DOWN TO THE HADRONIC SCALE:



$\Lambda < \text{MeV}$

PERFORM A NUCLEAR MANY-BODY CALCULATION
TO MATCH IT TO NUCLEAR MATRIX ELEMENTS:



MOST PARAMETERS EXCEPT FOR FEW ALREADY PRESENT IN STANDARD MODEL

$$\Lambda > \text{TeV}$$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



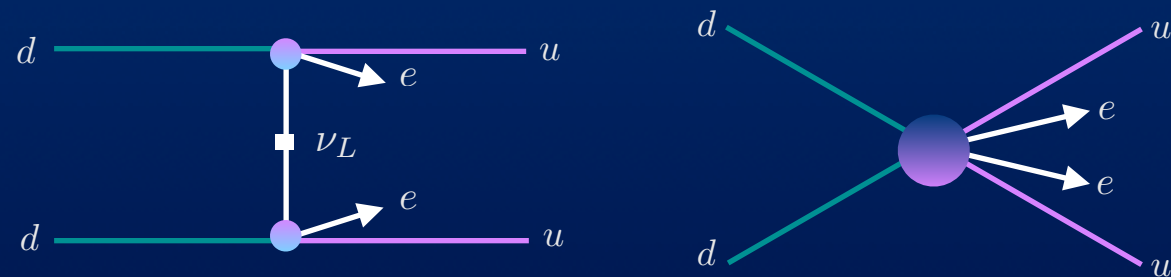
$$\Lambda \sim 10^2 \text{ GeV}$$

RUN IT DOWN TO BELOW THE EW SYMMETRY BREAKING SCALE:



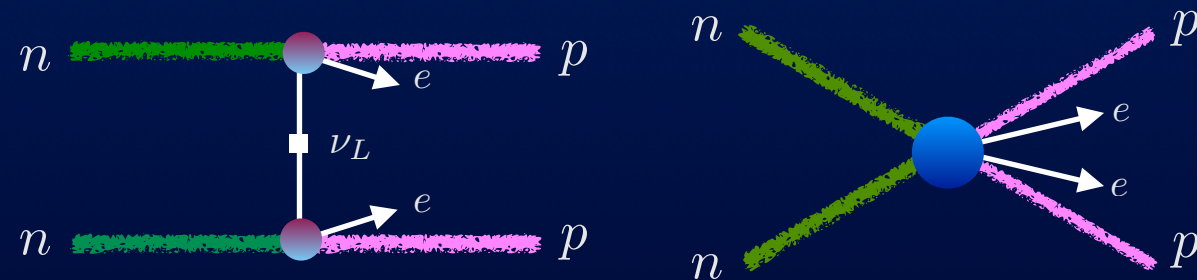
$$\Lambda \sim 2 \text{ GeV}$$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



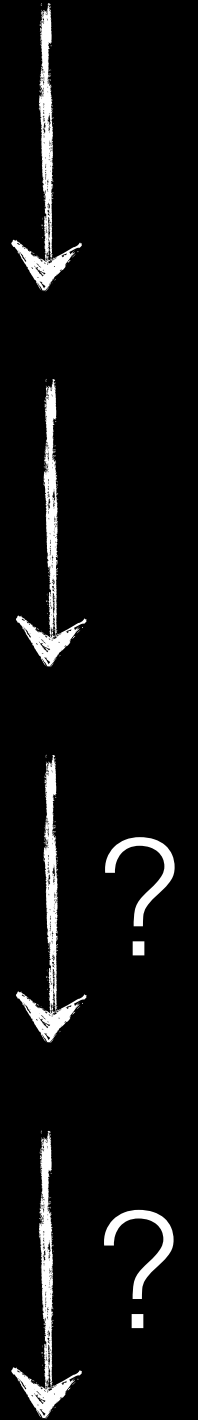
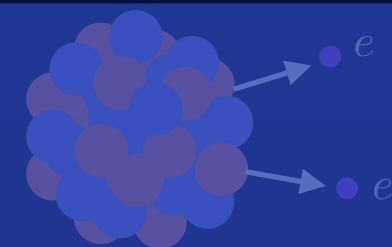
$$\Lambda < \text{GeV}$$

RUN IT DOWN TO THE HADRONIC SCALE:



$$\Lambda < \text{MeV}$$

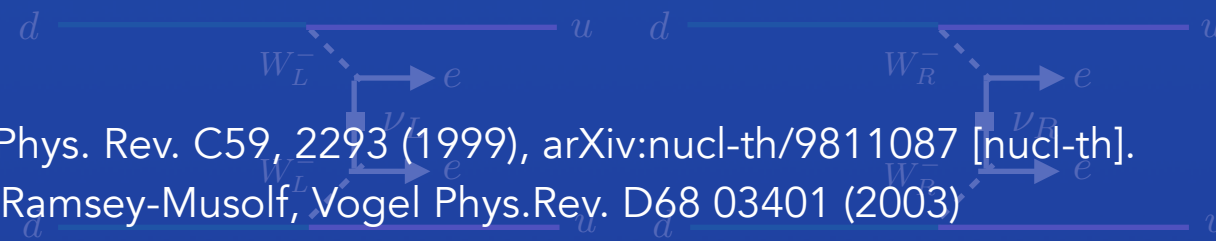
USE NUCLEAR MANY-BODY CALCULATION TO MATCH IT TO NUCLEAR MATRIX ELEMENTS:



MOST PARAMETERS EXCEPT FOR FEW ALREADY PRESENT IN STANDARD MODEL

$$\Lambda > \text{TeV}$$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



Savage, Phys. Rev. C59, 2293 (1999), arXiv:nucl-th/9811087 [nucl-th].

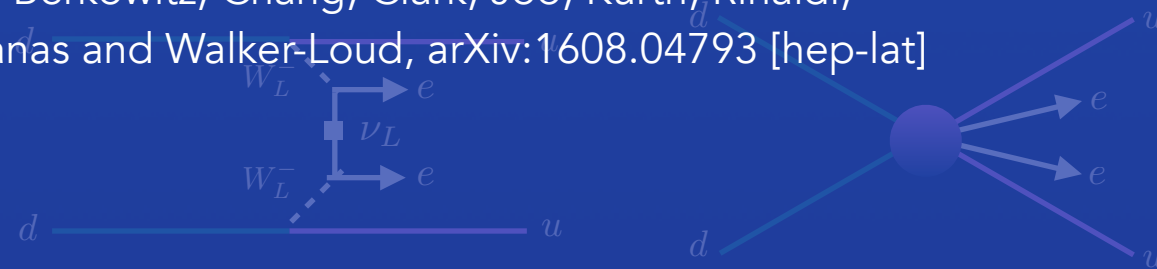
Prezeau, Ramsey-Musolf, Vogel Phys.Rev. D68 03401 (2003)

Cirigliano, Dekens, Graesser and Mereghetti, arXiv:1701.01443 [hep-ph].

$$\Lambda \sim 10^2 \text{ GeV}$$

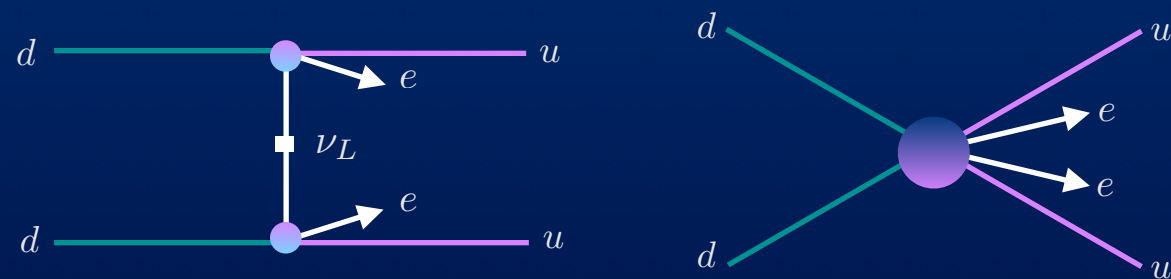
RUN IT DOWN TO BELOW THE EW SYMMETRY BREAKING SCALE:

Nicholson, Berkowitz, Chang, Clark, Joo, Kurth, Rinaldi,
Tiburzi, Vranas and Walker-Loud, arXiv:1608.04793 [hep-lat]



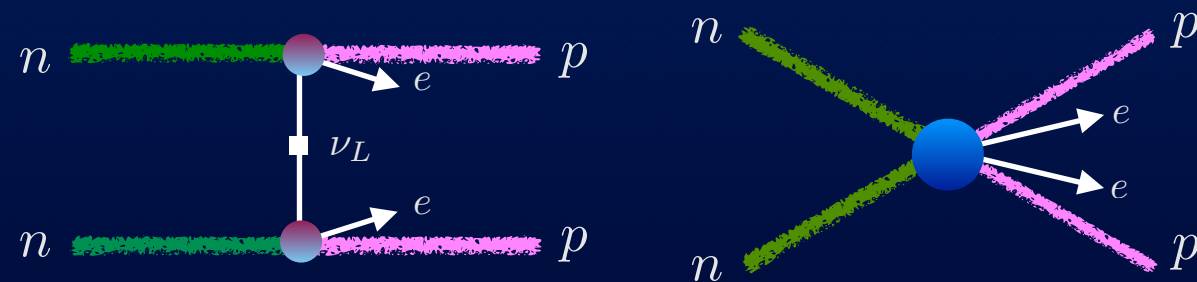
$$\Lambda \sim 2 \text{ GeV}$$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



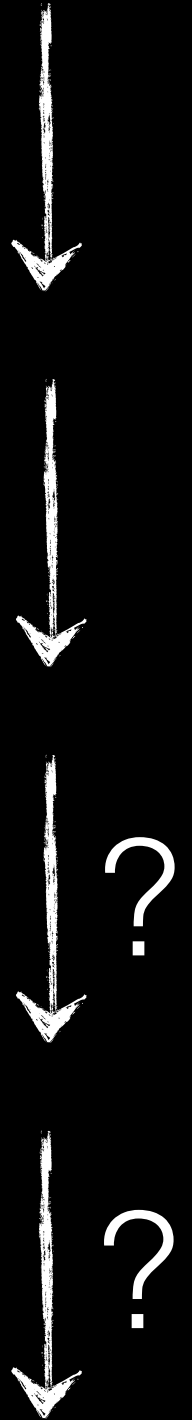
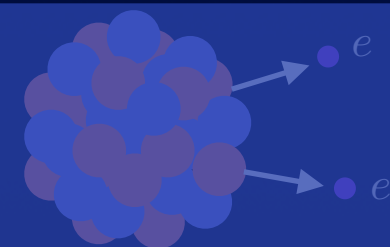
$$\Lambda < \text{GeV}$$

RUN IT DOWN TO THE HADRONIC SCALE:



