Fundamental Symmetries & Neutrinos: Beyond the Standard Model

M.J. Ramsey-Musolf

U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

DNP Town Meeting, Chicago
September 2014

The Nuclear Physics Opportunity

- *Nuclear physics studies of fundamental symmetries & neutrinos provide a unique window into deep mysteries about the fundamental laws of nature*
- *A targeted program of nuclear physics experiments and theoretical studies are poised to make significant discoveries and provide key insights about the new Standard Model of fundamental interactions*
- *The opportunities for both discovery and insight are stronger and more compelling than ever*

Goals for this talk

- *Set the context for town meeting discussion: What are key scientific questions & how do they fit in the broader context ?*
- *Highlight compelling opportunities for NP*
- $0\nu\beta\beta$ *– decay & EDMs: Articulate implications of either discovery or null results & identify benchmark sensitivities and time scales to maintain relevance*
- *Highlight key theoretical challenges that must be addressed to fully realize impact of experiments*

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*** Theory landscape for other topics addressed by subsequent speakers*

Outline

I. *Fundamental symmetries & neutrinos: the BSM context*

II. $0\nu\beta\beta$ *- decay*

III. *Electric dipole moments*

IV. *Outlook*

I. The BSM Context

Scientific Questions

2007 NSAC LRP:

- *What are the masses of neutrinos and how have they shaped the evolution of the universe?*
- *Why is there more matter than antimatter in the present universe?*
- *What are the unseen forces that disappeared from view as the universe cooled?*

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- *Is lepton number a good symmetry of nature ?*
- *What is the scale Λ of neutrino mass generation ? Traditional see-saw scale ? TeV scale ?*
- *Do dynamics of neutrino mass generation provide ingredients for baryogenesis via leptogenesis ?*

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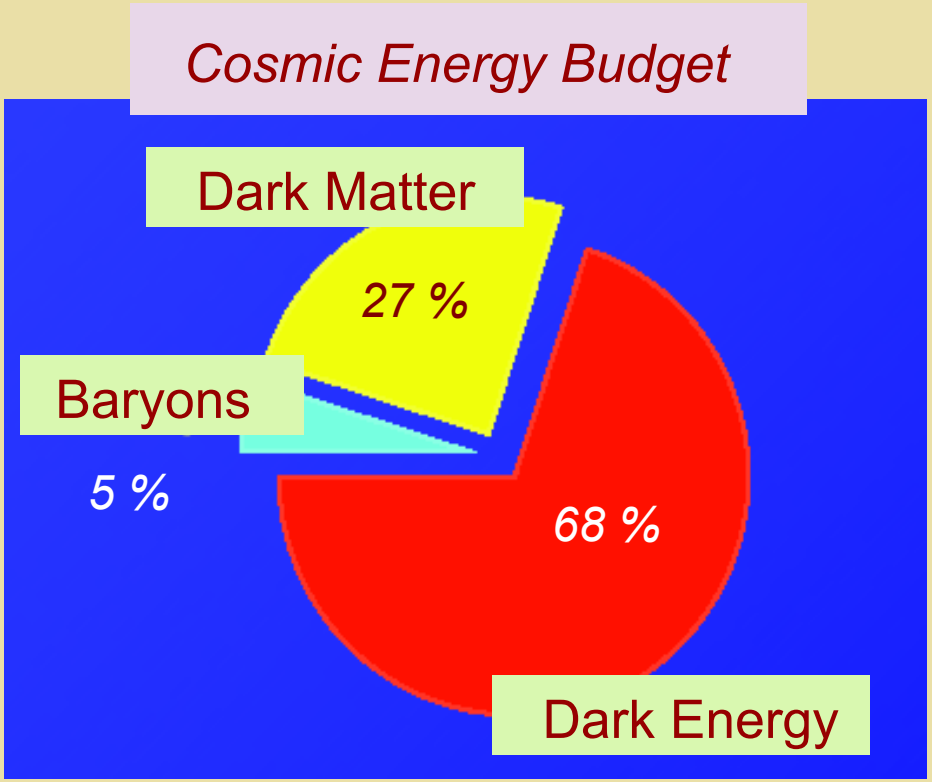
The Origin of Matter



Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

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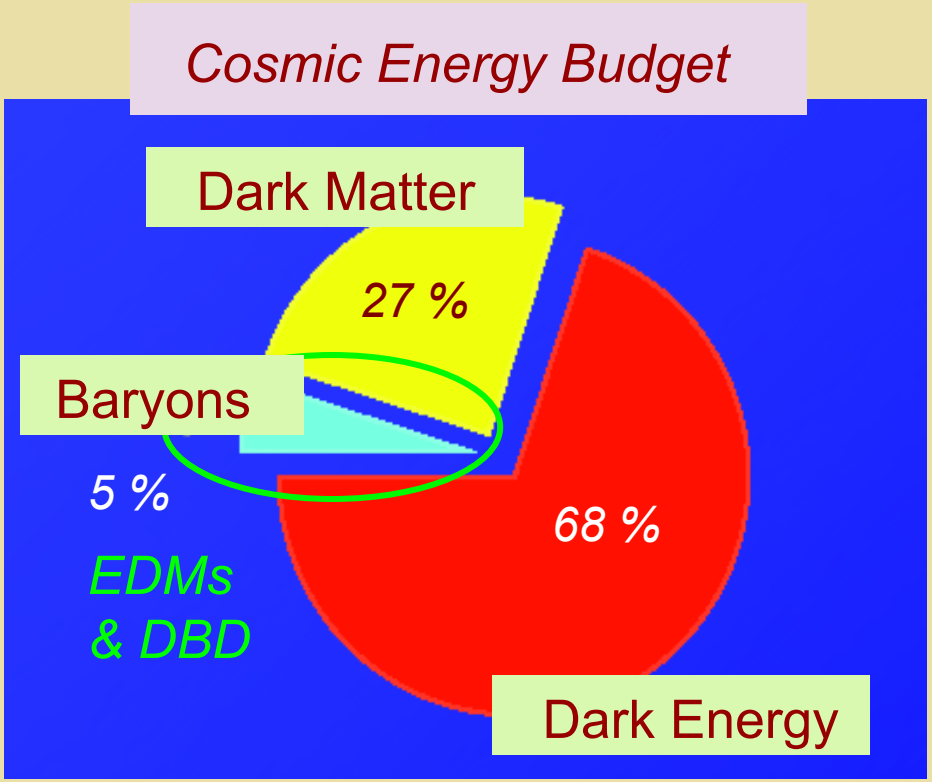

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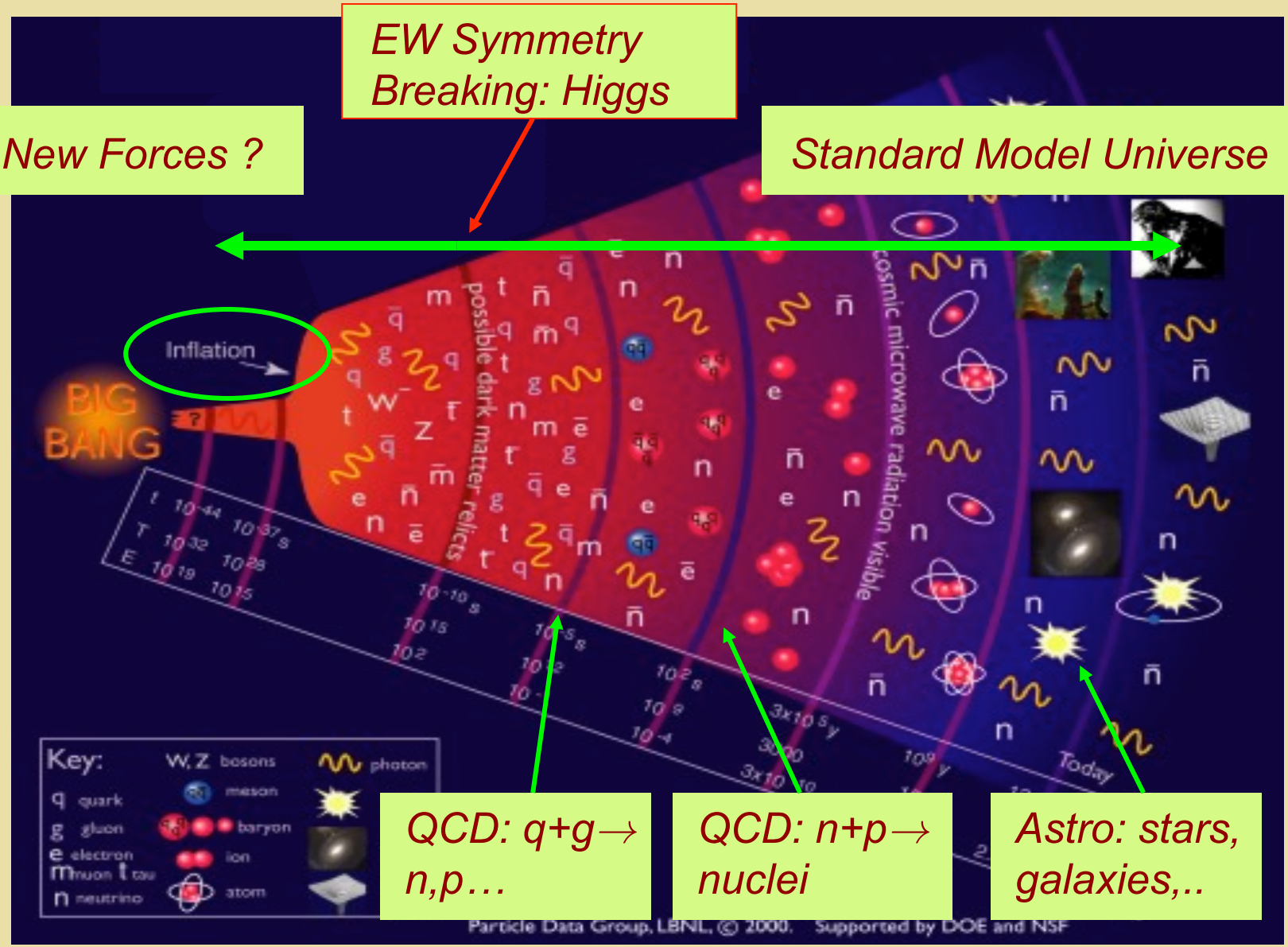
Symmetries & Cosmic History



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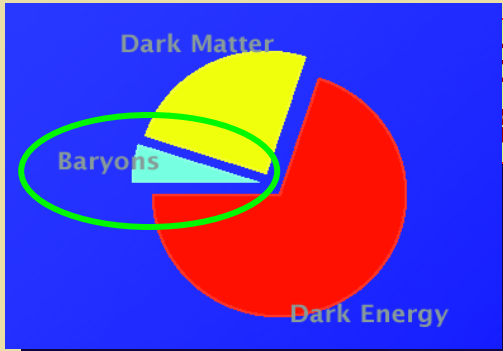
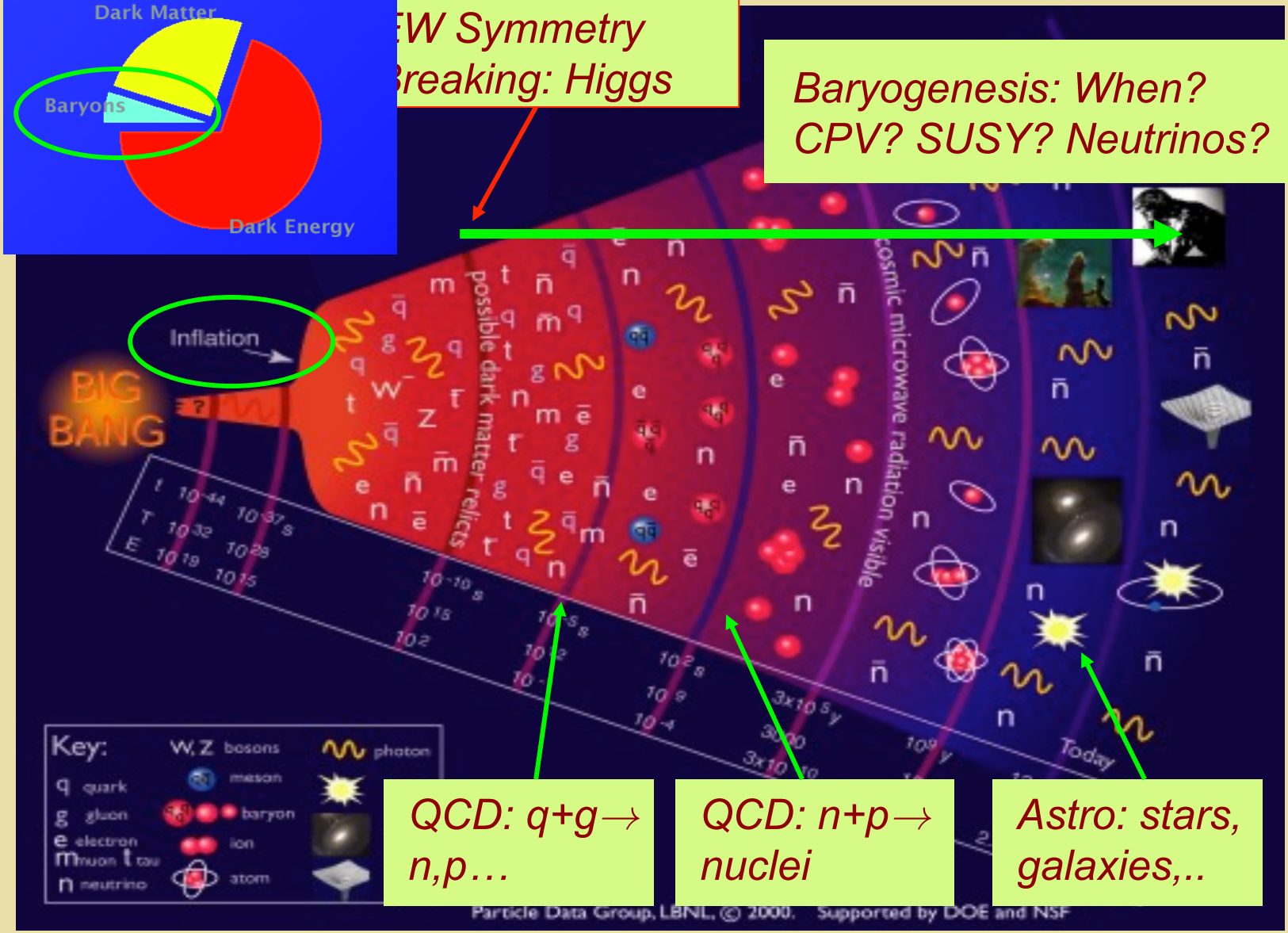


EW Symmetry Breaking: Higgs

Baryogenesis: When? CPV? SUSY? Neutrinos?



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Astro: stars, galaxies,..

