INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

News from sub-(G)eV FI(N)Ps

J. Jaeckel[*]

G. Alonso[*], F. Calore[y], P. Carenza[o], L. DiLuzio[oo], C. Eckner[y],
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M. Spannowsky[†], L. Thormaehlen[*], J. Vogel[L], M. Wittner[*], W. Yin[T]
And the Wavelike Dark Matter Community

[*] Heidelberg U., [y] LAPTH Annecy, [o] Stockholm U., [oo] U. Padua, [u] Wroclaw U., [k] U.Zaragoza, [b] Barry U., [p] DESY, [g] Bari U., [s] Salerno U., [L] LLNL Livermore, [†] IPPP Durham, [T] Tohoku U., [G] Goettingen U.

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Moral flexibility

Feebly Interacting (Non)Particle

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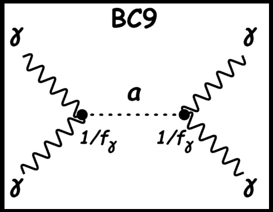
Astro-News

Reminder ALP couplings: f_a

- **Photon coupling**

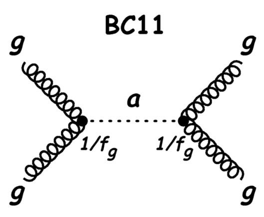
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} \phi F^{\mu} \tilde{F}_{\mu\nu}$$



$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

- **Gluon coupling**

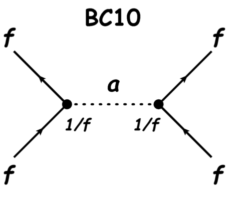
$$\mathcal{L} \supset \frac{1}{4} g_{agg} \phi G^{\mu} \tilde{G}_{\mu\nu}$$



$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- **Fermion couplings**

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^{\mu} \gamma^5 \psi$$



Reminder ALP couplings: f_a

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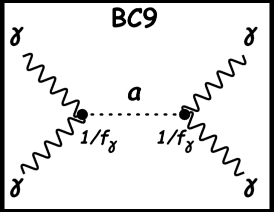
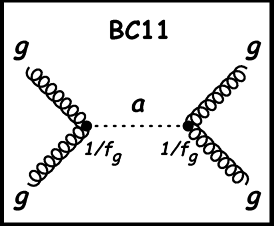


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} \phi F^{\mu} \tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

Large scale f_a
→
Weak/Feeble coupling

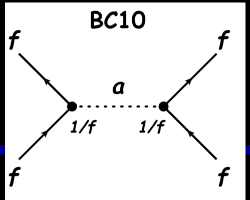
- **Gluon coupling**



$$\mathcal{L} \supset \frac{1}{4} g_{agg} \phi G^{\mu} \tilde{G}_{\mu\nu}$$

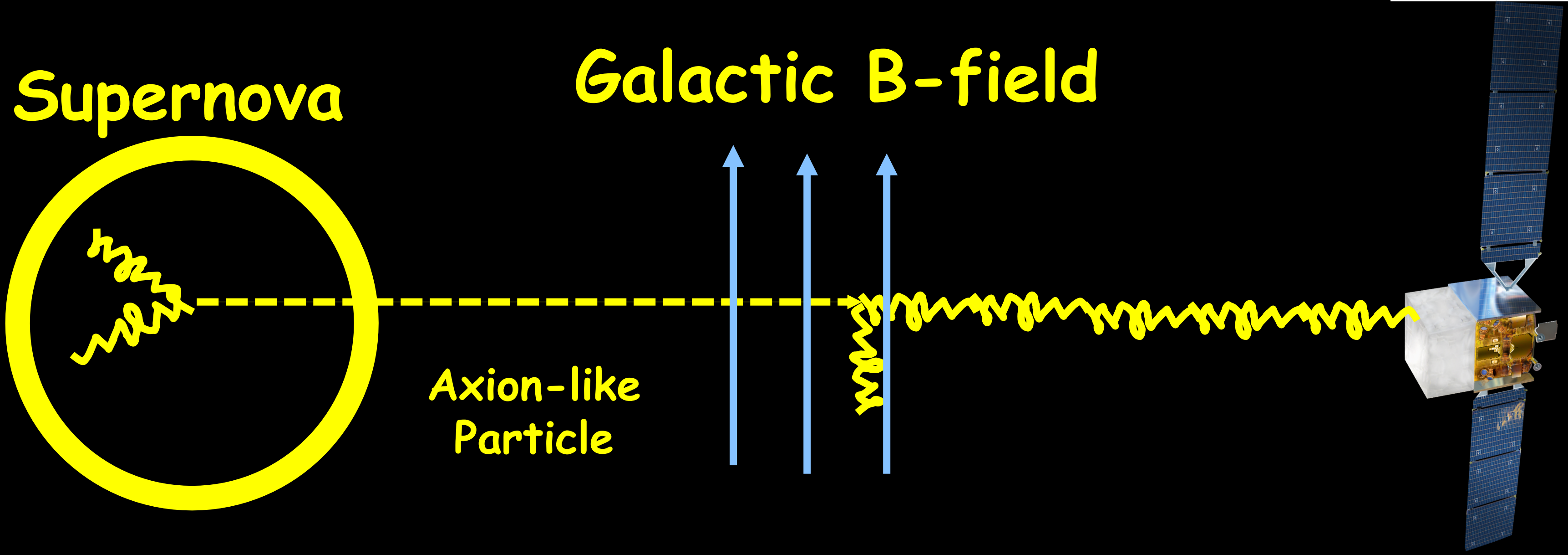
$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- **Fermion couplings**



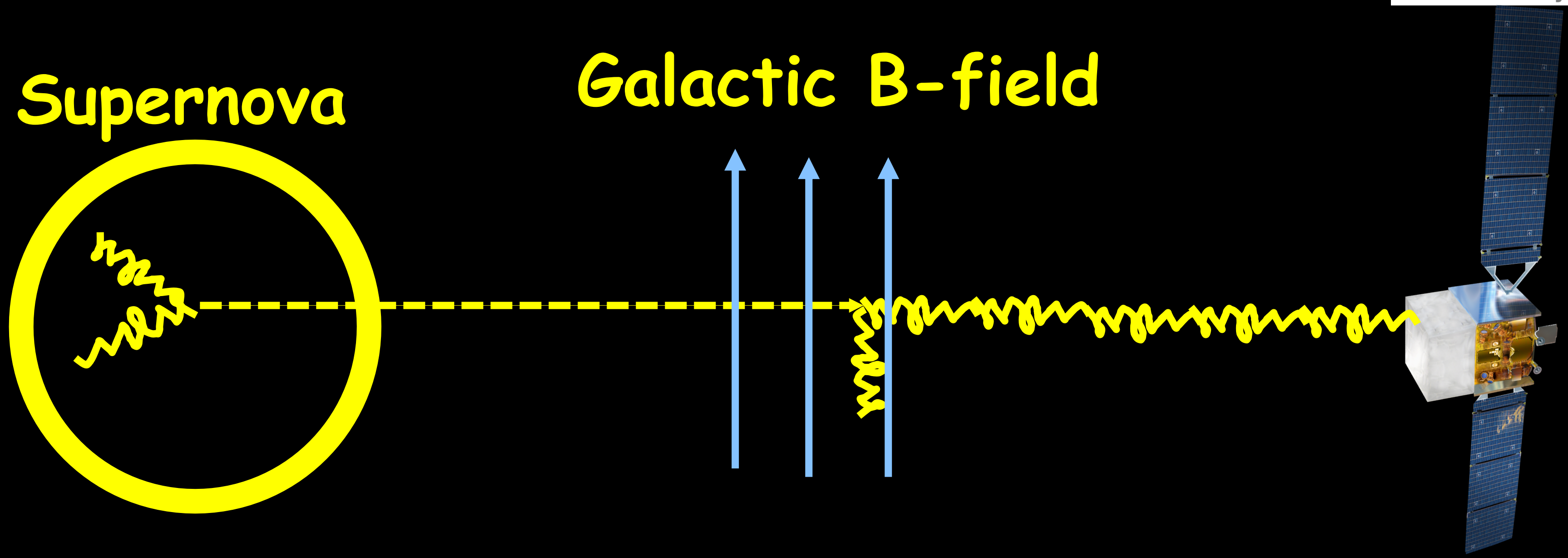
$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

