Perspectives on C and CP Violation (and more) in η Decay

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Precision tests of fundamental physics
with light mesons
ECT* —Trento
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Puzzles

Existing observed and measured effects defy the SM

New theoretical underpinnings unclear

The cosmic baryon asymmetry

$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (6.12 \pm 0.04) \times 10^{-10}$$

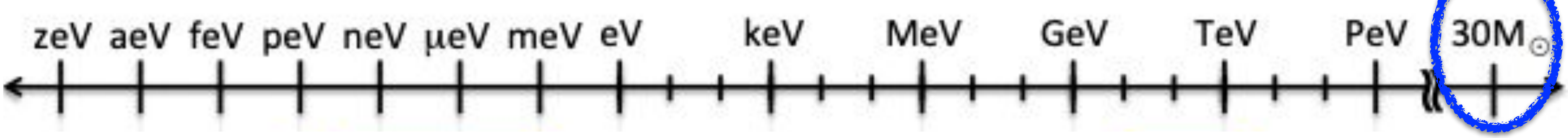
[Planck, 2020; PDG, 2022]

Dark matter

Particle Masses

Fits in Galaxy

Elementary Particle



"Fuzzy DM"

"WIMPs"

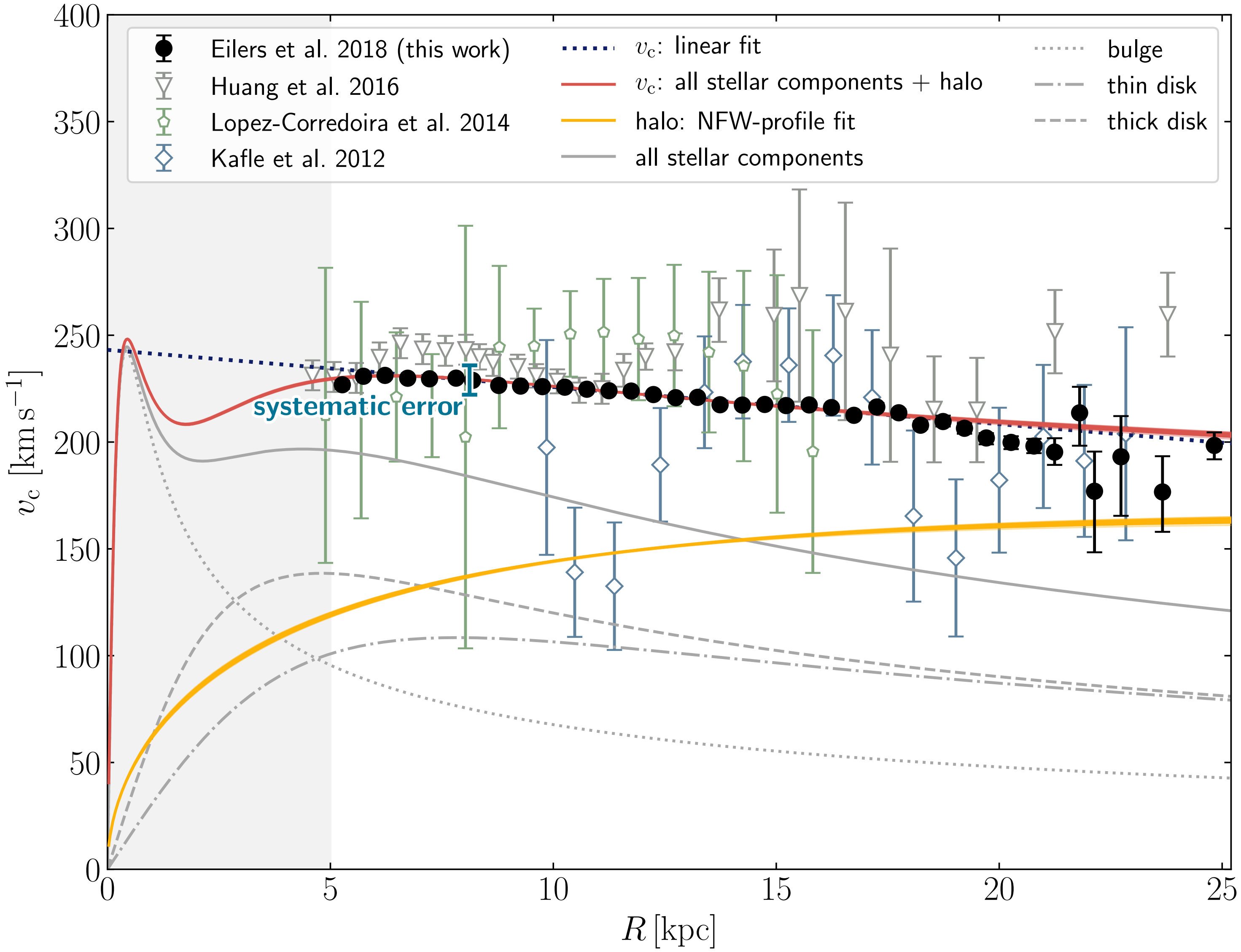
"Exotics"

The neutrinos' masses

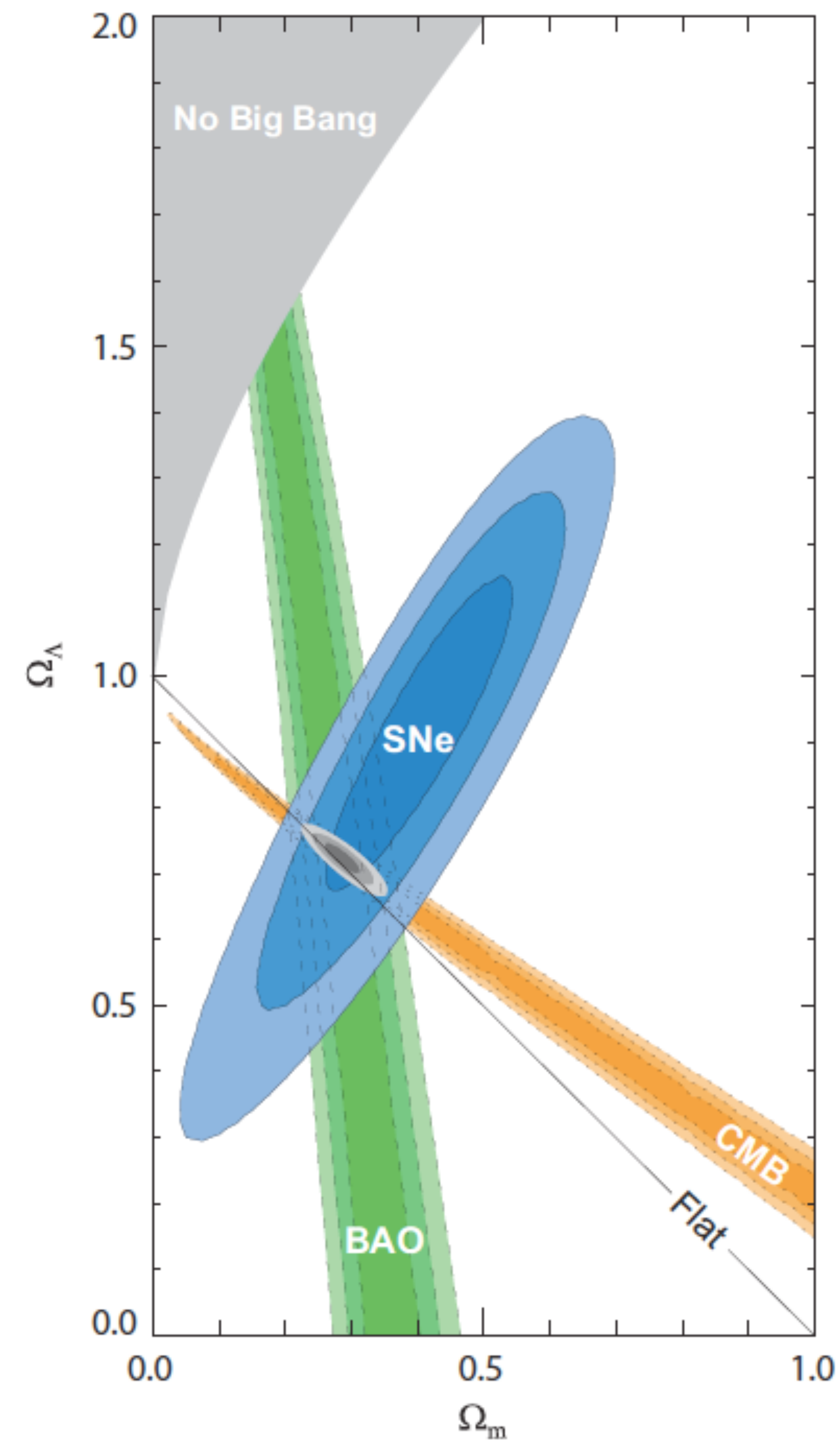
$$m_{\nu_i} \ll m_e \,!$$

Observational Evidence for Dark Matter ranges from "local" to cosmic scales

Rotation Curve of our Milky Way with Gaia DR2!
Eilers et al., 2018, "red-clump giants"



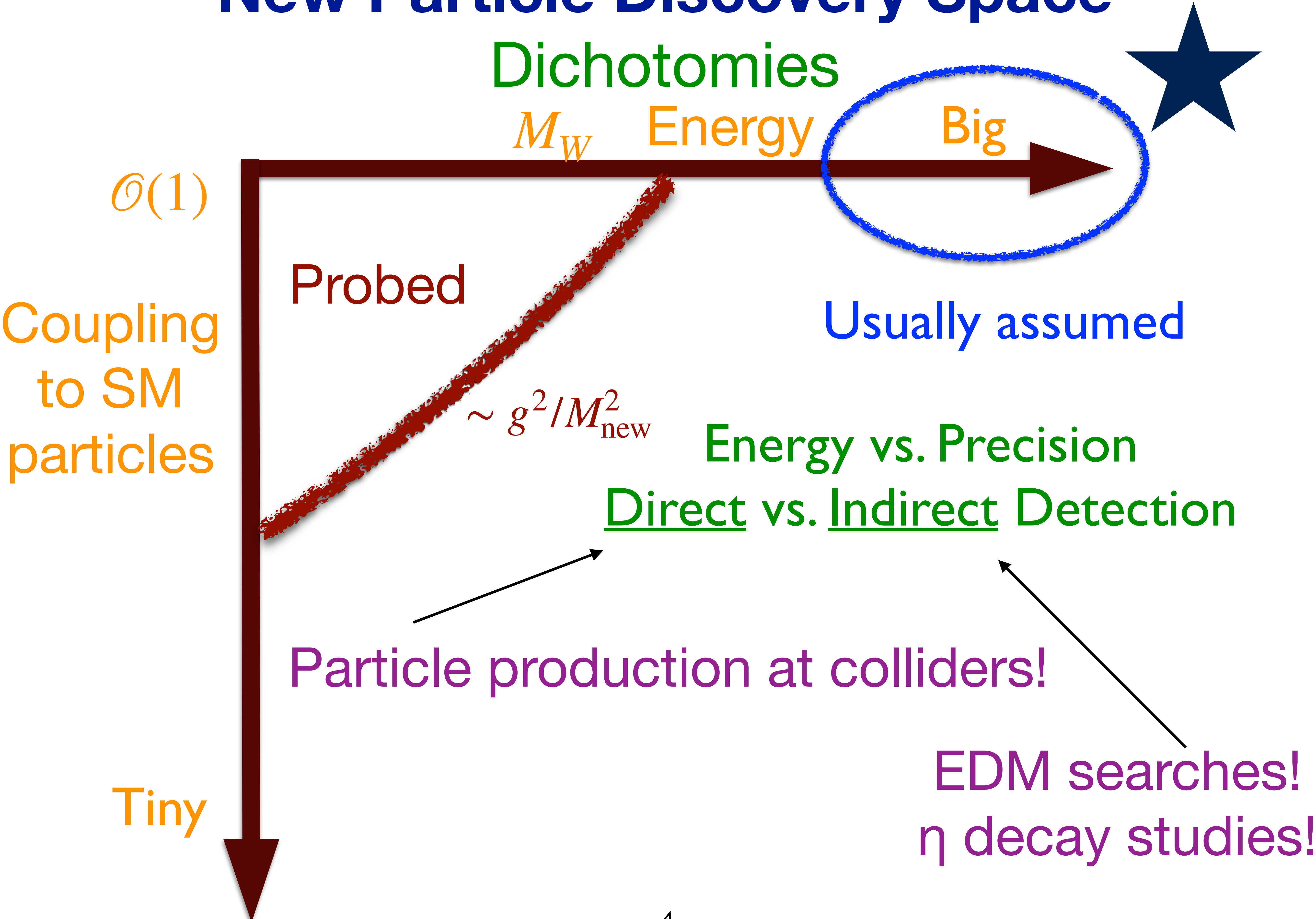
The observed circular speed does not track the luminous mass.



[PDG, RPP, 2017]

Most of the cosmic energy budget is of an unknown form!

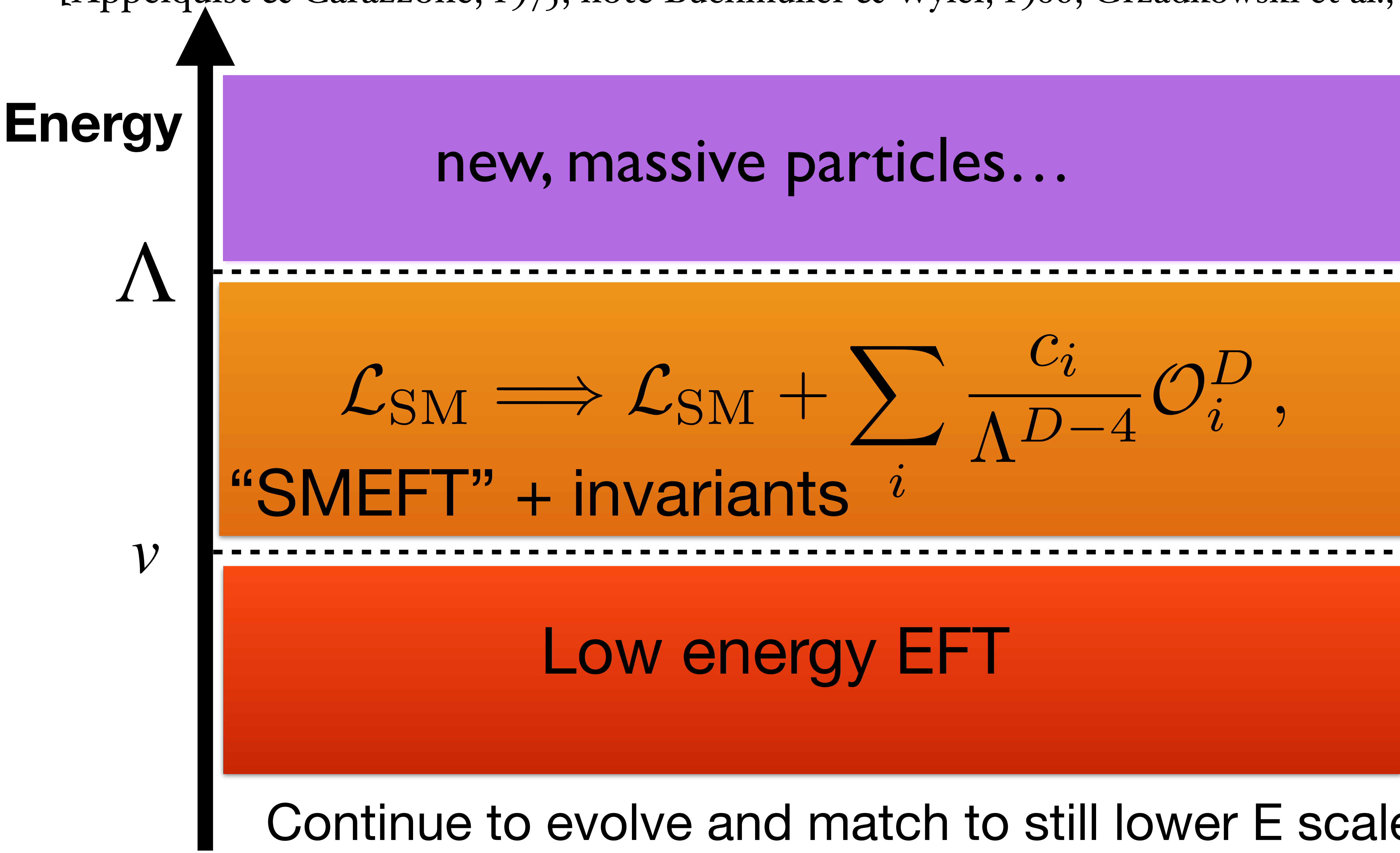
New Particle Discovery Space



Model Independent Analysis

Assuming new physics scale Λ **heavy** cf. to the weak scale v

[Appelquist & Carazzone, 1975; note Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]



Continue to evolve and match to still lower E scales & EFTs as needed….

Aspects of SMEFT

Assumes new physics scale Λ **heavy** cf. to the weak scale v

Assumes SM gauge symmetries & particle content

Assumes the scalar sector is weakly coupled

[cf. Buchalla, Cata, & Krause, 2015]

Theorem: if EW symmetry is unbroken

the operators have even (odd) mass dimension d

if $(B-L)/2$ is even (odd) [Kobach, 2016]

Assert T &/or P, or B or L &/or B-L… broken:
different “SMEFT” operators enter in each case

(i) How to use it?

→ (ii) How to test it (its convergence)? **Revealing?!**

(iii) What new issues arise in complex, many-body systems? (not today)

Applying SMEFT: Proton Decay ($|\Delta B| = 1$)

Assuming new physics **heavy** cf. to the weak scale

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

[Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

e.g.: $p \to e^+ \pi^0$

$$\mathscr{L}^{(d=6)}_{|\Delta B|=1} \supset \sum_i \frac{c_i}{\Lambda^2_{|\Delta B|=1}} (qqq\ell)_i + \text{h.c.}$$

Many?

For c_i work in an explicit BSM model or make $\mathcal{O}(1)$ — with matrix element experimental limit bounds $\Lambda_{\rm new}$ …

here $\Lambda_{|\Delta B|=1} \simeq 10^{15}\,{\rm GeV}$

Local operator: LQCD to compute its hadronic matrix element

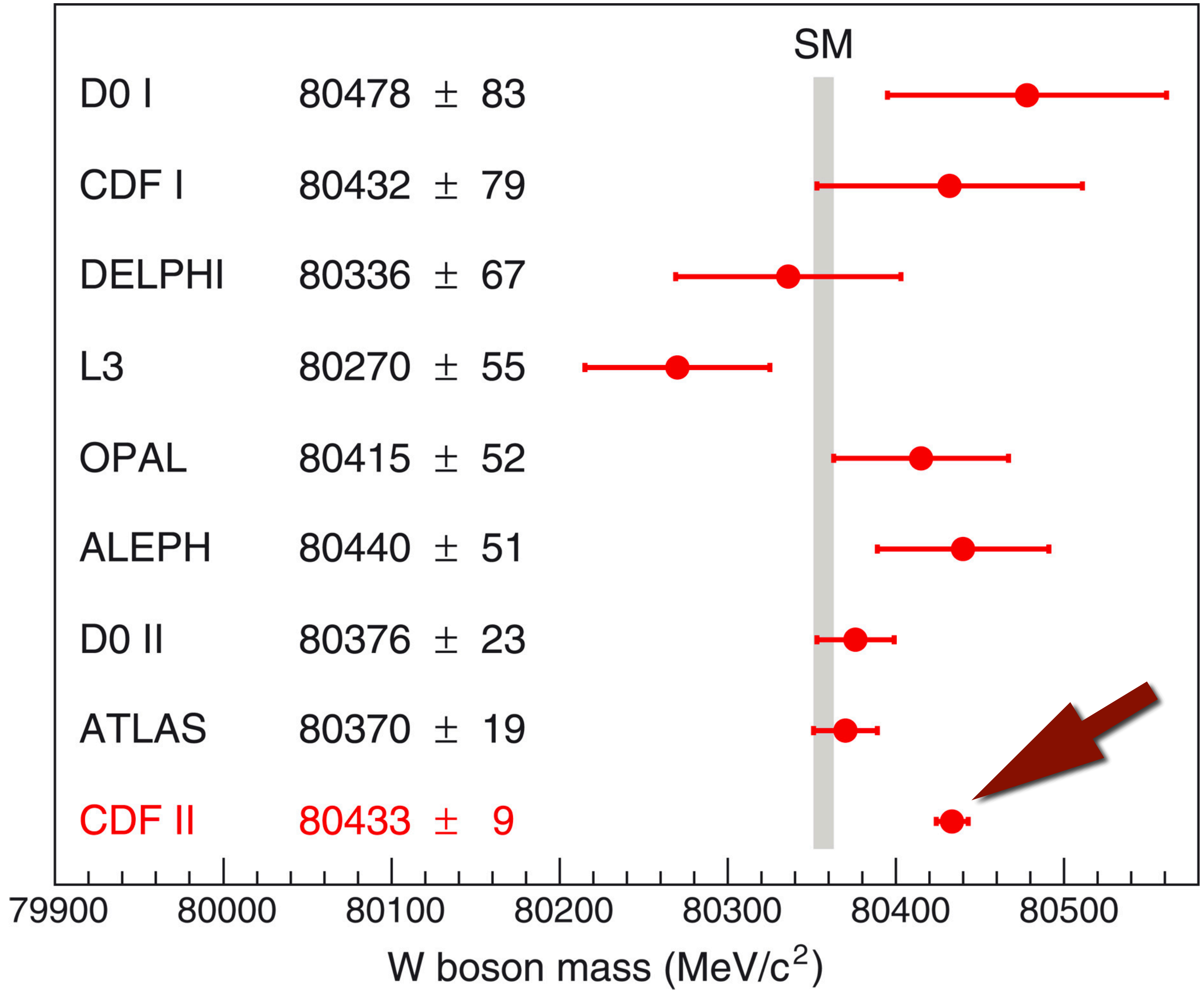
[e.g., Aoki et al., FLAG review, 2111.09849]

Applying SMEFT: Precision W Mass

Explain with new dim-6 operators?

At odds with global EWPO fit by ~7σ

[de Blas et al., 2112.07274]



[CDF: Aaltonen et al., Science 376 (2022), 170]

Enter, e.g.,

$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H \right\rvert^2$
$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)\,(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)\,(\bar{q}_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)\,(\bar{l}_s \gamma^\mu l_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p \tau^I \gamma_\mu l_r)\,(\bar{q}_s \tau^I \gamma^\mu q_t)$

$$\frac{\delta m_W^2}{m_W^2} = v^2\, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w} C_{HD} + \frac{s_w}{c_w} \left(2\, C^{(3)}_{Hl} - C_{ll} \right) \right]$$

CKM unitarity!

δG$_F$!

[Cirigliano et al., 2204.08440]

Stress testing the SMEFT framework

LECs of natural size?

Probed via experiment!

Weakly coupled scalar sector?

Enter $b \to c\tau\bar{\nu}_\tau$: study angular distribution to fit all LEC's; is the scale of d=6 suppression universal?

[Burgess et al., 2111.07421]

Convergence?
Processes with leading higher dimension operators?

Enter Dalitz asymmetry in $\eta \to \pi^+\pi^-\pi^0$

[Gardner & Shi, 2020 & in prep, note 2203.07651 (REDTOP)]

Hadronic CP violation

C versus P violation

"What do we really know about T-odd, P-even interactions?" [Khriplovich & Lamoreaux, "CP Violation without Strangeness", 1997]

Answer: the strength of a T odd, P even interaction can be estimated: dress it with a P odd radiative correction to yield a T odd, P odd interaction and cf with an EDM limit. *They're tiny!*

No, the answer depends on whether parity is a symmetry of the high energy theory. If it is not, then the argued connection does not follow!

[Ramsey-Musolf, 1999]

Thus in SMEFT we can expect them to be independent

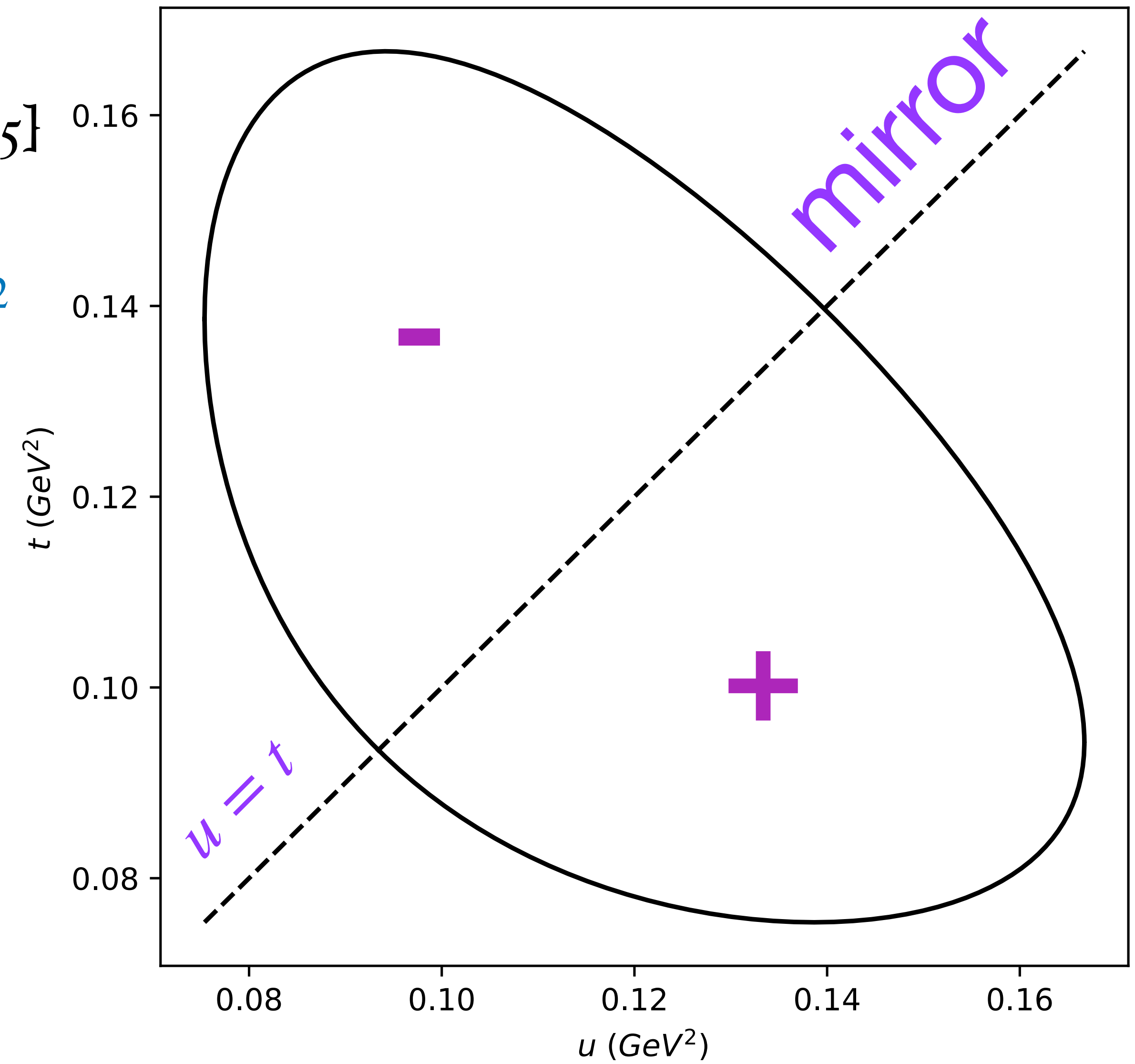
Dalitz Plot (Charge) Asymmetry in η to 3π

Breaks C (and CP) symmetries

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

$$s = (p_{\pi^+} + p_{\pi^-})^2, \quad t = (p_{\pi^-} + p_{\pi^0})^2, \quad u = (p_{\pi^+} + p_{\pi^0})^2$$

$$A_{LR} = \frac{N_+ - N_-}{N_+ + N_-} \qquad (N_+ : \; u > t, \;\; N_- : \; u < t)$$



Features of $\eta \to \pi^+\pi^-\pi^0$

$$\pi^+\pi^-\pi^0 : \;\; C = -(-1)^I$$ [TD Lee, 1965]

final states	decay amplitude
★ $I = 1, \; C = +1$	C conserving $\lvert \Delta I \rvert = 1$
$I = 0, \; C = -1$	C breaking $\lvert \Delta I \rvert = 0$
$I = 2, \; C = -1$	C breaking $\lvert \Delta I \rvert = 2$
…	…

J=0 3π state of even parity: here, then, C and CP are broken

Dalitz Plot Asymmetries

E.g., enter C and CP violation in $\eta \to \pi^+\pi^-\pi^0$ via a **momentum asymmetry** about the mirror line in the Dalitz plot

Can occur in both heavy and light flavor decays

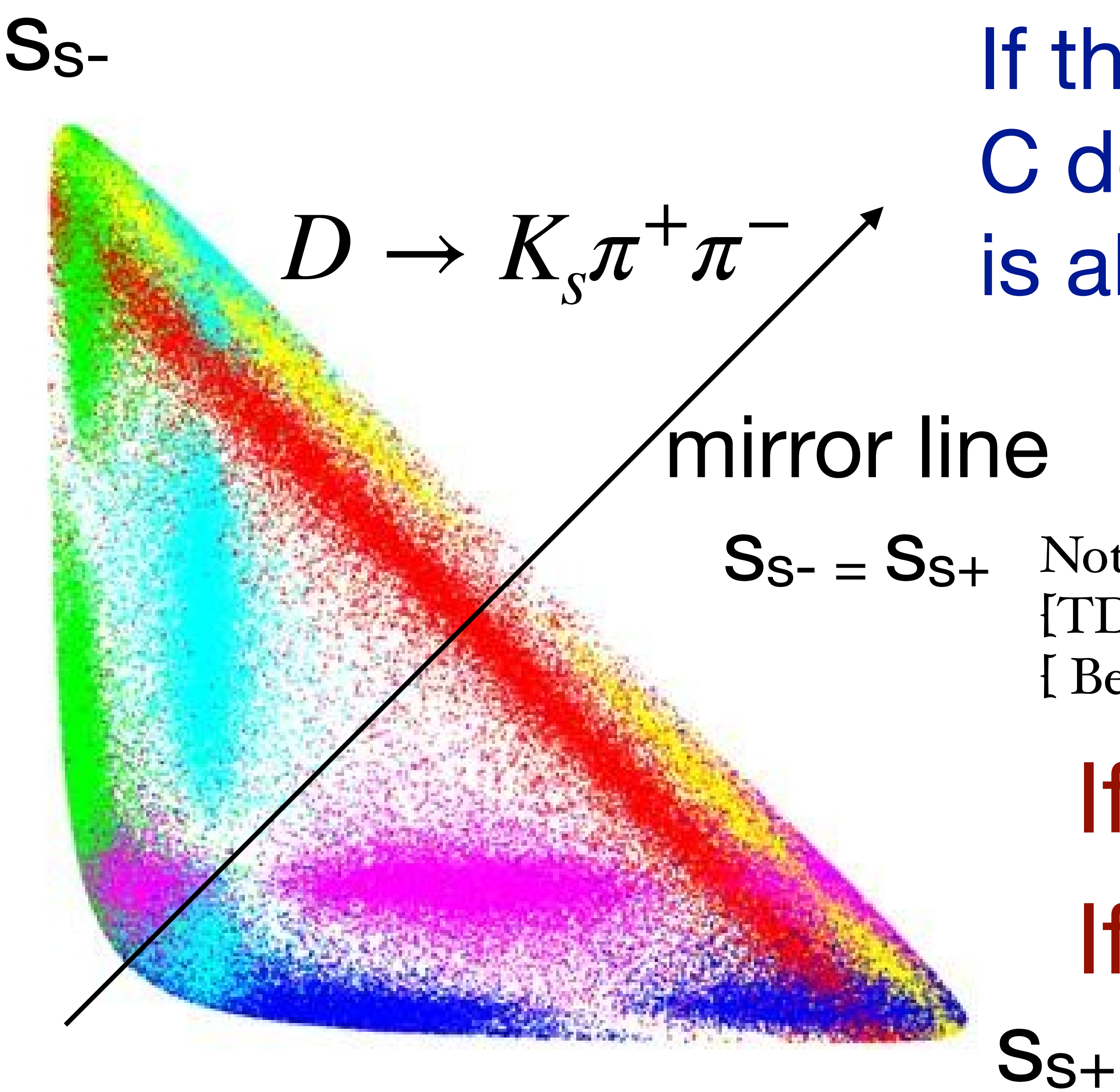


Image: Tom Latham [Tim Gershon]

If the initial and final states are C definite, then mirror symmetry is also a CP test [SG & Jusak Tandean, 2004]

In $\eta \to \pi^+\pi^-\pi^0$ the Dalitz plot asymmetry is a C odd and CP odd observable

Note old "C odd" papers [SG & Jun Shi, 2020]
[TD Lee & L Wolfenstein,1965; Lee, 1965; Nauenberg, 1965]
[Bernstein, Feinberg, & Lee, 1965; Barshay ,1965]

★ If $|\Delta F| = 0$, then $d = 8$

If $|\Delta F| = 1$, then $d = 6$

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

REDTOP: 2203.07651

Analyzing method (SMEFT)

analyzing procedure

start at new physics energy scale and pick operators that are CPV

↓

Higgs acquires VEV,
express $SU(2)_L \times U(1)_Y$ gauge bosons in terms of physical ones $(W^{\pm}, Z, \gamma)$
list the CP odd pieces

↓

at $E \lesssim M_W$, integrate out $W^{\pm}, Z$

↓

analyzing operators with definite P, C

list the lowest C&CP odd operators

example

$$(\bar{q}_L \sigma^{\mu\nu} \Gamma_W^d d_R) \tau^i \varphi W^i_{\mu\nu} + \mathrm{h.c.}$$

↓

$$v i \mathrm{Im}(\Gamma_W^d) \Big[(\bar{u}_L \sigma^{\mu\nu} d_R) \partial_\mu W^+_\nu - (\bar{d}_R \sigma^{\mu\nu} u_L) \partial_\mu W^-_\nu + \ldots \Big]$$

↓

$$i \mathrm{Im}(\Gamma_W^d) \frac{gv}{2m_W^2} [(\bar{u}_L \sigma^{\mu\nu} d_R) \partial_\mu (\bar{d}'_L \gamma_\nu u_L) - (\bar{d}_R \sigma^{\mu\nu} u_L) \partial_\mu (\bar{u}_L \gamma_\nu d'_L)] + \cdots$$

↓

$$\cdots v [(\bar{u} \sigma^{\mu\nu} \gamma_5 d) \partial_\mu (\bar{d}' \gamma_\nu u) + (\bar{d} \sigma^{\mu\nu} \gamma_5 u) \partial_\mu (\bar{u} \gamma_\nu d')] \cdots$$

P odd C even

$$\cdots v [(\bar{u} \sigma^{\mu\nu} d) \partial_\mu (\bar{d}' \gamma_\nu u) - (\bar{d} \sigma^{\mu\nu} u) \partial_\mu (\bar{u} \gamma_\nu d')] \cdots$$

C odd P even

Results

Flavor-changing vs flavor-conserving interactions

		flavor changing	flavor conserving
lowest mass dimension	P-odd and CP-odd	6	6
	C-odd and CP-odd	6	8
	patterns of P-odd and CP-odd vs C-odd and CP-odd	one-to-one corresponding with different combinations of LEC	Distinct

flavor-changing example:

$$\frac{1}{4} i\mathrm{Im}(C_{q^4}^{(1)prst} + C_{q^4}^{(3)prst} + C_{u^4}^{prst} + C_{q^2u^2}^{(1)prst})[(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t) - (\bar{u}_t\gamma^\mu u_s)(\bar{u}_r\gamma_\mu u_p)]$$ **C&CP odd**

$$\frac{1}{4} i\mathrm{Im}(-C_{q^4}^{(1)prst} - C_{q^4}^{(3)prst} + C_{u^4}^{prst} - C_{q^2u^2}^{(1)prst})[(\bar{u}_p\gamma_\mu\gamma_5 u_r)(\bar{u}_s\gamma^\mu u_t) - (\bar{u}_t\gamma^\mu u_s)(\bar{u}_r\gamma_\mu\gamma_5 u_p)]$$ **P&CP odd**

Results

Sample C odd, CP odd operators

$\frac{v}{\sqrt{2}}(\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 u_r)$	$-G_F i C^{pr}_{quZ\varphi}$
$\frac{v}{\sqrt{2}}(\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p)\partial_\mu(\bar{d}_r\gamma_\nu\gamma_5 d_r)$	$G_F i C^{pr}_{qdZ\varphi}$
$\frac{v}{\sqrt{2}}(\bar{d}_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 u_r)$	$-G_F i C^{pr}_{quZ\varphi}$
$\frac{v}{\sqrt{2}}(\bar{d}_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{d}_r\gamma_\nu\gamma_5 d_r)$	$G_F i C^{pr}_{qdZ\varphi}$
$\frac{v}{\sqrt{2}}\Big[V_{u_r d_p}(\bar{d}_p\sigma^{\mu\nu}u_r)\partial_\mu(\bar{u}_r\gamma_\nu d_p)$ $-V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}d_p)\partial_\mu(\bar{d}_p\gamma_\nu u_r)\Big]$	$2G_F i[\mathrm{Im}(C^{pr}_{quW\varphi}) - \mathrm{Im}(C^{rp}_{qdW\varphi})]$
$\frac{v}{\sqrt{2}}\Big[V_{u_r d_p}(\bar{d}_p\sigma^{\mu\nu}\gamma_5 u_r)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 d_p)$ $+V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{d}_p\gamma_\nu\gamma_5 u_r)\Big]$	$-2G_F i[\mathrm{Im}(C^{pr}_{quW\varphi}) + \mathrm{Im}(C^{rp}_{qdW\varphi})]$

Summary

We have considered the C and CP violation in η decay

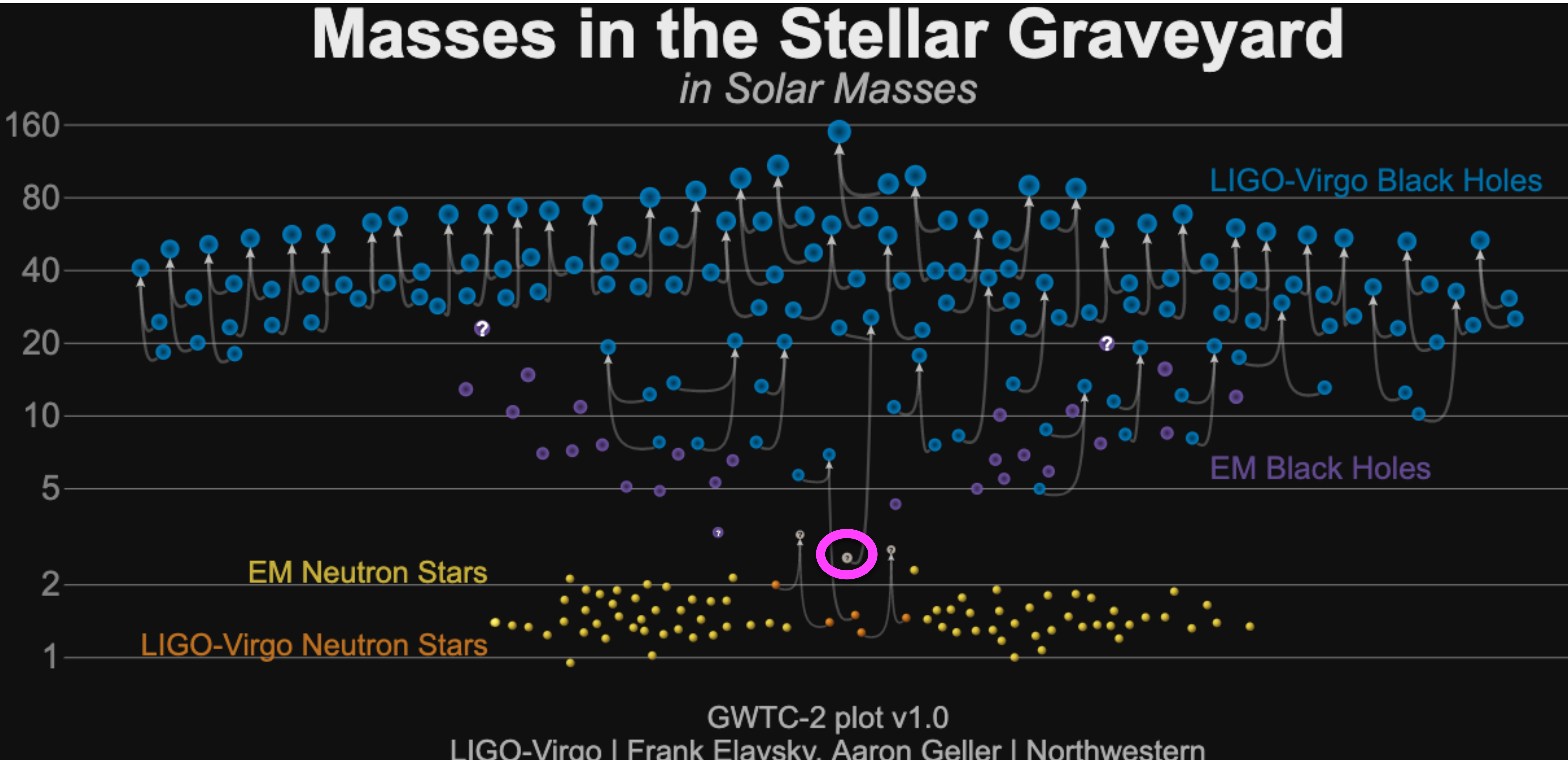
The flavor conserving C and CP odd operators start in mass-dimension 8 in SMEFT, while for P and CP odd ones the lowest mass-dimension is 6.

The new physics sources of a Dalitz asymmetry in $\eta \to \pi^+\pi^-\pi^0$decay and of a (neutron) EDM can be completely different.

Thus the empirical study of this process can point to physics beyond SMEFT

A Surprise: GW190814

A $2.6M_{\odot}$ object — neutron star or black hole?



https://ligo.northwestern.edu/media/mass-plot/index.html

New Short-Range Force?*

E.g., a $U(1)_{\mathrm{B}}$ gauge boson $B\ldots$

- Can be heavy ($\gtrsim 600\,\mathrm{MeV}$) and not so weakly coupled with little impact on NN phenomenology

- Generates a repulsive force between neutrons

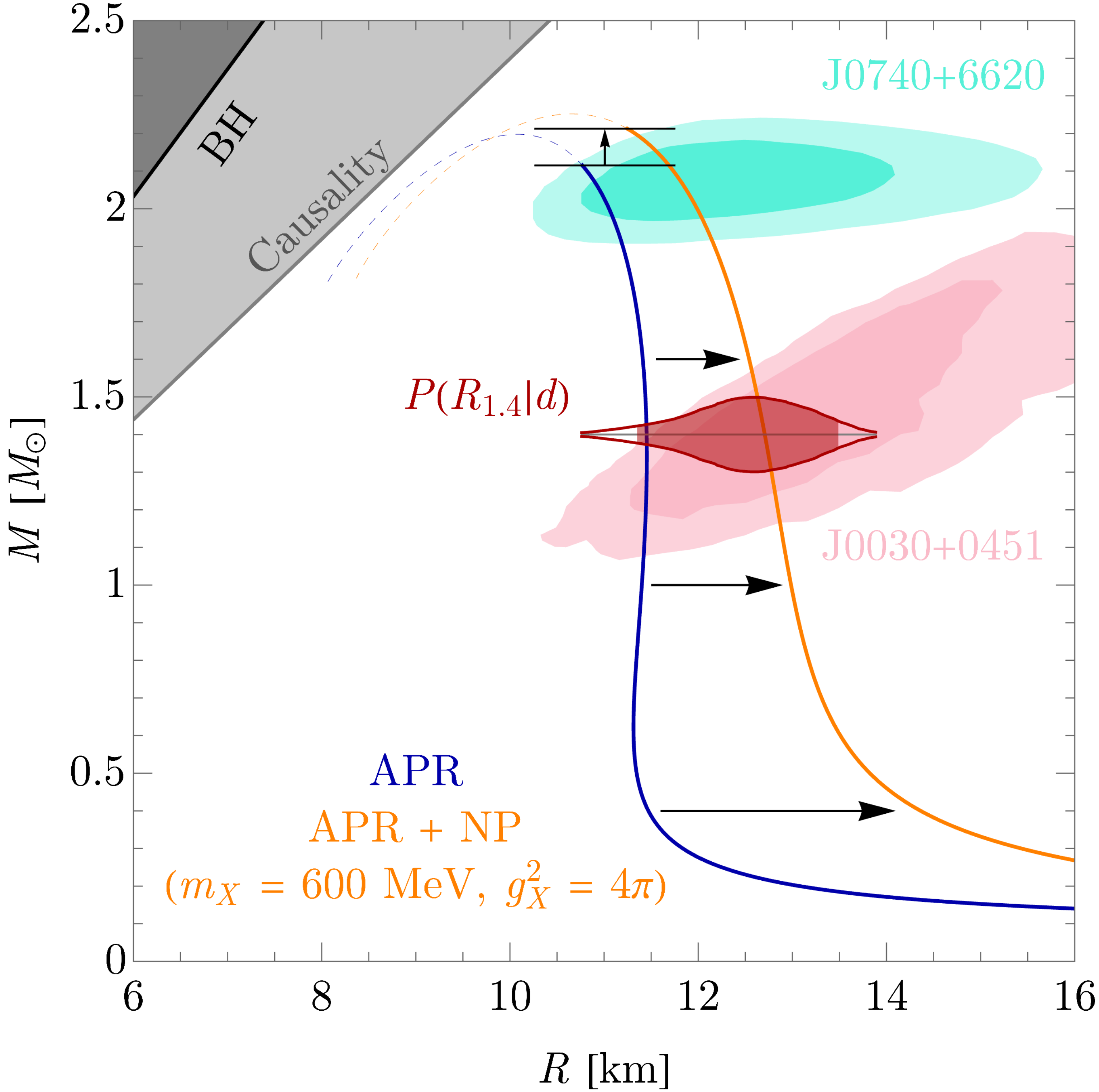
- Need to work within non-relativistic many-body physics for connection to NN physics

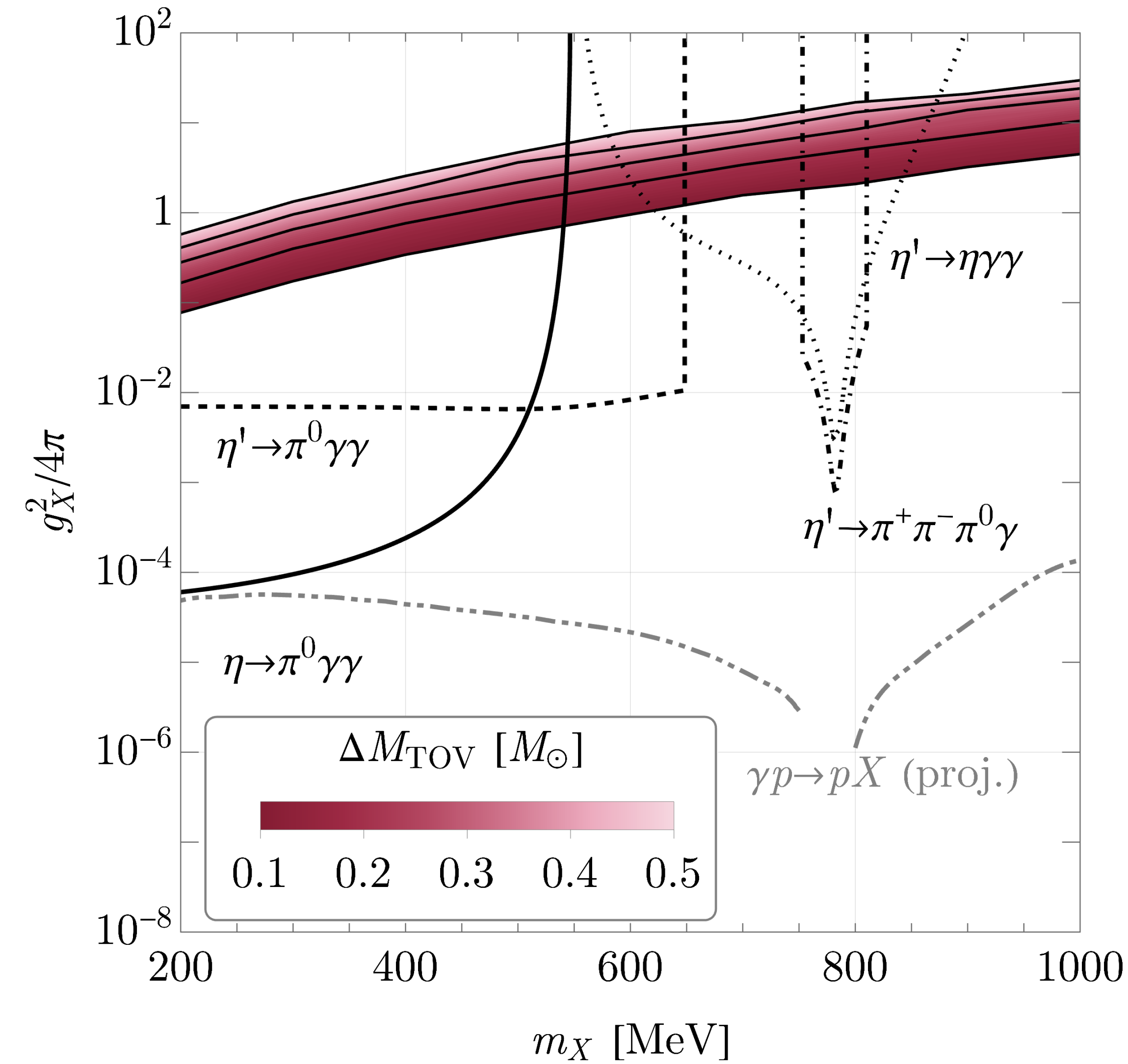
- Can modify neutron star properties to yield a larger maximum neutron star mass

[Berryman & SG, 2021]

Neutron Star Structure

with gauged $U(1)_{B_1}$





Test with rare eta decays!

[Tulin, 2014]

[Berryman & SG, 2021; Berryman, SG, & Zakeri, 2022]

Backup Slides

Extending the SM (QCD) with Gauged Baryon Number (or B-L)

Can be probed through observed breaking effects

- BNV can be **explicit.**

  $n\bar{n}$ oscillations ; $nn \to \nu\nu$; $e^- p \to e^+ \bar{p}$ ....

- BNV can be **apparent** (entrained with dark sectors).

  $n \to \chi\gamma; n \to \chi\chi\chi; nn \to \chi\chi$ ....

  cf. τ_n anomaly

- BNV can be **spontaneous.** Enter "mesogenesis" (Elor er al.)!

  massive mediator of gauged B or $B - L$ or ....

Implications for origins of the BAU, neutrino mass….

Enter neutron stars — as a BNV laboratory!