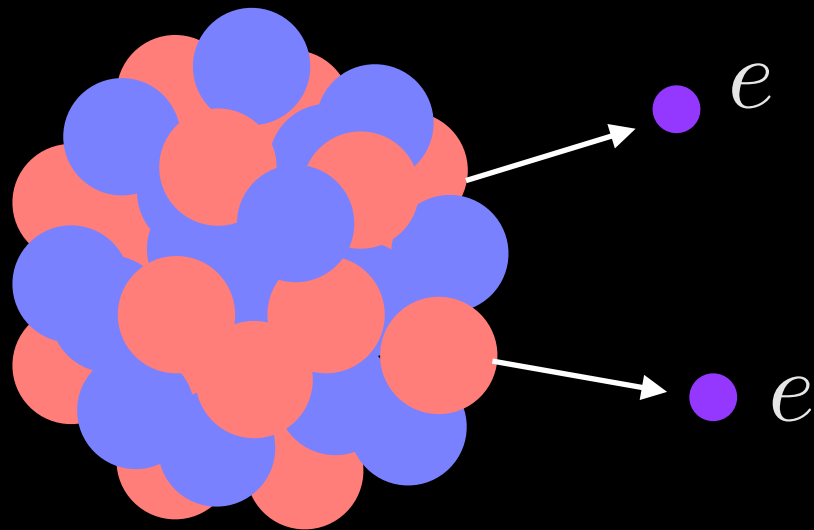
$$\Lambda < \text{MeV}$$

USE NUCLEAR MANY-BODY CALCULATION TO
MATCH IT TO NUCLEAR MATRIX ELEMENTS:

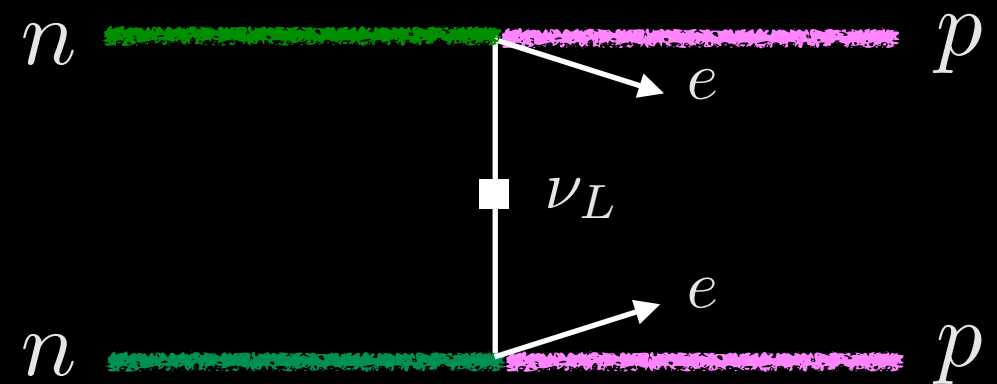


WHERE DO THE NUCLEAR UNCERTAINTIES
COME FROM? CAN WE DO BETTER?

$nn - pp$ TRANSITION FROM FIRST PRINCIPLES



MOMENTUM EXCHANGED: $q \sim 100$ MeV
THREE AND MULTI-NUCLEON EFFECTS?



BUT NATURE DOES NOT PROVIDE US WITH THE NNPP
TRANSITION RATE! HOW THEN MAY ONE DETERMINE
THE LOW-ENERGY CONSTANTS INVOLVED?

LATTICE QCD INPUT FOR THE AMPLITUDE

PACS-CS Collaboration, Yamazaki, Kuramashi and Ukawa, Phys.Rev. D81 (2010) 111504.

Yamazaki, Ishikawa, Kuramashi and Ukawa, Phys.Rev. D86 (2012) 074514.

Yamazaki, Ishikawa, Kuramashi and Ukawa, arXiv:1502.0418.

HALQCD Collaboration, Inoue et. al., Nucl. Phys. A881 (2012) 28–43.

Orginos, et al. [NPLQCD collaboration], Phys. Rev. D 92, 114512 (2015).

Berkowitz, et al. [CalLatt collaboration], arXiv:1508.00886 [hep-lat].

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THE AMPLITUDE IN EFFECTIVE FIELD THEORY

Pionless EFT for few nucleon systems:

Kaplan, Savage, and Wise, Phys. Lett., B424, 390 (1998)

Kaplan, Savage, and Wise, Nucl. Phys., B534, 329 (1998)

Chen, Rupak and Savage, Nucl. Phys. A 653, 386 (1999)

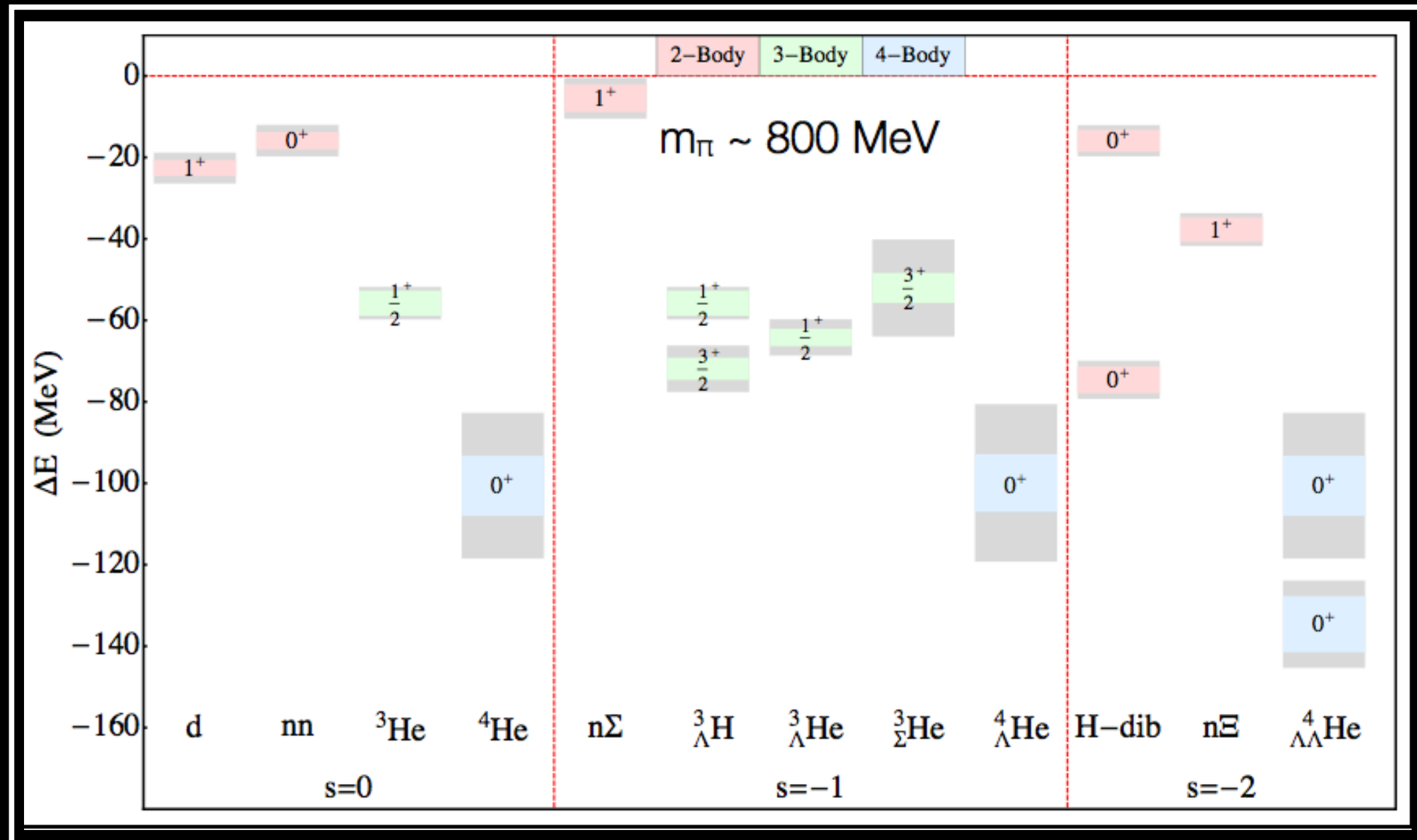
Beane, Bedaque, Savage and van Kolck, Nucl.Phys.A700 (2002)

Bedaque, Hammer and van Kolck, Phys.Rev.Lett. 82 (1999)

De-Leon, Platter and Gazit, arXiv:1611.10004 [nucl-th]. (2016)

Chiral two-body currents in nuclei: Gamow-Teller transitions and neutrinoless double-beta decay: Menéndez, Gazit and Schwenk, Phys.Rev.Lett.107:062501 (2011).

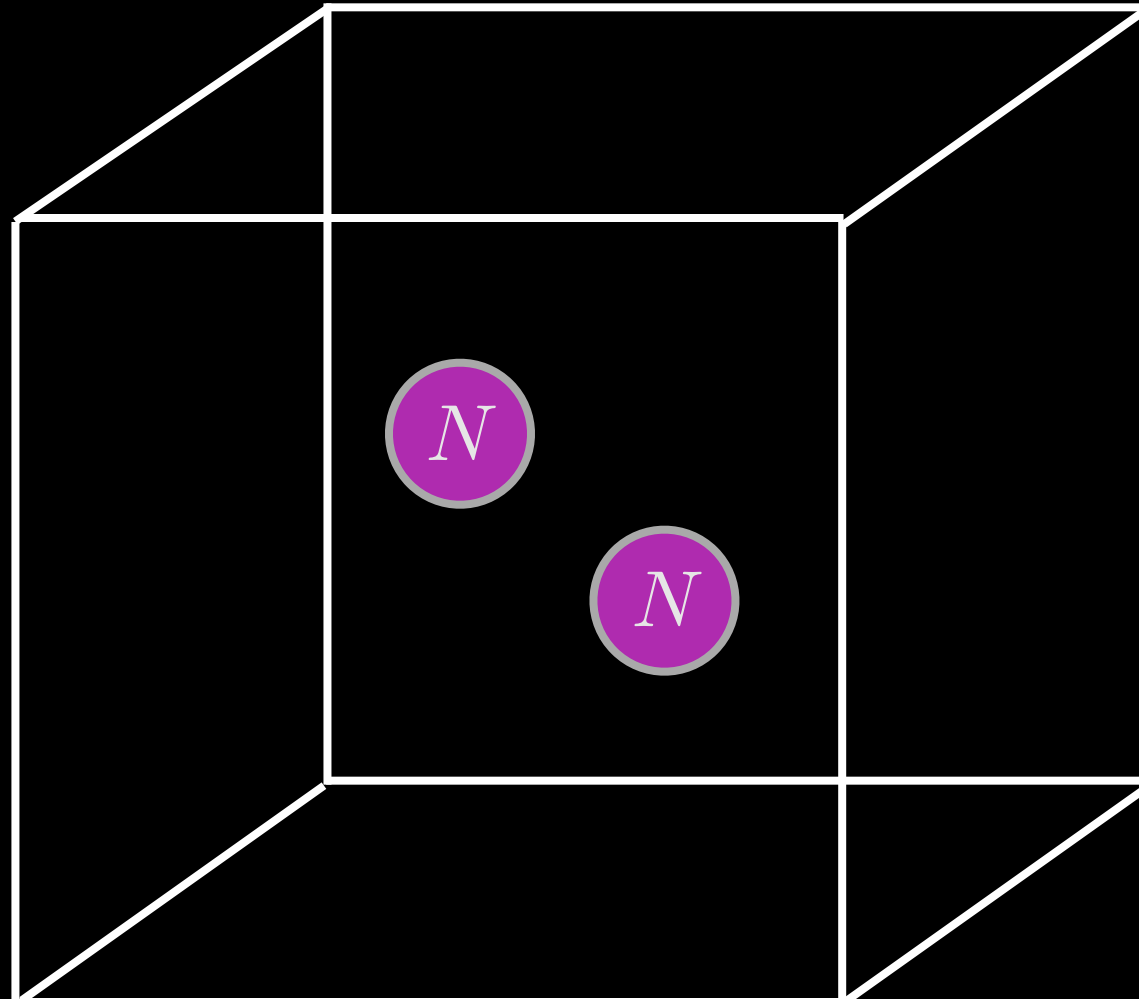
NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS



Beane, et al. (NPLQCD), Phys.Rev. D87 (2013) , Phys.Rev. C88 (2013)

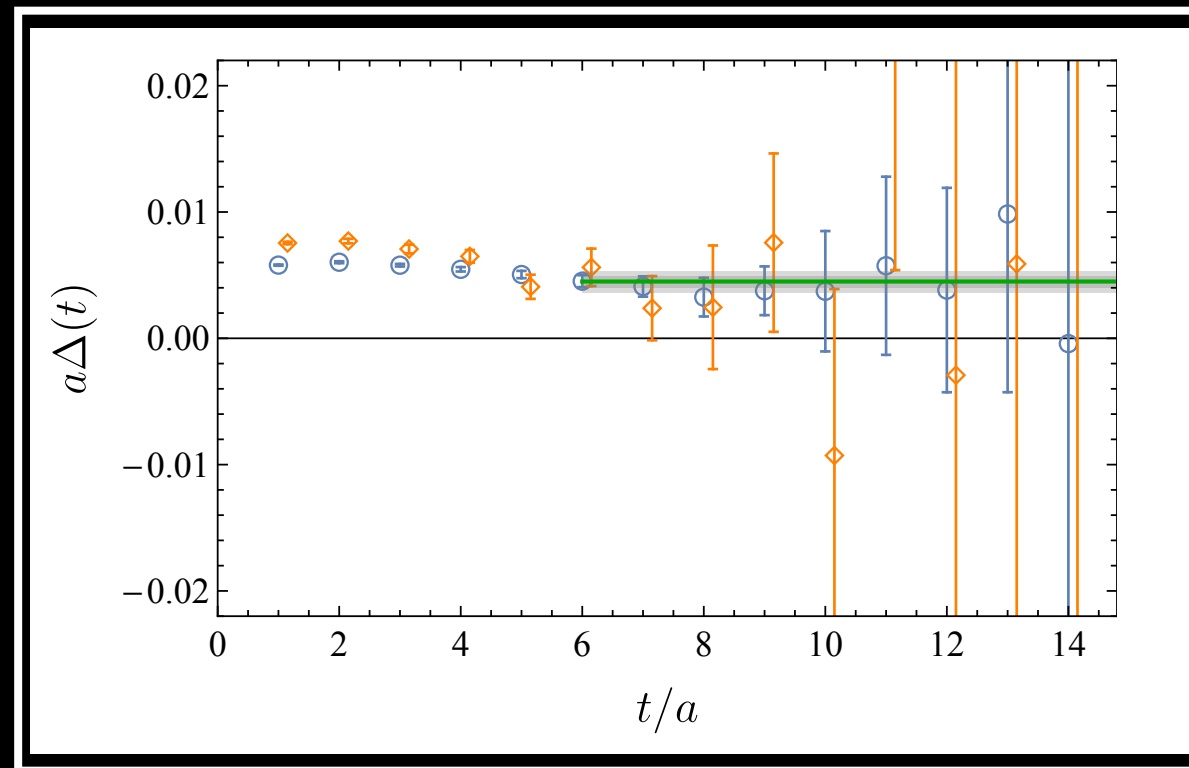
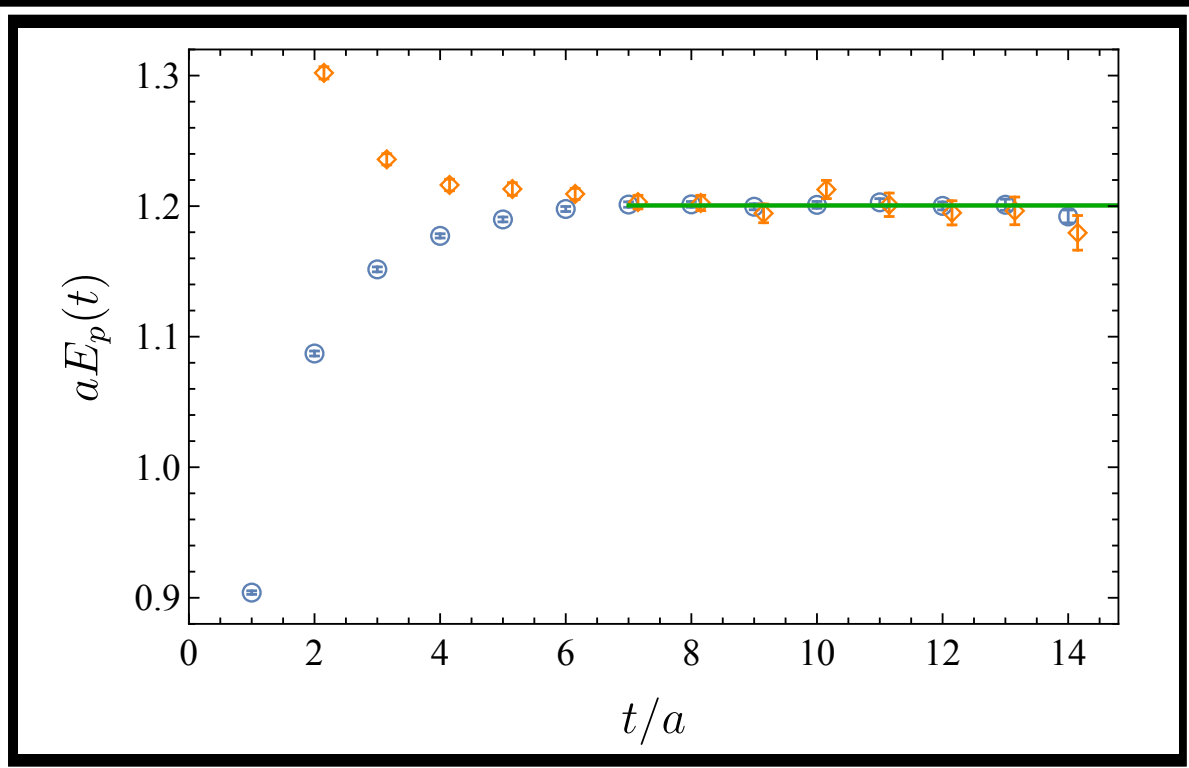
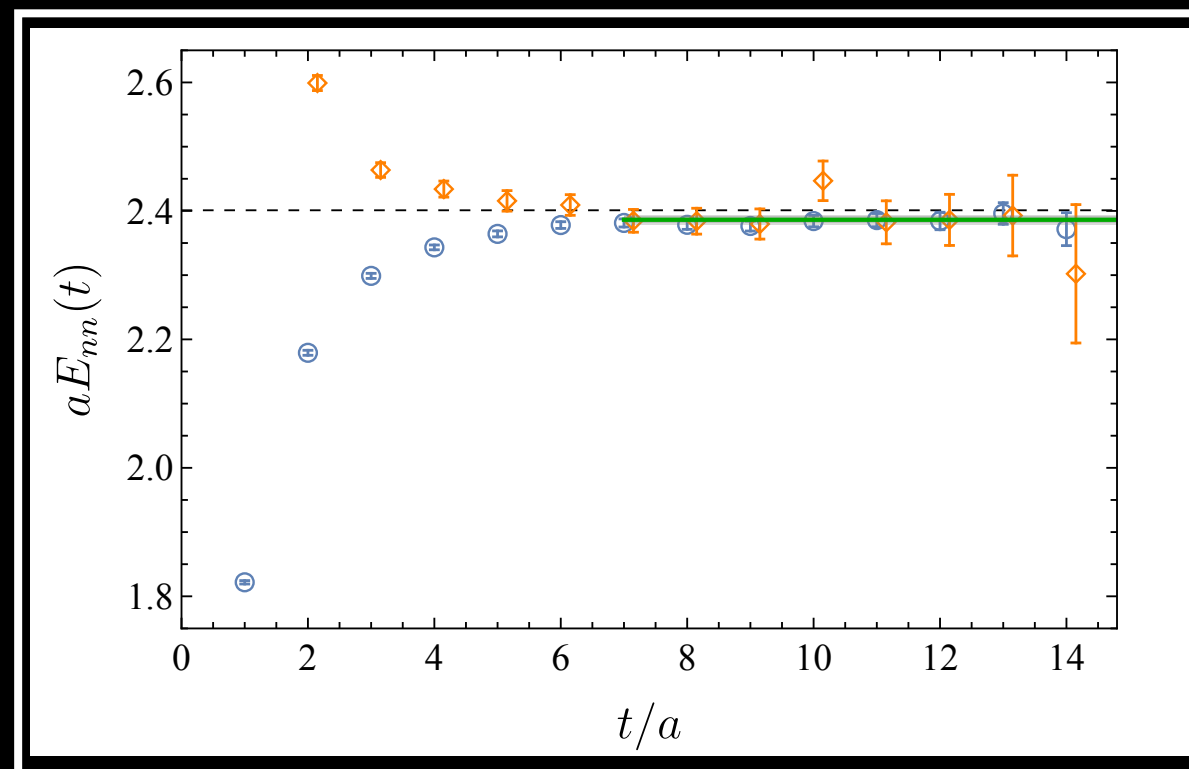
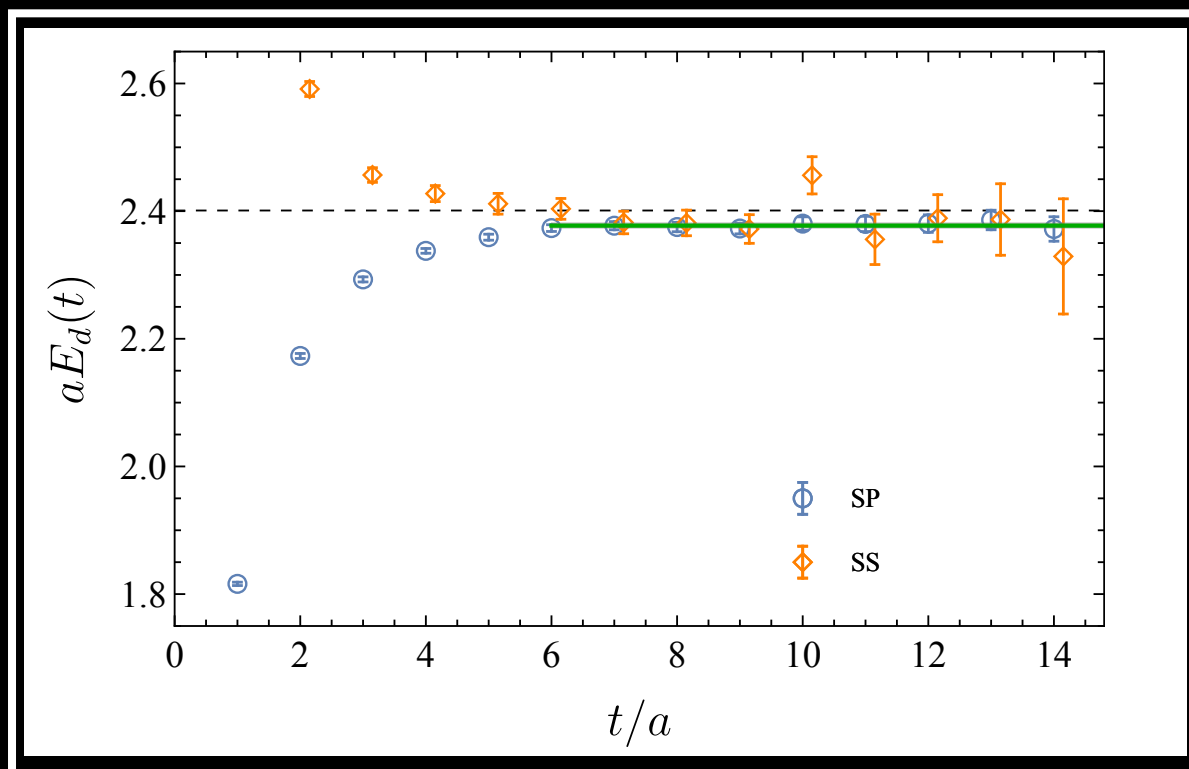
Barnea, Contessi, Gazit, Pederiva and van Kolck, Phys.Rev.Lett. 114, 052501 (2015).

