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JÜLICH FORSCHUNGSZENTRUM

Theory IV: Physics beyond the Standard Model

HPSS2014 | Schloss Rauischholzhausen | September 3, 2014 | Andreas Wirzba

Prolog: the Standard Model (SM) of particle physics

- **The** theory of **strong**, **electromagnetic** and **weak** interactions
- **Gauge field theory** based on $SU(3)_c \times SU(2)_L \times U(1)_Y$ with Yukawa couplings of the fermions to the Higgs
- **Extremely successful:**

  All fundamental particles detected and their properties mapped out

  Latest spectacular entry: the **Higgs boson** (2012, Nobel prize '13)

  Most precise theory ever formulated: anomalous magnetic moment a_e agrees to **11 digits** with experiment

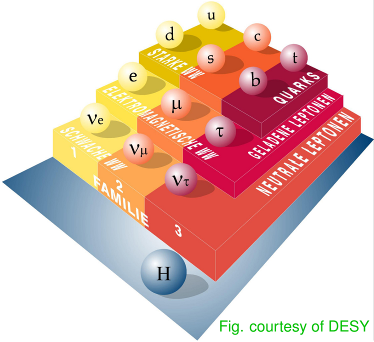


Fig. courtesy of DESY

- However, there are also '*dark clouds*' . . .

The clash of the Standard Models

- *Particle physics versus Cosmology*

  - Inflation
  - Gravity
  - **Dark matter**
  - **Matter-antimatter asymmetry and CP violation**
  - Dark energy

  plus sole SM problems as

  - □ Hierachy problem (fine-tuning)
  - □ Grand unification and proton decay
  - □ anomalous magnetic moment of muon
  - □ strong CP problem

  ...

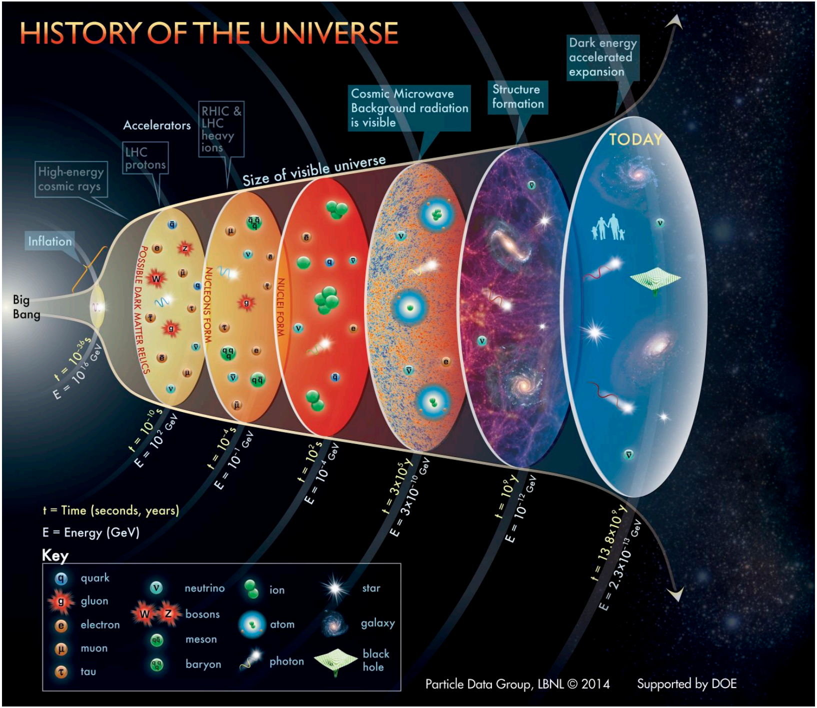


Fig. courtesy of PDG, LBNL © 2014

Matter Excess in the Universe

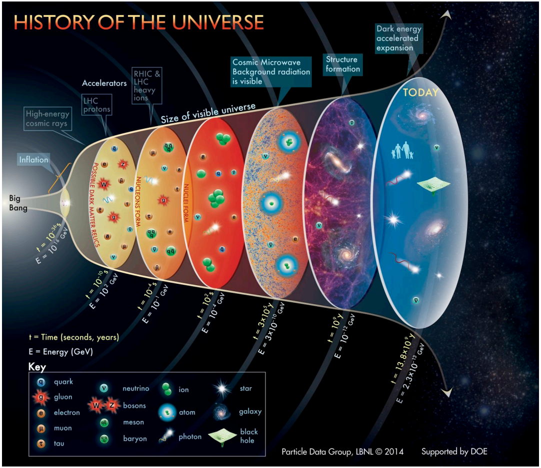


Fig. courtesy of PDG, LBNL ©2014

1. End of inflation: $n_B = n_{\bar{B}}$
2. **B**ig **B**ang **N**ucleosynthesis (t~3 min)
3. **C**osmic **M**icrowave **B**kgr. ($t \sim 3.8 \cdot 10^5$ y)

