Nuclei as Laboratories: Nuclear Tests of Fundamental Symmetries

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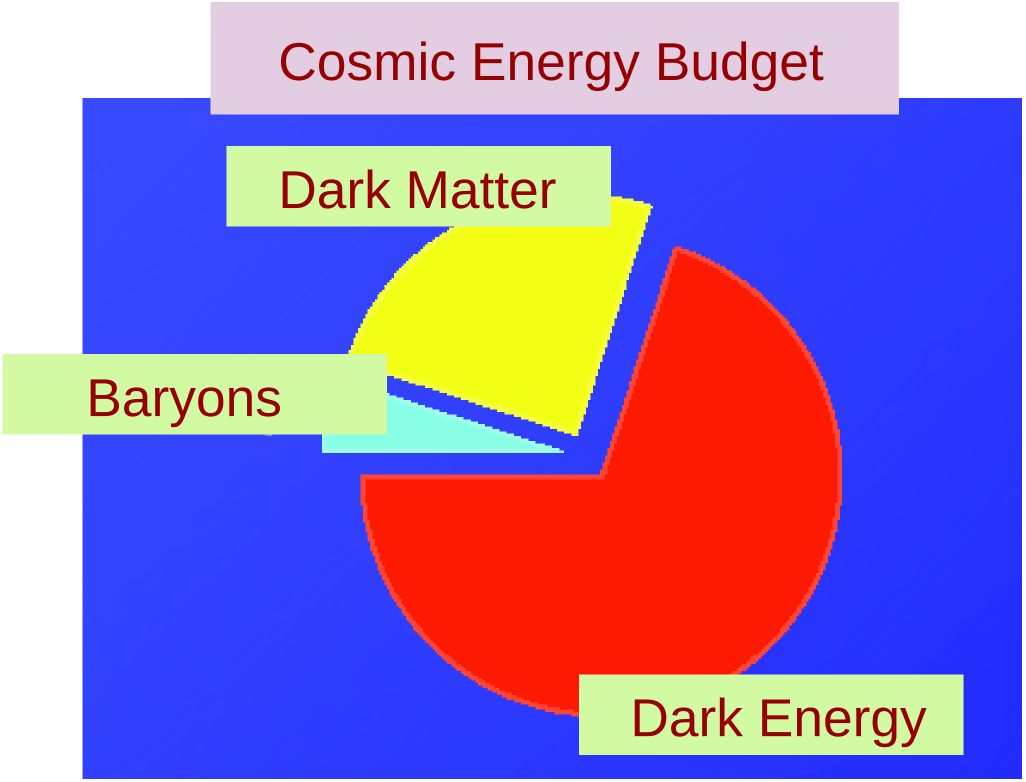
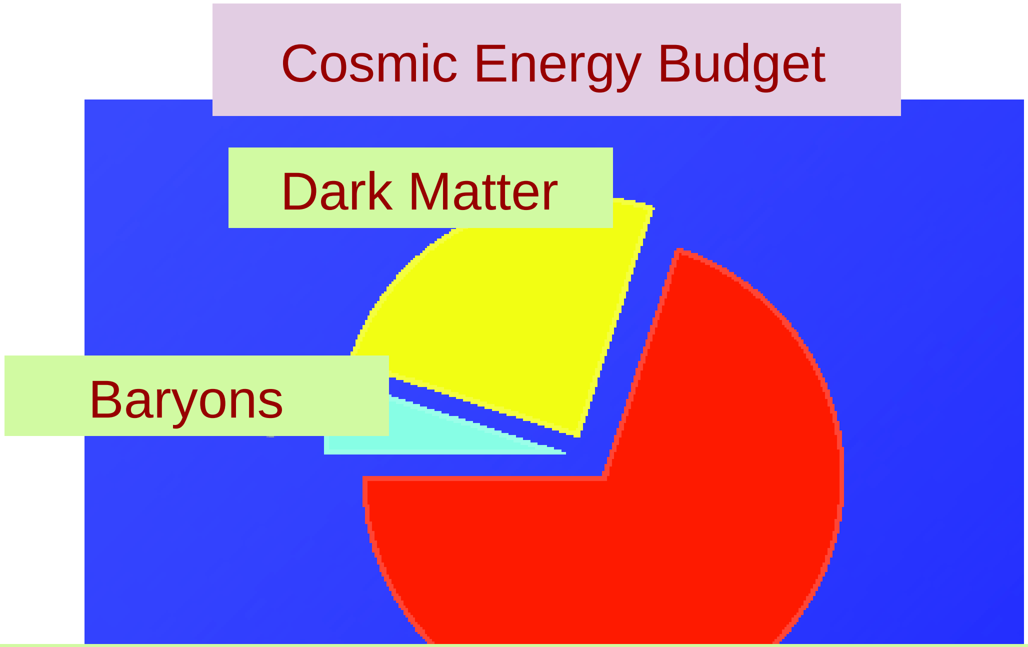
Nuclear Science



The mission: Explain the origin, evolution, and structure of the baryonic matter of the Universe

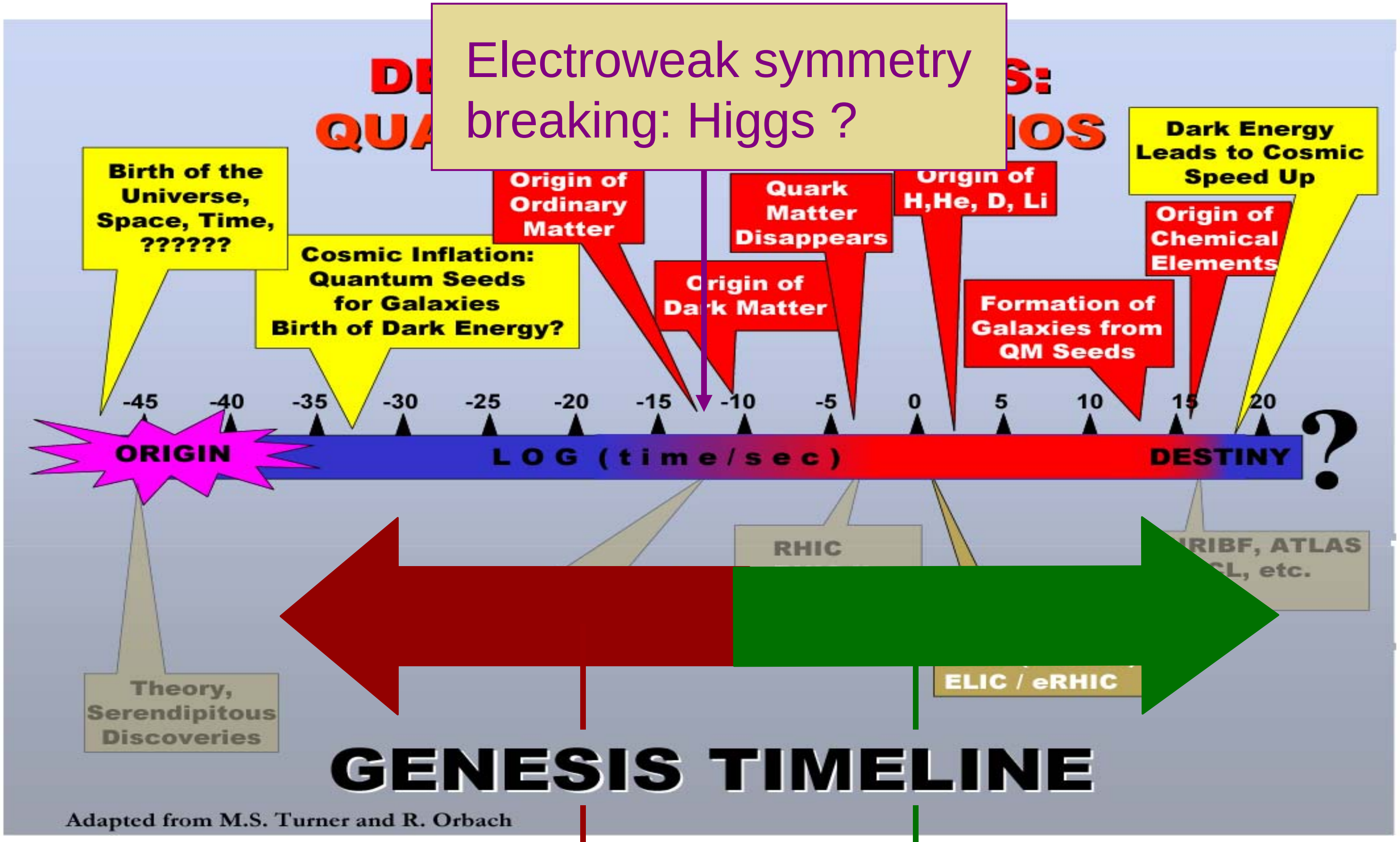
Nuclear Science



Three frontiers:

- *Fundamental symmetries & neutrinos*
- *Nuclei and nuclear astrophysics*
- *QCD*

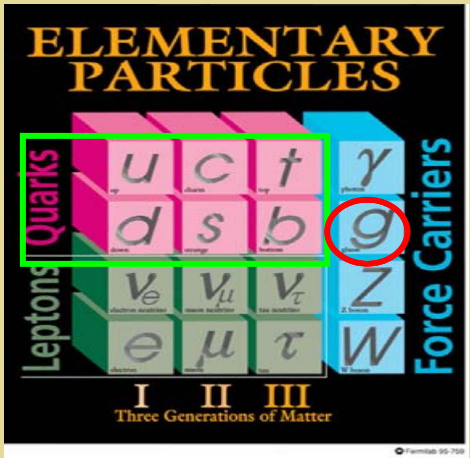
Fundamental Symmetries & Cosmic History



Beyond the SM

SM symmetry (broken)

Fundamental Symmetries & Cosmic History



Standard Model "unfinished business"

How does QCD affect the weak qq interaction?

Is there a long range weak NN interaction?

Beyond the SM

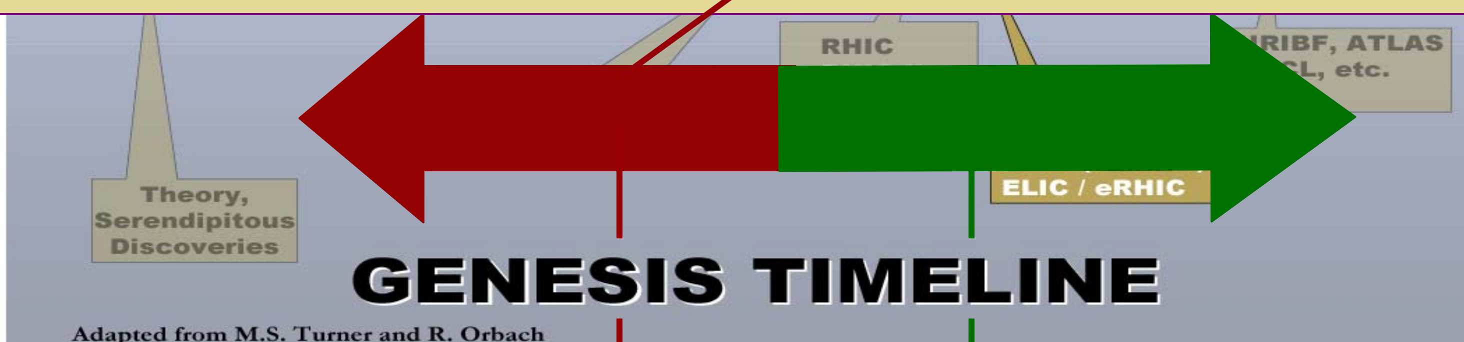
SM symmetry (broken)

Fundamental Symmetries & Cosmic History

Puzzles the Standard Model can't solve

1. *Origin of matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*

What are the symmetries (forces) of the early universe beyond those of the SM?



Beyond the SM

SM symmetry (broken)

What are the new fundamental symmetries?