NO BACKGROUND FIELD



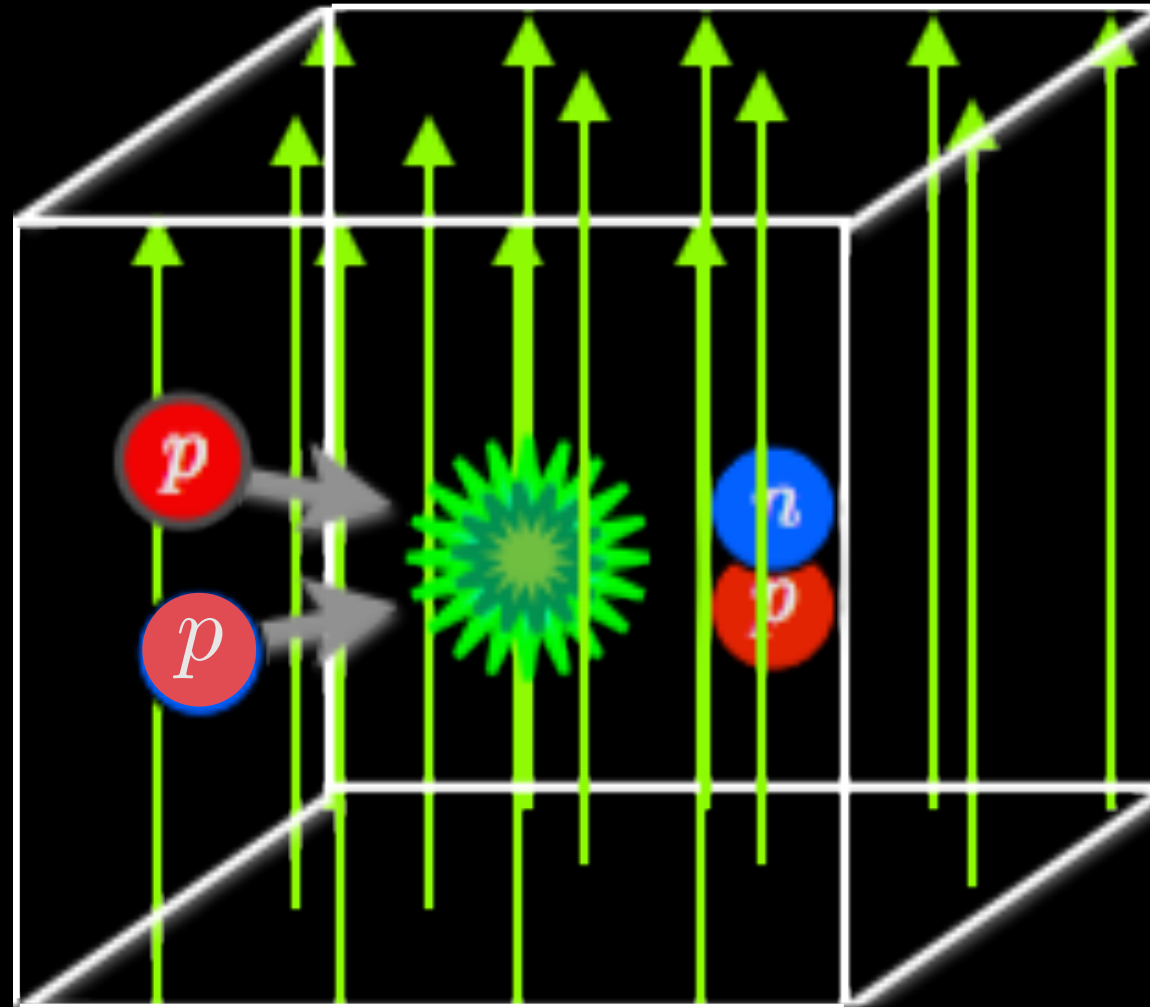
Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos, (NPLQCD collaboration), arXiv:1610.04545 [hep-latt], arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

NO BACKGROUND FIELD



Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos,
(NPLQCD collaboration), arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

FIRST-ORDER RESPONSE TO AXIAL FIELD



EQUIVALENTLY:

$$S_{\lambda_q; \Gamma}^{(q)}(x, y) = S^{(q)}(x, y) + \lambda_q \int dz S^{(q)}(x, z) \Gamma S^{(q)}(z, y)$$

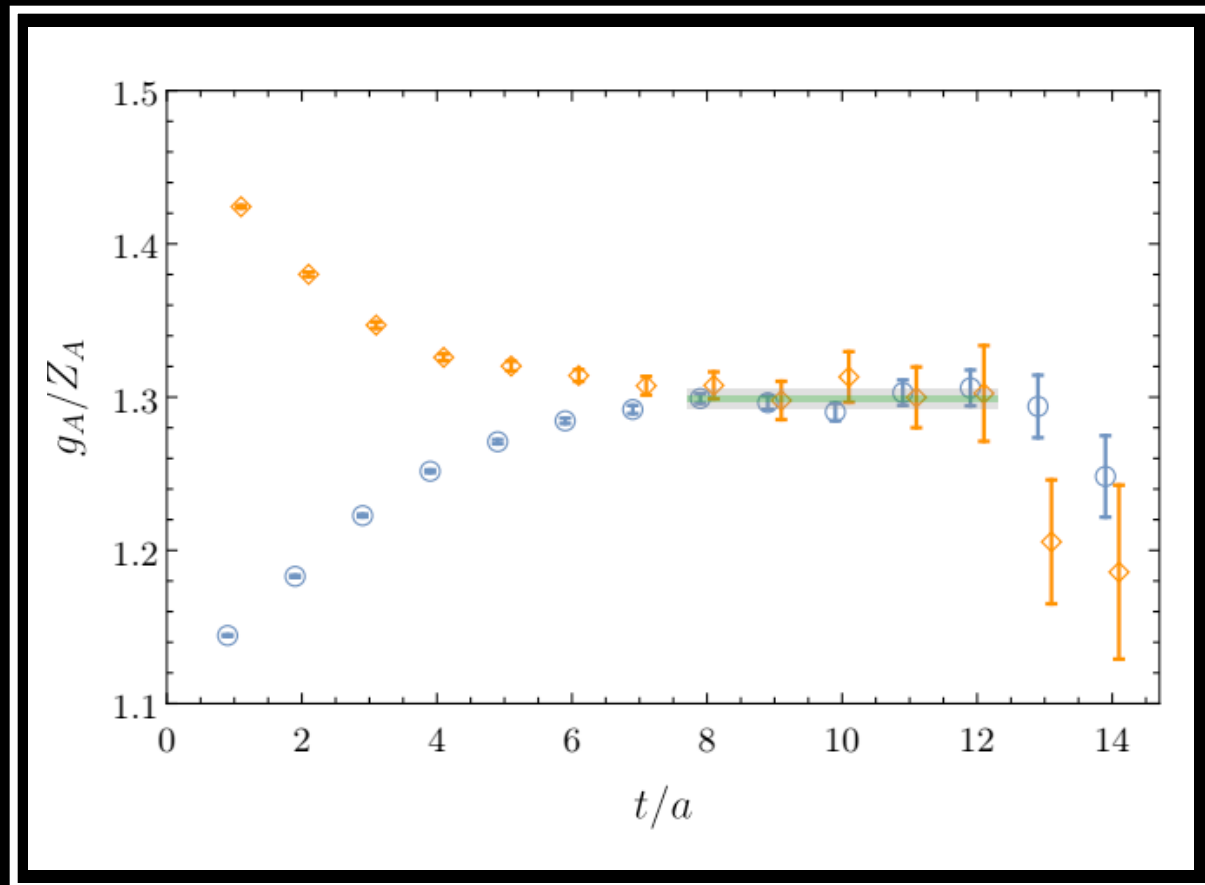
Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, Davoudi,
Detmold and Orginos, (NPLQCD collaboration), arXiv:1610.04545 [hep-latt].

Detmold and Savage, Nucl.Phys.A743, 170 (2004)
Briceno and ZD, Phys.Rev. D88, 094507 (2013)

