Physics of Plenitude

New Mechanisms at the TeV-scale

John March-Russell
University of Oxford

with Nathaniel Craig & later work with Matthew McCullough and Babiker Hassanain (and thanks to Mina Arvanitaki, Savas Dimopoulos and Sergei Dubovsky)

Minimalism

William of Ockham

"entia non sunt multiplicanda praeter necessitatem"

(entities must not be multiplied beyond necessity)

Plenitude

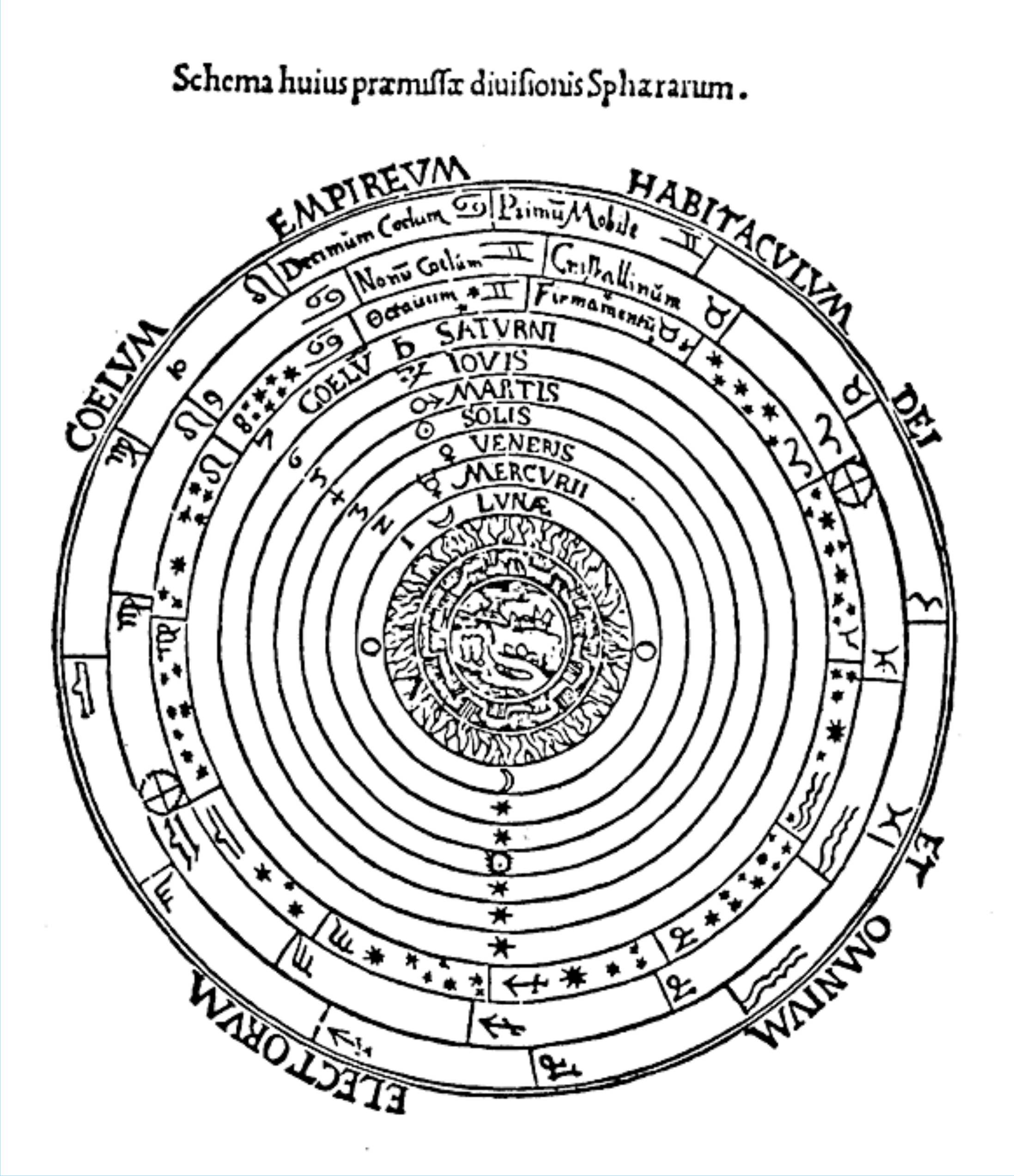
Gottfried Wilhelm Leibniz

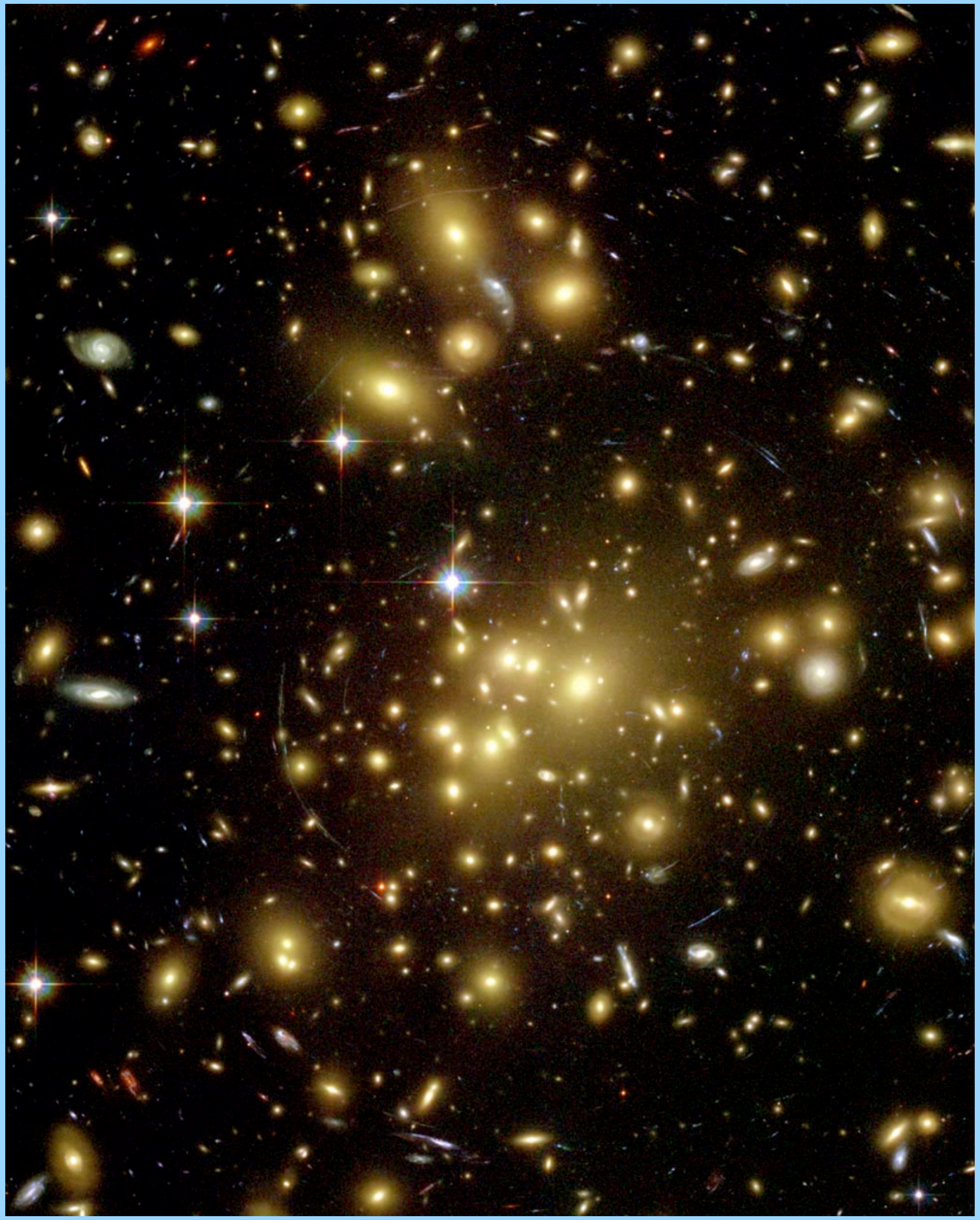
"This best of all possible worlds will contain all possibilities, with our finite experience of eternity giving no reason to dispute nature's perfection."

