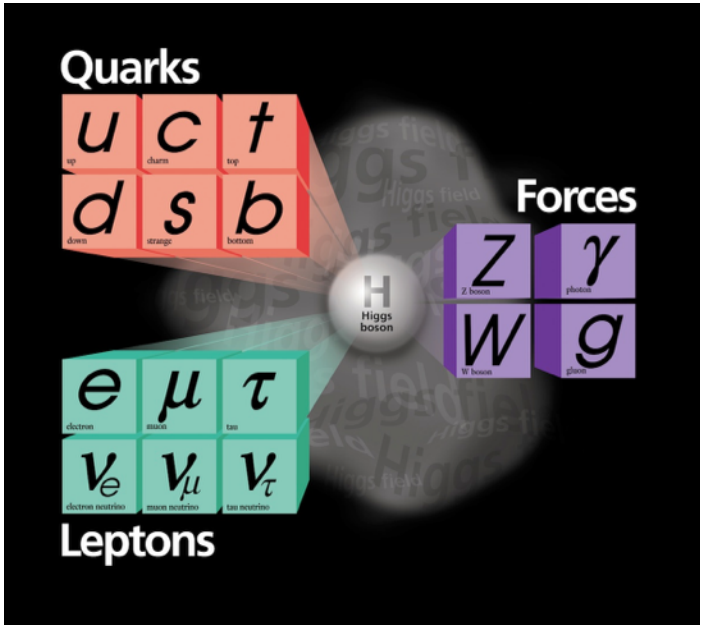
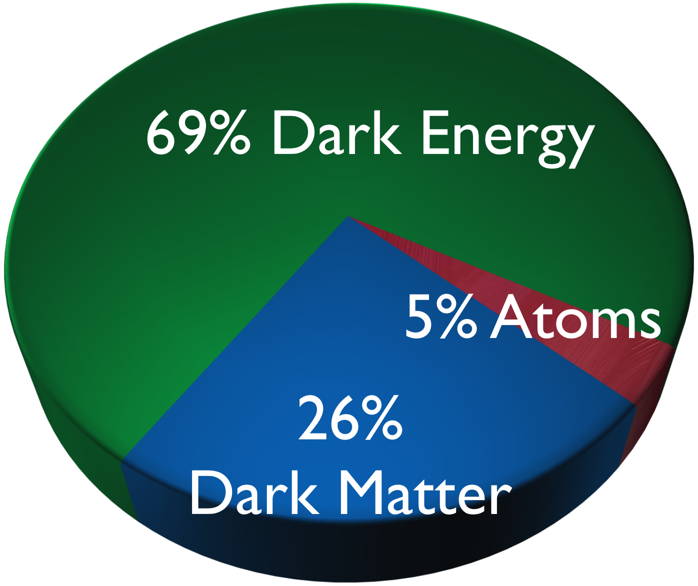
Theory: Dark Matter, Axions and very weakly-interacting particles

Thomas Schwetz-Mangold

The Future of Non-Collider-Physics, Helmholtz Institute Mainz, 27. 04. 17

Beyond the SM + ΛCDM





Where is new physics?

Beyond the SM + ΛCDM

observational evidences

- neutrino mass
- baryon asymmetry
- dark matter
- accelerated expansion
- cosmological density perturbations

theoretical arguments

- naturalness of the weak scale
- strong CP problem
- naturalness of the cosmological constant

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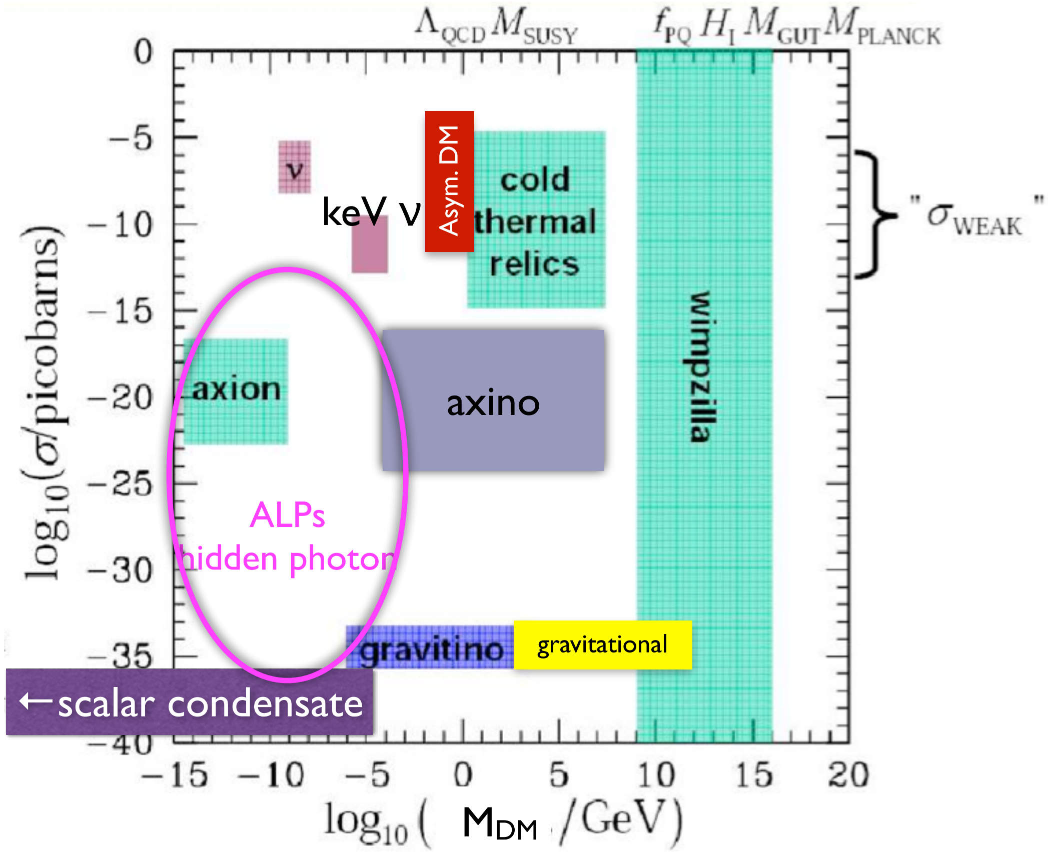
Challenge for particle physics



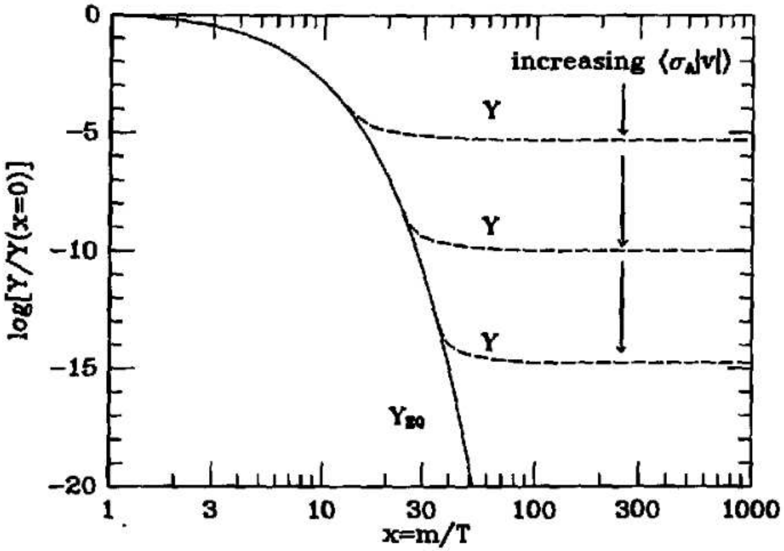
Challenge for me …

- try to comment on few of those DM candidates - necessarily incomplete
- give some arguments about „theoretical motivation“ (miracles)
- will not discuss specific experimental projects (see talks later today)
- strongly personal biased - apologizes…

Outline

- WIMPs (freeze-out)
  natural / un-natural
- FIMPs (freeze-in)
  gravitational, keV neutrinos
- Axions (QCD)
  ALPs, hidden photons

The WIMP hypothesis: thermal freeze-out



$$\Omega_{\rm DM} \approx \frac{2\times 10^{-37}{\rm cm}^2}{\langle\sigma_{\rm annih} v\rangle} \approx 0.23$$

Lee, Weinberg, 1977
Bernstein, Brown, Feinberg, 1985
Scherrer, Turner, 1986

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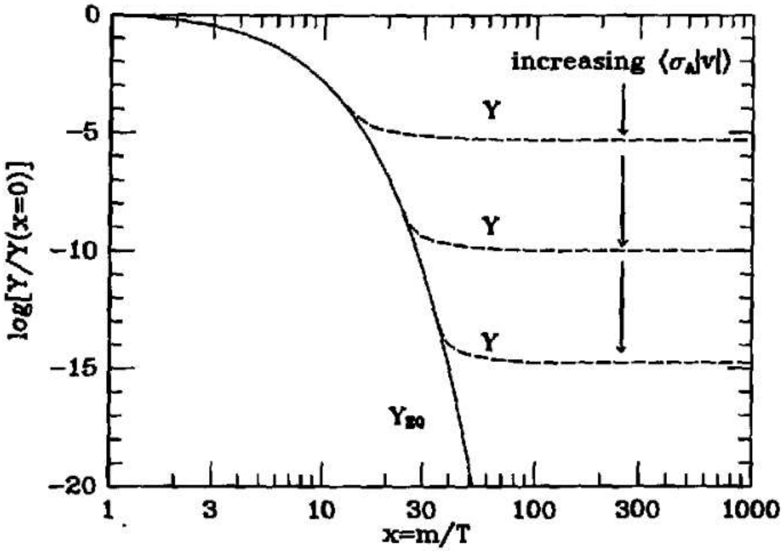

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Scherrer, Turner, 1986

"typical" annihilation cross section:

$$\langle\sigma_{\rm annih}v\rangle \sim \frac{g^4}{2\pi m^2} \simeq 6\times 10^{-37}{\rm cm}^2 \left(\frac{g}{0.1}\right)^4 \left(\frac{m}{100\,{\rm GeV}}\right)^{-2}$$

- "Weakly Interacting Massive Particle" (WIMP)
- relation with new physics at the TeV scale

The WIMP miracle

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2,$$

Naturalness of the Higgs mass suggests new physics close to the EW scale.

The same physics which cures the hierarchy problem may provide DM.

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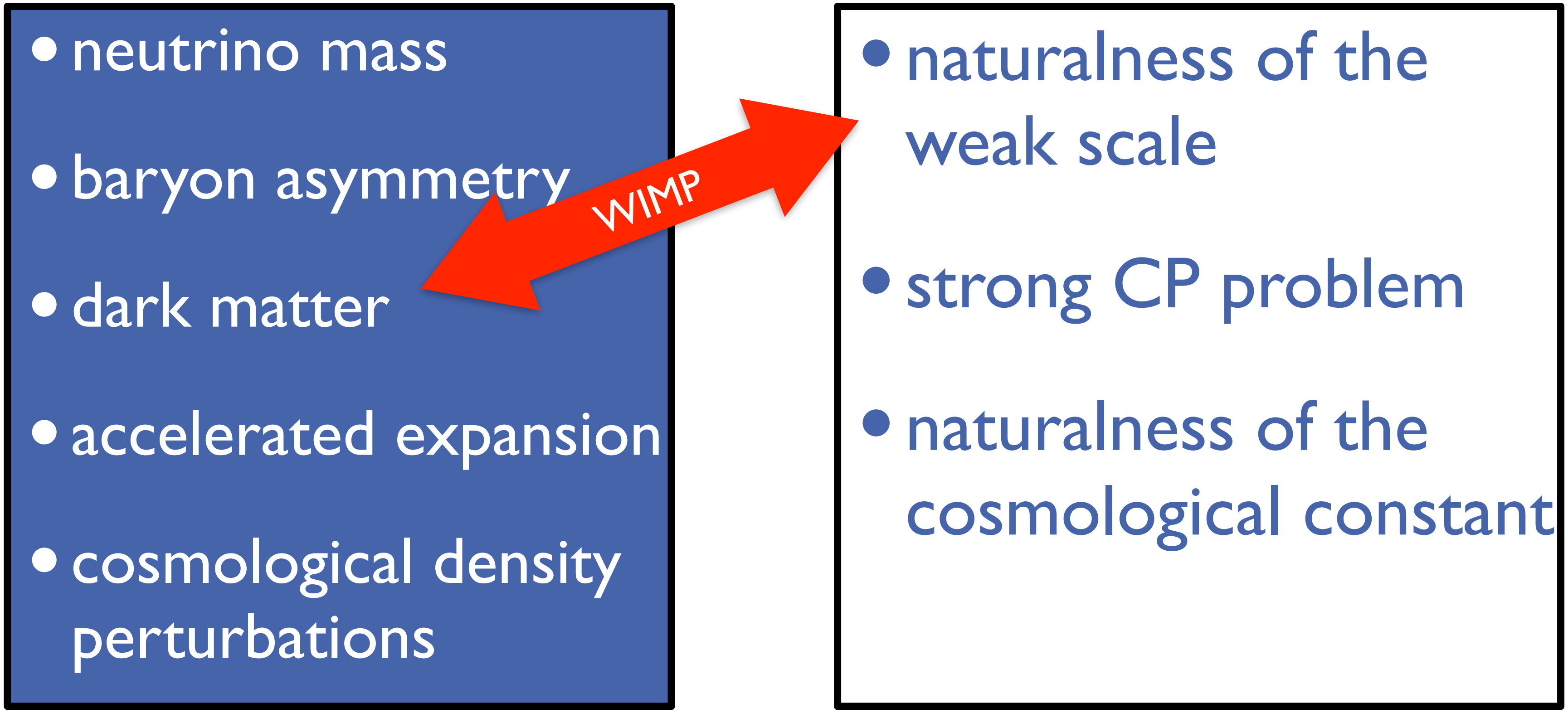
prime example: Supersymmetry (but there are others as well)