- *Why is there more matter than antimatter in the present universe?*

  Electric dipole moment searches

- *What are the unseen forces that disappeared from view as the universe cooled?*

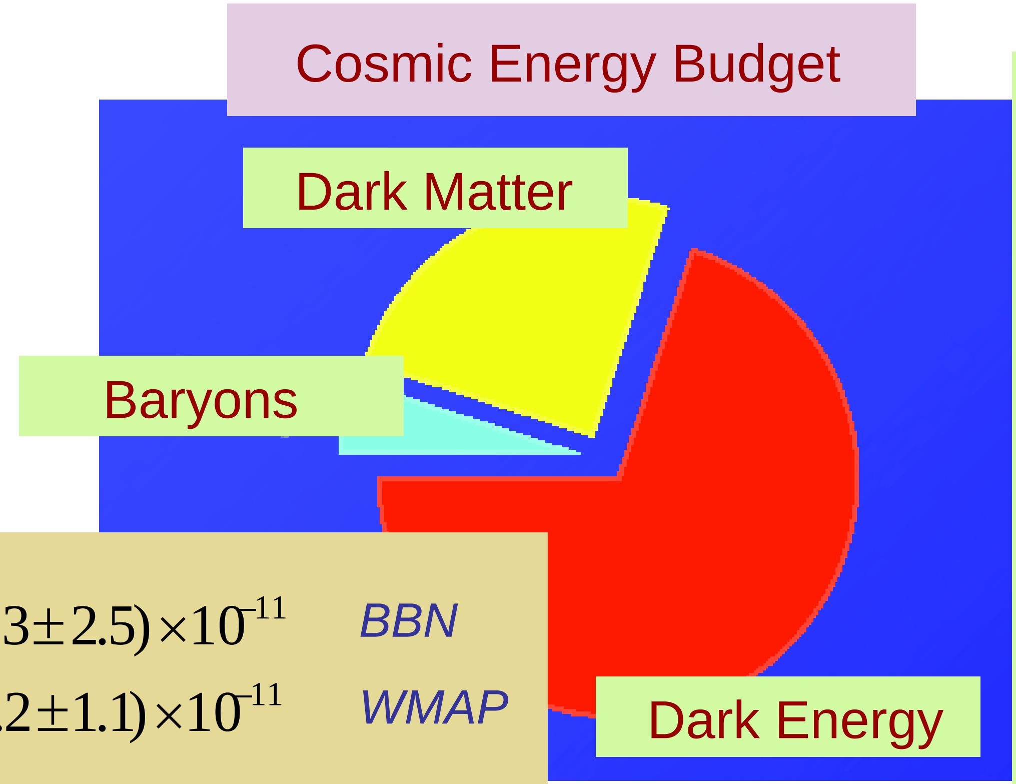
  Precision electroweak: weak decays, scattering, LFV

- *What are the masses of neutrinos and how have they shaped the evolution of the universe?*

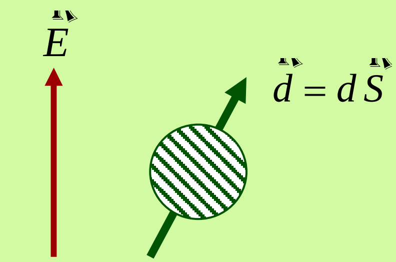
  Neutrino oscillations, $0\nu\beta\beta$-decay, θ_{13} , …

Tribble report

What is the origin of baryonic matter ?



$$Y_B = \frac{\rho_B}{s_\gamma} = \begin{matrix} (7.3 \pm 2.5) \times 10^{-11} & \textit{BBN} \\ (9.2 \pm 1.1) \times 10^{-11} & \textit{WMAP} \end{matrix}$$



$$\nu_{EDM} = -\frac{d\,\vec{S} \cdot \vec{E}}{h}$$

T-odd , CP-odd
by CPT theorem

What are the quantitative implications of new EDM experiments for explaining the origin of the baryonic component of the Universe ?

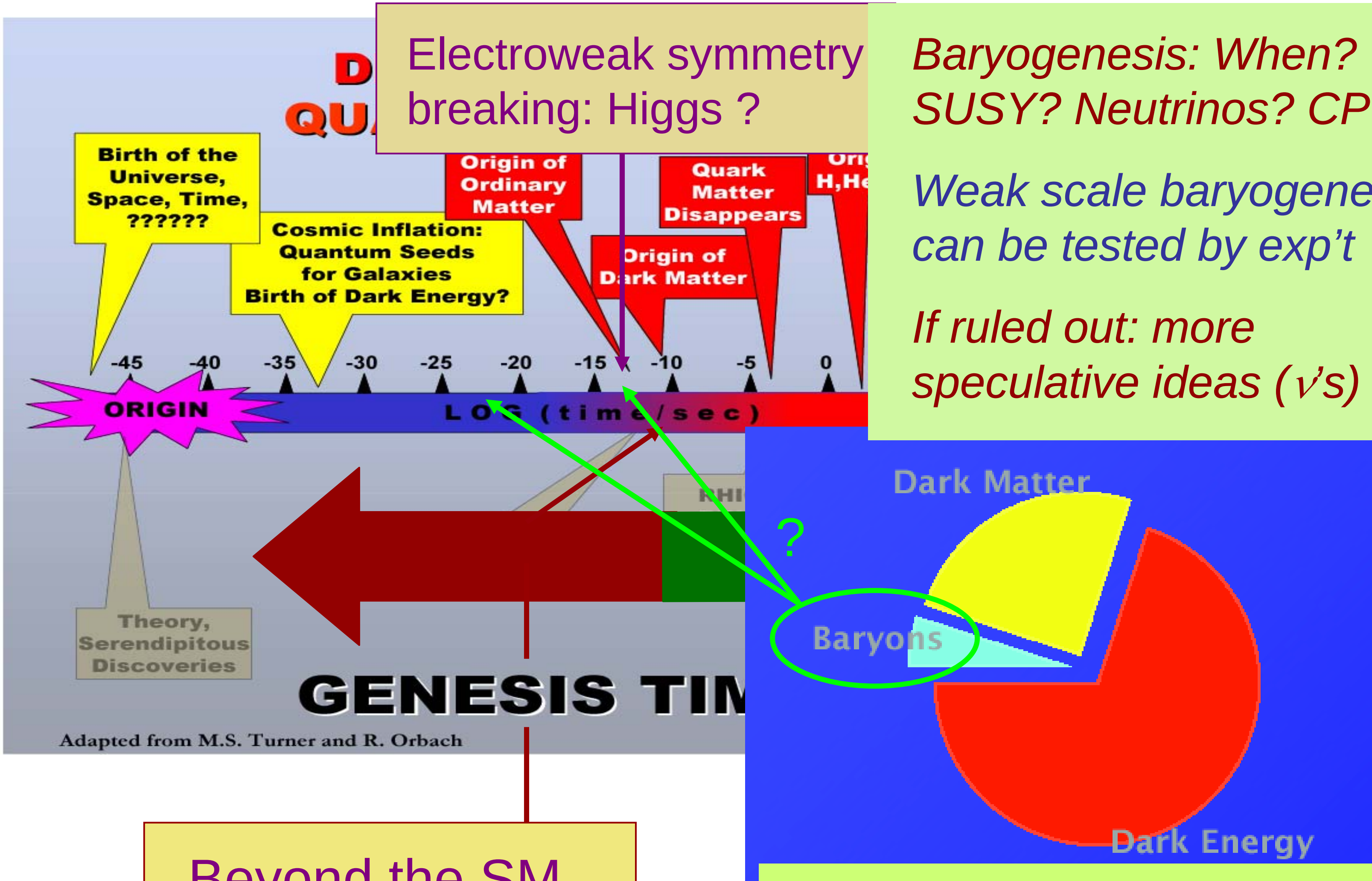
What is the origin of baryonic matter?

Electroweak symmetry breaking: Higgs ?

Baryogenesis: When? SUSY? Neutrinos? CPV?

Weak scale baryogenesis can be tested by exp't

If ruled out: more speculative ideas (ν's) ?



Beyond the SM

Cosmic Energy Budget

EW Baryogenesis: Standard Model

Sakharov:

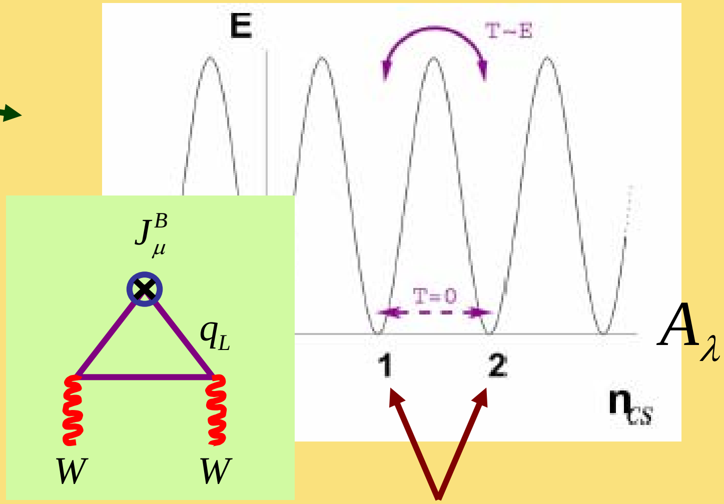
Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

Sakharov, 1967

Kuzmin, Rubakov, Shaposhnikov McLerran,…

Anomalous Processes



Different vacua: $\Delta(B+L) = \Delta N_{CS}$

Sphaleron Transitions

EW Baryogenesis: Standard Model

Shaposhnikov

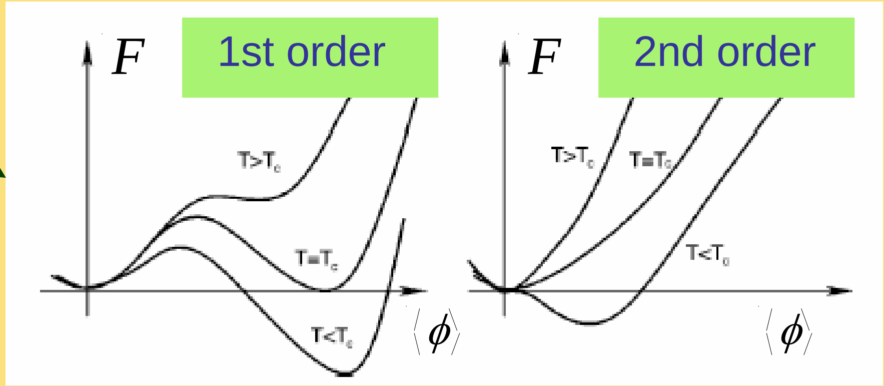
Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

Sakharov, 1967

$$J = s_{12}\, s_{13}\, s_{23}\, c_{12}\, c_{13}^{2}\, c_{23} \sin \delta_{13} = (2.88 \pm 0.33) \times 10^{-5}$$

$$\frac{m_t^4}{M_W^4}\frac{m_b^4}{M_W^4}\frac{m_c^2}{M_W^2}\frac{m_s^2}{M_W^2} \approx 3\times 10^{-13}$$



Increasing m_h →

- CP-violation too weak
- EW PT too weak

Baryogenesis: New Electroweak Physics

90's: *Cohen, Kaplan, Nelson*
Joyce, Prokopec, Turok

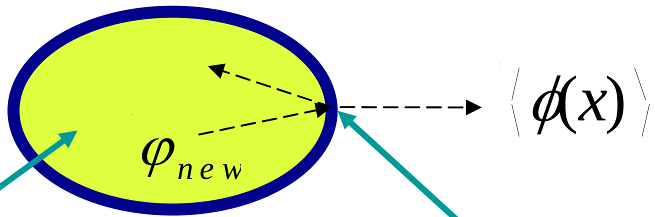
Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

Sakharov, 1967

Unbroken phase

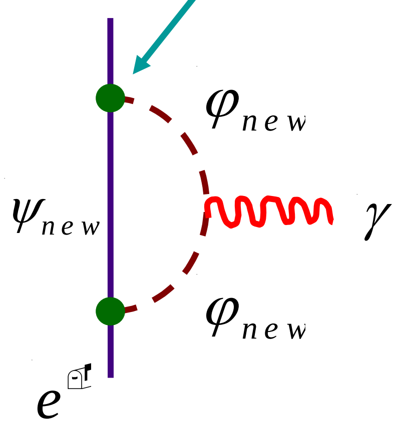
Topological transitions



Broken phase

1st order phase transition

CP Violation



- Is it viable?
- Can experiment constrain it?
- How reliably can we compute it?