Operator Analysis of EDMs

Multiple sources with $d \leq 6$ exist

Even a single TeV scale source can give rise to multiple GeV scale sources through QCD effects

[Chien et al., 2016]

$$\mathcal{L}^{d\leq 6} \supset \bar{\theta}\alpha_s G\tilde{G} + \sum_{i\in u,d,s} i(d_i \bar{q}_i (F\sigma)\gamma_5 q + \tilde{d}_i \bar{q}_i (G\sigma)\gamma_5 q) + d_G G G\tilde{G}$$

[Pospelov & Ritz, 2005]

LQCD studies of apropos neutron matrix elements exist (e.g., tensor charges) and is ongoing

[note FLAG review; Snowmass white paper 2203.08103]

★ Can all the low-energy CPV sources be determined?

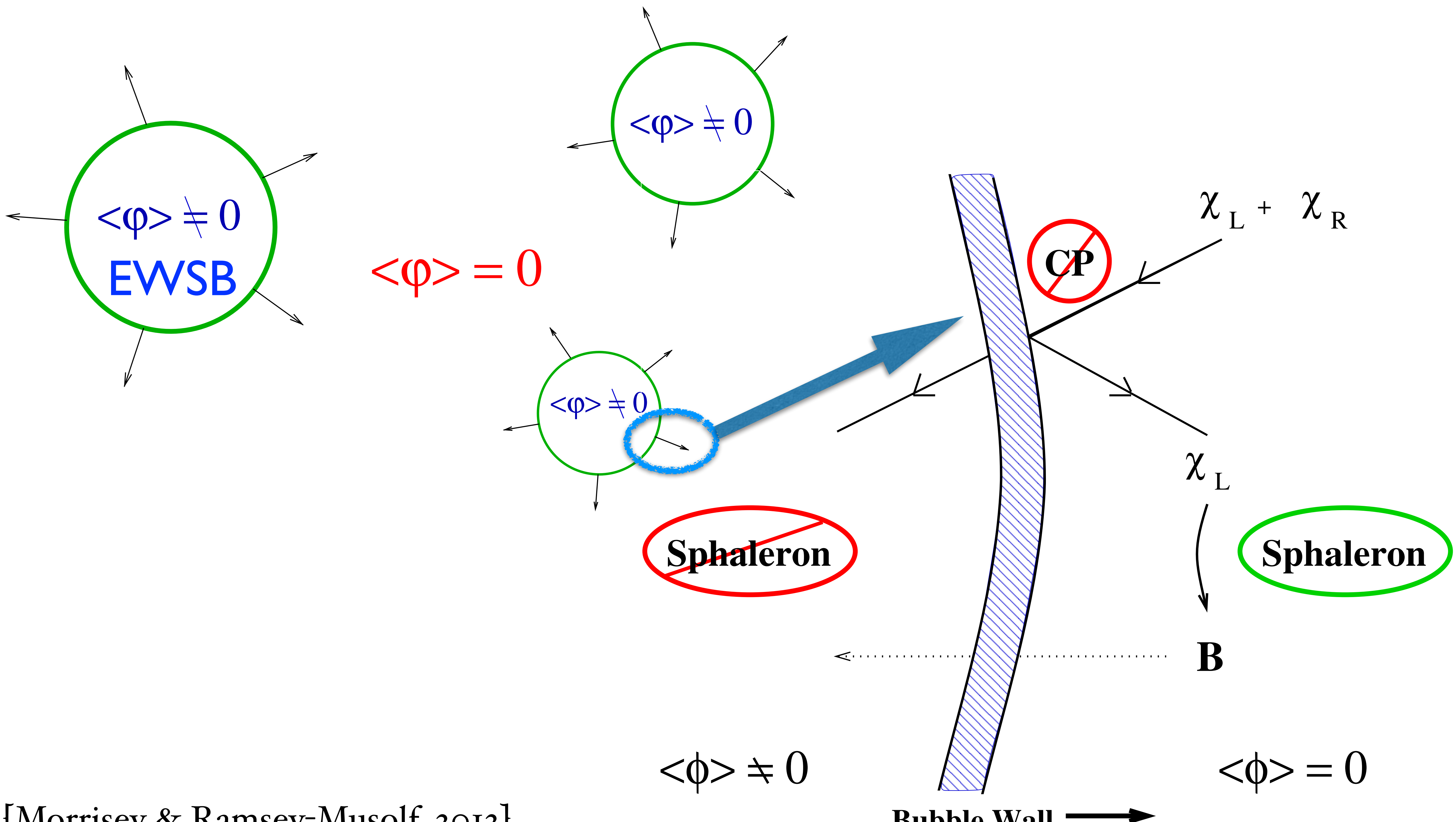
Need to interpret EDM limits in nuclei, atoms, molecules

Note $aG\tilde{G}$, $\partial_\mu a \bar{N}\gamma^\mu\gamma_5 N$ can act as axion *portals*

[Batell, Pospelov, & Ritz, 2009]

A Cosmic Baryon Asymmetry

Via (MSSM) electroweak baryogenesis



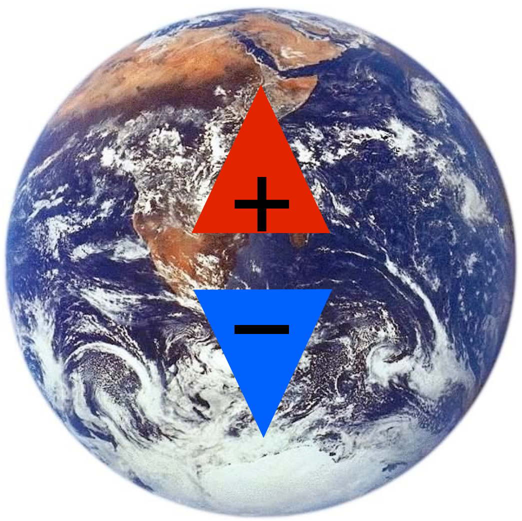
[Morrisey & Ramsey-Musolf, 2012]

EDMs to Probe CPV for a BAU?

Current limits for the electron and neutron strongly constrain models of EW baryogenesis

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

For a sense of scale:



Scaling the n to Earth's size implies a charge separation of < 4μm (cf. human hair width 40 μm)

Expts under development reach for 10-100x sensitivity

Applied electric fields can be enormously enhanced in atoms and molecules {Purcell and Ramsey, 1950}

ACME II, 2018 (ThO): $|d_e| < 1.1 \times 10^{-29}$ e-cm $[90\,\%$ C.L.$]$

Roussy et al., 2212.11841 (HfF^+): $|d_e| < 4.1 \times 10^{-30}$ e-cm $[90\,\%$ C.L.$]$

New CPV sources not yet observed….

A Cosmic Baryon Asymmetry

From particle physics?

The particle physics of the early universe can explain this asymmetry if B (baryon number), C (particle-antiparticle), and CP (matter-antimatter) violation all exist in a non-equilibrium environment. [Sakharov, 1967]

But what is the mechanism?

The SM almost has the right ingredients:

B? Yes, at high temperatures

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

Non-equilibrium dynamics? No. (!)

The Higgs particle is about 125 GeV in mass;
lattice simulations reveal the electroweak phase transition is NOT of first-order. [Kajantie, Laine, Rummukainen, Shaposhnikov, 1996; Rummukainen et al., 1998; Csikor, Fodor, Heitger, 1999]