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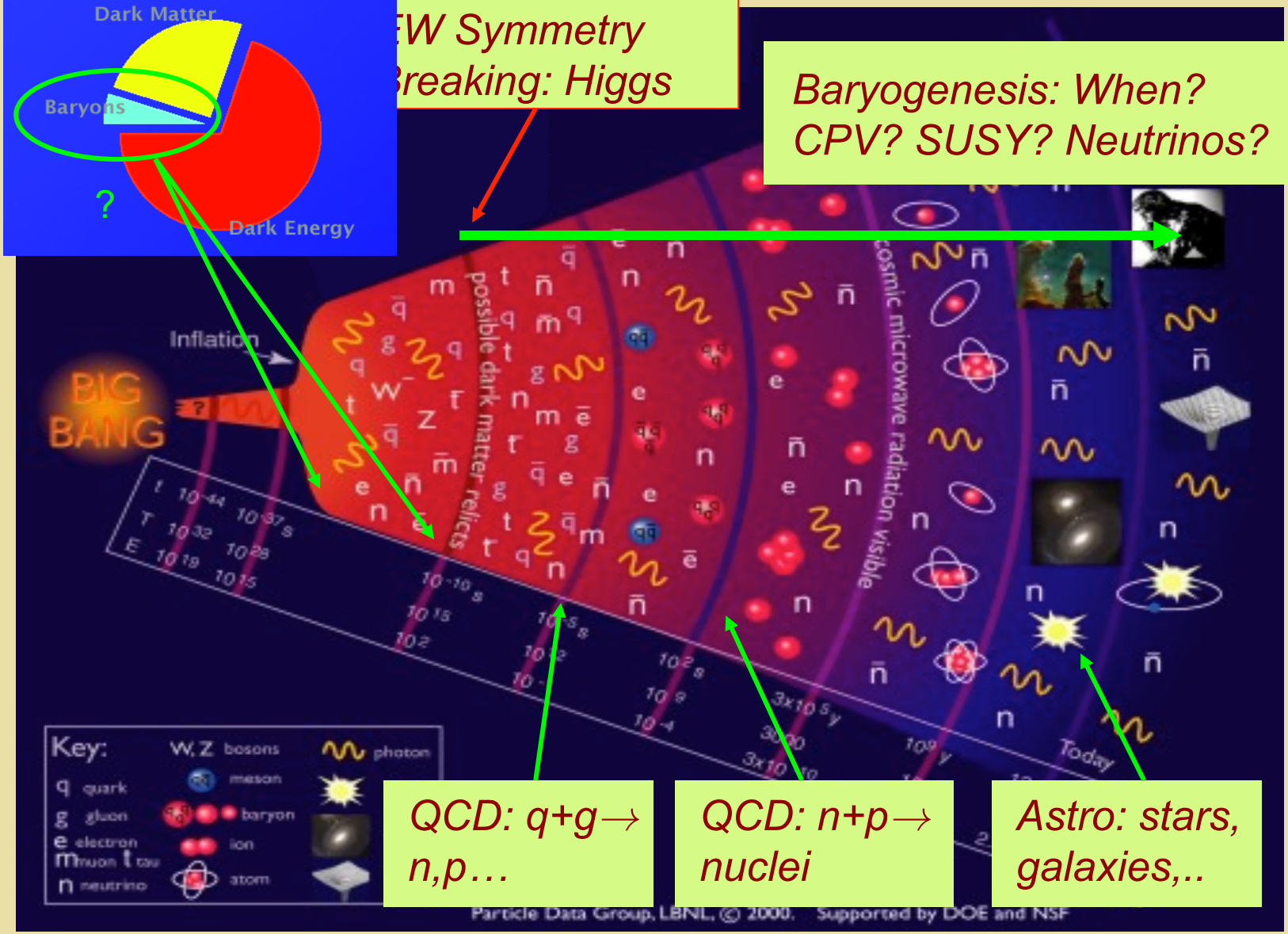

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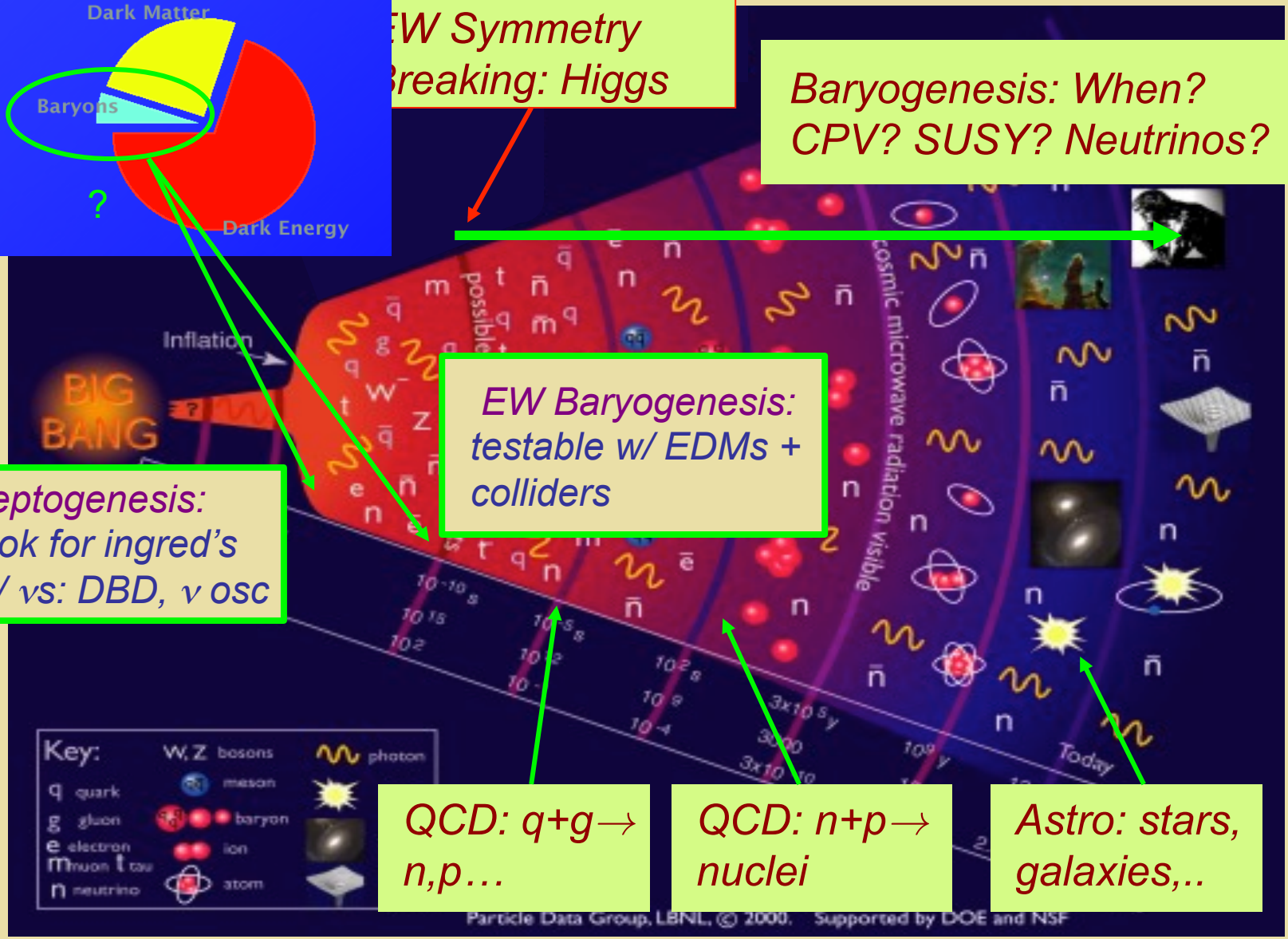

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EW Baryogenesis: testable w/ EDMs + colliders

Leptogenesis: look for ingred's w/ νs: DBD, ν osc

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The BSM Context: LHC Developments

- *Observation of Higgs-like scalar*
- *Non-observation of BSM particles*

The BSM Context: Questions

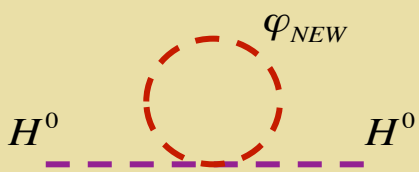
- *What are the BSM interactions and what is the associated mass scale?*
- *Are fundamental interactions "natural" ?*

Higgs Discovery

Higgs Discovery: Naturalness ?

Scalar fields are a simple

Scalar fields are theoretically problematic



$\Delta m^2 \sim \lambda \Lambda^2$

Discovery of a (probably) fundamental 125 GeV scalar :

Is it telling us anything about Λ ? Naturalness?

Higgs Discovery: Implications

✧ *Are fundamental interactions "natural" ?*

Are there new interactions that maintain naturalness (e.g., SUSY) ?

✧ *Is there an extended scalar sector ?*

Do its interactions conserve CP and/or lepton number ?

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Nothing else seen at LHC thus far

LHC Implications

- *Weak scale BSM physics (e.g., SUSY) is there but challenging for the hadronic collider*
- *BSM physics is there but a bit heavy (some fine tuning)*
- *We are thinking about the problem incorrectly (cosmological constant???)*

LHC Implications & Open Questions

- *Where are the new interactions ?*
- *What is the associated mass scale ? (Weak scale but compressed ? Ultralight ? Heavy ?)*
- *What fundamental symmetries do new interactions respect ? (Lepton number ? CP ? Lepton flavor ? Baryon number ?)*

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Compelling opportunity for nuclear physics !

The Nuclear Physics Program

Targeted program of experiments & theory

- *Nature of the neutrino & search for lepton number violation*
- *Yet unseen T-violation (CP-violation)*
- *Other key ingredients of the "New Standard Model"*

Four Components **

EDM searches: *BSM CPV, Origin of Matter*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

*** 2012 NSAC Subcommittee Report*

Four Components

This talk

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Subsequent speakers

II. $0\nu\beta\beta$ - Decay

- *Discovery potential & its significance*
- *Benchmark sensitivities*
- *Implications of null results & interplay with other experiments*
- *Challenges & opportunities for theory*

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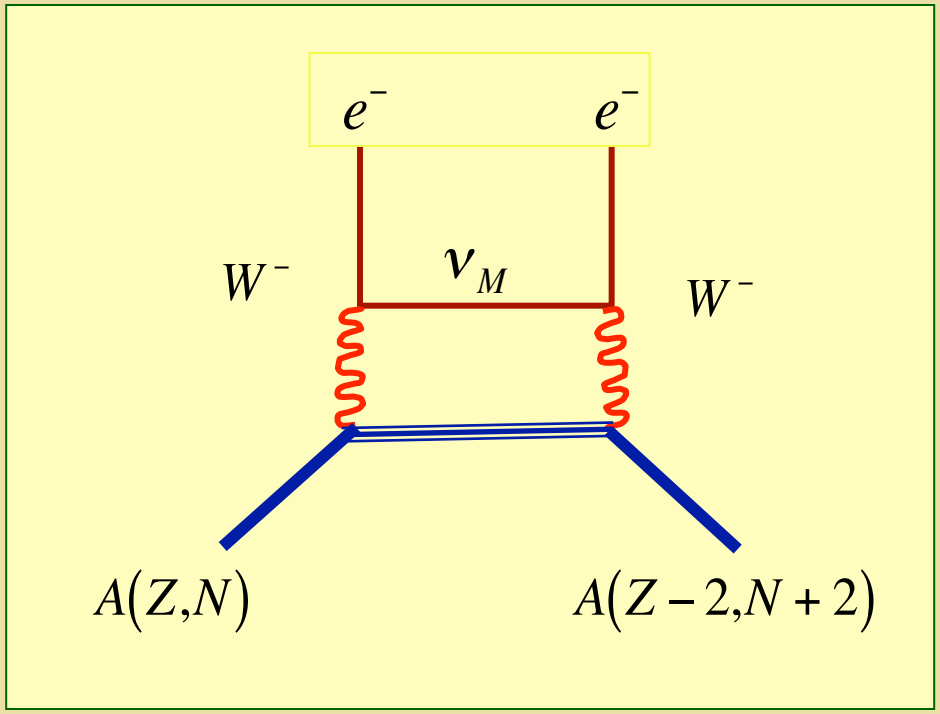

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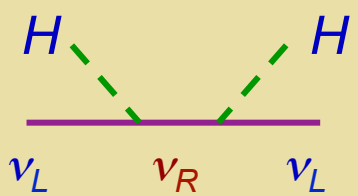
See-saw mechanism

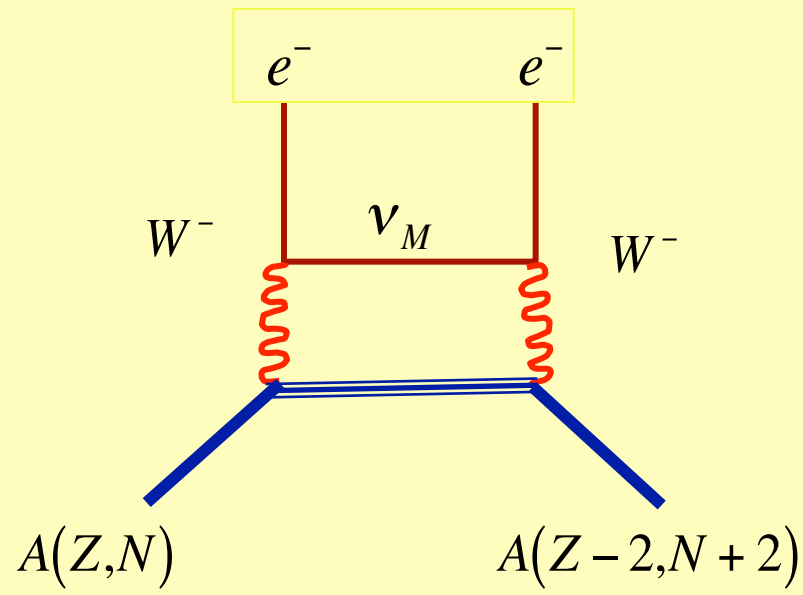


$$m_\nu = \frac{m_D^2}{M_R}$$

Leptogenesis

$$\Gamma(\nu_R \to \ell H) \;\neq\; \Gamma(\nu_R \to \bar{\ell} H^*)$$

Lepton Asym -> Baryon Asym



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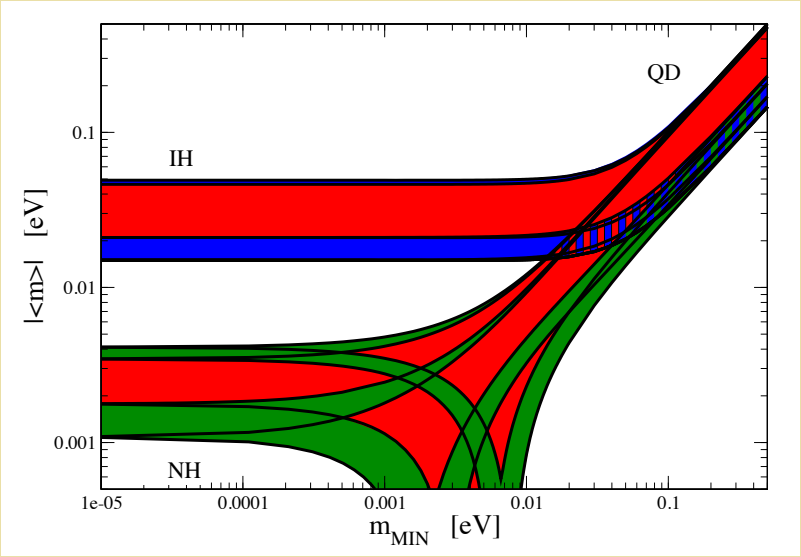