EDM Probes of New CP Violation

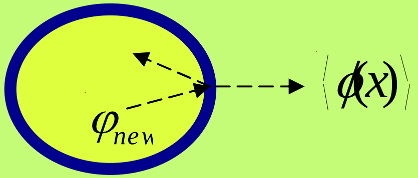
CKM → d_{SM}

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6 \times 10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3 \times 10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg	$< 10^{-33}$	$< 2.1 \times 10^{-28}$	$\rightarrow 10^{-32}$
μ	$< 10^{-28}$	$< 1.1 \times 10^{-18}$	$\rightarrow 10^{-24}$

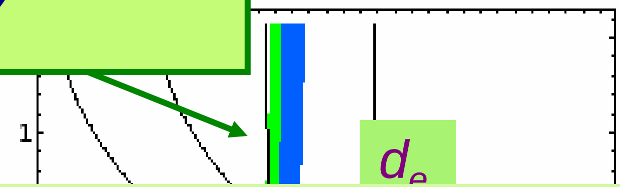
Also ^{225}Ra, ^{129}Xe, d

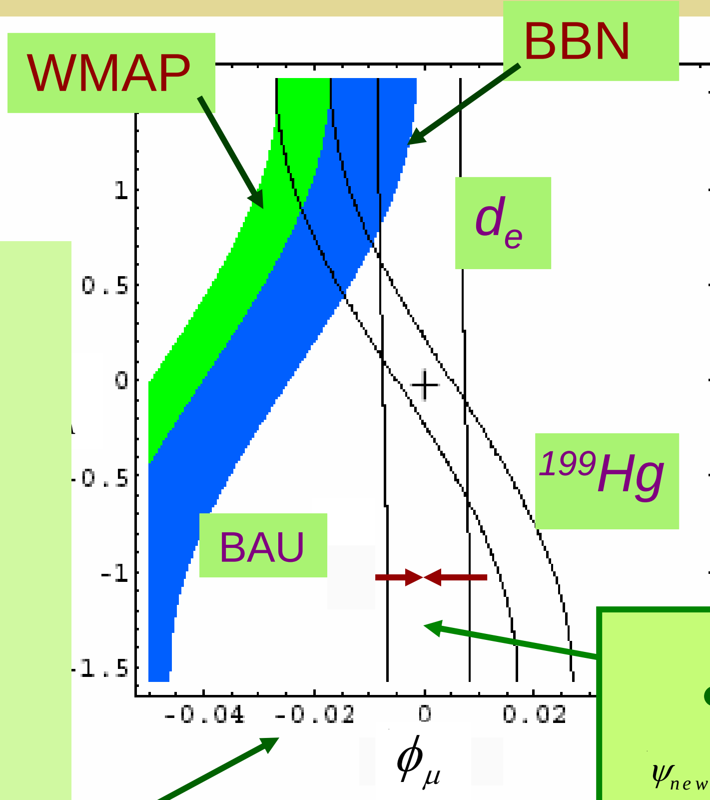
If an EDM is seen, can we identify the new physics?

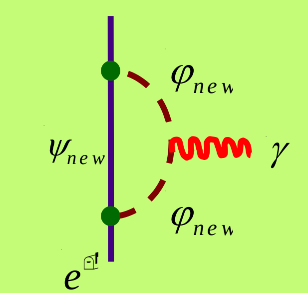
EDM constraints & SUSY CPV



Lee et al







- EDMs of different systems provide complementary probes: more atomic experiments (RIA)
- Nuclear theory: reliable calc's of atomic EDM dependence on ϕ_{CPV} and other new physics parameters (RIA?)
- Nuclear theory: reliable calcs of Y_B

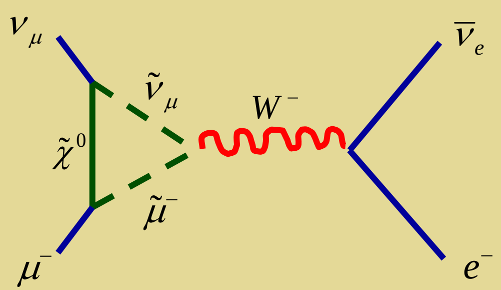
Different choices for SUSY parameters

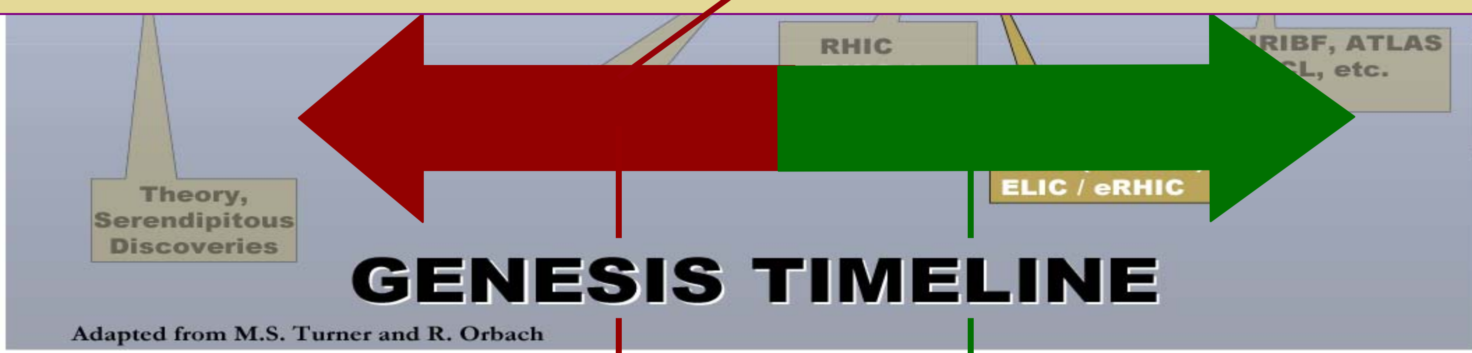
$$Y_B = \sum_k F_k(g_i, \tilde{M}_i; T, v_w, L_w, \ldots) \sin\phi_k$$

Fundamental Symmetries & Cosmic History

Unseen Forces: Supersymmetry ?

1. *Unification & gravity*
2. *Weak scale stability*
3. *Origin of matter*
4. *Neutrinos*





Beyond the SM

SM symmetry (broken)

Weak decays & new physics

CKM unitarity ?

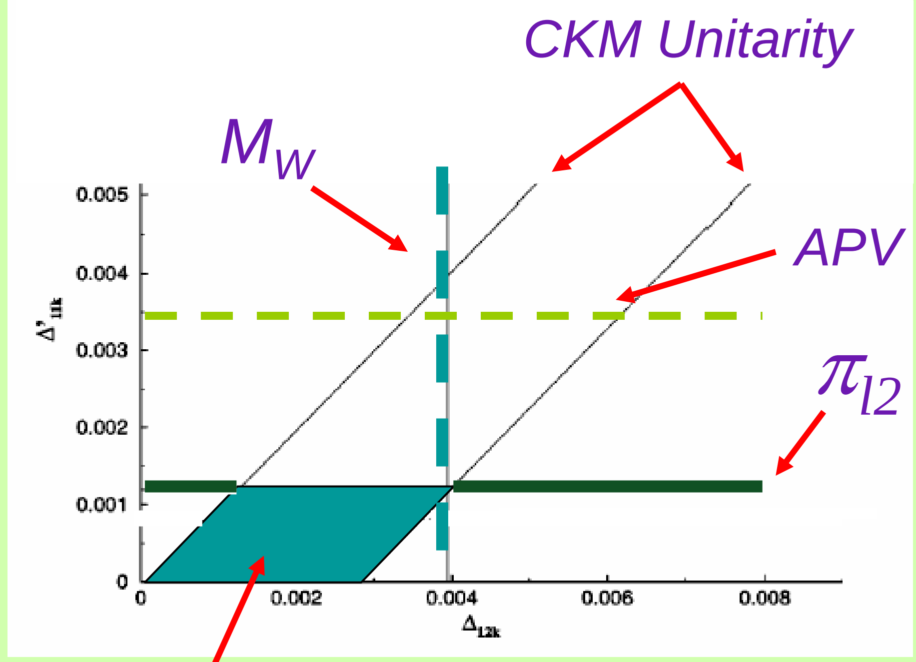
$$d \to u\, e^- \, \bar{\nu}_e \ldots$$

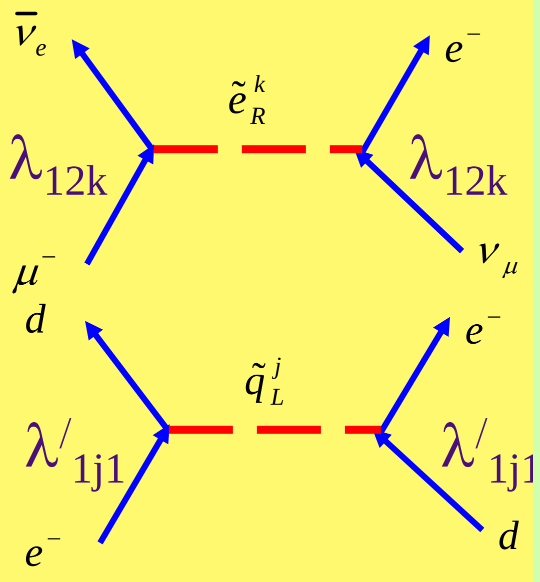
$$s \to u\, e^- \, \bar{\nu}_e \ldots$$

$$b \to u\, e^- \, \bar{\nu}_e \ldots$$

R Parity Violation

Kurylov, R-M, Su



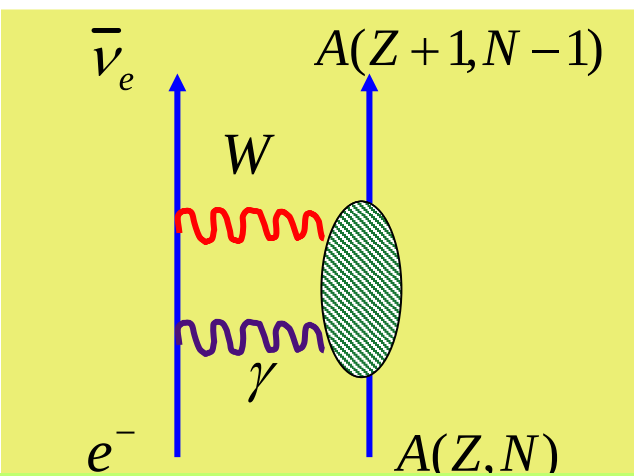


No long-lived LSP or SUSY DM

Weak decays

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

SM theory input



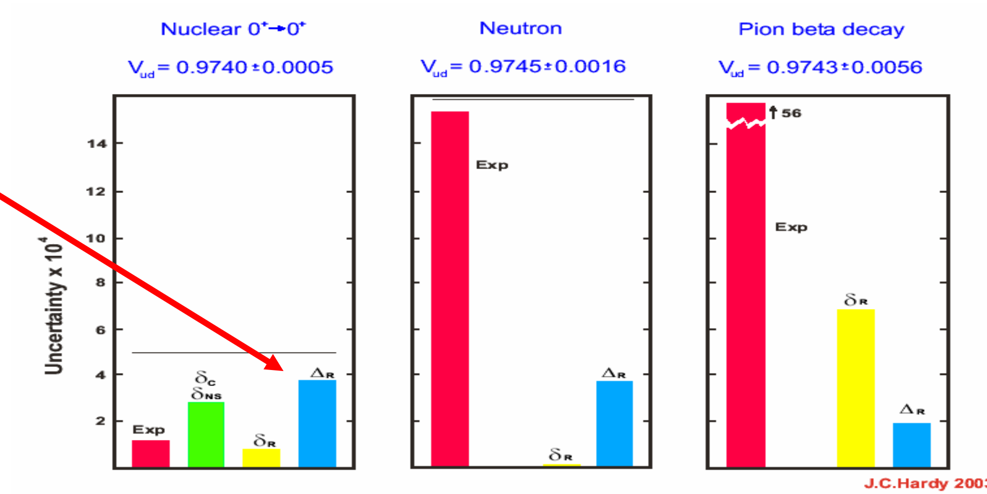
Nuclear structure effects?