- SM(s) *prediction:* *
  $(n_B - n_{\bar{B}})/n_\gamma|_{\mathrm{CMB}} \sim 10^{-18}$
- *Planck* 2013:
  $n_B/n_\gamma|_{\mathrm{CMB}} = (6.047 \pm 0.074) 10^{-10}$
  $n_\gamma|_{\mathrm{CMB}} = 410.7(T/2.7255\,\mathrm{K})^3 \mathrm{cm}^{-3}$
  PDG 2013 partial update
- BBN D/H (& He/H ratios):
  $5.7 \cdot 10^{-10} < n_B/n_\gamma < 6.7 \cdot 10^{-10}$
  PDG 2013 partial update

$(*)$ $2J^{\mathrm{CKM}}_{\mathrm{Jarlskog}}(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) \sim 10^{-18} M_{\mathrm{EW}}^{12}$

Part I: Dark Matter

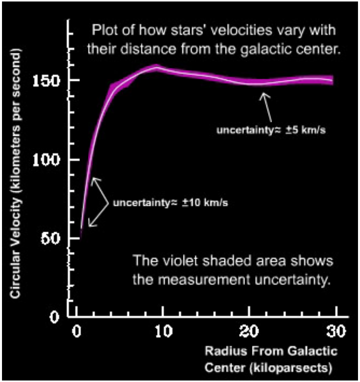
Evidences for Dark Matter

via **gravitational effects** on visible matter, radiation and large scale structures of the universe

Evidences for Dark Matter

via **gravitational effects** on visible matter, radiation and large scale structures of the universe

- Rotation curves



Figs. courtesy of PDG, LBNL ©2005, 2007

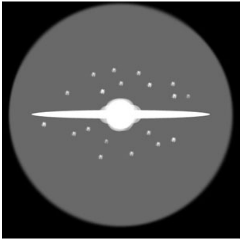
Vera Rubin '75; precursors: Jan Oort '32, Fritz Zwicky '33

$$\Rightarrow \quad v(r) = \sqrt{\frac{G_N M(r)}{r}} \approx \text{constant}$$

instead of $1/\sqrt{r}$

$$\Rightarrow \quad M(r) \propto r \quad \text{instead of constant}$$

Dark mass : visible mass $\approx$ 6 : 1



Evidences for Dark Matter

via **gravitational effects** on visible matter, radiation and large scale structures of the universe

- Rotation curves
- Anisotropies in the Cosmic Microwave Background

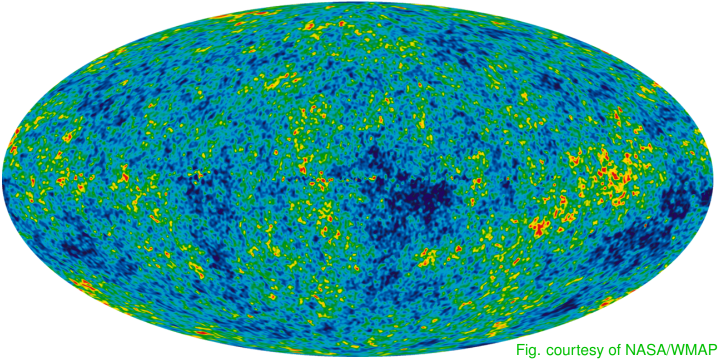


Fig. courtesy of NASA/WMAP

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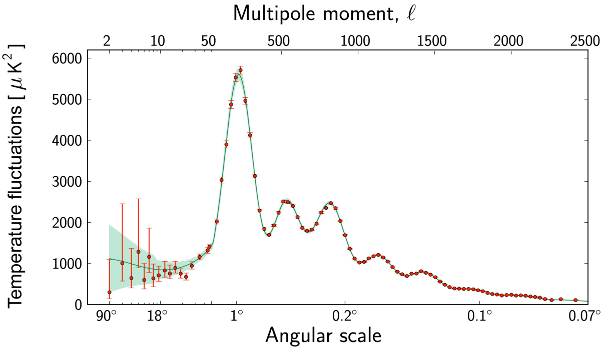

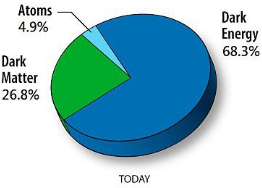

Fig. courtesy of NASA/Wikimedia

Fig. courtesy ESA/*Planck* Collaboration (via PDG)