Supernova are a “hot“ laboratory



https://science.nasa.gov/toolkits/spacecraft-icons

Supernova are a “hot“ laboratory

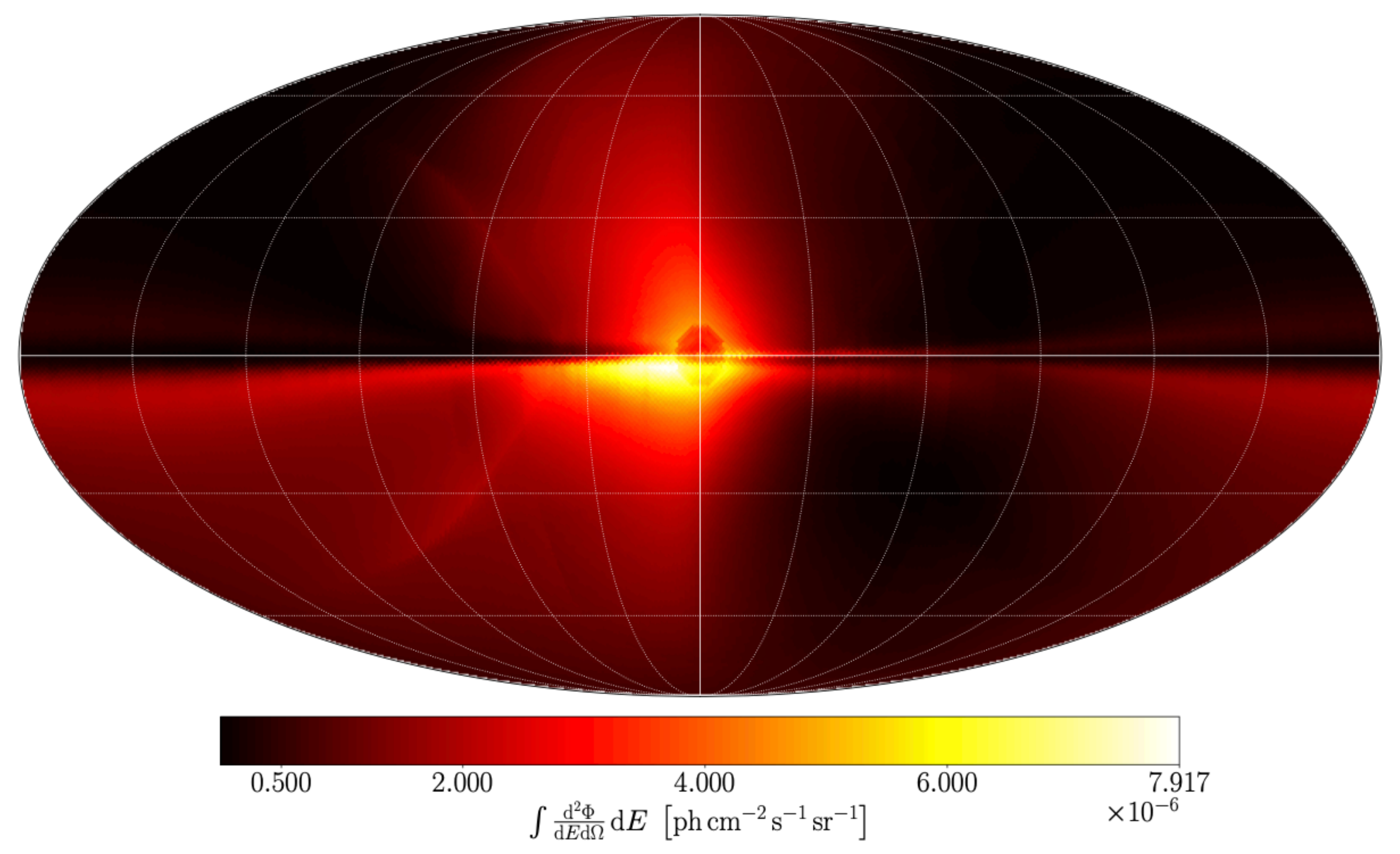


https://science.nasa.gov/toolkits/spacecraft-icons

What's new?

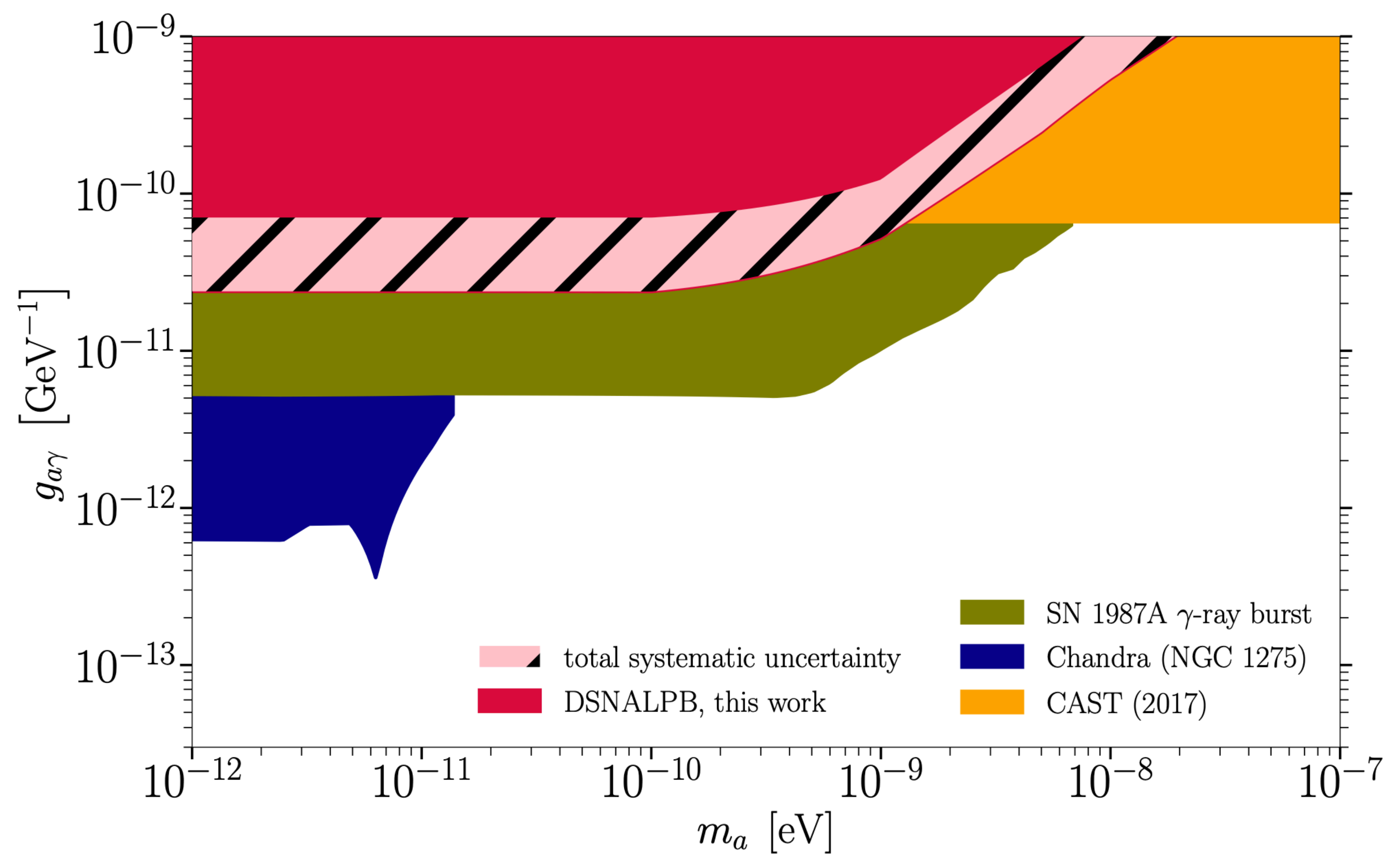
- Use SN background (i.e. all past SN)
- Better SN control (different masses)
- Fermi data (spatial distribution etc)
- Take into account O(20%) effects (gravitational red-shift, alpha particles...)

The „predicted“ picture



https://arxiv.org/pdf/2110.03679.pdf

The constraint



https://arxiv.org/pdf/2110.03679.pdf

Other couplings

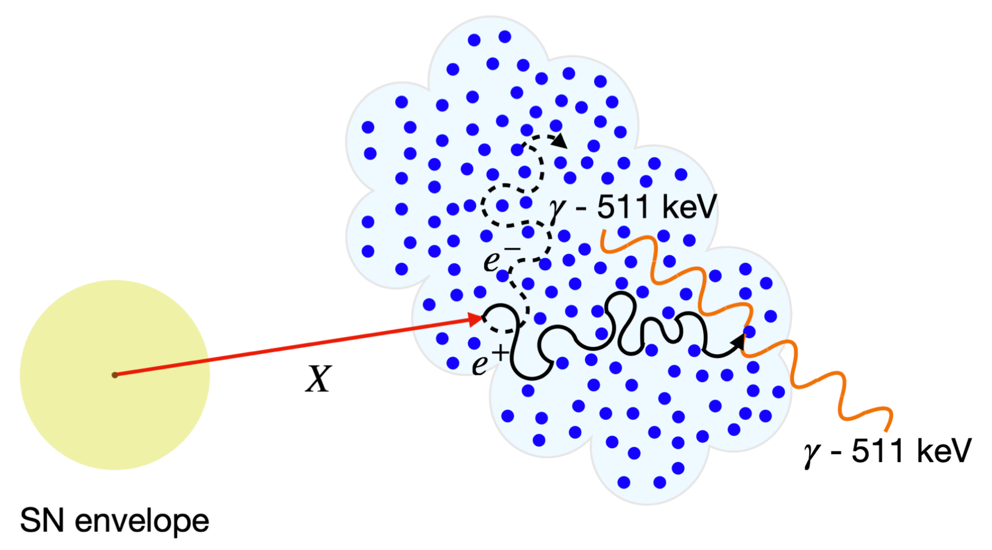
- Also allows to constrain other couplings
- For example:

Combination of

proton coupling (efficient production)