β-decay

$$n \rightarrow p\, e^-\, \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1, N+1)\, e^+\, \nu_e$$

$$\pi^+ \rightarrow \pi^0\, e^+\, \nu_e$$



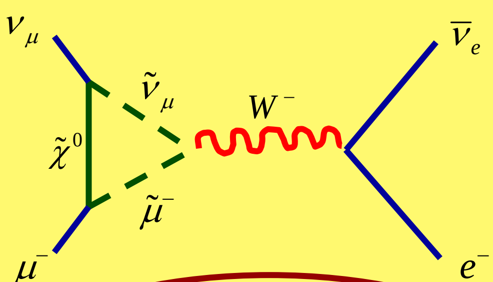
$$M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\hat{\alpha}}{2\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

Weak decays & new physics

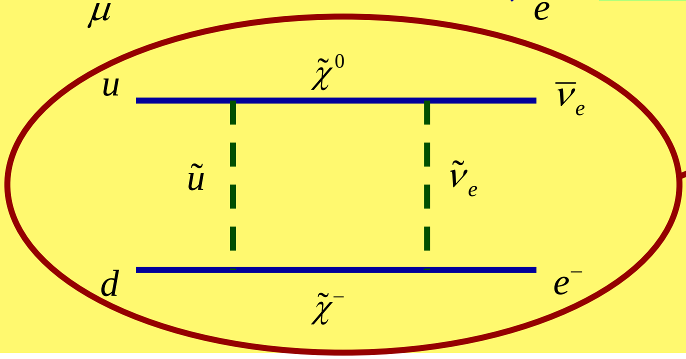
Correlations

$$d \rightarrow u\, e^- \,\overline{\nu}_e$$
$$s \rightarrow u\, e^- \,\overline{\nu}_e$$
$$b \rightarrow u\, e^- \,\overline{\nu}_e$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.00$$



$+\ldots$

SUSY

$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \ldots$$

Non (V-A) x (V-A) interactions: m_e/E

β-decay at RIA?

Fundamental Symmetries & Cosmic History

Neutrinos ?

Are they their own antiparticles?

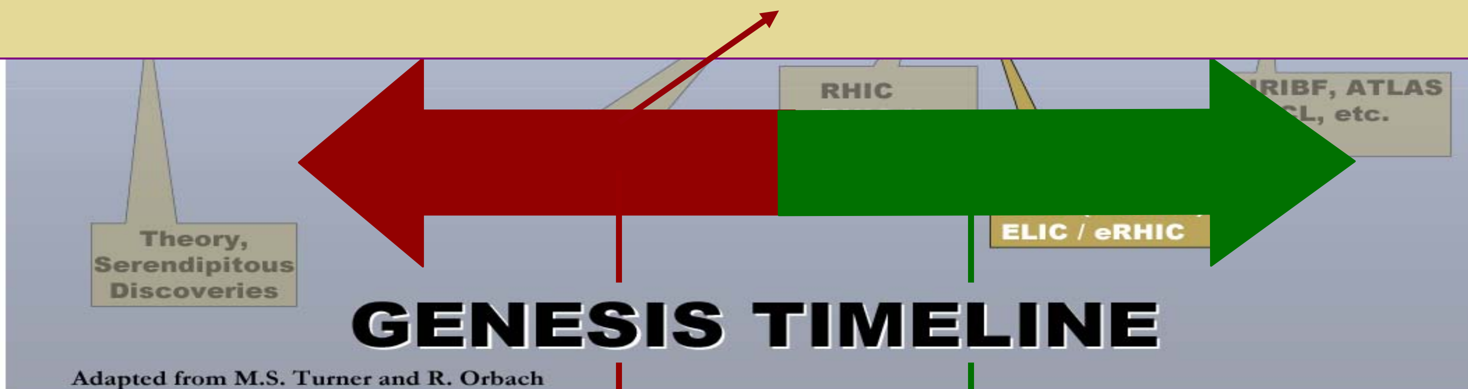
Why are their masses so small?

Can they have magnetic moments?

Implications of m_ν for neutrino interactions ?

LFV & LNV ?

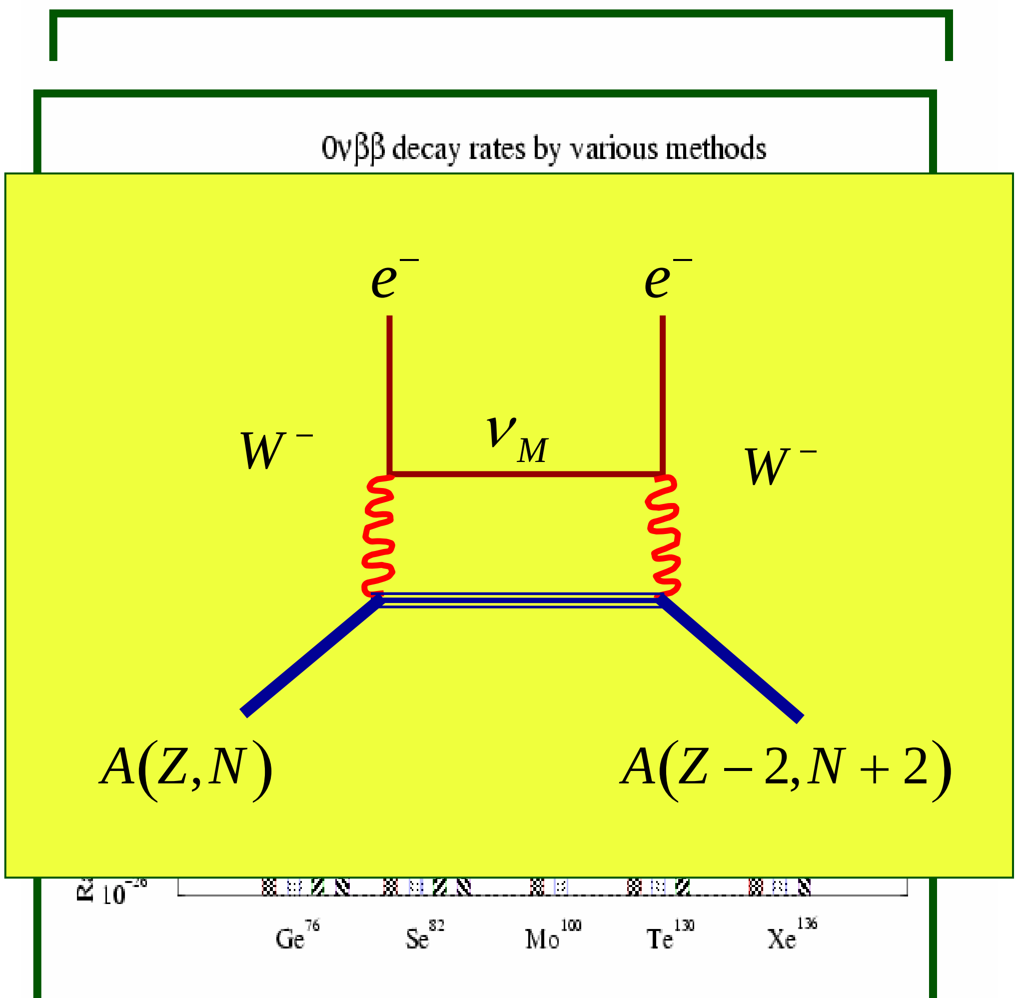
What is m_ν?

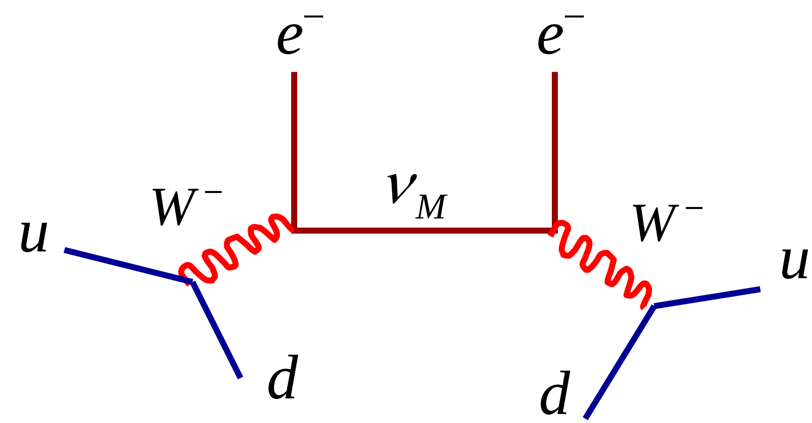


Beyond the SM

SM symmetry (broken)

$0\nu\ \beta\beta$ - decay probes the charge conjugation properties of the neutrino





Light ν_M : Nuclear matrix elements difficult to compute

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k\ e^{2i\delta}$$

$0\nu\ \beta\beta$ - decay: *heavy particle exchange*

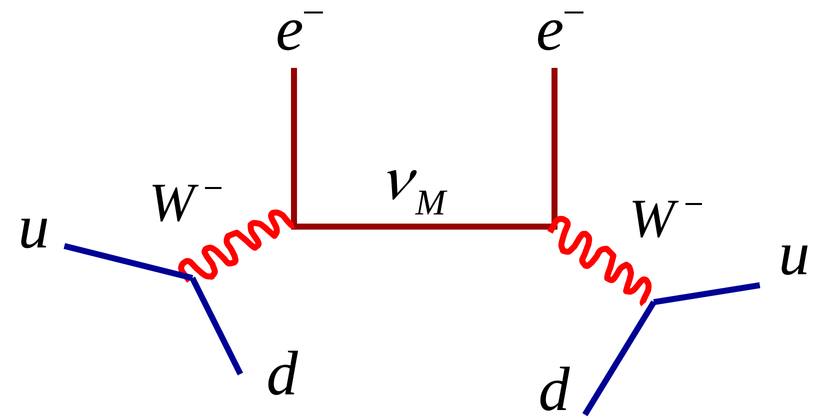
$$\frac{M_H}{M_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda_{\beta\beta}^5 m_{\beta\beta}} \sim O(1)$$

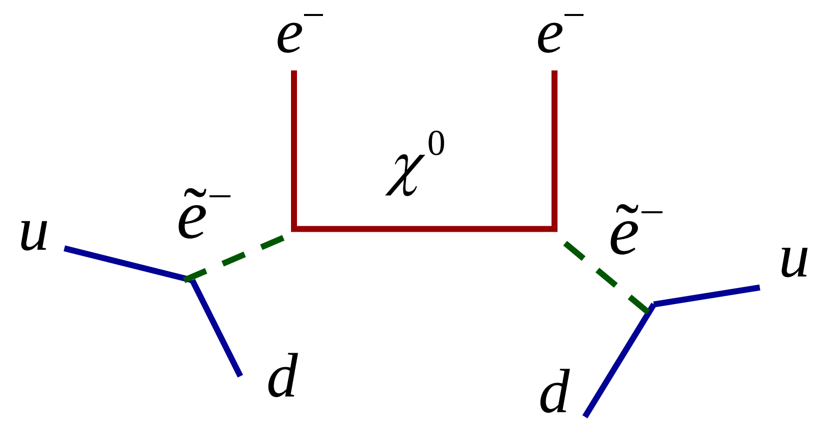
$$m_{\beta\beta} \sim 0.1\ eV$$

$$\Lambda_{\beta\beta} \sim 1\ TeV$$

$$\bar{k} \sim 50\ MeV$$

How do we compute & separate heavy particle exchange effects?