The WIMP miracle



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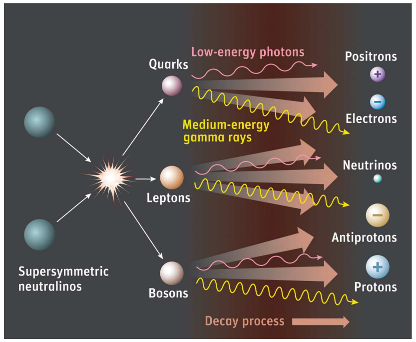
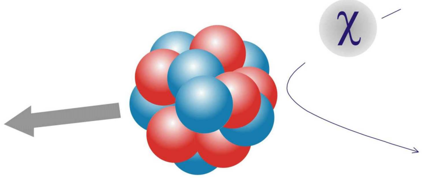
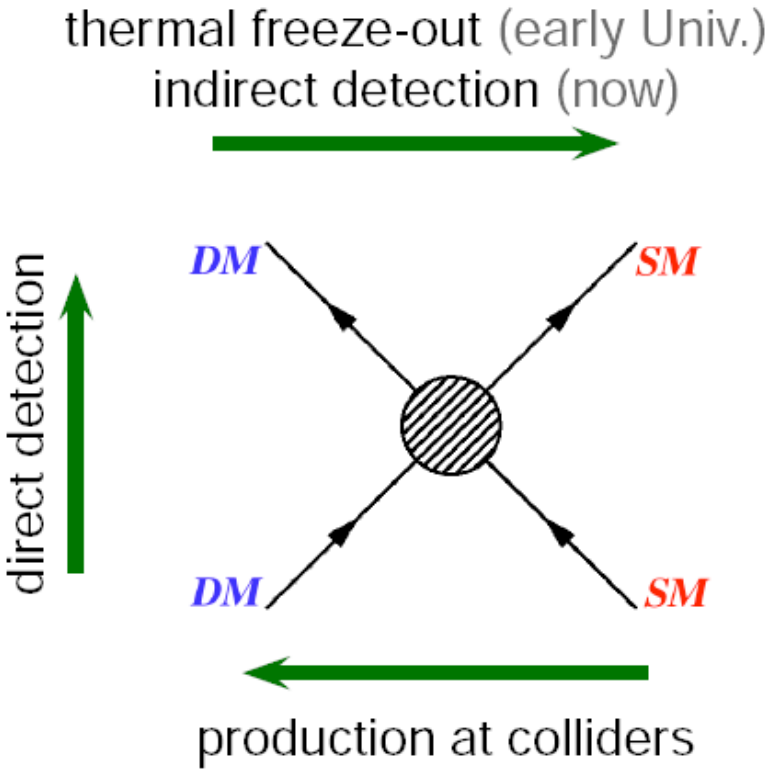
WIMP searches



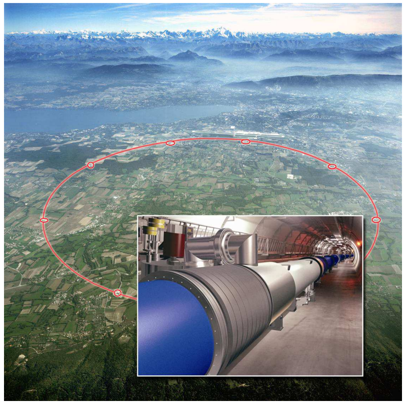




thermal freeze-out (early Univ.)
indirect detection (now)

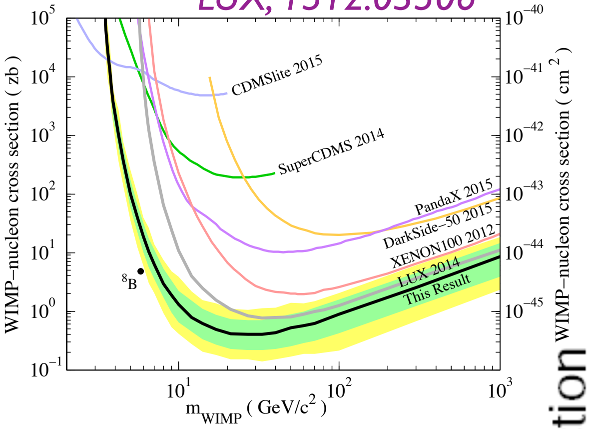
direct detection

production at colliders



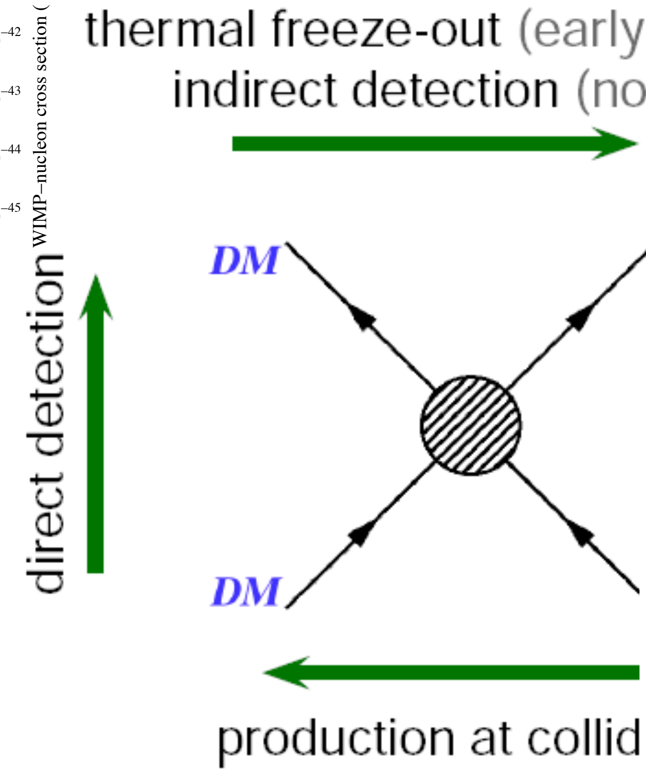
WIMP searches

LUX, 1512.03506



$\sigma_{scatt} < 10^{-45}$ cm^2 ↔

$\sigma_{annih.} \sim 10^{-36}$ cm^2



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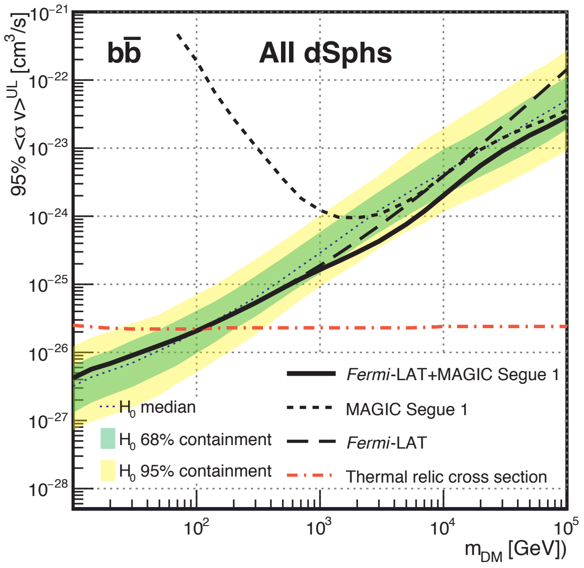
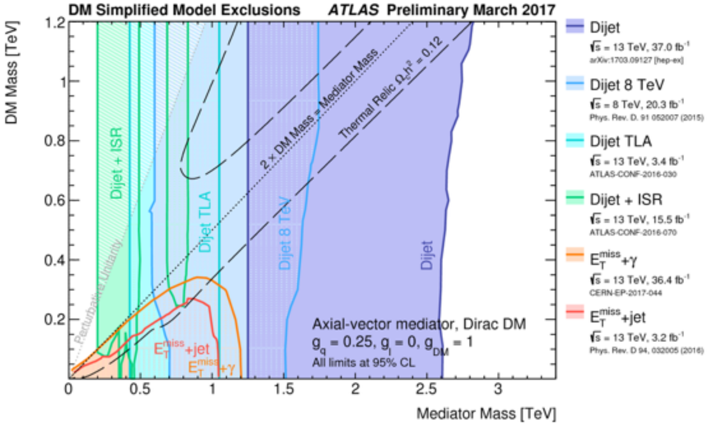
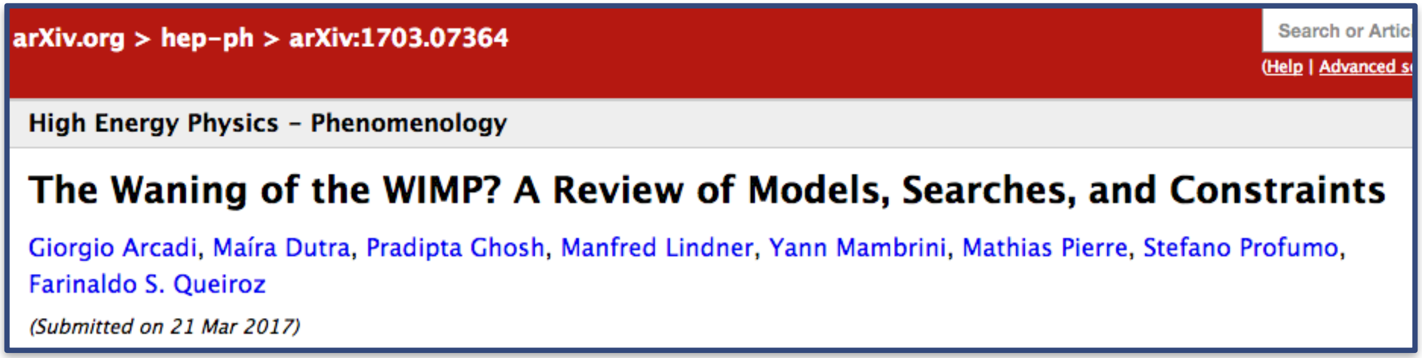
FERMI & MAGIC, 1601.06590





WIMP hypothesis is getting cornered



arXiv.org > hep-ph > arXiv:1703.07364

High Energy Physics – Phenomenology

The Waning of the WIMP? A Review of Models, Searches, and Constraints

Giorgio Arcadi, Maíra Dutra, Pradipta Ghosh, Manfred Lindner, Yann Mambrini, Mathias Pierre, Stefano Profumo, Farinaldo S. Queiroz

(Submitted on 21 Mar 2017)

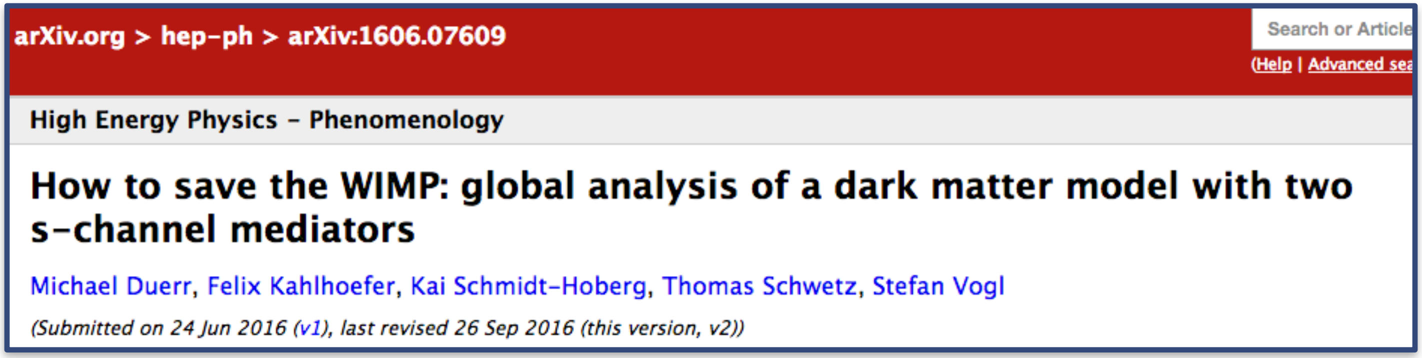
arXiv.org > hep-ph > arXiv:1611.00804

High Energy Physics – Phenomenology

The last refuge of mixed wino–Higgsino dark matter

Martin Beneke, Aoife Bharucha, Andrzej Hryczuk, Stefan Recksiegel, Pedro Ruiz–Femenia

(Submitted on 2 Nov 2016)



arXiv.org > hep-ph > arXiv:1606.07609

High Energy Physics – Phenomenology

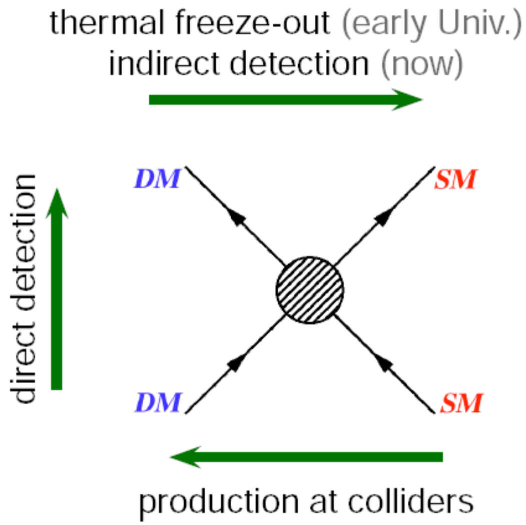
How to save the WIMP: global analysis of a dark matter model with two s–channel mediators

Michael Duerr, Felix Kahlhoefer, Kai Schmidt–Hoberg, Thomas Schwetz, Stefan Vogl

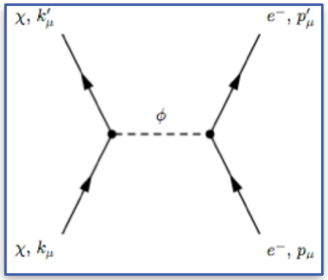
(Submitted on 24 Jun 2016 (v1), last revised 26 Sep 2016 (this version, v2))

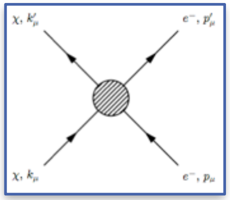
The comparison is necessarily model dependent

UV-complete models (SUSY)



“simplified” models
DM particle + mediator



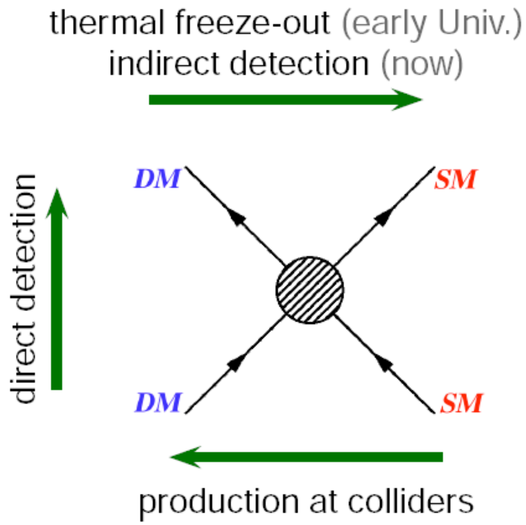


EFT: only SM + DM particle

The comparison is necessarily model dependent

UV-complete models (SUSY)

MSSM industry



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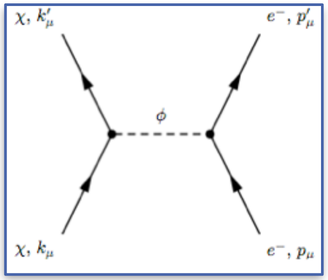

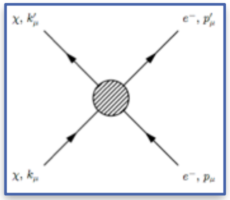

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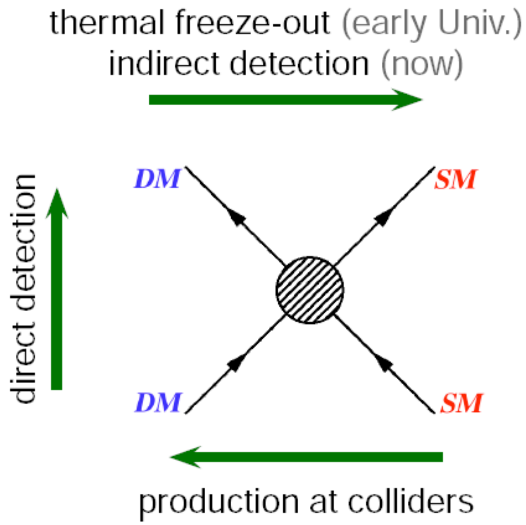