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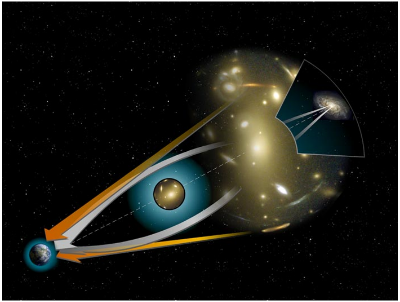

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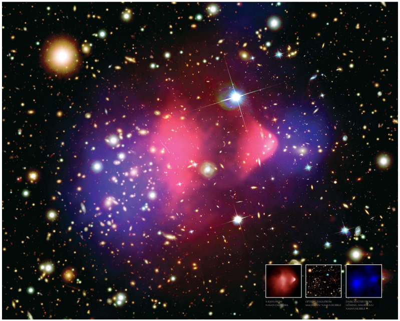

e.g., by the Bullet Cluster
of distant background objects

dark mass : visible mass $\approx$ 10 : 1

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI;
Magellan/U.Arizona/D.Clowe et al.

Fig. courtesy of CHANDRA, NASA

Dark matter particles

interact only by gravity and maybe by (a) weak interaction

Examples:

WIMPs (= weakly interacting massive particles)
LSP (= lightest superparticle),
axions, neutrinos (light or sterile), ...

Detection:

- **direct detection experiments**: search for scattering of DM particles off atomic nuclei from cosmic rays
- **indirect detection**: search for the products of DM annihilations (excess of gamma rays, antiprotons or positrons)
- **production experiments in the Lab** producing either an excess of standard model particles or dark matter particles (missing mass)

Overview of Theories of Dark Matter particles

Here we are

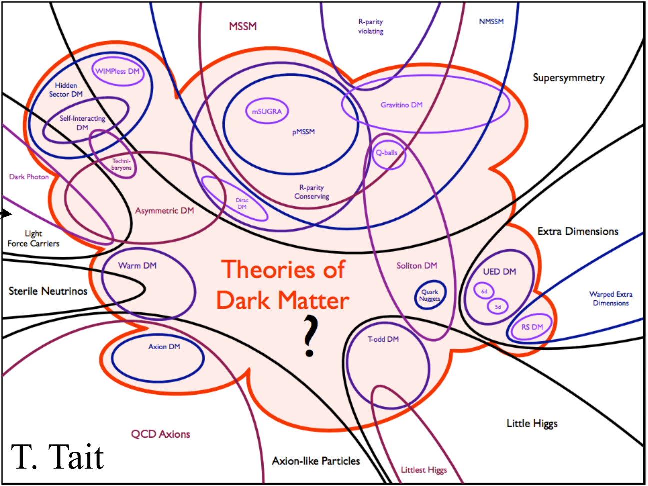

Fig. courtesy of Tim M.P. Tait, University of California, Irvine

Far too much → we must limit ourselves → Light Dark Matter only

Light Dark Matter with $m_{DM} < 1\,\text{GeV}$?

1. **Cold** dark matter versus **Hot** dark matter

   Non-relativistic (WIMP, axion, LSP, ν_{ster}, ...) vs. **relativistic** (ν_e, ν_μ, ν_τ) particles

   Bottom-up vs. **top-down** structure formation of galaxies and ...

   $\hookrightarrow$ observations of high-red shift galaxies (Hubble Ultra-Deep Field)

   $\Longrightarrow$ CDM wins

2. Lee-Weinberg bound on WIMPs B.W. Lee & S. Weinberg, *PRL*'77

   $$\sigma^{\text{DM}}_{\text{annih.}} \approx m^2_{\text{DM}}/M^4_{Z,Z'} \quad \longrightarrow \quad m_{DM} \gtrsim 2\,\text{GeV}\,, \quad \text{otherwise}$$

   too high **relic WIMP density** such that universe would close again.

3. Light Dark Matter seems to be excluded

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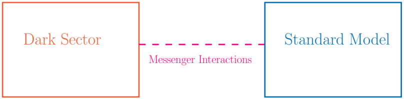
   $\hookrightarrow$ Dark Carrier or Dark Force Portals

Dark Carrier Portals

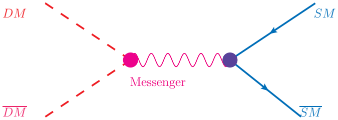
Neutral hidden sectors

- interacting with DM particles,
- but only weakly coupled to the SM



Dark Carrier Portals

Neutral hidden sectors



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Only three **flavor-universal** portals in the SM with leading (relevant or marginal) interactions

1. Higgs interaction with a scalar operator $O_s H^\dagger H$
2. right-handed neutrino coupling LHN_R
3. kinetic mixing of new U(1) vector U_μ with the hypercharge $B_{\mu\nu} U^{\mu\nu}$

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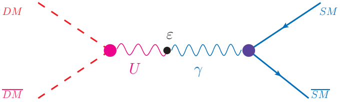