Minimalism

Plenitude

For the solar system





Changes the way we think about our own solar system

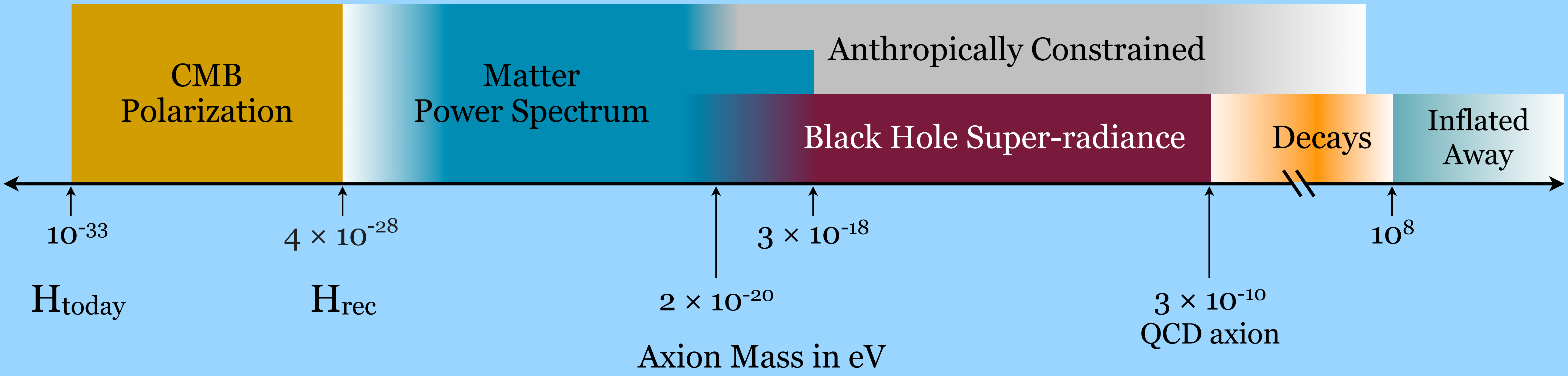
Minimalism Plenitude

String Theory

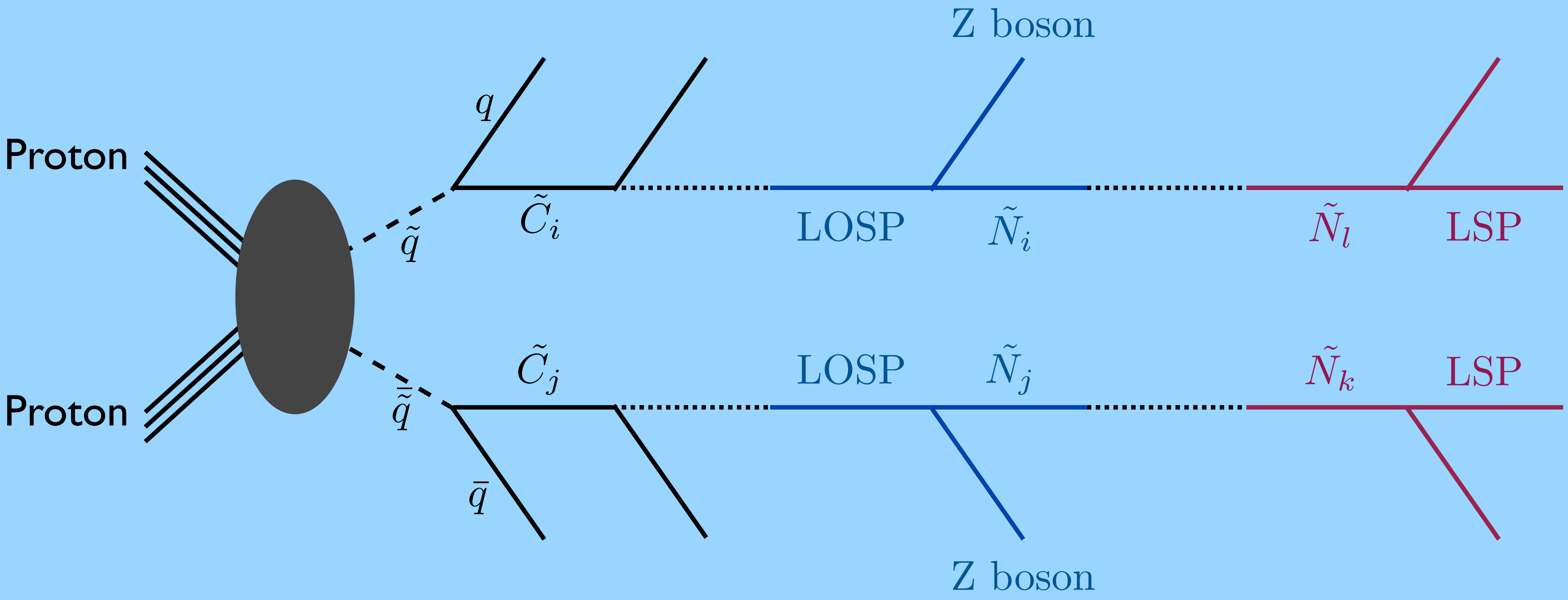
Implies plenitude of Universes &
plenitude of light particles and hidden sectors in our Universe