FIRST-ORDER RESPONSE TO AXIAL FIELD

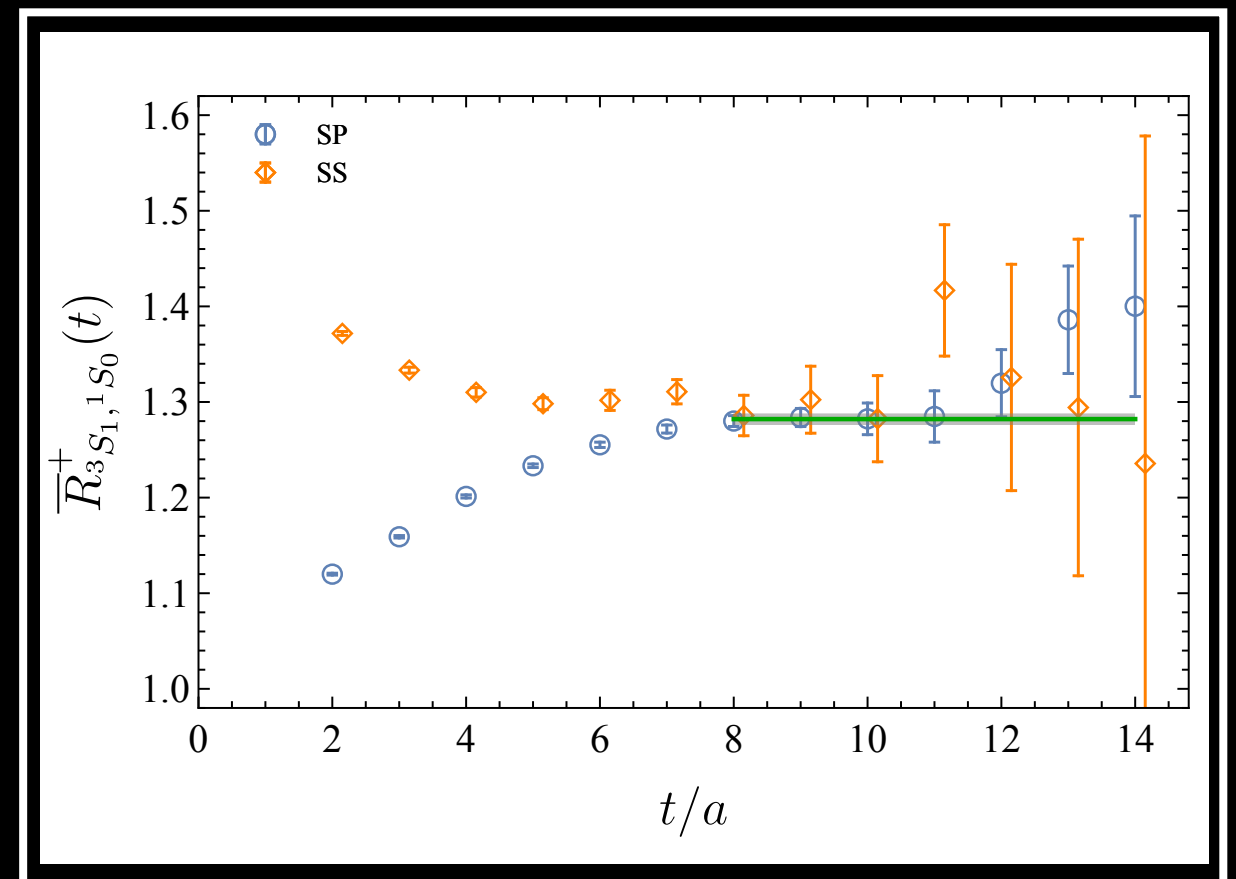
@ $m_\pi \approx 800$ MeV

$$\langle p | A_3^3 | p \rangle$$



PROTON AXIAL CHARGE

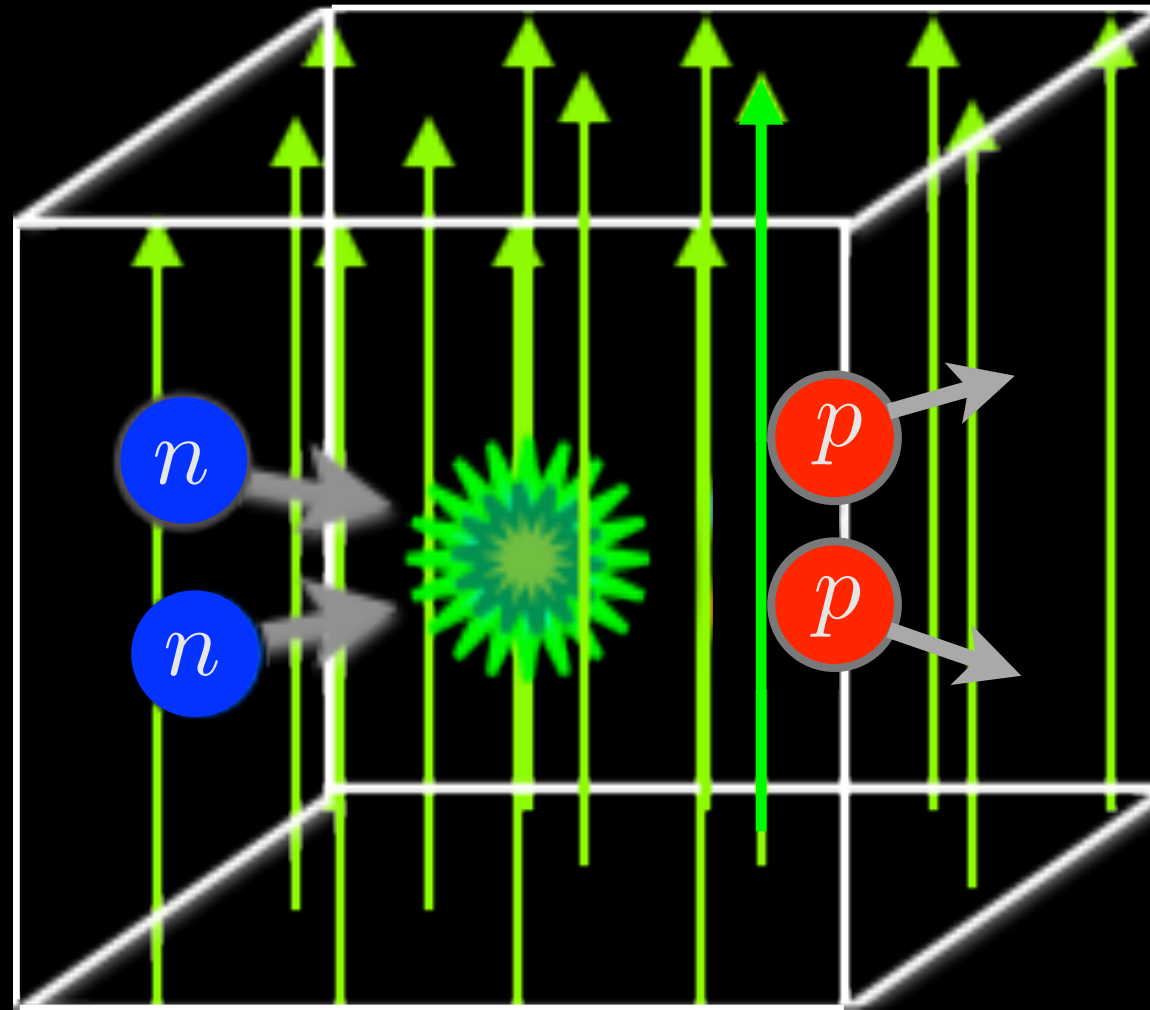
$$\langle pp | A_3^+ | d \rangle$$



PP TO DEUTERON MATRIX ELEMENT

Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos, (NPLQCD collaboration), arXiv:1610.04545 [hep-lat], arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

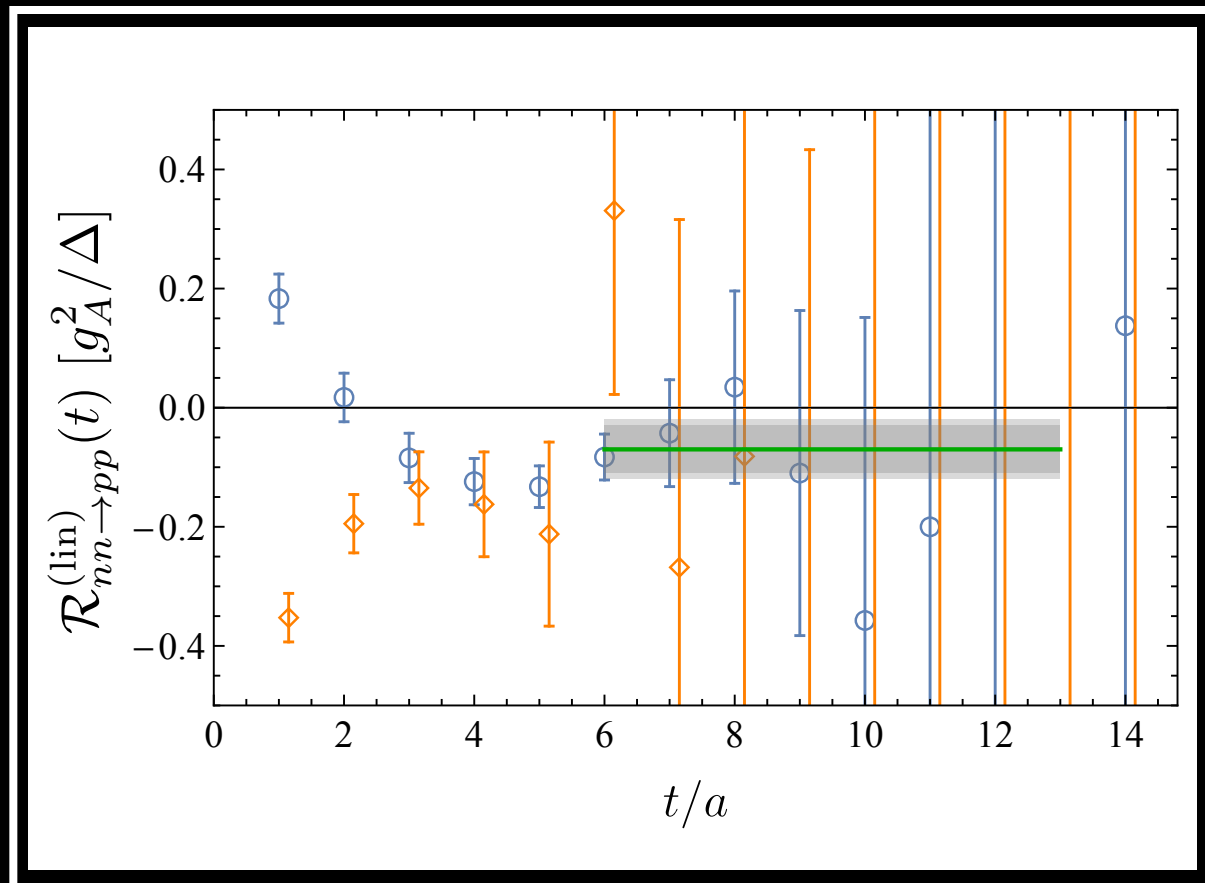
SECOND-ORDER RESPONSE TO AXIAL FIELD



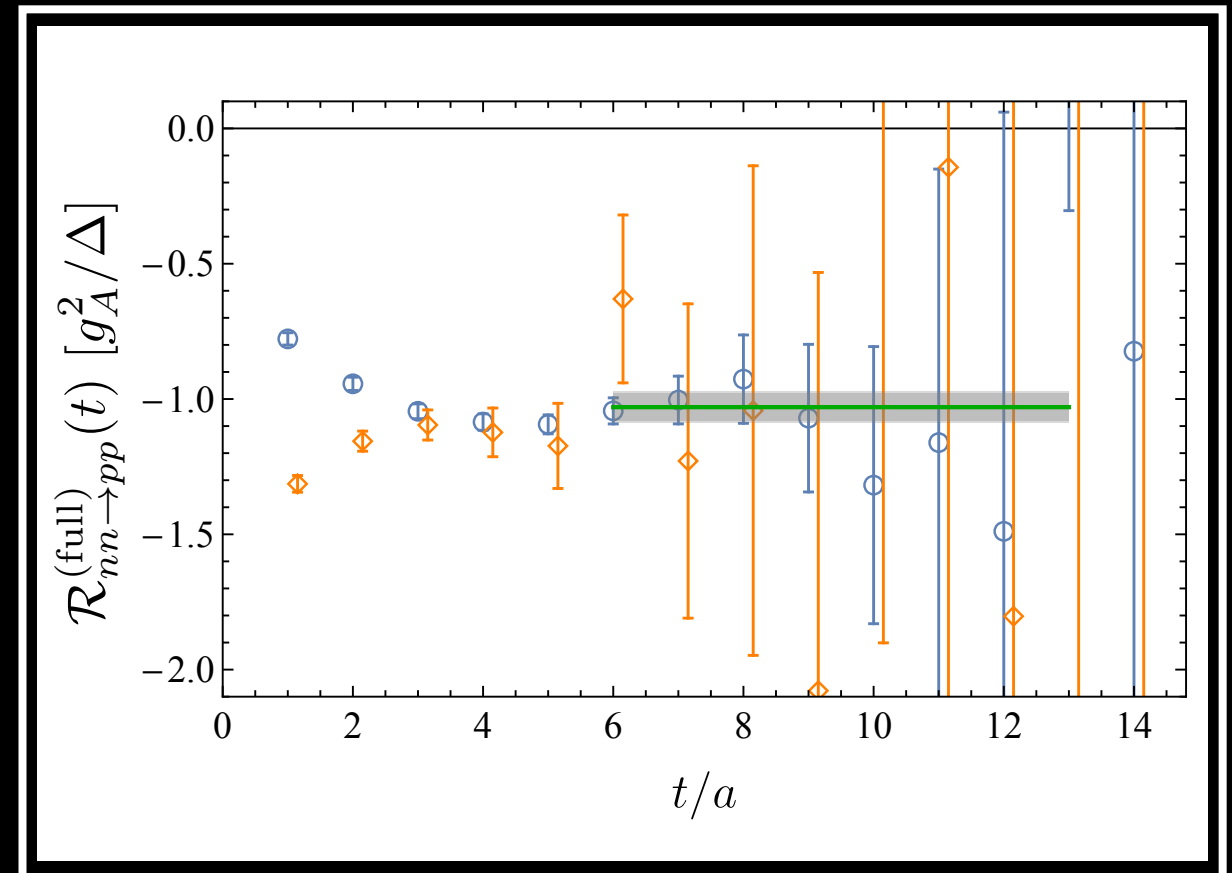
Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos,
(NPLQCD collaboration), arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