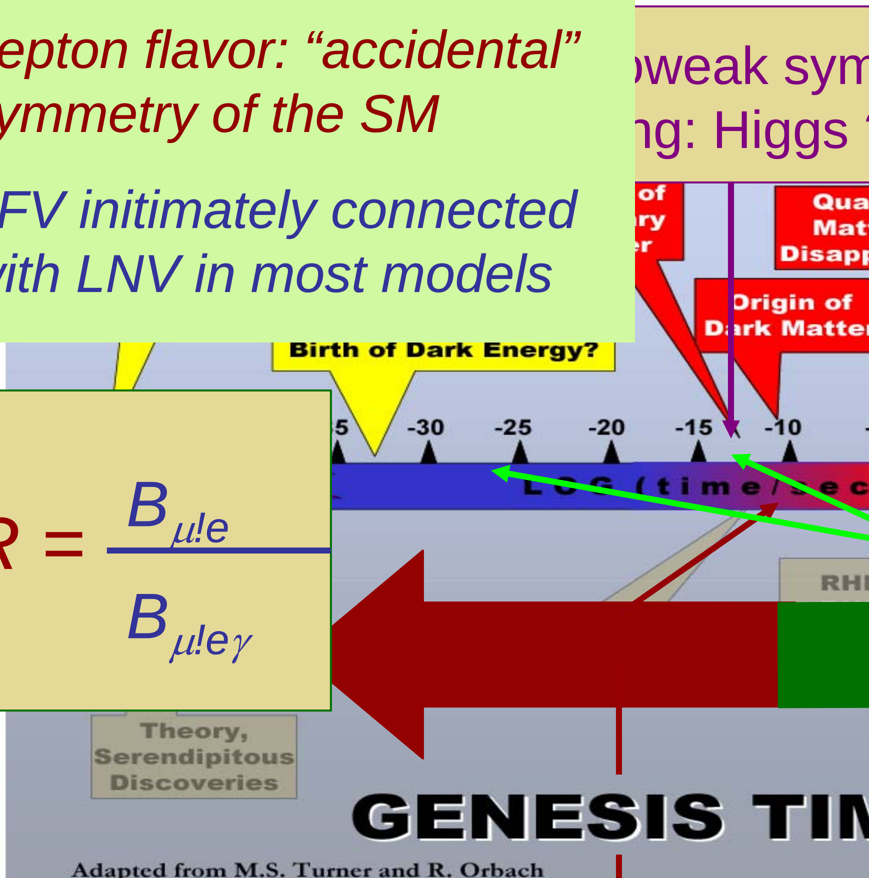


LF and LN: symmetries of the early universe?

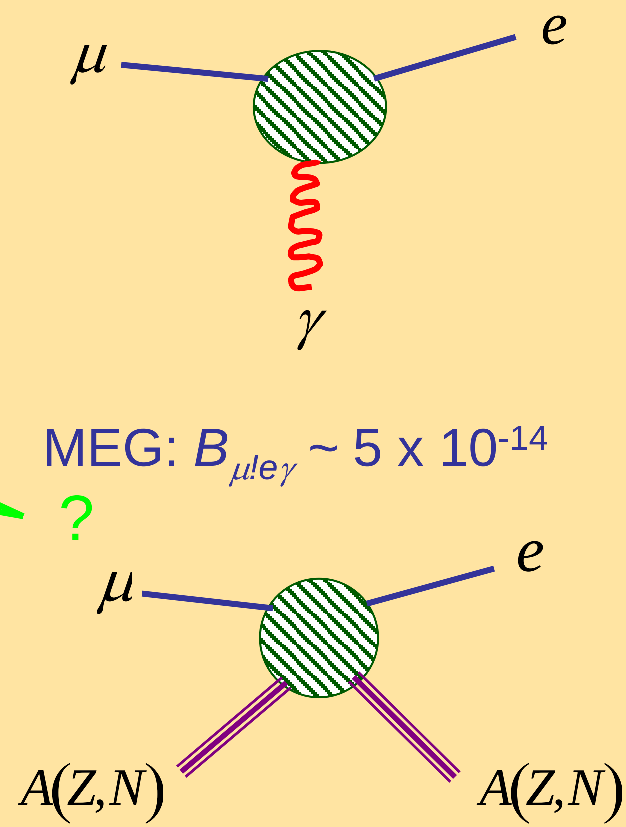
Lepton flavor: "accidental" symmetry of the SM

LFV initimately connected with LNV in most models

$$R = \frac{B_{\mu \to e}}{B_{\mu \to e\gamma}}$$



Beyond the SM



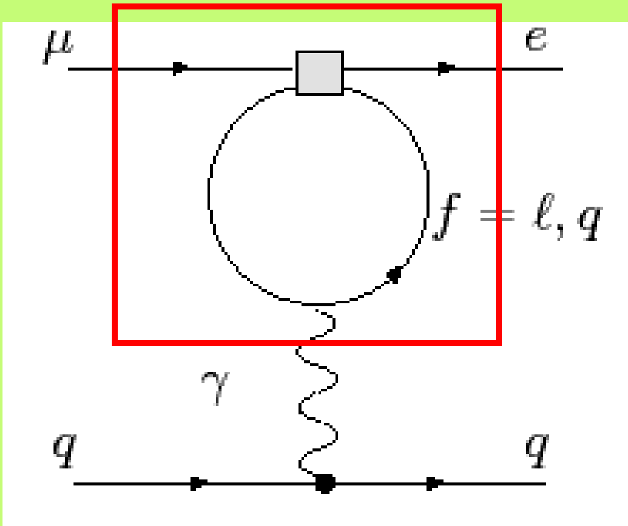
MEG: $B_{\mu \to e\gamma} \sim 5 \times 10^{-14}$

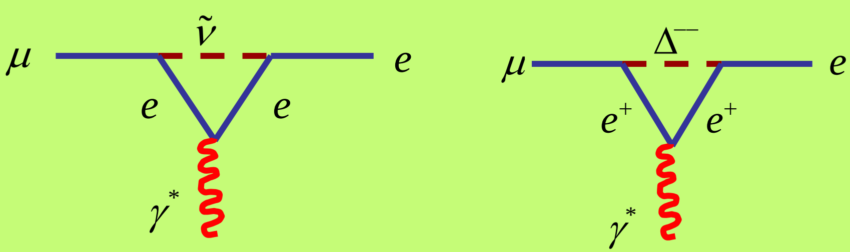
MECO: $B_{\mu \to e} \sim 5 \times 10^{-17}$

Also PRIME

LF and LN: symmetries of the early universe?

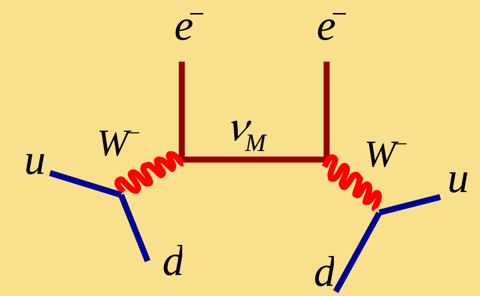
Electroweak sym
breaking: Higgs ?



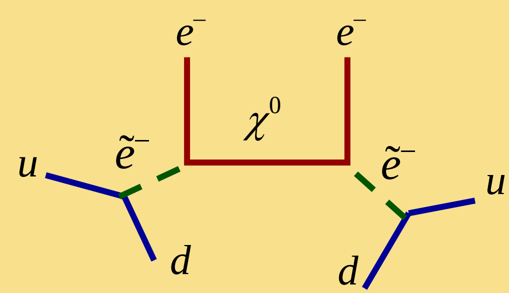


Logarithmic enhancements of *R*

$0\nu\beta\beta$ decay



Light ν_M exchange ?

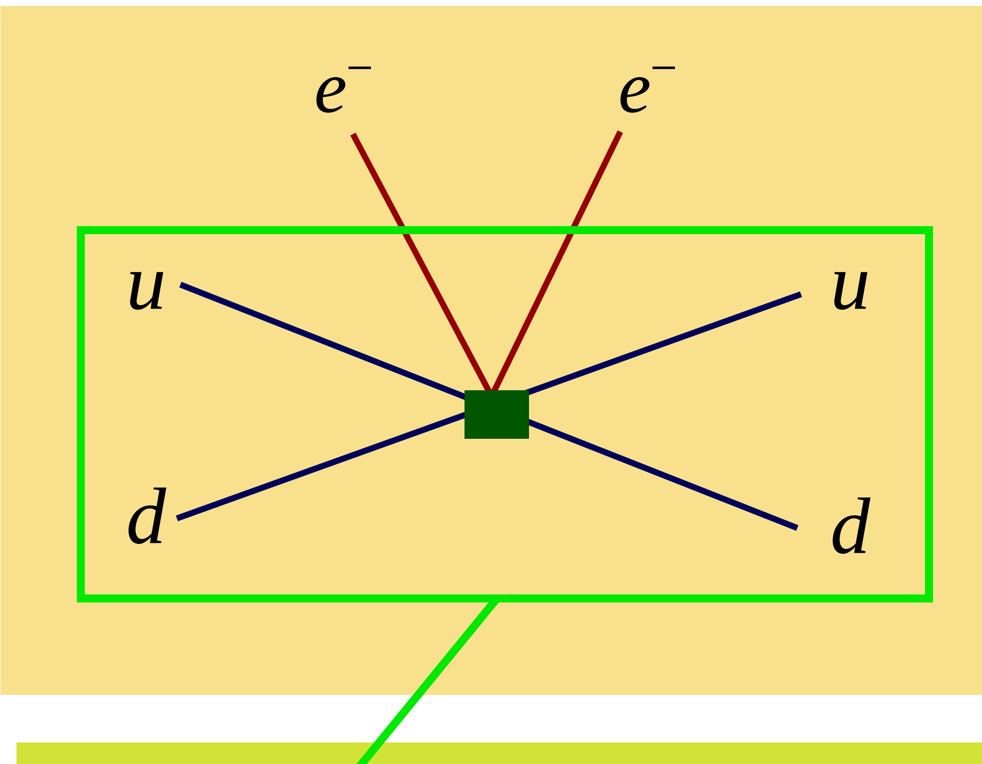


Heavy particle exchange ?

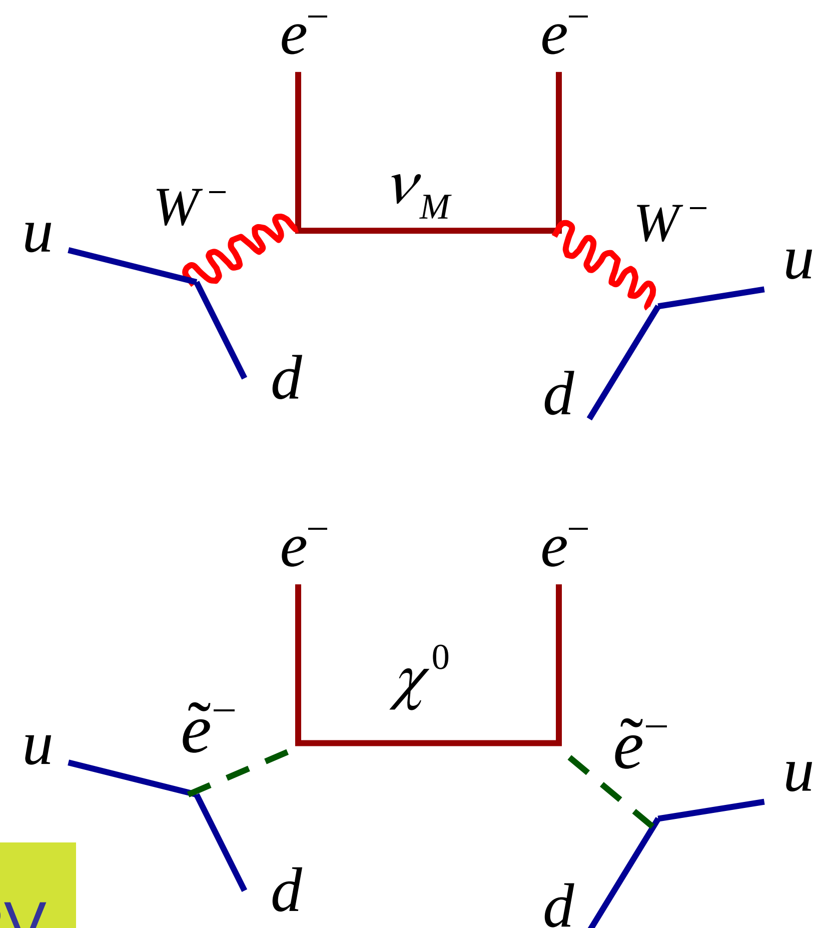
Low scale LFV: *R ~ O(1)* GUT scale LFV: *R ~ O(α)*

$0\nu\ \beta\beta$ - decay: heavy particle exchange

How do we compute & separate heavy particle exchange effects?



4 quark operator, as in hadronic PV



$0\nu\,\beta\beta$ - decay: *effective field theory*

We have a clear separation of scales

$$\Lambda_{\beta\beta} >>> \Lambda_{\chi} >> k_F$$

- L-violating new physics
- Non-perturbative QCD
- Nuclear dynamics

$0\nu\ \beta\beta$ - decay in effective field theory

Operator classification

$$\mathcal{L}(q,e) \quad ! \quad \mathcal{L}(\pi,N,e)$$

$$\mu = M_{WEAK}$$

$$\mu = M_{HAD}$$

Spacetime & chiral transformation properties

0ν ββ - decay in effective field theory

Operator classification

$$\mu = M_{WEAK}$$

$$\mathcal{L}(q,e) = \frac{G_F^2}{\Lambda_{\beta\beta}} \sum_{j=1}^{14} C_j(\mu)\, \hat{O}_j^{++}\, \bar{e}\Gamma_j e^c \quad + \quad h.c.$$

e.g.

$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^a q_L \; \bar{q}_R \gamma_\mu \tau^b q_R$$

0ν ββ - decay: ***a* = *b* = +**

$0\nu\ \beta\beta$ - decay in effective field theory

Operator classification

$$\mu = M_{WEAK}$$

$$\hat{O}^{ab}_{1+} = \bar{q}_L \gamma^\mu \tau^a q_L \ \bar{q}_R \gamma_\mu \tau^b q_R$$

Chiral transformations: $SU(2)_L \times SU(2)_R$

$$q_L \to L\, q_L \qquad q_R \to R\, q_R \qquad \begin{matrix} L \\ R \end{matrix} = \exp\left(i\, \vec{\theta}_{\substack{L \\ R}} \cdot \frac{\vec{\tau}}{2} P_{\substack{L \\ R}} \right)$$

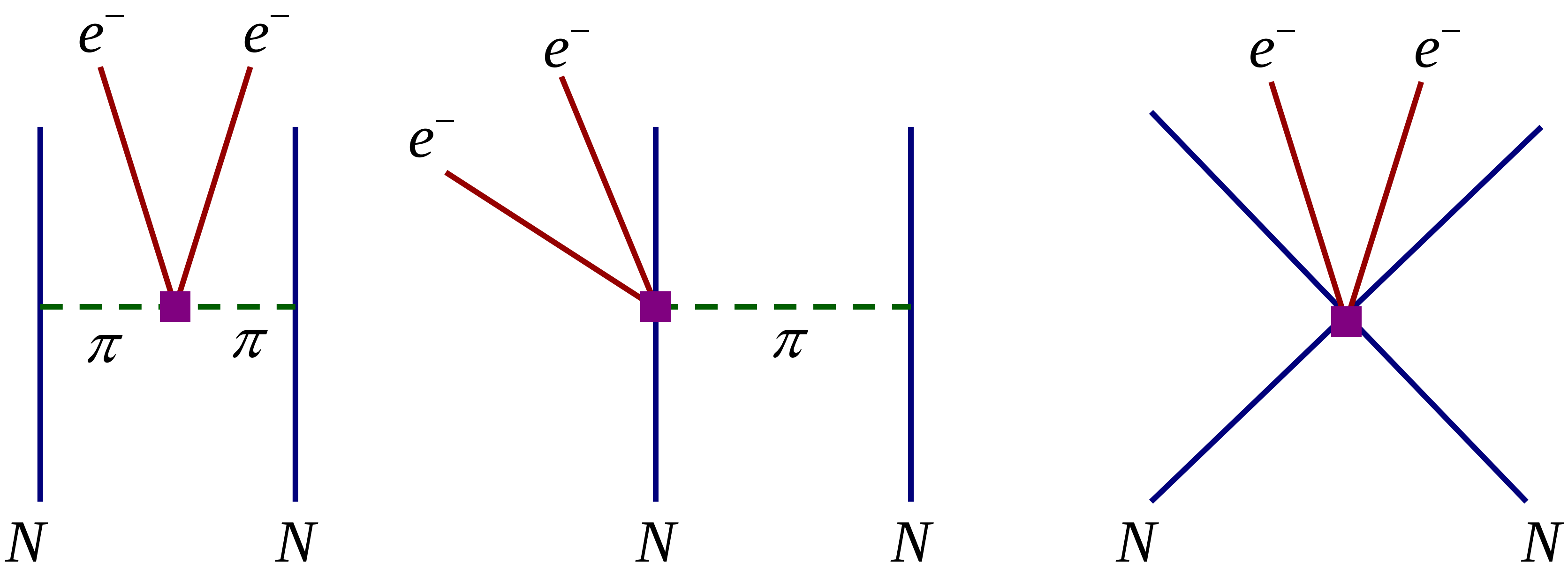
$$\hat{O}^{ab}_{1+} \in (3_L,\ 3_R)$$

Parity transformations: $q_L \leftrightarrow q_R$

$0\nu\ \beta\beta$ - decay: $\boldsymbol{a = b = +}$

$$\hat{O}^{++}_{1+} \leftrightarrow \hat{O}^{++}_{1+}$$

$0\nu\ \beta\beta$ - decay in effective field theory



$K_{\pi\pi}\ p^{-2}$

$K_{\pi NN}\ p^{-1}$

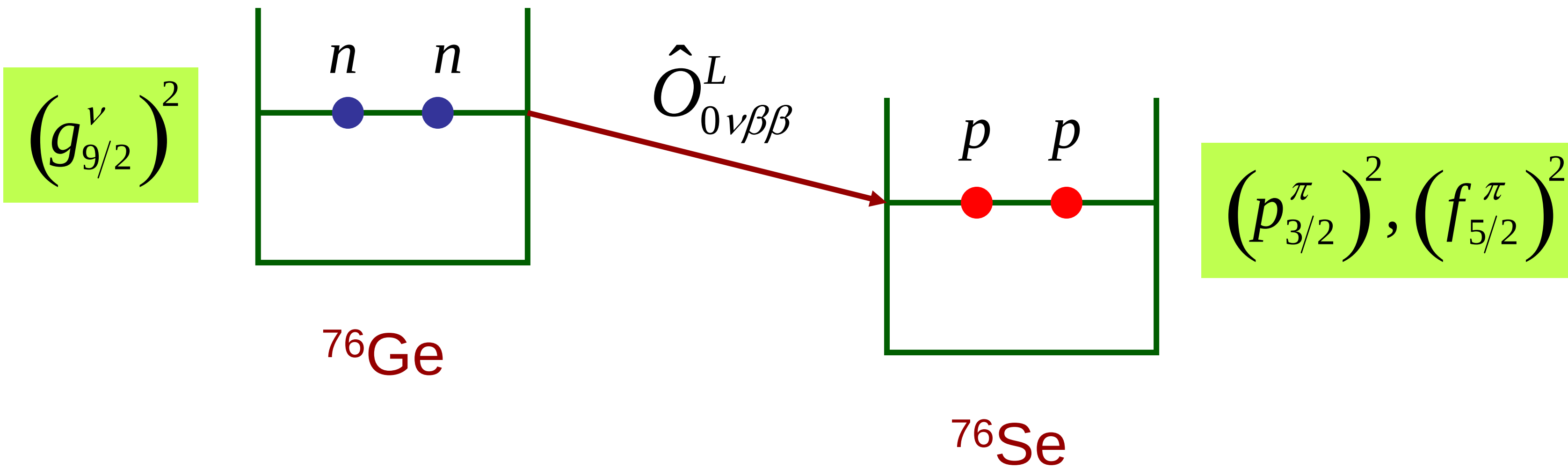
$K_{NNNN}\ p^{0}$

$\mathcal{O}(p^{-2})$ for $\hat{O}^{++}_{1+}$ $\mathcal{O}(p^{0})$ for $\hat{O}^{++}_{3+}$

Enhanced effects for some models ?

An open question

Is the power counting of operators sufficient to understand weak matrix elements in nuclei ?



$\mathbb{L} = 0,\ldots,9$ $\qquad$ $\mathbb{L}' = 0,\ldots,5$

An open question

Is the power counting of operators sufficient to understand weak matrix elements in nuclei ?

$\mathbb{L} = 0, \ldots, 9$ $\qquad \hat{O}^{L}_{0\nu\beta\beta}$ $\qquad \mathbb{L}' = 0, \ldots, 5$

naive

M_{fi}	$\sim$	p^0	$\mathbb{L} = \mathbb{L}' = 0$	$\hat{O}^{L=0}_{0\nu\beta\beta}$
M_{fi}	$\sim$	p^2	$\mathbb{L} = 2, \mathbb{L}' = 0$	$\hat{O}^{L=2}_{0\nu\beta\beta}$
M_{fi}	$\sim$	p^2	$\mathbb{L} = 0, \mathbb{L}' = 2$	$\hat{O}^{L=2}_{0\nu\beta\beta}$
M_{fi}	$\sim$	p^4	$\mathbb{L} = 4, \mathbb{L}' = 0$	$\hat{O}^{L=4}_{0\nu\beta\beta}$ etc.

An open question

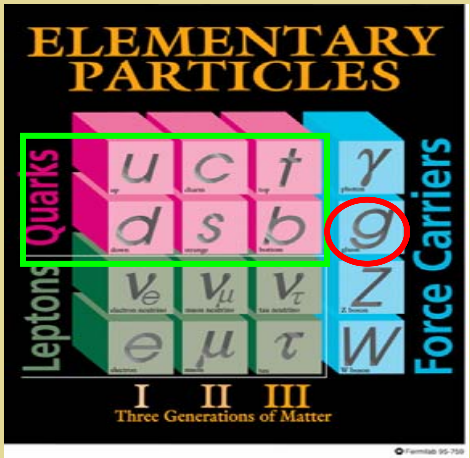
Complications:

- Bound state wavefunctions (*e.g., h.o.)* don't obey simple power counting
- Configuration mixing is important in heavy nuclei

Is the power counting of operators sufficient to understand weak matrix elements in nuclei ?

- *More theoretical study required (RIA)*
- *Hadronic PV may provide an empirical test*

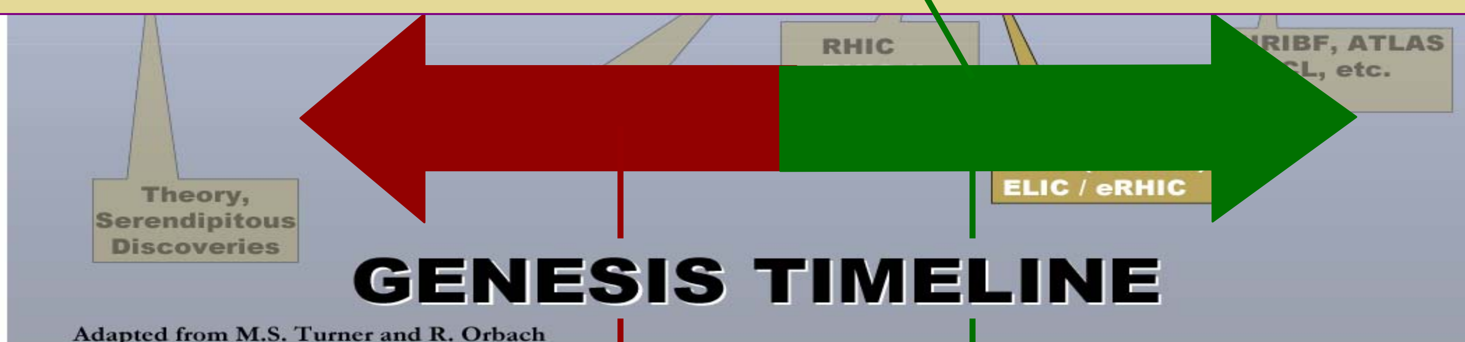
Fundamental Symmetries & Cosmic History



Standard Model "unfinished business"

How does QCD affect the weak qq interaction?

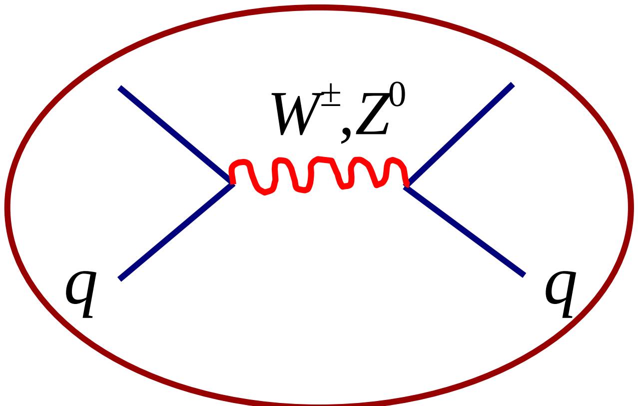
Is there a long range weak NN interaction?