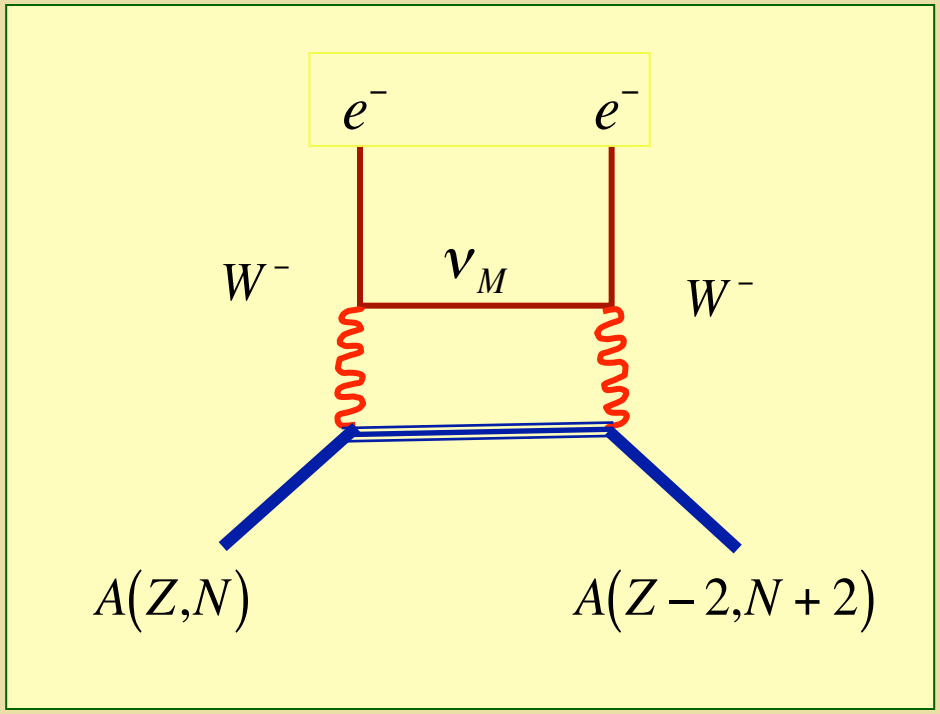

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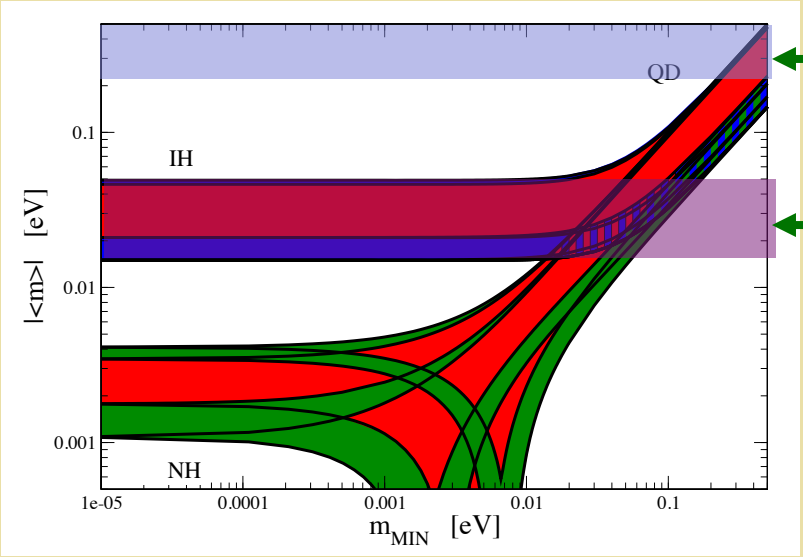

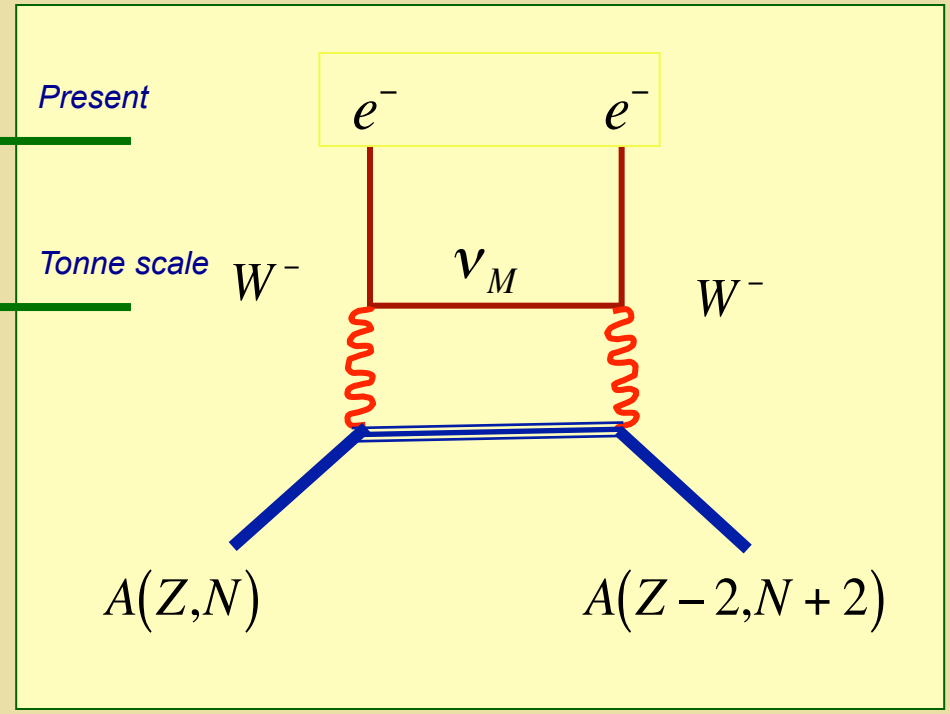

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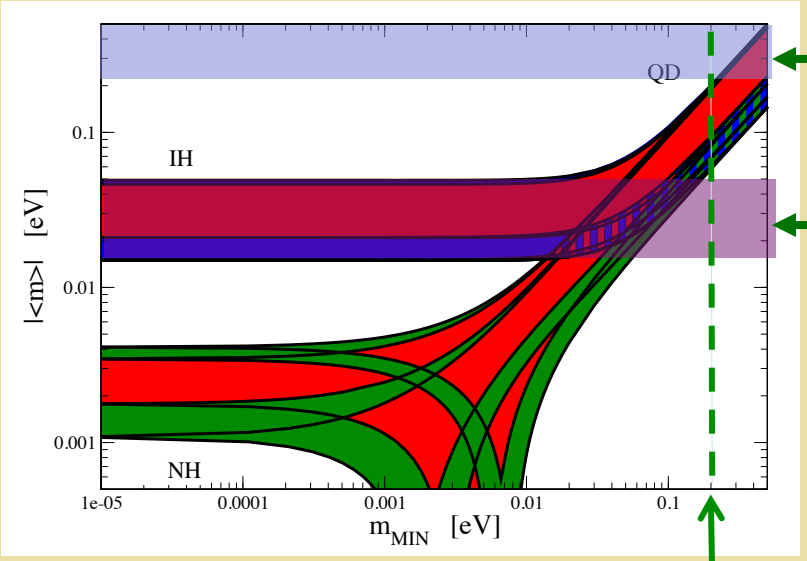
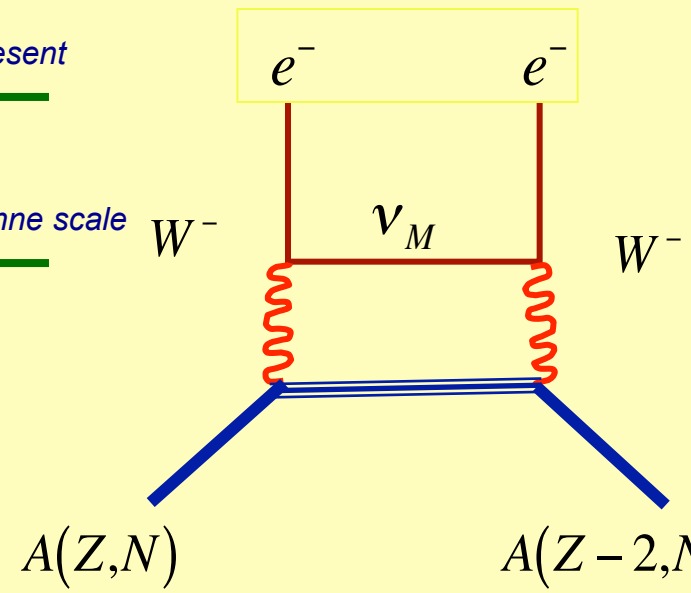


KATRIN

Present

Tonne scale



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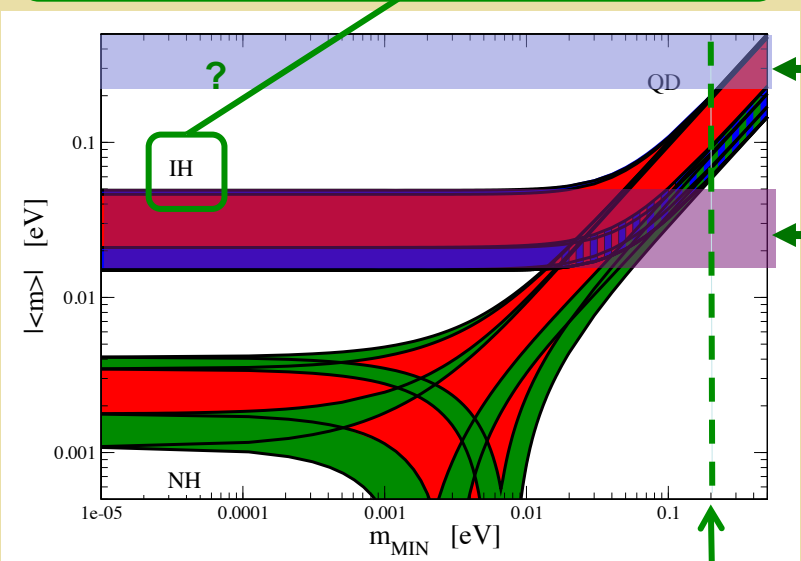

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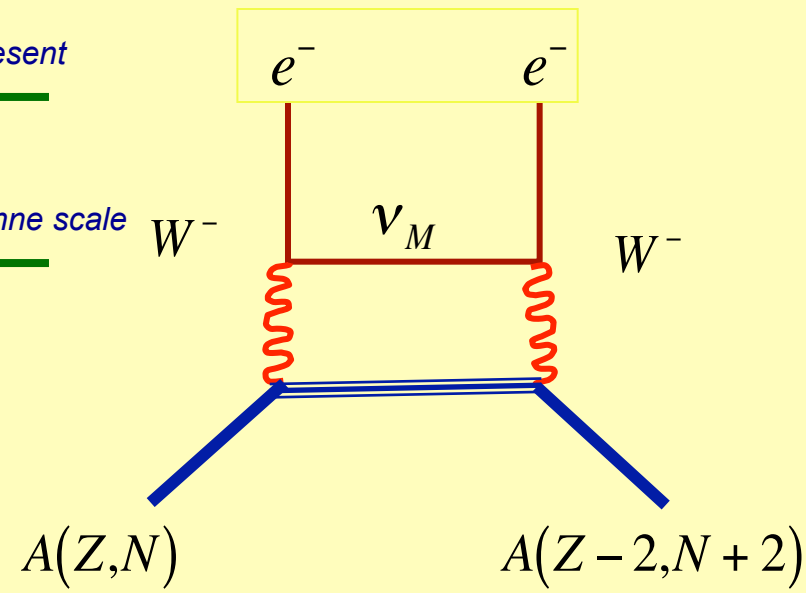

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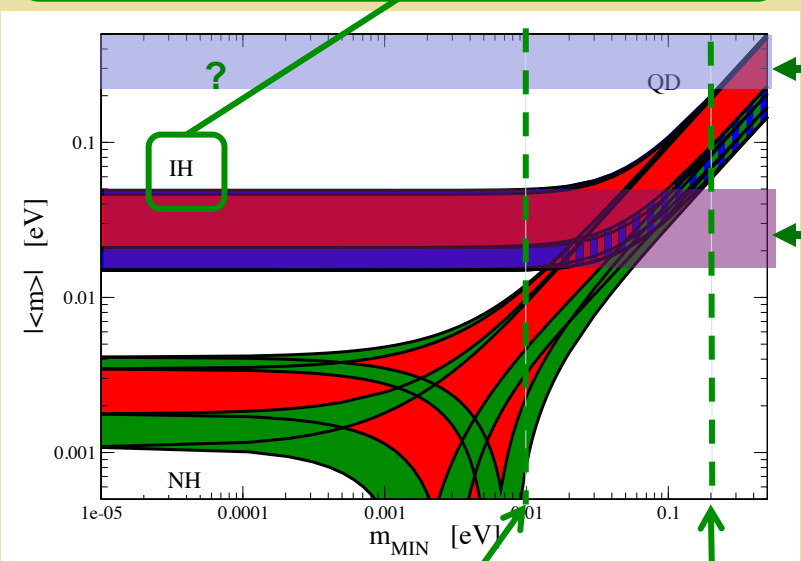

Cosmo future ?

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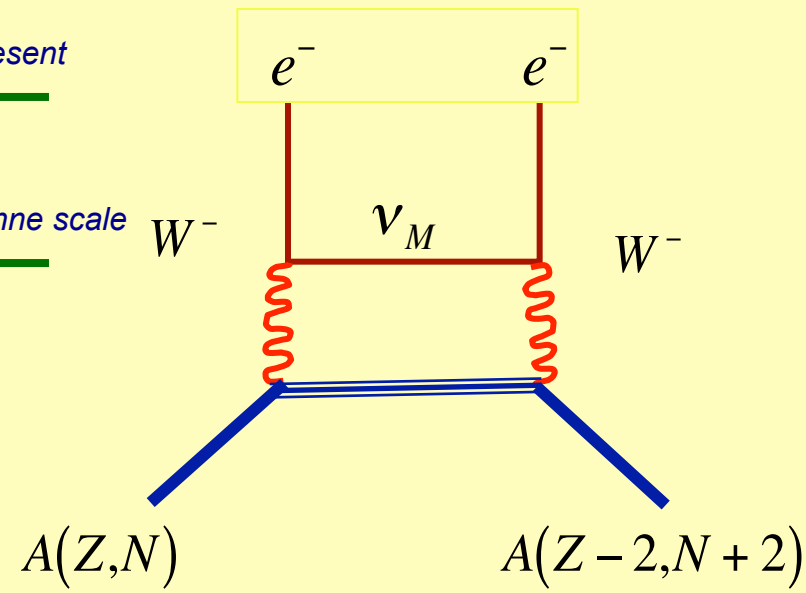

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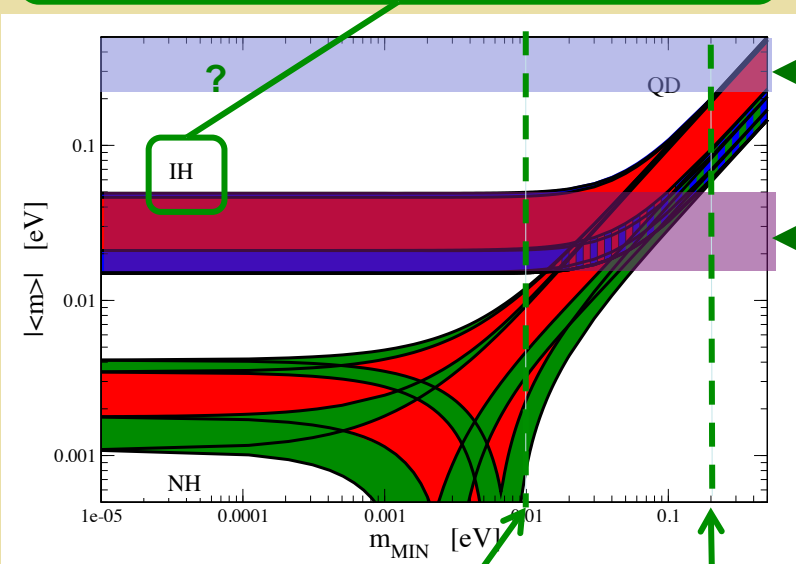

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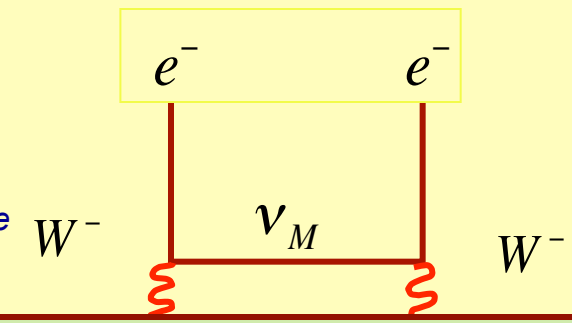