SECOND-ORDER RESPONSE TO AXIAL FIELD

$$\langle pp | A_3^+ A_3^+ | nn \rangle \quad @ \quad m_\pi \approx 800 \text{ MeV}$$



SHORT-DISTANCE CONTRIBUTION



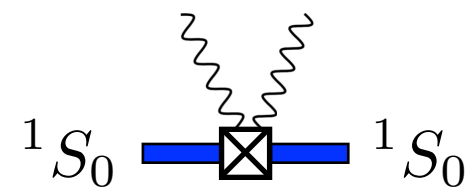
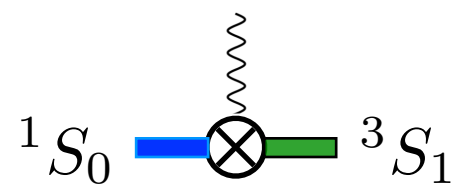
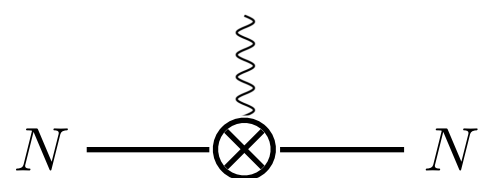
THE FULL MATRIX ELEMENT

SUGGESTS QUENCHING GA IS NOT ENOUGH!

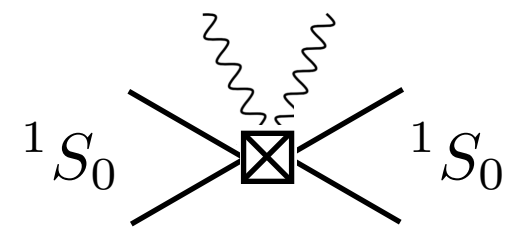
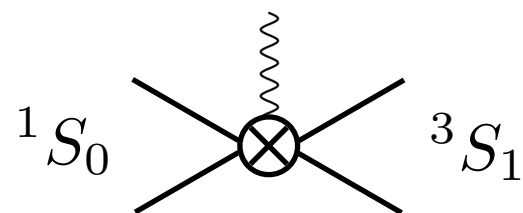
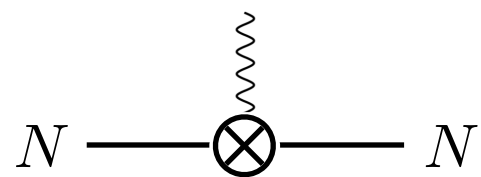
Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos,
(NPLQCD collaboration), arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

HOW CAN LATTICE QCD FINDINGS BECOME
USEFUL TO NUCLEAR MANY-BODY CALCULATION?

DOUBLE-BETA DECAY AND EFT



OR



Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos,
(NPLQCD collaboration), arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

SECOND-ORDER RESPONSE TO AXIAL FIELD

$$\begin{aligned}
 iC_{nnpp} = & \left(\begin{array}{c|c|c} \text{blue circle} & & \\ \hline & \text{green circle} & \\ \hline & & \text{blue circle} \end{array} \right) \left(\begin{array}{c|c|c} \text{blue line} & \text{blue line with } \otimes & \text{blue line with } \otimes \otimes + \text{blue line with } \otimes \square \\ \hline \text{blue line with } \otimes & \text{blue line} & \text{blue line with } \otimes \\ \hline \text{blue line with } \otimes \otimes + \text{blue line with } \otimes \square & \text{blue line with } \otimes & \text{blue line} \end{array} \right) \\
 \times & \left[\mathbf{1} + \underbrace{\left(\begin{array}{c|c|c} \text{blue circle with } \otimes & \text{blue circle with } \otimes & \text{blue circle with } \otimes \otimes \\ \hline \text{blue circle with } \otimes & \text{blue circle with } \otimes & \text{blue circle with } \otimes \otimes \\ \hline \text{blue circle with } \otimes \otimes & \text{blue circle with } \otimes & \text{blue circle with } \otimes \otimes \end{array} \right)}_{\text{II}} \underbrace{\left(\begin{array}{c|c|c} \text{blue line} & \text{blue line with } \otimes & \text{blue line with } \otimes \otimes + \text{blue line with } \otimes \square \\ \hline \text{blue line with } \otimes & \text{blue line} & \text{blue line with } \otimes \\ \hline \text{blue line with } \otimes \otimes + \text{blue line with } \otimes \square & \text{blue line with } \otimes & \text{blue line} \end{array} \right)}_{\text{ID}} + \dots \right] \underbrace{\left(\begin{array}{c|c|c} \text{blue circle} & & \\ \hline & \text{green circle} & \\ \hline & & \text{blue circle} \end{array} \right)}_{\text{Y}}
 \end{aligned}$$

Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos,
(NPLQCD collaboration), arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

SECOND-ORDER RESPONSE TO AXIAL FIELD

$$M_{pp \rightarrow d} = g_A(1 + S) - \mathbb{L}_{1,A}$$

AND

$$M_{nn \rightarrow pp} = -\frac{|M_{pp \rightarrow d}|^2}{\Delta} + \frac{M g_A^2}{4\gamma_s^2} - \mathbb{H}_{2,S}$$

$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8) \text{ fm}$$

$$@ m_\pi \approx 800 \text{ MeV}$$

LESSON FROM 800 MEV WORLD:

AXIAL POLARIZABILITY COULD BE IMPORTANT. CANNOT BE CONSTRAINED BY SINGLE-BETA DECAY PROCESSES.

Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos,
(NPLQCD collaboration), arXiv:1701.03456 [hep-lat], arXiv:1701.???? [hep-lat].

AFTER ALL THIS FORMALISM AND NUMERICAL
WORK COME TOGETHER, WHAT WILL COME NEXT?

BOTTOM-UP APPROACH: MATCHING THE HIGH SCALE TO LOW SCALE

$\Lambda > \text{TeV}$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



$\Lambda \sim 10^2 \text{ GeV}$

RUN IT DOWN TO BELOW THE EW SYMMETRY BREAKING SCALE:



$\Lambda \sim 2 \text{ GeV}$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



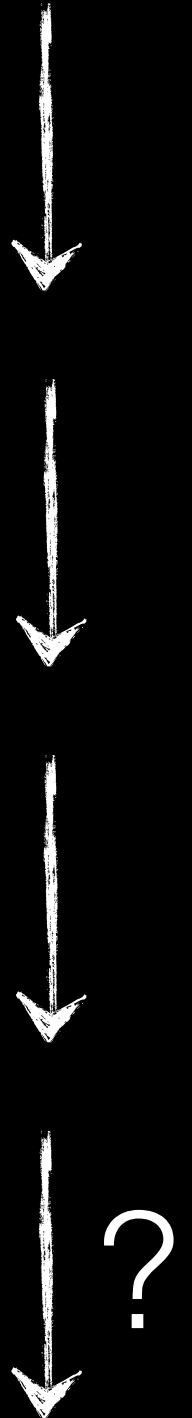
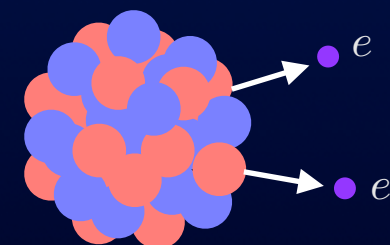
$\Lambda < \text{GeV}$

RUN IT DOWN TO THE HADRONIC SCALE:



$\Lambda < \text{MeV}$

USE NUCLEAR MANY-BODY CALCULATION TO
MATCH IT TO NUCLEAR MATRIX ELEMENTS:

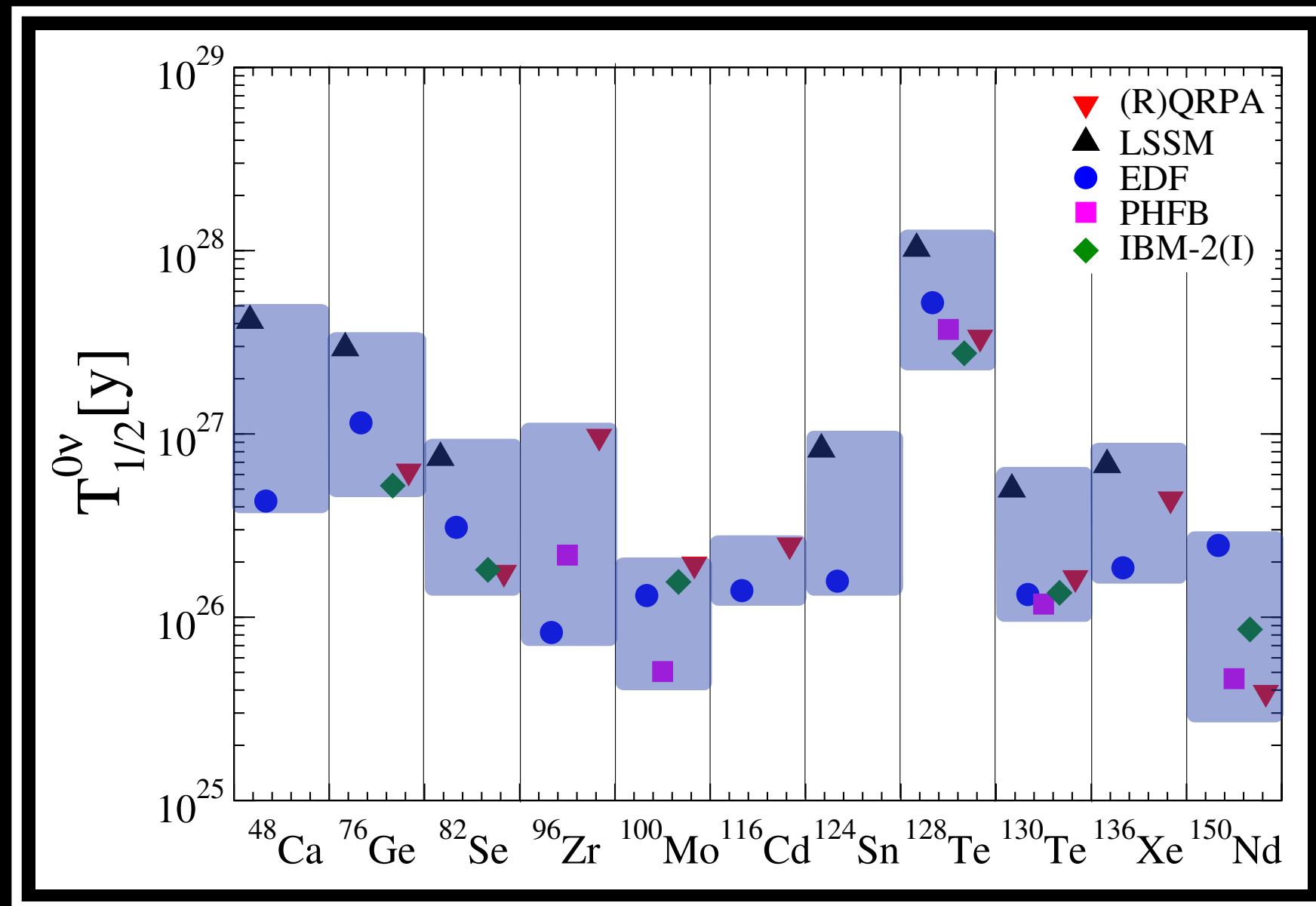


CURRENT STATUS OF NUCLEAR MATRIX ELEMENTS

DECAY RATE

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

NUCLEAR MATRIX ELEMENT IN LIGHT
NEUTRINO EXCHANGE SCENARIO



Avignone, Elliott and Engel, REVIEWS OF MODERN PHYSICS, VOLUME 80 (2008)

