Constraining Axion from the *Light*

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Work to appear with
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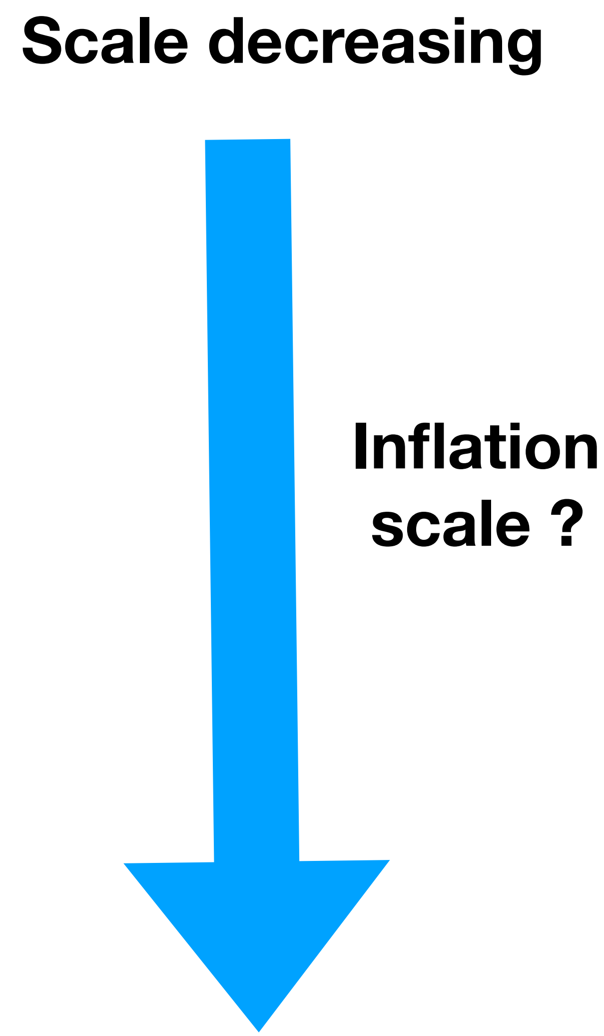
Outline

- Axion models
    - QCD axion
    - Axion as dark matter candidate (Non-Thermal, Thermal)
    - Axion inflation
- Axion detection: through coupling to photon:
    - Various lab proposals
    - Astrophysical probes (spectral distortion, GRB, etc)
- Photon propagation modification from axion

Early Universe Picture:



- Spontaneously breaking of the Peccei-Quinn symmetry, or some U(1).
    - Nambu-Goldstone bosons became axions
    - Massless, flat potential.
- Further explicit breaking of the shift symmetry by gauge instanton, etc
    - Axion becames massive, acquires a potential
- Axion rolling: inflation/axion relaxing: dark matter

Axion and axion-like particle

- Integrating out charged heavy extra fermions;

KSVZ (Kim-Shifman-Vainshtein-Zakharov) model and DFSZ (Dine-Fischler-Srednicki-Zhitnitsky) model

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}\partial_\mu a_i' \,\partial^\mu a_i' - \frac{\alpha_s}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{ig}'\frac{a_i'}{f_{a_i'}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} \\
&\quad -\frac{\alpha}{8\pi}\left(\sum_{i=1}^{n_{\rm ax}} C_{i\gamma}'\frac{a_i'}{f_{a_i'}}\right) F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\sum_{i=1}^{n_{\rm ax}} C_{ie}'\frac{\partial_\mu a_i'}{f_{a_i'}}\right)\bar{e}\gamma^\mu\gamma_5 e + \ldots .
\end{aligned}
$$

  - The couplings to the SM fermions may or may not vanish.
  - Above independent couplings are independent of each others, with the same decay constant f.

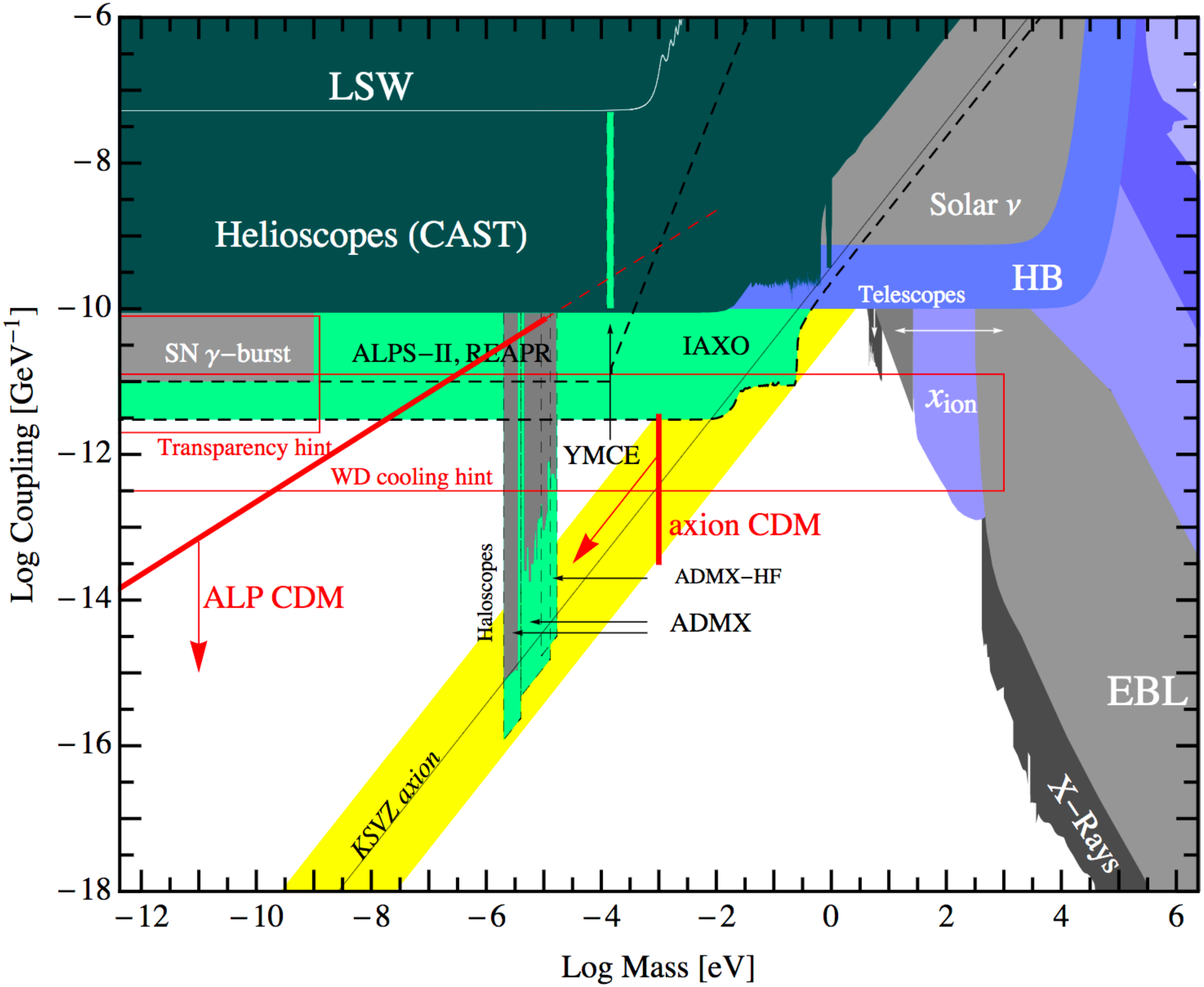
- Chern-Simon types of coupling to the gauge field: $\dfrac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}, \ \dfrac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$

Axion as dark matter:

- Producing mechanism:

  - Misalignment of vacuum energy $\langle a \rangle = \bar{a}(t) = a_0 \sin m_a t \,,$
  - Thermalize with the SM particles
  - Decaying products of cosmic defects

- All give rise to very different constraints on axion mass and decay constant.

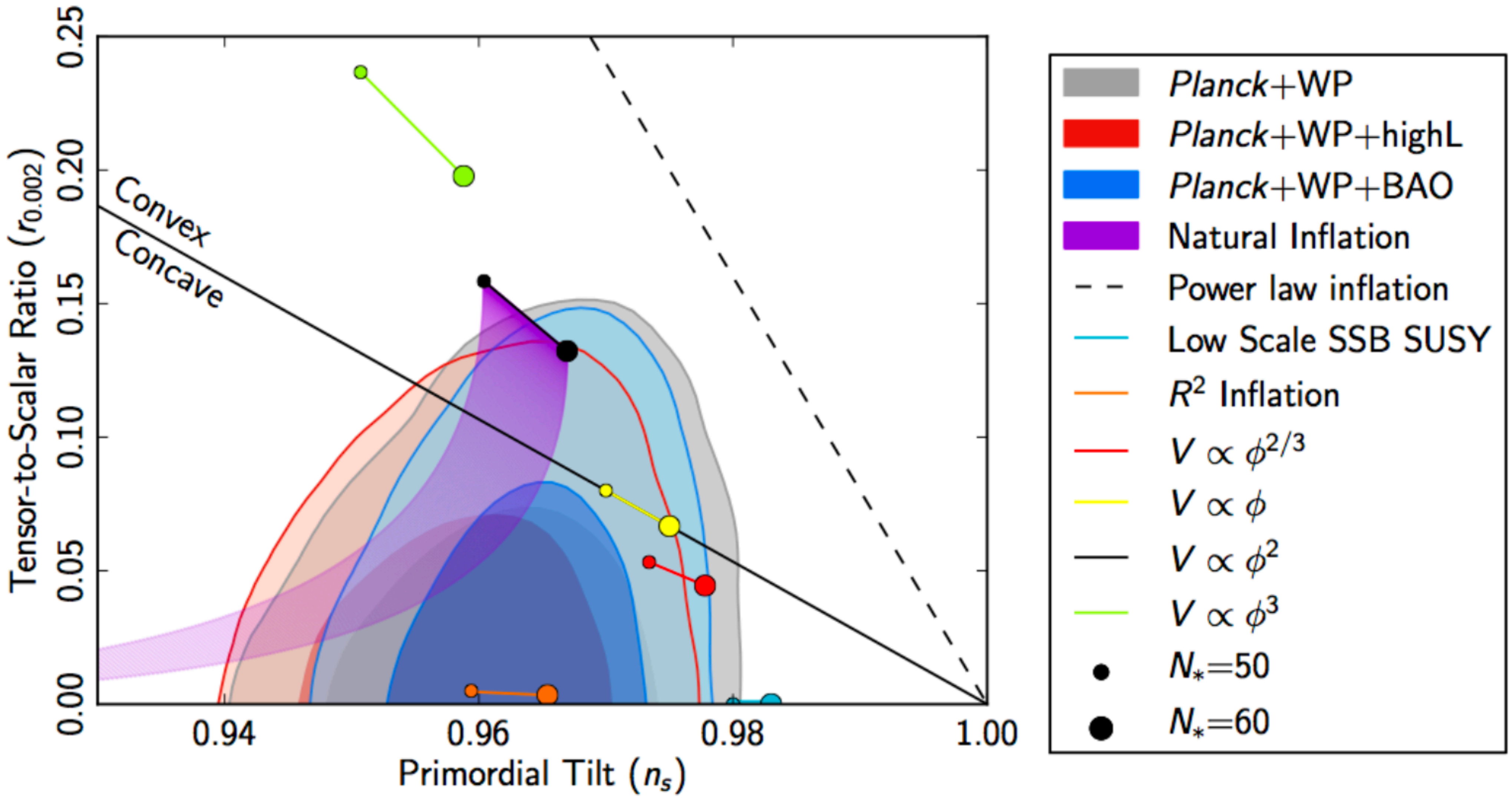


A. Ringwald, 2012

Axion inflation

- Axion as an inflaton : acquires potential in many different ways, e.g:
    - Natural inflation: $V = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right) \right]$
    - Axion monodromy: $V_{\rm sr}(\varphi) = \mu^3 \left[\sqrt{\varphi^2 + \varphi_c^2} - \varphi_c \right]$ for $\varphi \gg \varphi_c$
- Face constraints from cosmic data.

Can Axion be both inflaton and dark matter?



Planck collaboration, 2013

Axion searches

- Make use of axion-photon couplings:
    - In the presence of magnetic field: axion converting to photon/EM fields
    - Different cosmic photon sources modification: spectral distortion, gamma ray burst, supernova..etc
    - Laboratory experiments.
- Dark matter oscillating axion: inducing neutron EDM. *P. W. Graham, S. Rajendran, 2013*

$$\mathcal{L} \ni -\frac{i}{2} g_d \, a \, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}.$$

$$d_n^{\mathrm{QCD}} \approx \left(9 \times 10^{-35} \, e \cdot \mathrm{cm}\right) \cos\left(m_a t\right).$$

- Axion derivative couplings to fermions: time-dependent mixing of opposite-parity states in fermion systems.

Y. V. Stadnik, V. V. Flambaum, 2013

Modifying photon propagation:

- Axion background solution, e.g: rolling as inflaton or oscillating as non-thermal DM $\langle a \rangle = \bar{a}(t) = a_0 \sin m_a t\,,$
- Look at the photon action: $S_{\rm photon} = \int d^4x \left[-\frac{1}{4} F_{\mu\nu}^2 - \frac{g_{a\gamma\gamma}}{4} \bar{a}(t) \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} \right]$
- EOM $\partial_\mu F^{\mu\nu} + g_{\phi\gamma\gamma} \dot{\bar{a}}(t) \epsilon^{0\nu\rho\sigma} F_{\rho\sigma} = 0\,.$ $\longrightarrow$ $\frac{d\omega_\pm}{dk} = \frac{k \pm \frac{\dot{\phi}}{2M}}{\sqrt{k^2 \pm k \frac{\dot{\phi}}{M}}}$
- To compare, for the saxion: $\frac{d\omega_\pm}{dk} = \frac{2\left[1 + \frac{g_{\phi\gamma\gamma}\phi(t)k}{2}\right]}{\sqrt{g_{\phi\gamma\gamma}^2 \dot{\phi}^2(t) + 4\left[1 + \frac{g_{\phi\gamma\gamma}\phi(t)k}{2}\right]^2}}$
- One can also look at this effect in scattering amplitude of photons:

$$\delta(\vec{b}, s) = \frac{1}{2s} \int \frac{d^{D-2}\vec{q}}{(2\pi)^{D-2}} e^{i\vec{q}.\vec{b}} \mathcal{M}_t(\vec{q})$$

Conclusion:

- Multiple interesting searches going on, probing mass and decay constant.
- Some of them put constraints on different DM and inflationary scenarios.
- We study an potential detectable new effect on the axion-photon couplings.

Thank you