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Only three **flavor-universal** portals in the SM
with leading (relevant or marginal) interactions

1. Higgs interaction with a scalar operator $O_s H^\dagger H$
2. right-handed neutrino coupling $L H N_R$
3. kinetic mixing of new U(1) vector U_μ with the hypercharge $B_{\mu\nu} U^{\mu\nu}$

$\hookrightarrow$ bilinear mixing with the photon: $\boxed{\text{Dark Photon Portal}}$

$\hookrightarrow$ experimentally testable, allows for a vector which is naturally light

$$\hookrightarrow \mathcal{L}_V = -\frac{\varepsilon}{2} F_{\mu\nu} U^{\mu\nu} + \tfrac{1}{2} m_U^2 U^\mu U_\mu - \tfrac{1}{4} U_{\mu\nu} U^{\mu\nu}$$

Just two parameters: ε and m_U

(m_U either fundamental Stückelberg mass or generated by a Dark Higgs mechanism)

What is the dark photon of MeV – GeV mass good for?

- Excess of galactic electron and/or positron cosmic rays

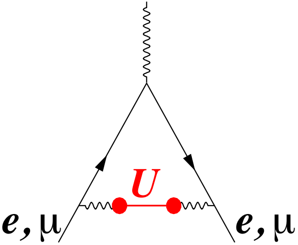
  ATIC *Nature* '08; H.E.S.S. *PRL* '08; PAMELA *Nature* '09

- narrow 0.511 MeV γ ray emission from the galactic center

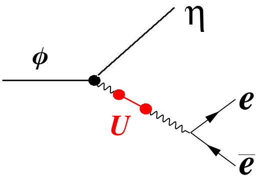
  INTEGRAL, *A&A* '03

- $a_\mu = \frac{1}{2}(g-2)_\mu$ discrepancy (of the anom. mag. mom. of the muon)

  $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (288 \pm 80) \cdot 10^{-11}$ (*i.e.* 3.6 σ) Bennett et al. (Muon G-2) Coll., *PRD* '06



e.g. $\longrightarrow$



with $\varepsilon \sim 1\text{–}2 \cdot 10^{-3}$ and $m_U \sim 10\text{–}100$ MeV

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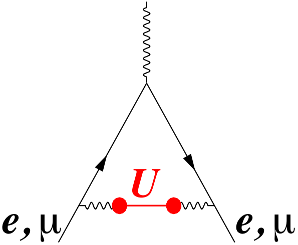
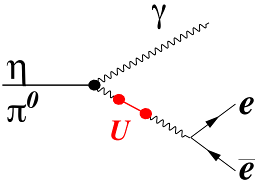


$\xrightarrow{\text{e.g.}}$



with $\varepsilon \sim 1$–$2 \cdot 10^{-3}$ and $m_U \sim 10$–$100\,\text{MeV}$

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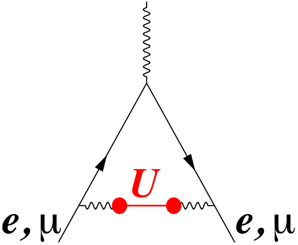

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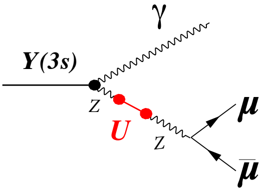

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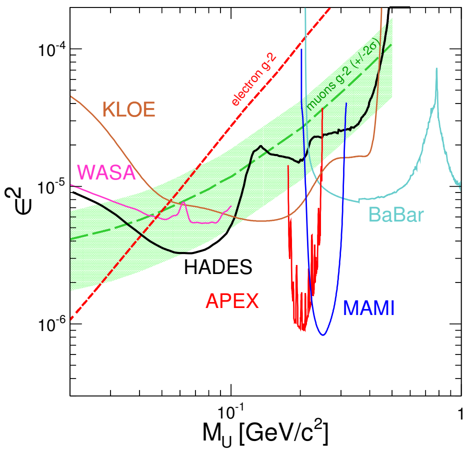
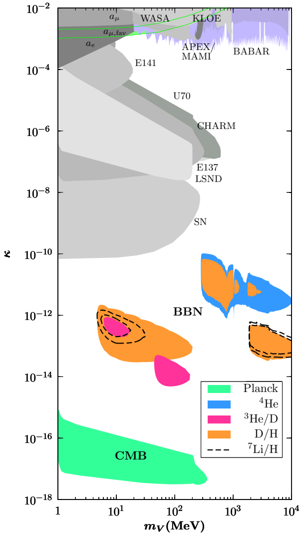
Bounds on coupling and mass of the dark photon