Vergados, Ejiri and Simkovic, Rep. Prog. Phys. 75 106301 (2012)

Menendez, Gazit, and Schwenk, Phys.Rev.Lett.107, 062501 (2011)

A REMARK ON PHILOSOPHY:
HOW IT GUIDED US TO ASKING A SCIENTIFIC
QUESTION

A PHILOSOPHICAL THOUGHT



Bostrom

ARE YOU LIVING IN A COMPUTER SIMULATION?

BY NICK BOSTROM

Faculty of Philosophy, Oxford University

Published in *Philosophical Quarterly* (2003) Vol. 53, No. 211, pp. 243-255.

(I)



HUMAN BEING GOES EXTINCT BEFORE REACHING A POST-HUMAN STAGE.

(II)



HUMAN BEING WILL NOT DEVELOP SUFFICIENT TECHNOLOGY TO SIMULATE ITS OWN REVOLUTIONARY HISTORY.

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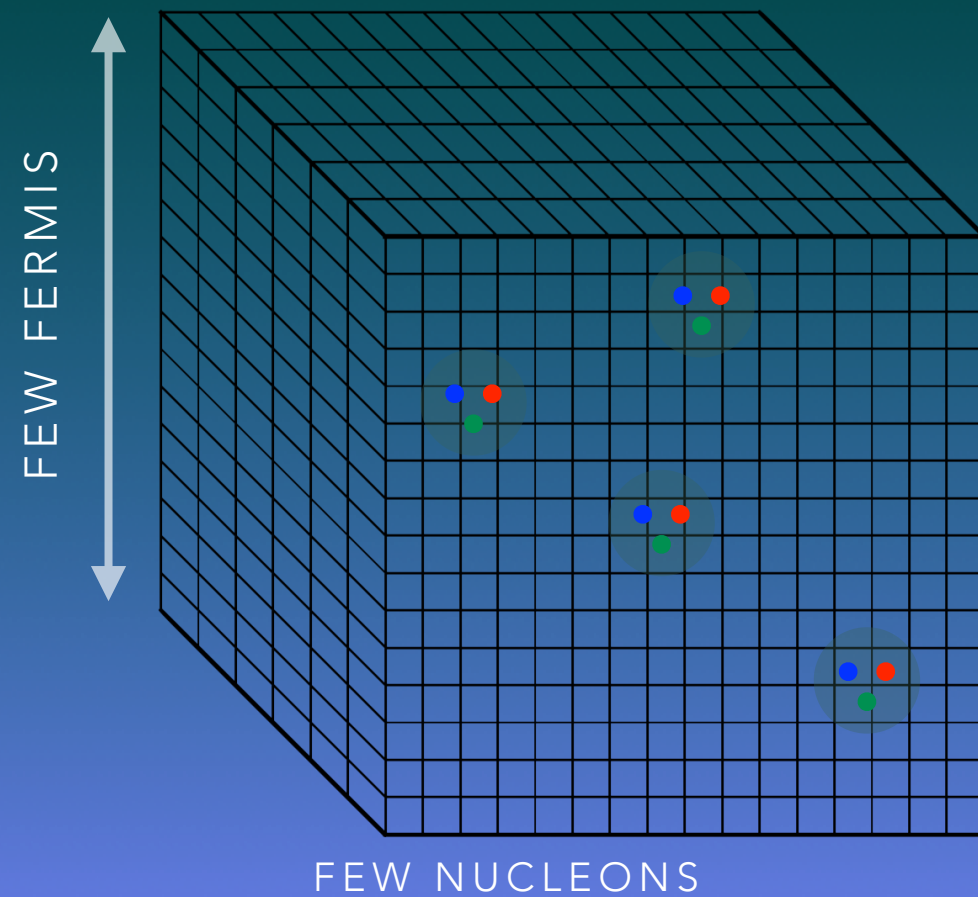


HUMAN BEING WILL NOT DEVELOP SUFFICIENT TECHNOLOGY TO SIMULATE ITS OWN REVOLUTIONARY HISTORY.

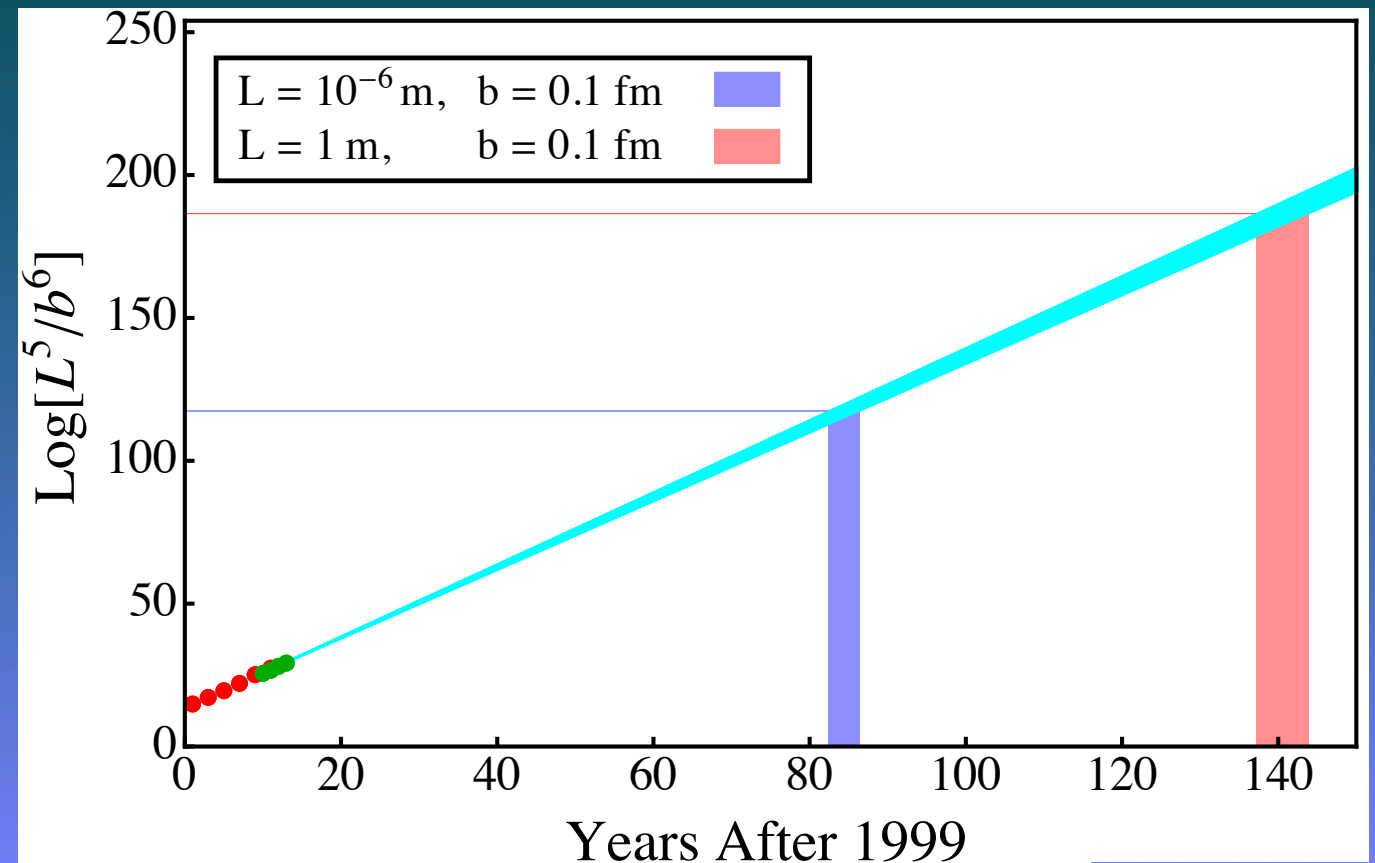
(III) WE ARE CURRENTLY LIVING IN A COMPUTER SIMULATION!

AND AN OBSERVED TREND

WHERE WE ARE TODAY



NOT TOO FAR IN FUTURE!



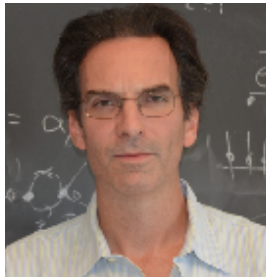
BOSTROM'S SECOND SCENARIO DOESN'T SEEM UNLIKELY ...IF WE DON'T GO EXTINCT SOON!

IT'S LIKELY THAT WE ARE ALREADY SIMULATED!

BUT HOW CAN WE KNOW?