Beyond the SM

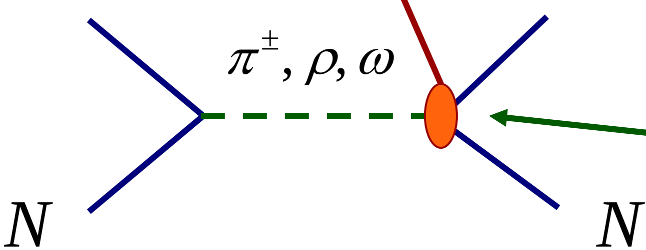
SM symmetry (broken)

The weak qq force is short range



$$\lambda_{W,Z} \sim 0.002\, fm \ll R_{COR}$$

Meson-exchange model



Seven PV meson-nucleon couplings

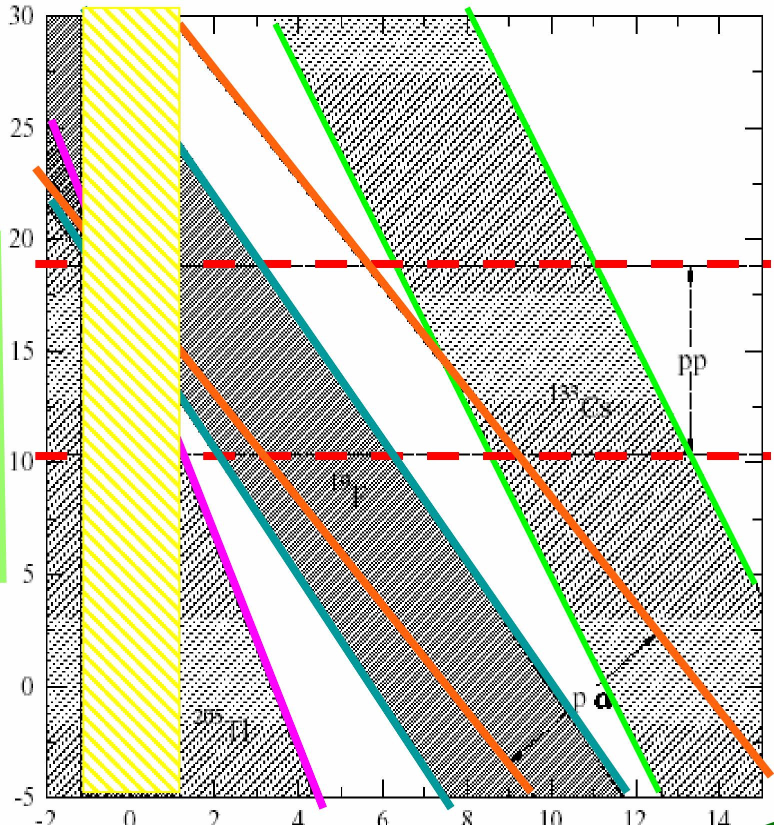
$$h_\pi^1,\ h_\rho^{0,1,2},\ h_\omega^{0,1},\ h_\rho^{1\prime}$$

Use parity-violation to filter out EM & strong interactions

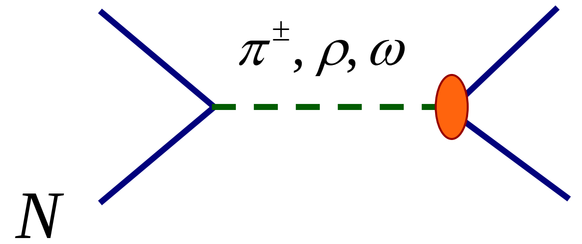
Desplanques, Donoghue, &Holstein (DDH)

Is the weak NN force short range ?

T=0 force

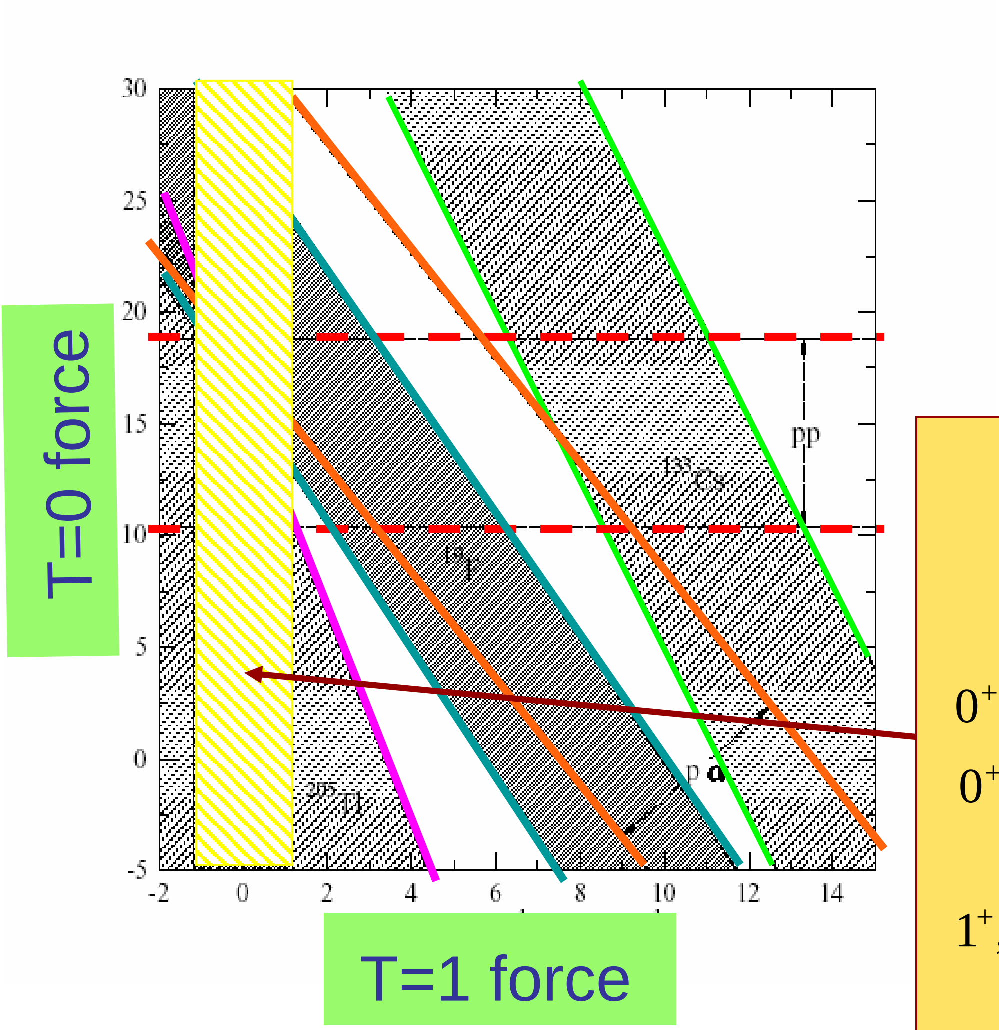


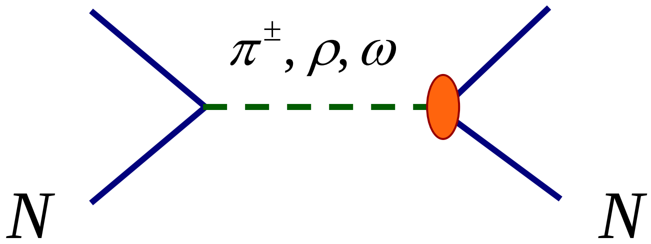
T=1 force

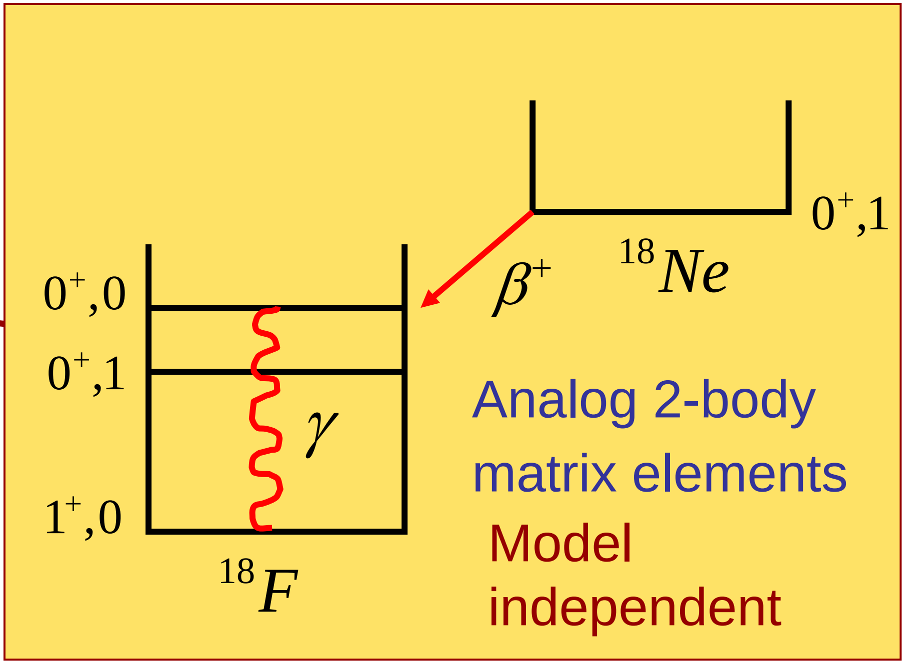


Long range: π-exchange?

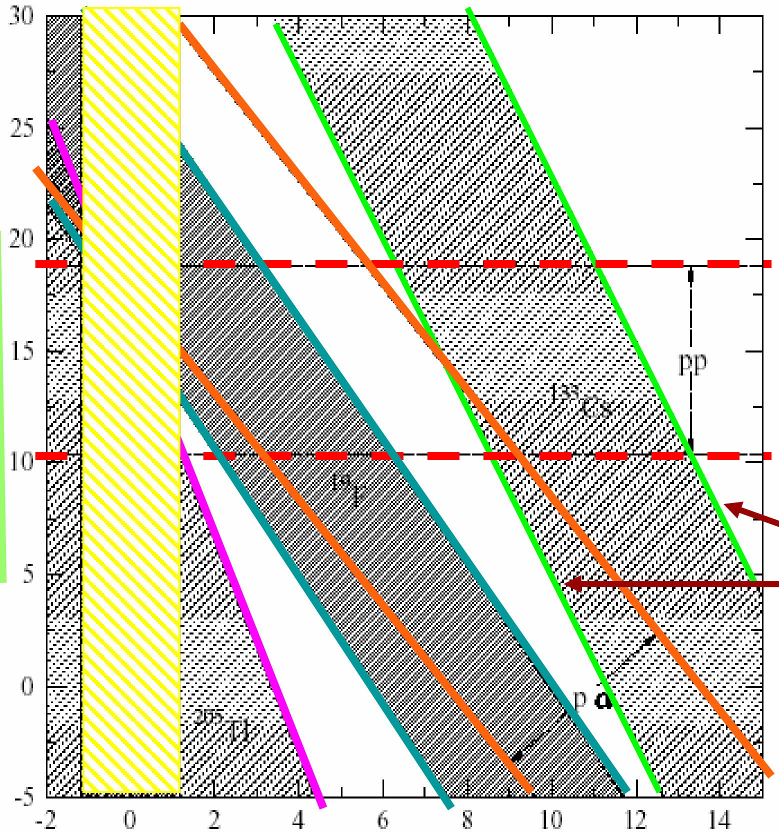
Is the weak NN force short range ?





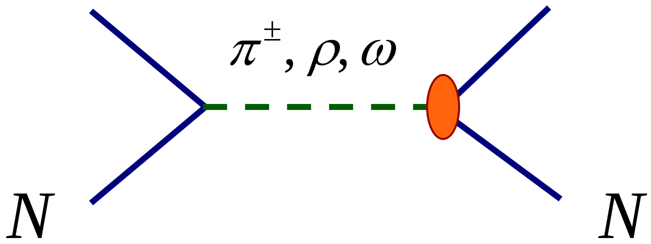


Is the weak NN force short range ?