A Plenitude of Light States

- A Plenitude of Axions



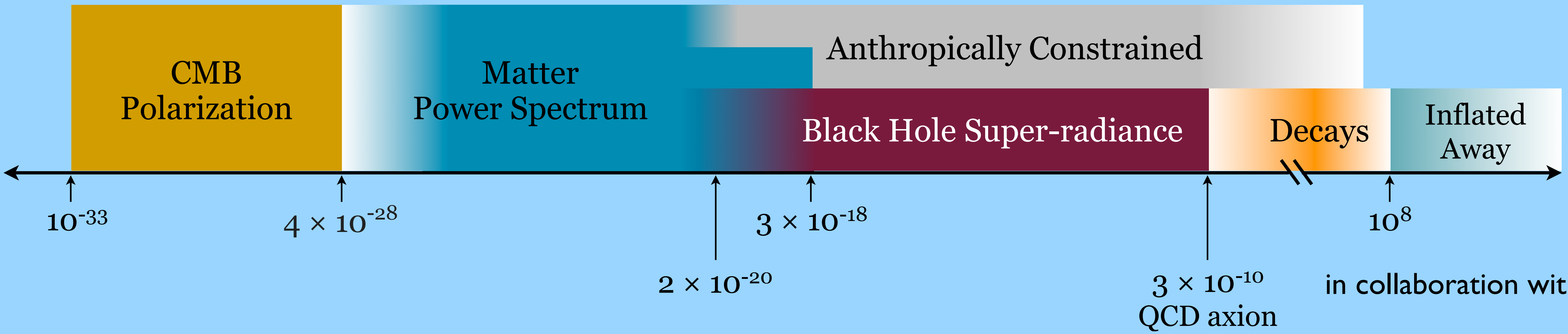
- A Plenitude of Gauge Bosons & Gauginos (& Goldstini)



The Axiverse

Taking properties of axions in string theory seriously, there exists a plenitude of axions with log-flat distribution of masses

In the next decade cosmo and astro observations will be exploring 23 orders of magnitude in energy



in collaboration with

Asimina Arvanitaki
Savas Dimopoulos
Sergei Dubovsky
Nemanja Kaloper

Is a fake symmetry broken by QCD plus $< 10^{-10} \times$ QCD common in a fundamental theory?

In string theory: YES & NO

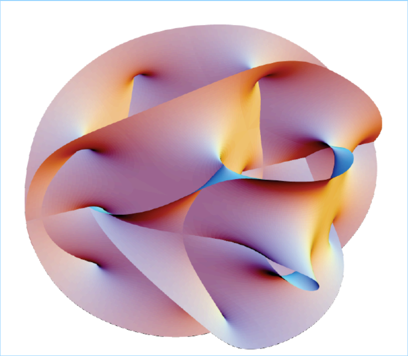
antisymmetric forms

B_2

$C_{0,2,4}$ (IIA)

$C_{1,3}$ (IIB)

compactification →



many (100-10000) massless axions from topology, eg:

$$a_i = \int_{\Sigma_3^i} C_3$$

axions can be removed from the spectrum by fluxes, branes, orientifold planes, but many survive....

Chern-Simons coupling → axionic couplings

(Green-Schwarz anomaly cancelation)

String theory does NOT predict the QCD axion

Must suppress all possible non-pert string effects that contribute to the axion mass $> 10^{-10}$×QCD $\Longrightarrow$ action (eg, of Euclidian wrapped D-brane) $\boxed{S \gtrsim 200}$: QCD axion constraint on string model building

(requires size of compact dimensions to be moderately $> \ell_s$)

Impacts physics of all the string axions

$$\boxed{m_a \sim \frac{\mu_{UV}^2}{f_a} e^{-S/2}}$$

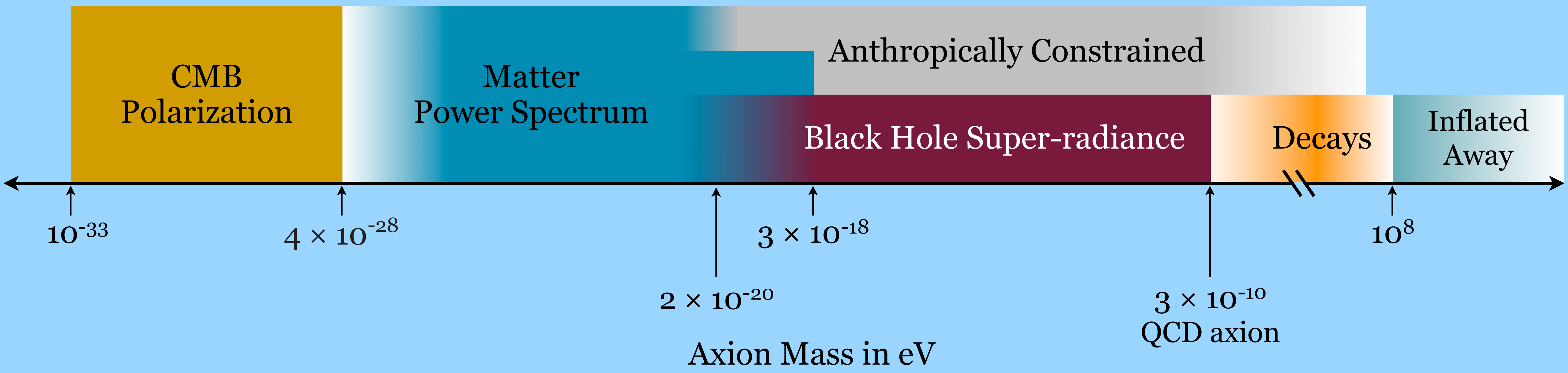
Axion masses exponentially sensitive to S

$$\boxed{f_a \sim \frac{M_{pl}}{S} \sim 10^{16}\mathrm{GeV}}$$

Axion couplings only linearly sensitive to S

QCD axion should not be special $\Longrightarrow$ should be *many* light axions

$f_a \sim M_{GUT}$ m: homogeneously distributed over log(energy)