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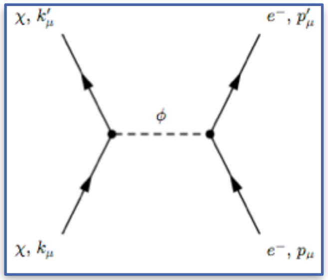
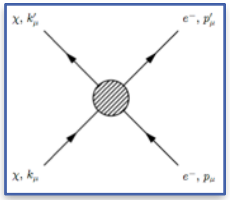
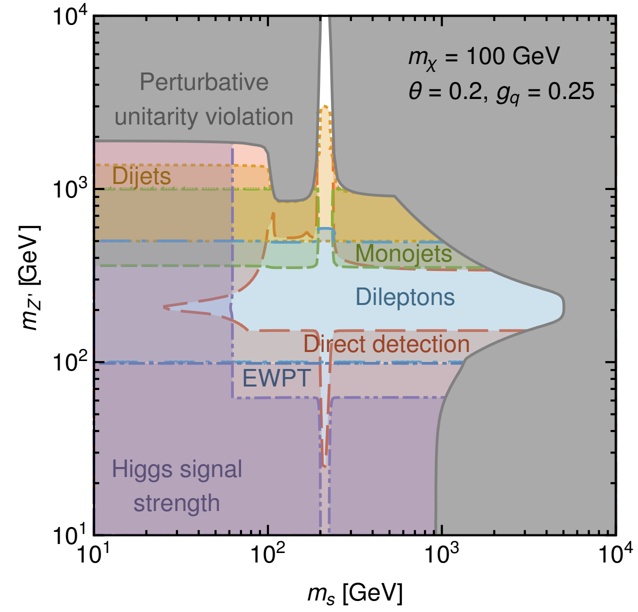


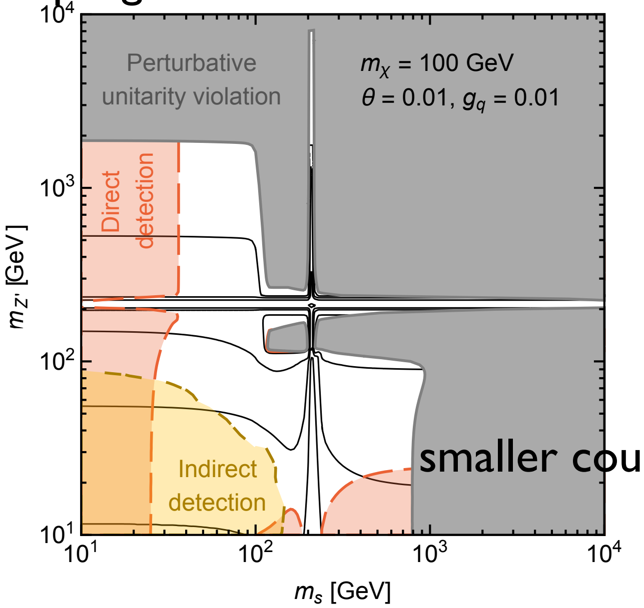


EFT: only SM + DM particle

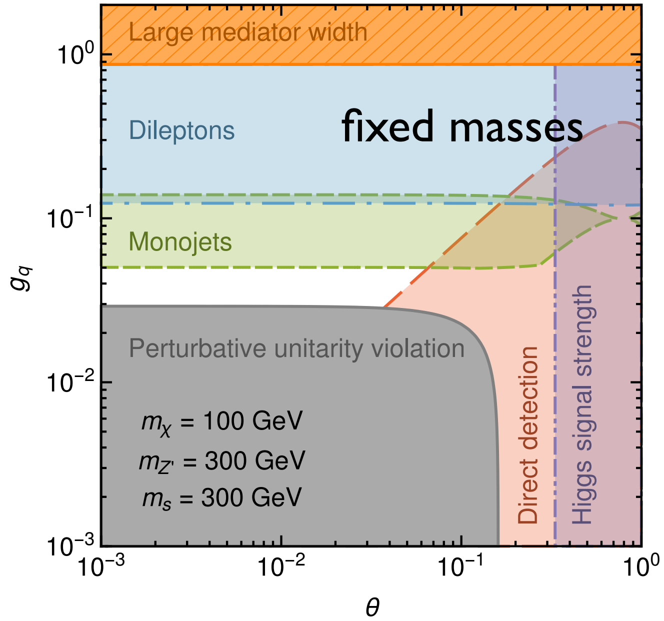
conceptual problems

constraints for fixed couplings on SM side





smaller couplings



fixed masses

Example for a particular simplified model:

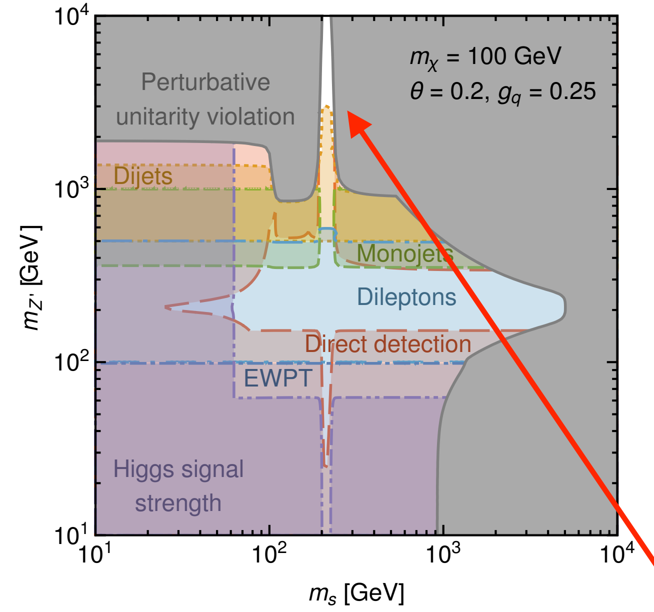
fermionic DM

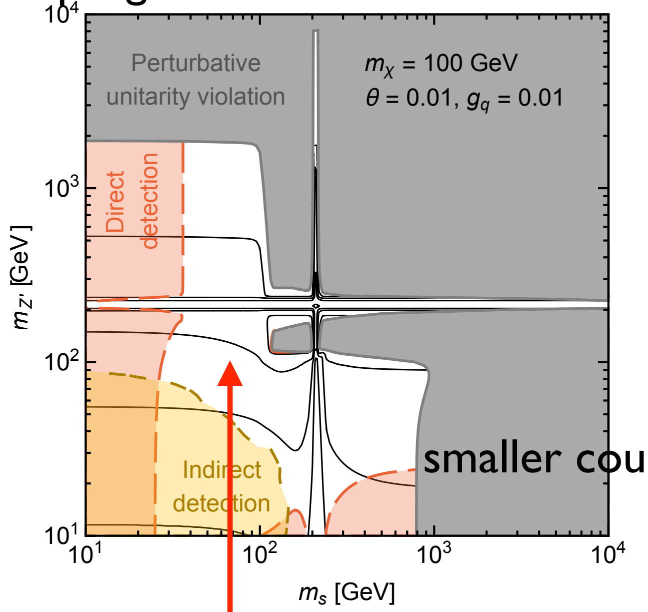
dark U(1) → vector boson

dark Higgs to break U(1)

Dürr, Kahlhöfer, Schmidt-Hoberg, TS, Vogl, 16

constraints for fixed couplings on SM side





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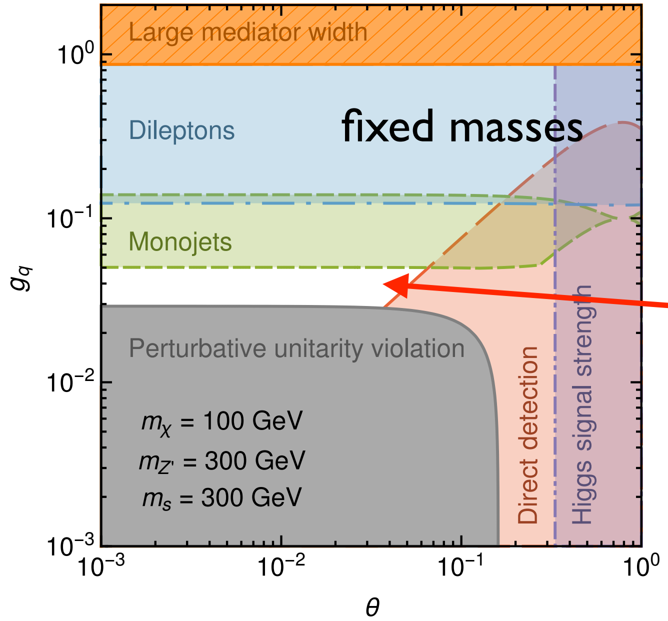
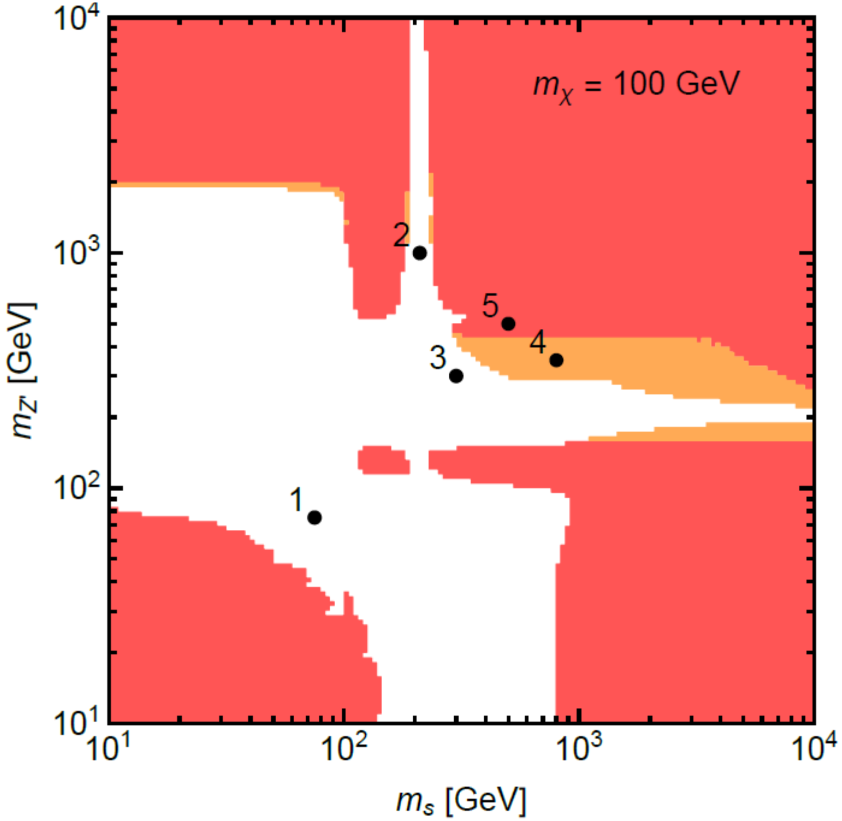


fixed masses

WIMP is cornered

global parameter scan

Dürr, Kahlhöfer, Schmidt-Hoberg, TS, Vogl, 1606.07609

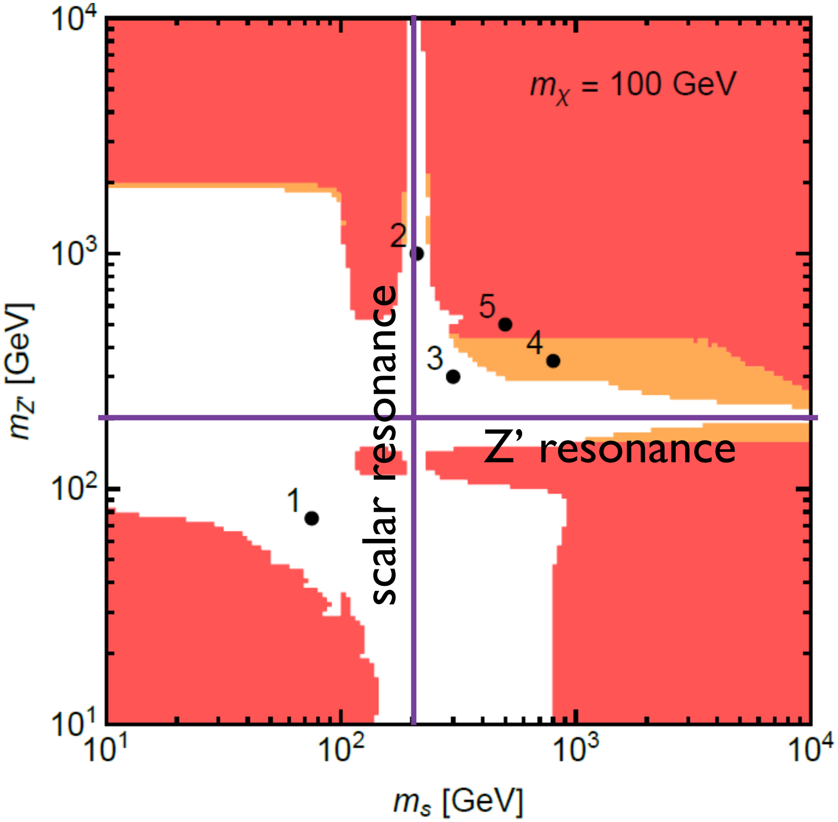


Red: All coupling combinations are excluded by at least one constraint.

White: At least one coupling combination is compatible with all constraints.

Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'} > 0.3$).