T=0 force

T=1 force

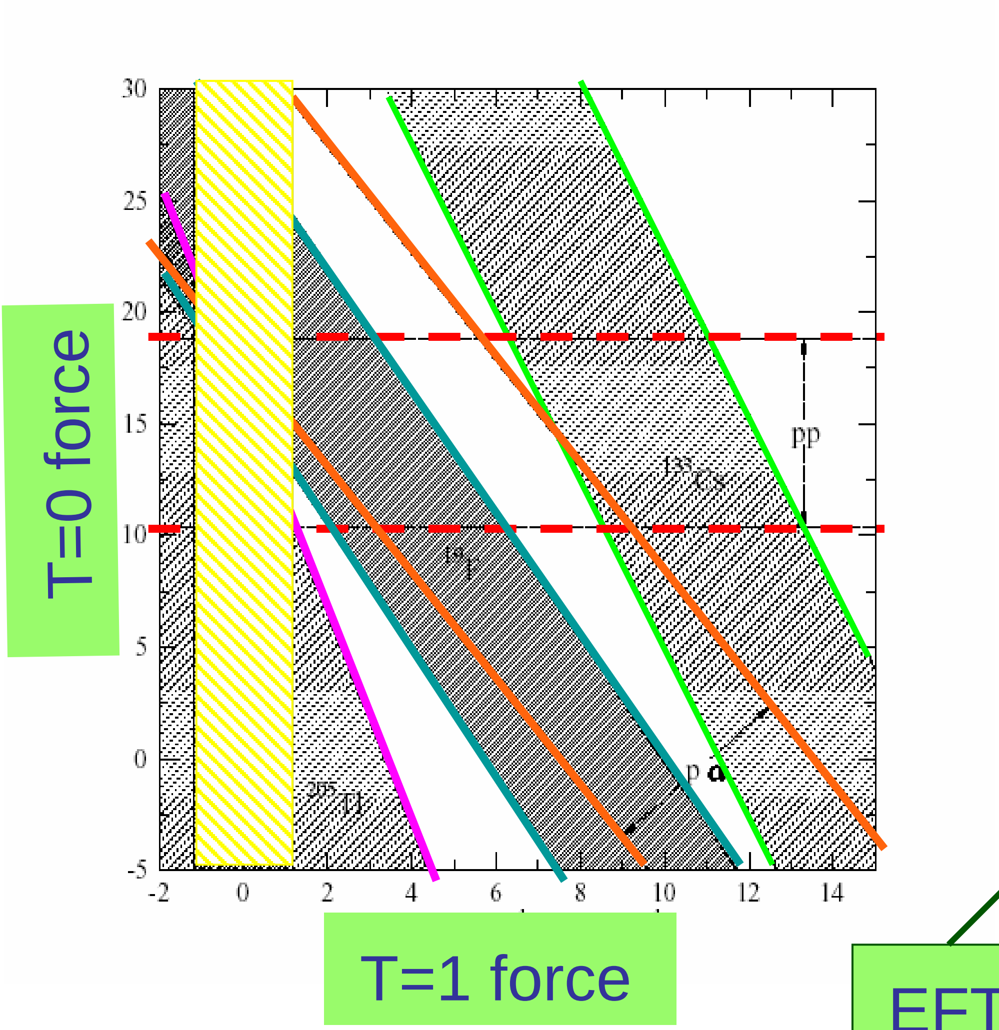


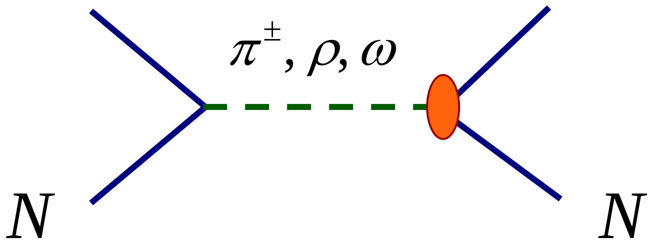
^{133}Cs Anapole moment

Boulder, atomic PV

$h_\pi \sim 10\ g_\pi$

Is the weak NN force short range ?



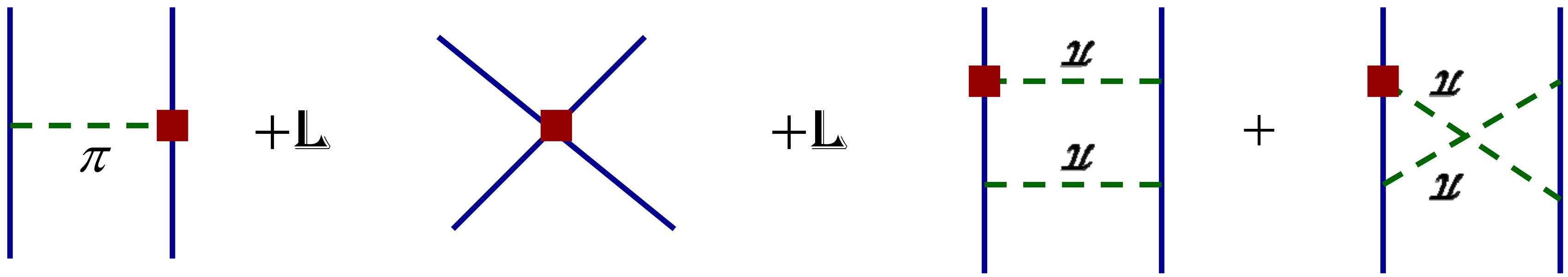


- Problem with expt's
- Problem with nuc th'y
- Problem with model
- No problem (1σ)

EFT

Hadronic PV: Effective Field Theory

PV Potential



Long Range | Short Range | Medium Range

$h^1_{\pi NN}$ $k^{1a}_{\pi NN}$ $\lambda_s^{1,2,3},\ \lambda_t,\ \rho_t$ $h^1_{\pi NN}$

$O(p^{-1})$ $O(p)$ $O(p)$ $O(p)$

A program of few-body measurements

Pionless theory | *Ab initio few-body calcs*

$$m_N \lambda_{pp} = -1.22 A_L(\vec{p}p)$$

$$m_N \rho_t = -9.35 A_L(\vec{n}p \to d\gamma)$$

$$m_N \lambda_{pn} = 1.6 A_L(\vec{p}p) - 3.7 A_L(\vec{p}\alpha) + 37 A_\gamma(\vec{n}p \to d\gamma) - 2 P_\gamma(\vec{n}p \to d\gamma)$$

$$m_N \lambda_t = 0.4 A_L(\vec{p}p) - 0.7 A_L(\vec{p}\alpha) + 7 A_\gamma(\vec{n}p \to d\gamma) + P_\gamma(\vec{n}p \to d\gamma)$$

$$m_N \lambda_{nn} = 1.6 A_L(\vec{p}p) - 0.7 A_L(\vec{p}\alpha) + 33.3 A_\gamma(\vec{n}p \to d\gamma) - 1.08 P_\gamma(\vec{n}p \to d\gamma) + 0.83 \frac{d\phi_{n\alpha}}{dz}$$

Done

LANSCE

HARD*

NIST

$$\lambda_{pp} = \lambda_s^0 + \lambda_s^1 + \lambda_s^2 / \sqrt{6}$$

$$\lambda_{nn} = \lambda_s^0 - \lambda_s^1 + \lambda_s^2 / \sqrt{6}$$

$$\lambda_{pn} = \lambda_s^0 - 2 \lambda_s^2 / \sqrt{6}$$

*HIGS $A_L(\vec{\gamma}d \to np)$

A program of few-body measurements

Complete determination of PV NN & γNN interactions through $\mathcal{O}$(p)

Attempt to understand the λ^i, h_π *etc.* from QCD

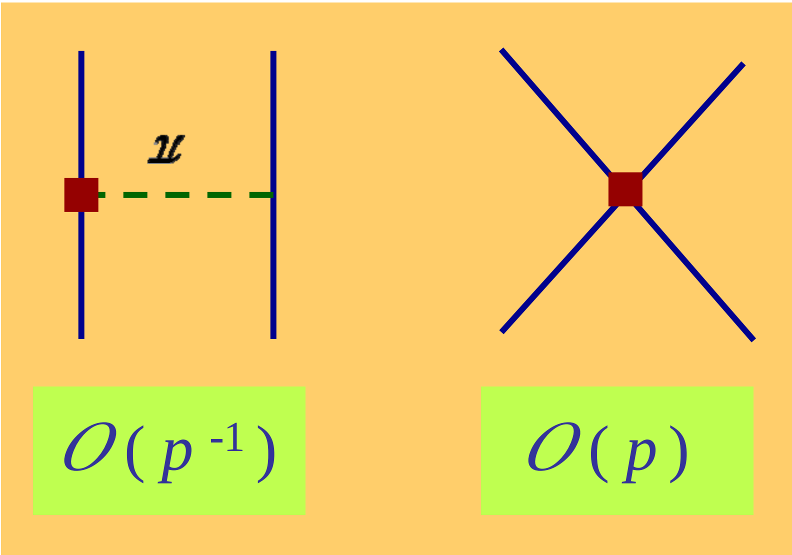
Attempt to understand *nuclear* PV observables systematically

Are the PV LEC's "natural"?

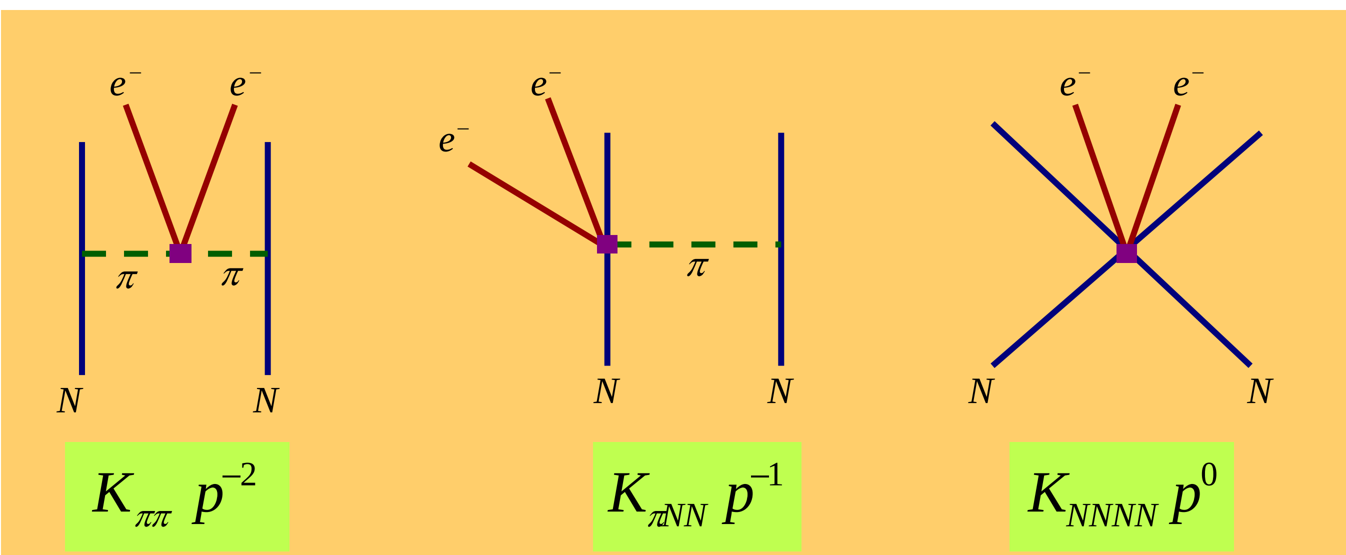
Does EFT power counting work in nuclei ?

Hadronic PV in n-rich nuclei ?

Hadronic PV as a probe



- Determine V_{PV} through $\mathcal{O}$(p) from PV low-energy *few-body* studies where power counting works
- Re-analyze *nuclear* PV observables using this V_{PV}



Conclusions

- *Nuclei provide unique and powerful laboratories in which to probe the fundamental symmetries of the early universe*
- *RIA will provide opportunities to carry out new and complementary experiments whose impact can live on well into the LHC era*
- *A number of theoretical challenges remain to be addressed at the level of field theory, QCD, and nuclear structure*
- *New experimental and theoretical efforts in nuclear structure physics are a key component of this quest*