HADES Coll., arXiv:1311.0216



A. Fradette et al., arXiv:1407.0993

Part II: electric dipole moments of subatomic particles

- Unfortunately, here only very brief
- For more details,

  see **Jörg Pretz**' *EDM* lecture, today, 11:05

or see:

A. Wirzba, Nucl. Phys. A **928** (2014), 116-127 (http://dx.doi.org/10.1016/j.nuclphysa.2014.04.003), arXiv:1404.6131 [hep-ph] (http://arxiv.org/abs/1404.6131)

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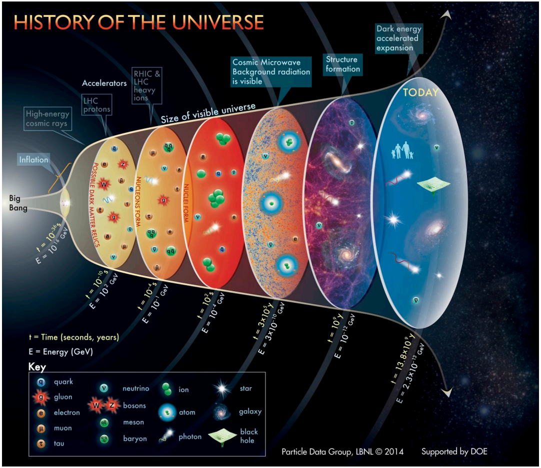

Fig. courtesy of PDG, LBNL ©2014

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  PDG 2013 part. update

Sakharov conditions ('67)

for dyn. generation of net B:

1 B violation to depart from initial B=0

2 C & CP violation
to distinguish B and $\bar{B}$ production rates

3 out of thermal equilibrium
to dist. B production from back reaction
and to escape $\langle B \rangle$=0 if CPT holds

(*) $2J^{\mathrm{CKM}}_{\mathrm{Jarlskog}}(m_t^2-m_u^2)(m_t^2-m_c^2)(m_c^2-m_u^2)(m_b^2-m_d^2)(m_b^2-m_s^2)(m_s^2-m_d^2) \sim 10^{-18} M^{12}_{\mathrm{EW}}$

▸ in the SM?

CP violation and the Electric Dipole Moment (EDM)

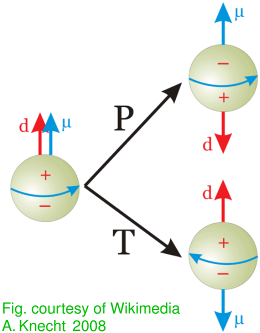

Fig. courtesy of Wikimedia
A. Knecht 2008

EDM: $\vec{d} = \sum_i \vec{r}_i \, e_i \xrightarrow[\text{particles}]{\text{subatomic}} d \cdot \vec{S}/|\vec{S}|$

(polar) (axial)

$$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

P: $\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$

T: $\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$

Any *non-vanishing EDM* of a non-deg. (subatomic) particle violates **P** & **T**

- Assuming CPT to hold, CP is violated as well
  $\hookrightarrow$ subatomic EDMs: "rear window" to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $|d_n| \sim 10^{-31} e\,\text{cm}$, $|d_e| \sim 10^{-38} e\,\text{cm}$
- Current bounds: $|d_n| < 3 \cdot 10^{-26} e\,\text{cm}$, $|d_p| < 8 \cdot 10^{-25} e\,\text{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\text{cm}$

n: Baker et al. (2006), p prediction: Dimitriev & Sen'kov (2003)*, e: Baron et al.(2013)†

* from $|d_{^{199}\text{Hg}}| < 3.1 \cdot 10^{-29} e\,\text{cm}$ bound of Griffith et al. (2009) † from polar ThO: $|d_{ThO}| \lesssim 10^{-21} e\,\text{cm}$

Theorem: Permanent EDMs of *non*-selfconjugate* particles *with* spin $j \neq 0$

Let $\langle j^{\mathrm{P}} | \vec{d} \, | j^{\mathrm{P}} \rangle = d \, \langle j^{\mathrm{P}} | \vec{J} \, | j^{\mathrm{P}} \rangle$ with $\vec{d} \equiv \int \vec{r} \rho(\vec{r}) \mathrm{d}^3 r$ be an EDM operator in a stationary state $|j^{\mathrm{P}}\rangle$ of definite parity P and nonzero spin j, such that

$$\langle j^{\mathrm{P}} | \vec{d} \, | j^{\mathrm{P}} \rangle \to \mp \langle j^{\mathrm{P}} | \vec{d} \, | j^{\mathrm{P}} \rangle \;\; \& \;\; \langle j^{\mathrm{P}} | \vec{J} \, | j^{\mathrm{P}} \rangle \to \pm \langle j^{\mathrm{P}} | \vec{J} \, | j^{\mathrm{P}} \rangle \;\; \text{under} \; \begin{cases} \text{space reflection,} \\ \text{time reversal.} \end{cases}$$

If $d \neq 0$ and $|j^{\mathrm{P}}\rangle$ has *no* degeneracy (besides rotational), *then* $\cancel{P}$ & $\cancel{T}$.

* *non*-selfconjugate particle is *not* its own antiparticle ⇒ at least one “charge" *non*-zero

Werner Bernreuther (RWTH Aachen, 2012)

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State $|j^{\rm P}\rangle$ can be *‘elementary’* particle (quark, charged lepton, $W^\pm$ boson, Dirac neutrino, ...)

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State $|j^P\rangle$ can be *‘elementary’* particle (quark, charged lepton, $W^\pm$ boson, Dirac neutrino, ...)

‘Isn’t an elementary particle a point-particle without structure? How can such a particle be polarized and support an EDM?’

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Let $\langle j^{\mathrm{P}} | \vec{d} \, | j^{\mathrm{P}} \rangle = d \, \langle j^{\mathrm{P}} | \vec{J} \, | j^{\mathrm{P}} \rangle$ with $\vec{d} \equiv \int \vec{r} \rho(\vec{r}) \mathrm{d}^3 r$ be an EDM operator in a stationary state $|j^{\mathrm{P}}\rangle$ of definite parity P and nonzero spin j, such that

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State $|j^{\mathrm{P}}\rangle$ can be *‘elementary’* particle (quark, charged lepton, $W^{\pm}$ boson, Dirac neutrino, ...)

‘Isn’t an elementary particle a point-particle without structure?
How can such a particle be polarized and support an EDM?’

$\boxed{\text{There are always vacuum polarizations with rich short-distance structure}}$

($g-2$ of the electron and muon aren’t exactly zero either)

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‘What about the huge EDMs of H_2O or NH_3 molecules?’

Theorem: Permanent EDMs of *non*-selfconjugate* particles *with* spin $j \neq 0$

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‘What about the huge EDMs of H_2O or NH_3 molecules?’

The ground states of these molecules at non-zero temperatures or strong E-fields are mixtures of at least 2 opposite parity states:

$\boxed{\text{The theorem doesn't apply for degenerate states: neither } \cancel{T} \text{ nor } \cancel{P} \text{ !}}$

Theorem: Permanent EDMs of *non*-selfconjugate* particles *with* spin $j\neq 0$

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‘But what about the induced EDM (polarization)?’

The induced EDM is *quadratic* in the electric field and *not* $\cancel{P}$ or $\cancel{T}$

induced EDM	$\longleftrightarrow$	quadratic Stark effect ($\propto E^2$)
permanent EDM	$\longleftrightarrow$	linear Stark effect ($\propto E$)

Theorem: Permanent EDMs of *non*-selfconjugate* particles *with* spin $j \neq 0$

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If the interactions are described by an action which is

local, Lorentz-invariant, and hermitian

then CPT invariance holds: thus $\boxed{\cancel{T} \iff \cancel{CP}}$

A *naive* estimate of the scale of the nucleon EDM

Khriplovich & Lamoreaux (1997); Kolya Nikolaev (2012)

- CP & P conserving magnetic moment $\sim$ nuclear magneton μ_N

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\, e\,\mathrm{cm}\,.$$

- A nonzero EDM requires

  parity P violation: the price to pay is $\sim 10^{-7}$

  $\left(G_F \cdot F_\pi^2 \sim 10^{-7} \text{ with } G_F \approx 1.166 \cdot 10^{-5}\mathrm{GeV}^{-2} \right)$,

  and **CP violation**: the price to pay is $\sim 10^{-3}$

  $\left(|\eta_{+-}| \equiv |\mathcal{A}(K_L^0 \to \pi^+\pi^-)| / |\mathcal{A}(K_S^0 \to \pi^+\pi^-)| = (2.232 \pm 0.011) \cdot 10^{-3} \right)$.

- In summary: $\boxed{|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\, e\,\mathrm{cm}}$

- In SM (without θ term): extra $G_F F_\pi^2$ factor to undo flavor change

$$\hookrightarrow \quad \boxed{\left|d_N^{\mathrm{SM}}\right| \sim 10^{-7} \times 10^{-24}\, e\,\mathrm{cm} \sim 10^{-31}\, e\,\mathrm{cm}}$$

$\hookrightarrow$ *The empirical window* for search of physics BSM(θ=0) is

$$\boxed{10^{-24}\, e\,\mathrm{cm} > |d_N| > 10^{-30}\, e\,\mathrm{cm}.}$$

Chronology of upper bounds on the neutron EDM

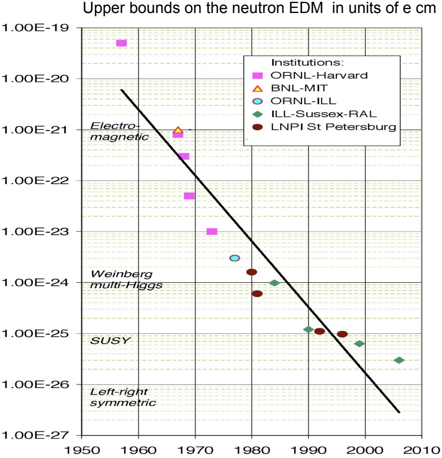


Fig. courtesy of N.N. Nikolaev

Smith, Purcell, Ramsey (1957) .... Baker et al. (2006)

↪ 5 to 6 orders above SM predictions which are out of reach !

Three motivations for EDM searches

Why are EDMs interesting to measure?

A search for new physics which is ***'background free'***

Many beyond-the-SM models predict large EDMs: ***Complementary to LHC search***

Matter/Antimatter asymmetry requires more CPV: ***EDMs are excellent probes***

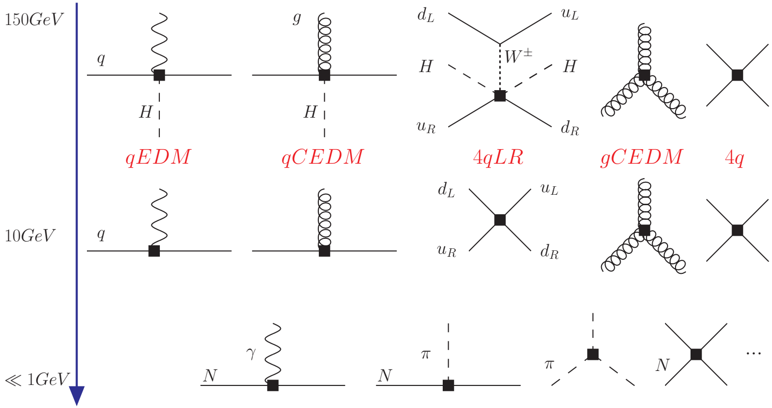
courtesy of J. de Vries

Some questions that you hopefully can answer:

- Why is physics **beyond** the Standard Model expected?
- What are the evidences for dark matter?
- How can light DM escape the Lee-Weinberg bound?
- Why is especially the dark photon so appealing?
- How can a point particle (e.g. an electron) support an EDM?
- Why don't the nonzero EDMs of certain molecules signal $\not{CP}$?
- What is the natural scale of a neutron EDM *i.g.* (in the SM)?
- How large is the EDM window for *New Physics* searches?

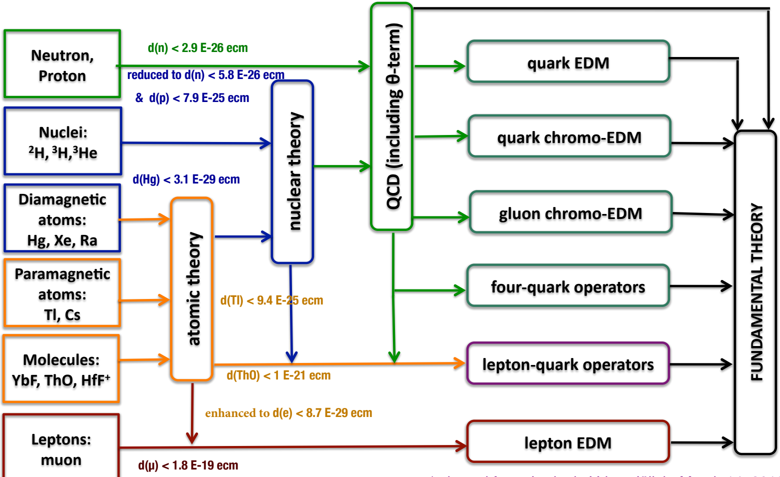
From CP-violating BSM operators to hadronic ones

W. Dekens & J. de Vries *JHEP* '13



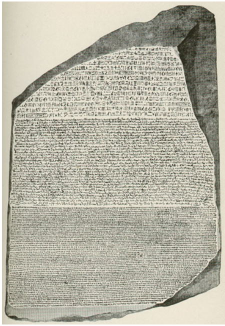
Road map from EDM Measurements to EDM Sources

Experimentalist's point of view → ← Theorist's point of view



(adapted from Jordy de Vries, Jülich, March 14, 2013)

EDM Rosetta Stone
from ‘quarkish/machine’ to ‘hadronic/human’ language?



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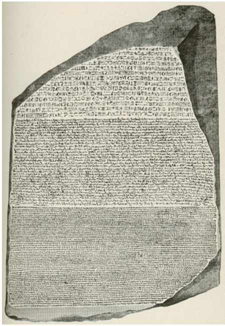
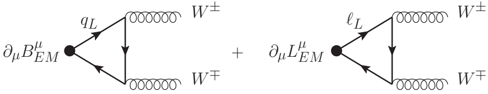


↪ Symmetries (esp. chiral one) plus Goldstone Theorem
Low-Energy Effective Field Theory with External Sources
i.e. Chiral Perturbation Theory (suitably extended)

Jump slides

EW Baryogenesis: Standard Model

Conservation of the EM current under weak ($L - R$) interactions:

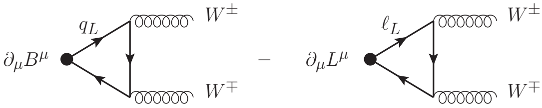


$$\propto \; N_c \cdot (Q_u + Q_d) \; + \; (0 - 1) \; = \; 1 - 1 \; = \; 0$$

$\hookrightarrow \Delta\left(Q_B + Q_L\right) = 0$ (charge conservation!)

EW Baryogenesis: Standard Model

Conservation of the Baryon−Lepton current under $(L-R)$ interactions:



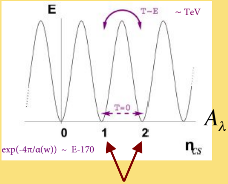
$\propto N_c \cdot 1/3 - 1 = 1 - 1 = 0$

$\hookrightarrow \Delta(B-L) = 0$ but $\Delta(B+L) \neq 0$!

Sakharov criteria

1. B violation ✓
   ($\Delta(B{+}L) \neq 0$ sphaleron transitions)
2. C & CP violation *x*
   (CKM determinant)
3. Nonequilibrium dynamics *x*
   (only fast cross over for $\mu_{chem} = 0$)

Anomalous Processes



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

Sphaleron Transitions

Construction of the CKM matrix

Since weak interactions do not respect the global flavor symmetry, there is mixing within the groups of quarks with the same charge:

$$U \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix} \to \tilde{U} = M_U U\,, \qquad D \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix} \to \tilde{D} = M_D D\,,$$

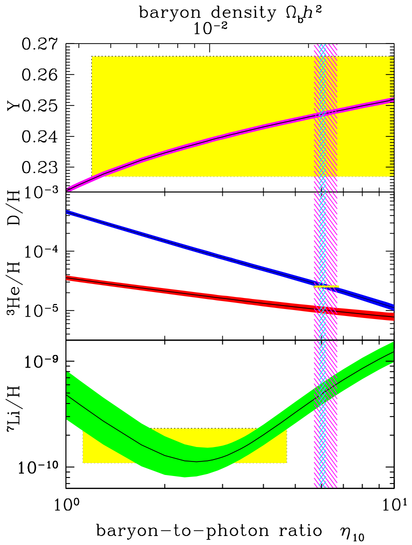
where M_U & M_D are 3×3 unitary matrices

$\hookrightarrow$ charged weak current: $J_\mu = \bar{\tilde{U}}^\mu \gamma_\mu (1-\gamma_5) \tilde{D}^\mu = \bar{U} \gamma_\mu (1-\gamma_5) \underbrace{M_U^\dagger M_D}_{\text{CKM matrix } M} D\,.$

- M unitary $N_f \times N_f$ matrix for N_f quark families $\rightsquigarrow$ $\boxed{N_f^2 \text{ real parameters}}$.
- $2N_f - 1$ of these can be absorbed by the relative phases of the quark wave functions $\rightsquigarrow$ $\boxed{(N_f-1)^2}$ remaining parameters:

  $N_f = 2$: one remaining real parameter: *Cabibbo angle*
  $N_f = 3$: $O(3)$ matrix with $\frac{1}{2}3 \cdot (3-1) = 3$ angles *plus* 1 $\cancel{CP}$ phase
- Lepton case: neutrinos may be Majoranas: $\rightsquigarrow$ 3 angles plus 3 $\cancel{CP}$ phases
- If phase(s) present, M complex matrix, whereas CP invariance $\rightsquigarrow$ $M^* = M$!

Big Bang Nucleosynthesis (BBN)



$$\frac{1}{\eta_B} e^{-\Delta_D/T} \overset{!}{\approx} 1 \quad \text{with } \Delta_D = 2.23\,\text{MeV}$$

$$\text{and} \quad \eta_{10} = 10^{10}\eta_B = 10^{10} n_B/n_\gamma ,$$

$$Y \equiv \rho(^4\text{He})/\rho(\text{H}) = \frac{2n/p}{1+n/p} \simeq 0.25$$

if $n/p \approx 1/7$

Fig. courtesy of PDG update '13

back