WIMP hypothesis survives only in special corners:



- close to an s-channel resonance:

  $\chi\chi \rightarrow$ s/Z' $\rightarrow$ SM SM

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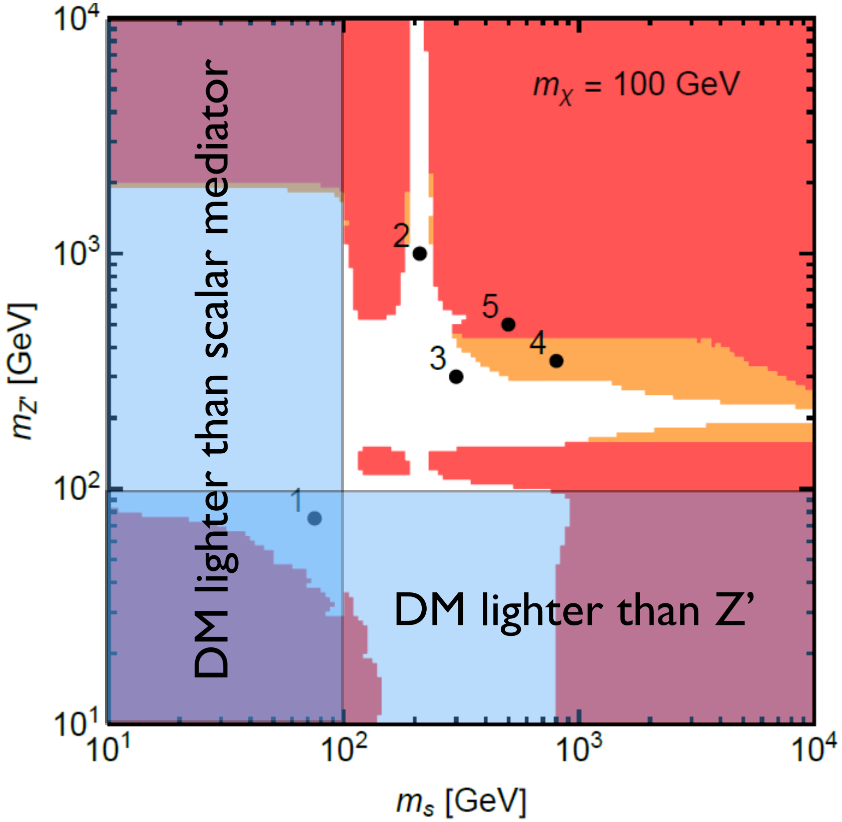

- close to an s-channel resonance:
  $\chi\chi \rightarrow$ s/Z' $\rightarrow$ SM SM
- one or both mediators are lighter than DM → „terminator“ or „secluded DM“

Saving the WIMP by a light mediator: Secluded DM

Pospelov, Ritz, Voloshin, 2007

$$\mathcal{L} = - \sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi$$

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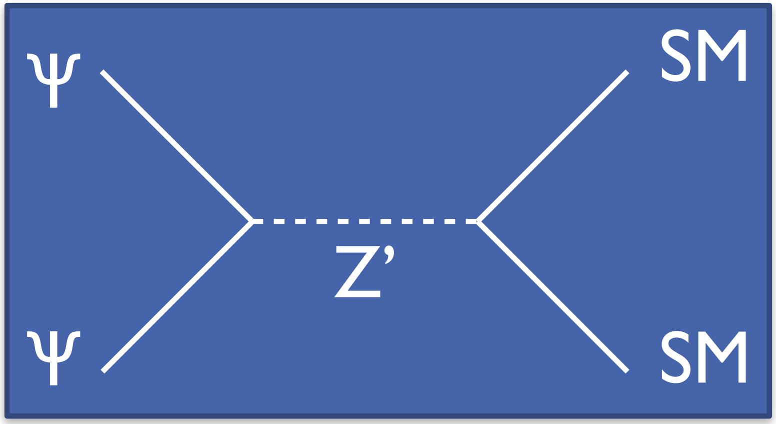

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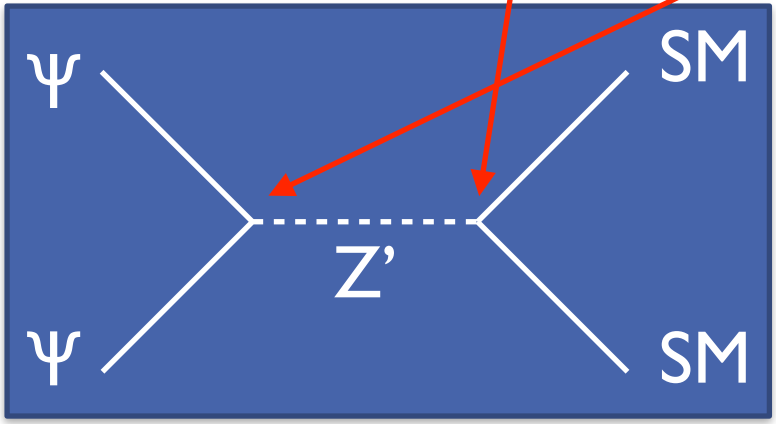

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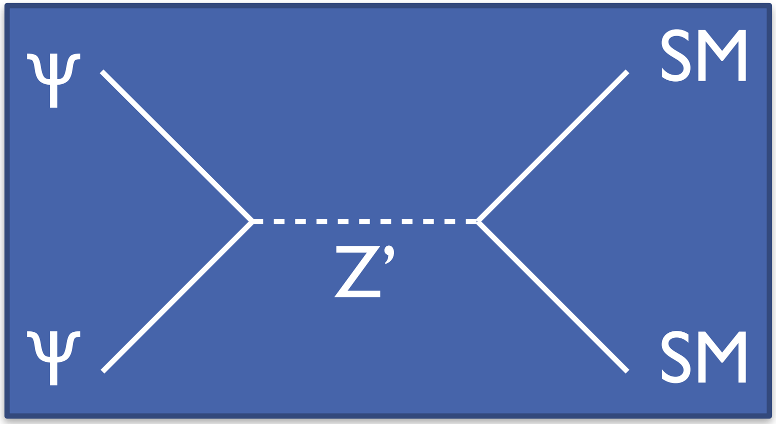
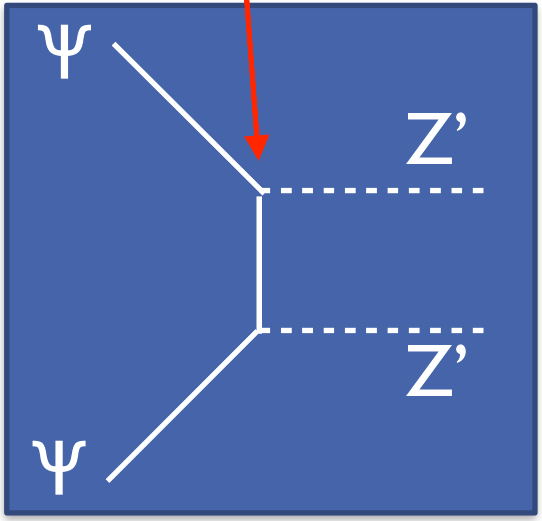
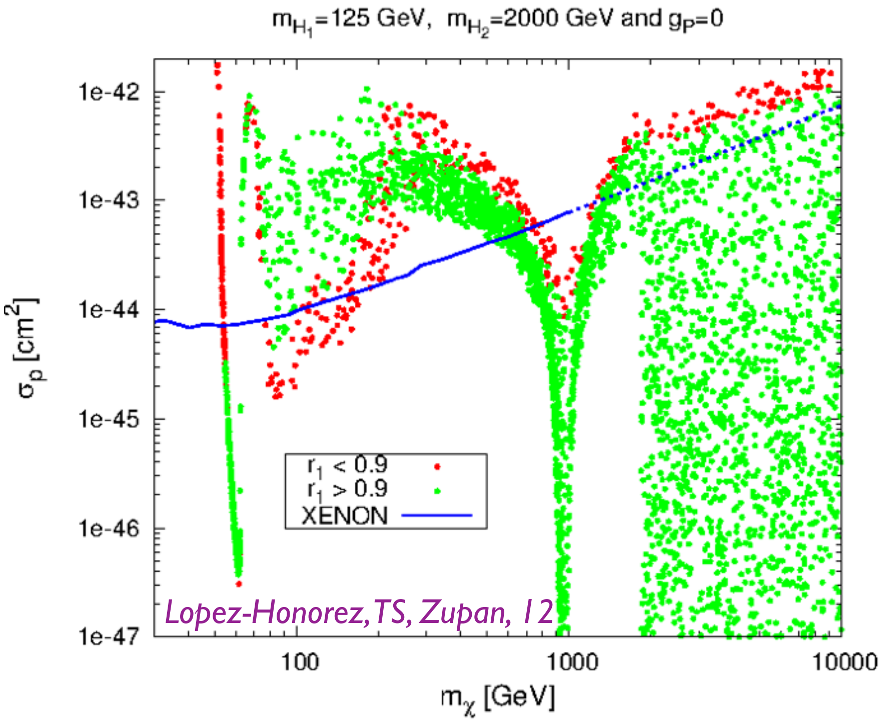
$m_{DM} > m_{Z'}$





Saving the WIMP by a light mediator: Secluded DM

example from a Higgs portal model



Lopez-Honorez, TS, Zupan, 12

Saving the WIMP by a light mediator: Secluded DM

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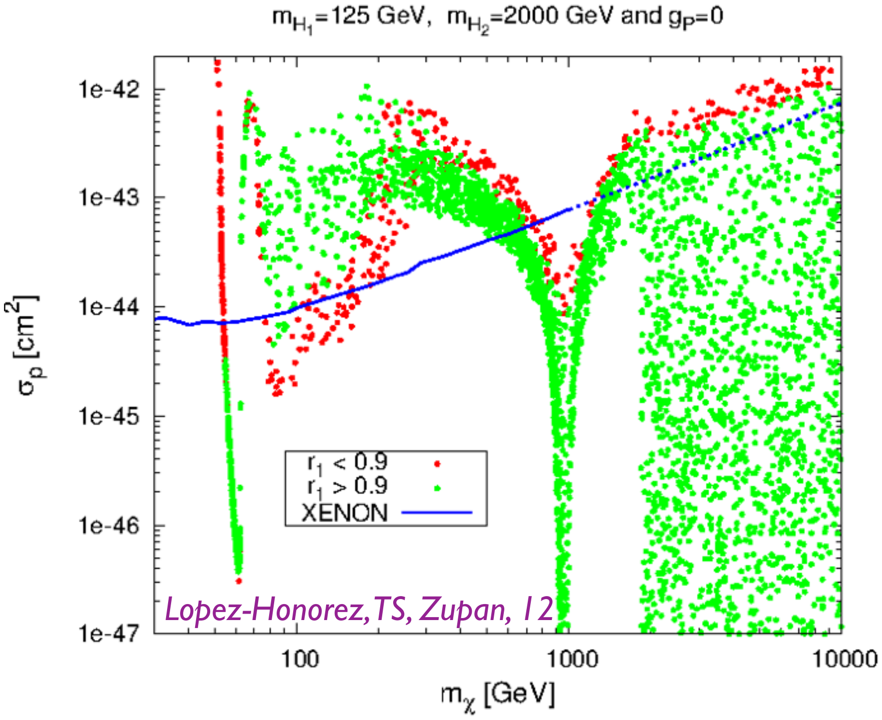
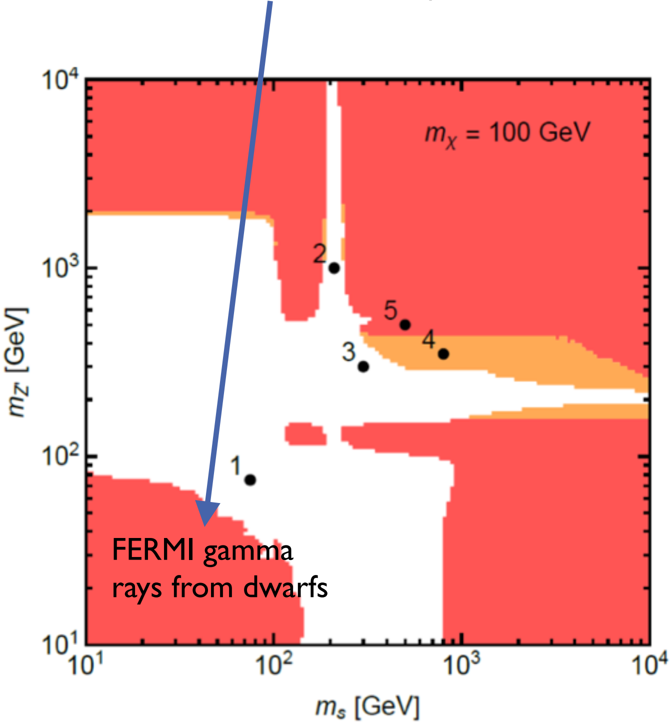


Lopez-Honorez, TS, Zupan, 12

in some cases there may be a signal in indirect searches (s-channel annih.)



FERMI gamma rays from dwarfs

SUSY neutralino DM Example:

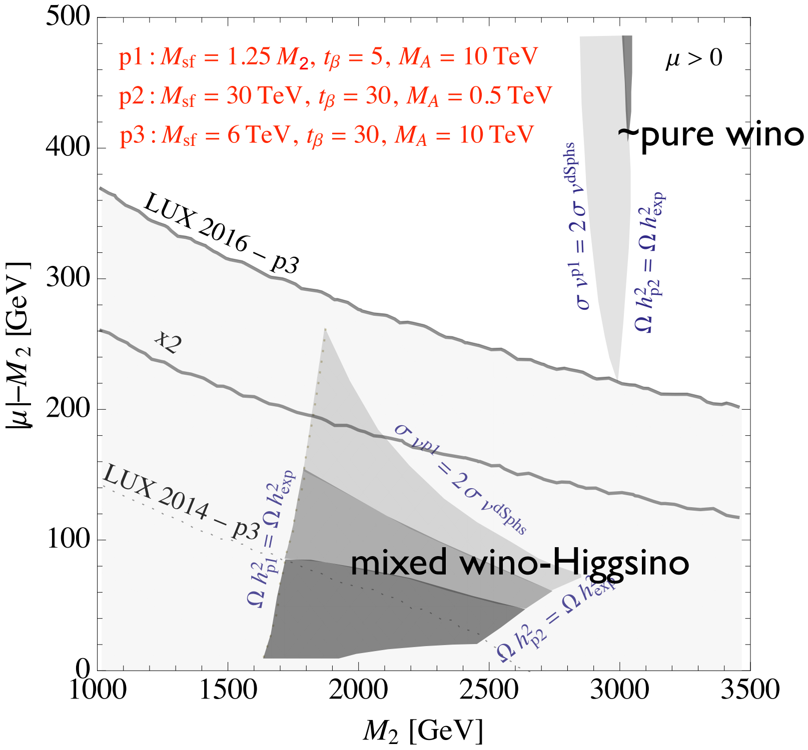
arXiv.org > hep-ph > arXiv:1611.00804

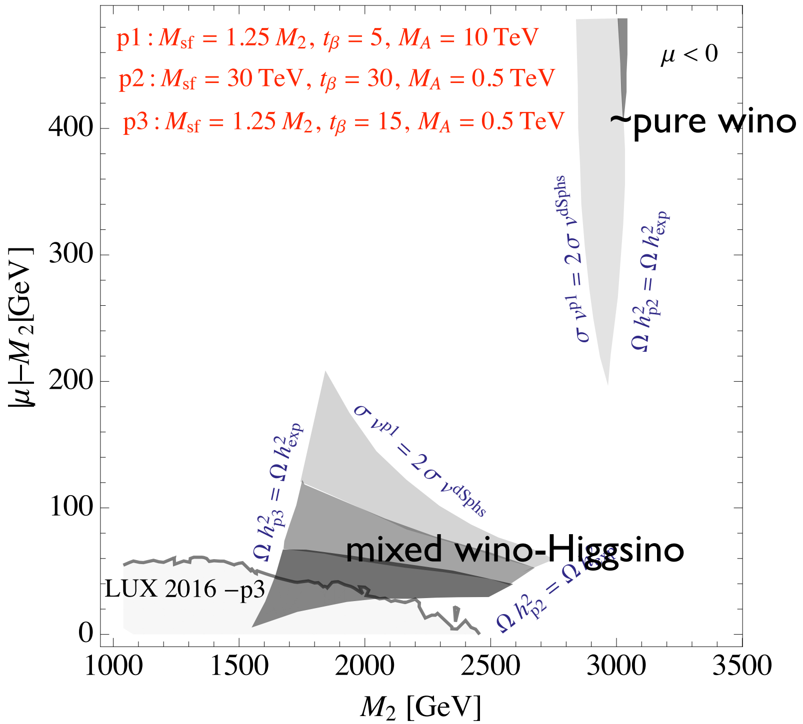
High Energy Physics – Phenomenology

The last refuge of mixed wino-Higgsino dark matter

Martin Beneke, Aoife Bharucha, Andrzej Hryczuk, Stefan Recksiegel, Pedro Ruiz-Femenia

(Submitted on 2 Nov 2016)





SUSY neutralino DM

„adopting a less conservative approach […] the entire parameter region [… is] in strong tension with the indirect searches“

arXiv.org > hep-ph > arXiv:1611.00804

High Energy Physics – Phenomenology

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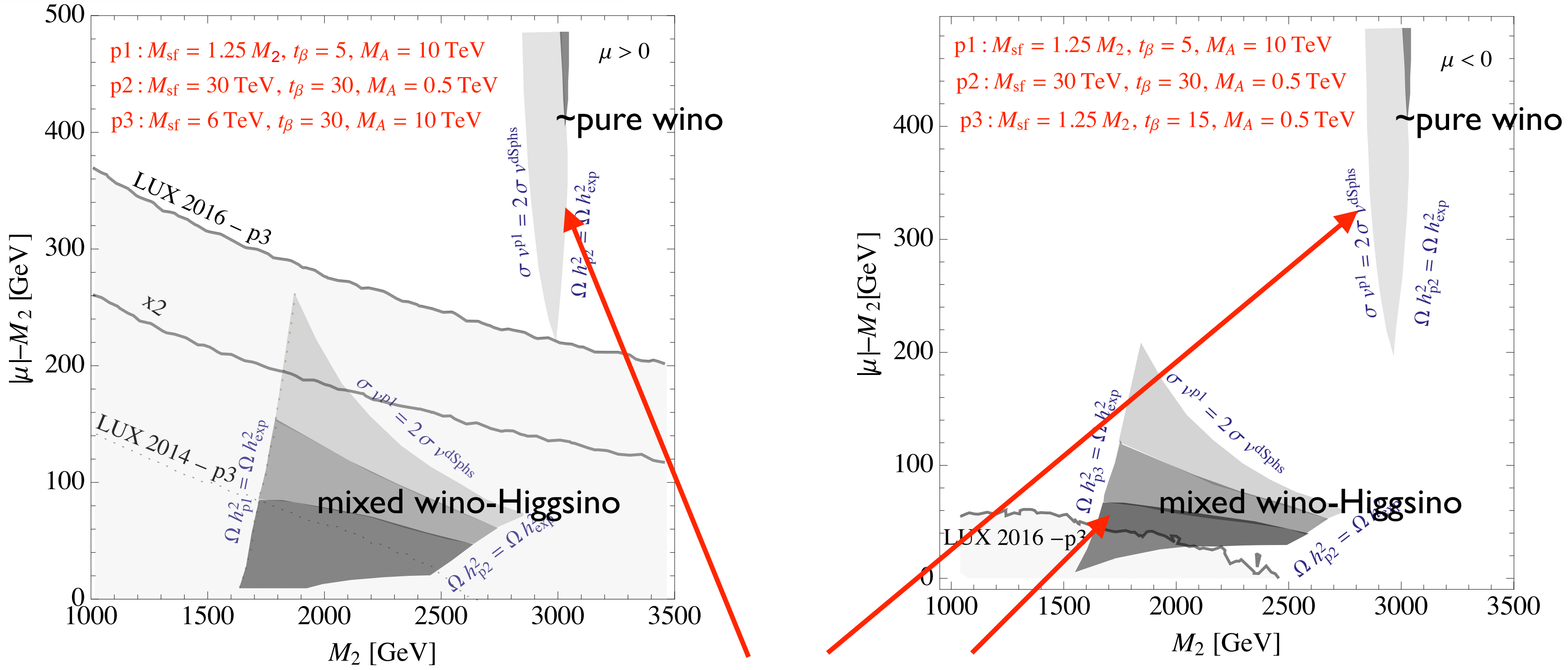


WIMP is cornered

Remarks on WIMPs

- WIMP hypothesis under scrutiny by experiment
- always possible to „hide“ the WIMP but the core parameter space will be covered

Remarks on WIMPs

- WIMP hypothesis under scrutiny by experiment
- always possible to „hide“ the WIMP but the core parameter space will be covered
- Where is the new physics at LHC? Does the naturalness argument for the EW scale fail?
- How attractive is the WIMP without the naturalness argument? (No miracle any more)

WIMPs without naturalness

Many many models …(very incomplete list)

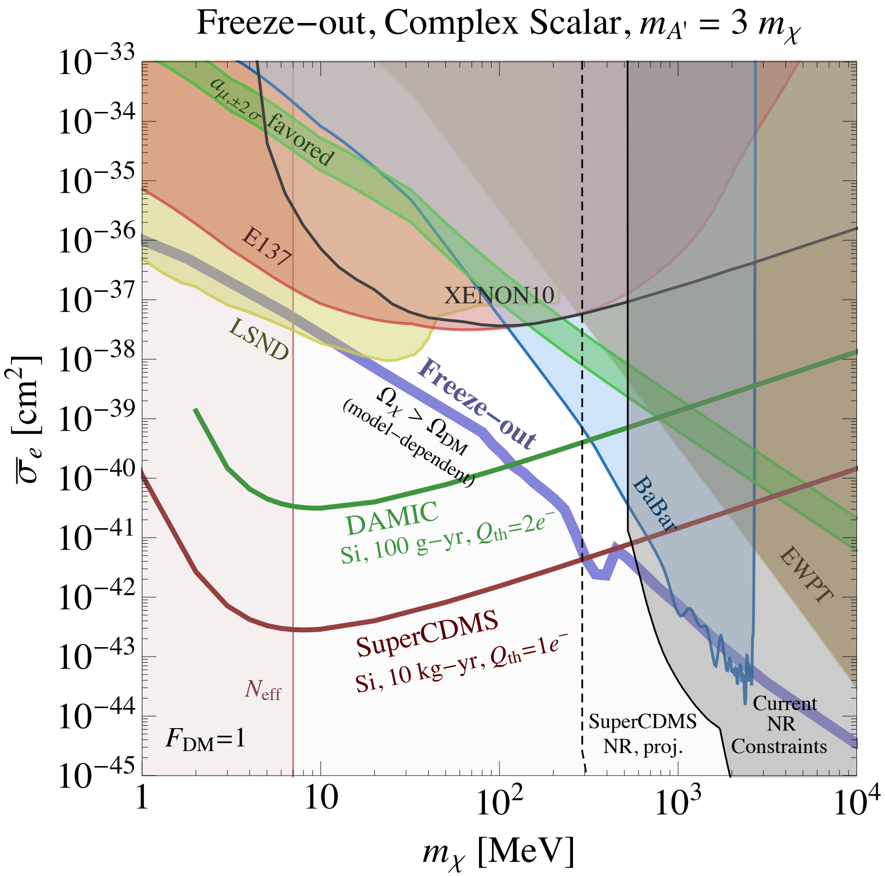
- Higgs portal DM
- DM as SU(2) x U(1) representation
  [minimal DM, Cirelli, Fornengo, Strumia, 05]
- Weak scale neutrino mass models linked to DM
  [Scotogenic Model, E. Ma, 05,…]
- many more…

WIMPs without naturalness

- freeze-out works for a wide range of mass-scales connection to weak-scale physics is lost

Ex.: complex scalar DM interacting with a massive dark photon

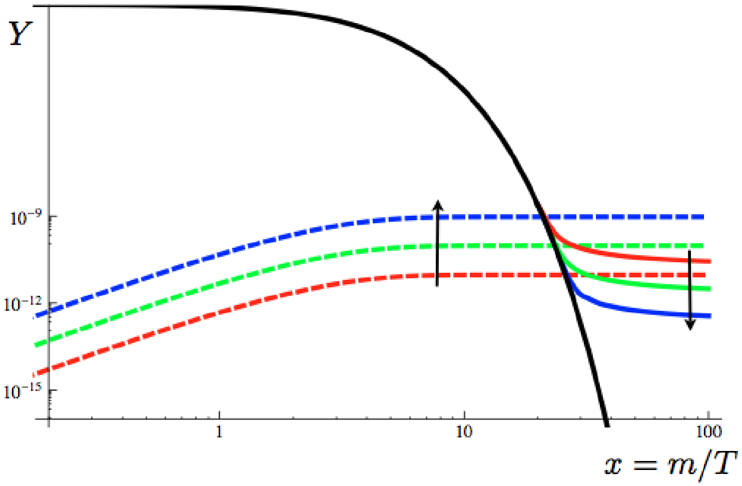
R. Essig et al., 1509.01598



Freeze−out, Complex Scalar, $m_{A'} = 3\, m_\chi$

DM production via freeze-in (FIMP)

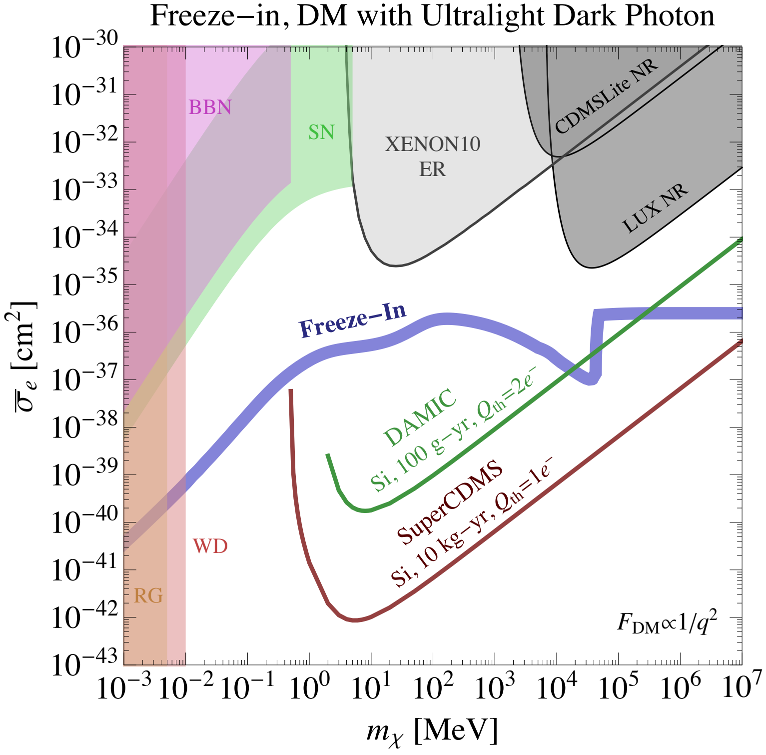
- particle never in thermal equilibrium
- (tiny) interactions with thermal bath produce the DM until the interaction rate << expansion
- relic abundance proportional to interaction strength



Hall, Jedamzik, March-Russel, West, 09

DM production via freeze-in (FIMP)

- works for a huge range of masses
- testability very model dependent
- many model realizations of this mechanism



R. Essig et al., 1509.01598

Nightmare scenario: gravitational interacting DM

- DM interacts only via gravity
  Planck scale suppressed operators:

$$\mathcal{L}_I = \frac{1}{M_{Pl}^n} \mathcal{O}_{\rm DM} \mathcal{O}_{\rm SM}$$

- freeze-in mechanism can produce right amount of DM for

$$\mathrm{TeV} \lesssim m_X \lesssim 10^{11} \mathrm{GeV}$$

Tang, Wu, 1604.04701

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$$\mathcal{L}_I = \frac{1}{M_{Pl}^n} \mathcal{O}_{\rm DM} \mathcal{O}_{\rm SM}$$

- freeze-in mechanism can produce right amount of DM for

$$\mathrm{TeV} \lesssim m_X \lesssim 10^{11} \mathrm{GeV}$$

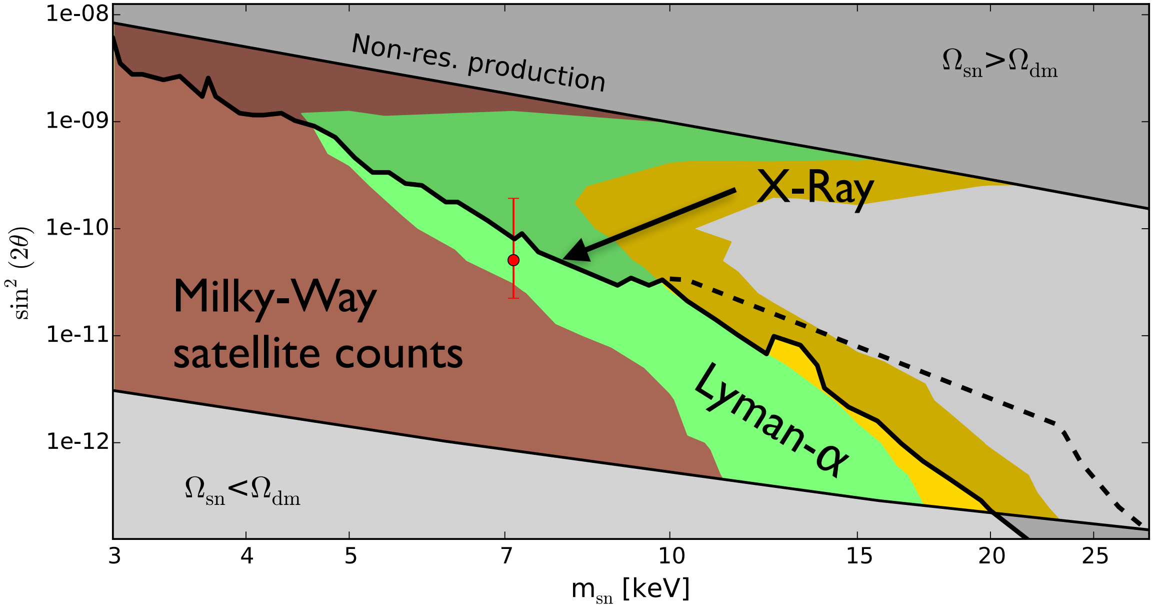
Tang, Wu, 1604.04701

- Bi-metric gravity: consistent generalization of GR
  including a massless and a massive graviton → DM

Babichev, Marzola, Raidal, Schmidt-May, Urban, Veermae, von Strauss, 16

keV sterile neutrino DM matter

- it is likely that sterile neutrinos exist (which scale?)
- mixing angle required by DM is too small to be relevant for neutrino mass generation via seesaw
- simplest production mechanism (oscillations) ruled out
  → more complicated mechanisms (resonant prod., scalar decay)



A. Schneider, 1601.07553

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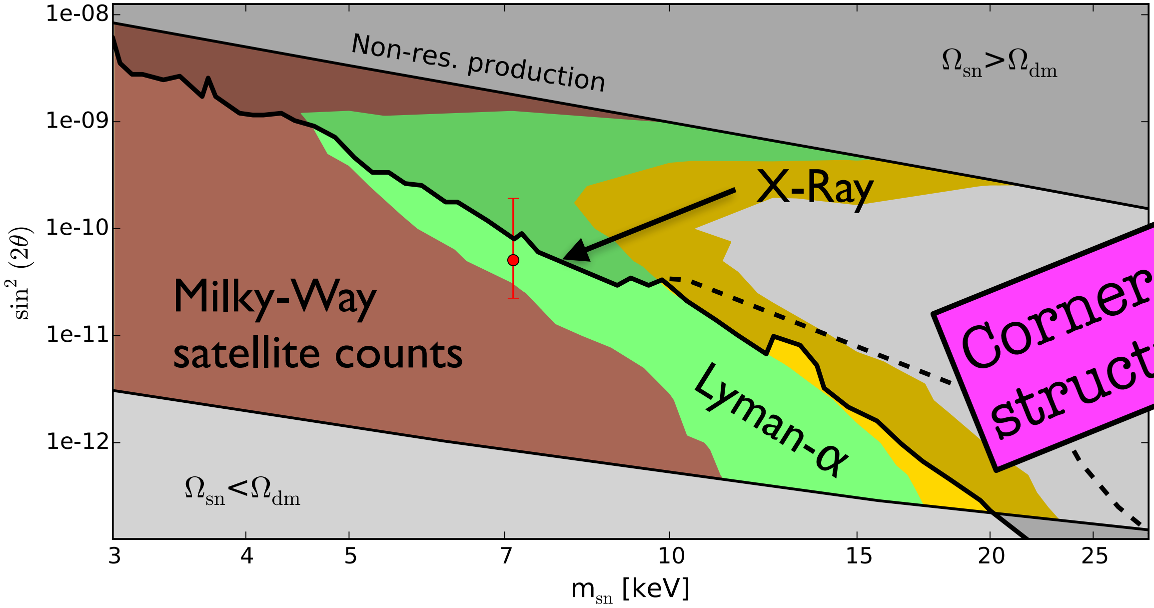
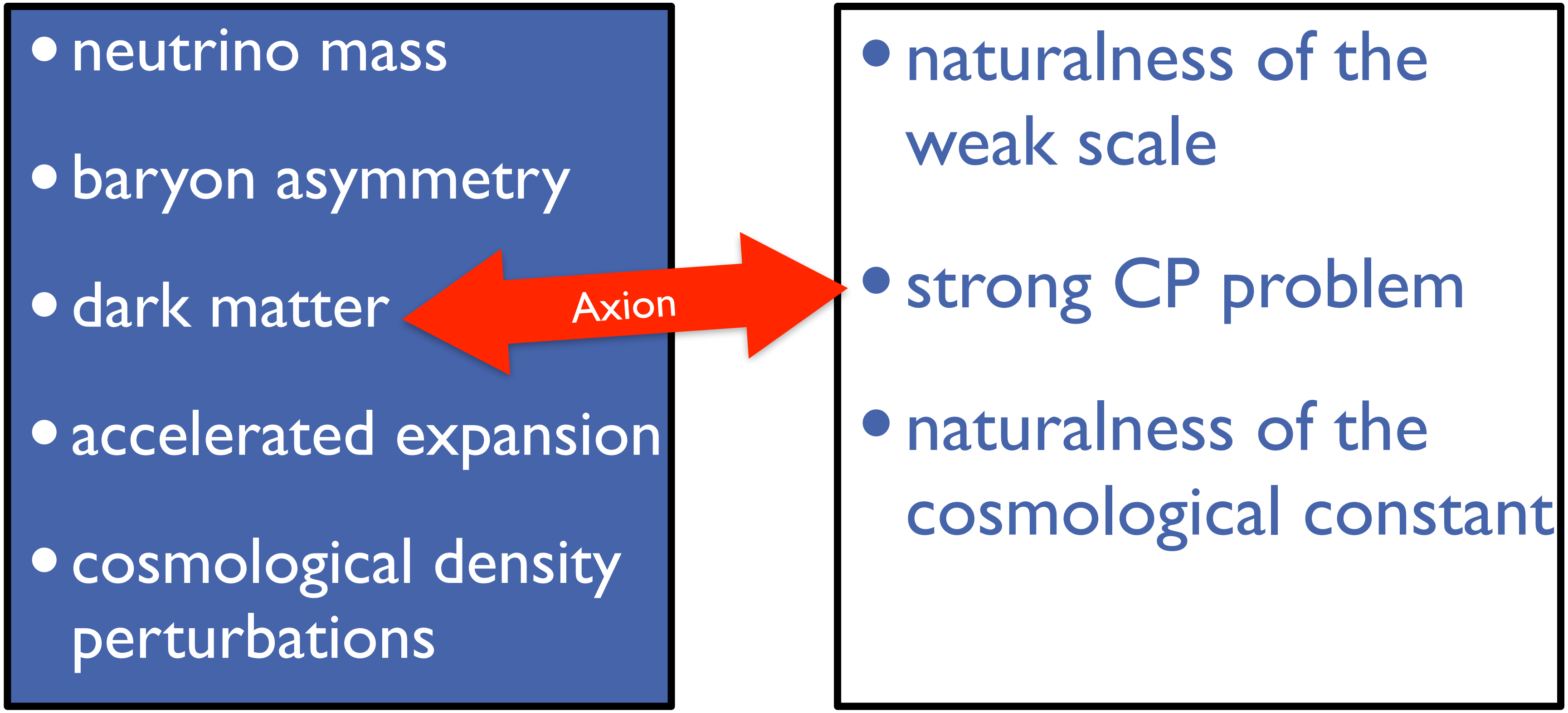


Cornered by X-ray limits and structure formation constraints

A. Schneider, 1601.07553

Axion DM



observational evidences

- neutrino mass
- baryon asymmetry
- dark matter
- accelerated expansion
- cosmological density perturbations

theoretical arguments

- naturalness of the weak scale
- strong CP problem
- naturalness of the cosmological constant

The strong CP problem

$$\mathcal{L}_{\theta\mathrm{QCD}} = \frac{\theta_{\mathrm{QCD}}}{32\pi^2}\mathrm{Tr}\ G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \theta_{\mathrm{QCD}} = \tilde{\theta}_{\mathrm{QCD}} + \arg\,\mathrm{det}M_u M_d$$

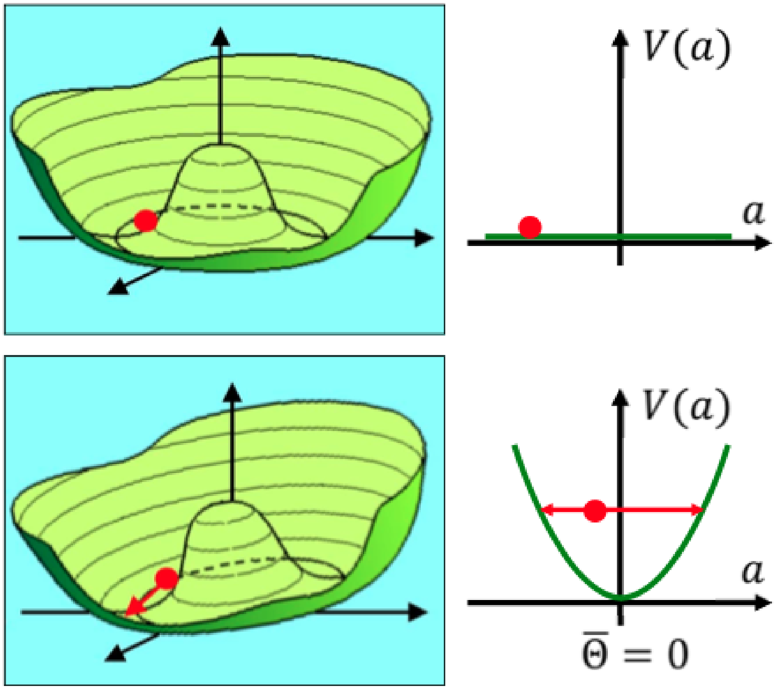
- limit on neutron electric dipole moment:

$$\boxed{\theta_{\mathrm{QCD}} \lesssim 10^{-10}}$$

- requires cancellation between bare angle and contribution from quark masses at the 10^{-10} level.

Axion solution

plots from G. Raffelt



- introduce a global U(1) symmetry (PQ)
- gets broken at high scale f_{PQ}
- axion is the p-Goldstone of the U(1)
- receives a mass by non-perturbative QCD instanton effects
- axion potential drives the theta-angle dynamically to zero

Axion solution

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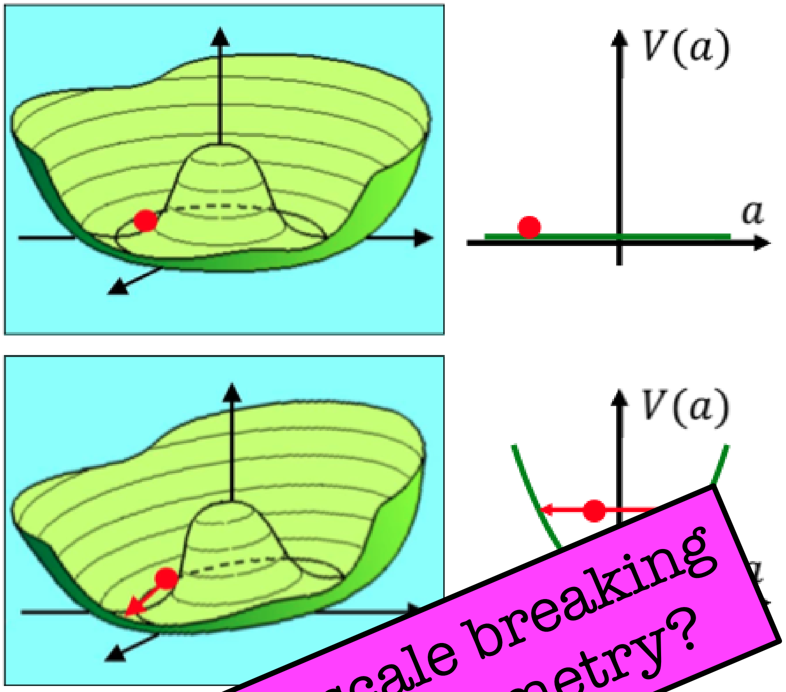

Planck-scale breaking of global symmetry?

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The QCD Axion

- mass determined by PQ breaking scale:

$$m_0 \simeq \frac{m_\pi f_\pi}{f_{\rm PQ}} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 10^{-4}\ {\rm eV}\ \frac{6 \times 10^{10}\,{\rm GeV}}{f_{\rm PQ}}\,.$$

- all interactions with SM suppressed by $f_{\rm PQ}$

- single parameter model!

Axion relic abundance

WIMP (freeze-out)

$$\Gamma_{\rm annih} \sim H(T)$$

Axions (ALPs)

$$m_a(T) \sim H(T)$$

- Axion field starts oscillating when its mass becomes comparable to the expansion rate
- cosmic energy density behaves like non-relativistic matter

$$\boxed{\rho(a) \sim f_{\rm PQ}^2 m(a_*) m_0 \overline{\theta}^2 \left(\frac{a_*}{a}\right)^3}$$

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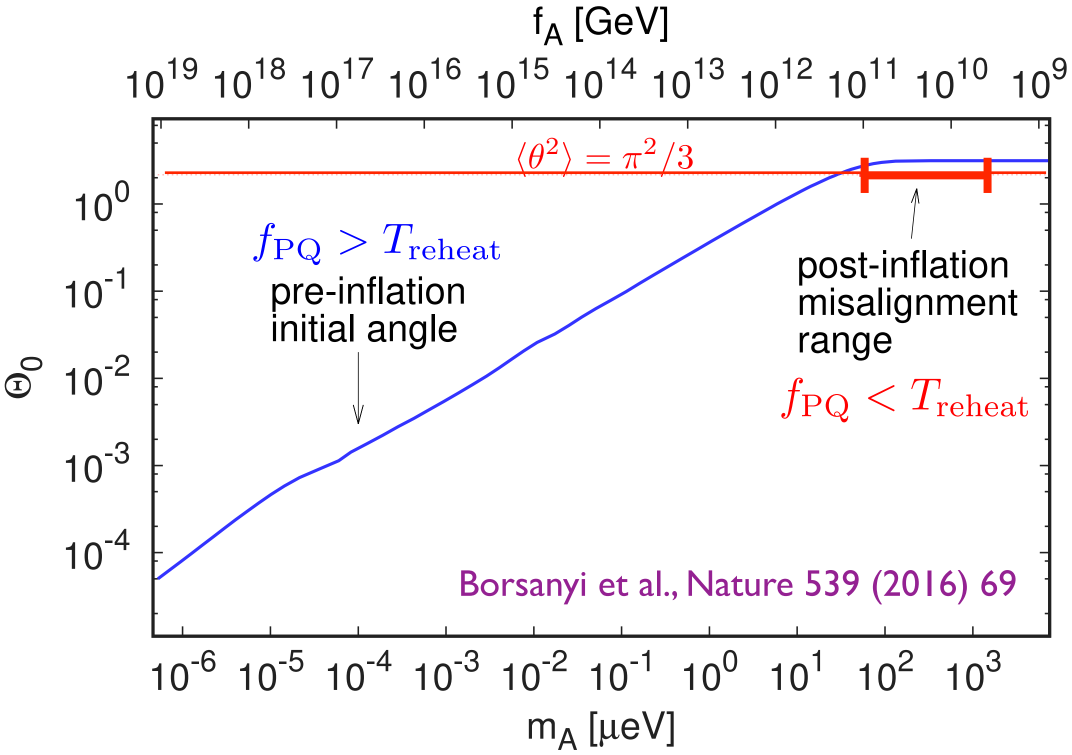
misalignment angle

Axion relic abundance

$$\Omega_a^{\rm mis} h^2 \sim \theta_0^2 \left(\frac{f_{\rm PQ}}{10^{12}\,{\rm GeV}}\right)^{7/6}$$

- pre-inflation: unique misaligment angle in observable Universe → accurate prediction for given θ_0

- post-inflation: average misaligment angle, but additional contributions from domain walls and strings (difficult to calculate)