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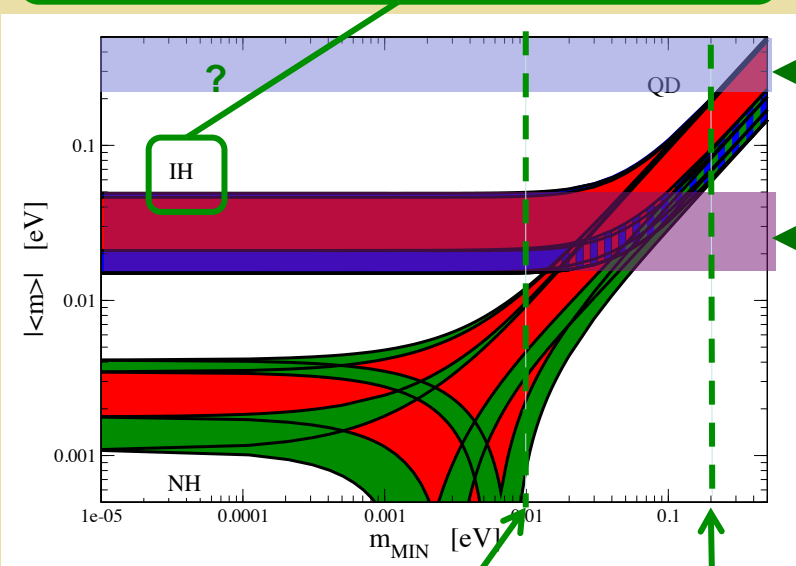

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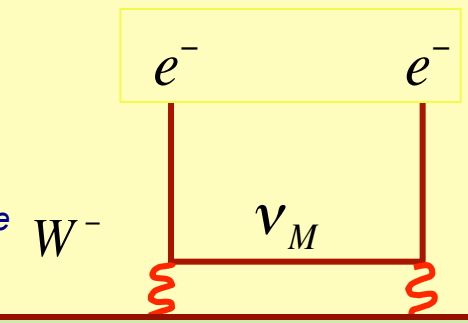

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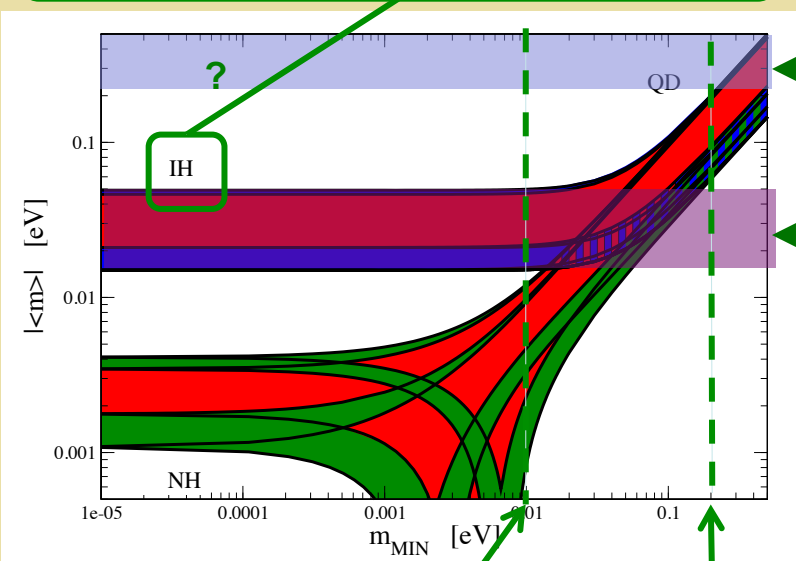

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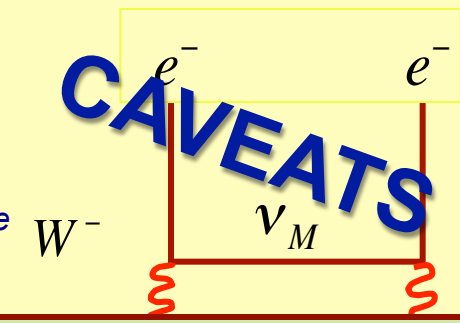

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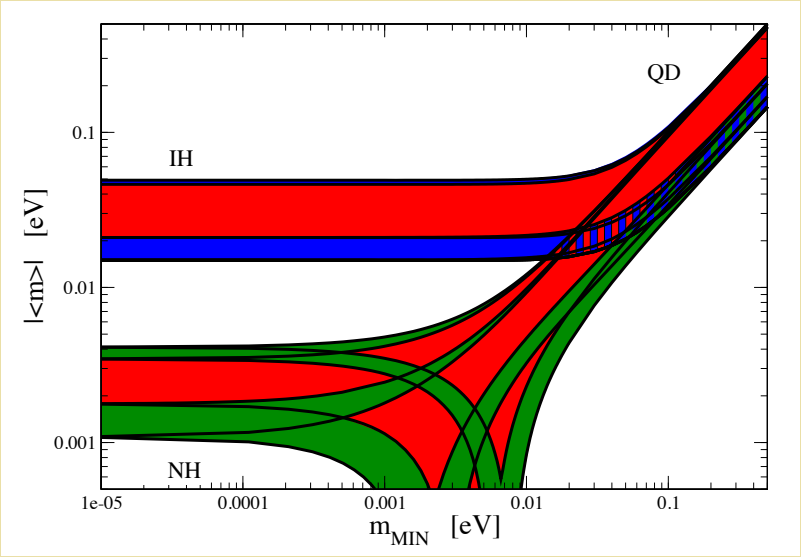
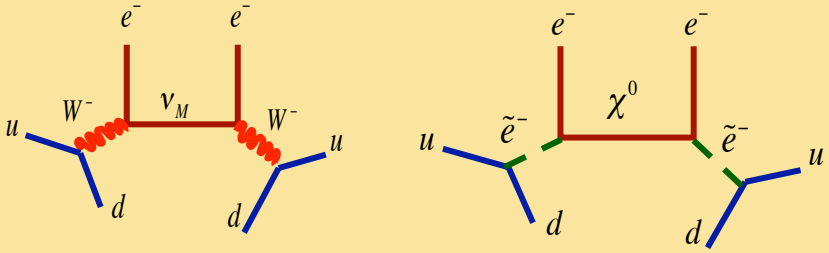


Theory Challenge: matrix elements + mechanism

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



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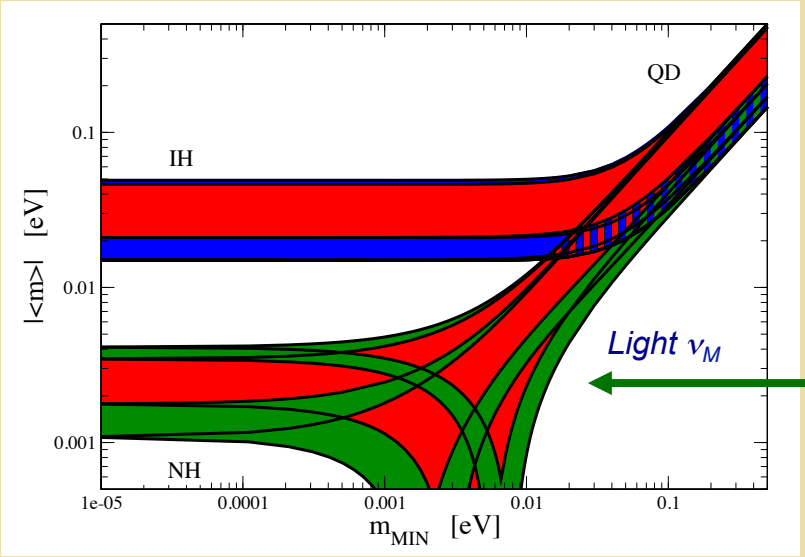

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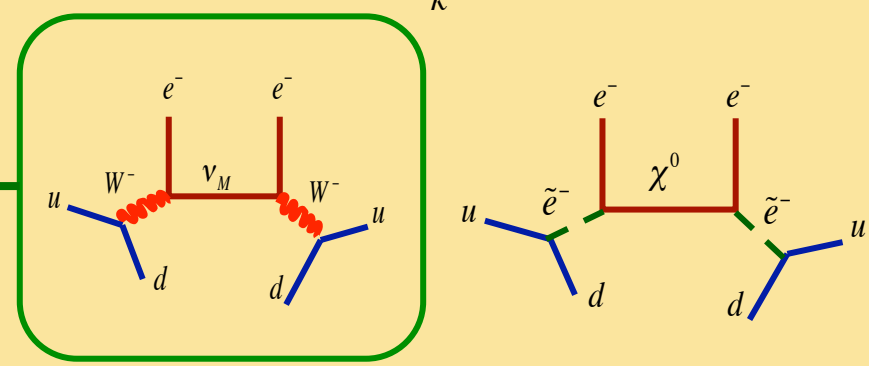


$0\nu\beta\beta$-Decay: LNV? Mass Term?

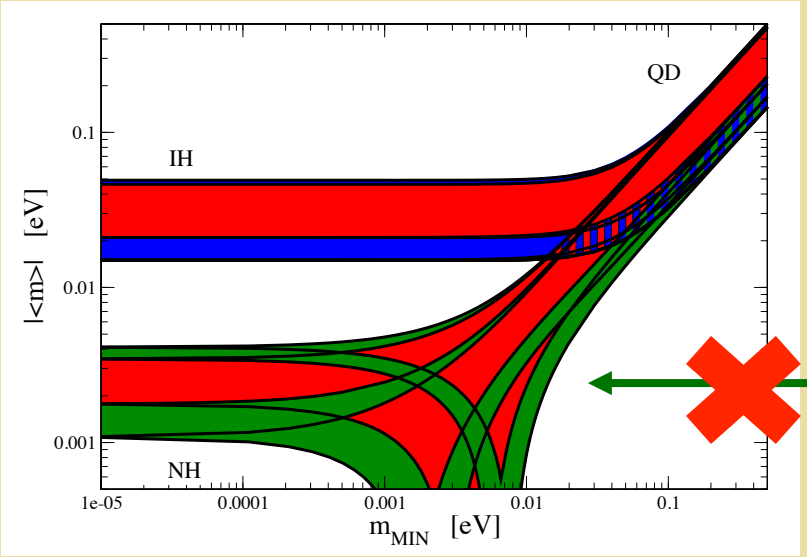
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; {\rm h.c.}$$

Majorana

Benchmark Sensitivity



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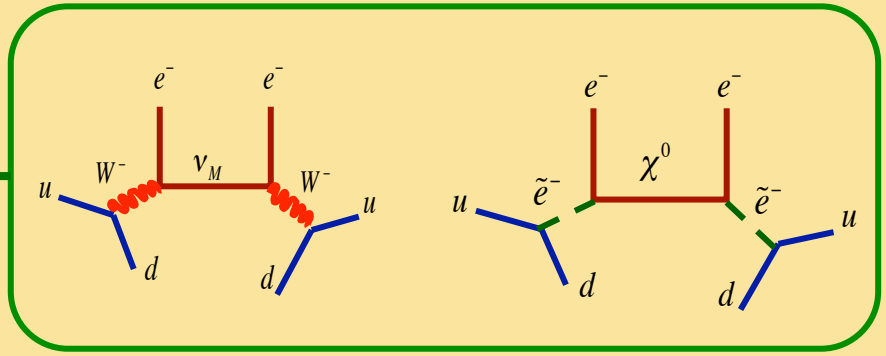

Heavy ν_M or other heavy LNV

$0\nu\beta\beta$-Decay: TeV Scale LNV

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Dirac

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Majorana

Mechanism: does light ν_M exchange dominate ?

$$\frac{A_{\rm heavy}}{A_{\rm light}} \sim \frac{M_W^2\, k_{\rm eff}^2}{\Lambda^5\, m_\nu^{\rm eff}}$$

O(1) for Λ ~ TeV

How to calc effects reliably ?
How to disentangle H & L ?

Theory Challenge: matrix elements + mechanism

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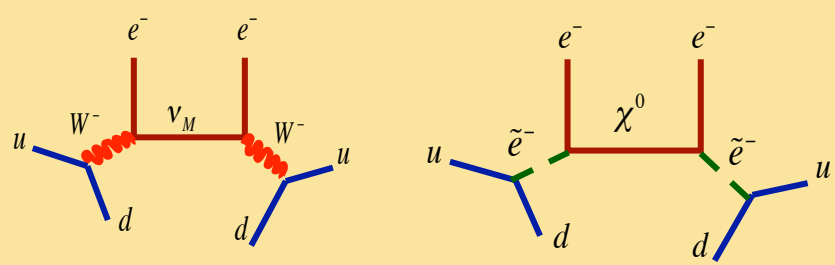

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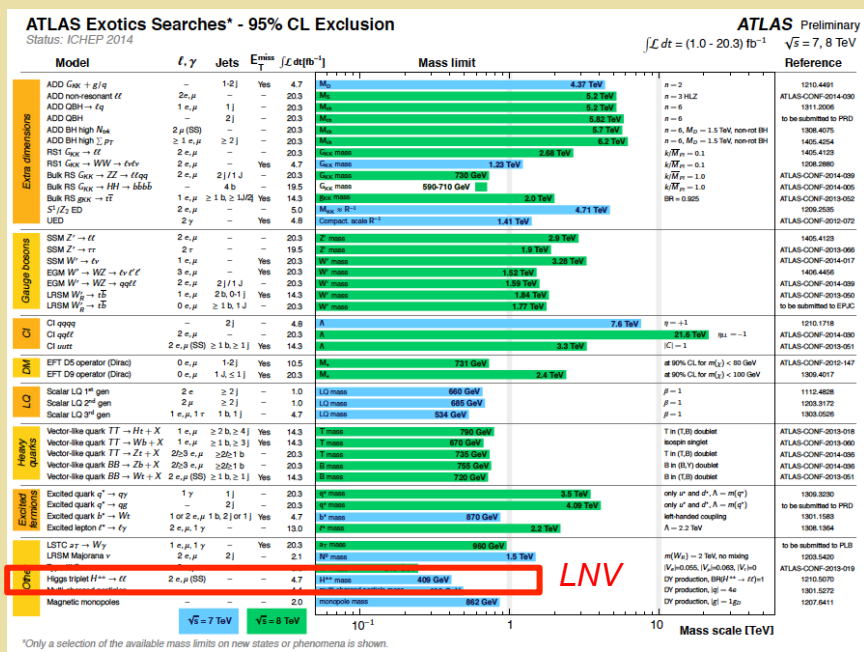
Majorana

LNV at the LHC



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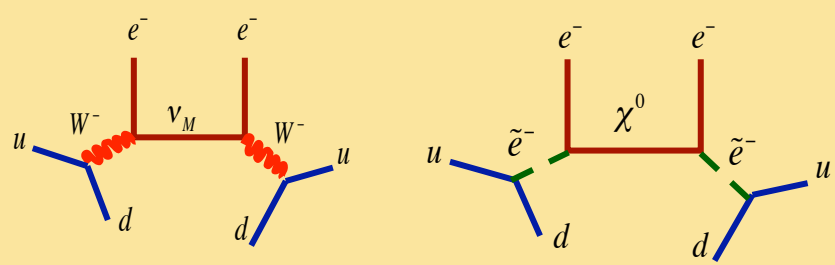