CMB Polarization

Matter Power Spectrum

Anthropically Constrained

Black Hole Super-radiance

Decays

Inflated Away

10^{-33}

4×10^{-28}

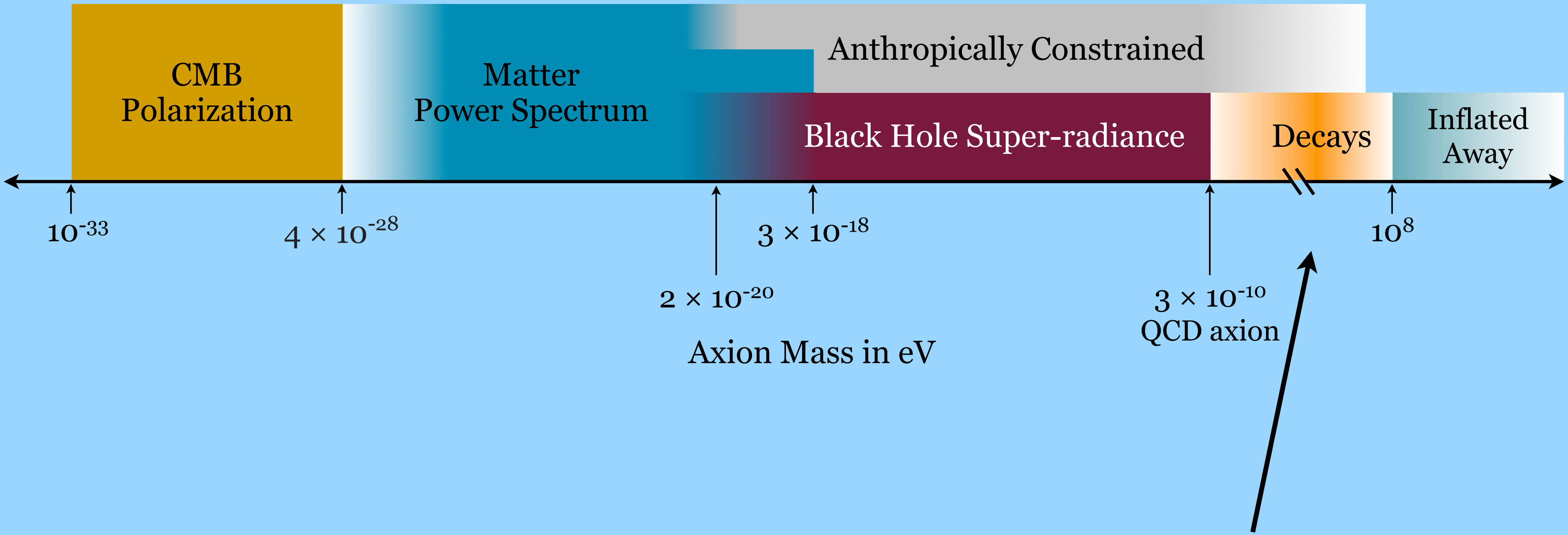
2×10^{-20}

3×10^{-18}

3×10^{-10}
QCD axion

10^{8}

Axion Mass in eV



this region today's topic

Solving the CP-problem of EW Baryogenesis

in collaboration with Nathaniel Craig (to appear v. soon)

- EW baryogenesis is most elegant, and testable, of all baryogenesis mechanisms suggested so far

- Most implementations be-devilled by the problem of sufficient CP violation

- The CKM phase is insufficient due to the smallness of quark flavour mixing. New sources must satisfy stringent EDM constraints

Will show: an initially mis-aligned axion with associated partially-hidden confining gauge theory with scale ~ TeV efficiently feeds-in CP-violation to SM during the EWPT (automatically only during EWPT)

Mechanism is testable at LHC & provides reason for hidden-valley/ quirk physics to be at TeV

Illustrative (non-susy) model

cf. Kuzmin, Shaposhnikov & Tkachev for QCD axion

$G = SU(N)$ hidden confining theory with matter content

	$SU(N)_G$	$SU(2)_L$	$U(1)_Y$
Q	$\square$	2	Y_Q
$\overline{Q}$	$\overline{\square}$	2	$-Y_Q$
U	$\square$	1	$-1/2 + Y_Q$
$\overline{U}$	$\overline{\square}$	1	$1/2 - Y_Q$

optionally, matter can be charged under SU(3) colour too, leading to mildly stronger constraints and different LHC phenomenology

$$\mathcal{L}_G \supset -\mu_Q Q\overline{Q} - \mu_U U\overline{U} - \lambda H Q\overline{U} - \lambda' H^\dagger \overline{Q} U + \text{ h.c.}$$

$\Longrightarrow$ hyperquark mass matrix

$$\mathcal{M} = \begin{pmatrix} \mu_Q & \frac{1}{\sqrt{2}}\lambda v(T) \\ \frac{1}{\sqrt{2}}\lambda' v(T) & \mu_U \end{pmatrix}$$

finite-T SM Higgs vev

integrate out massive hyperquarks

$SU(2)_{weak}$ field strength

$$\mathcal{L}_{eff} \sim \frac{\alpha_W \alpha_G}{64\pi^2} \frac{1}{m_Q^4(T)} W_{\mu\nu} \tilde{W}^{\mu\nu} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

G-sector axion is misaligned (and not yet relaxed at EW epoch) so effective theta-angle for G-sector $\theta_G \neq 0$

$$\Longrightarrow \quad \frac{\alpha_G}{8\pi} \langle G\tilde{G} \rangle = m_a^2(T) f_G^2 \sin\theta_G \neq 0$$

finite-T G-axion mass

G-axion decay const ($f_G \sim 10^{16}\,\mathrm{GeV}$ if stringy, or $f_G \lesssim 10^{13}\,\mathrm{GeV}$ if not anthro)

⟹ T-(and thus t-)dependent effective theta angle for SU(2)

$$\mathcal{L}_{eff} \sim \underbrace{\left[\frac{1}{m_Q^4(T)} m_a^2(T) f_G^2 \sin\theta_G\right]}_{\Phi(T)} \frac{g^2}{32\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu}$$

⟹ effective chemical potential for SU(2) Chern-Simons number

$$\mu_{CS} \simeq \sin\theta_G f_G^2 \frac{d}{dt}\left(\frac{m_a^2(T,v)}{m_Q^4(T)}\right)$$

Time variation of $\Phi(T)$ not set by Hubble expansion at T_c (suppressed by T_c/M_{pl})

During 1st-order EWPT, Higgs vev $v(T)$ changes suddenly and thus changes hyperquark and G-axion masses suddenly (& in bubble wall)

$\Longrightarrow$ bias in baryon-number produced by EW non-perturbative effects ("sphalerons") during EWPT

$$\Delta n_B \simeq \frac{n_f}{T}\int_0^\infty dt\,\Gamma_a(t)\mu_{CS}(t)$$

$$\begin{aligned} \Gamma_a &\simeq 30(\alpha_w)^5 T^4 && \text{(symmetric)} \\ \Gamma_a &\simeq (\alpha_w T)^{-3} m_W^7 e^{-E_{sph}/T} && \text{(broken)} \end{aligned}$$

Gives total baryon asymmetry (rough simple approx for bubble case):

$$\Delta \equiv \frac{n_B}{s} \sim \frac{675}{\pi g_*} n_f \alpha_w^5 \left(\frac{m_t}{T_c}\right)^2 \left(\frac{m_h}{T_c}\right) \delta\Phi$$

Change in effective SU(2) theta angle $\delta\Phi$ across wall depends on hyperquark mass and particularly G-confinement scale relative to T_c

(G-sector axion mis-alignment only physical through G non-perturbative effects)

What goes wrong if $\Lambda_G < T_c < m_Q$?

