# CP Violation: Past, Present, and Future

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Bad Honnef
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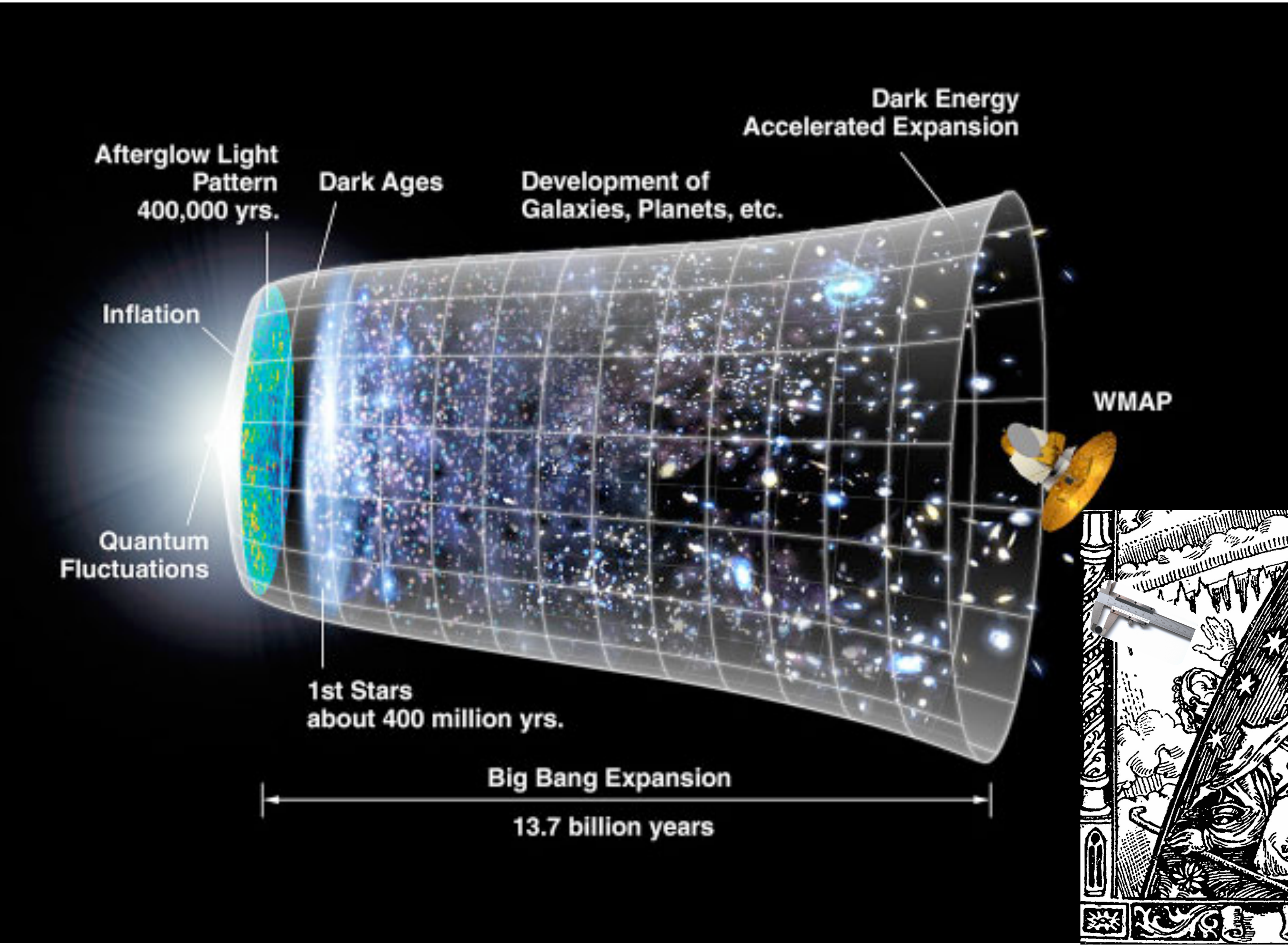
# A Matter-Dominated Universe?

## Precision Measurements of CP Violation Constrain its Mechanism



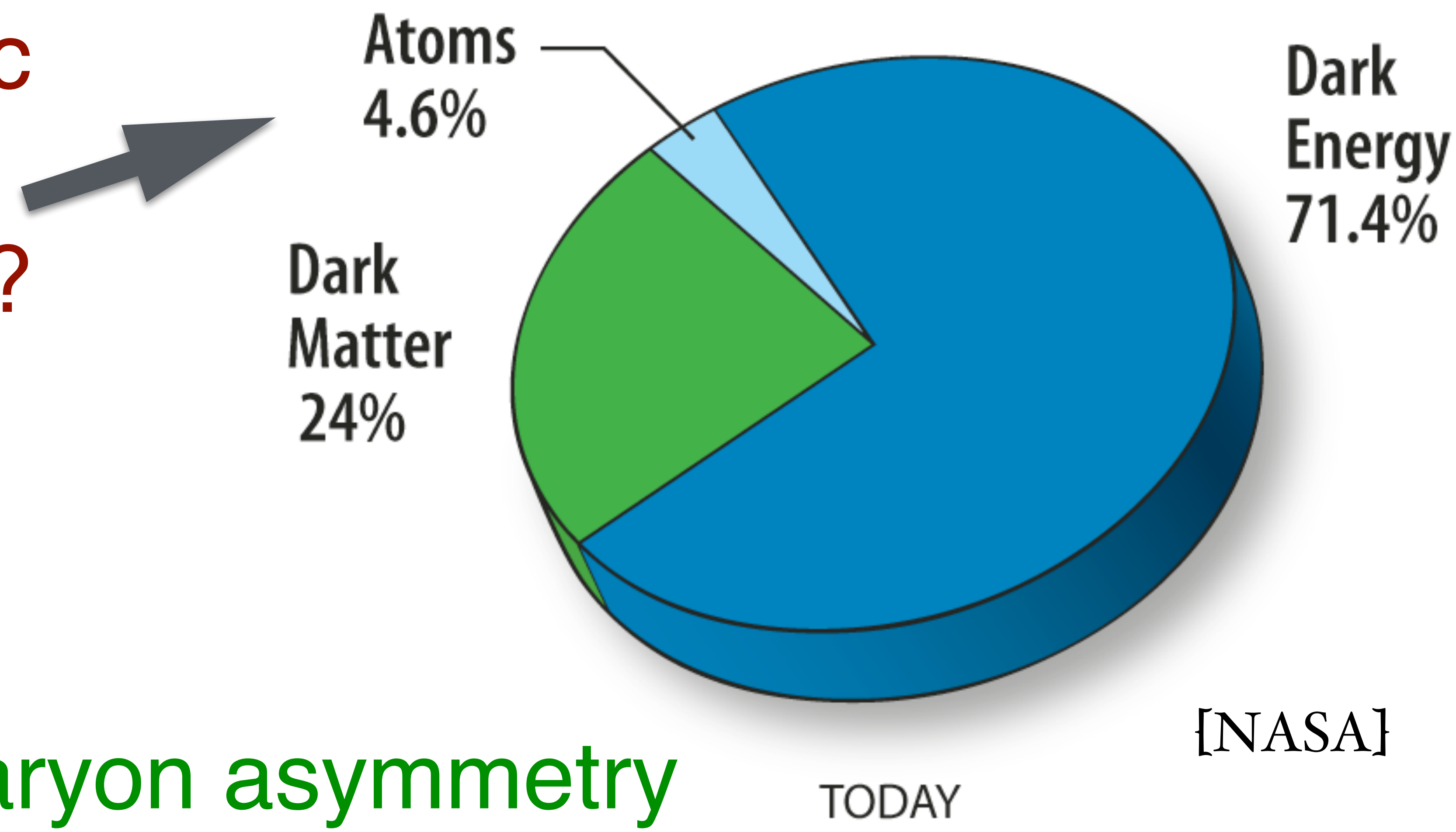

[http://www.nasa.gov/vision/universe/starsgalaxies/wmap_pol.html]

[after C. Flammarion, 1888]

# Three Puzzles

Drive new physics searches

Why is the cosmic energy budget in baryons so small? (and what is everything else?!)




[NASA]

And the cosmic baryon asymmetry

$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (5.96 \pm 0.28) \times 10^{-10}$$ [Steigman, 2012]

so large?

And why is the neutrino mass so very small?

$$m_\nu < 1.1\,\text{eV}\,(90\,\%\,\text{CL})$$ [KATRIN, 2019]

# A Cosmic Baryon Asymmetry

Confronting the observed D/H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$

**By initial condition?**

We interpret the CMB in terms of an inflationary model, so that this seems unlikely. [Krnjaic, PRD 96 (2017)]

**From particle physics?**

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

Non-equilibrium dynamics are required to avoid "washout" of an asymmetry by back reactions

# The Puzzle of the Missing Antimatter

The baryon asymmetry of the universe (BAU) derives from physics beyond the standard model!

The SM almost has the right ingredients:

B? Yes, at high temperatures

C and CP? Yes, but CP is "special"

Early numerical estimates are much too small. ← $\eta < 10^{-26}$

[Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

Non-equilibrium dynamics? No. (!)

The Higgs particle is too massive to yield a first-order electroweak phase transition

[e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

So that the SM mechanism fails altogether

And we seek new sources of CP violation....

# Recipes for a Baryon Asymmetry?

The BAU derives from physics beyond the standard model!

What new mechanisms are possible?

There are **many** & very probably more to discover

**What are the ingredients? Well…**

It could involve weak scale supersymmetry.

→ Probe new CPV phases through permanent EDM searches

It could involve an lepton asymmetry that is transferred to baryons —or involve a post-sphaleron baryogenesis mechanism.

→ Discover fundamental Majorana dynamics through discovery of $0\nu\,\beta\beta$ decay or of $n\overline{n}$ oscillations

It could involve a dark matter particle asymmetry that is transferred to baryons.

→ Discover a dark magnetic moment (Faraday rotation for light asymmetric DM [SG 2008, 2009]; or DM direct detection…)

# On CP Violation (with quarks)

## Timeline and definitions

### How CP can be violated…

in decay:

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

in mixing:

$$\left|\frac{q}{p}\right| \neq 1$$

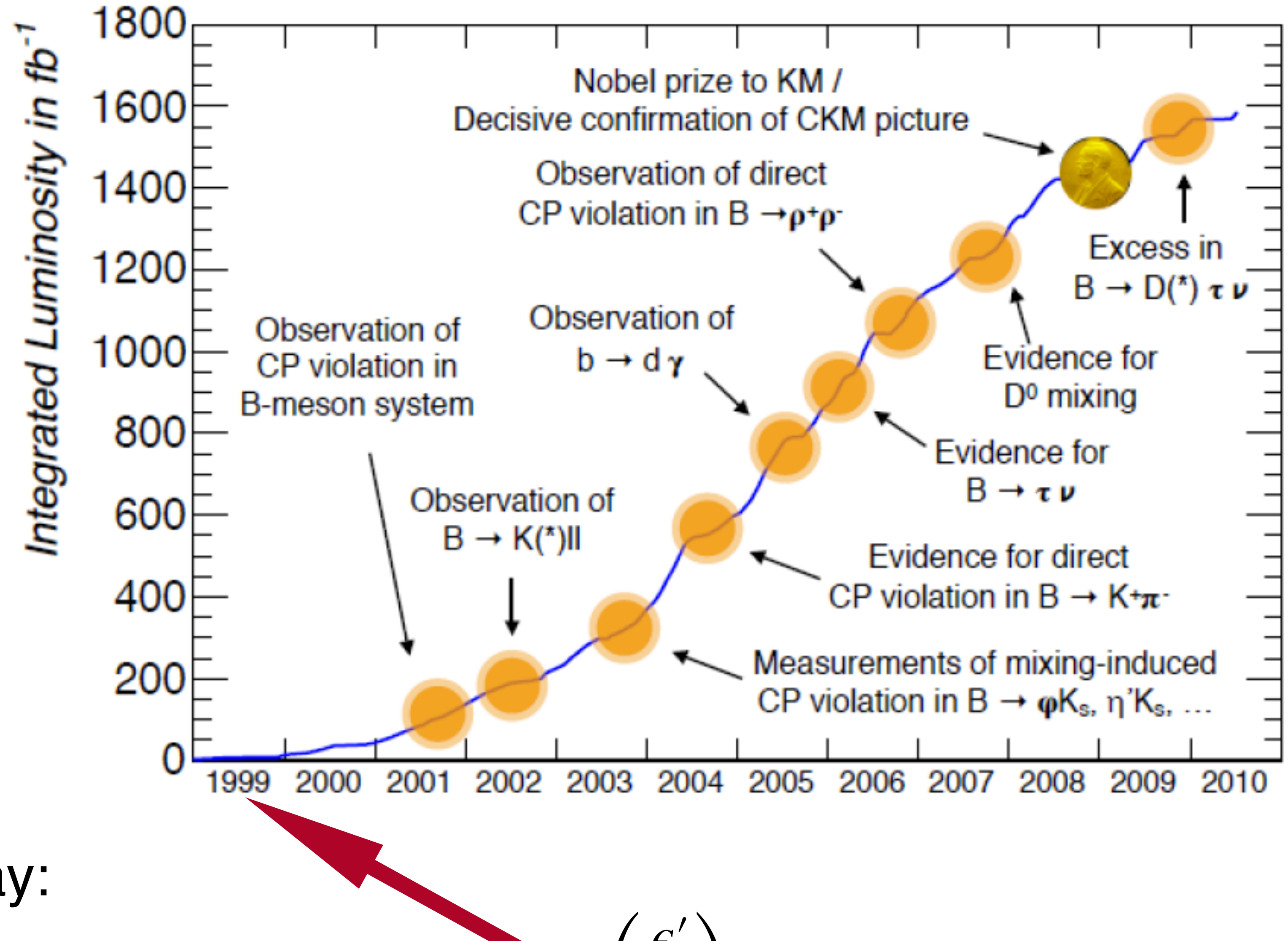
in interference between mixing & decay:

cf. $M_0 \to f$ and $M_0 \to \overline{M}_0 \to f$

$$\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0$$

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

[Bennett, BELLE2-TALK-CONF-2017-094]




$\Re\left(\frac{\epsilon'}{\epsilon}\right) \neq 0$ [KTeV, NA48,1999]

$\Gamma(K_L \to \pi\pi) \neq 0$ [Christensen et al.,1964] ; $\epsilon \neq 0$

Large CPV effects possible in the B system!

[Bigi and Sanda; Carter, Dunietz… 1980's]

# CP violation in the SM

## Observed effects appear through quark mixing under the weak interaction

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \quad ; \quad V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The Cabibbo-Kobayashi-Maskawa (CKM) matrix is a unitary 3x3 matrix with 4 parameters in the Standard Model

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

[Wolfenstein, 1983]

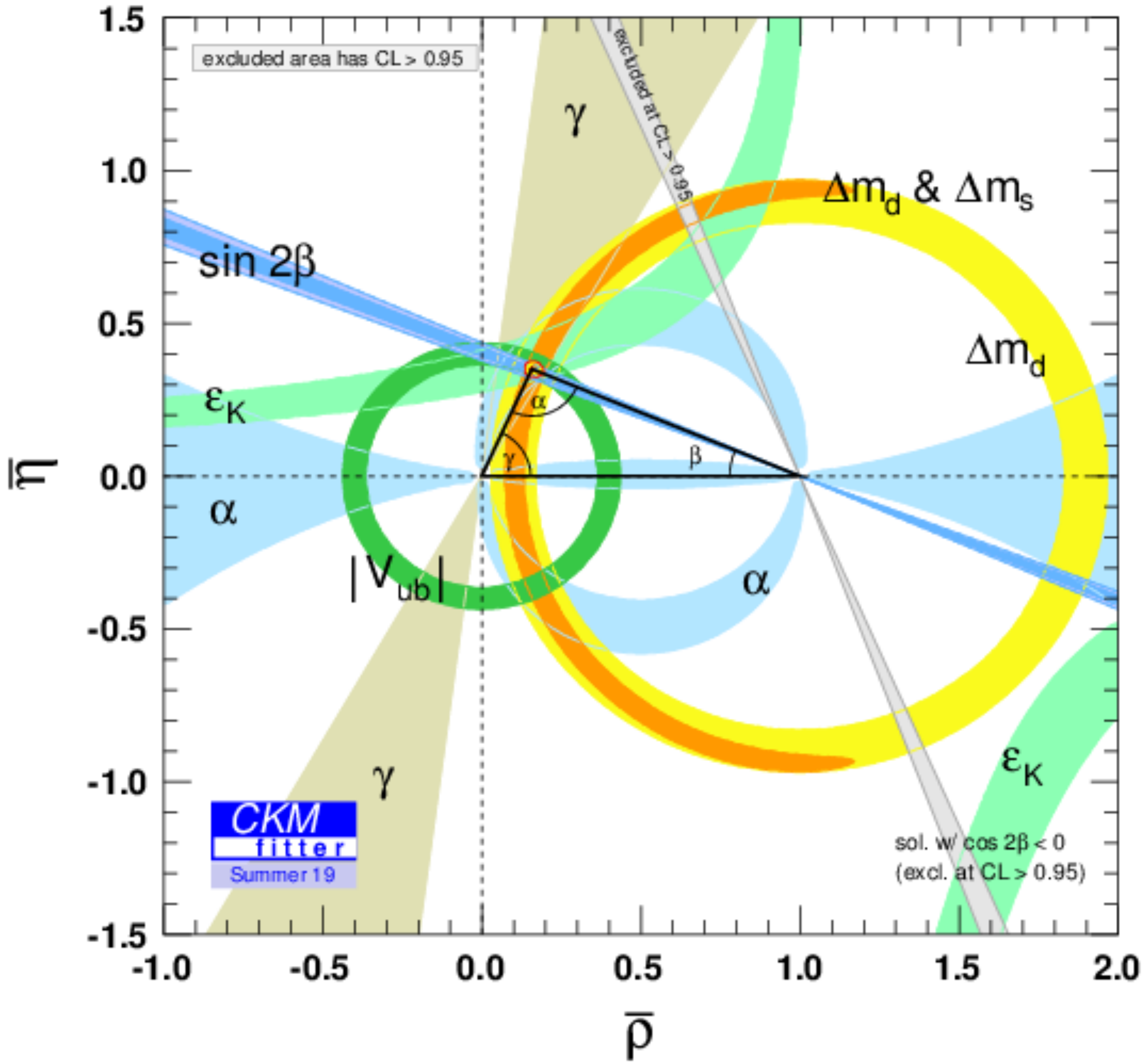
Quark mixing is hierarchical: $\lambda \simeq 0.2$ & $\eta \neq 0$ (CPV)!

The CKM matrix describes **all** flavor and CP violation **observed** in charged-current processes…

# Observed CP violation in the SM

Testing the **Relationships** [L. Wolfenstein (Kaon '99)]

Enter "the" unitarity triangle — each term of $\mathcal{O}(\lambda^3)$




[CKM Fitter: Charles et al., 1501.05013]

Are $\bar{\eta}$ and $\bar{\rho}$ universal?

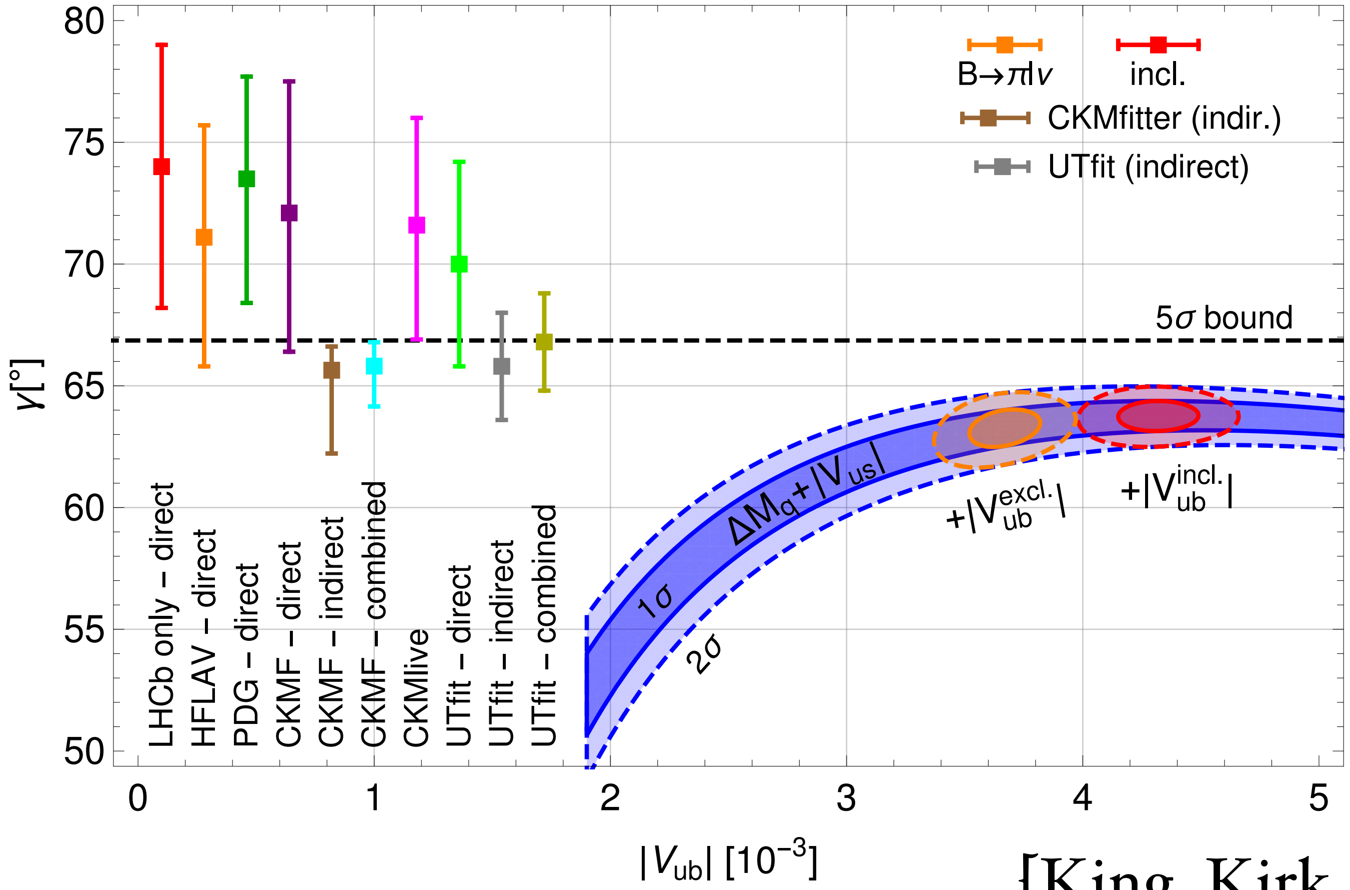
Is the CKM matrix unitary?

cf. CPV (yes?) to CP conserving (no?!) tests…

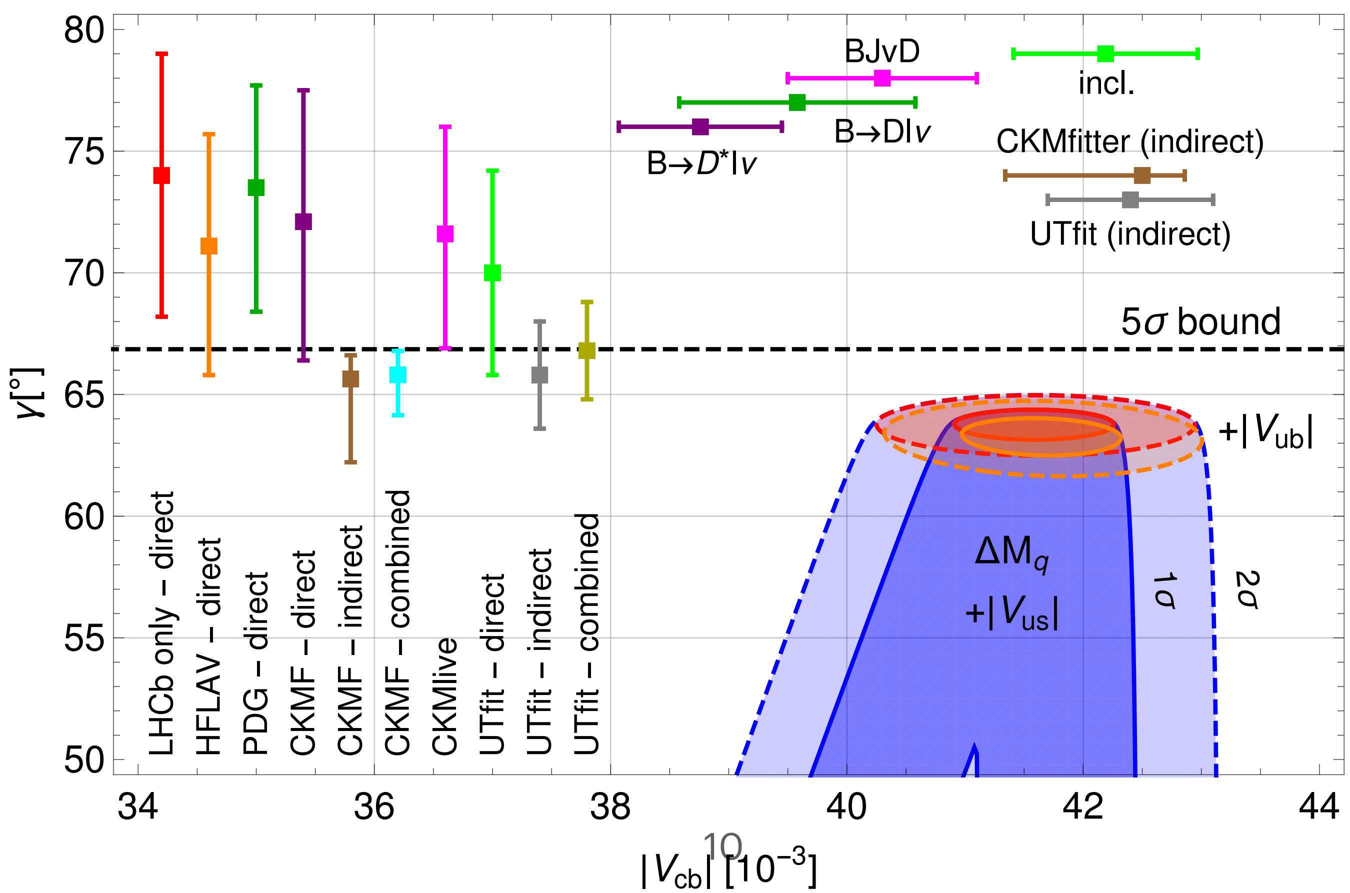
Expect much improved tests from LHCb & Belle II!

N.B. lattice QCD plays a key role!

# Stress Testing the **Relationships**




[King, Kirk, Lenz, & Rauh, 1911.07856]

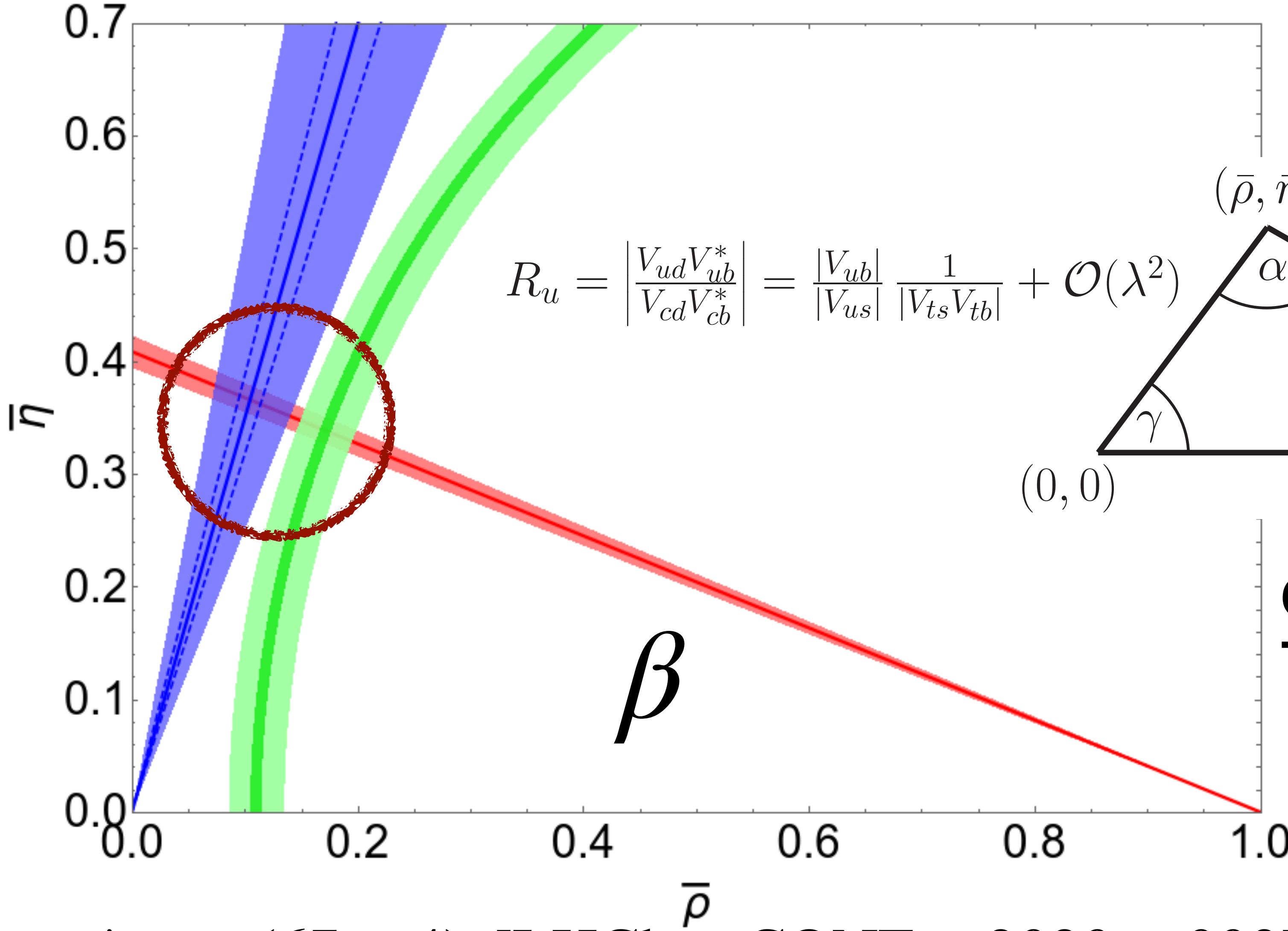



Note reliance on $|V_{us}|$
[PDG 2018]

# Stress Testing the **Relationships**

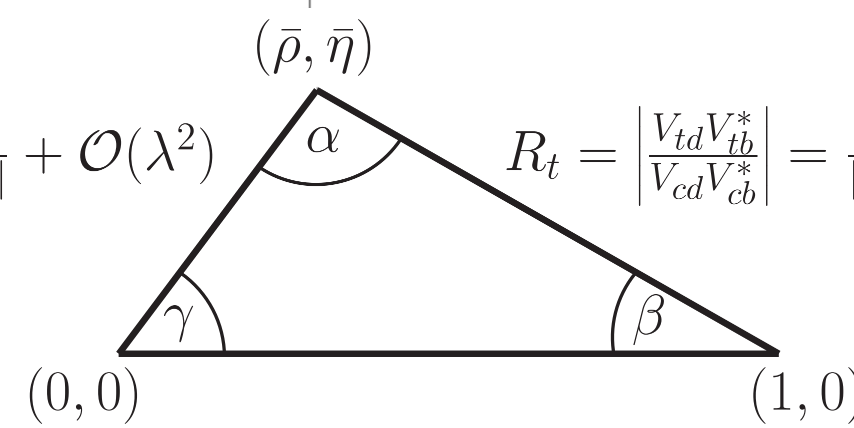
## Are $\bar{\eta}$ and $\bar{\rho}$ universal? Is the CKM matrix unitary?

$\gamma$ [LHCb]* $\Delta M$ [King et al., 1911.07856; also Blanke and Buras, 2019]




Note "apex" study:

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \frac{|V_{ub}|}{|V_{us}|}\frac{1}{|V_{ts}V_{tb}|} + \mathcal{O}(\lambda^2)$$




$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \frac{1}{|V_{us}|}\left|\frac{V_{td}}{V_{ts}}\right| + \mathcal{O}(\lambda^2)$$

cf. sides to angles…
The triangle may not close?

* $\gamma = (67 \pm 4)^\circ$ [LHCb – CONF – 2020 – 003]

## Is $\beta$ universal?

Study penguin-dominated $\beta$ modes…
$B \to \eta' K_S, \phi K_S$ (SM effects in QCDf) [Belle II]

## Note also CPC test:

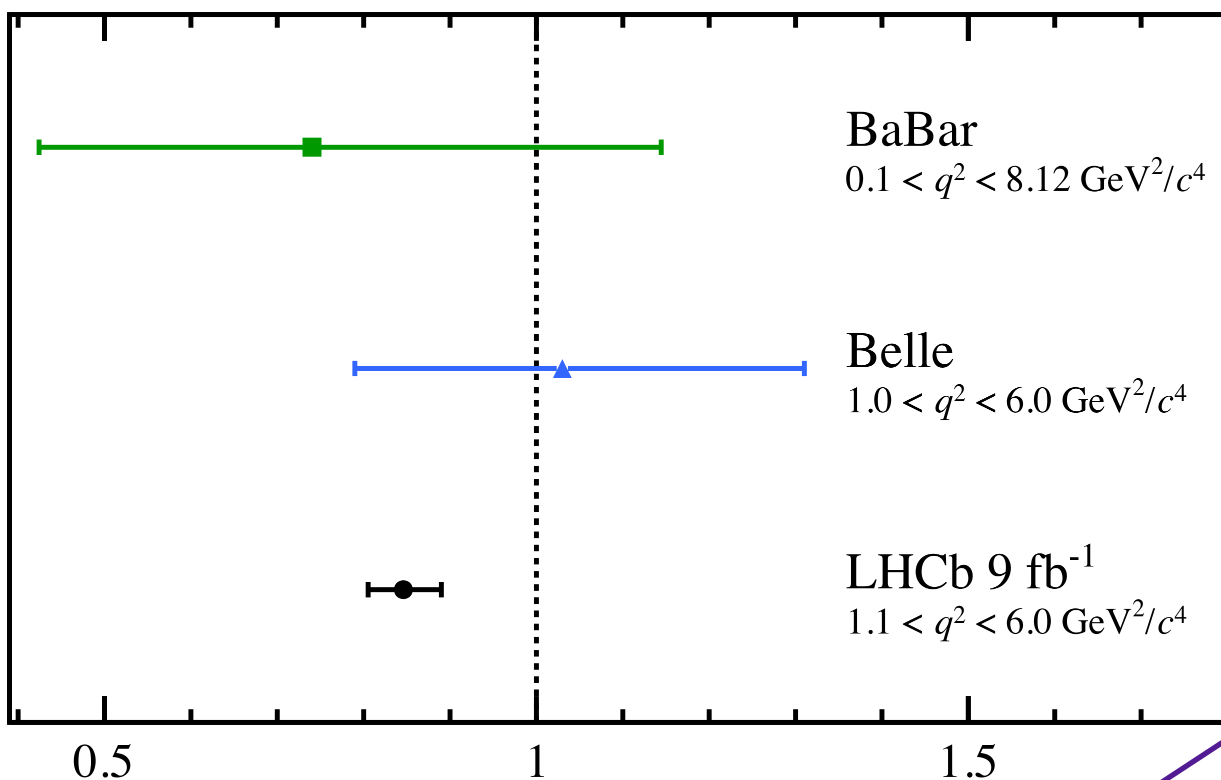
[Seng et al., 2020] $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$ (?!)

# Stress Testing the **Relationships**

## Does lepton flavor universality (LFU) hold?

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+e^-)K^+)}$$

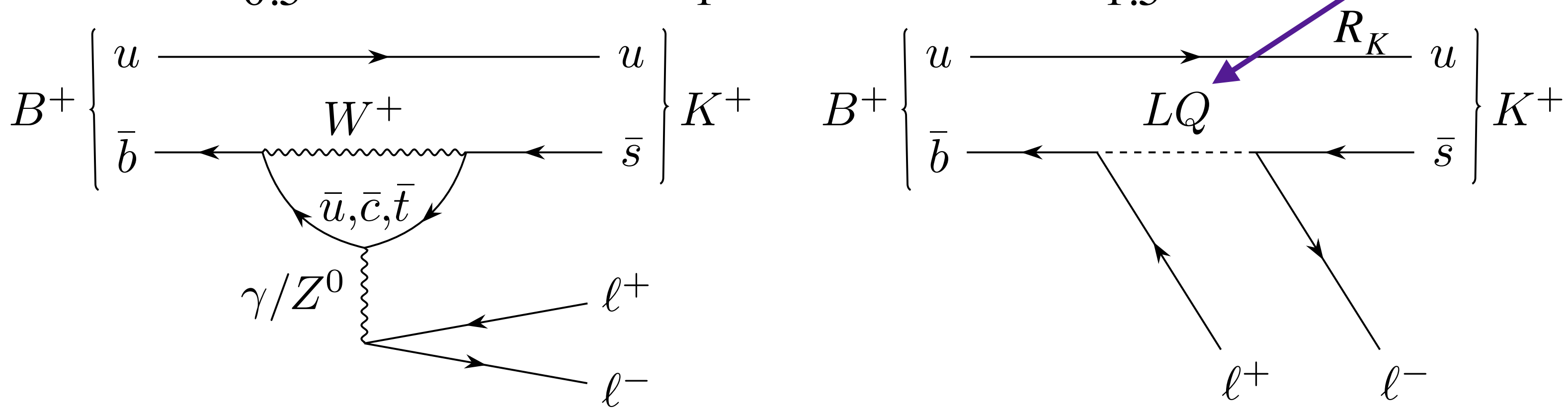
~3.1 σ Anomaly




[LHCb, 2103.11769]

N.B. also $R_{D^{(*)}}$ anomalies at similar significance… further studies planned at Belle II

"Leptoquark"




Now turn to **lepton moments**; hints of LFU violation?

# Electric & Magnetic Dipole Moments

**A permanent EDM breaks parity (P) & time-reversal (T)**

$$\mathscr{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Intrinsic property: $\vec{\mu}, \vec{d} \propto \vec{S}$ [spin]

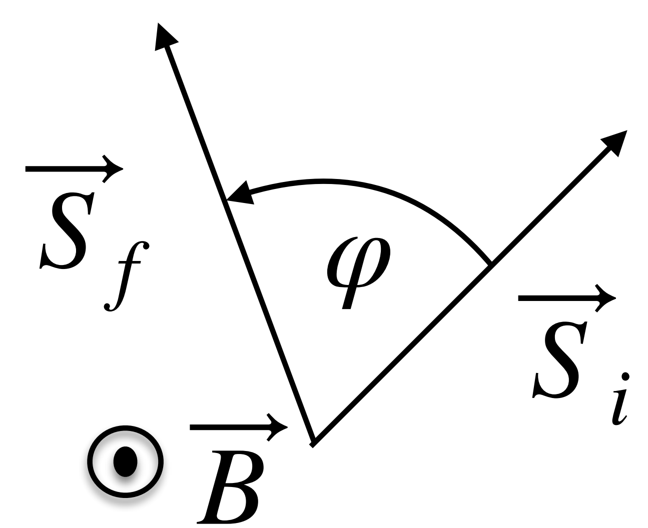
Maxwell Equations… $-\vec{\mu} \cdot \vec{B}$ is P even, T even

$-\vec{d} \cdot \vec{E}$ is P odd, T odd

Note if T is broken so is CP [CPT unbroken]

Classically, the spin precesses if there is a torque:

$$\vec{\tau} = \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$$



# Electric & Magnetic Dipole Moments

Taken relativistically for fermion f with charge -e

$$\mathcal{H} = e\bar{\psi}_f\gamma^\mu\psi_f A_\mu + a_f\frac{1}{4}\bar{\psi}_f\sigma^{\mu\nu}\psi_f F_{\mu\nu} + d_f\frac{i}{2}\bar{\psi}_f\sigma^{\mu\nu}\gamma_5\psi_f F_{\mu\nu}$$

photon field $A_\mu$ $\qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

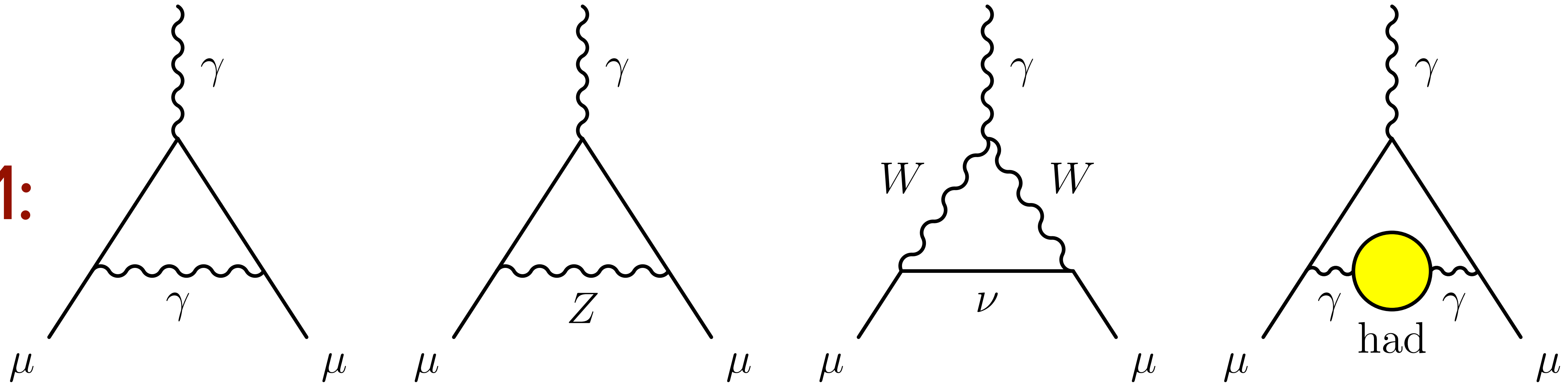
$$\mu_f = g_f\frac{e}{2m_f} \qquad g_f = 2 + 2a_f$$

$a_f$ is an anomalous magnetic moment

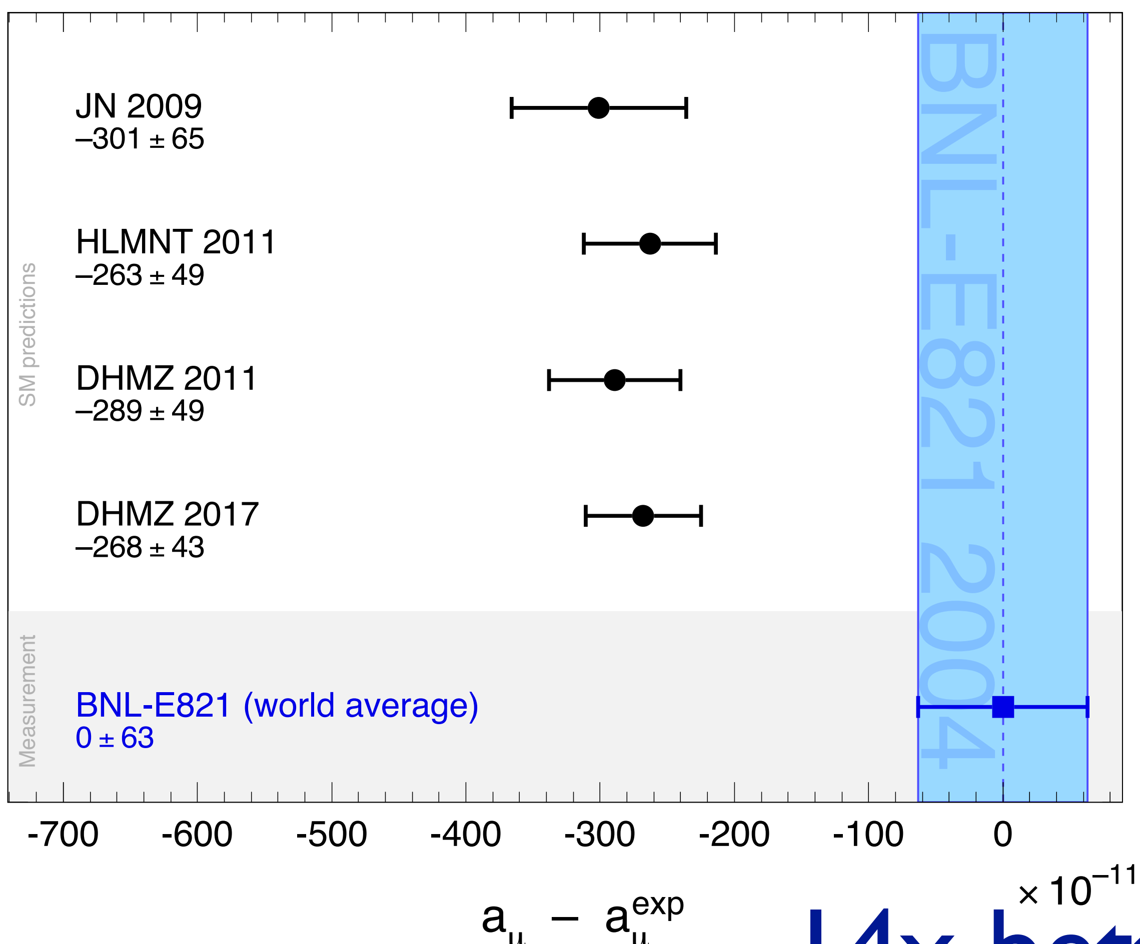
For an elementary fermion $a_f$ and $d_f$ can only be generated through loop corrections (N.B. D>4)

# The μ Magnetic Moment Anomaly

SM:




(Biggest Uncertainty)




[Hoecker & Marciano, in RPP, PDG, 2018]

$\Delta a_\mu \sim 3.5\sigma$

"interesting but not conclusive"

14x better than in 1970's (CERN)

# New $(g-2)_\mu$ Experiment at Fermilab

Aim:
4x better than BNL-E821 (2004) !

But there is a $(g-2)_e$ anomaly also…

July 26, 2013

# Lepton Magnetic Moments & α

**$a_f$ in QED perturbation now known to $(\alpha/\pi)^5$ !**

[Aoyama, Hayakawa, Kinoshita, Nio, 2012; Aoyama, Kinoshita, Nio, 2018 & 2019 ]

SM: $a_f = a_f(\text{QED}) + a_f(\text{weak}) + a_f(\text{hadron})$

**Very small**

0.026 ppb 1.47 ppb [electron]

Using $a_e$ (expt) $= 1\ 159\ 652\ 180.73\ (28) \times 10^{-12}$

[Hanneke, Fogwell, Gabrielse, 2008]

This, with $a_e$ in the SM, yields

$$\alpha^{-1}(a_e) = 137.035\ 999\ 1496\ (13)\ (14)\ (330)$$

(Expt!)

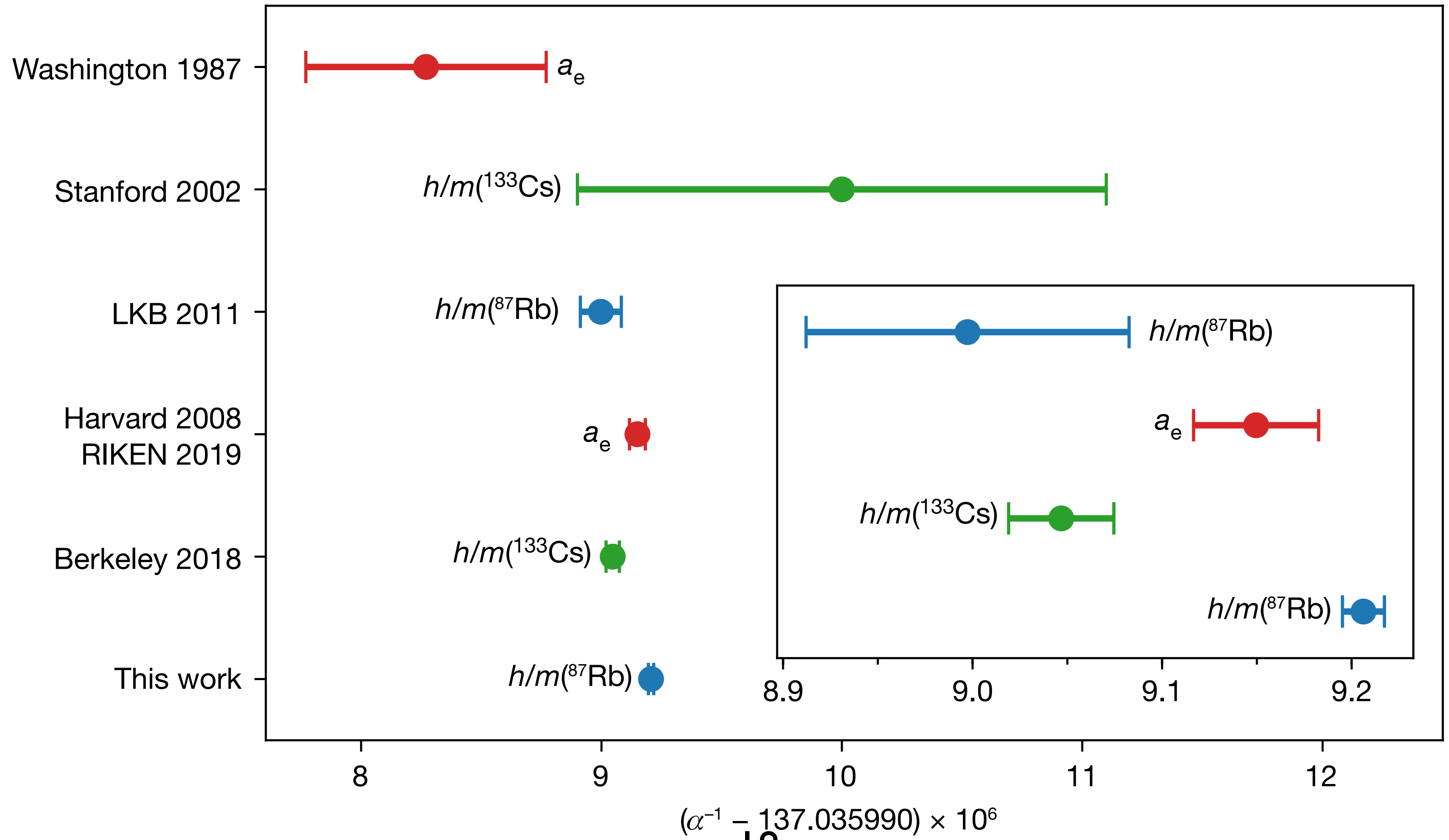
# New Paths to α

The measurement of $a_e \equiv (g\text{-}2)_e/2$ was once the only way to determine the fine-structure constant α precisely

[… Hanneke, Fogwell, Gabrielse, 2008]

Now with $h/M_X$ (for X=Rb or Cs) from **atom interferometry** we have another precise way of determine α

[Bouchendira et al., 2011 [Rb]; Parker et al., 2018 [Cs]; Morel et al., 2020 [Rb]]



# $a_\mu$ and $a_e$ Probe Physics Beyond the SM

[Aoyama, Kinoshita, Nio, 2019 ]

$$a_e^{EXP} - a_e^{SM}\ [\text{Rb}, 2011] = (-131 \pm 77) \times 10^{-14}$$

$$a_e^{EXP} - a_e^{SM}\ [\text{Rb}, 2020] = (+48 \pm 30) \times 10^{-14}$$

~1.6 σ

$$a_e^{EXP} - a_e^{SM}\ [\text{Cs}, 2018] = (-88 \pm 36) \times 10^{-14}$$

~2.4 σ

$$a_\mu^{EXP} - a_\mu^{SM} = (2.74 \pm 0.73) \times 10^{-9}$$

(!)

~3.7 σ

Both the relative sign and size are important.

A viable new-physics solution cannot distinguish μ and e only by their mass! ($\Delta a_e$ [Cs] is 10x too big!)

# $a_\mu$ & $a_e$ Signal Lepton Flavor Universality (LFU) Violation

"LFU" means that μ and e differ only in their mass

$$(\delta a_f)_{new} \sim m_f^{\,2} / M_{new}^2$$

**Note** $m_\mu^2/m_e^2 \sim 4.2\text{x}10^4$

Thus $\Delta a_e$ [Cs,Rb] implies a $\Delta a_\mu$ that is too large w.r.t. BNL E821!

Perhaps LFU is violated

If so, this also suggests the appearance of "light" new physics

# Interpreting $\Delta a_\mu$ & $\Delta a_e$

## Challenging to explain both at once

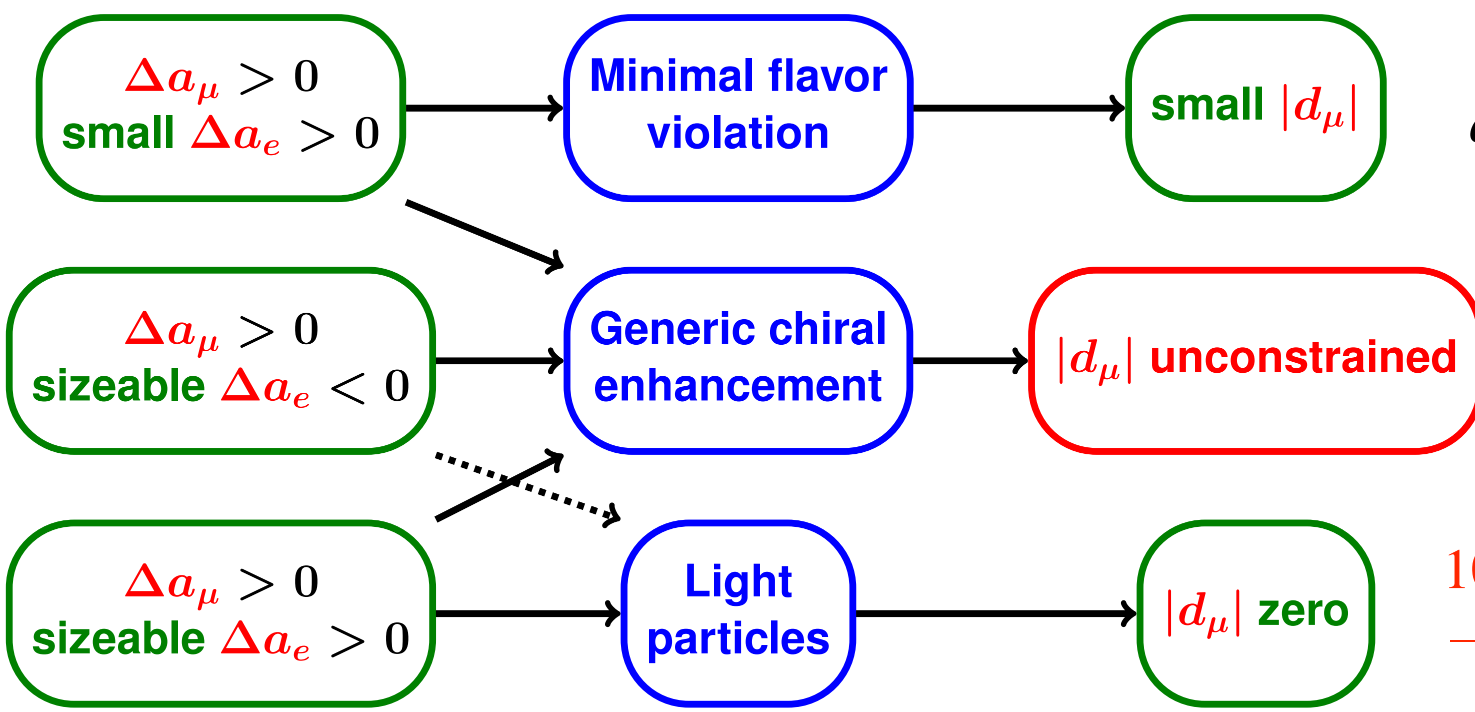
## BSM solutions (t<2020) treat μ and e differently

[Davoudiasl & Marciano, 2018][Liu, Wagner, Wang, 2018] [Crivellin and Hoferichter, 2018]
[Hiller et al., 2019] [Fayet, 2007; Kahn et al., 2017][SG & Yan, 2020]

## Enter EFT treatment; severe limit

$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13} \,@\, 90\,\%\,\mathrm{CL}$$ [MEG: Baldini et al., 2016]

decouples $e$ and $\mu$ sectors, so $d_\mu$ need not be set by $d_e$!




$$d_\mu^{\mathrm{MFV}} \sim \frac{m_\mu}{m_e} d_e < 2 \times 10^{-27}\ \text{e-cm}$$

$$d_\mu^{\mathrm{expt}} < 1.5 \times 10^{-19}\text{e-cm} \,@\, 90\,\%\,\mathrm{CL}$$

[Bennett et al., 2009]

$10^2$ improvement at Fermilab/J-PARC; — and 10x more at PSI — are possible!

[Crivellin and Hoferichter, 1905.03789]

# EDMs & Sensitivity to New Physics

**The electric and (anomalous) magnetic moments change chirality**

$$\bar{\psi}\sigma^{\mu\nu}\psi = (\bar{\psi}_L\sigma^{\mu\nu}\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\psi_L)$$

$$\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi = (\bar{\psi}_L\sigma^{\mu\nu}\gamma_5\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\gamma_5\psi_L)$$

By dimensional analysis we infer the scaling

$$d_f \sim e\frac{\alpha}{4\pi}\frac{m_f}{\Lambda^2}\sin\phi_{\mathrm{CP}}$$

New Physics Scale

$$d_{d\,\mathrm{quark}} \sim 10^{-3} e\frac{m_d(\mathrm{MeV})}{\Lambda(\mathrm{TeV})^2} \sim 10^{-25}\frac{1}{\Lambda(\mathrm{TeV})^2} e - \mathrm{cm}$$

Neutron: $d_n < 1.8 \times 10^{-26}$ e-cm [90 % C.L.] {Abel et al., 2020}

EDM experiments have (at least) TeV scale sensitivity

Applied electric fields can be enormously enhanced in atoms and molecules: world's best EDM limit $^{199}$Hg

{Graner et al., 2016}

# EDMs in the SM

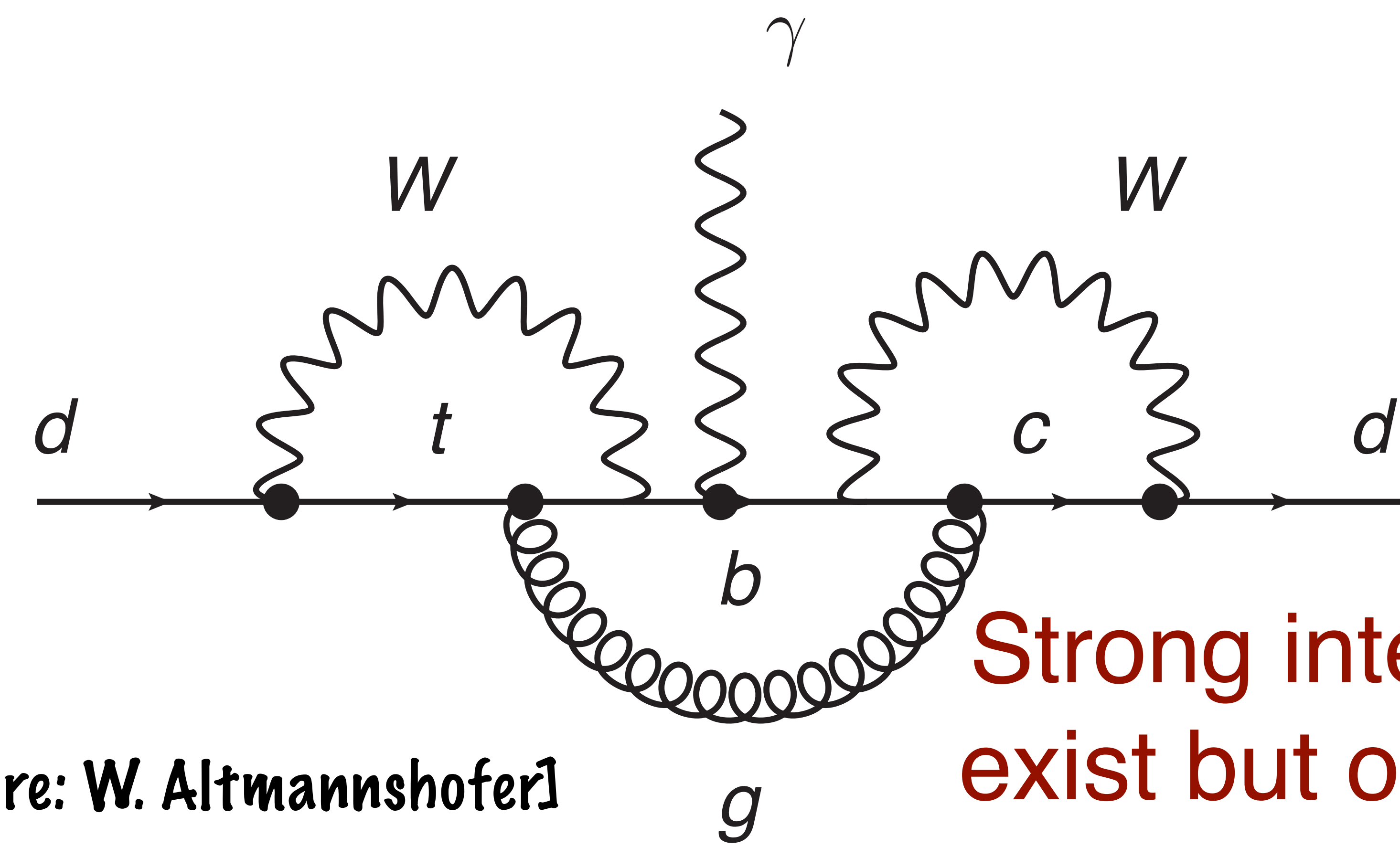
The contribution from the CKM matrix first appears in three-loop order!

The EDM is flavor diagonal, so that…

at one-loop order no "Im V…" piece survives

at two-loop order the "Im V…" piece vanishes [Shabalin, 1978]

at three-loop order the gluon-mediated terms dominate [Khriplovich, 1986]




[figure: W. Altmannshofer]

$|d_d| \sim 10^{-34}$ e-cm

[Czarnecki & Krause, 1997]

Inaccessibly small!

Strong interaction enhancements exist but only by $10^{2 \text{ or } 3}$ in neutron

[Gavela et al., 1982: Khriplovich & Zhitnitsky, 1982; Mannel & Uraltsev, 2012;... Seng, 2015]

# Lepton EDMs in the SM

The contribution from the CKM matrix first appears in four-loop order!

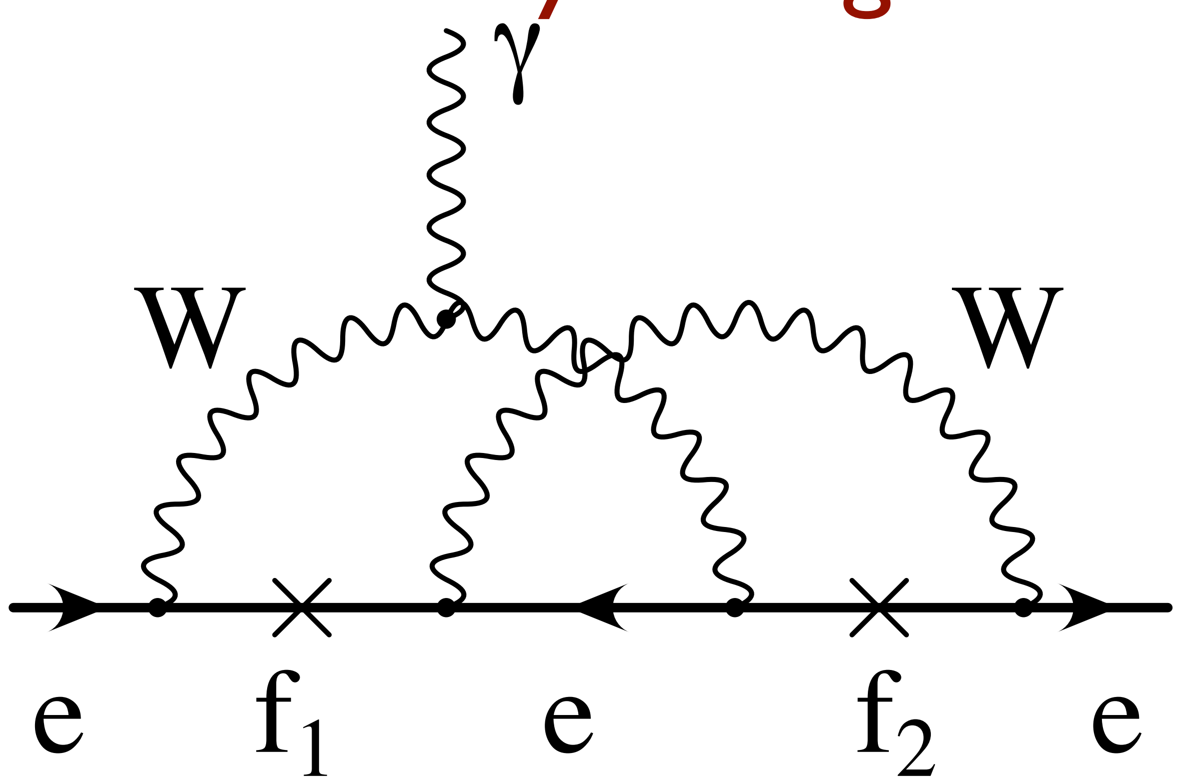
*cf.* $d_e^{eff}$ *from CPV e-N*
[Pospelov & Ritz, 2013]

$d_e \sim 10^{-44}$ e-cm [Khriplovich & Pospelov, 1991]

Majorana neutrinos can enhance a lepton EDM

[Ng & Ng, 1996]

but not nearly enough to make it "visible"




For "fine tuned" parameters

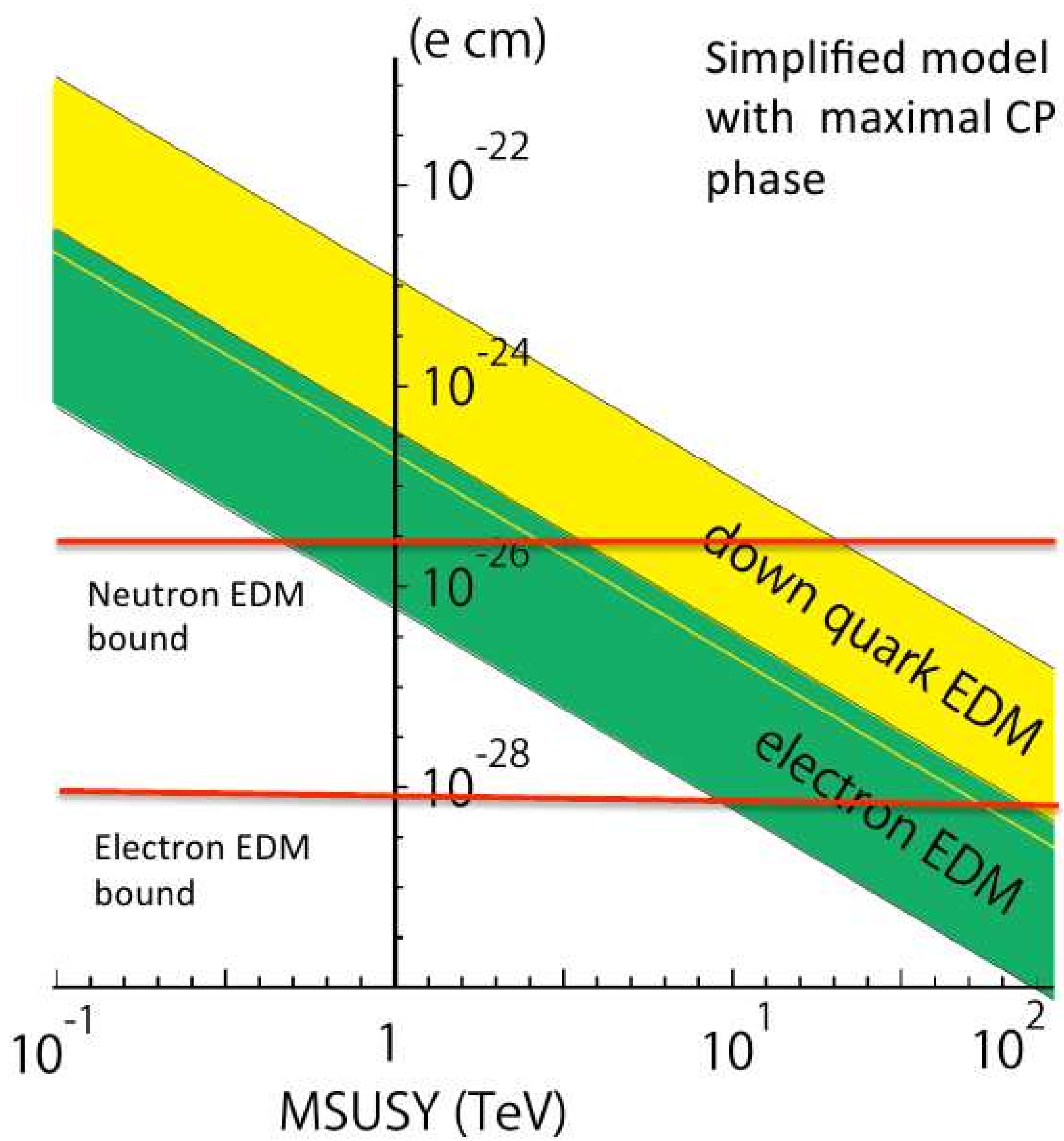
$d_e \lesssim 10^{-33}$ e-cm

[Archambault, Czarnecki, & Pospelov, 2004]

Look to CPV in **ν** oscillations to probe leptogenesis!

# EDMs & the SUSY CP Problem

## Models with O(1) CP phases & weak scale supersymmetry




(Hisano @ Moriond EW 2014)

[Figure: W. Altmannshofer]

An EDM can now appear at one loop!

EDM bounds push super partner masses far above the TeV scale!

Different models can make the pertinent CP phases effectively small…

LHC results now suggest “decoupling” is a partial answer

# Model Independent Analysis Framework

**Suppose new physics enters at an energy scale**

$$E > \Lambda$$

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \,,$$

where the new operators have mass dimension D>4
and we impose $SU(2)_L \times U(1)$ gauge invariance
on the operator basis [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

**We can consider all the CP-violating terms that appear at a fixed D**

# Operator Analysis of EDMs

## The flavor-diagonal effective Lagrangian at ~1 GeV

$$\mathcal{L}_{\text{dim }4} \supset \bar{\theta}\alpha_s G\tilde{G}$$

can appear in the IR even if an axion acts [Chien et al., arXiv:1510.00725, JHEP 2016]

$$\mathcal{L}_{\text{“dim 6”}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F\sigma\gamma_5 q + \tilde{d}_q \bar{q} G\sigma\gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F\sigma\gamma_5 l$$

$$\mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G\tilde{G} + \sum_{f,f',\Gamma} C'_{ff'} (\bar{f}\Gamma f')_{LL} (\bar{f}\Gamma f')_{RR}$$

$$\mathcal{L}_{\text{“dim 8”}} \supset \sum_{q,\Gamma} C_{qq} \bar{q}\Gamma q \bar{q}\Gamma i\gamma_5 q + C_{qe} \bar{q}\Gamma q \bar{e}\Gamma i\gamma_5 e + \cdots$$

[Ritz, CIPANP, 2015]

Many sources: note effective hierarchy imposed by $SU(2) \times U(1)$ gauge invariance (chirality change!)

Limits on new CPV sources often taken “one at a time”

# Operator Analysis of EDMs

Connecting from high to low scales

A single TeV scale CPV source may give rise to multiple GeV scale sources

Explicit studies of operator mixing & running effects are now available

[Chien et al., arXiv:1510.00725, JHEP 2016; Cirigliano, Dekens, de Vries, Merenghetti, 2016 & 2016]

Lattice QCD studies of apropos single-nucleon matrix elements

Enter isoscalar & isovector tensor charges… & more!

[Bhattacharya et al., 2015 & 2016; Gupta et al., arXiv:1801.03130…]

Determining the parameters of the low energy effective Lagrangian experimentally is a distinct problem

Can all the low-energy CPV sources be determined?

★ Need to interpret EDM limits in complex systems: atoms, molecules, and nuclei — or not?! (p, d)

Note talks today by Rob Timmermans and Rajan Gupta!

# A Vast Range of Dark Matter Candidates

## Particle Masses

Fits in Galaxy — Elementary Part.

$10^{-22}$ eV 1 eV 1 keV 1 GeV 100 TeV $10^{19}$ GeV

"Fuzzy DM" "WIMPs" Exotics

"Black Holes"

$n_{DM} \lambda_{dB}^3 >> 1$ $n_{DM} \lambda_{dB}^3 << 1$

Cosmology!

Behaves like a classical field

Rare collisions

Study in underground expts!

Uncertainty Principle washes out cosmic short-scale structure

New probes!! [GPS networks, atomic clocks…]

[A. Derevianko,…]

[after Y. Kahn]

# Ultralight Dark Matter

## Cosmic history constraints

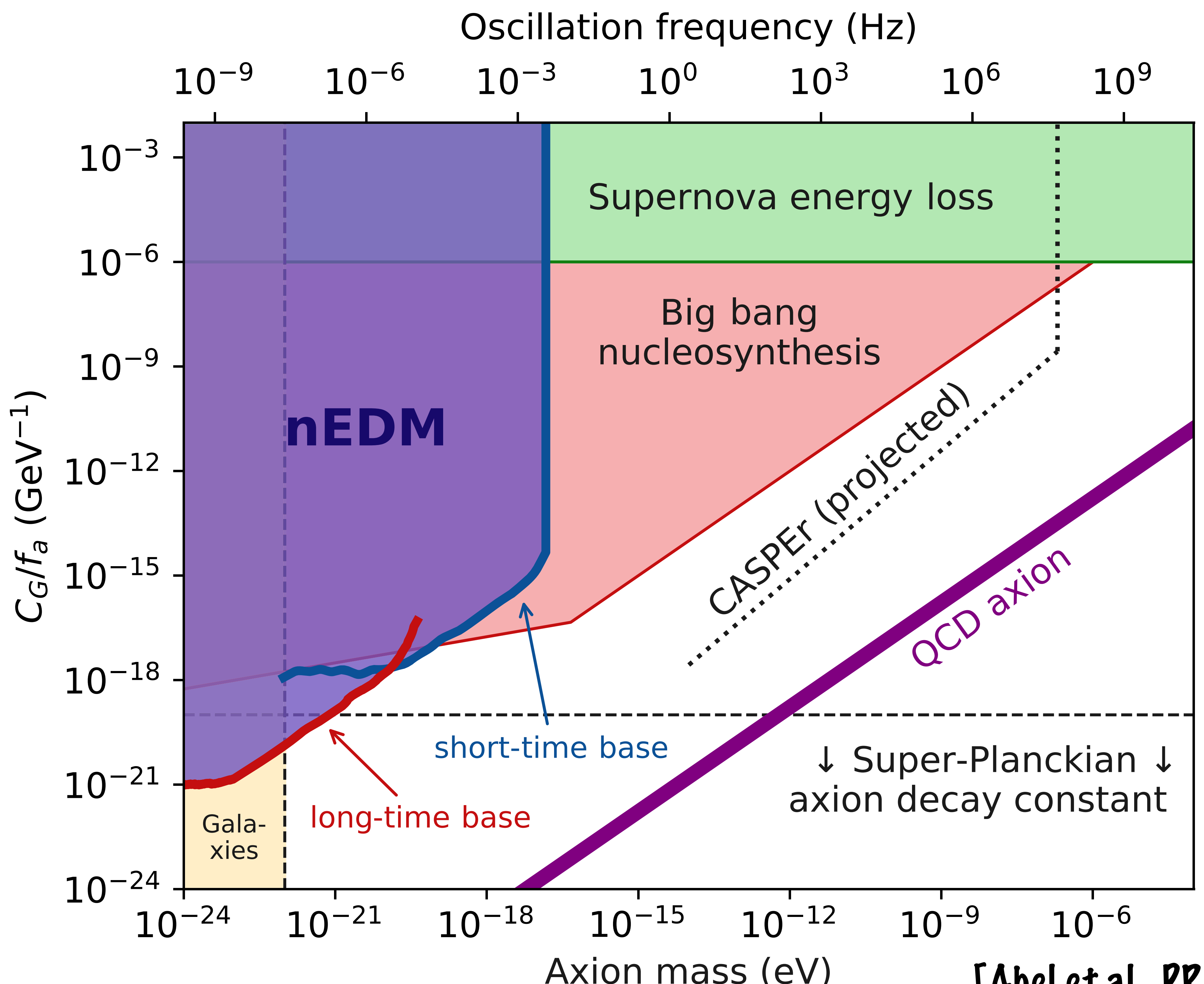
Observations of the CMB power spectrum constrain the ratio of tensor (gravitational wave) to scalar (density fluctuations) power r

$r < 0.07$ at 95% C.L. [Ade et al., PRL 116 (2016) 031302] (BICEP2 + Keck + Planck)]

This quantity has not been detected making ultralight (axion-like) dark matter ($m_a \sim 10^{-22}$ eV) "fuzzy (quantum wave) dark matter" possible….

[Hu, Barkana, Gruzinov, PRL 85 (2000) 1158;
Schive, Chiueh, Broadhurst, Nat. Phys. 10 (2014) 496...;
Graham & Rajendran, PRD 84 (2011) 055013,... for direct detection prospects ]

# Direct Detection: Ultralight Dark Matter




[Abel et al., PRX, 2017]

Note talk today by Peter Graham!

# Summary

Through new and continuing efforts in the study of CP violation worldwide (with focus on relationships!) cracks in the SM are beginning to show!

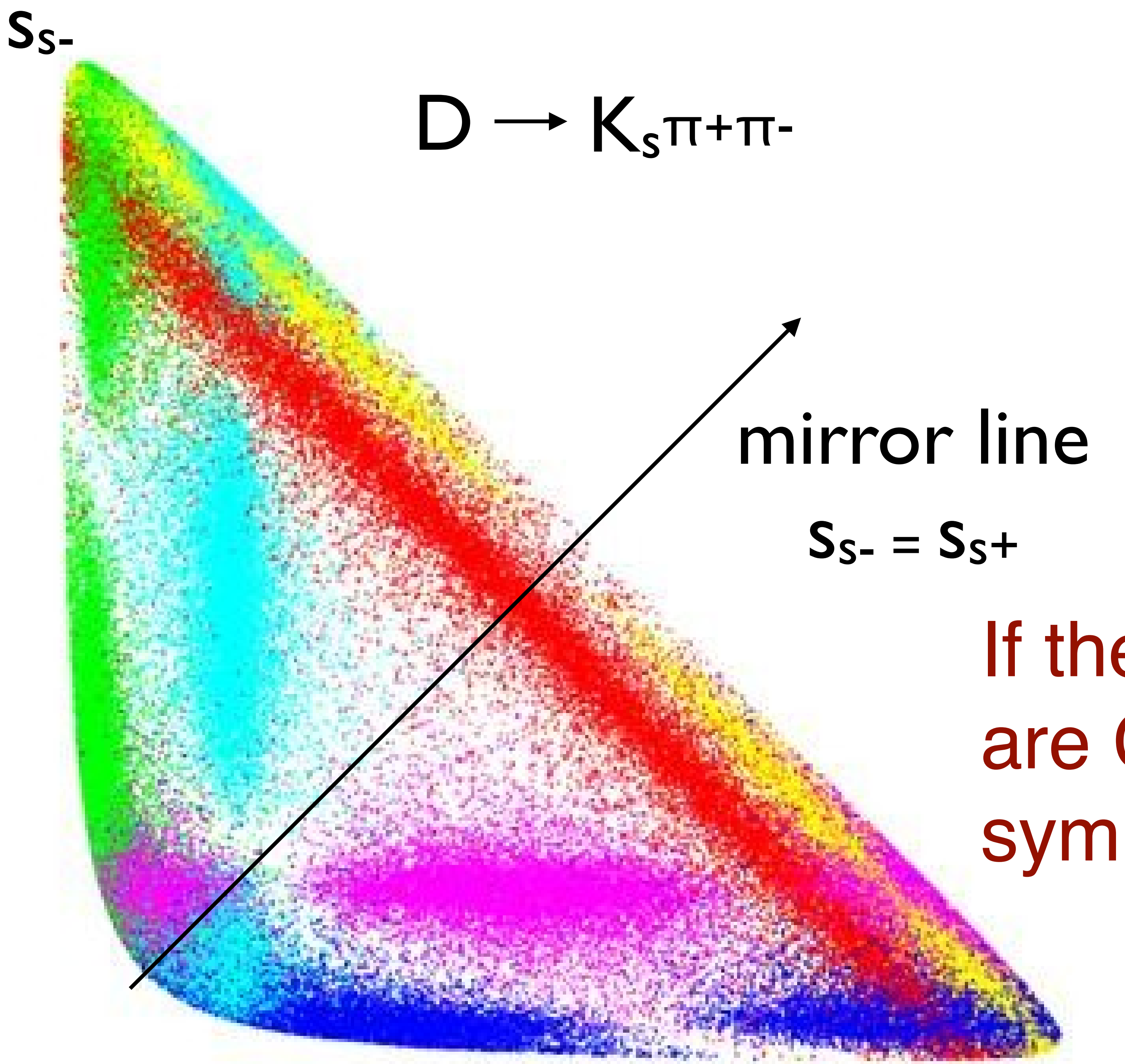
EDM experiments continue to be uniquely sensitive to new sources of CP violation; direct study of $d_n$ vs. $d_p$ (and $d_d$) yields relationships between new CPV sources….

The possibility of significant improvements in $d_\mu$ may shed light on the $\Delta a_e$ & $\Delta a_\mu$ puzzles

EDM experiments can also be used to limit the appearance of ultralight (axion-like) dark matter &….

# Dalitz Studies of CP Violation

## Apropos to both heavy and light flavor decays




[Image Credit: Tom Latham [Tim Gershon]]

Consider population asymmetry about the mirror line in neutral $0^-$ decay

If the initial and final states are C definite, then mirror symmetry is also a CP test

[SG & Tandean, 2004]

# Dalitz Studies of CP Violation

**For |ΔF|=1 decays**

- In untagged $B \to \pi^+ \pi^- \pi^0$ decay CPV appears in the SM
- All such dimension six operators can be rewritten as C definite combinations, the asymmetry is C and CP odd

To realize C violation in dimension six |ΔF|=1 operators are necessary

[Jun Shi, Ph.D UK 2020; SG & Jun Shi, 2021, in preparation]

**For |ΔF|=0 decays** [Enter η decays!]

N.B. mirror symmetry breaking in the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot is a C odd and CP odd observable (by CPT this is a T odd, P even test)!

[SG & Jun Shi, PRD 2020]

C violation first appears in dimension eight (in SM EFT), in distinction to the dimension six operators for EDMs

Note old "C odd" papers [TD Lee & L Wolfenstein,1965; Lee, 1965; Nauenberg, 1965]

[ Bernstein, Feinberg, & Lee, 1965; Barshay ,1965]

# Backup Slides

# A Cosmic Baryon Asymmetry (BAU)

## Assessments in two different epochs agree!

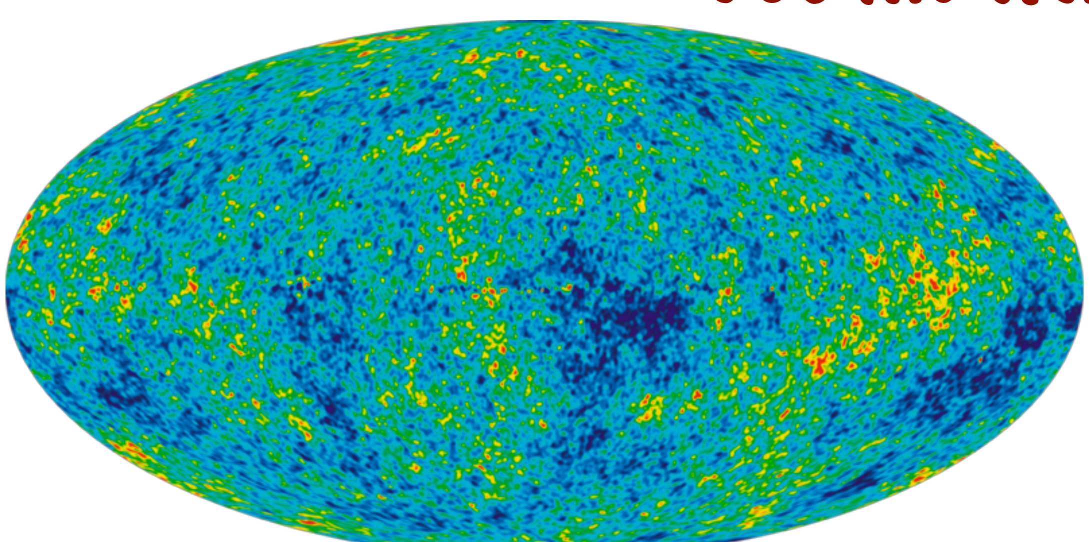
[George Gamow, AIP]

### Big-Bang Nucleosynthesis (BBN)

"$\alpha, \beta, \gamma$" Alpher, Bethe, Gamow, "The Origin of the Chemical Elements," 1948

Lightest Elements are made in the Big-Bang, but prediction depends on the BAU

### Cosmic Microwave Background (CMB)

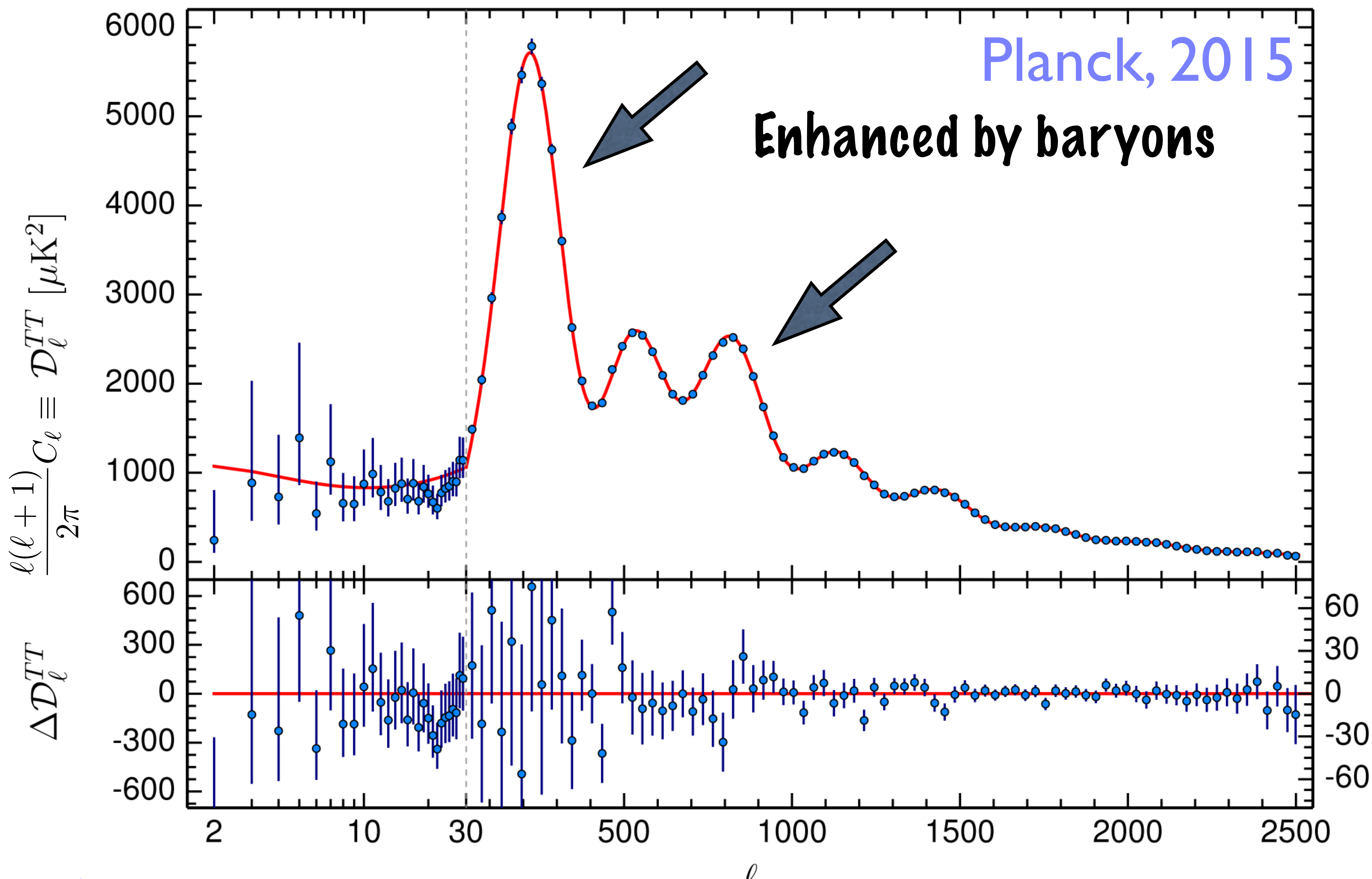


Dicke, Peebles, Roll, & Wilkinson, 1965; Penzias & Wilson, 1965

Pattern of Acoustic Peaks reveals baryonic matter

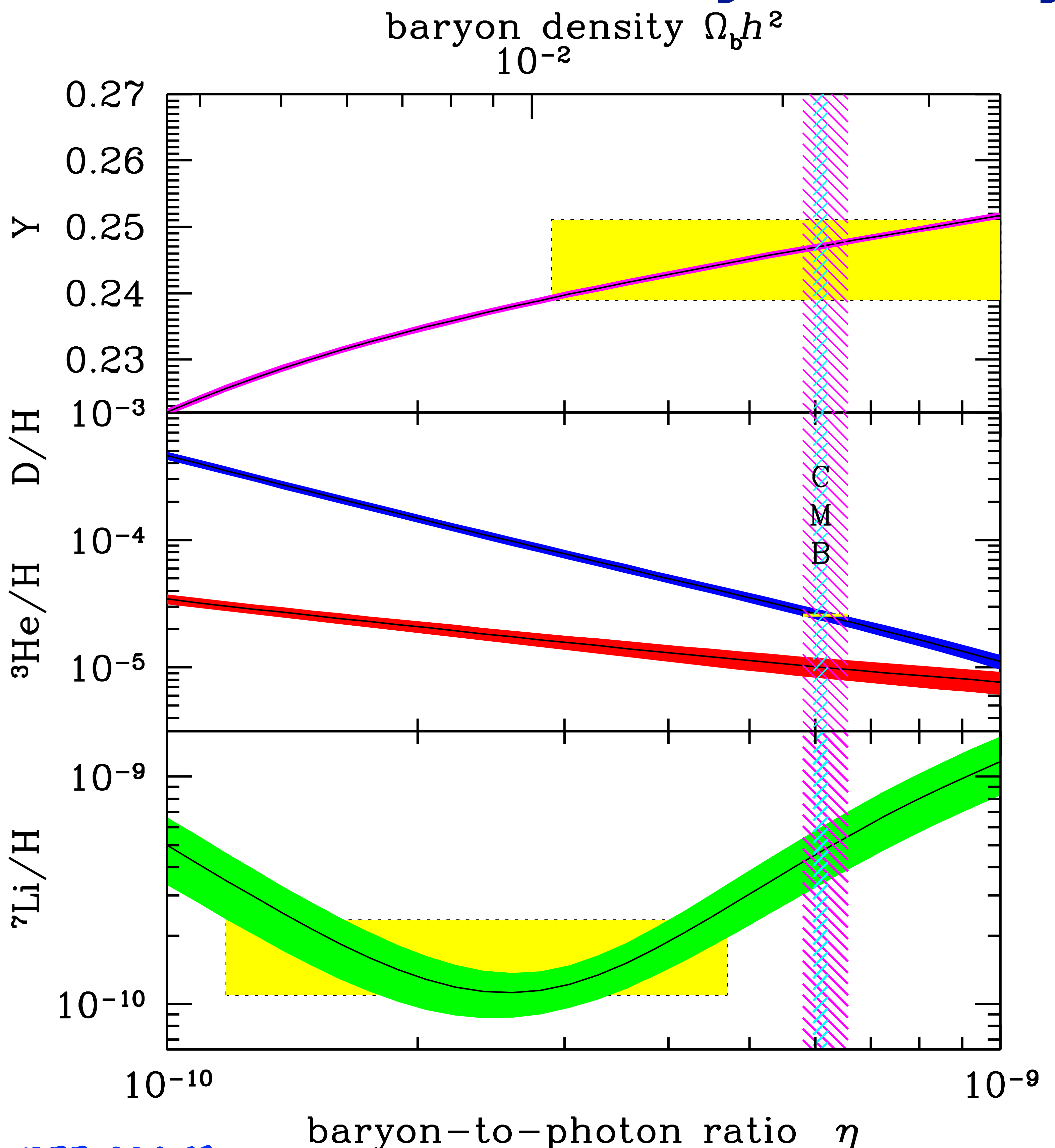
# A Cosmic Baryon Asymmetry

**Patterns of acoustic waves reveal net baryon number!**




[https:wiki.cosmos.esa.int/planckpla2015/index.php/CMB_spectrum_%26_Likelihood_Code]

# A Cosmic Baryon Asymmetry




BAU from BBN & observed D/H & $^4$He/H concordance

BAU from CMB is more precise

[Both @ 95% CL]

[PDG, RPP, 2017]