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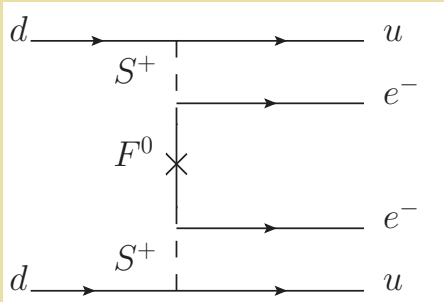
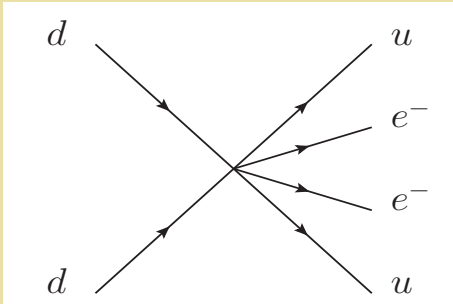


$0\nu\beta\beta$ - decay



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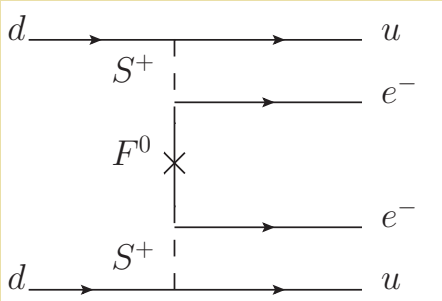

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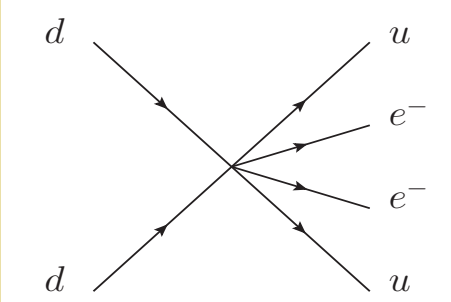

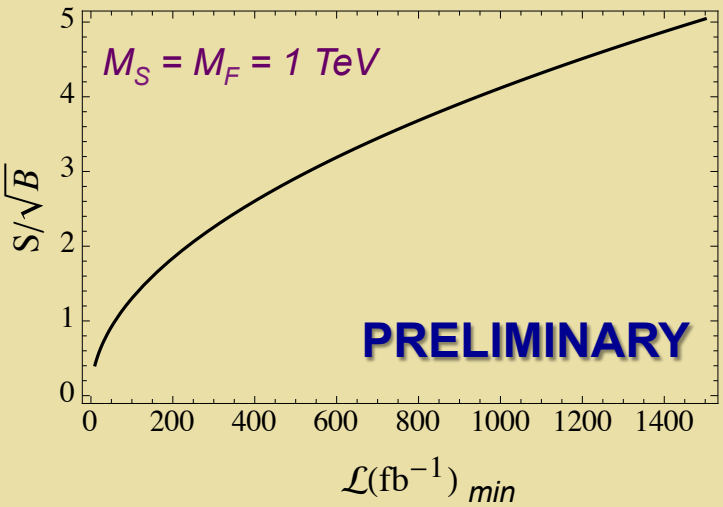

T. Peng, MR-M, P. Winslow in prog

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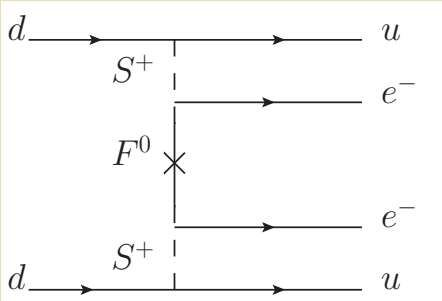

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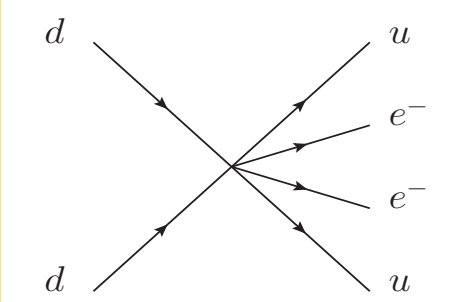

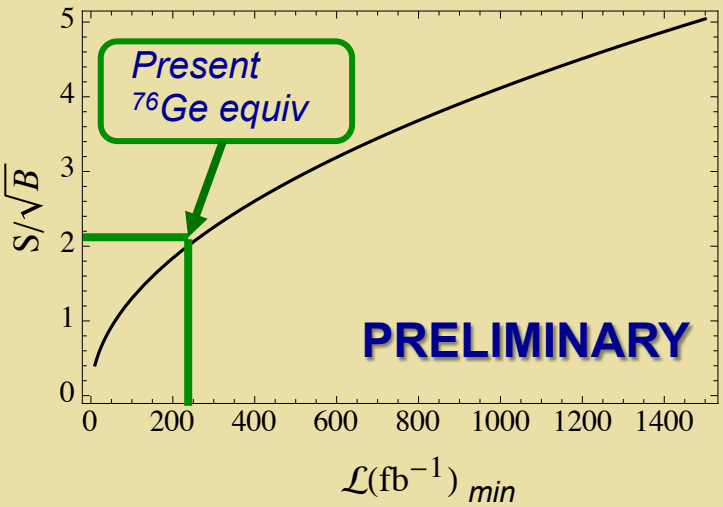

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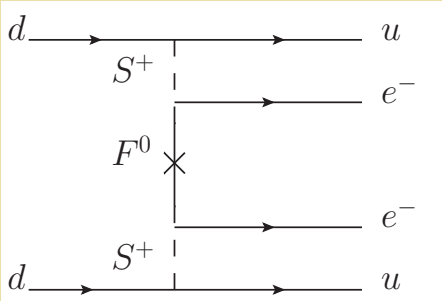

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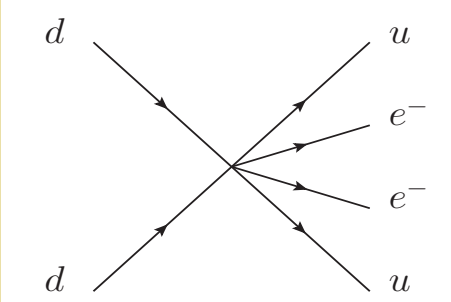

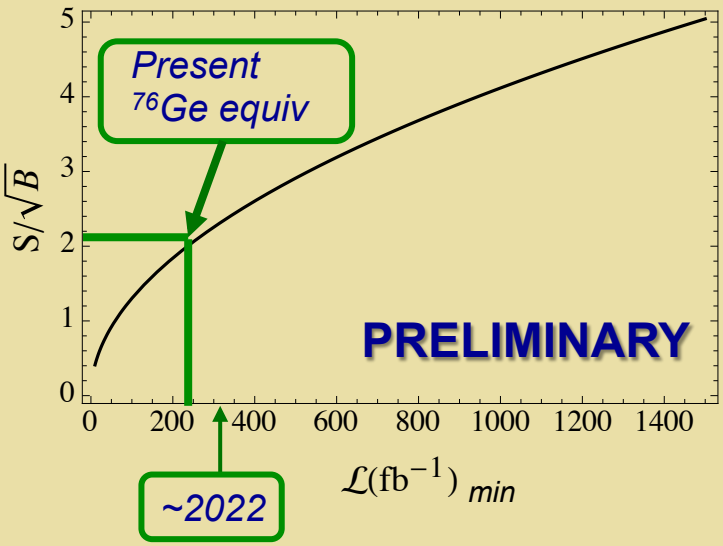

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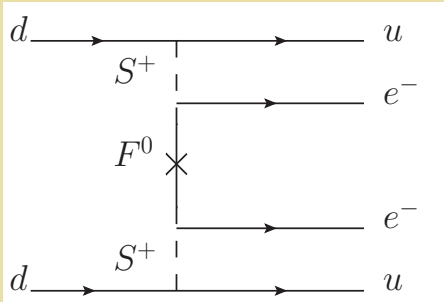

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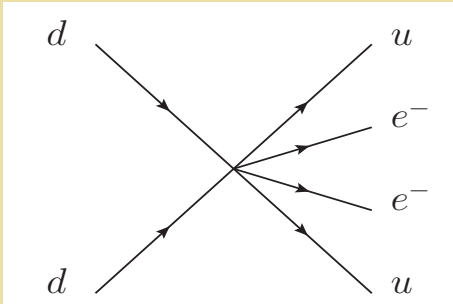

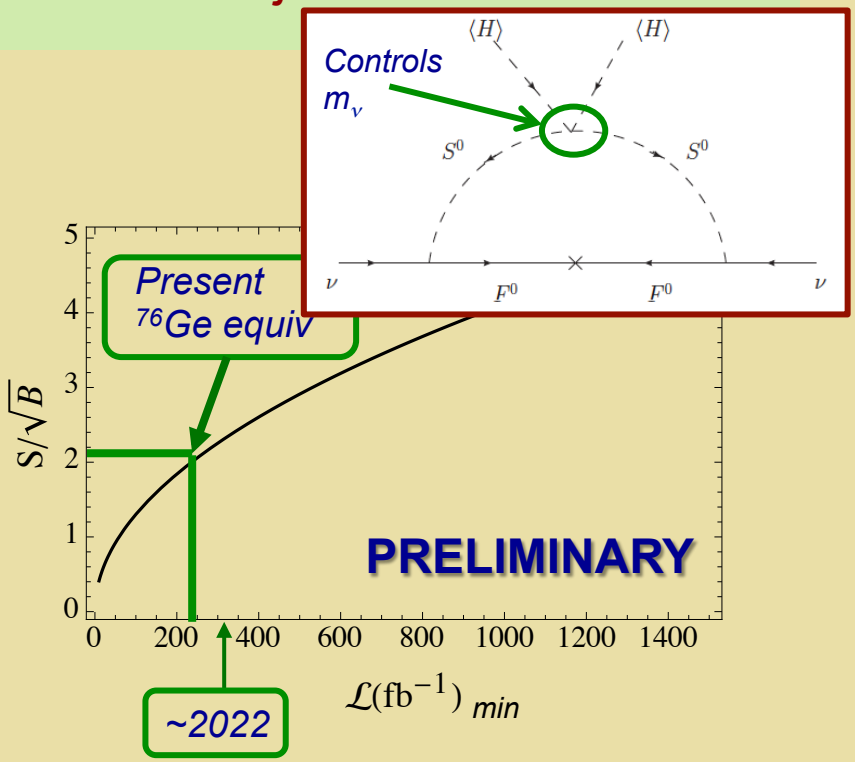

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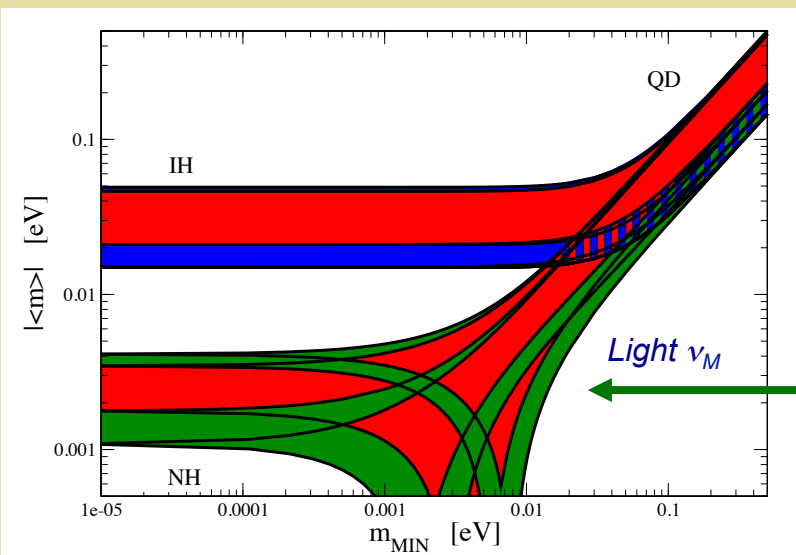

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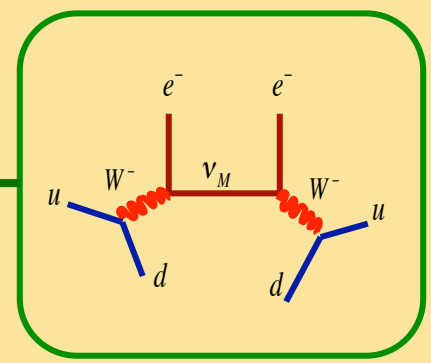

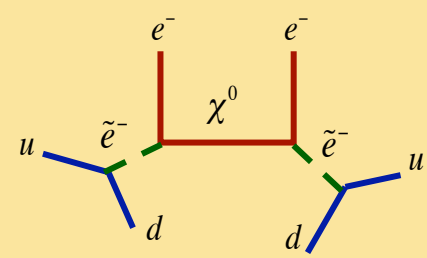

$0\nu\beta\beta$-Decay: Nuclear Matrix Elements

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Majorana

Light ν_M exchange: can we determine m_ν

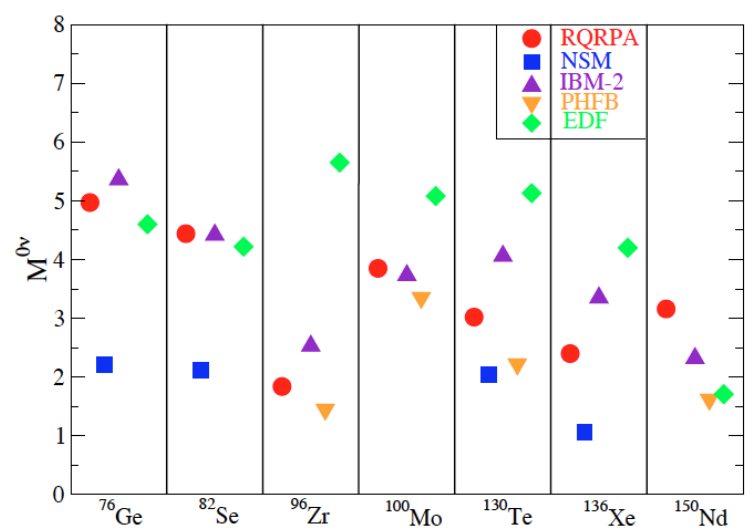
$$\frac{1}{T_{1/2}} = G^{0\nu}(E,Z)\left|M_{0\nu}\right|^2 \langle m_\nu^{\rm eff}\rangle^2$$

Shell Model vs. QRPA

Configs near Fermi surface

Levels above Fermi surface

P. Vogel



See Jon Engel Talk

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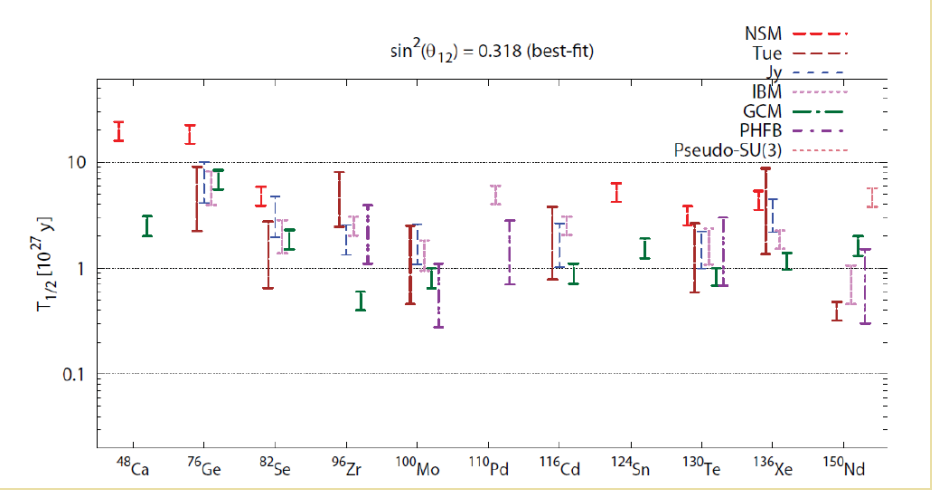