In this case, at $T = T_c$ the G-axion only obtains a tiny mass through finite-T instanton effects. Using the dilute-instanton-gas approximation

$$\begin{aligned} m_a^2 f_G^2 &\approx \Lambda_G^4 \left(\frac{\Lambda_G}{T}\right)^7 \\ &\ll \Lambda_G^4 \qquad \text{for } \Lambda_G \ll T_c \end{aligned}$$

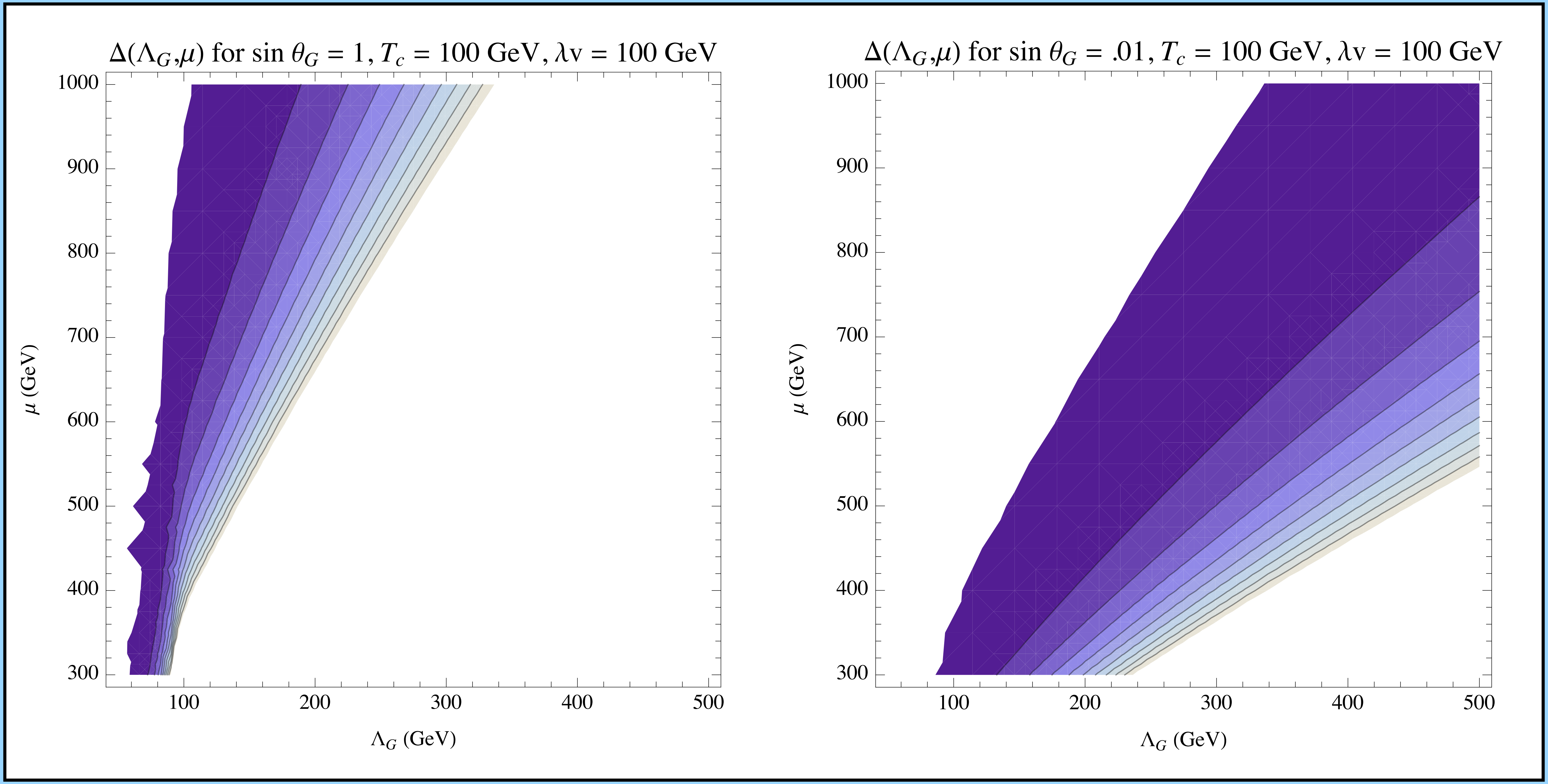
(Gross, Pisarski, Yaffe)

Explains why mechanism doesn't work for G=QCD itself

(Kuzmin, Shaposhnikov, Tkachev)

Must have $\Lambda_G \gtrsim T_c$ for efficient axion-assisted EW baryogenesis (AAEB)

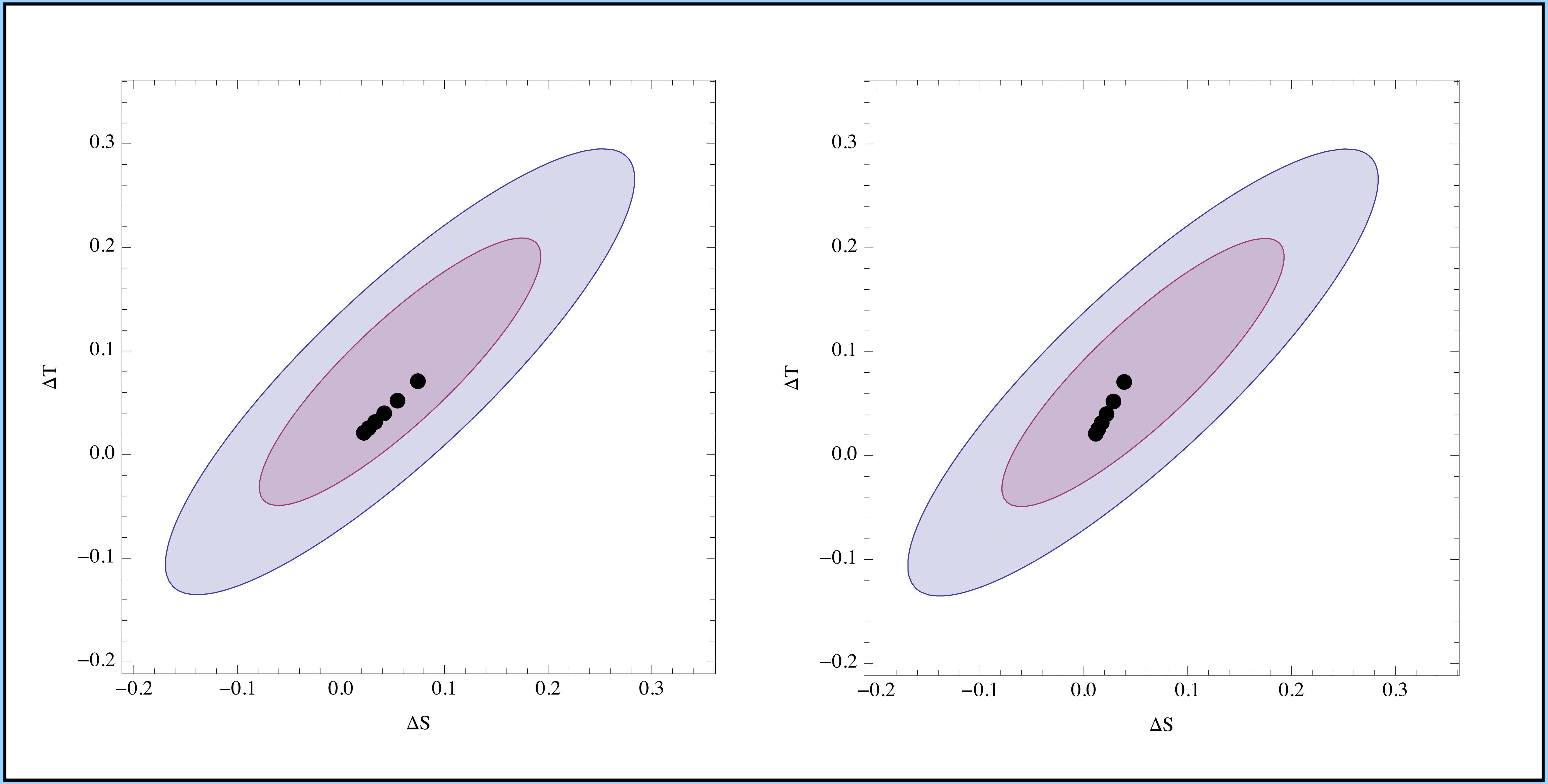
End result: for $\Lambda_G \gtrsim T_c$ and $m_Q \lesssim \mathrm{TeV}$ get substantial final baryon asymmetry



