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News from String Axions and other weird beasts

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HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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String Axions

Mostly based on 2203.08833 (with M. Cicoli, A. Hebecker, M. Wittner)
and
2102.00006 (with Wen Yin)

String theory: Moduli and Axions

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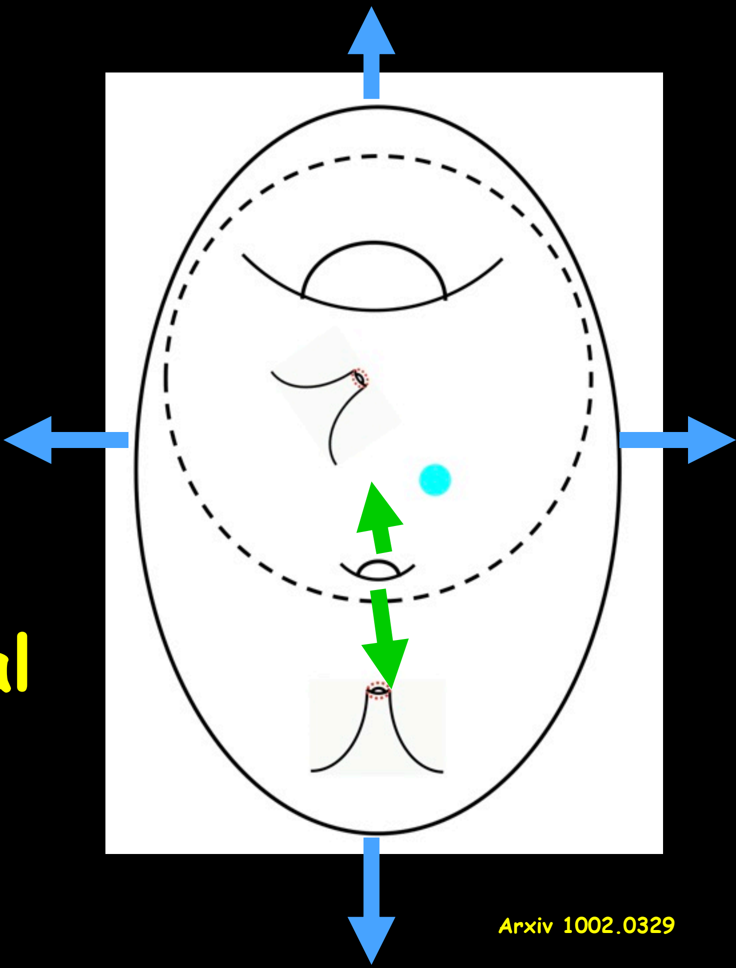
- String theory needs Extra Dimensions

Must compactify

- Shape and size deformations correspond to fields:
  Moduli (WISPs) and Axions
  Connected to the fundamental scale, here string scale



Arxiv 1002.0329

WISPs candidates

Axions and Moduli

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- Gauge field terms

$$\mathcal{L} = \frac{1}{g^2} F^2 + i\theta F\tilde{F}$$

+ Supersymmetry/supergravity

$$\mathcal{L} = \mathrm{Re}[f(\Phi)]F^2 + \mathrm{Im}[f(\Phi)]F\tilde{F}$$

Scalar ALP/moduli coupling + pseudoscalar ALP coupling

Axions and Moduli

- Gauge couplings always field dependent (no free coupling constants)

- Axions + Moduli always present in String theory

String Axions
General Features

Need for large volume

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- Generically

$$f_a \sim \frac{M_P}{\sqrt{\mathcal{V}}}$$

Volume in string units

→ If we want sub-Planckian axion we need large (even LARGE) volume

An underappreciated feature

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String axions have ``pre-inflationary'' cosmo!

Why?

- Actually do not result from the usual spontaneous symmetry breaking
- Exist during inflation
  (otherwise don't understand string inflation)
- Axion string tension expected to be higher than string scale
- Too high temperature → Decompactification

String Axions
Dark Radiation Hydra

Axionic/ALPy Dark Radiation

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- Many (string) models feature a
  long-lived modulus Φ
- This reheats the Universe $\Phi \rightarrow SM$
- Significant branching ratio into axions/ALPs

$$\Phi \rightarrow a + a$$

- These a are effective degrees relativistic of freedom visible in BBN and CMB
- often dangerous „Dark Radiation Problem“

M. Cicoli, J. P. Conlon, and F. Quevedo, “Dark radiation in LARGE volume models,” Phys. Rev. D **87** no. 4, (2013) 043520, arXiv:1208.3562 [hep-ph].

T. Higaki and F. Takahashi, “Dark Radiation and Dark Matter in Large Volume Compactifications,” JHEP **11** (2012) 125, arXiv:1208.3563 [hep-ph].

A. Hebecker, P. Mangat, F. Rompineve, and L. T. Witkowski, “Dark Radiation predictions from general Large Volume Scenarios,” JHEP **09** (2014) 140, arXiv:1403.6810 [hep-ph].

S. Angus, “Dark Radiation in Anisotropic LARGE Volume Compactifications,” JHEP **10** (2014) 184, arXiv:1403.6473 [hep-ph].

+ . . . + https://arxiv.org/pdf/2203.08833.pdf

The dark radiation problem

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- String models usually have **too much axionic dark radiation**
- Reason: Long-lived volume modulus ϕ_b dominates the Universe before reheating it

$$BR_{\phi_b \to aa} \sim \frac{\Gamma_{\phi_b \to aa}}{\Gamma_{\phi_b \to SM} + \Gamma_{\phi_b \to aa}} \sim \frac{1}{1+2z^2} \sim \mathcal{O}(1)$$

➔

$$\Delta N_{\rm eff} \sim 6.1 \left(\frac{11}{g_\star^4 g_{\star,S}^{-3}} \right)^{1/3} BR(\phi \to aa)$$

But: **CMB + Co. say:** $\Delta N_{\rm eff} \lesssim 0.2 - 0.4$

Solution: Decay to Higgses

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- SUSY breaking generates coupling to Higgses

.... an actually not so long calculation...

$$m_H^2 \sim m_{3/2}^2 \left[c_0 + c_{\rm loop} \ln\left(\frac{m_{\rm KK}}{m_{3/2}}\right)\right]$$

$$m_H^2 \sim \left(\frac{W_0}{\mathcal{V}}\right)^2 \left[c_0 + c_{\rm loop} \ln\left(\frac{\mathcal{V}^{1/2}}{W_0}\right)\right] M_P^2$$

$$\mathcal{V} \sim \tau_b^{3/2} \sim \exp\left(\sqrt{\frac{3}{2}}\phi_b\right)$$

$$\mathcal{L} \supset \sim \left(m_{3/2}^2 \frac{c_{\rm loop}}{2}\sqrt{\frac{3}{2}}\right) h^2 \frac{\delta\phi_b}{M_P} \sim m_{3/2}^2\, c_{\rm loop}\, h^2 \frac{\delta\phi_b}{M_P}$$

$$\Gamma_{\phi_b \to hh} \sim \frac{m_{3/2}^4 c_{\rm loop}^2}{m_{\tau_b} M_P^2} \sim (c_{\rm loop}\mathcal{V})^2 \frac{m_{\tau_b}^3}{M_P^2} \gg \Gamma_{\phi_b \to a_b a_b}$$

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➔

$$BR_{\phi_b \to aa} \ll 1$$

➔ Problem solved!

https://arxiv.org/pdf/2203.08833.pdf

Or is it?

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- Well, it's a Hydra ;-)

Inflaton may be longest-lived modulus

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- Inflaton decay now slower than volume modulus

$$\Gamma_{\text{inflaton}} \sim \mathcal{V}^{-4} \gtrsim \Gamma_{\phi_b} \sim c_{\text{loop}}^2 \mathcal{V}^{-2.5}$$

- May dominate Universe

$$BR(inflaton \rightarrow a + X) \sim \frac{1}{1+x}$$

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O(100)

Thanks to decays to MANY SM gauge bosons!

https://arxiv.org/pdf/2203.08833.pdf

Dark Radiation
is useful

We expect some dark radiation

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$$\Delta N_{\rm eff} \sim 6.1 \left(\frac{11}{g_\star^4 g_{\star,S}^{-3}}\right)^{1/3} BR(\phi \to aa) \simeq 0.3 \left(\frac{11}{g_*^4 g_{*,S}^{-3}}\right)^{1/3} \simeq 0.14$$

$$g_* = g_{*,S} = 106.75$$

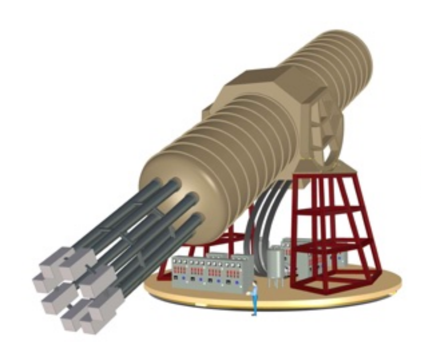
This dark radiation is made from axions.
A significant part is QCD axions

↓

Detectable

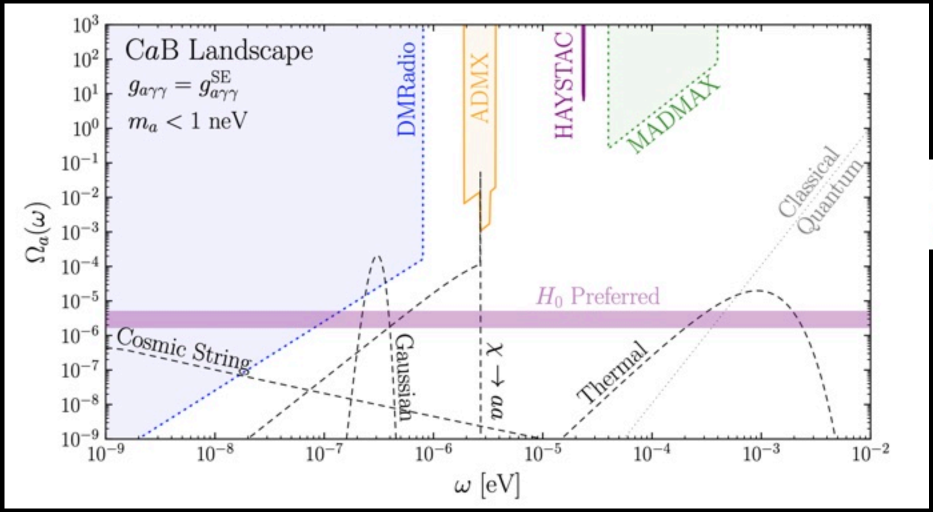
Dark Radiation may be detectable + Useful

- For example in IAXO



Physics potential of the International Axion Observatory (IAXO)
IAXO Collaboration • E. Armengaud (IRFU, Saclay) et al. (Apr 19, 2019)
Published in: *JCAP* 06 (2019) 047 • e-Print: 1904.09155 [hep-ph]

- But also other experiments



Cosmic axion background
Jeff A. Dror (UC, Santa Cruz and UC, Santa Cruz, Inst. Part. Phys. and UC, Berkeley and LBNL, Berkeley), Hitoshi Murayama (UC, Berkeley and LBNL, Berkeley and Tokyo U., IPMU), Nicholas L. Rodd (UC, Berkeley and LBNL, Berkeley)

- Might be interesting to think beyond scalar photon couplings!

New tool to probe Reheating

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- This dark radiation may allow to get access to information about reheating

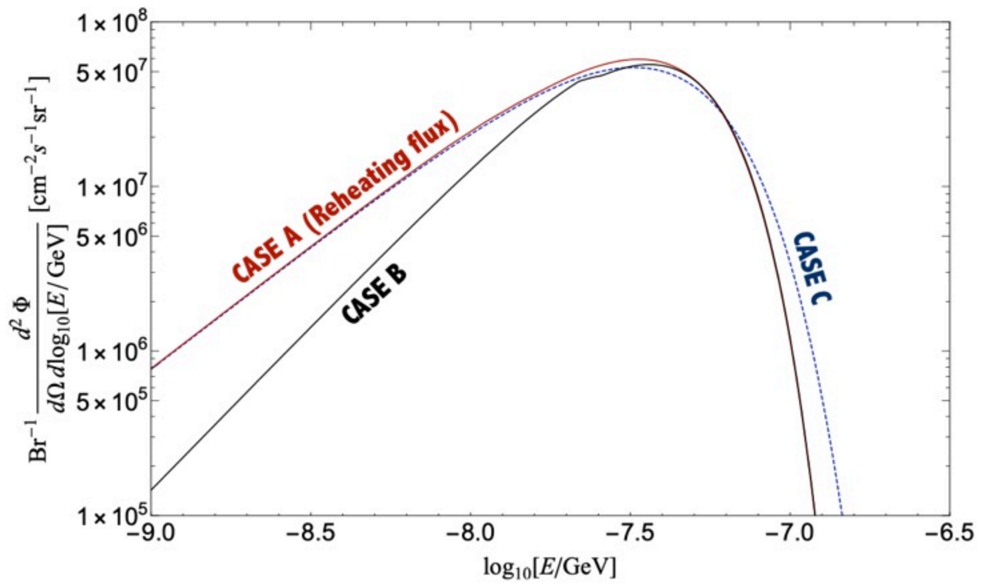

Figure. 1. The differential flux of the messenger particle, $d^2\Phi/d\log_{10} E d\Omega$. CASE A ($\phi$ once dominated the Universe) and CASE B (ϕ never dominates the Universe and decay in the radiation dominant epoch) are shown in red and black lines, respectively. We also show the flux for CASE C where a subdominant ϕ decays in the matter dominant era as the blue dashed line.

https://arxiv.org/pdf/2102.00006.pdf

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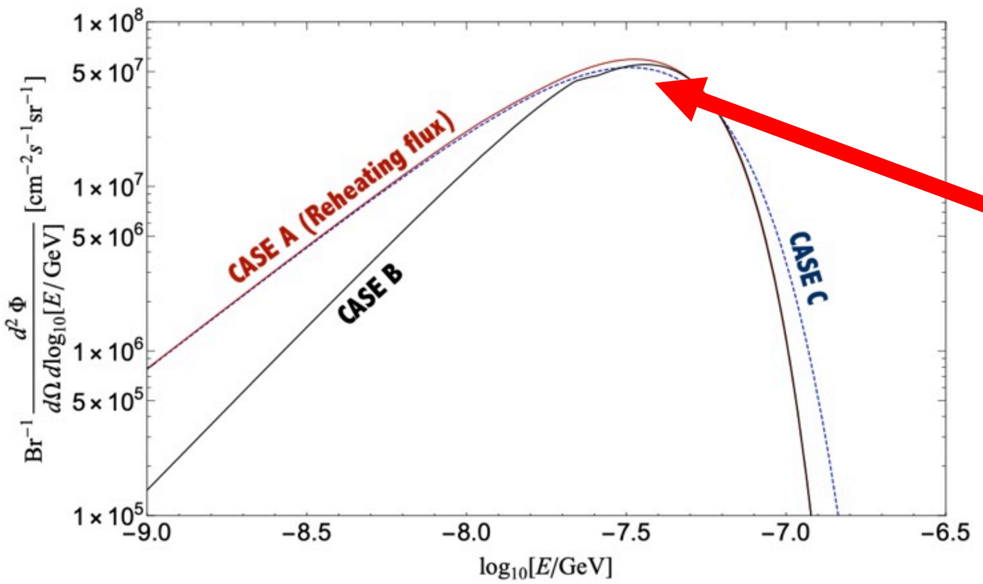

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Measures

$$\frac{m_\Phi}{T_\Phi}$$

https://arxiv.org/pdf/2102.00006.pdf

Measure reheating temperature

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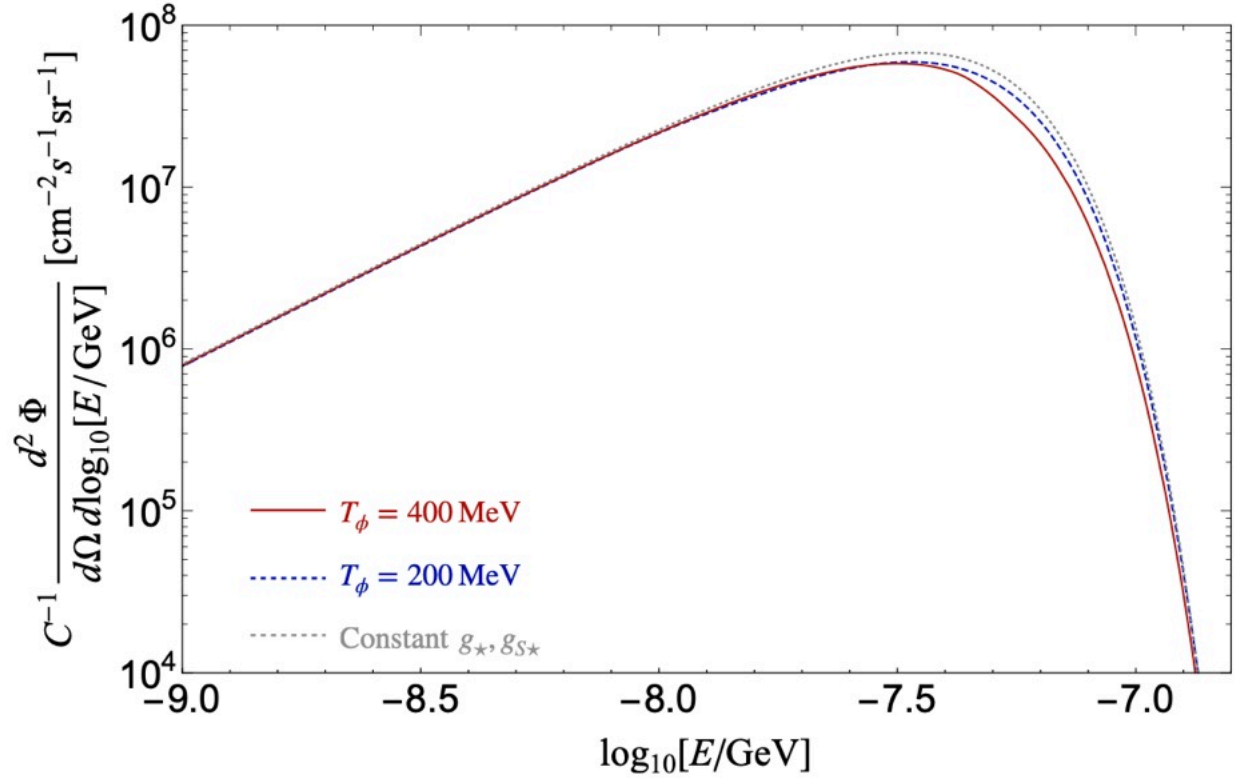

Figure. 2. The reheating flux dependence on the decoupling effect: $T_\phi = 400\,\mathrm{MeV}$ (red-solid line) and $T_\phi = 200\,\mathrm{MeV}$ (blue-dashed line, CASE A). We take $g_\star, g_{s\star}$ temperature in-

https://arxiv.org/pdf/2102.00006.pdf

Going Crazy: Poincare violation

Probing Poincaré Violation #1

Rick S. Gupta (Durham U., IPPP and Tata Inst.), Joerg Jaeckel (U. Heidelberg, ITP), Michael Spannowsky (Durham U., IPPP)
(Nov 8, 2022)

e-Print: 2211.04490 [hep-ph]

Poincare Symmetry

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- Lorentz Invariance (➔Kostelecky et al)

- Time Translation Invariance
  ➔ Energy Conservation

We start here

- Space Translation Invariance
  ➔ Momentum Conbservation

Looking at PV QED

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- Simple implementation: Time varying couplings

$$L = i\bar{\psi}\not{D}_\mu\psi - \mathrm{m}(x)\bar{\psi}\psi - i\tilde{\mathrm{m}}(x)\bar{\psi}\gamma^5\psi - \frac{\mathrm{Z(x)}}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{\mathrm{Z}}(x)}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Looking at PV QED

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- What's new?
  - Consider broad range of time-variations (future)
  - Take energy violation seriously

Looking at PV QED

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- Simple implementation: Time varying couplings

$$\mathrm{L} = i\bar{\psi}\not{D}_\mu\psi - \mathrm{m}(x)\bar{\psi}\psi - i\tilde{\mathrm{m}}(x)\bar{\psi}\gamma^5\psi - \frac{\mathrm{Z(x)}}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{\mathrm{Z}}(x)}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- For now: Simple periodic time variation

$$\begin{aligned}
\delta\mathrm{Z}(x) &= Z(x) - 1 = \sum_\omega \delta Z(\omega)\cos\omega t \\
\tilde{\mathrm{Z}}(x) &= \sum_\omega \tilde{Z}(\omega)\cos\omega t \\
\frac{\delta\mathrm{m}(x)}{m_e} &= \frac{\mathrm{m}(x) - m_e}{m_e} = \sum_\omega \frac{\delta m(\omega)}{m_e}\cos\omega t \\
\frac{\tilde{\mathrm{m}}(x)}{m_e} &= \sum_\omega \frac{\tilde{m}(\omega)}{m_e}\cos\omega t
\end{aligned}$$

Looking at PV QED

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- Simple implementation: Time varying couplings

$$L = i\bar{\psi}\not{D}_\mu\psi - m(x)\bar{\psi}\psi - i\tilde{m}(x)\bar{\psi}\gamma^5\psi - \frac{Z(x)}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{Z}(x)}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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\frac{\tilde{m}(x)}{m_e} &= \sum_\omega \frac{\tilde{m}(\omega)}{m_e}\cos\omega t
\end{aligned}$$

Might be interesting to allow for broad spectrum, or even white noise

Breaks Lorentz invariance, too

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- Time varying couplings have

$$\partial_\mu \delta Z(x) \neq 0$$

- Non-vanishing Lorentz vector ➔ Lorentz symmetry is broken, too

➔ Need to specify rest frame

➔ We take CMB rest frame

Looks like (pseudo-)Scalar DM?

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- One origin of oscillation could be scalar DM

$$\delta Z(t) \sim g\phi(t) \sim g\phi_0(t)\cos(mt)$$

- We want to be more general
  (less constrained by reason)
  - DM predicts specific $\phi_0(t) \sim a^{-3/2}$
    vs. we consider $\phi_0(t) \sim const$
  - No gravitational clumping (+fixed frequency spectrum)
  - No particle excitations
    ➔ astrophysical energy loss bounds gone
  - No forces from a particle exchange
    ➔ no fifth forces

Results

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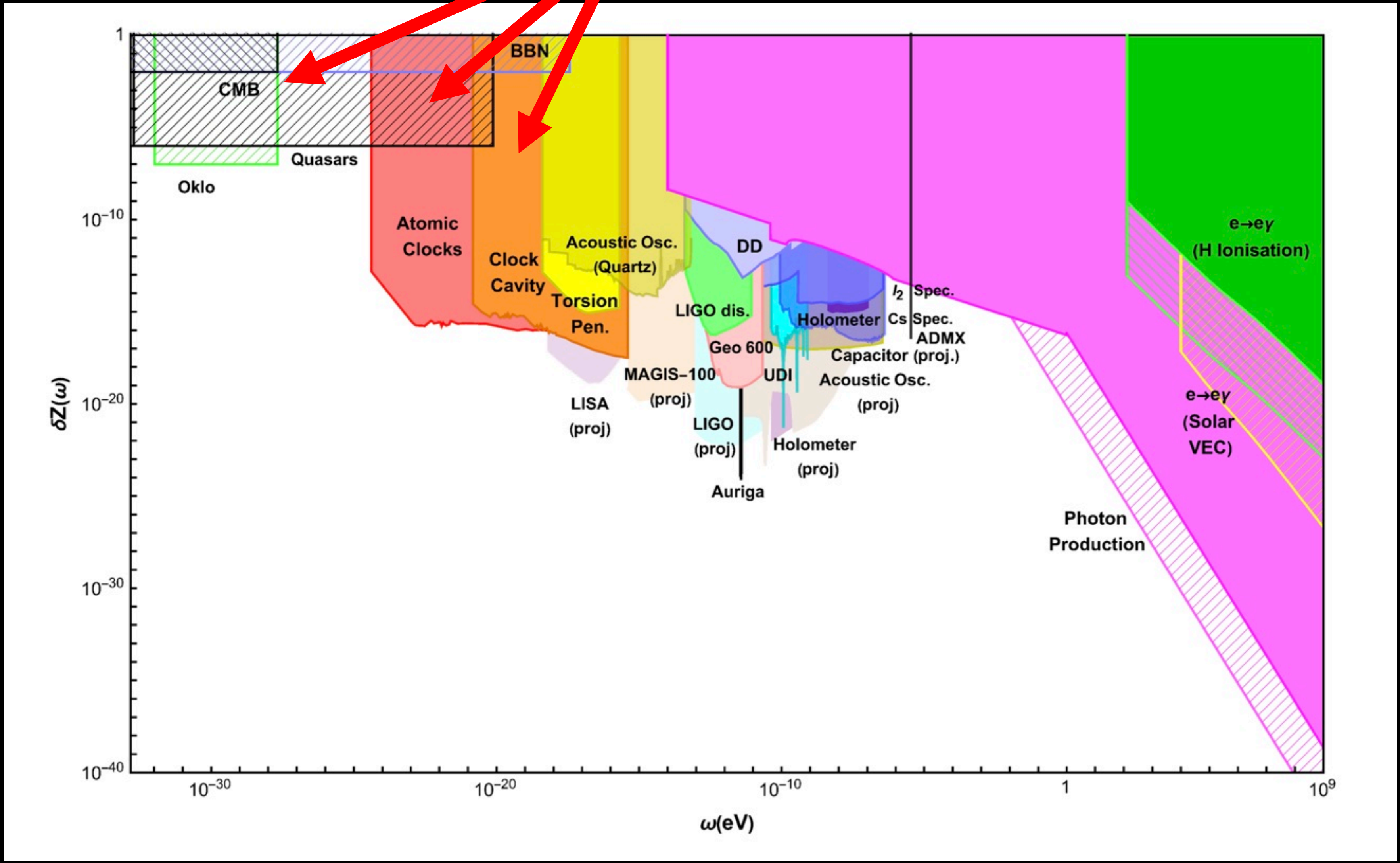
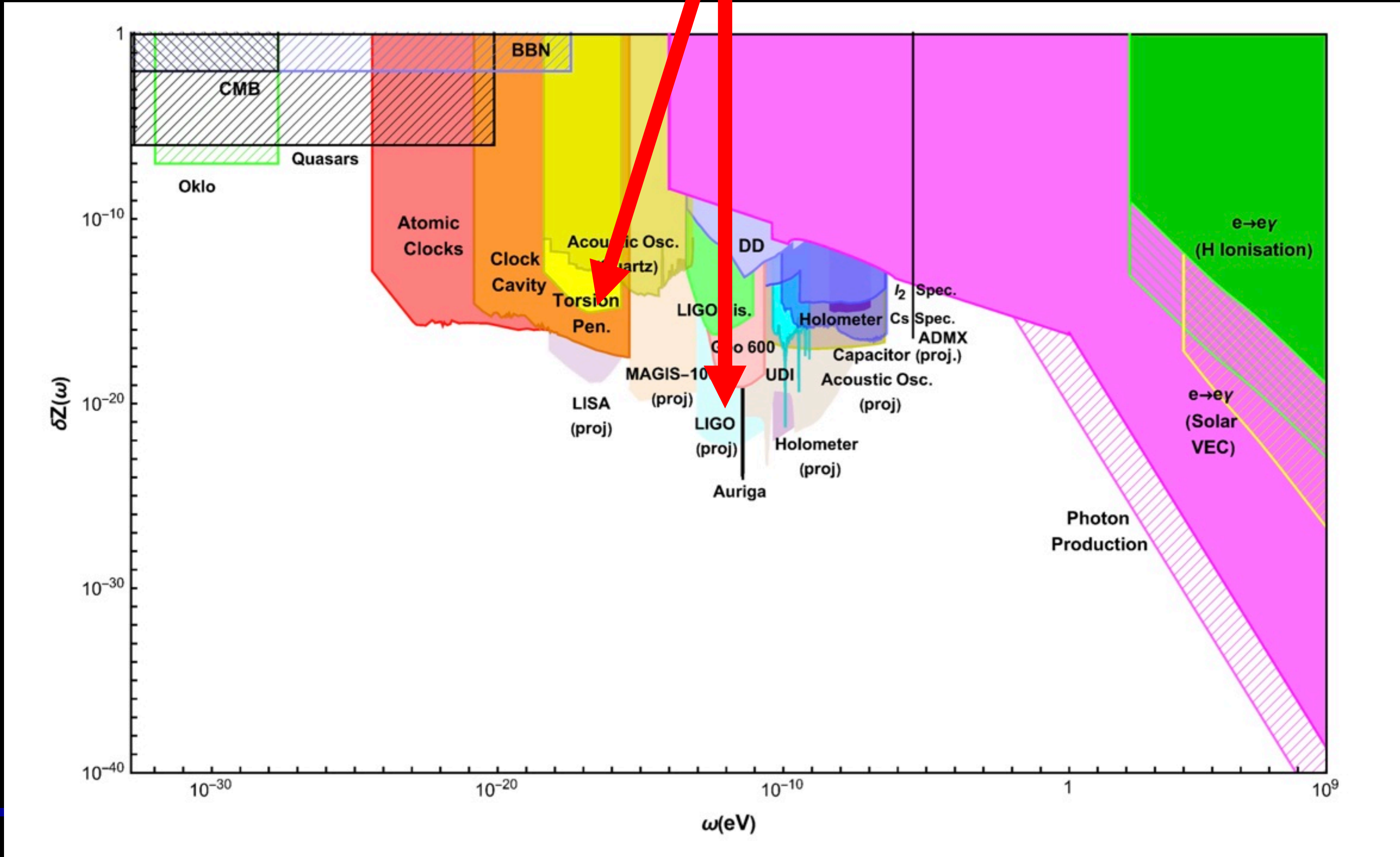
- "Standard" limits from time varying constants



Results

- Oscillating Forces in experiments moving with repect to the rest frame (a la DM)



Particles from nothing

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- An $\delta Z \sim \cos(\omega t)$ is like an oscillating driving force for photons

➔ Photon creation

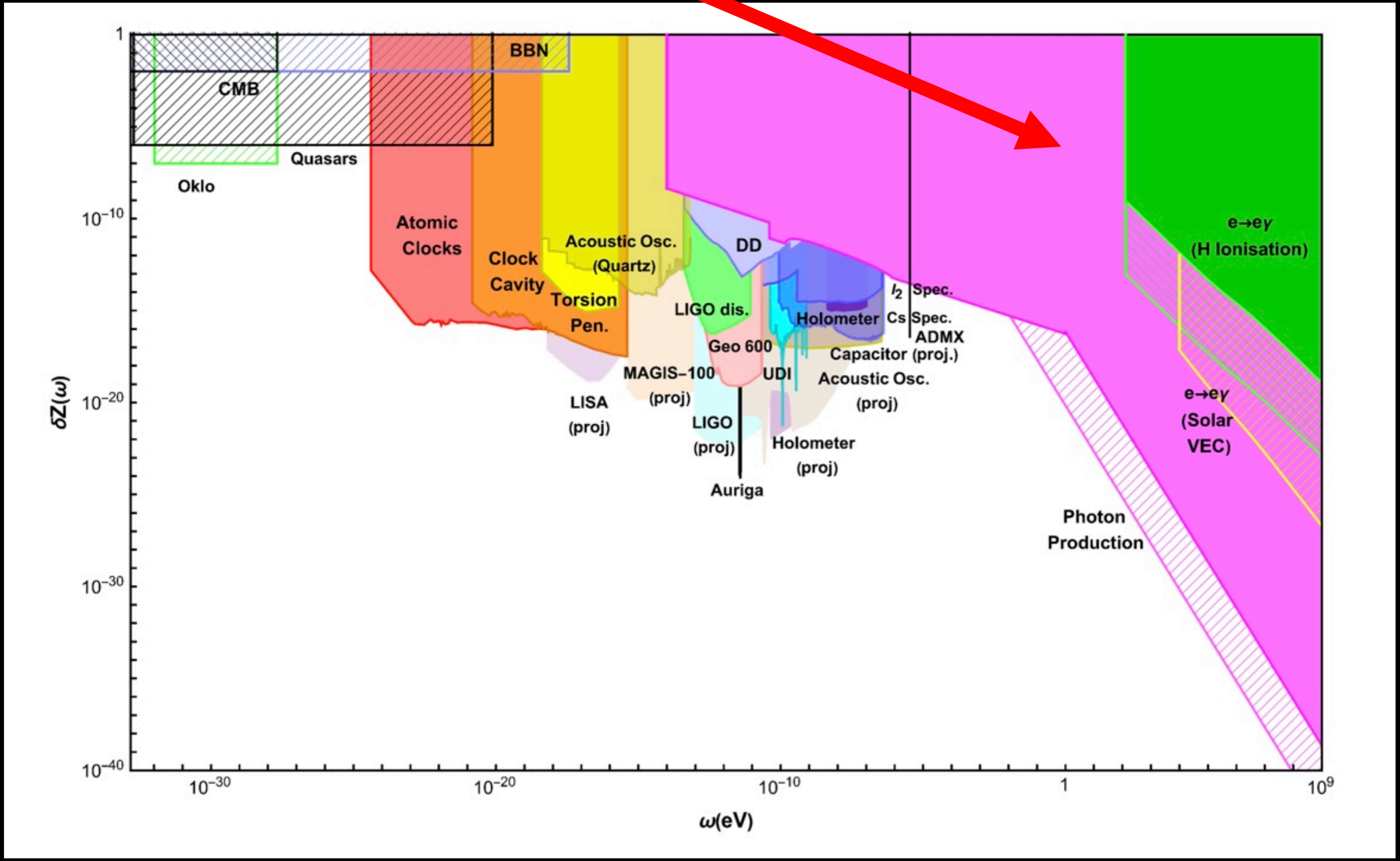
$$\dot{n}_{\gamma}(\omega) \;=\; (2N_k + 1)\frac{(\delta Z(\omega))^2\omega^4\beta_{\gamma}}{64\pi},$$

(analog to resonant DM decay)

- Visible Photons, too much energy created etc.

Results

- Particle creation from vacuum (too much)



Energy violation in scattering events

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- Energy violation in scattering possible

$$e+\gamma \quad (E) \to e+\gamma \quad (E \pm omega)$$

- Expect (because of phase space)

$$\sigma(E \to E-\omega) < \sigma(E+\omega)$$

➔ Net energy gain on average

➔ For example Sun would „gain“ energy

Results

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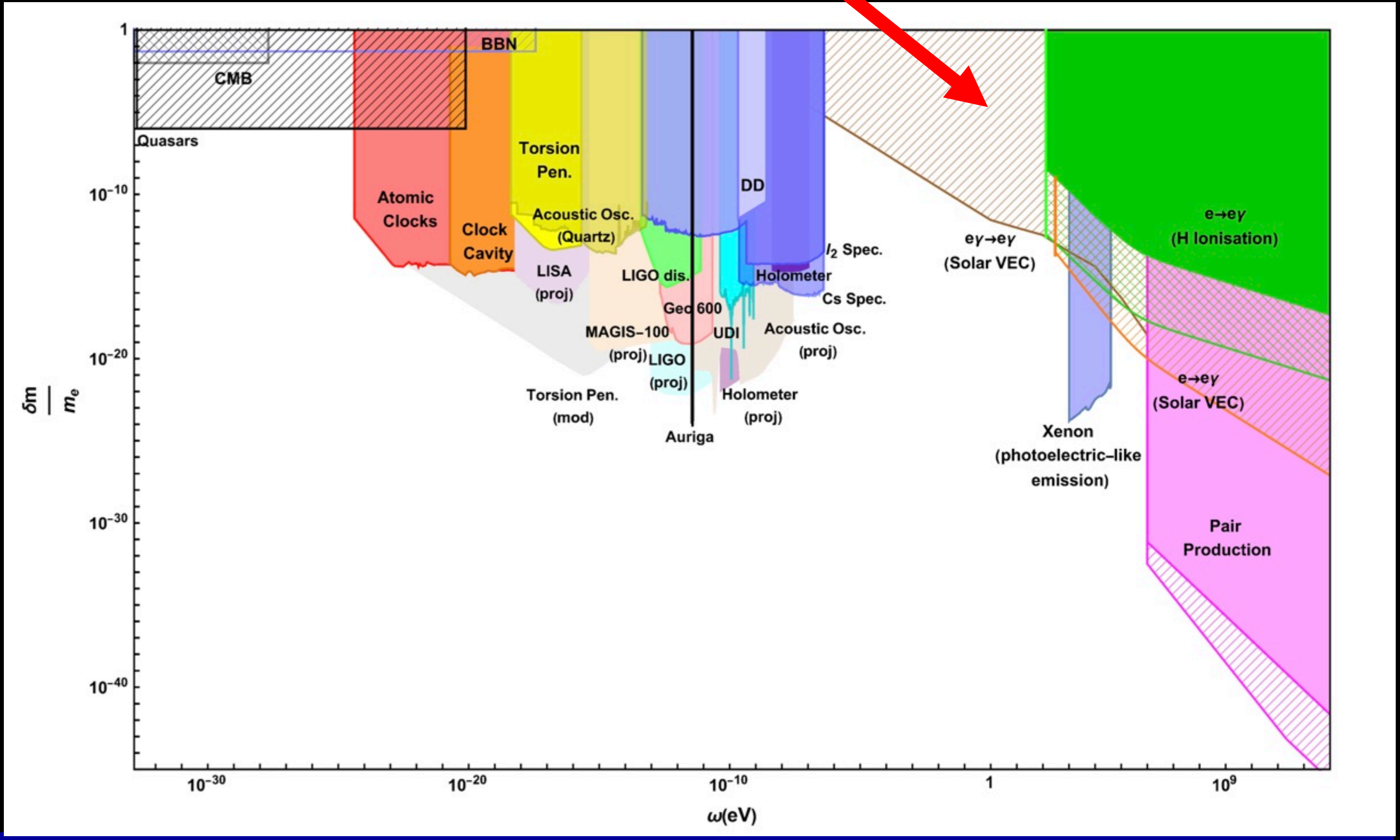
- Energy conservation in Sun is important for the electron couplings...



Conclusions

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Conclusions

- String axions have ``pre-inflationary" cosmo
- Cosmic, „Dark Radiation" of Axions used to be a problem. But this Hydra is slain!

- Now: interesting for detection + probing cosmology
- Crazy Things like Poincare Violation/Energy Violation/Momentum Violation should also occasionally be tested

  ➔ Might be interesting to search for variations/driving forces with non-trivial spectrum