NSAC Subcommittee

See Jon Engel Talk

III. Electric Dipole Moments

- *Discovery potential & interpretation: need for searches in multiple systems*
- *Benchmark sensitivities: three examples*
- *Challenges & opportunities for theory*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

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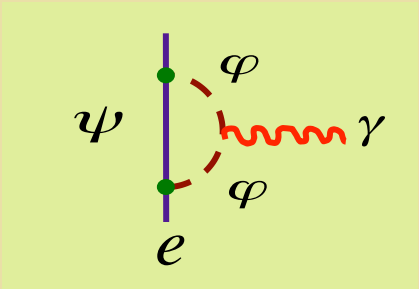
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

M < 500 GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

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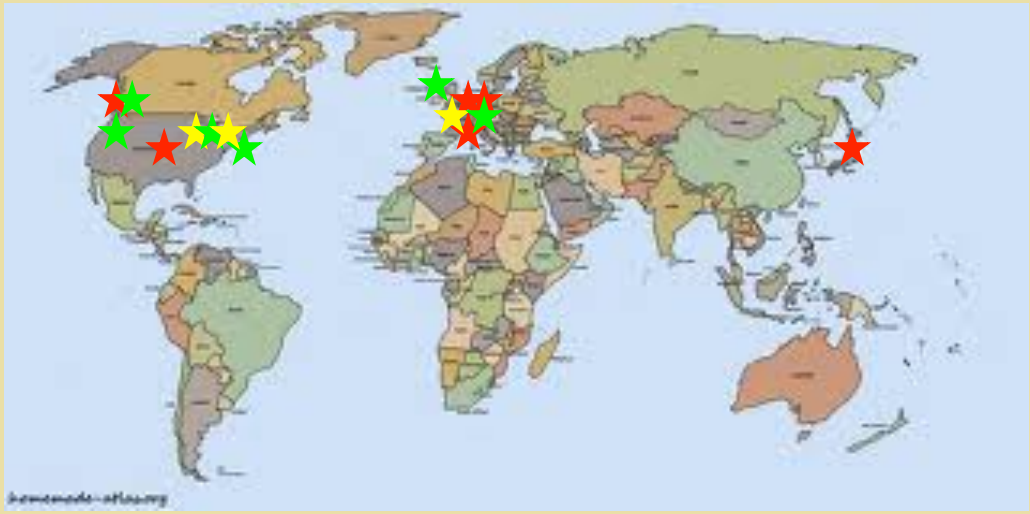


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

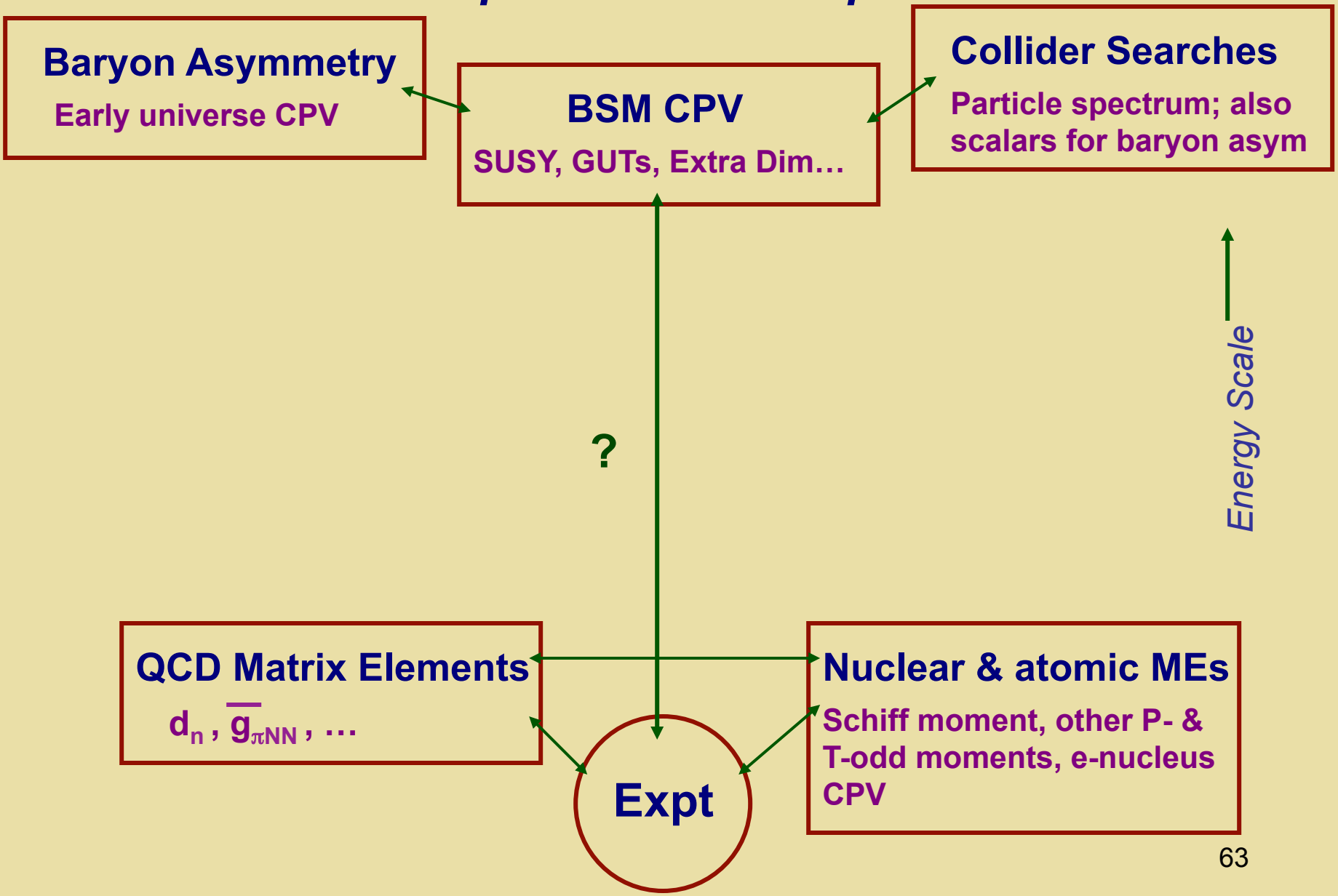
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales



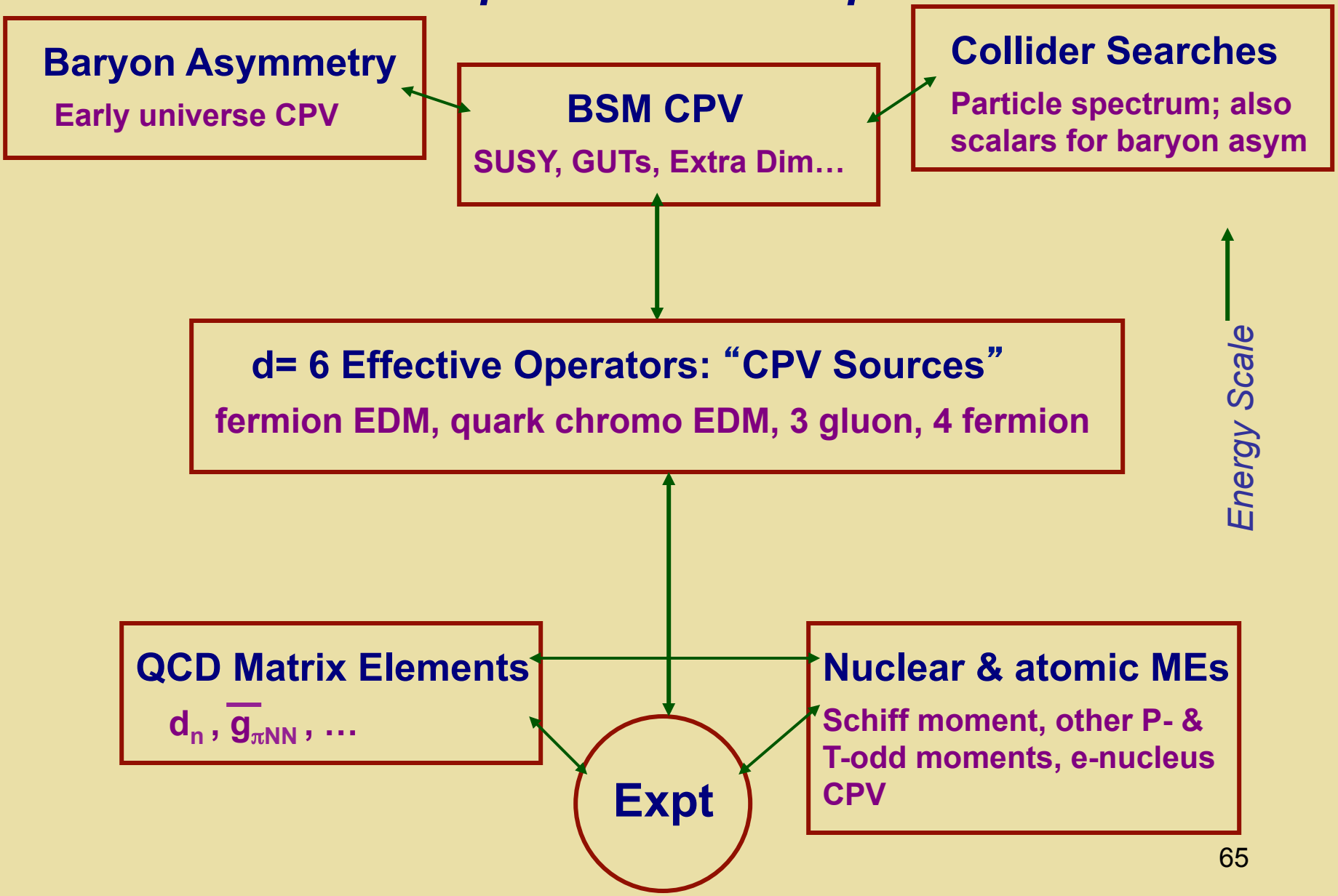
Effective Operators: The Bridge

$$\mathcal{L}_{\rm CPV} = \mathcal{L}_{\rm CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}^{\rm eff}_{\rm BSM}$$

$$\mathcal{L}^{\rm eff}_{\rm BSM} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)}$$

+…

EDM Interpretation & Multiple Scales



Wilson Coefficients: Summary

δ_f	*fermion EDM*	*(3)*
$\tilde{\delta}_q$	*quark CEDM*	*(2)*
$C_{\tilde{G}}$	*3 gluon*	*(1)*
C_{quqd}	*non-leptonic*	*(2)*
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$C_{\varphi ud}$	*induced 4f*	*(1)*

12 total + $\overline{\theta}$

light flavors only (e,u,d)

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Complementary searches needed

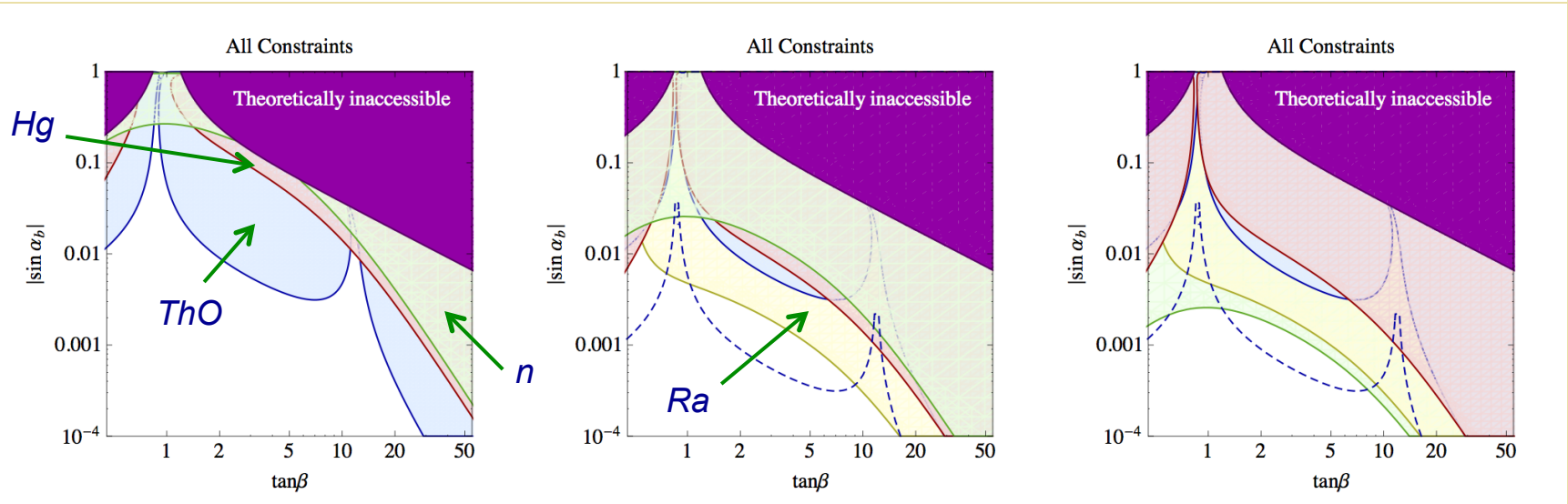
Complementarity: Three Illustrations

- *CPV in an extended scalar sector (2HDM): "Higgs portal CPV"*
- *Weak scale baryogenesis (MSSM)*
- *Model-independent*

Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present

sin α_b : CPV scalar mixing

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

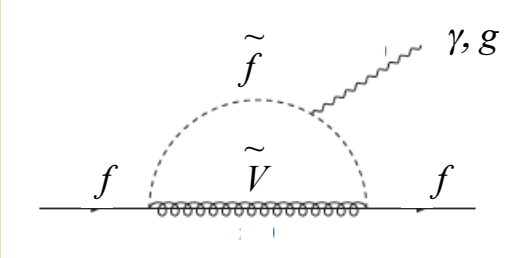
d_A(Hg) x 0.1

d_{ThO} x 0.1

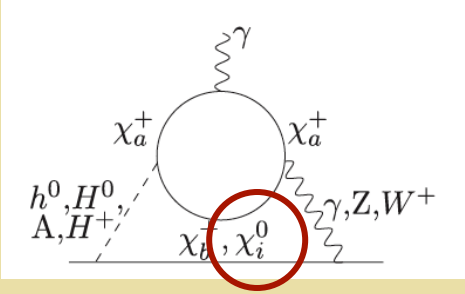
d_A(Ra)