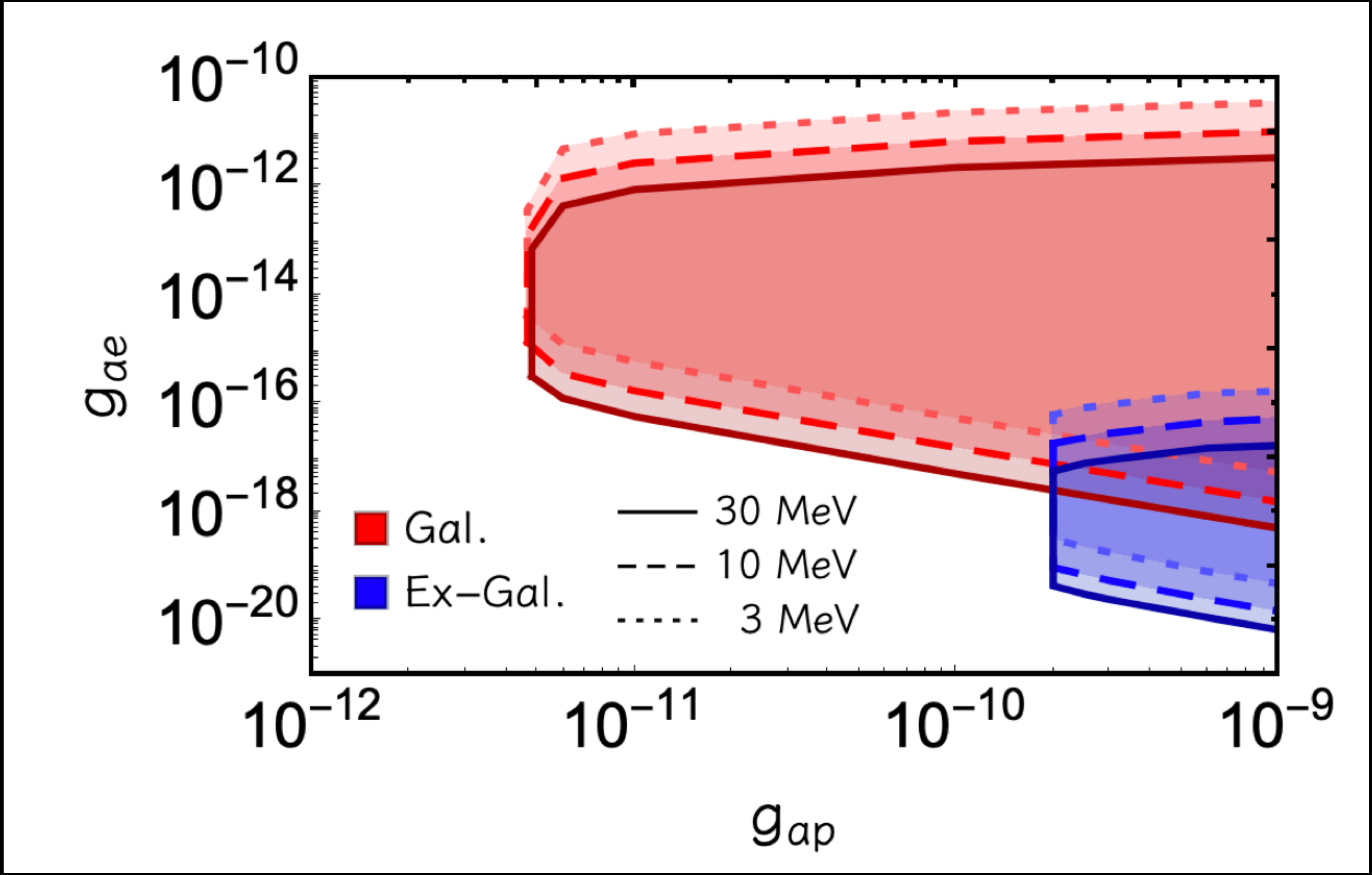
\+

electron coupling (decay to e+e-pairs, of which the e+ annihilates with background)



https://arxiv.org/pdf/2112.08382.pdf

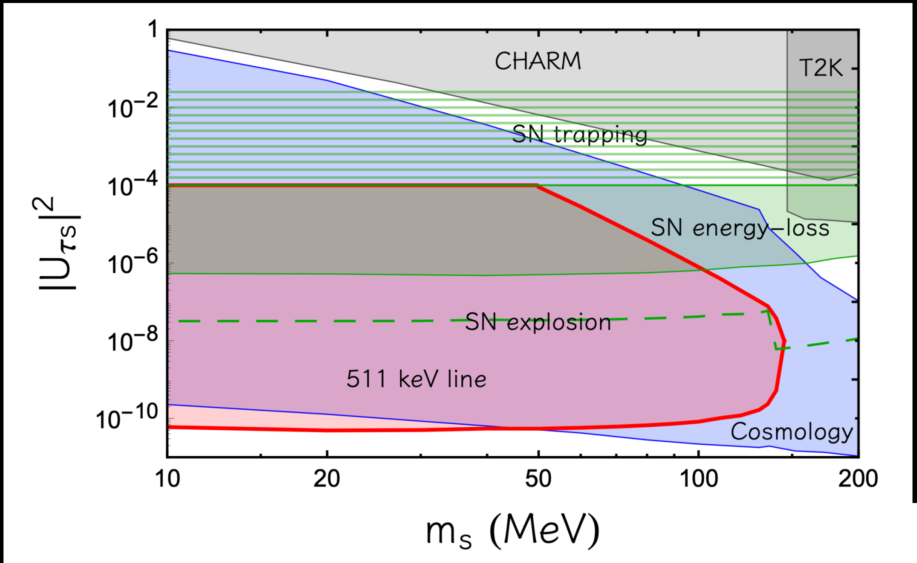
The constraint



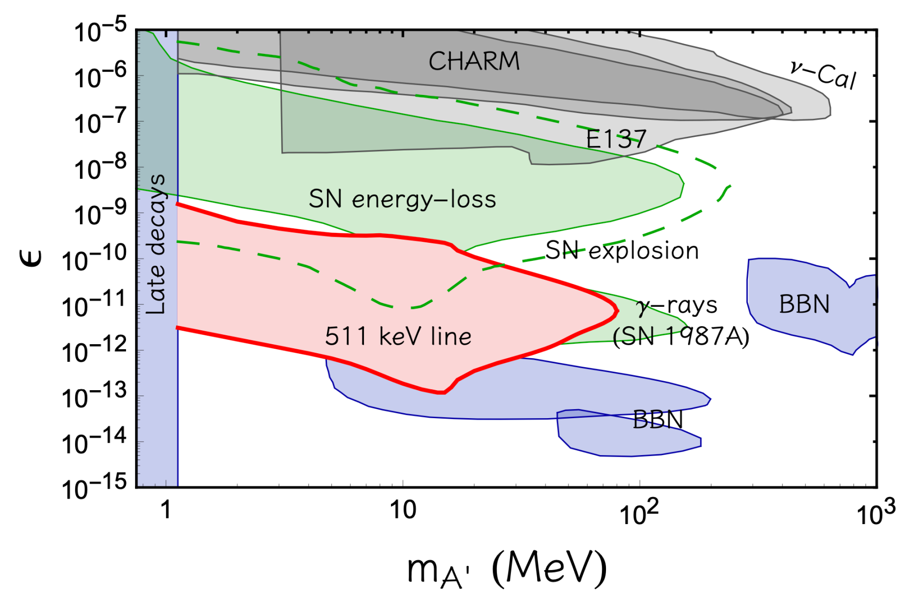
https://arxiv.org/pdf/2107.02186.pdf

Other FIPs

Sterile Neutrinos



Dark Photons

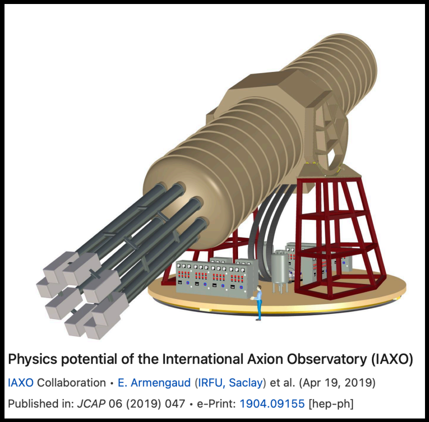


https://arxiv.org/pdf/2112.08382.pdf

Astro-News

@Home

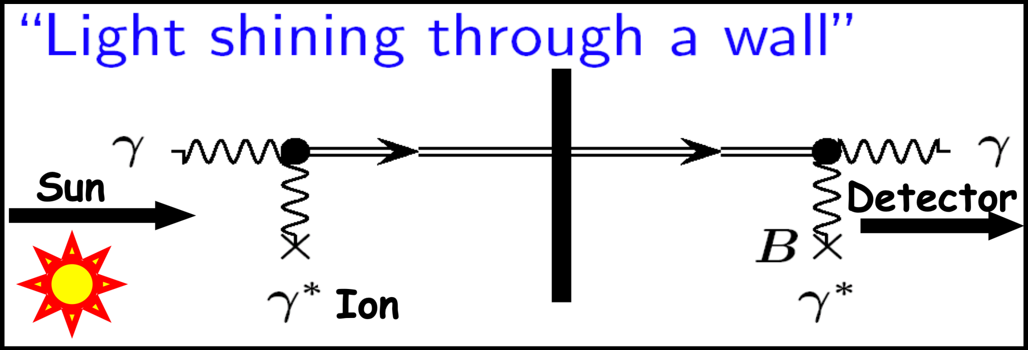
IAXO hopefully coming



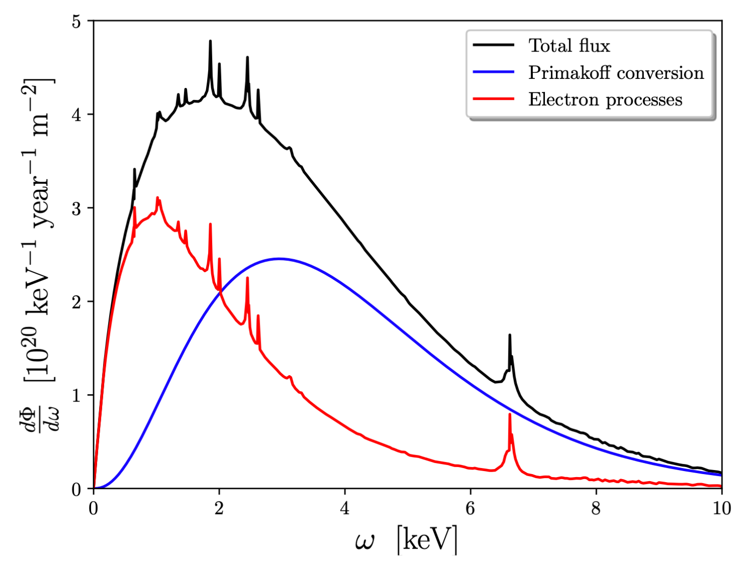
Physics potential of the International Axion Observatory (IAXO)

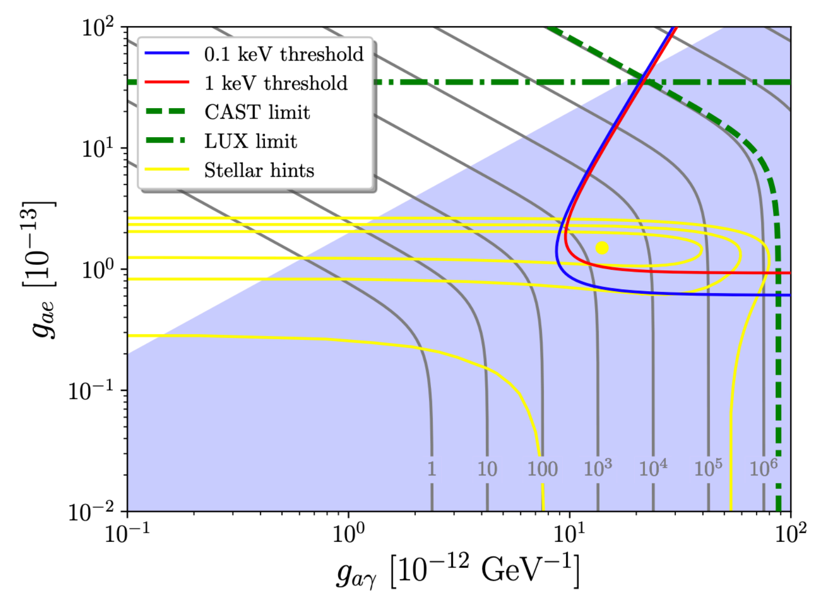
IAXO Collaboration • E. Armengaud (IRFU, Saclay) et al. (Apr 19, 2019)

Published in: *JCAP* 06 (2019) 047 • e-Print: 1904.09155 [hep-ph]



Look at spectrum

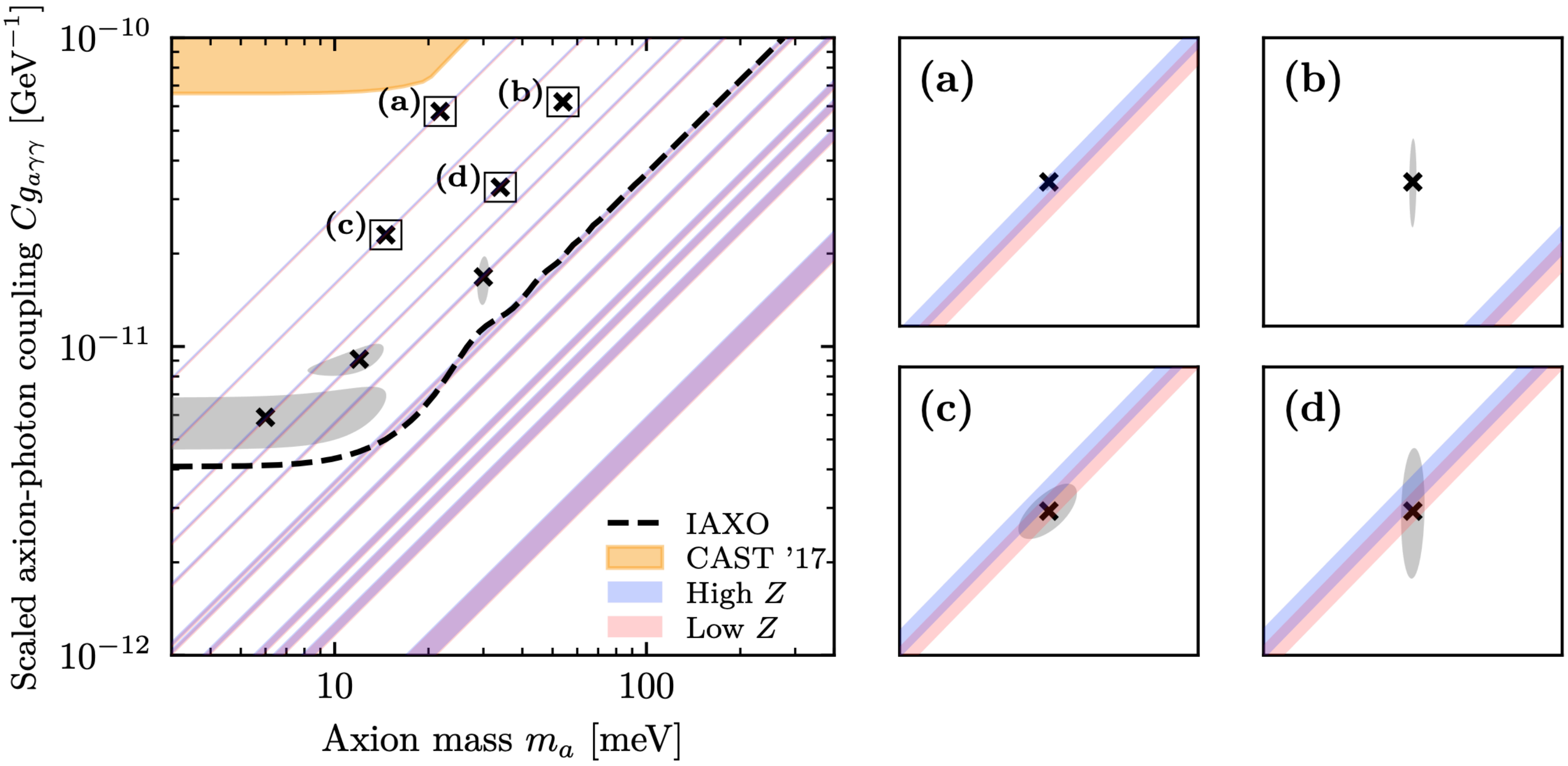




Measure electron and photon → coupling separately

https://arxiv.org/pdf/1811.09278.pdf

Determine Axion model



https://arxiv.org/pdf/2101.08789.pdf

Could also do nucleon coupling?

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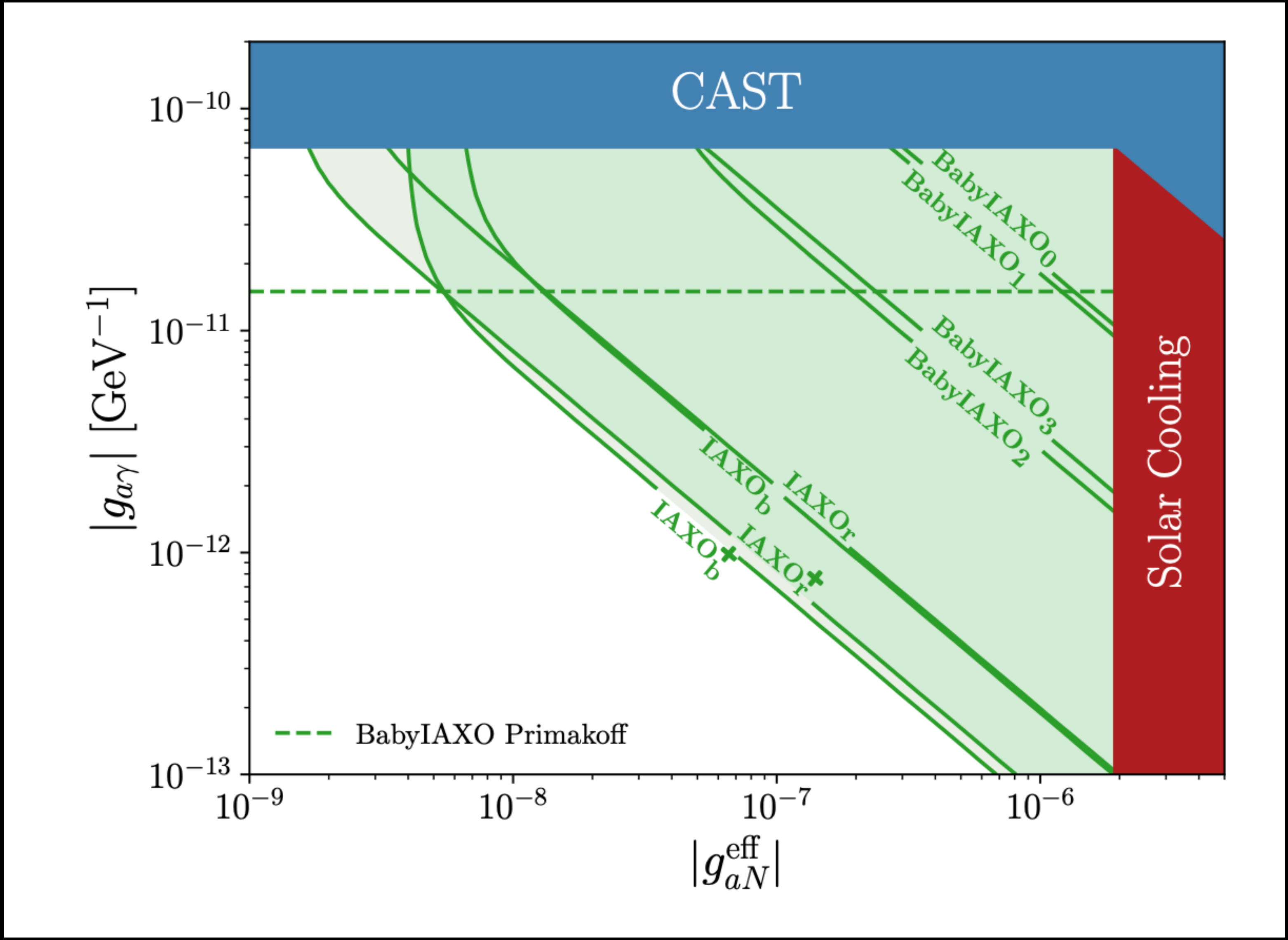
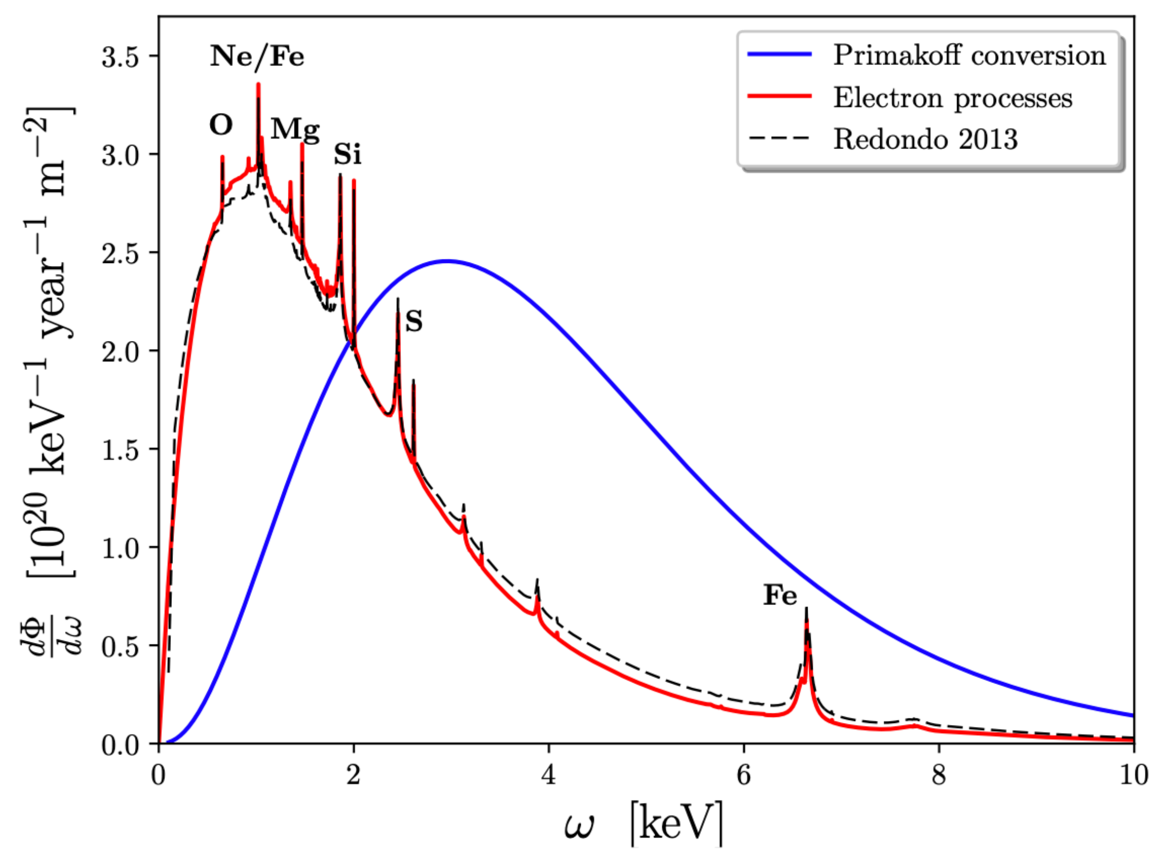
University



https://arxiv.org/pdf/2111.06407.pdf

Look inside sun and measure content



https://arxiv.org/pdf/1908.10878.pdf

Cosmo-News

Axionic/ALPy Dark Radiation

- Many (string) models feature a

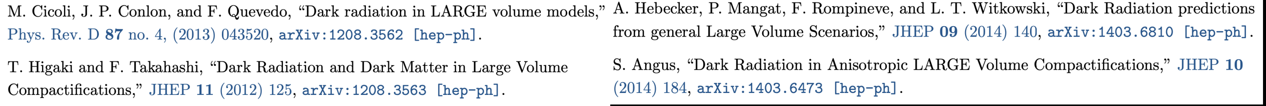
  long-lived modulus Φ

- 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

- String models usually have too much axionic dark radiation

- Reason: Long-lived volume modulus ϕ_b dominates the Universe before reheating it

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

➔

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

But:

$$\Delta N_{\text{eff}} \lesssim 0.2 - 0.4$$

Possible Solution: Decay to Higgses

- SUSY breaking generates coupling to Higgses

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

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

➔

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

➔ **Problem reduced**

(or at least pushed to inflationary sector)

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

Inflaton may be longes-lived modulus

- 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

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

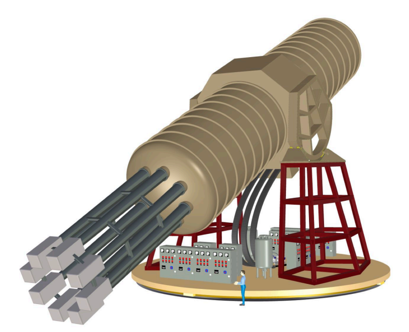
O(1)-O(100)
work in progress*

---

*Thanks to Michele Cicoli for crucial ideas

Dark Radiation may be detectable + Useful

- For example in IAXO



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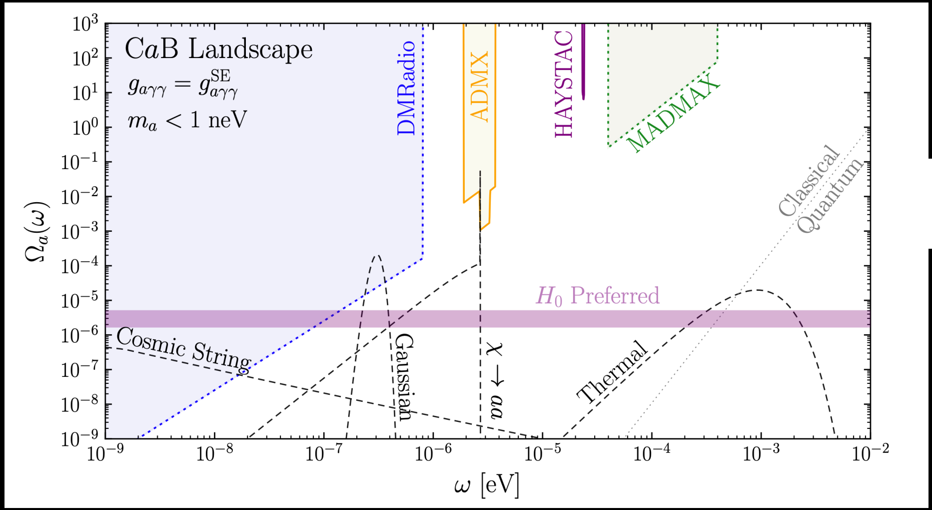
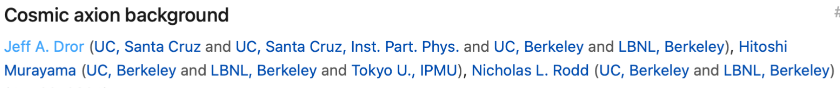
- But also other experiments





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

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

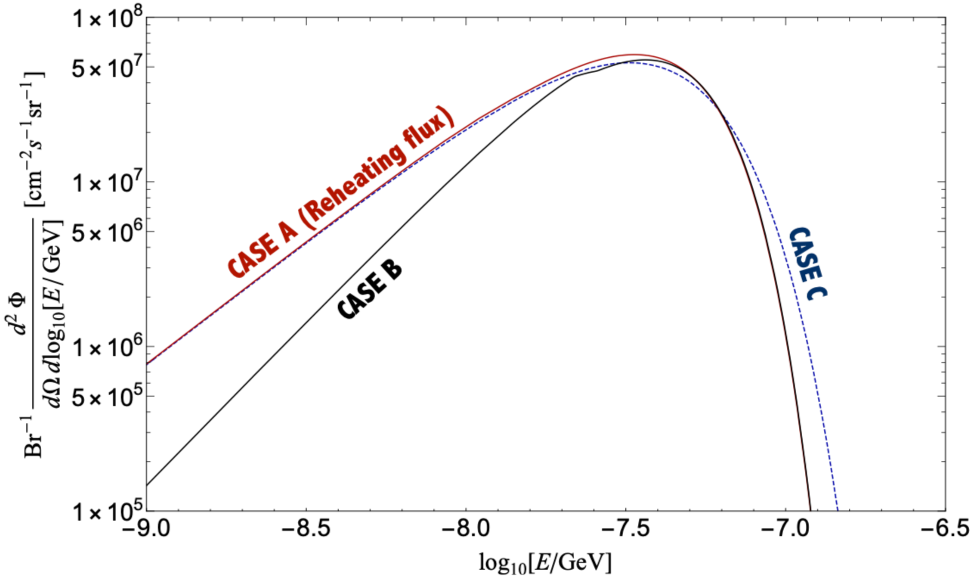


Figure. 1. The differential flux of the messenger particle, $d^2\Phi/d\log_{10}E d\Omega$. CASE A ($\phi$ once dominated the Universe) and CASE B (ϕ never dominates the Universe and decay in the radiation dominant epoch) are shown in red and black lines, respectively. We also show the flux for CASE C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

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

New tool to probe Reheating

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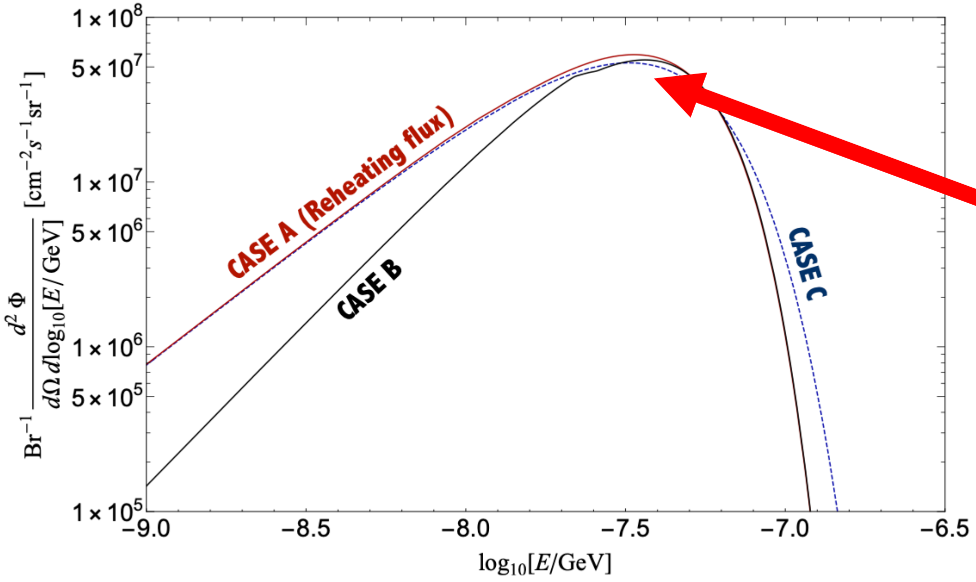

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Measures

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

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

Measure reheating temperature

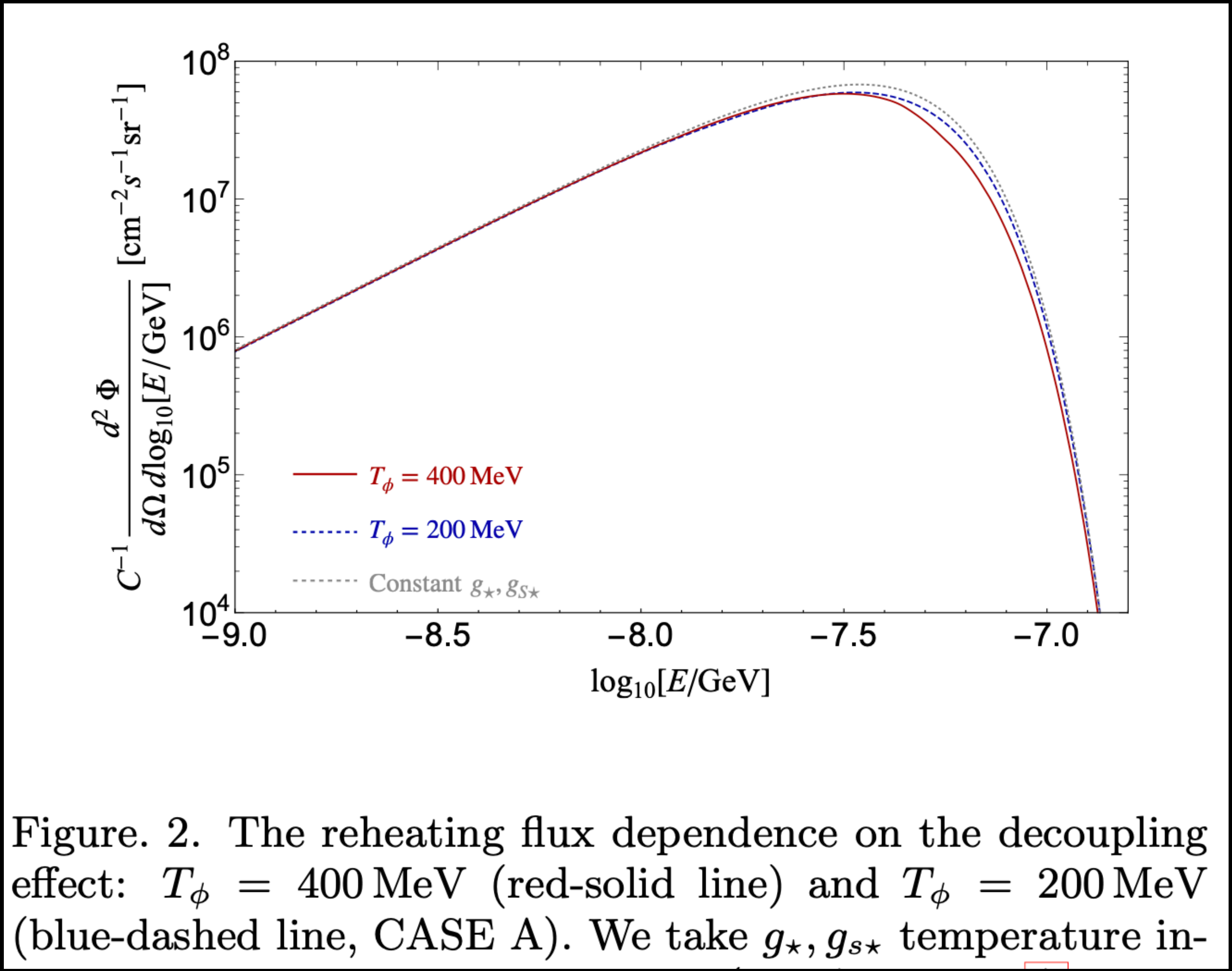


Figure. 2. The reheating flux dependence on the decoupling effect: $T_\phi = 400$ MeV (red-solid line) and $T_\phi = 200$ MeV (blue-dashed line, CASE A). We take $g_\star, g_{s\star}$ temperature in-

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

Crazy-News

Crazy-News

Poincare Symmetry Violation

Poincare Symmetry

- Lorentz Invariance (➔Kostelecky et al)
- Time Translation Invariance
  ➔ Energy Conservation
- Space Translation Invariance
  ➔ Momentum Conbservation

We start here

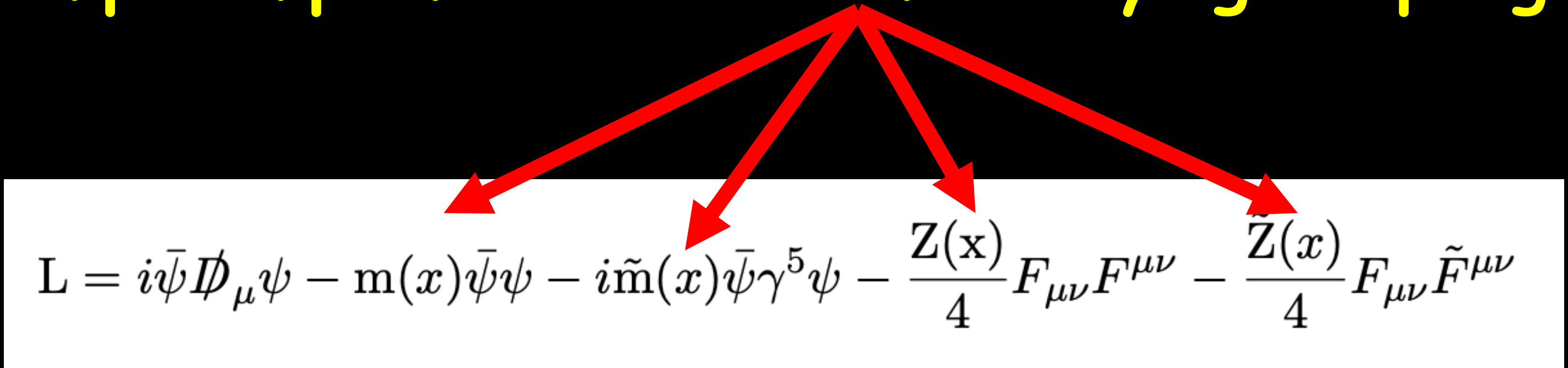
Looking at PV QED

- Simple implementation: Time varying couplings

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

Looking at PV QED

- Simple implementation: Time varying couplings



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

Looking at PV QED

- 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

- Simple implementation: Time varying couplings

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

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\frac{\delta\mathrm{m}(x)}{m_e} &= \frac{\mathrm{m}(x) - m_e}{m_e} = \sum_\omega \frac{\delta\mathrm{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}$$

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

Breaks Lorentz invariance, too

- 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?

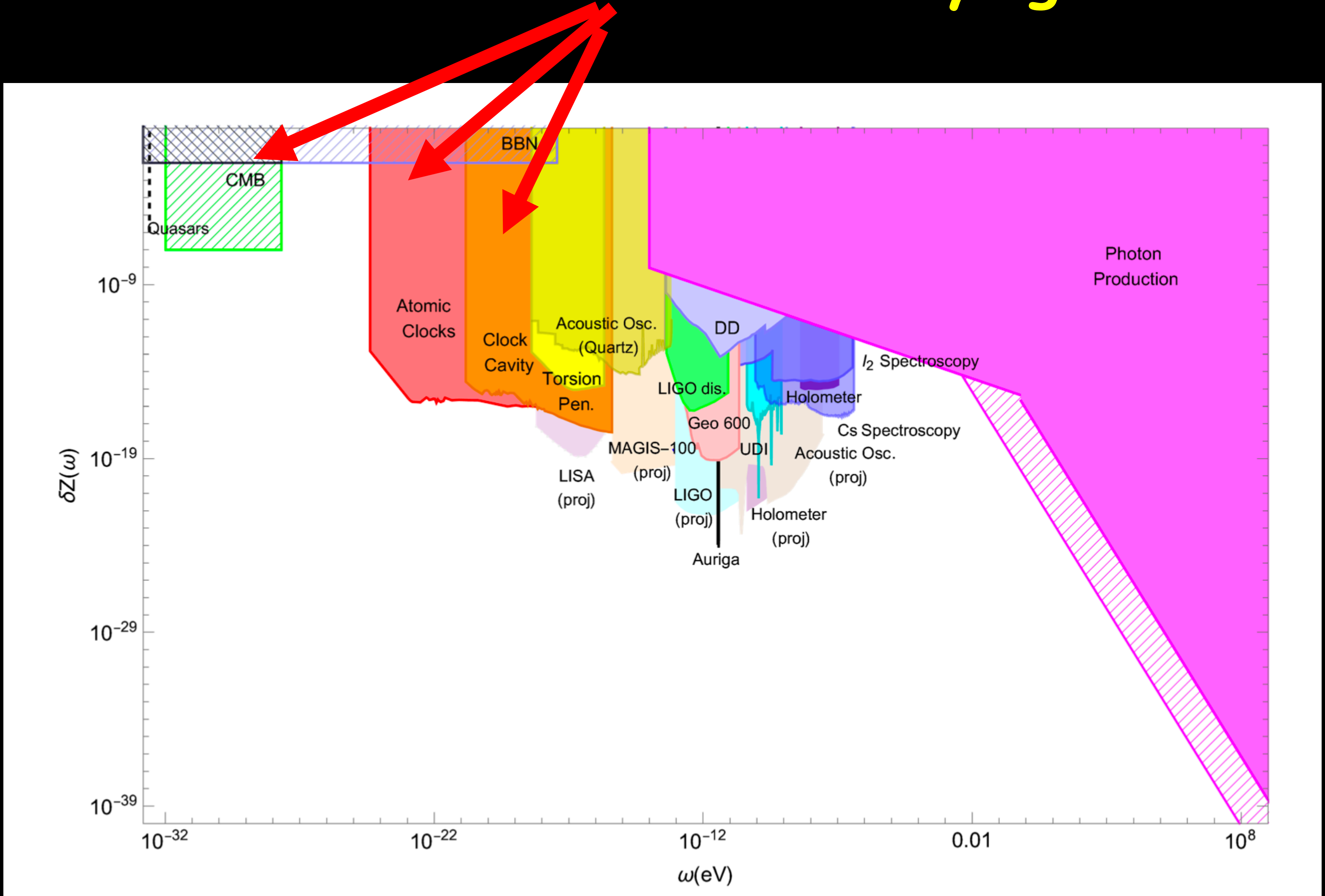
- One origin of oscillation could be scalar DM

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

- 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

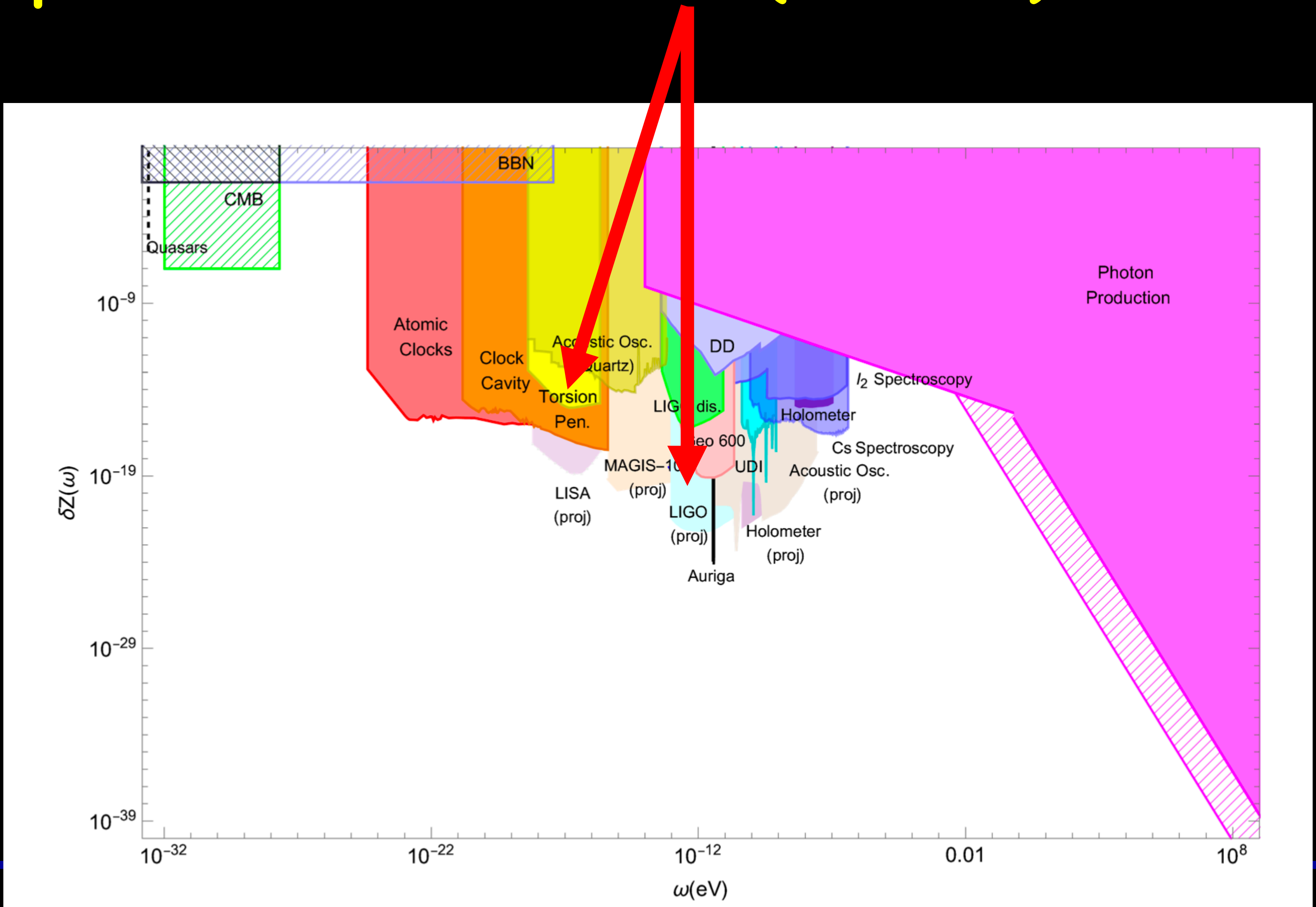
Results

- “Standard“ limits from time varying constants



Results

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



Particles from nothing

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

➔ Photon creation

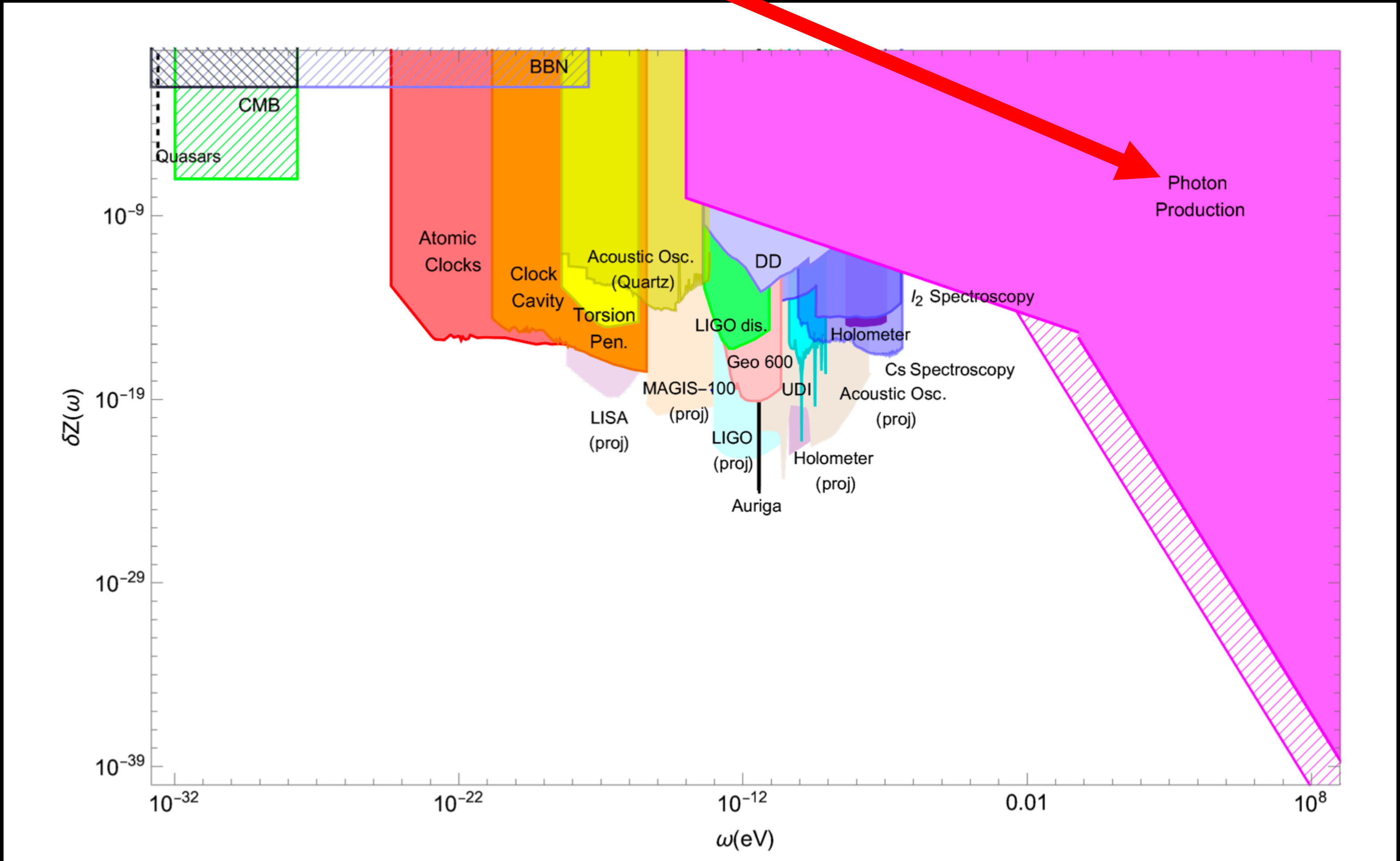
$$\dot{n}_\gamma(\omega) \quad = \quad (2N_k + 1)\frac{(\delta Z(\omega))^2 \omega^4 \beta_\gamma}{64\pi},$$

(analog to resonant DM decay)

- Visible Photons, too much energy created etc.

Results

- Particle creation from vacuum (too much)



Energy violation in scattering events

- Energy violation in scattering possible

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

- Expect (because of phase space)

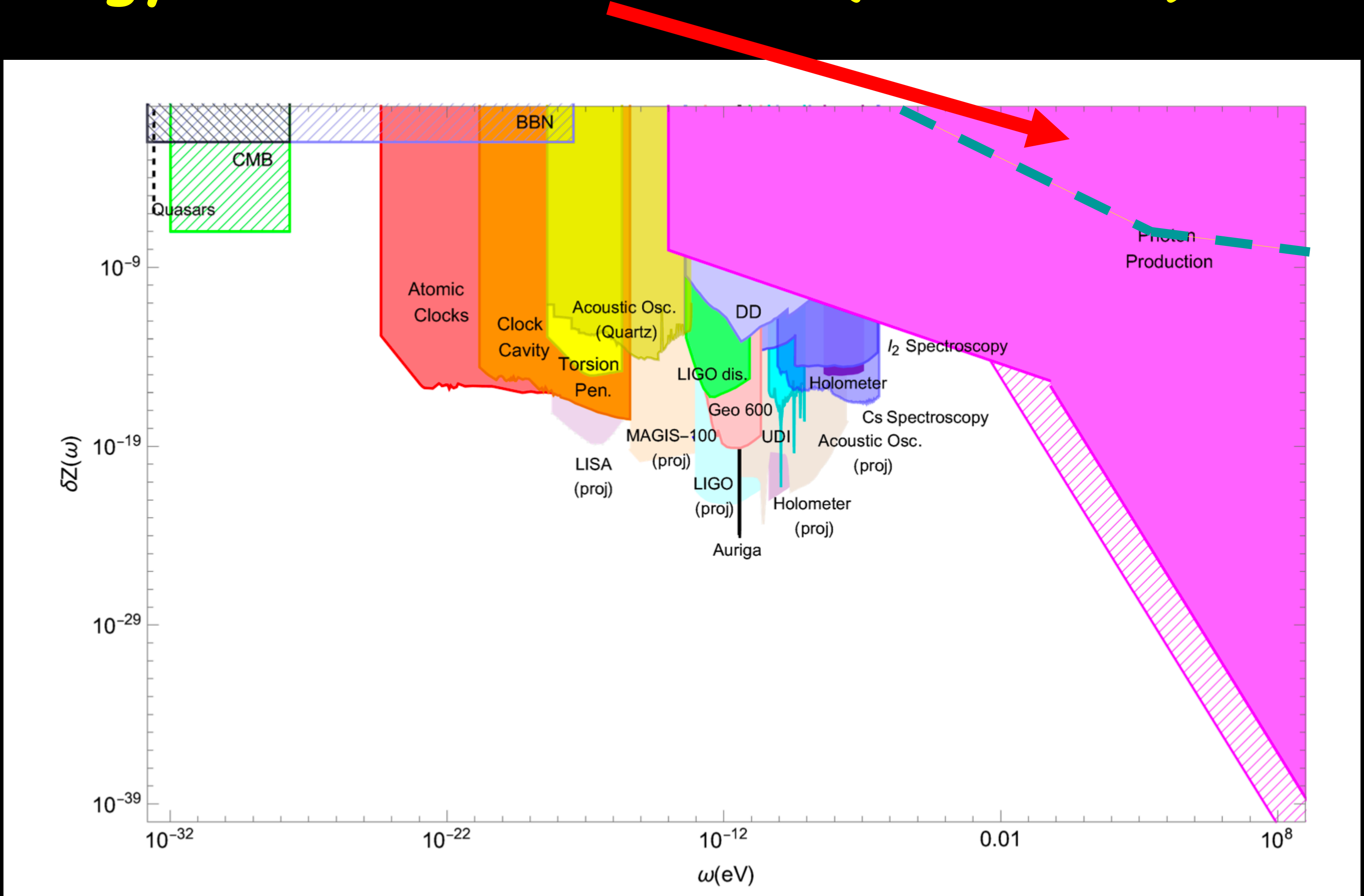
$$\sigma(E \to E - \omega) < \sigma(E + \omega)$$

➔ Net energy gain on average

➔ For example Sun would „gain" energy

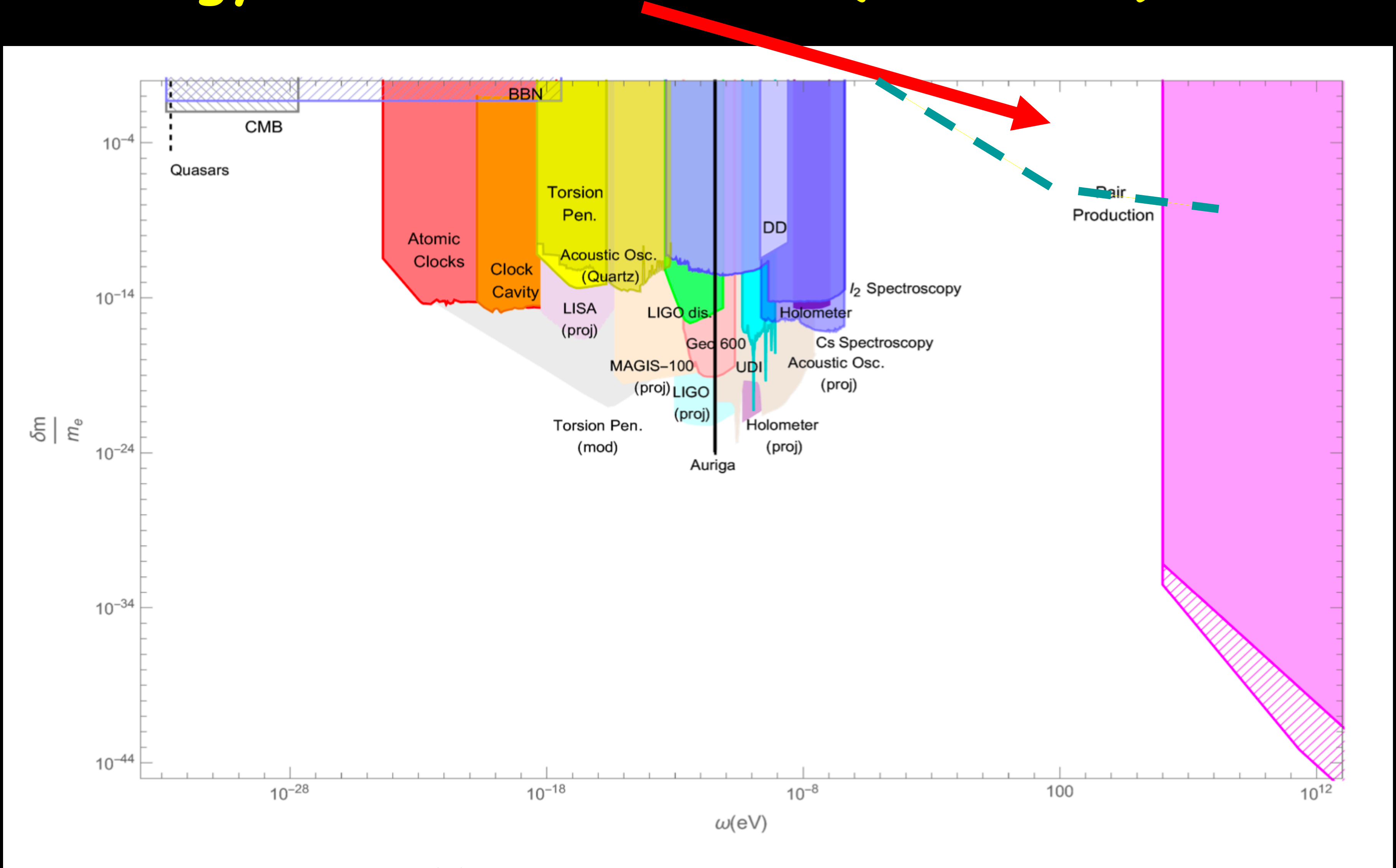
Results

- Energy conservation in Sun (TBC(larified))



Results: Better for pseudoscalars

- Energy conservation in Sun (TBC(larified))



Conclusions

Conclusions

- Astrophysical limits continue to improve
- Supernova rich source or FIPs
- Consider variety and combination of couplings

- Cosmic, „Dark Radiation“ of FIPs 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