Range $10^{-11} < \Delta < 10^{-9}$ from dark to light

Experimental Constraints & Signals

Mainly involve messenger states (which share similarities to "quirks")



Corrections to electroweak precision observables S, T for $\mu = 300, 350, ..., 550$ GeV and $\lambda v = 100$ GeV assuming $Y_Q = 0$ (left) and $Y_Q = 1/2$ (right). The $68\%, 95\%$ CL ellipses are shown; best fit is achieved by $(\Delta S, \Delta T) = (0.057, 0.080)$

- Direct searches limit $m_Q \gtrsim 200\ \mathrm{GeV}$
  - $l + \gamma + \not{E}_T$; CDF Run II limits on anomalous events involving a high-p_T charged lepton and photon with missing transverse energy based on 929 pb^{-1} of data exclude masses for color-singlet hyperfermions below 200 GeV; the bound for colored hyperfermions is ~ 250 GeV.
  - $2\gamma + \gamma$ and $2\gamma + \tau$; CDF Run II limits on the inclusive production of diphoton events with a third photon based on 1155 pb^{-1} place a similar limit on hyperfermion masses, excluding $\lesssim 200$ GeV. Limits from a diphoton plus tau search on 2014 pb^{-1} place limits on hyperquark masses below 250 GeV assuming $\lambda \sim 1$ (may be relaxed for smaller Yukawa couplings)
- Hypercolor cosmology rich but not constraining (again similar to quirks)

  Lightest hyperquark is absolutely stable, but....

  Confining hypercolor interactions ensure all hypercolor bound states annihilate efficiently into lightest G-mesons, which then decay rapidly into SM states via coupling to EW gauge bosons or Higgs; for $\Lambda_G > 1\ \mathrm{GeV}$ decays happen well before BBN
- Hypercolor axion has similar search prospects to usual (DM) axions

Extensions & Comments

- Can "retrofit" any weak-scale BSM thy with sufficiently strong EWPT

- Susy case straightforward but with additional features:

$$W_G = \mu Q\overline{Q} + \mu' U\overline{U} + \lambda H_u \overline{Q} U + \lambda' H_d Q \overline{U}$$

  the weak-scale vector masses now have natural explantion as additional "μ-terms"

- Known that a vector-like 4th-generation can substantially ameliorate the little-hierarchy problem. Our hyperquarks are automatically in mass range (and of multiplicity) to do this

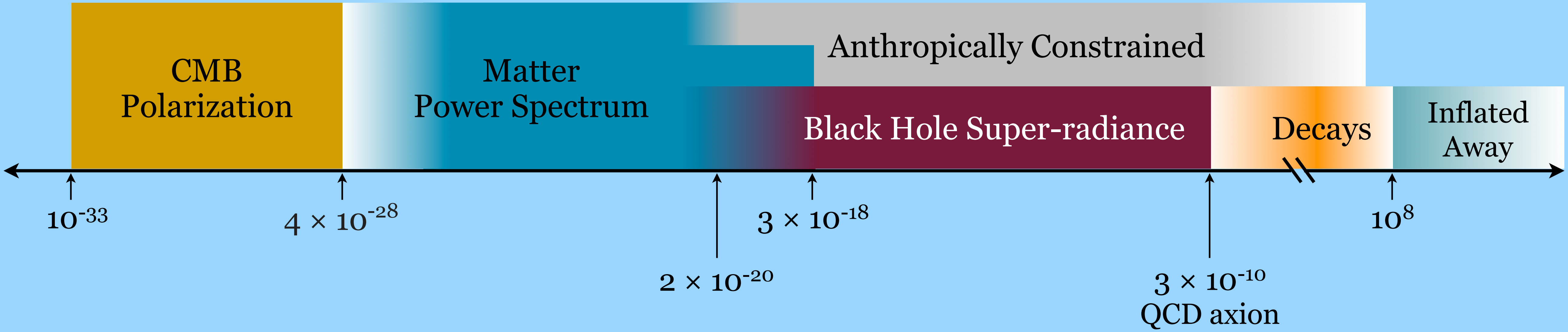
- The connection of the hidden scale and masses of the "quirk-like" messengers to the EW scale via the axion assisted electroweak baryogenesis mechanism provides a reason for such new, hidden valley physics to lie at the weak scale

Plenitude of states and sectors that landscape predicts is useful and testable

In the next decade cosmo and astro observations will be exploring 23 orders of magnitude in energy

have a chance to observationally explore the topology of the compactification manifold

astrophysical BHs serve as a probe of string theory



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Photi- & Photini-verse

in collaboration with

Asimina Arvanitaki
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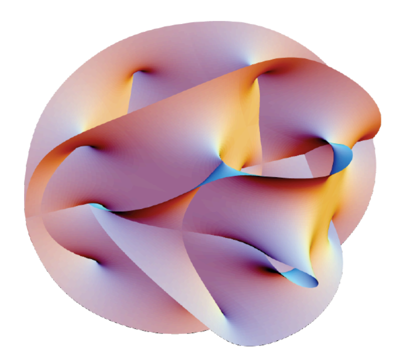
Many U(1)'s can arise in string thy: D-branes,...

One interesting class from RR antisymmetric forms

$$C_4 \quad (IIB)$$
$$C_3 \quad (IIA)$$

$$\xrightarrow{\text{compactification}}$$



many (few10's-100's) KK zero modes from topology

eg, $X_i^\mu = \int_{\Sigma_i^3} C_4$

Inherits gauge symm from 10d abelian gauge symm of RR field

Important property of RR U(1)'s: typically no light charged states

due to fact that arise from multi-index fields that naturally couple to branes (Polchinski) not point particles

From effective field theory point of view applies more generally (eg, D-brane U(1)'s,...):

- If states that carry their charge vector-like then expect states to be superheavy. O(1) fraction should remain unbroken
- Can only couple through $F_{\mu\nu}$: Can only couple to hypercharge field strength

Uniquely couple to us via kinetic mixing with $U(1)_Y$

$$\Delta\mathcal{L} = -\frac{1}{4}\begin{pmatrix} X^i_{\mu\nu} & B_{\mu\nu} \end{pmatrix} \mathcal{F} \begin{pmatrix} X^{i\mu\nu} \\ B^{\mu\nu} \end{pmatrix}$$

$$\mathcal{F} = \begin{pmatrix} f_{ij} & \epsilon_i \\ \epsilon_j^T & 1 \end{pmatrix}$$

non-decoupling & sensitive to UV physics

Can be diagonalized (Holdom) and b/c of absence of light charged states U(1)'s *entirely decouple* from us

only remnant: hypercharge norm changes:

$$g_Y \to \frac{g_Y}{\sqrt{1-\sum_i \epsilon_i^2}}$$

No signals from massless photons

very light Z's different: can have gravitational Kerr super-radiance signals even if Z's completely decoupled from us