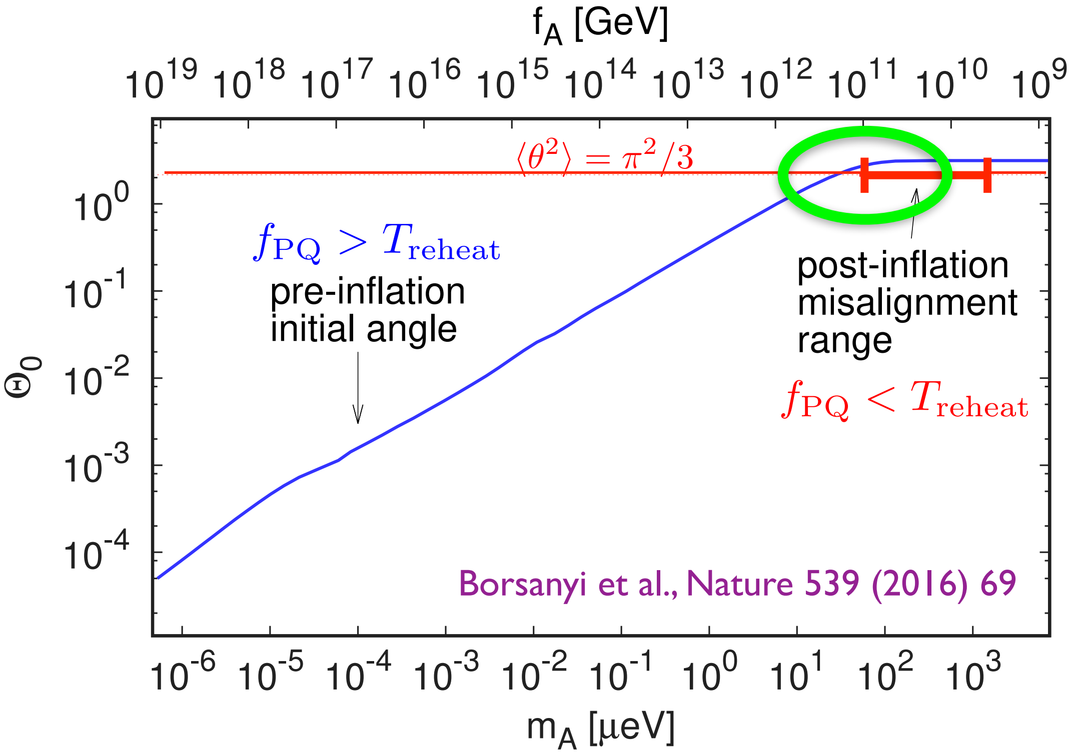
Axion relic abundance

$$\Omega_a^{\rm mis} h^2 \sim \theta_0^2 \left(\frac{f_{\rm PQ}}{10^{12}\,{\rm GeV}}\right)^{7/6}$$

- relic abundance comparable to observed DM abundance for $\theta_0 \sim 1$ and

$$f_{\rm PQ} \sim 10^{11}\,{\rm GeV}$$

$$m_a \sim 10^{-4}\,{\rm eV}$$



Borsanyi et al., Nature 539 (2016) 69

Axion relic abundance

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Is there an „axion miracle“?

the strong CP problem by itself does not point to a particular energy scale

Axion miracle? - some numerology

$$f_{\mathrm{PQ}} \sim 10^{11}\,\mathrm{GeV}$$
$$m_a \sim 10^{-4}\,\mathrm{eV}$$

$$\boxed{f_{\mathrm{PQ}} \sim \Lambda_{\mathrm{seesaw}}}$$

- associate PQ symmetry with U(1) lepton number
- Axion and Majoron become identical

Langacker, Peccei, Yanagida, 1986
Ballesteros, Redondo, Ringwald, Tamarit, 2016

Axion miracle? - some numerology

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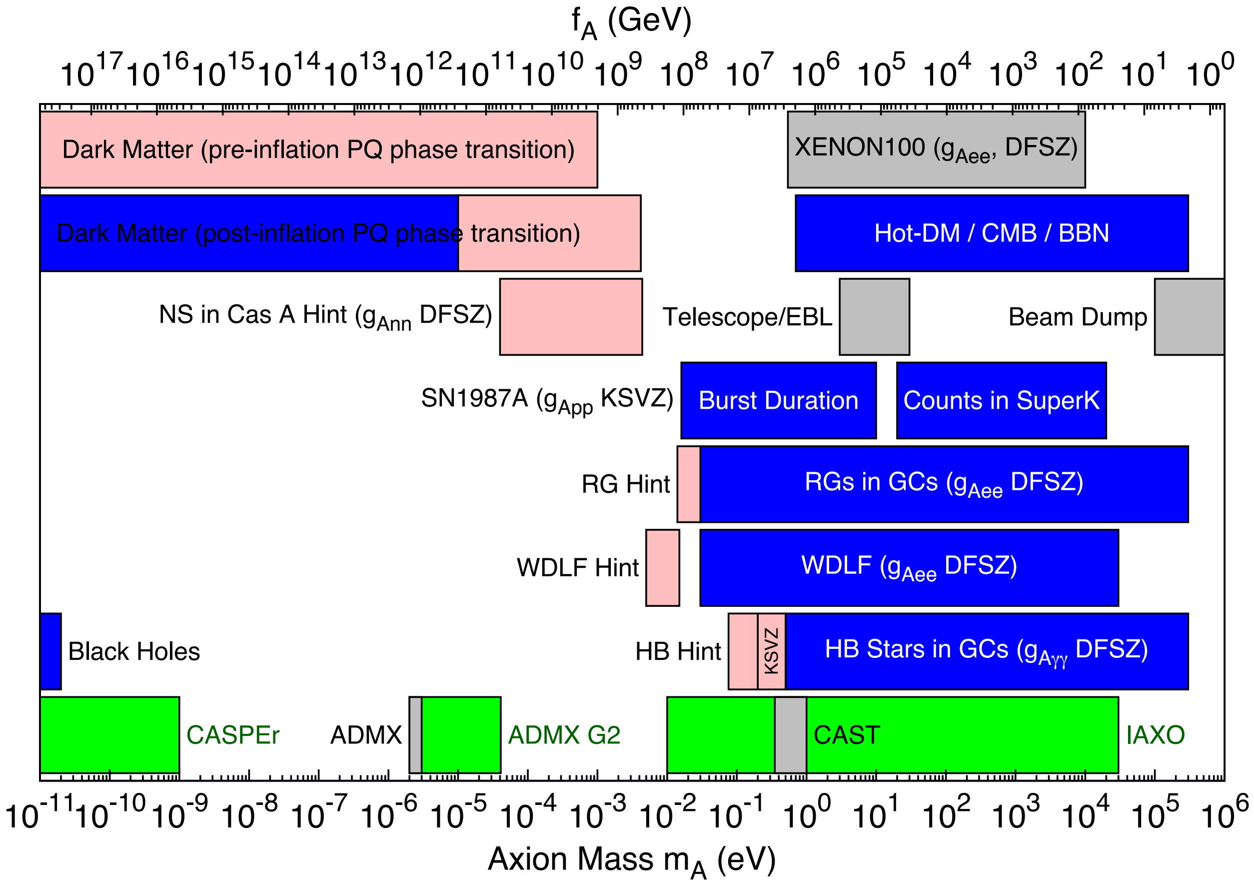
- associate PQ symmetry with U(1) lepton number
- Axion and Majoron become identical

$$m_a \sim \frac{m_\pi^2}{f_{\mathrm{PQ}}} \qquad m_\nu \sim y^2 \frac{\langle H \rangle^2}{\Lambda_{\mathrm{seesaw}}}$$

coincidence?

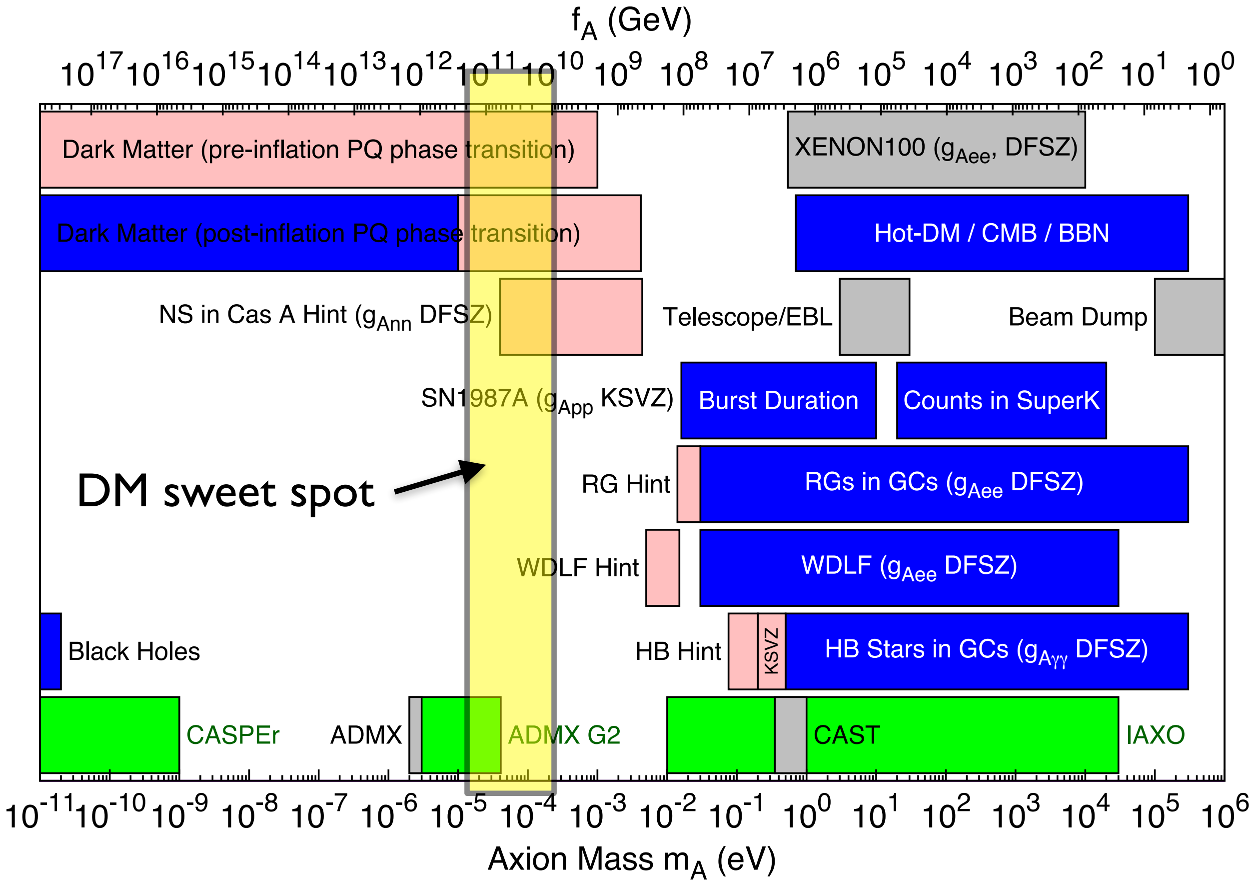
QCD axion parameter space



PDG 2015, A. Ringwald, L. Rosenberg, G. Rybka

experimentally excluded, astro/cosmo excluded,
sensitivity of planned experiments, „preferred“ region

QCD axion parameter space



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Axion-like particles (ALPs)

remember, for the QCD axion:

$$m_a \sim \frac{m_\pi^2}{f_{\mathrm{PQ}}} \qquad g_a \sim \frac{1}{f_{\mathrm{PQ}}}$$

Axion-like particles (ALPs)

remember, for the QCD axion:

fixed by QCD

$$m_a \sim \frac{\boxed{m_\pi^2}}{f_{\rm PQ}} \qquad\qquad g_a \sim \frac{1}{f_{\rm PQ}}$$

Axion-like particles (ALPs)

remember, for the QCD axion:

$$m_a \sim \frac{m_\pi^2}{f_{\rm PQ}} \qquad\qquad g_a \sim \frac{1}{f_{\rm PQ}}$$

ALP: let’s give up the explanation of the strong CP problem
Axion → p-Goldstone of a general U(1)
other new physics to generate mass for the Goldstone

$$m_a \sim \frac{m_{\rm non\text{-}pert}^2}{f_a} \qquad\qquad g_a \sim \frac{1}{f_a}$$

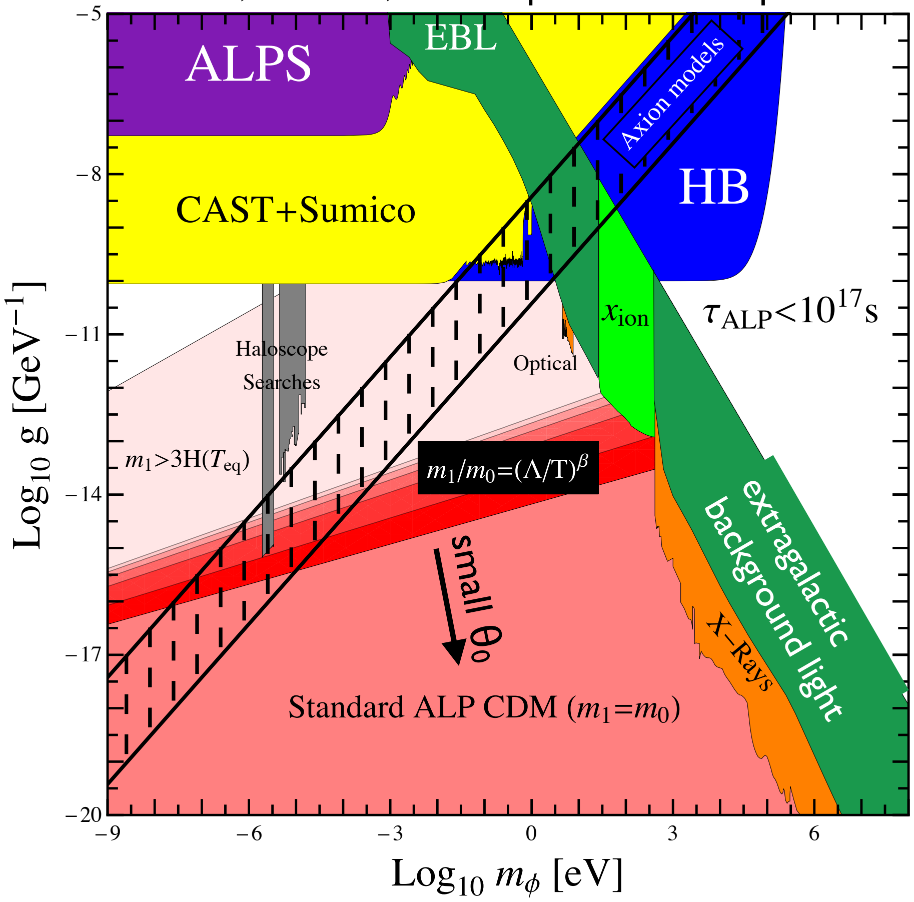
mass and coupling (or f_a) become independent
generic prediction in many BSM models

ALP DM parameter space

$$\boxed{\rho(a) \sim f_{\mathrm{PQ}}^2 m(a_*) m_0 \bar{\theta}^2 \left(\frac{a_*}{a}\right)^3}$$

- ALP mass and $g \sim 1/f_a$ are now independent
- red region: viable DM parameter space