Inoue, R-M, Zhang: 1403.4257

EDMs & EW Baryogenesis: MSSM

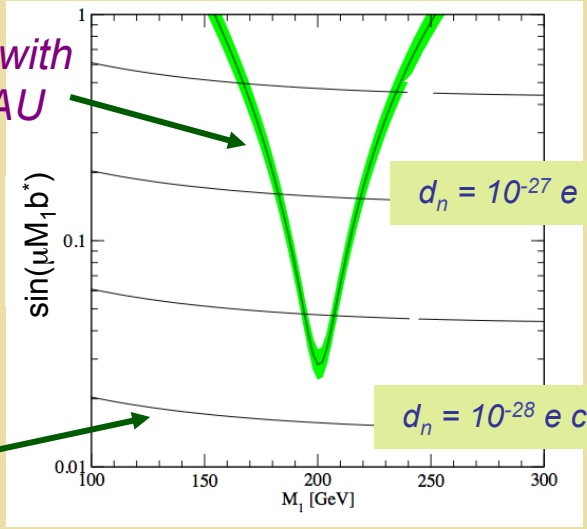


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

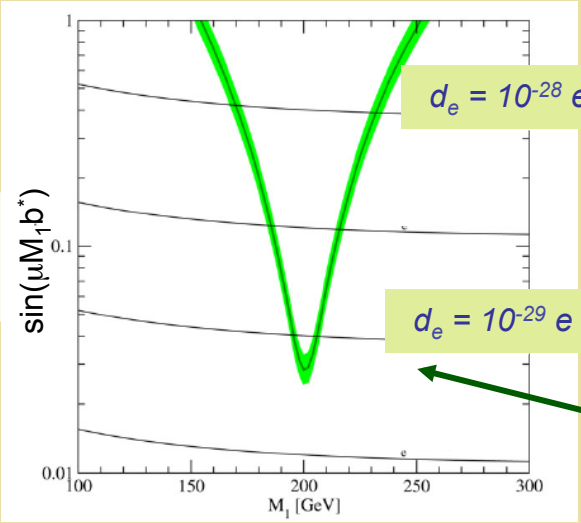


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



Next gen d_n

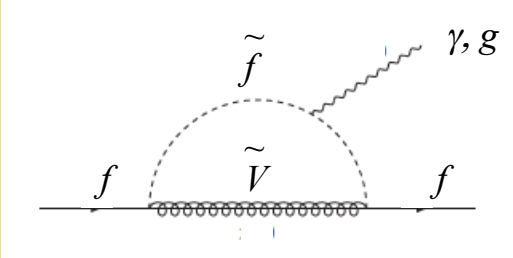


ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM



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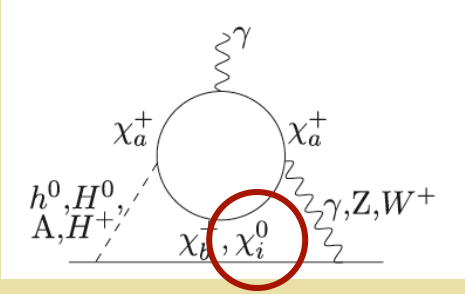

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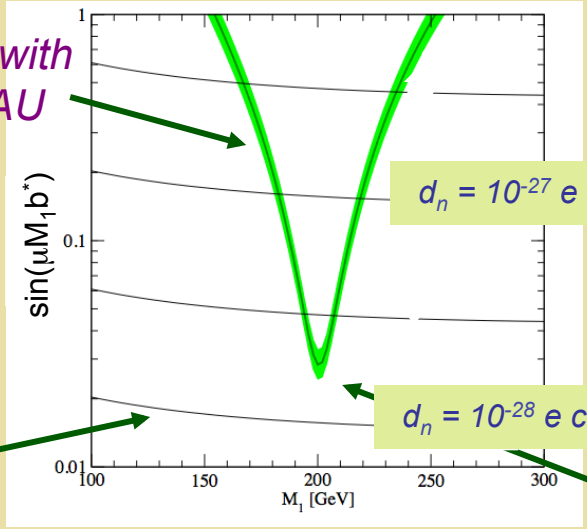

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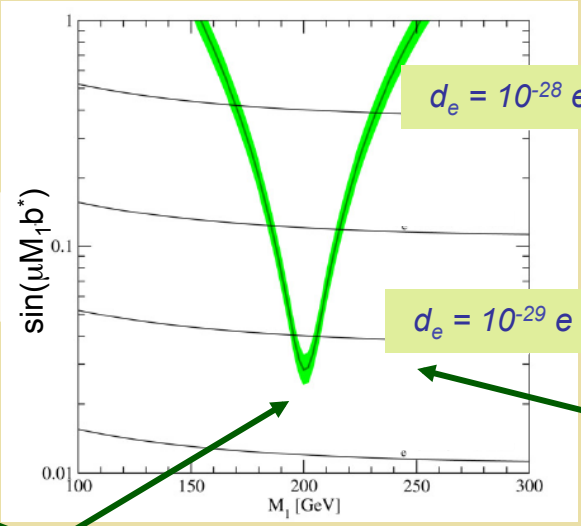

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Li, Profumo, RM '09-'10

Compressed spectrum (stealthy SUSY)

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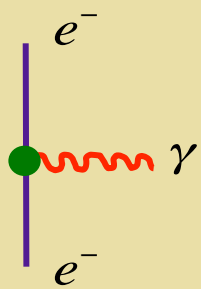
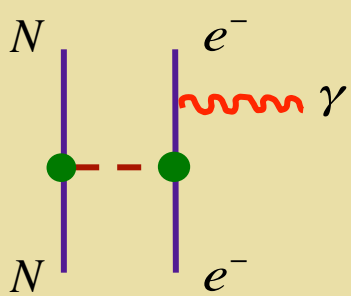
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)



Tl, YbF, ThO…

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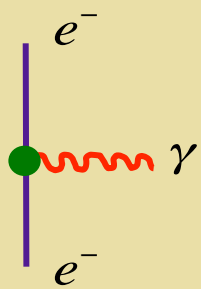

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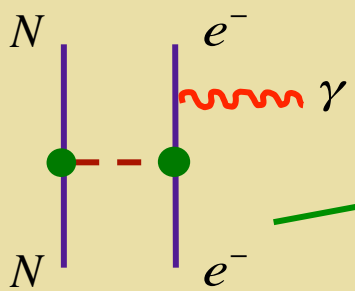

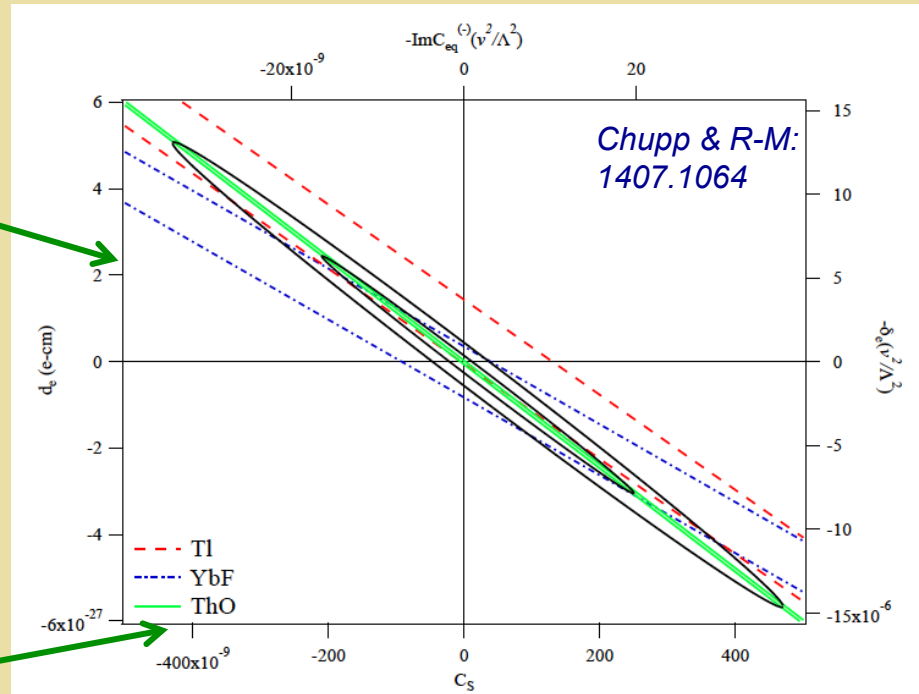

Tl, YbF, ThO…

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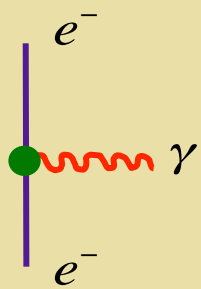

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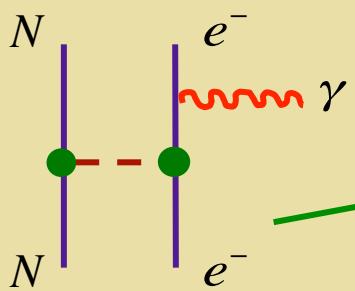
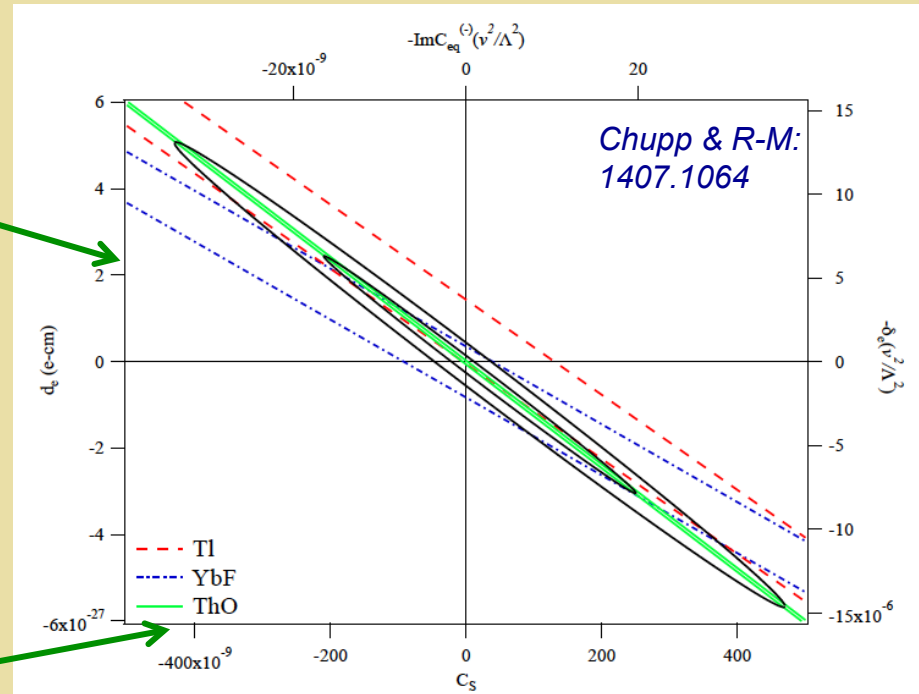


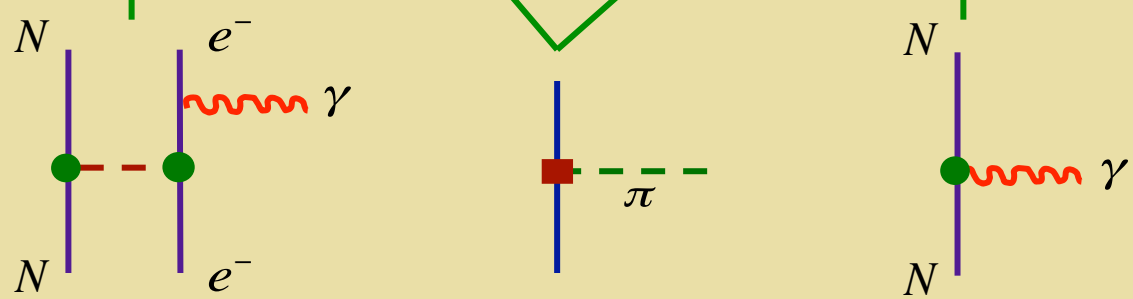


$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	C_S (global)

Tl, YbF, ThO…

Diamagnetic Global Fit

	$C_T \times 10^7$	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Exact solution	1.265	-6.687×10^{-10}	1.4308×10^{-10}	9.878×10^{-24}
Range from best values of α_{ij}	$(-7.6 - 9.5)$	$(-5.0 - 4.0) \times 10^{-9}$	$(-0.2 - 0.4) \times 10^{-9}$	$(-5.9 - 7.4) \times 10^{-23}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-7.6 - 8.4)$	$(-7.0 - 4.0) \times 10^{-9}$	$(0 - 0.2) \times 10^{-9}$	$(5.9 - 10.4) \times 10^{-23}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-9.2 - 12.4)$	$(-4.0 - 4.0) \times 10^{-9}$	$(-0.4 - 0.8) \times 10^{-9}$	$(-5.9 - 5.9) \times 10^{-23}$
Range from full variation of α_{ij}	$(-10.8 - 15.6)$	$(-10.0 - 8.1) \times 10^{-9}$	$(-0.6 - 1.2) \times 10^{-9}$	$(-12.0 - 14.8) \times 10^{-23}$



Tensor eq *TVPV πNN* *Short distance d_n*

Chupp & R-M: 1407.1064

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Isoscalar CEDM

$$\tilde{\delta}_q^{(+)} \left(\frac{v}{\Lambda}\right)^2 \lesssim 0.01 \qquad \Lambda \gtrsim (2\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$$

Caveat: Large hadronic uncertainty

Chupp & R-M: 1407.1064

Hadronic Matrix Elements

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09-0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2-1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2-20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4-40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2-0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8-2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4-12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16-50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2-40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1-10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10-80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Engel, R-M, van Kolck '13

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Engel, R-M, van Kolck '13

Nuclear Matrix Elements

$$S = a_0\, g\, \bar{g}_\pi^{(0)} + a_1\, g\, \bar{g}_\pi^{(1)} + a_2\, g\, \bar{g}_\pi^{(2)}$$

Nucl.	Best value		
	a_0	a_1	a_2
^{199}Hg	0.01	$\pm$ 0.02	0.02
^{129}Xe	−0.008	−0.006	−0.009
^{225}Ra	−1.5	6.0	−4.0

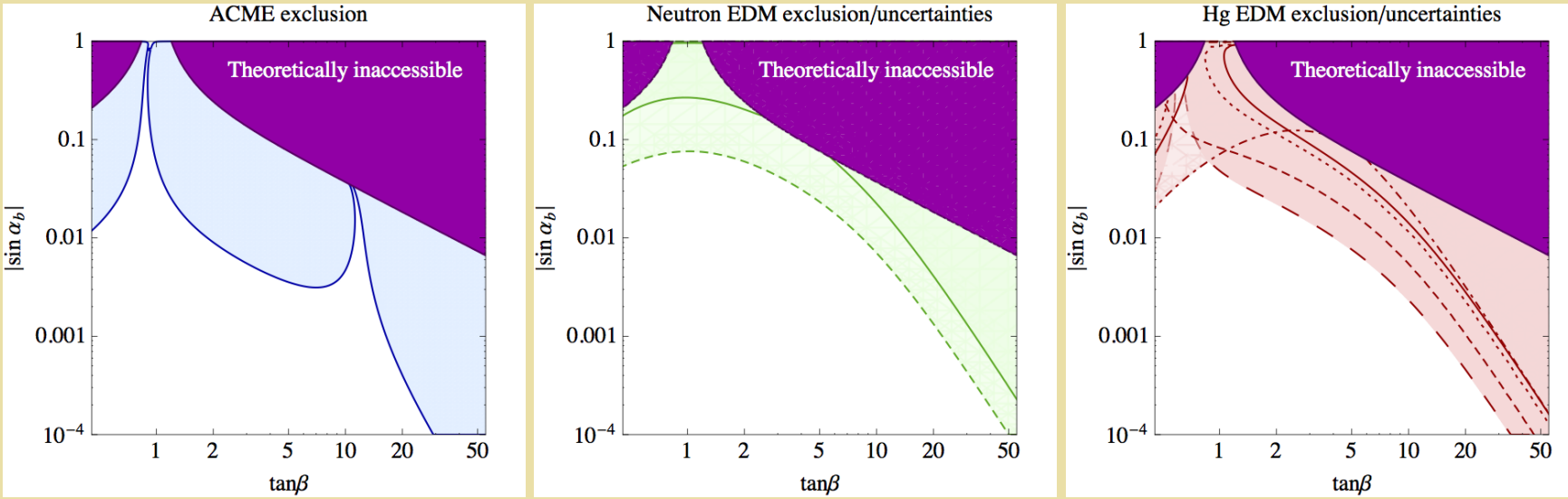
Range		
a_0	a_1	a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

Engel, R-M, van Kolck '13

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

IV. Outlook

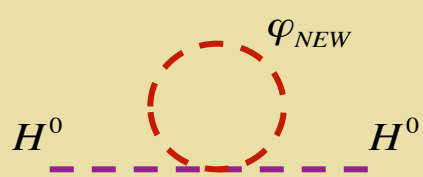
- *Nuclear physics studies of fundamental symmetries & neutrinos provide a unique window into deep mysteries about the fundamental laws of nature*
- *A targeted program of nuclear physics experiments and theoretical studies are poised to make significant discoveries and provide key insights about the new Standard Model of fundamental interactions*
- *The opportunities for both discovery and insight are stronger and more compelling than ever*

Back Up

Scalar Fields in Particle Physics

Scalar fields are a simple

Scalar fields are theoretically problematic



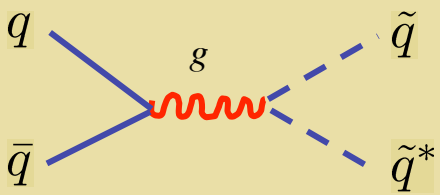
$\Delta m^2 \sim \lambda \Lambda^2$

Discovery of a (probably) fundamental 125 GeV scalar :

$m_h^2 \sim \lambda v^2$ & $G_F \sim 1/v^2$: *what keeps* G_F *"large" ?*

LHC BSM Challenge: Light but Compressed ?