LED TO A PHYSICS SPECULATION



Constraints on the Universe as a Numerical Simulation

Silas R. Beane,^{1,2,*} Zohreh Davoudi,^{3,†} and Martin J. Savage^{3,‡}

¹*Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA*

²*Helmholtz-Institut für Strahlen- und Kernphysik (Theorie),
Universität Bonn, D-53115 Bonn, Germany*

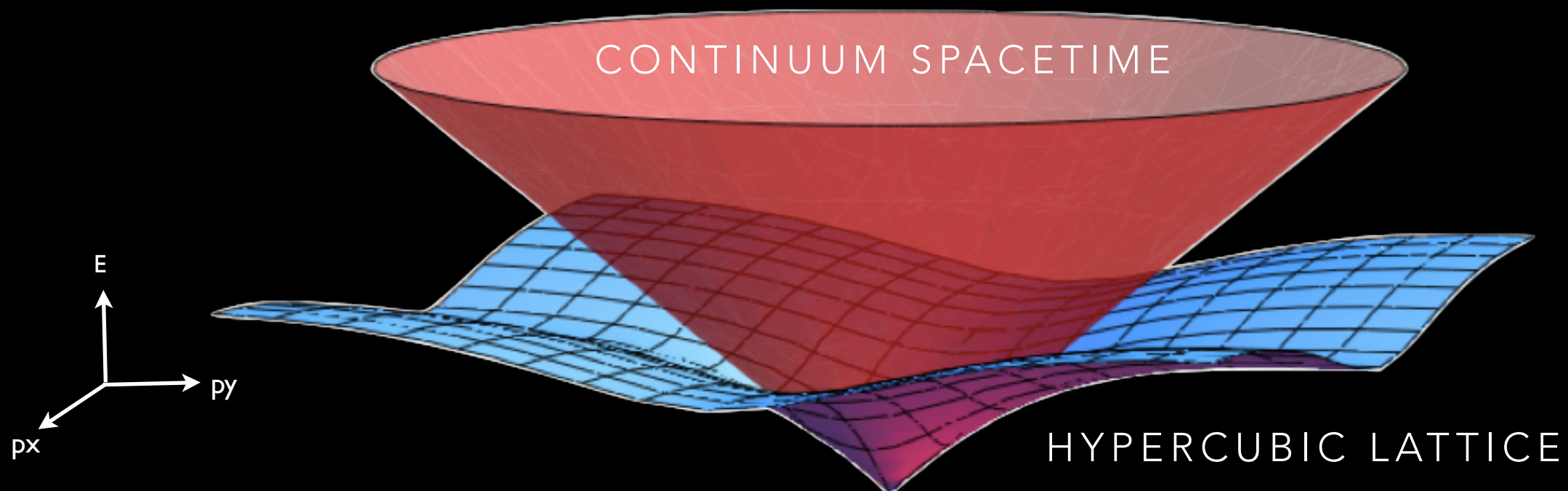
³*Department of Physics, University of Washington,
Box 351560, Seattle, WA 98195, USA*

(Dated: March 9, 2013 - 9:18)



Abstract

Observable consequences of the hypothesis that the observed universe is a numerical simulation performed on a space-time lattice or grid are explored. The simulation scenario is first motivated by extrapolating current trends in computational resource requirements for lattice QCD into the future. Using the historical development of lattice gauge theory technology as a guide, we assume that our universe is an early numerical simulation and investigate potentially-observable consequences. Among the observables that are considered are the muon $g - 2$ and the current differences between determinations of α , but the most stringent bound on the inverse lattice spacing of the universe, $b^{-1} \gtrsim 10^{11}$ GeV, is derived from the high-energy cut off of the cosmic ray spectrum. The numerical simulation scenario could reveal itself in the distributions of the highest energy cosmic rays exhibiting a degree of rotational symmetry breaking that reflects the structure of the underlying lattice.



TO CONCLUDE...

THE GOAL OF NUCLEAR PHYSICS RESEARCH IS TO PROVIDE RELIABLE PREDICTIONS FOR COMPLEX PHENOMENA IN NATURE AND TO HELP ISOLATE NON-STANDARD MODEL INTERACTIONS.

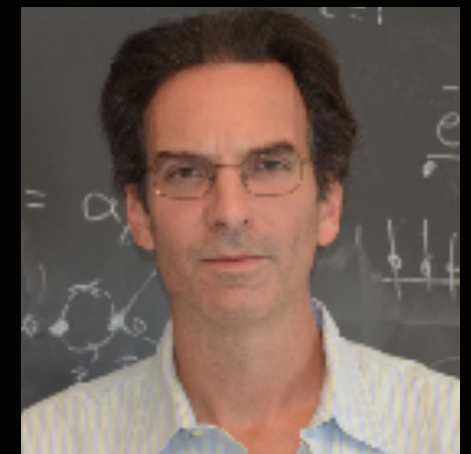
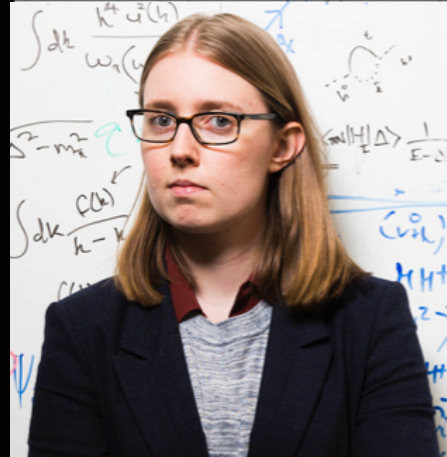
A FIRST-PRINCIPLES APPROACH TO NP BASED ON QCD IS POSSIBLE. TO CONNECT TO MANY-BODY CALCULATIONS EFTS ARE NEEDED.

I PRESENTED ONE SUCH PATH TO OBTAIN NUCLEAR MATRIX ELEMENTS IN DOUBLE-BETA DECAYS IN ONE SCENARIO.

SHORT-DISTANCE CONTRIBUTIONS BEYOND THE BORN TERM (AXIAL POL.) MAY BE IMPORTANT IN BI-LOCAL MATRIX ELEMENT FOR NN TO PP..

GIVEN OUR ABILITY TO SIMULATE THE LAWS OF NATURE, HOW CAN WE KNOW IF THE NATURE IS NOT SIMULATED?

THE COLLABORATION

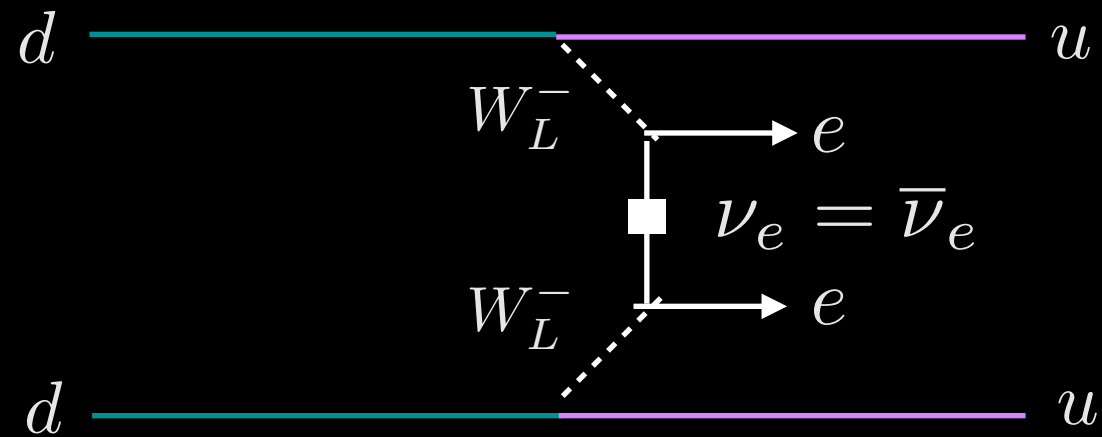


THANK YOU!

BACKUP SLIDES

POSSIBLE SCENARIOS FOR 0VBB DECAY:

1) NOT FAR FROM THE STANDARD MODEL: LIGHT NEUTRINO EXCHANGE



REQUIRES JUST A LITTLE BIT OF DEVIATION FROM STANDARD MODEL

- $$\mathcal{L}_M = -\frac{m_L}{2} [(\overline{\nu_L})^c \nu_L + \text{h.c.}] - \frac{m_R}{2} [(\overline{\nu_R})^c \nu_R + \text{h.c.}]$$

Leading dimensions 5 interaction:

$$\frac{1}{\Lambda} \overline{\nu^c} \nu H H$$

Majorana (1937)

Weinberg (1979)

CAN EVEN ADD A DIRAC MASS TERM WITH NO NEED TO A BIG FINE TUNING

- $$\mathcal{L}_D = -m_D (\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L)$$

The Yukawa interaction: $Y_\nu \overline{\nu_L} \nu_R H$

THANKS TO THE SEESAW MECHANISM

Gell-Mann et al. (1979); Yanagida (1979);
Mohapatra and Senjanovic (1980)

$$\mathcal{M} = \begin{pmatrix} m_L & m_D^T \\ m_D & m_R \end{pmatrix} \rightarrow m_l \approx -\frac{m_D^2}{m_R}, \quad M_h \approx m_R \rightarrow m_R \gg 1 \text{ TeV}$$

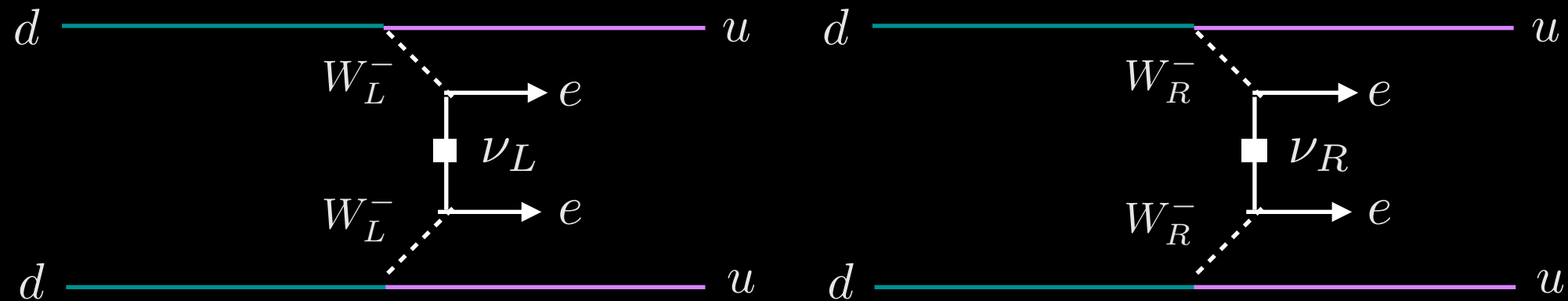
POSSIBLE SCENARIOS FOR 0VBB DECAY:

2) MORE DEVIATION FROM THE STANDARD MODEL: HEAVY NEUTRINO EXCHANGE

EXAMPLE: LEFT-RIGHT SYMMETRIC MODELS

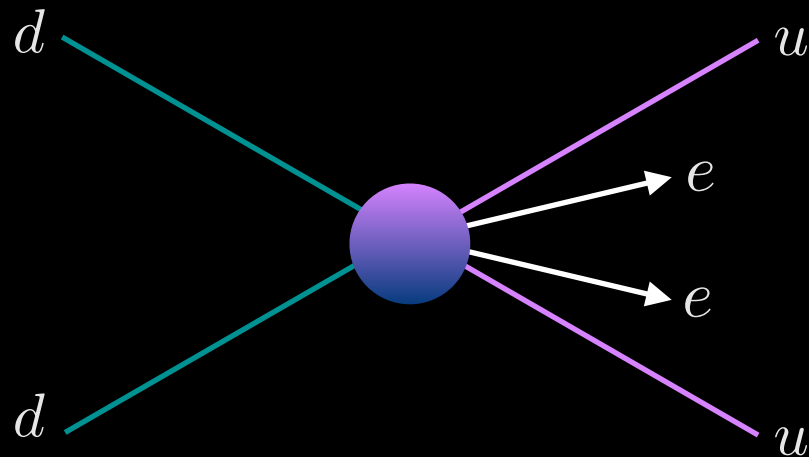
Mohapatra, Pati, Senjanovic (1974-1975)

Mohapatra, Marshak (1979-1980)



AND MANY MORE...

WITH ANY HIGH SCALE INVOLVED, A GENERAL EFFECTIVE INTERACTION IS:



$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^5} \bar{q} q \bar{q} q e^c e$$

$$\Lambda \sim 1 \text{ TeV}$$

AND NO MATTER WHAT GOES ON IN THE ``BLACK BOX'', WE HAVE ALREADY LEARNED NEUTRINOS ARE MAJORANA!

Schechter and Valle (1982)