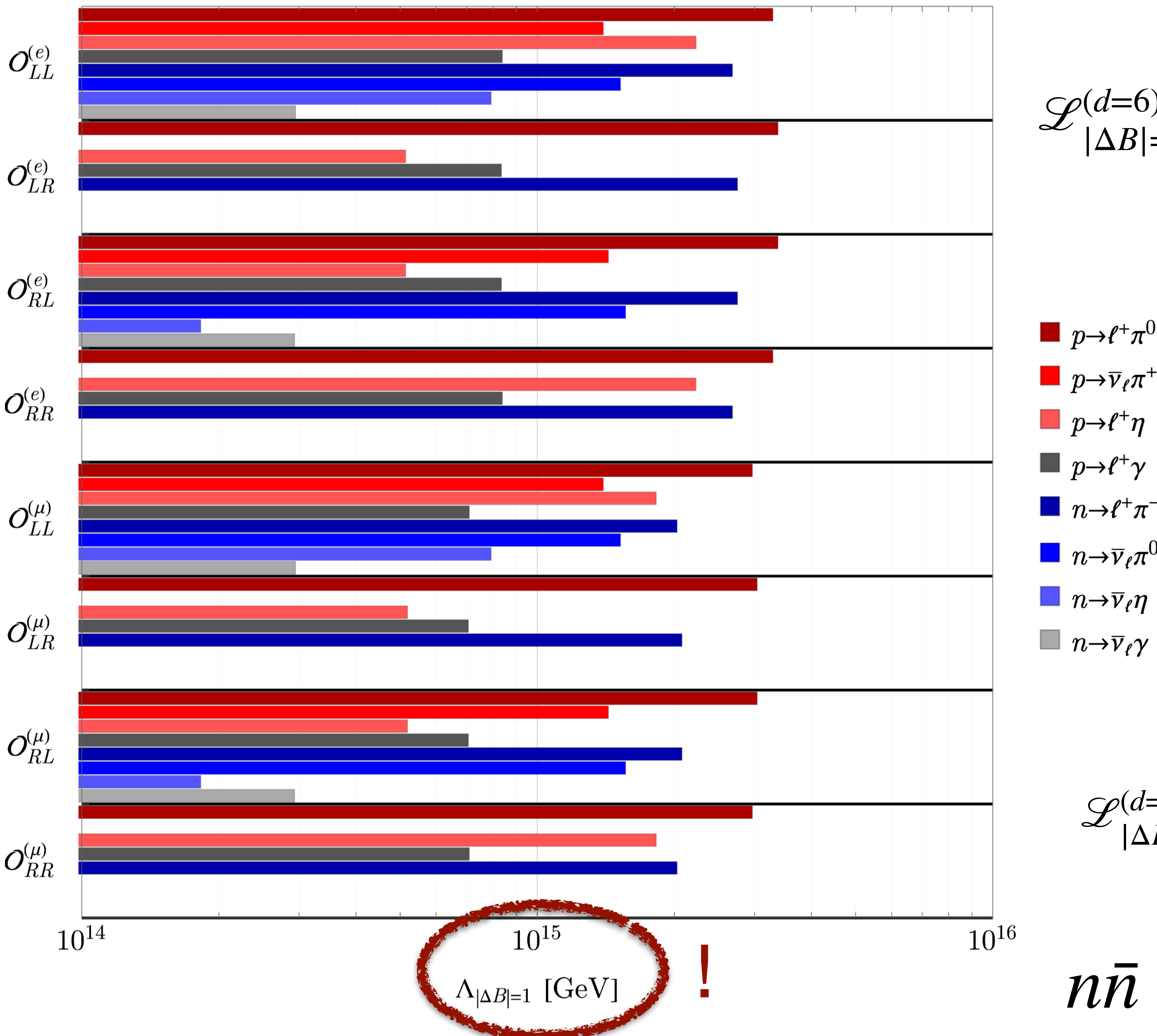
Thus the SM cannot explain it

And we seek new sources of CPV….

Limits on $|\Delta B| = 1$ Decays

Mediated by mass dimension 6 operators in SMEFT

[Berryman, SG, & Zakeri, 2022]



$$\mathscr{L}^{(d=6)}_{|\Delta B|=1} \supset \sum_i \frac{c_i}{\Lambda^2_{|\Delta B|=1}}(qqq\ell)_i + \text{h.c.}$$

dim 6

But the origin of $|\Delta B| = 2$ processes can be distinct!

[Marshak & Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013....]

$$\mathscr{L}^{(d=9)}_{|\Delta B|=2} \supset \sum_i \frac{c_i}{\Lambda^5_{|\Delta B|=2}}(qqqqqq)_i + \text{h.c.}$$

dim 9

$n\bar{n}$ expt'l limit yields

$$\Lambda_{|\Delta B|=2} \gtrsim 10^{5.5}\ \text{GeV}$$

Λ: take one operator at a time (!)

EDM Measurement Principle

Much simplified!

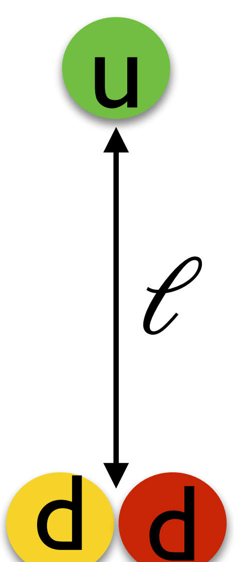
Consider the precession frequency

$$\nu = \frac{1}{2\pi}\frac{d\varphi}{dt} = \frac{2\overrightarrow{\mu} \cdot \overrightarrow{B} \pm 2\vec{d} \cdot \overrightarrow{E}}{h}$$

and its *change* under $\overrightarrow{E}$ field reversal

B must be very well determined!

The experimental sensitivity to the energy $\vec{d} \cdot \overrightarrow{E}$ is set by



$$\sigma_d \sim \frac{\hbar}{|\overrightarrow{E}|T_m\sqrt{N}}$$

T_m measurement time

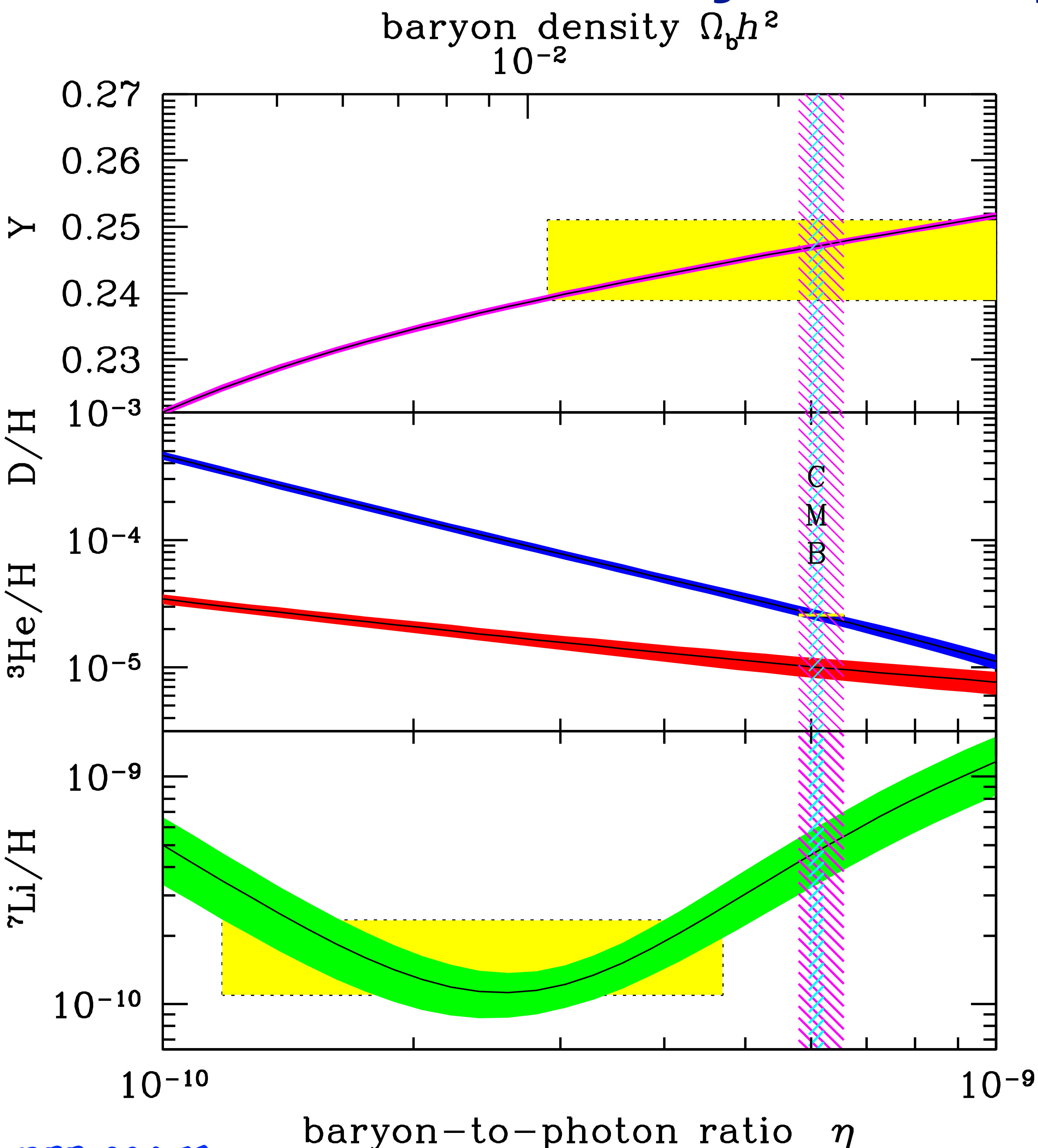
N number of counts

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

[Abel et al., 2020]

Estimate: $d \sim \frac{2}{3}e\ell \sim 6 \times 10^{-15}$ e-cm if $\ell \sim 0.1 r_p$ (!)

A Cosmic Baryon Asymmetry



Theory requires n lifetime value

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

BAU from CMB is more precise

[Both @ 95% CL]

[PDG, RPP, 2017]