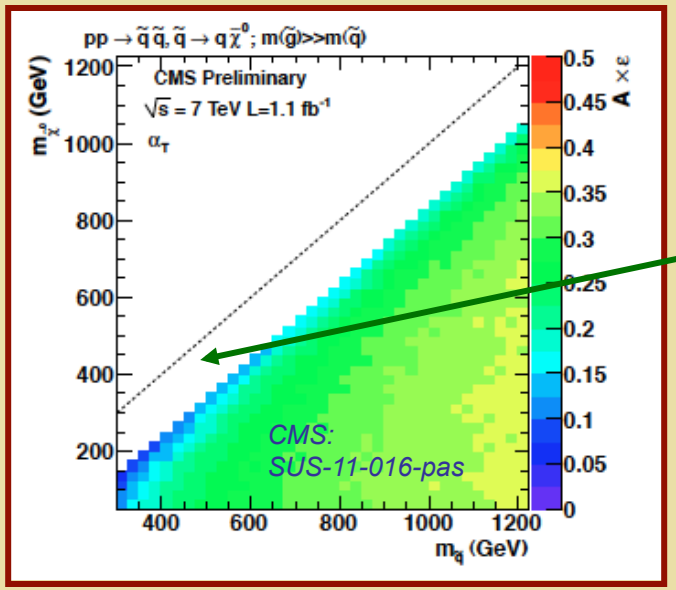
Pair production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$

$$\tilde{q} \to q' + \tilde{\chi}^{\pm} \to \ell + \nu + q' + \tilde{\chi}_1^0$$

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$



No exclusion yet (jets analysis): is sub-TeV SUSY hiding here?

If so, will it show up in precision tests ?

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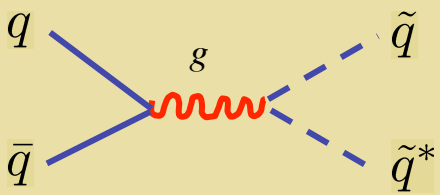

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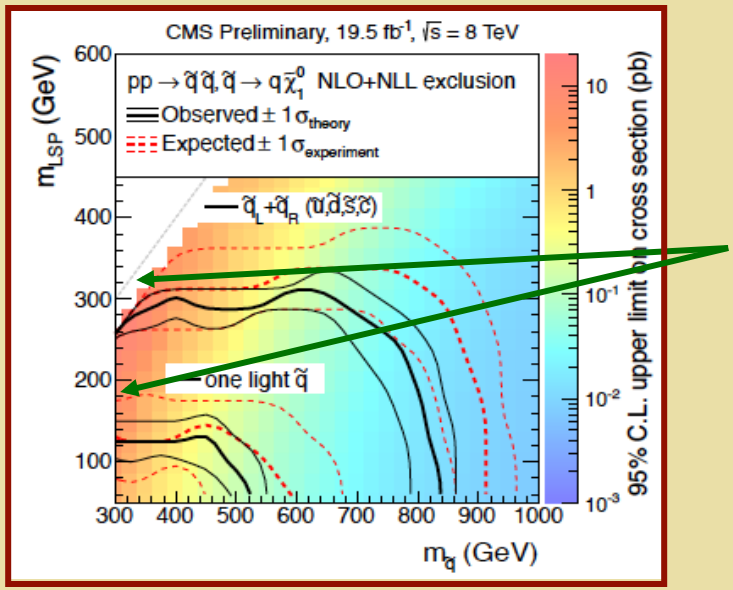

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CMS: SUS-13-012-pas

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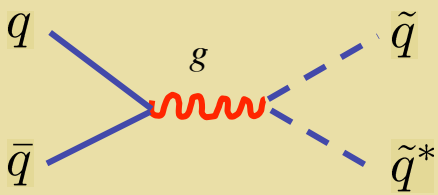

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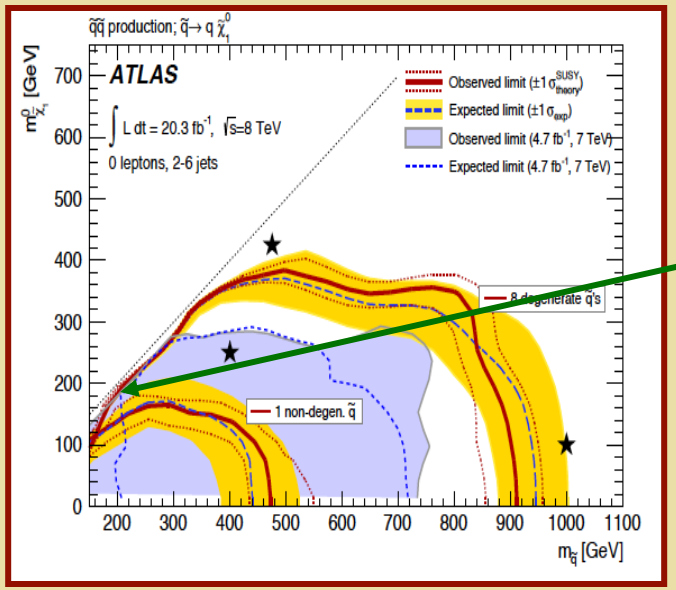

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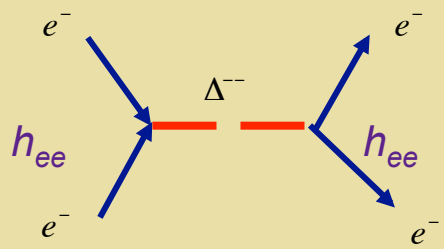
ATLAS: 1405.7875

Moller & Lepton Number Violation

Left-Right Symmetric Model

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.}$$

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix},$$



$$\mathcal{L}_\delta = \frac{g^2}{4} h_{ij} h^*_{km} \left[\frac{1}{M^2_{\delta^{++}_R}} (\bar{l}^c_{iR} l_{jR})(\bar{l}_{kR} l^c_{mR}) + (L \leftrightarrow R) \right].$$

Moller & LNV: Phenomenology

Left-Right Symmetric Model

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Neutrino Mass: $< \delta_L^0 > = 0$

$0\nu\beta\beta$: $h^L \neq h^R$

$\mu \to 3e$:

$$|h_{\mu e} h^*_{ee}| \leq 1.55 \times 10^{-4} \sqrt{\frac{B_{\mu \to 3e}}{10^{-12}}} \left(\frac{M_{\delta^{++}_{L,R}}}{1\text{TeV}}\right)^2.$$

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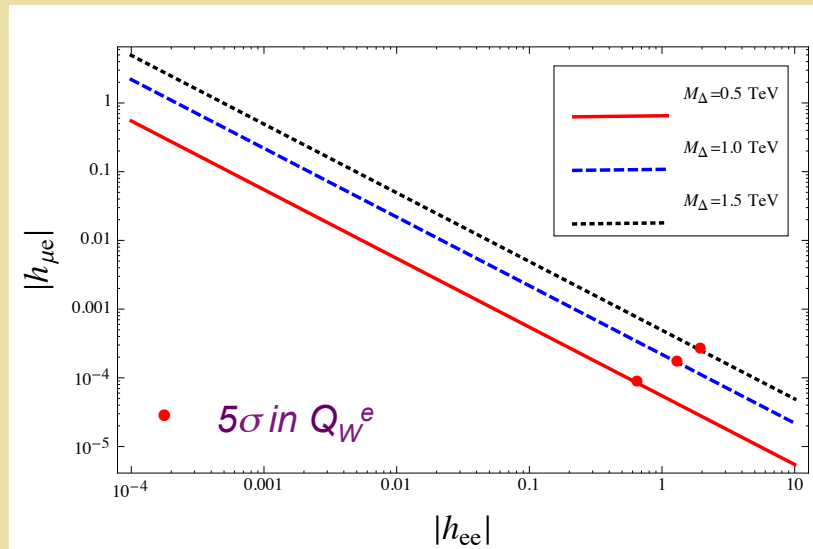


Chao, Li, R-M in prep

BSM Origins

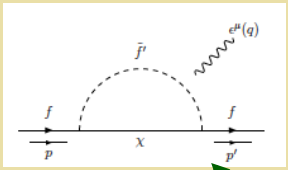
EDM: γff

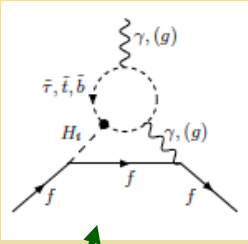
CEDM: gff

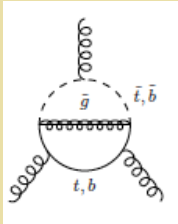
Weinberg ggg:

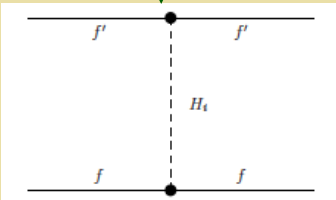
Four fermion

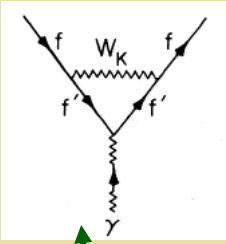
udHH

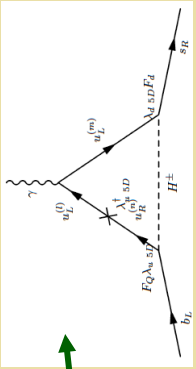








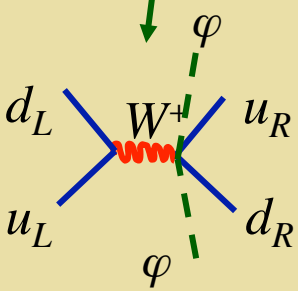




MSSM

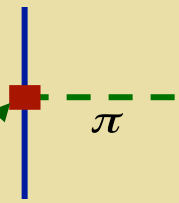
LRSM

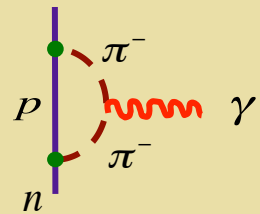
RS

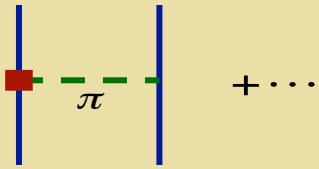


Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction







- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

Nucleon EDM

Nuclear EDM & Schiff moment

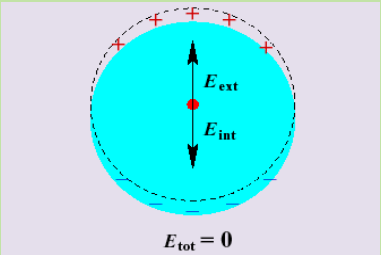
+ quark EDM

+ ~~quark EDM~~

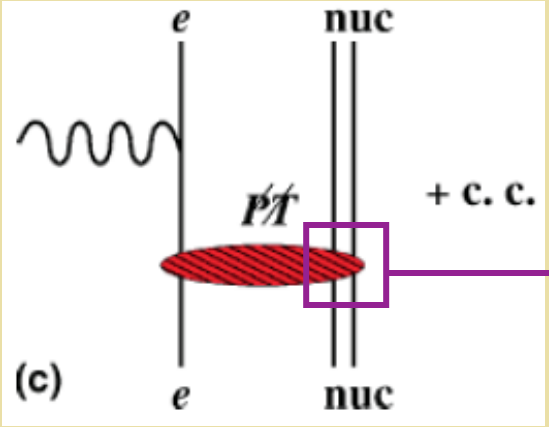
Neutron, proton & light nuclei (future), diamagnetic atoms

Diamagnetic Systems: Schiff Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Schiff moment, MQM,…

Nuclear Schiff Moment

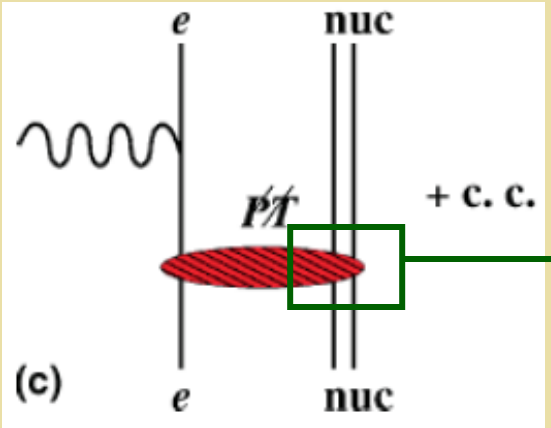
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

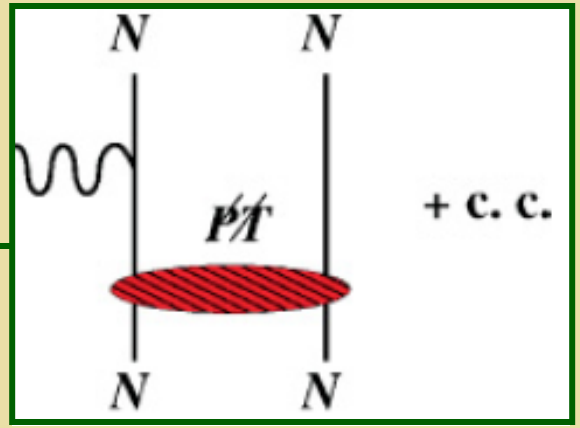
$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements





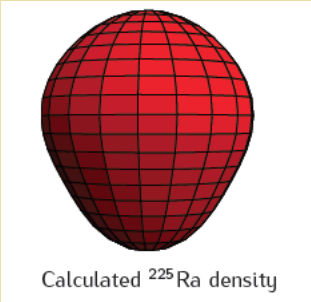
Schiff moment, MQM,…

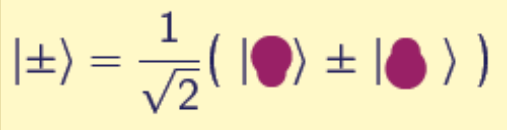
Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

EDMs of diamagnetic atoms (^{199}Hg)

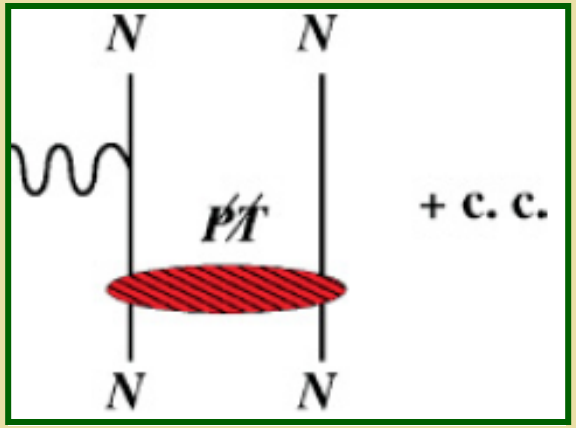
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation





Opposite parity states mixed by H^{TVPV}



Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

"Nuclear amplifier"

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel