Physics case for axions and other WISPs.

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Mini-workshop on searches for new particles with high power lasers,
Forschungszentrum Jülich/Institut für Kernphysik,
24./25. Oktober 2012

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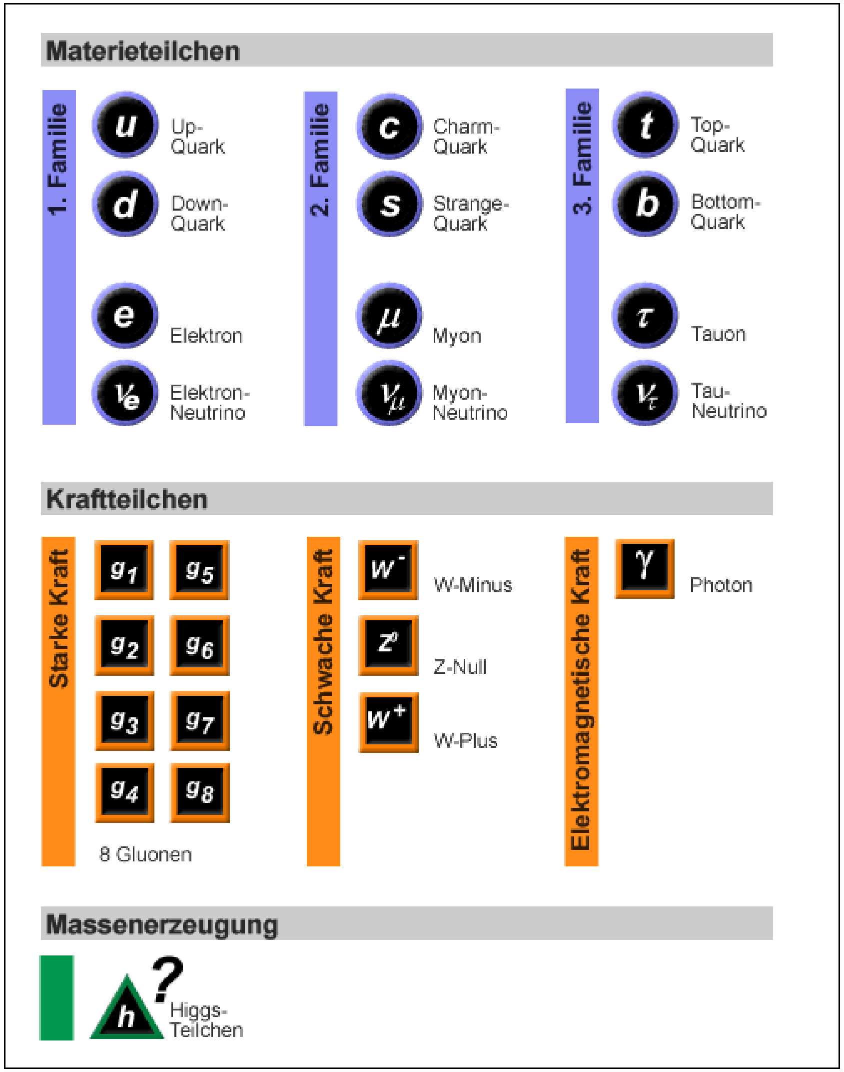
Particles beyond the Standard Model?!

- Standard Model (SM) of particle physics describes basic properties of known matter and forces



Particles beyond the Standard Model?!

- Standard Model (SM) of particle physics describes basic properties of known matter and forces
- SM not a complete and fundamental theory:
  - No satisfactory explanation for values of its many parameters
  - No reconciliation of gravity with quantum mechanics

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{{\rm gauge}/\psi} \; . \tag{1}$$

Here,

$$\mathcal{L}_{\rm Dirac} = i\bar{e}^i_{\rm L}\not{\partial} e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\not{\partial}\nu^i_{\rm L} + i\bar{e}^i_{\rm R}\not{\partial} e^i_{\rm R} + i\bar{u}^i_{\rm L}\not{\partial} u^i_{\rm L} + i\bar{d}^i_{\rm L}\not{\partial} d^i_{\rm L} + i\bar{u}^i_{\rm R}\not{\partial} u^i_{\rm R} + i\bar{d}^i_{\rm R}\not{\partial} d^i_{\rm R} \; ; \tag{2}$$

$$\mathcal{L}_{\rm mass} = -v\left(\lambda^i_e \bar{e}^i_{\rm L} e^i_{\rm R} + \lambda^i_u \bar{u}^i_{\rm L} u^i_{\rm R} + \lambda^i_d \bar{d}^i_{\rm L} d^i_{\rm R} + {\rm h.c.}\right) - M^2_{\rm W} W^+_\mu W^{-\mu} - \frac{M^2_{\rm W}}{2\cos^2\theta_W} Z_\mu Z^\mu \; ; \tag{3}$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA} \; , \tag{4}$$

where

$$\begin{aligned} G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc} A^b_\mu A^c_\nu \\ W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \; , \end{aligned} \tag{5}$$

and

$$\begin{aligned} \mathcal{L}_{WZA} = \; & ig_2\cos\theta_{\rm W}\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right] \\ & +ie\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right] \\ & +g_2^2\cos^2\theta_{\rm W}\left(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu} Z_\nu Z^\nu\right) \\ & +g_2^2\left(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu} A_\nu A^\nu\right) \\ & +g_2 e\cos\theta_{\rm W}\left[W^+_\mu W^-_\nu\left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2W^+_\mu W^{-\mu} Z_\nu A^\nu\right] \\ & +\frac{1}{2}g_2^2\left(W^+_\mu W^-_\nu\right)\left(W^{+\mu}W^{-\nu} - W^{+\nu}W^{-\mu}\right) \; ; \end{aligned} \tag{6}$$

and

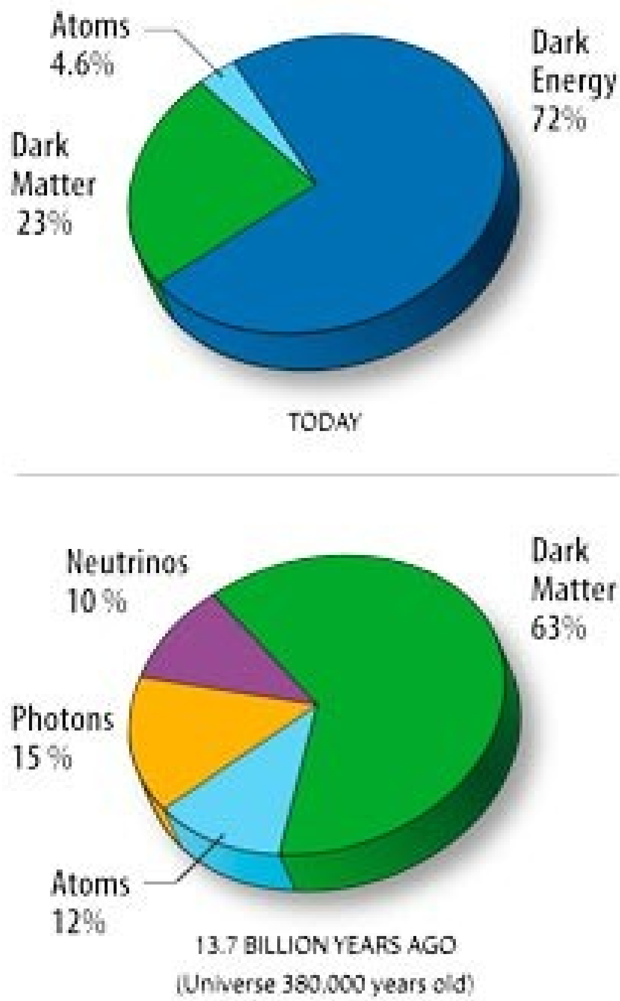
$$\mathcal{L}_{{\rm gauge}/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A \; , \tag{7}$$

where

$$\begin{aligned} J^{\mu a}_{(3)} &= \bar{u}^i\gamma^\mu T^a_{(3)} u^i + \bar{d}^i\gamma^\mu T^a_{(3)} d^i \\ J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\ J^\mu_{W^-} &= (J^\mu_{W^+})^* \\ J^\mu_Z &= \frac{1}{\cos\theta_{\rm W}}\Big[\frac{1}{2}\bar{\nu}^i_{\rm L}\gamma^\mu\nu^i_{\rm L} + \left(-\frac{1}{2} + \sin^2\theta_{\rm W}\right)\bar{e}^i_{\rm L}\gamma^\mu e^i_{\rm L} + (\sin^2\theta_{\rm W})\bar{e}^i_{\rm R}\gamma^\mu e^i_{\rm R} \\ & \quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm L}\gamma^\mu u^i_{\rm L} + \left(-\frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm R}\gamma^\mu u^i_{\rm R} \\ & \quad + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm L}\gamma^\mu d^i_{\rm L} + \left(\frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm R}\gamma^\mu d^i_{\rm R}\Big] \\ J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i \; . \end{aligned} \tag{8}$$

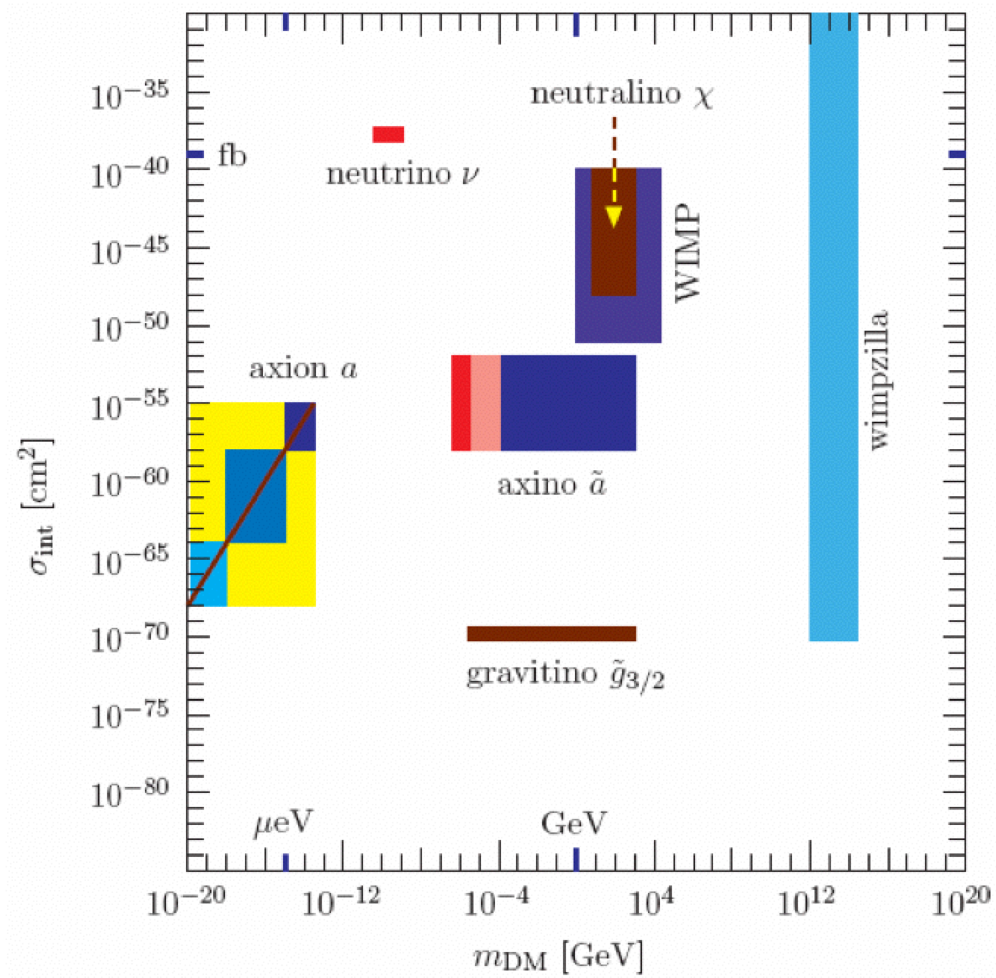
Particles beyond the Standard Model?!

- Standard Model (SM) of particle physics describes basic properties of known matter and forces
- SM not a complete and fundamental theory:
  - No satisfactory explanation for values of its many parameters
  - No reconciliation of gravity with quantum mechanics
  - No explanation of the origin of dark energy and dark matter



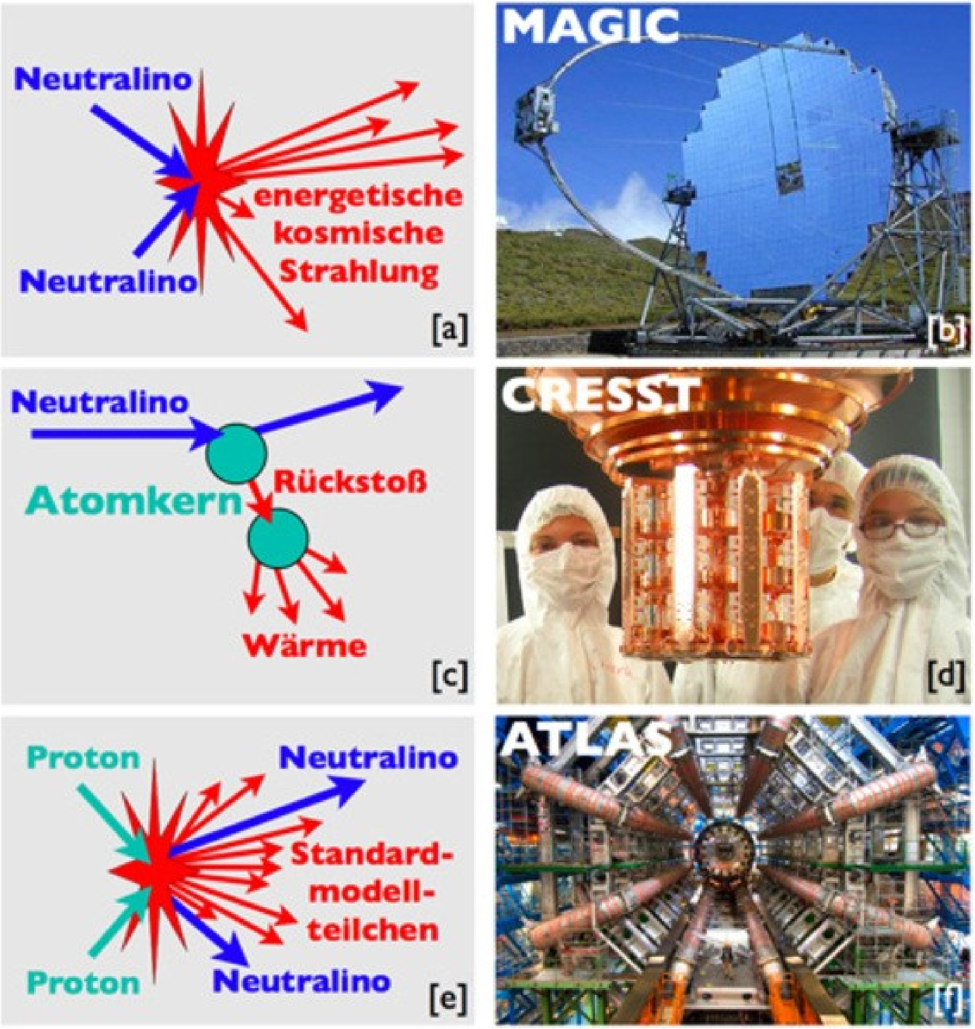
Particles beyond the Standard Model?!

- Particle candidates of dark matter should feature
  - Feeble interactions with SM and with themselves
  - Non-relativistic momentum distribution at beginning of structure formation
  - Stability on cosmological time scales
- These features can be realised by
  - Weakly interacting massive particles (WIMPs), e.g. neutralino LSP in case of SUSY extension
  - Very weakly interacting slim (in the sense of very light) particles (WISPs), e.g. axion in case of PQ extension



Worldwide hunt for dark matter candidates

- WIMPy dark matter:
  - Direct detection (WIMP scattering on nucleons)
  - Indirect detection in cosmic rays
  - Production of WIMPs at accelerators



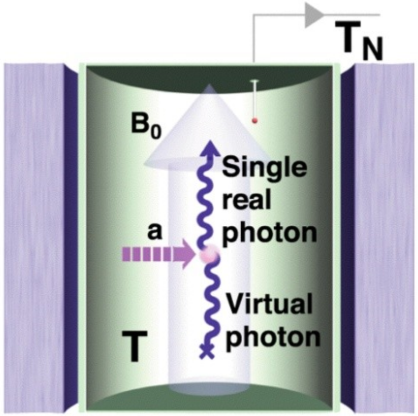
Worldwide hunt for dark matter candidates

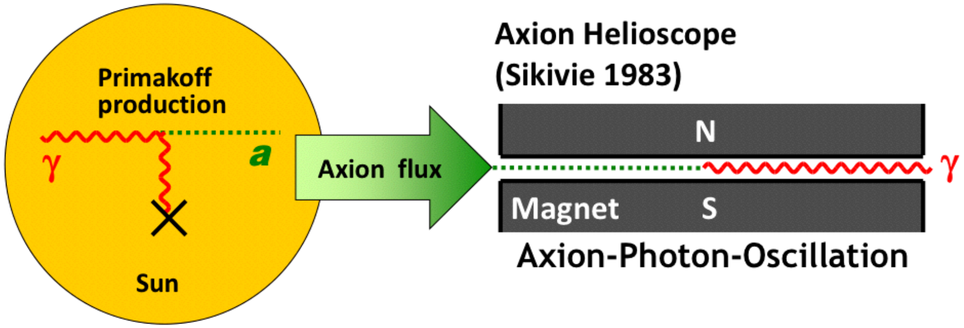
> WIMPy dark matter:

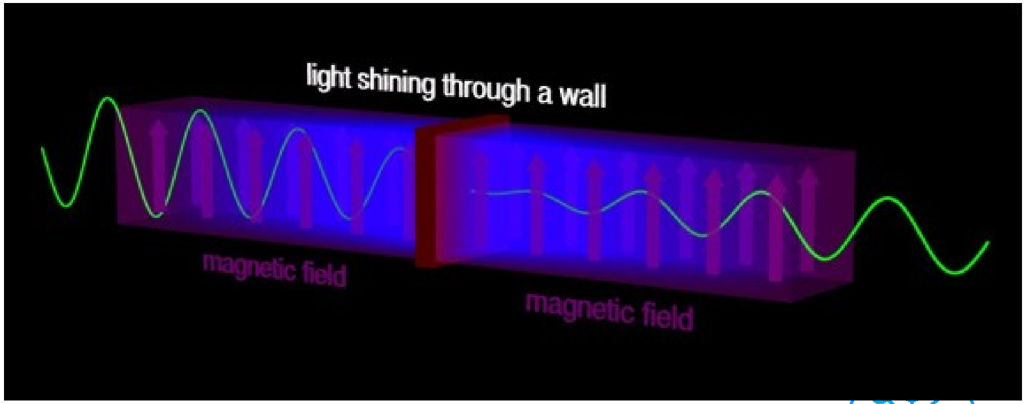
- Direct detection (WIMP scattering on nucleons)
- Indirect detection in cosmic rays
- Production of WIMPs at accele-rators

> WISPy dark matter:

- Direct detection (WISP signals in microwave cavities)
- Indirect detection in astrophysics and cosmology
- Production of WISPs with lasers and detection via light-shining-through-a-wall







Strong CP problem and QCD axion

> QCD allows for CP-violating term in Lagrangian,

$$\mathcal{L}_{\mathrm{CP-viol.}} = \frac{\alpha_s}{4\pi}\,\theta\,\mathrm{tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu}$$

> Strong CP problem = lack of explanation why experimentally $\theta < 10^{-10}$

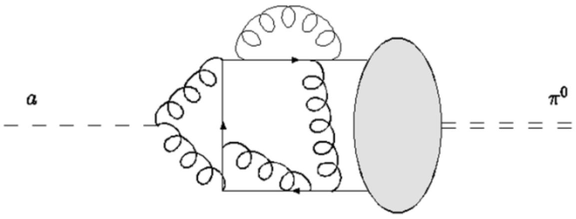
> Peccei-Quinn solution: introduce axion field a(x) as dynamical theta parameter, $\theta \to a(x)/f_a$, enjoying a shift symmetry, $a \to a + \mathrm{const.}$, broken only by anomalous couplings to gauge fields,

$$\mathcal{L} \supset \frac{1}{2}\,\partial_\mu a\,\partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma}\frac{a}{f_a}\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$+\sum_\Psi \left[\overline{\Psi}\gamma^\mu \tfrac{1}{2}(\tilde{X}_{\psi_R} + \tilde{X}_{\psi_L})\gamma_5\Psi + \overline{\Psi}\gamma^\mu \tfrac{1}{2}(\tilde{X}_{\psi_R} - \tilde{X}_{\psi_L})\Psi\right]\frac{\partial_\mu a}{f_a}$$

> Effective theta parameter spontaneously relaxes to zero

Strong CP problem and QCD axion

- Elementary particle excitation of axion field: QCD axion (Weinberg 78; Wilczek 78) , mixing with pion



- For large f_a, prime example of a WISP:
  - very light,

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \times \left(\frac{10^9\,\mathrm{GeV}}{f_a} \right)$$

  - very weakly coupled,

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma}\, a\, \vec{E} \cdot \vec{B},$$

$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_a} \sim 10^{-12}\ \mathrm{GeV}^{-1} \left(\frac{10^9\,\mathrm{GeV}}{f_a} \right)$$

Axion-like particles and hidden sector photons

- In 4D field theoretic extensions of SM, axion field realised as phase of a complex SU(2)xU(1) singlet scalar field whose vev breaks a global anomalous chiral U(1)_PQ symmetry
- At energies much below the symmetry breaking scale v_PQ the low-energy effective field theory is that of a (pseudo-)Nambu-Goldstone boson with decay constant

$$f_a = v_{\rm PQ}/C_{ag};$$

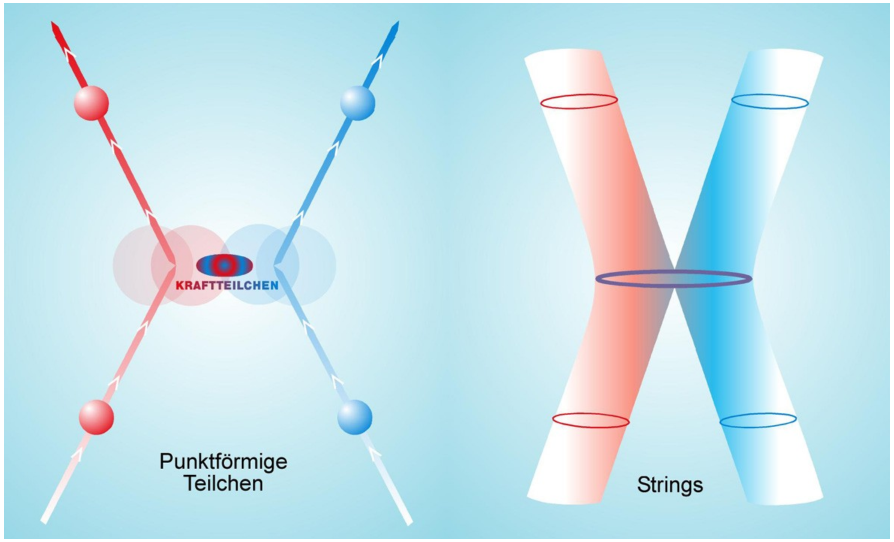
- More axion-like particles (ALPs) may arise as Nambu-Goldstone bosons from the breaking of other global symmetries

$$\begin{aligned}\mathcal{L} \supset & \frac{1}{2}\,\partial_\mu a_i\,\partial^\mu a_i - \frac{\alpha_s}{8\pi}\left(\bar\theta + C_{ig}\frac{a_i}{f_{a_i}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}C_{i\gamma}\frac{a_i}{f_{a_i}}\,F_{\mu\nu}\tilde{F}^{\mu\nu} \\ & + \sum_\Psi\left[\overline{\Psi}\gamma^\mu\frac{1}{2}(\tilde{X}^i_{\psi_R} + \tilde{X}^i_{\psi_L})\gamma_5\Psi + \overline{\Psi}\gamma^\mu\frac{1}{2}(\tilde{X}^i_{\psi_R} - \tilde{X}^i_{\psi_L})\Psi\right]\frac{\partial_\mu a_i}{f_{a_i}}\,,\end{aligned}$$

Axion-like particles and hidden sector photons

- Particular strong motivation for the existence of the axion and ALPs comes from string theory
- 4D low-energy effective field theory emerging from string theory predicts natural candidates for the QCD axion, often even an `axiverse´, containing many additional ALPs
  - KK zero modes of 10D antisymmetric form fields, the latter belonging to the massless spectrum of the bosonic string
  - Number of ALPs = number of cycles of 6D compactified manifold

  (Witten; Conlon; Cicoli, Goodsell, AR)



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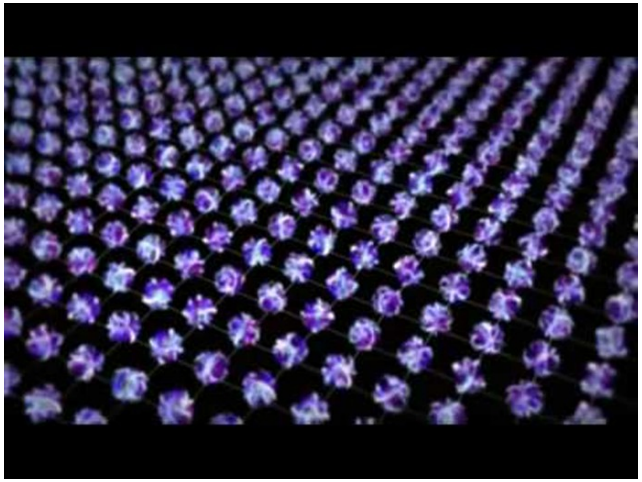
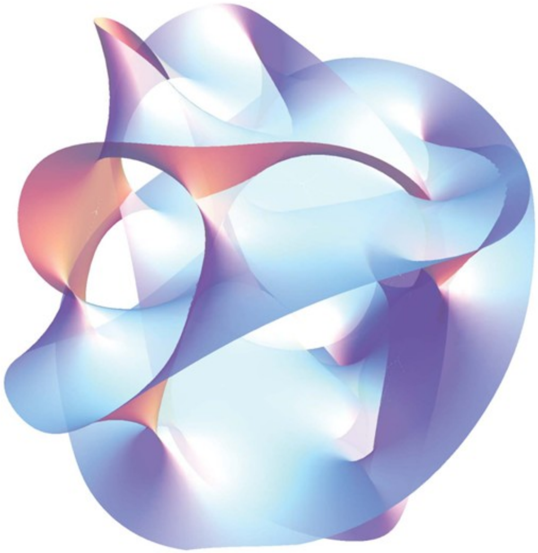
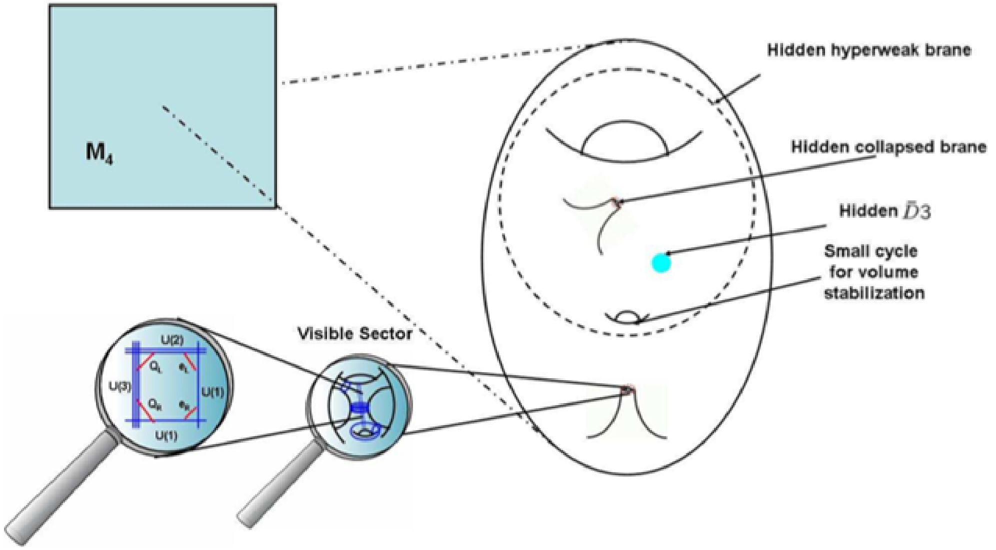




Axion-like particles and hidden sector photons

- Hidden sector photons – gauge bosons of a U(1) gauge group under which SM particles are not charged – are ubiquitous in string compactifications (Goodsell, AR)
  - From breaking of the hidden E_8 gauge group in the heterotic string
  - RR U(1)s arising as KK zero modes of closed string RR from fields
  - Massless excitations of space-time filling D-branes wrapping cycles in the extra dimensions separated from the SM cycles



Axion-like particles and hidden sector photons

- Some of these hidden U(1)s may remain unbroken down to very small scales. In this case, the dominant interaction with the SM will be through kinetic mixing with the photon,

$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\chi}{2} F_{\mu\nu} X^{\mu\nu} + \frac{m_{\gamma'}^2}{2} X_\mu X^\mu ,$$

- Occasionally, there is also light hidden matter charged under the hidden U(1)s. After diagonalisation of the gauge kinetic terms by a shift $X \to X + \chi A$, and a multiplicative charge renormalisation, one finds that the hidden sector matter particles acquire a minicharge, (Holdom)

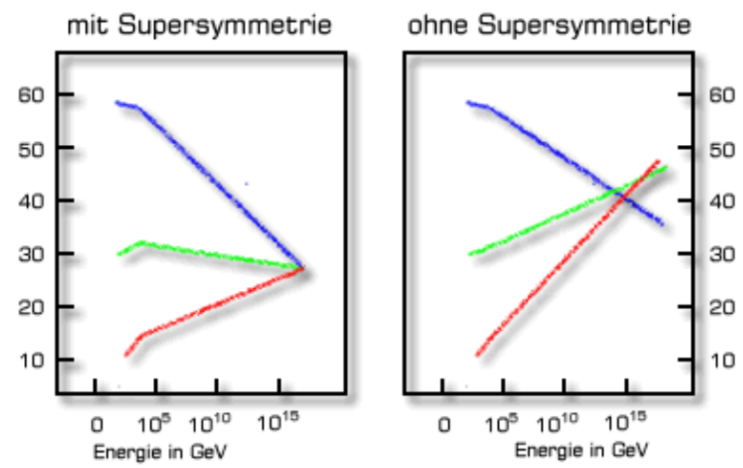
$$\epsilon = \chi g_h / e$$

Hot regions in WISPy parameter space from theory

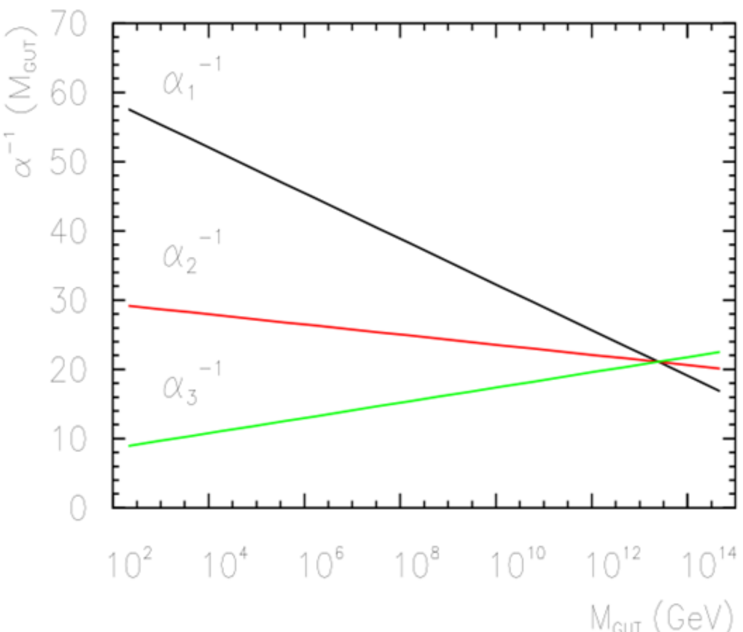
- Masses and couplings of axions and other WISPs to light SM particles, in particular photons, can only be predicted in terms of more fundamental parameters if an UV completion of the low-energy theory is specified
  - Embedding in GUT
  - Embedding in string theory
- Best motivated purely field theoretic UV completions yielding a QCD axion are the ones where the PQ symmetry is not imposed by hand, but in which it appears as an accidental or automatic consequence of local gauge invarince, renormalisability and the pattern of gauge symmetry breakdown (Georgi, Hall, Wise `81)
- Then axion decay constant ~ scale of gauge symmetry breaking, which can be of order $f_a \sim v_{\rm GUT} \sim 10^{16}\ {\rm GeV}$ for GUTs with minimal Higgs sector down to $f_a \sim 10^{10\div 13}\ {\rm GeV}$ for GUTs with non-minimal numbers of Higgses (Nilles, Raby; Dias et al.)

Hot regions in WISPy parameter space from theory

- Unification of gauge couplings in MSSM like extension of SM



- Unification of gauge couplings in multiple Higgs extension of SM (Dias et al.)



Hot regions in WISPy parameter space from theory

> From string theoretic ultraviolet completions, one expects the axion decay constant ~ string scale M_s

> Large Volume Scenario (LVS) of IIB string theory,

$$M_s \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim \sqrt{\frac{M_P\, m_{3/2}}{W_0}} \sim 10^{9\div 12}\,\mathrm{GeV}$$

- QCD axion in classic window, which is phenomenologically particularly attractive,

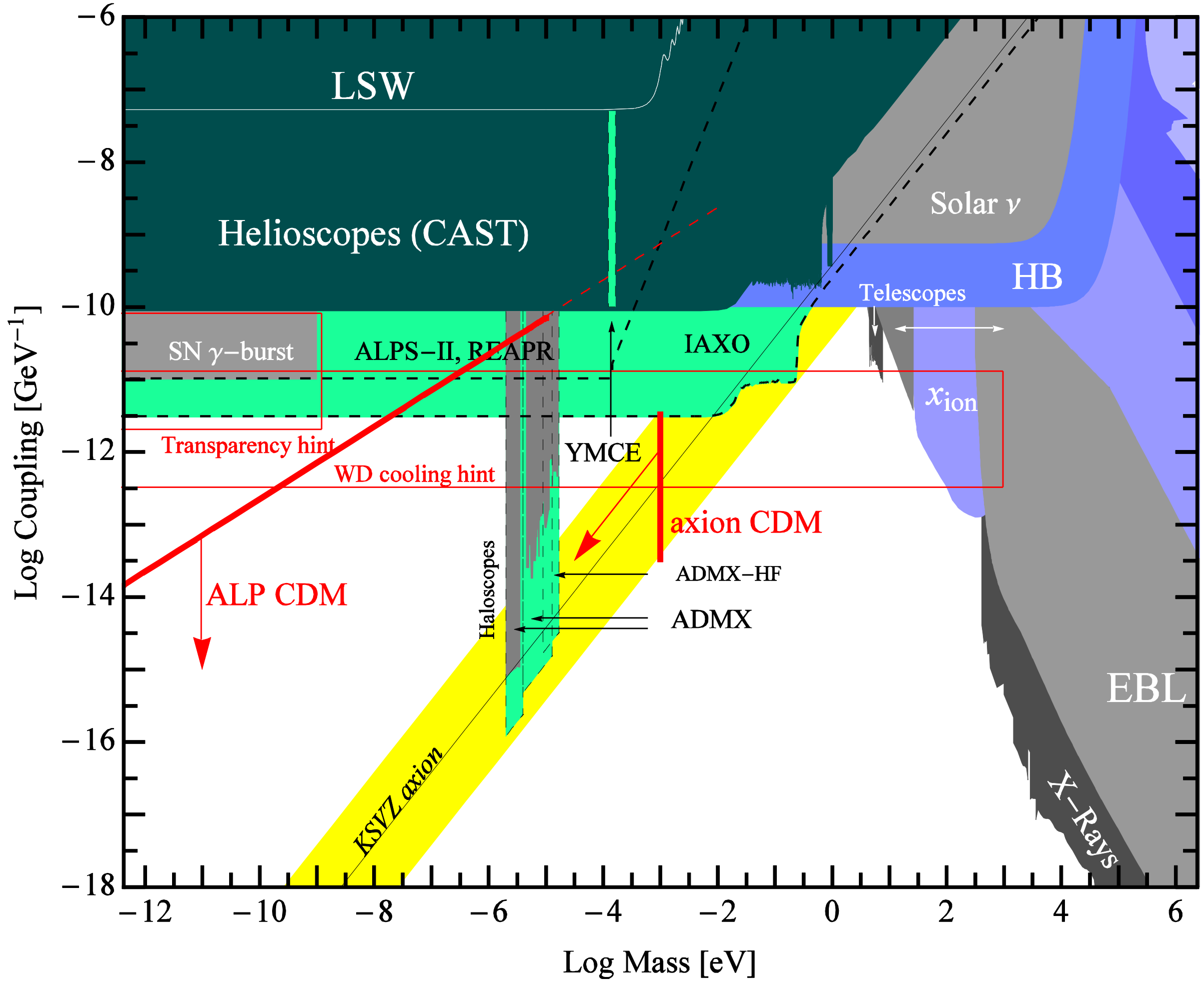
$$f_a \sim M_s \sim 10^{9\div 12}\,\mathrm{GeV}$$

- ALPs with

$$\begin{aligned} f_{a_i} &\sim f_a \sim M_s \sim 10^{9\div 12}\,\mathrm{GeV}, \\ C_{i\gamma} &\sim \mathcal{O}(1) \Rightarrow g_{i\gamma} \equiv \frac{\alpha}{2\pi f_{a_i}} C_{i\gamma} \sim 10^{-15} \div 10^{-11}\ \mathrm{GeV}^{-1}, \end{aligned}$$

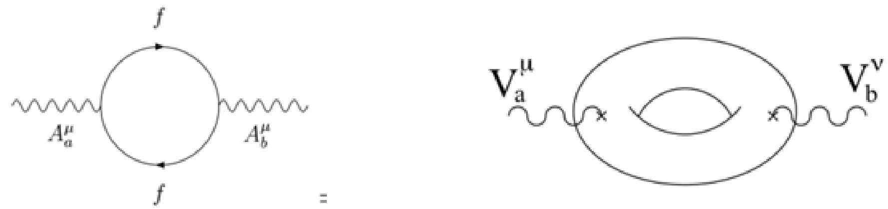
(Cicoli, Goodsell, AR `12)

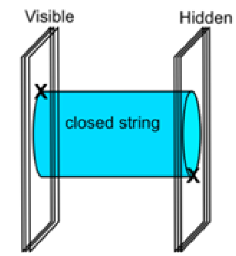
Hot regions in WISPy parameter space from theory



Hot regions in WISPy parameter space from theory

- Kinetic mixing is generated at one-loop by the exchange of heavy messengers that couple both to the visible U(1) as well as to the hidden U(1)





$$\chi \sim \frac{e g_h}{16\pi^2} C,$$

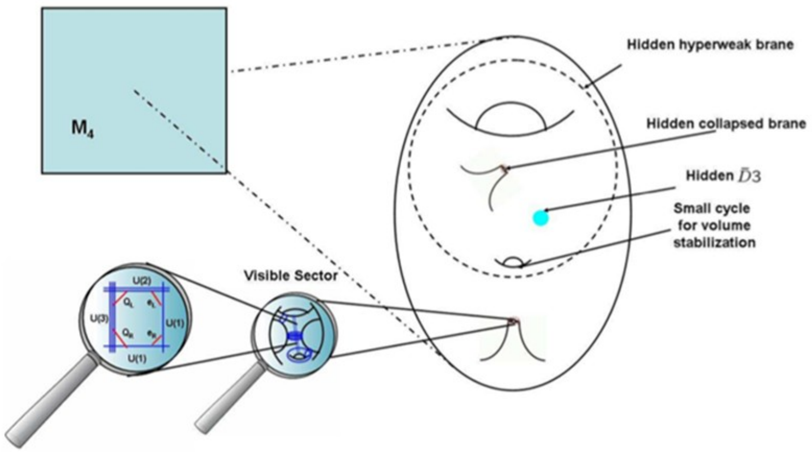
- In purely field theoretic extensions of the SM in 4D,

$$\chi \sim \frac{e g_h}{16\pi^2} C \sim 10^{-4}.$$

- Similar value expected from heterotic string theory (Goodsell, Ramos-Sanchez, AR)

Hot regions in WISPy parameter space from theory

- Type IIB string produces a much greater variety of possible values, e.g. mixing of a hidden U(1) associated with a large four cycle in an isotropic LVS compactification, cf.

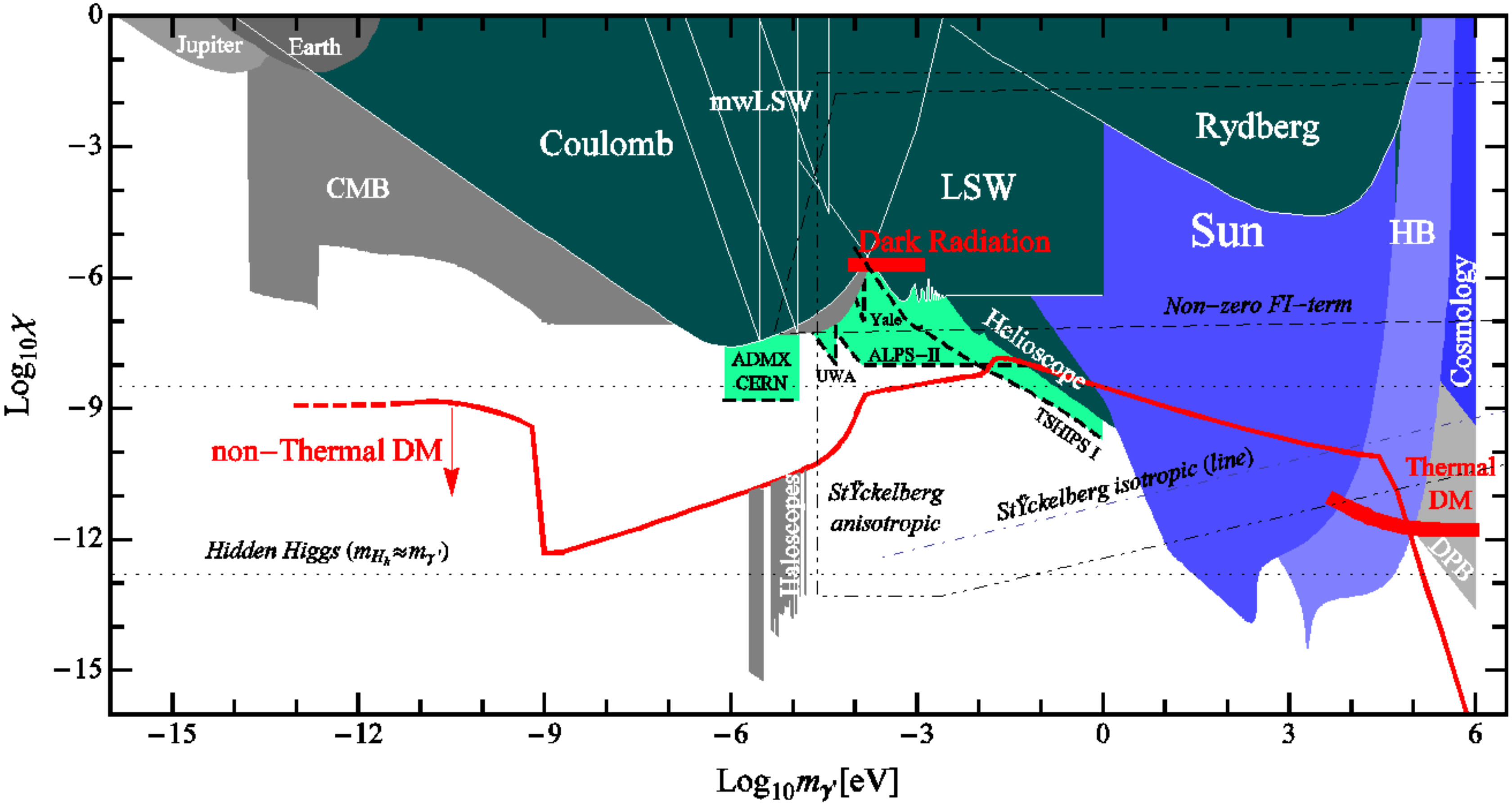


$$\chi \sim \frac{e}{16\pi^2} (M_s/M_P)^{-2/3} \sim 10^{-9}$$

(Goodsell,Jaeckel,Redondo,AR)

$$M_s \sim 10^{10}\ \mathrm{GeV}.$$

Hot regions in WISPy parameter space from theory



Astro/cosmo constraints/hints on WISPy parameters

- Theoretically favored masses and couplings of axions and other WISPs span a very wide range in parameter space. Correspondingly, searches for their signatures have to exploit a variety of observational and experimental techniques, ranging from cosmology and astrophysics to terrestrial laboratory experiments.
- Strongest bounds on their existence presently often come from their effects on stellar evolution, on the propagation of SM particles through astrophysical environments, and on big bang cosmology.

Astro/cosmo constraints/hints on WISPy parameters

- Non-observation of an anomalous energy loss of Horizontal Branch (HB) stars due to ALP emission, (Raffelt)

$$g_{i\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1} \Rightarrow \frac{f_{a_i}}{C_{i\gamma}} \gtrsim 10^{7}\ \mathrm{GeV},$$

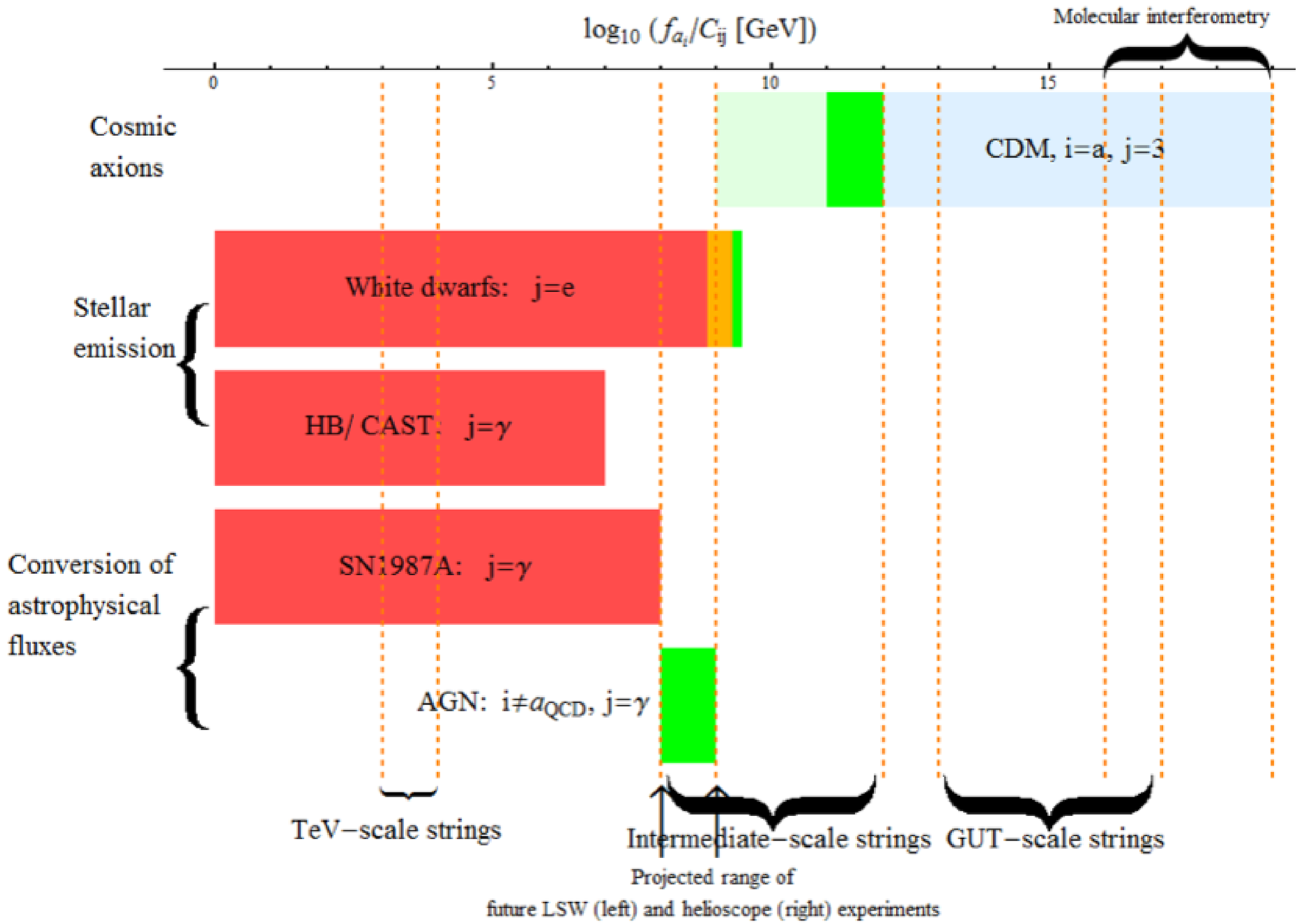
- Evidence for a non-standard energy loss in white dwarfs, consistent with the existence of a sub keV mass axion or ALP with (Isern et al.)

$$g_{ie} = (2.0 \div 7.0) \times 10^{-13} \Rightarrow \frac{f_{a_i}}{C_{ie}} \simeq (0.7 \div 2.6) \times 10^{9}\ \mathrm{GeV}\,.$$

- Absense of a gamma-ray burst due to axion/ALP-photon conversion in coincidence with neutrinos from SN1987A (Brockway et al.;Grifols et al)

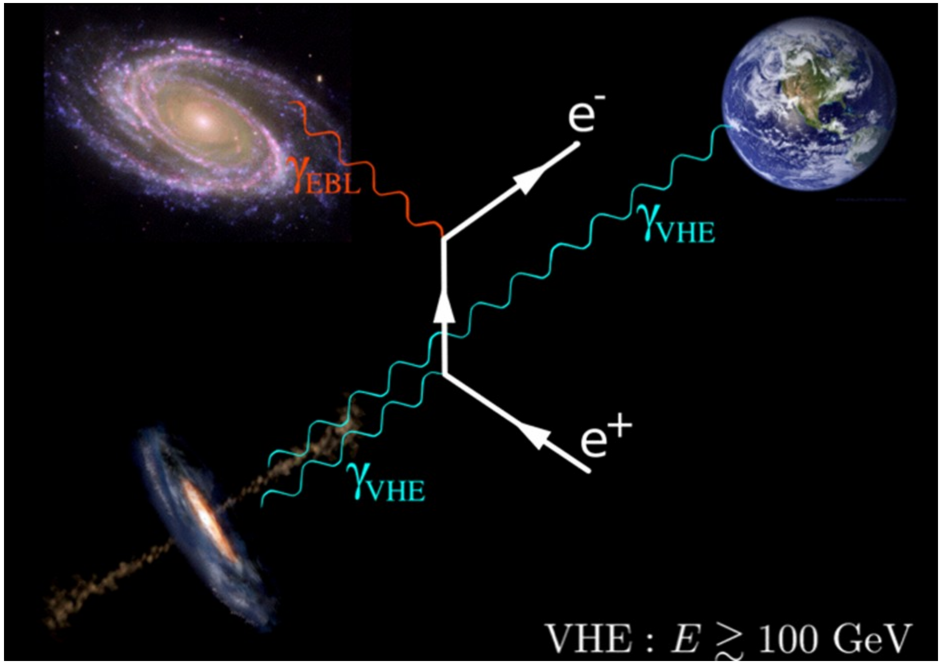
$$g_{a_i\gamma} \lesssim 10^{-11}\,\mathrm{GeV}^{-1} \Rightarrow \frac{f_{a_i}}{C_{i\gamma}} \gtrsim 10^{8}\,\mathrm{GeV}, \qquad m_i \lesssim 10^{-9}\ \mathrm{eV},$$

Astro/cosmo constraints/hints on WISPy parameters



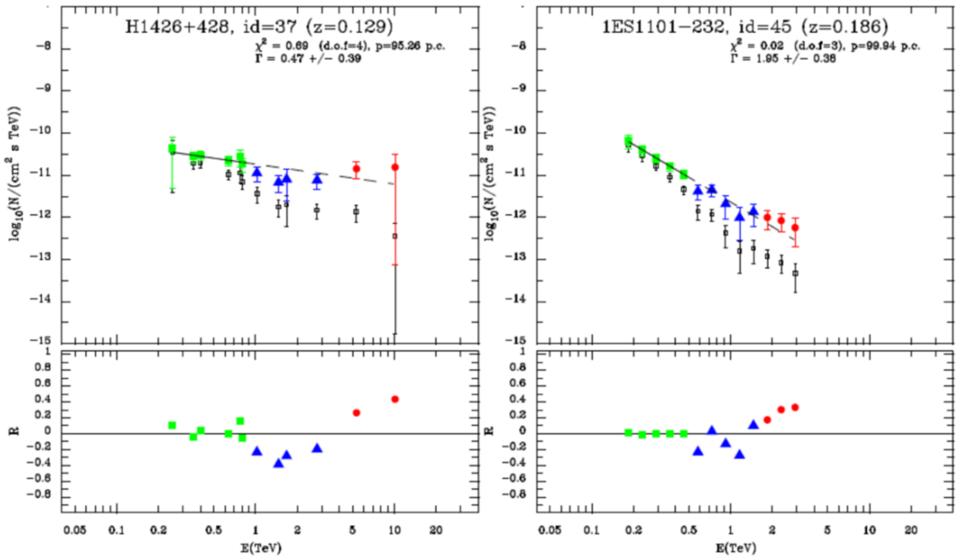
Astro/cosmo constraints/hints on WISPy parameters

- TeV photons from distant Active Galactic Nuclei (AGN) should show aborption features due to e+e- pair production at the Extragalactic Background Light (EBL)



Astro/cosmo constraints/hints on WISPy parameters

- TeV photons from distant Active Galactic Nuclei (AGN) should show aborption features due to e+e- pair production at the Extragalactic Background Light (EBL)
- Not the case: (e.g. Horns,Meyer)
  - Analysis of 50 spectra (HESS, MAGIC, Veritas): minimal EBL, absorption excluded by more than 4 sigma



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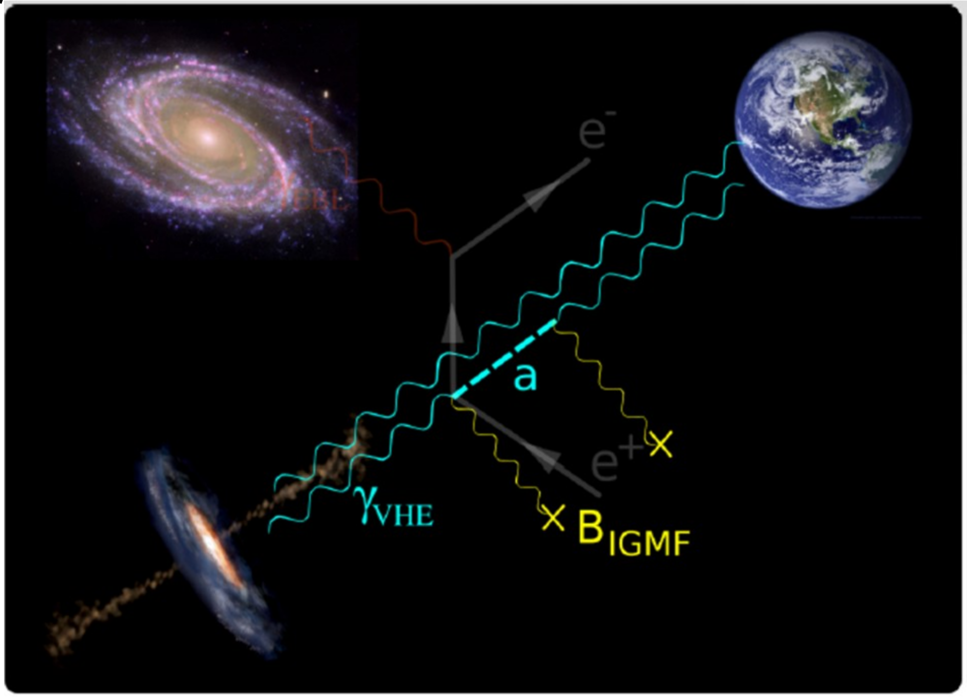
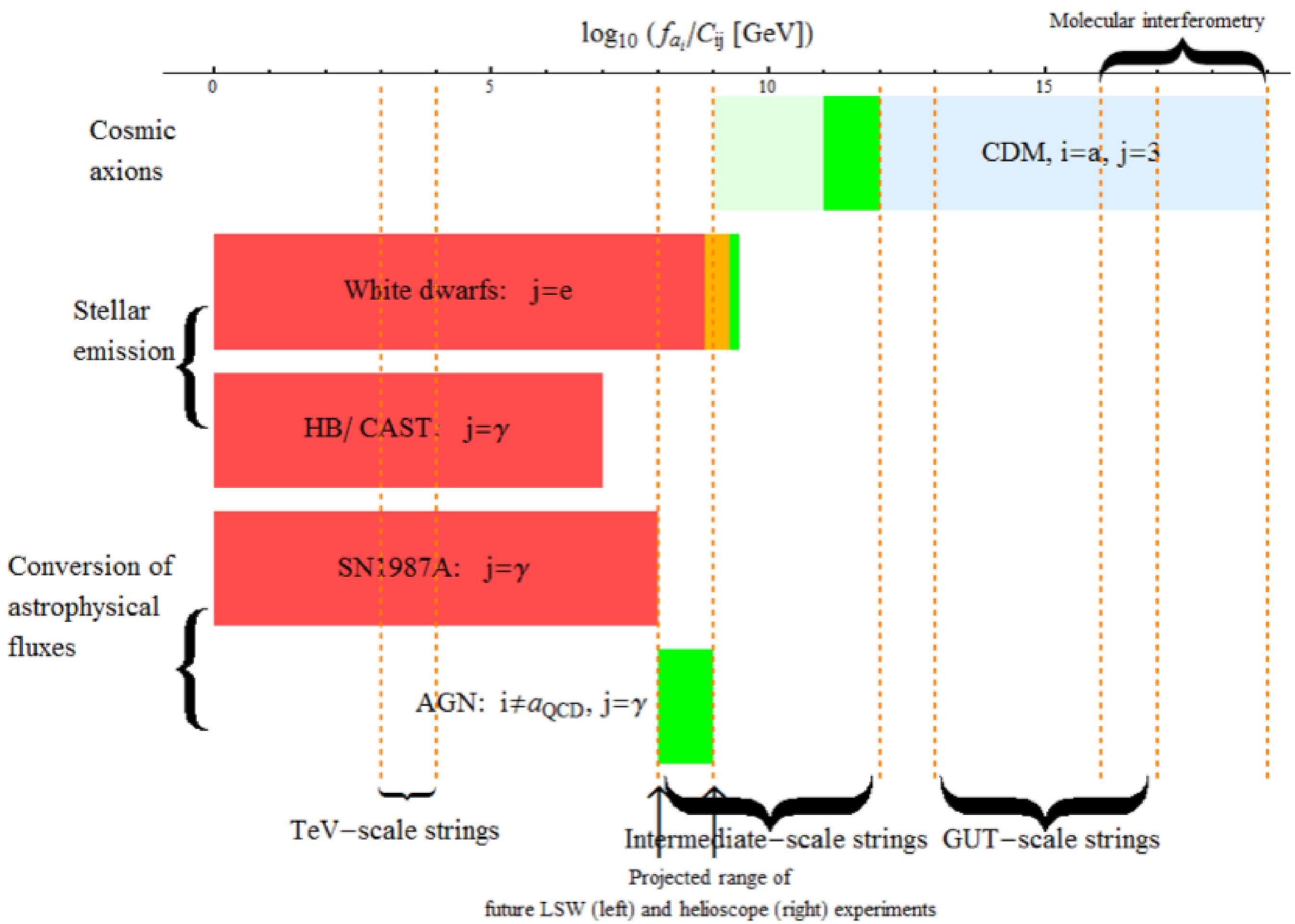


- Not the case: (e.g. Horns,Meyer)
  - Analysis of 50 spectra (HESS, MAGIC, Veritas): minimal EBL, absorption excluded by more than 4 sigma
- Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields

  (Roncadelli; Hooper et al.; Horns et al.)

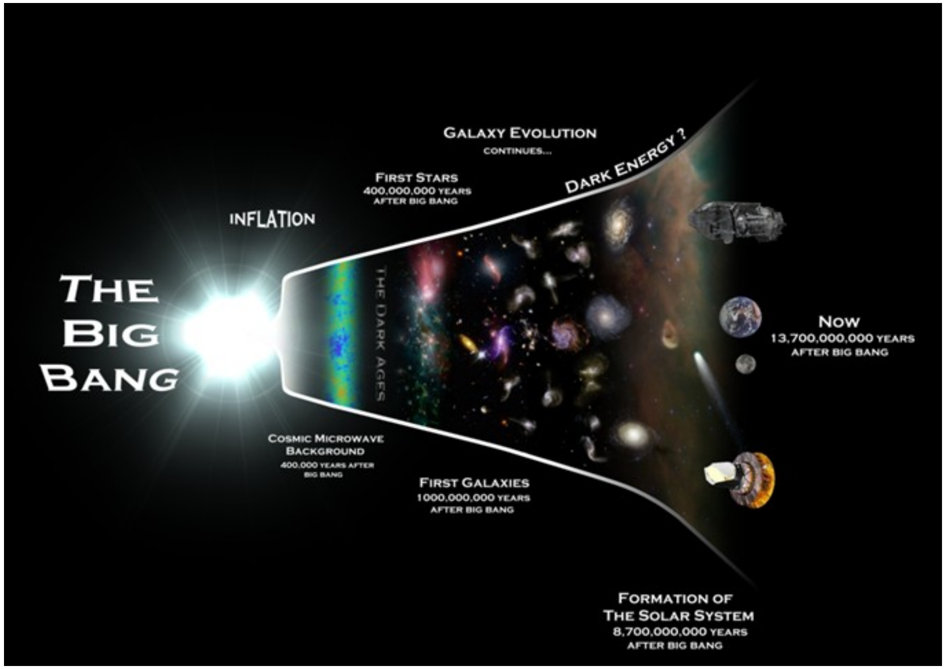
$$g_{i\gamma} \sim 10^{-11}\ \mathrm{GeV}^{-1} \Rightarrow f_{a_i}/C_{i\gamma} \sim 10^{8}\ \mathrm{GeV}.$$

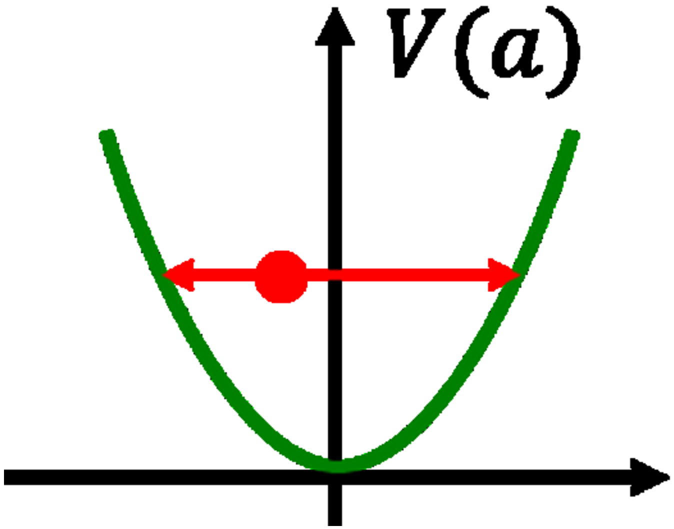
Astro/cosmo constraints/hints on WISPy parameters



WISPy dark matter

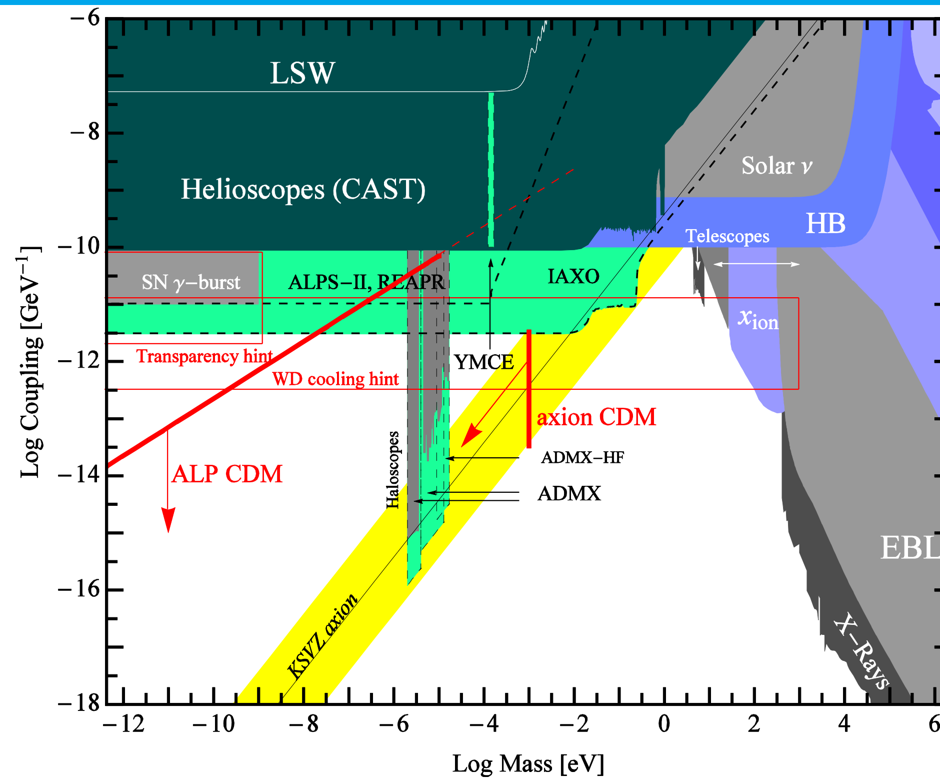
- After inflation: Axion or ALP fields spatially homogenous, random initial value
- Classical oscillations of axion/ALP fields = bose condensates = extremely non-relativistic dark matter





WISPy dark matter

- After inflation: Axion or ALP fields spatially homogenous, random initial value
- Classical oscillations of axion/ALP fields = bose condensates = extremely non-relativistic dark matter
- Cosmic mass fraction in axion or ALP cold dark matter,



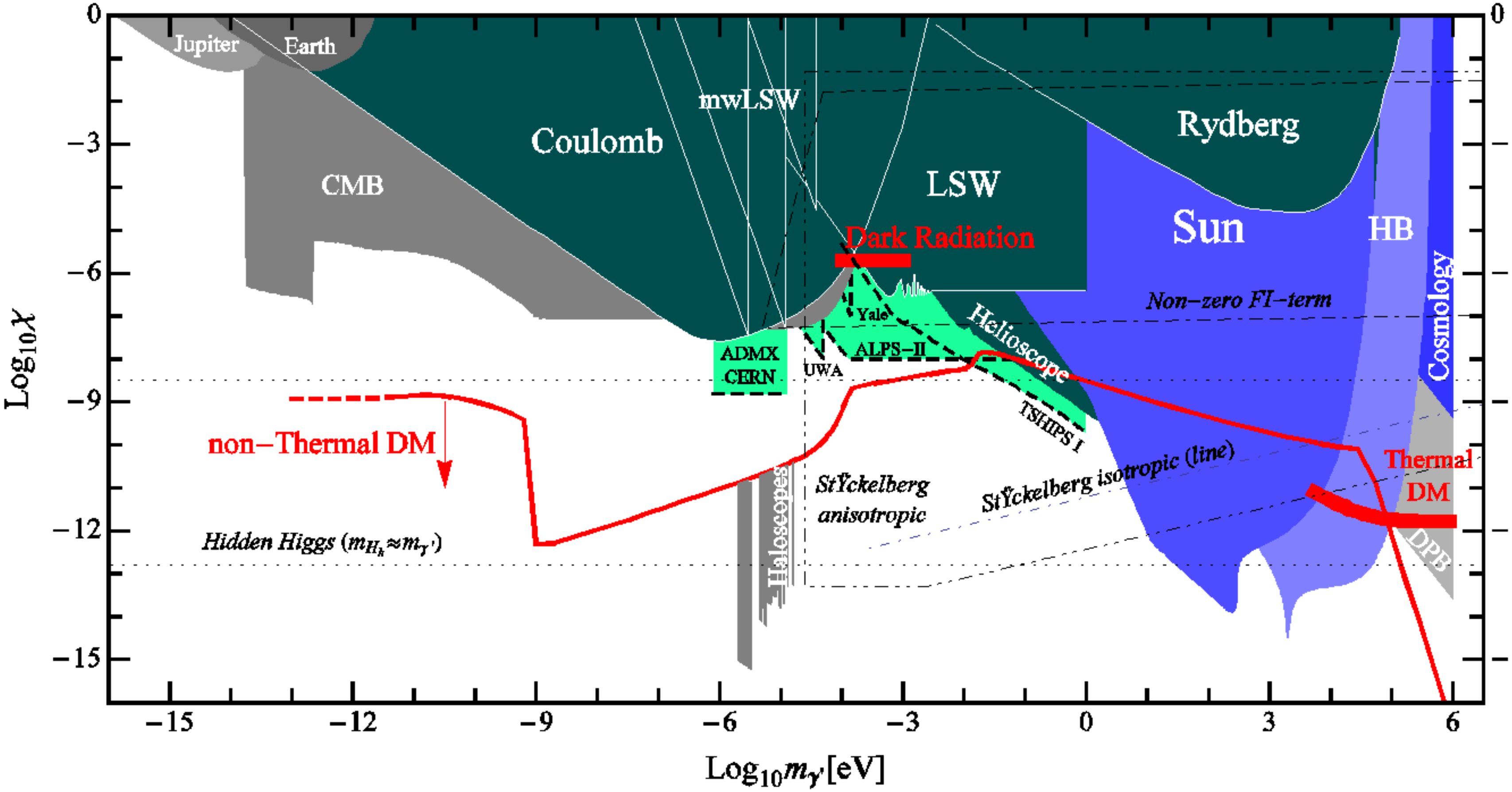
(Preskill et al.; Abbott et al.; Dine et al.)

$$\Omega_a h^2 \approx 0.71 \times \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \left(\frac{\Theta_a}{\pi}\right)^2 ,$$

$$\Omega_{a_i} h^2 \approx 0.16 \times \left(\frac{m_i}{\mathrm{eV}}\right)^{1/2} \left(\frac{f_{a_i}}{10^{11}\ \mathrm{GeV}}\right)^2 \left(\frac{\Theta_i}{\pi}\right)^2$$

(Arias et al.)

WISPy dark matter



Summary

- Solution of strong CP problem gives particularly strong motivation for existence of QCD axion
- Good reasons to expect also axion-like particles , light hidden sector gauge bosons as well as minicharged particles, in particular in string expired extensions of the SM
- There are hot regions in WISPy parameter space arising from well motivated UV completions of the SM
- These hot regions can be attacked by astrophysics, cosmology and terrestrial experiments