BUT the photini are coupled

difference is that they are massive from susy-breaking

$$\delta\mathcal{L} = iZ_{ij}\lambda_i^\dagger \not{\partial}\lambda_j + m_{ij}\lambda_i\lambda_j$$

and both kinetic and mass-mixing with bino are possible

Mass eigenstates interact with MSSM states via "bino portal"

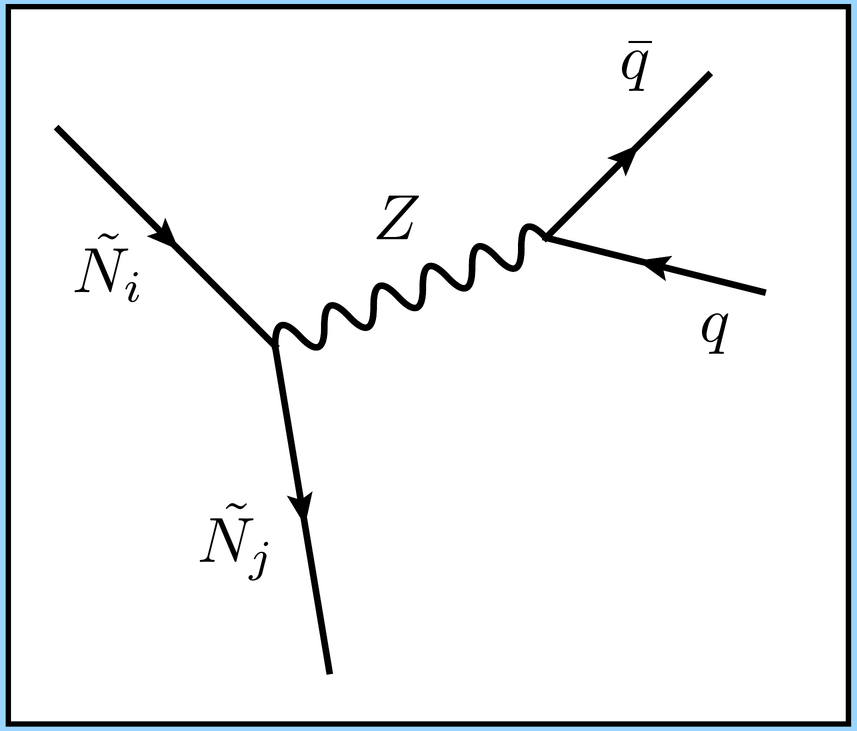
Let $\tilde{N}_I$ be mass e'states $I, J = 1, ..., n+4$

$$\tilde{N}_I = f_{IJ}\lambda_J$$

$$\lambda_I = (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u, \tilde{\gamma}_1, ..., \tilde{\gamma}_n)$$

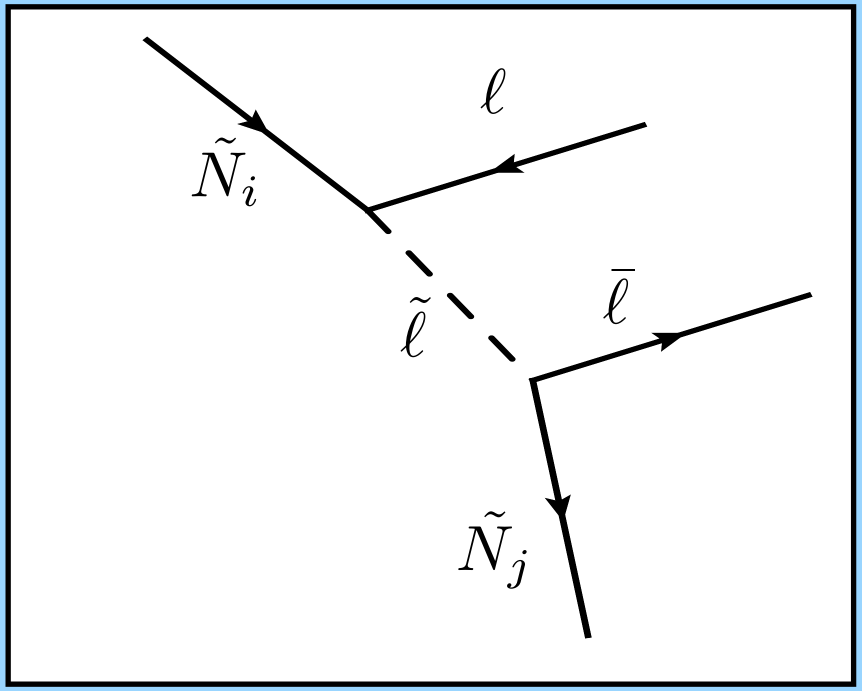
Inter-photini decays

$$f_{i1} \simeq \epsilon_i \frac{m_i}{m_1 - m_i} \qquad f_{i(2,3,4)} \simeq f_{1(2,3,4)} \epsilon_i \frac{m_i}{m_1 - m_i}$$



$$\Gamma^{Z^*}(\tilde{N}_i \to \tilde{N}_j + f\bar{f}) \simeq$$

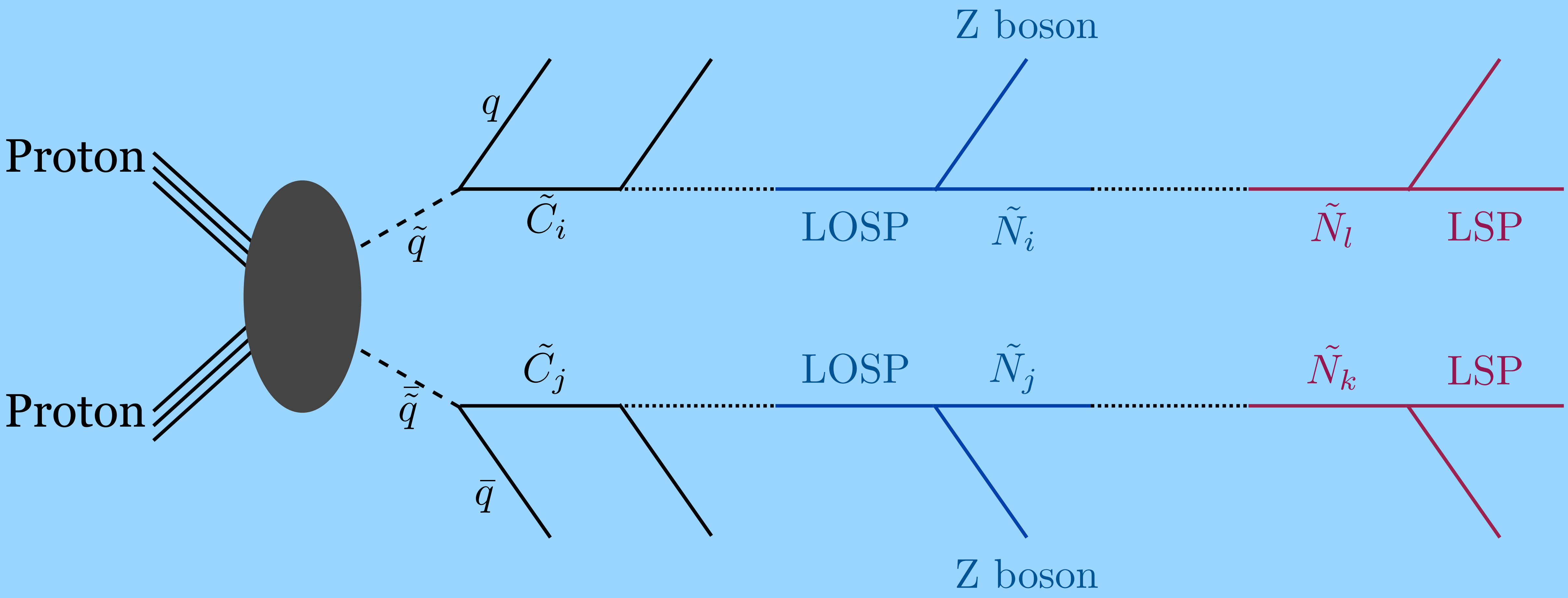
$$\frac{\alpha_W^2 \times \text{MSSM mixings}}{192\pi^3} (\epsilon_{eff,ij})^4 \left(\frac{M_i M_j}{M_{\tilde{B}}^2}\right)^2 \frac{(\delta m)^5}{m_Z^4}$$



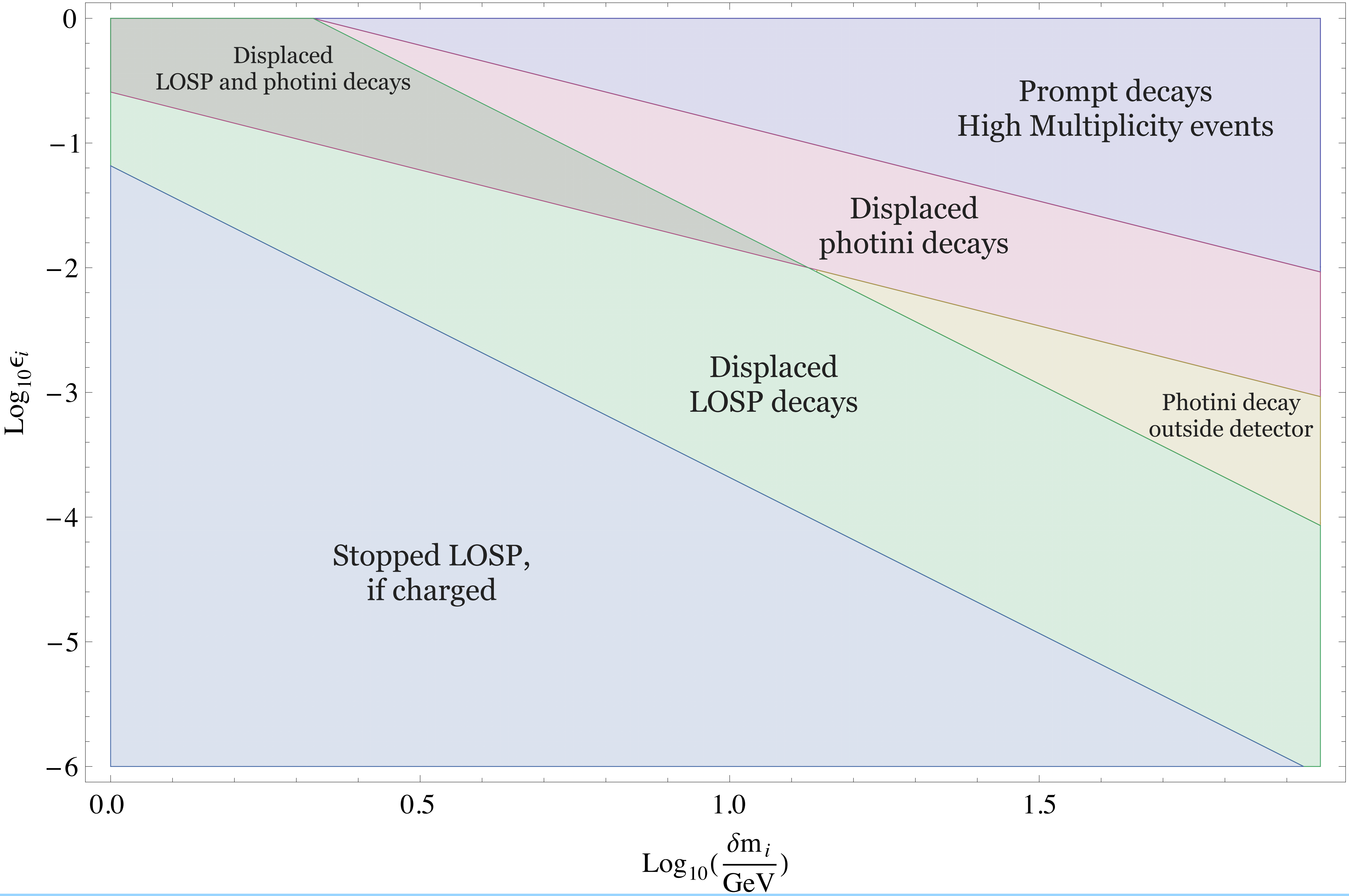
$$\Gamma^{\tilde{l}}(\tilde{N}_i \to \tilde{N}_j + f\bar{f}) \simeq$$

$$\frac{\alpha_W^2 \times \text{MSSM mixings}}{192\pi^3} (\epsilon_{eff,ij})^4 \left(\frac{M_i M_j}{M_{\tilde{B}}^2}\right)^2 \frac{(\delta m)^5}{m_{\tilde{l}}^4}$$

Modified Cascade decays at the LHC



Photini signatures at the LHC



- The various signatures can coexist as different photini can have varying mass-splittings and mixings

- Even if not in “dramatic signal” region, photini change LHC SUSY reconstruction in non-trivial ways, eg, there can appear to be multiple LSP’s with different masses & endpoint of 2 sides of cascade can differ: Discovery through reconstruction of masses and mass splittings

But there's more...

(work in progress)

- Inspired by photini idea, Cheung, Nomura & Thaler considered multiple Goldstini from multiple susy-breaking sectors $\Longrightarrow$ another source of big changes to LHC SUSY phenomenology. But physics is much richer than so far realised (N. Craig, JMR, M. McCullough)

- "Heavy" axiverse axions can enable electroweak baryogenesis to work (N. Craig, JMR)

- Super-radiance a powerful probe of many other very light bosonic states coupled only gravitationally to us (eg, very-light Z's, or warped throats with light string excitations) (JMR, J. Rosa)