ALPS, CAST+S, HB: indep. of DM assumption



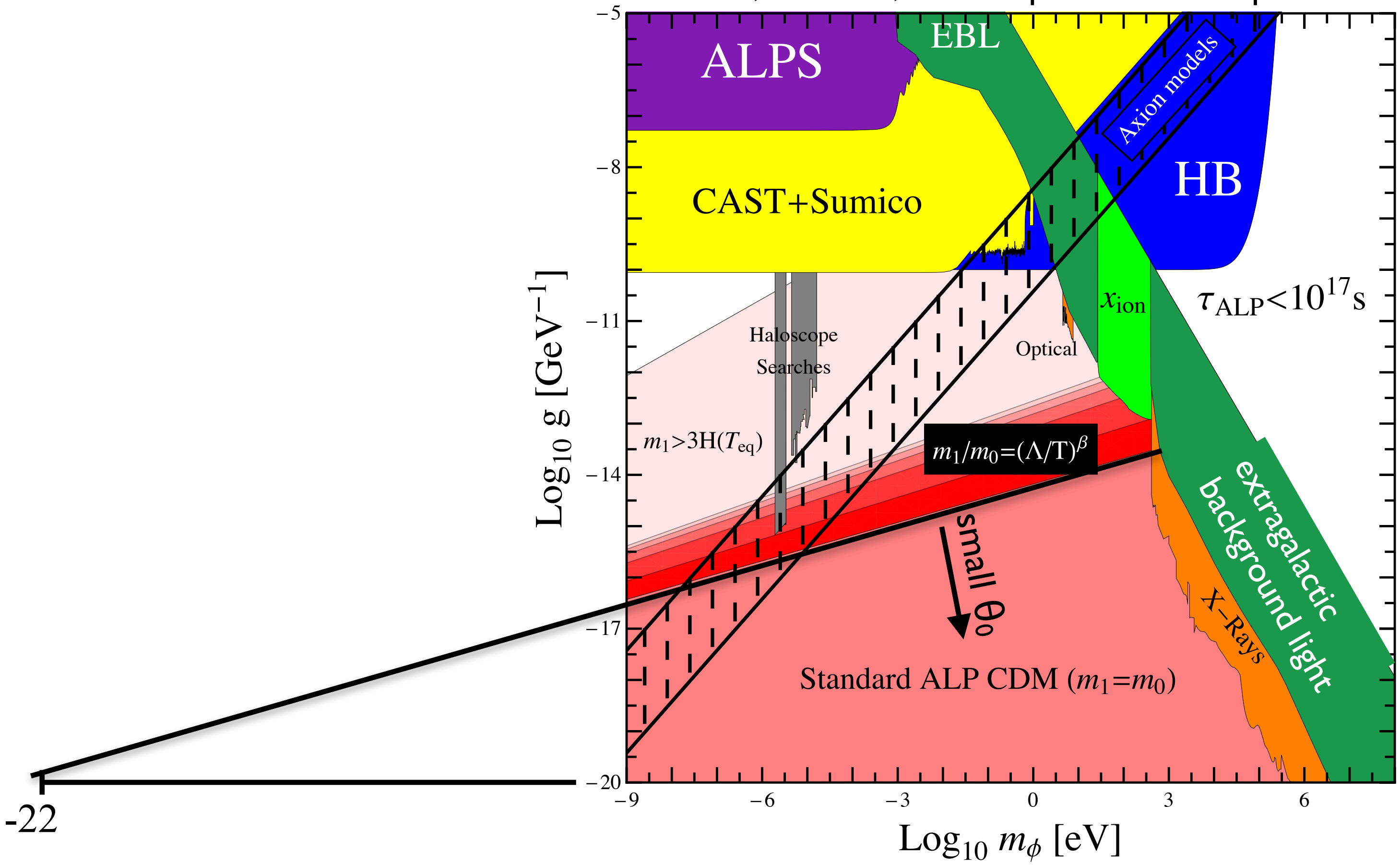
Arias, Cadamuro, Goodsell, Jäckel, Redondo, Ringwald, 12

Ultra-light scalar DM

- ALPs with m ~ 10^{-22} eV
- deBroglie wavelength becomes of order kpc (dwarf galaxy size)
- no structure smaller than this can form
- may address some issues with CDM
- „Fuzzy DM“ Hu, Barkana, Gruzinov, 2000

ALP miracle?

ALPS, CAST+S, HB: indep. of DM assumption

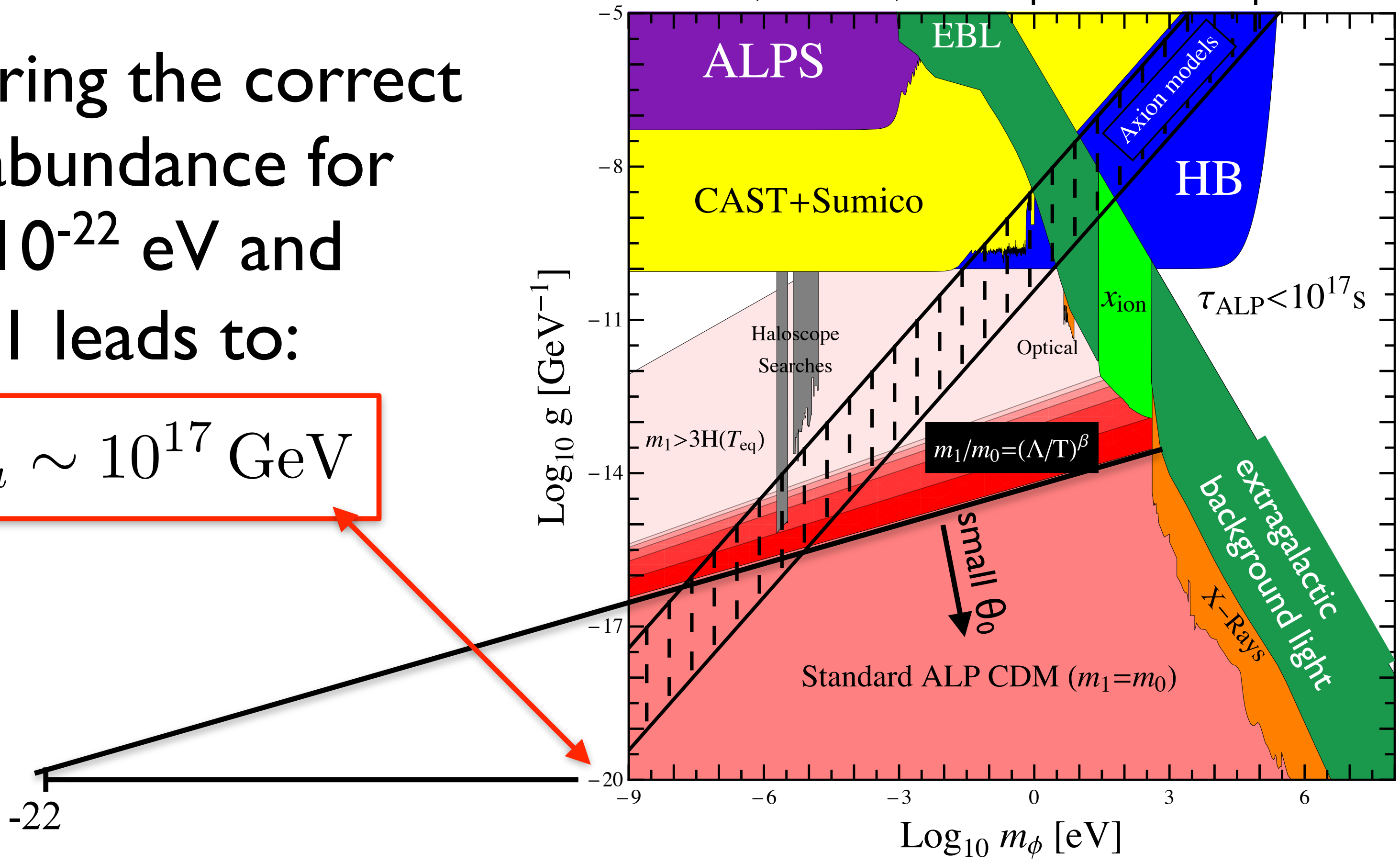


ALP miracle?

- requiring the correct DM abundance for m ~ 10^{-22} eV and θ_0 ~ 1 leads to:

$$\boxed{f_a \sim 10^{17}\,\mathrm{GeV}}$$

ALPS, CAST+S, HB: indep. of DM assumption



ALP miracle?

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$$\boxed{f_a \sim 10^{17}\,\mathrm{GeV}}$$

- preferred range for string-motivated ALPs is between the GUT and Planck scales:

$$\boxed{10^{16} \lesssim f_a \lesssim 10^{18}\,\mathrm{GeV}}$$

Hui, Ostriker, Tremaine, Witten, 16

Hidden photon DM (no miracles)

$$\mathcal{L} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{m_{\gamma'}^2}{2} X_\mu X^\mu + \mathcal{L}_{\text{grav}} + \mathcal{L}_I ,$$

$$\mathcal{L}_{\text{grav}} = \frac{\kappa}{12} R X_\mu X^\mu \qquad \mathcal{L}_I = -\frac{\chi}{2} X_{\mu\nu} F^{\mu\nu}$$

- light U(1) vector boson
- kinetically mixed with photon
- need to include coupling to gravity to describe cosmic evolution

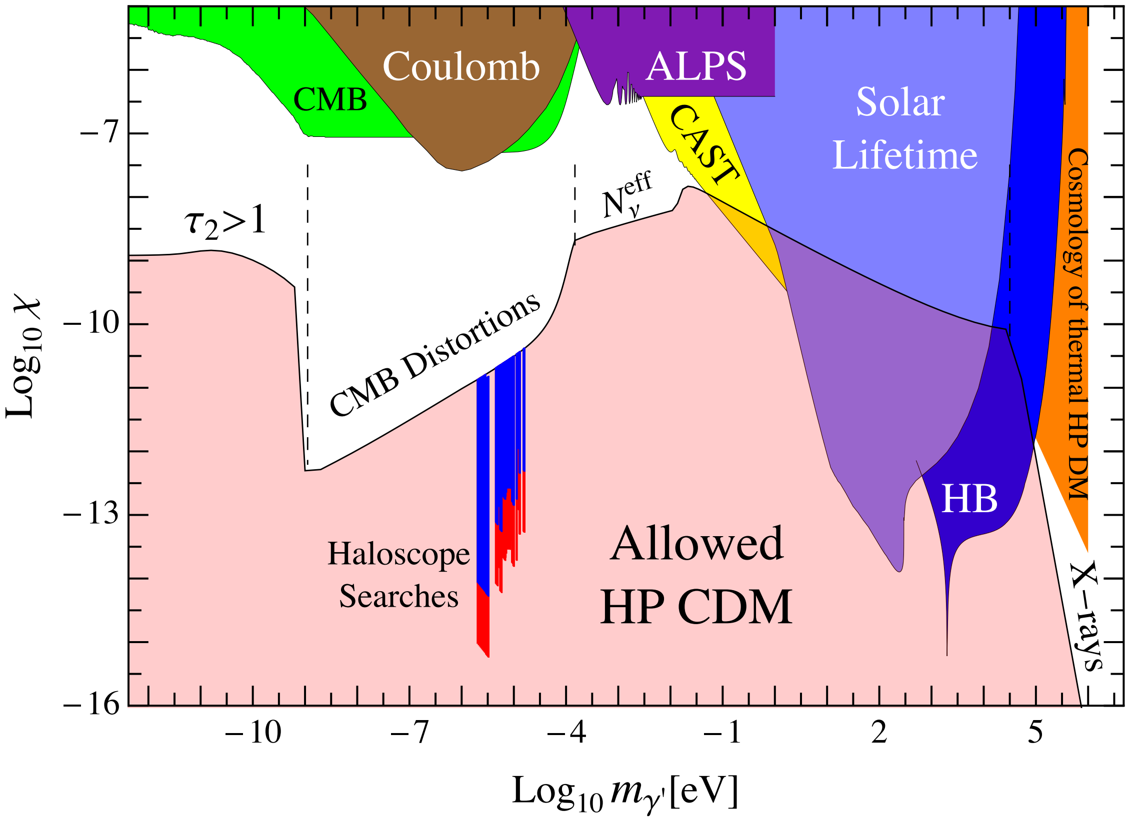
Hidden photon DM

- DM production by re-alignment mechanism
  Nelson, Scholtz, 11, Arias et al., 12

- initial field value not bounded
  (because not an angular field as for ALPs)
  easy to accommodate observed DM abundance

- alternative production during inflation
  P.W. Graham, J. Mardon, S. Rajendran, 1504.02102

Hidden photon DM



Arias, Cadamuro, Goodsell, Jäckel, Redondo, Ringwald, 12

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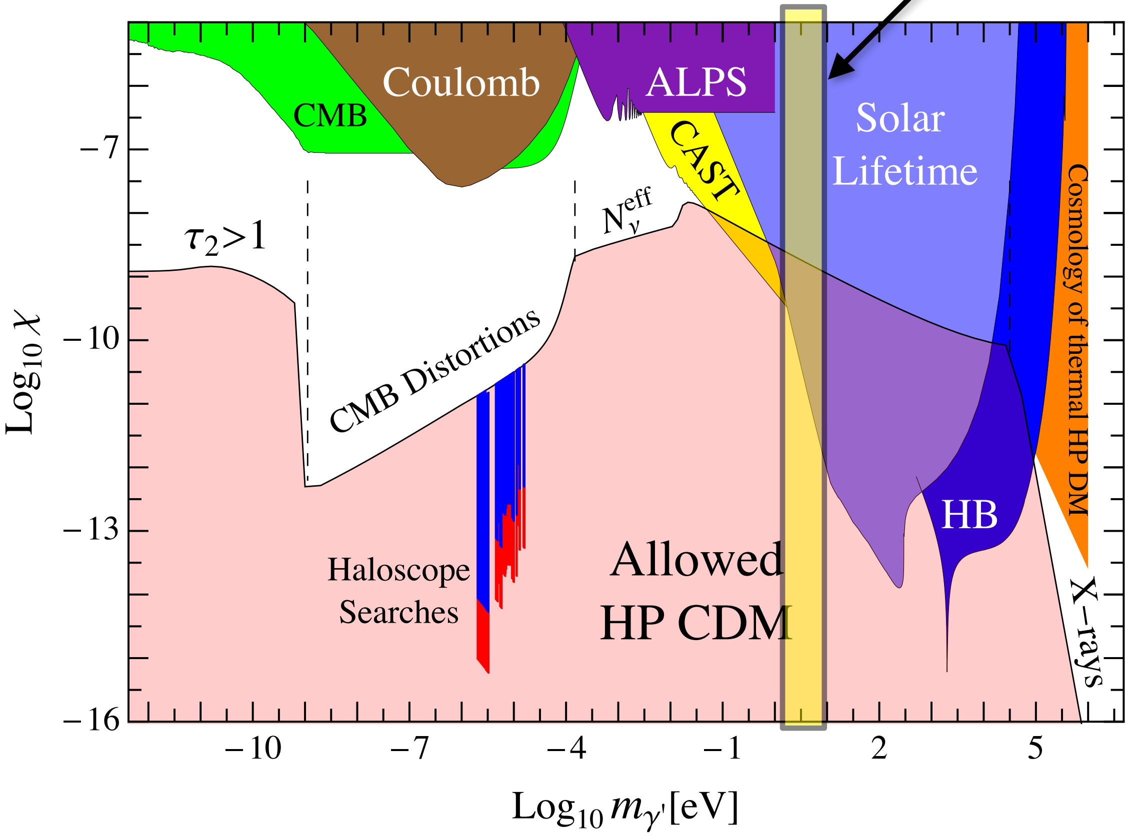

FUNK @ KIT
coming soon…

Arias, Cadamuro, Goodsell, Jäckel, Redondo, Ringwald, 12

Conclusions?

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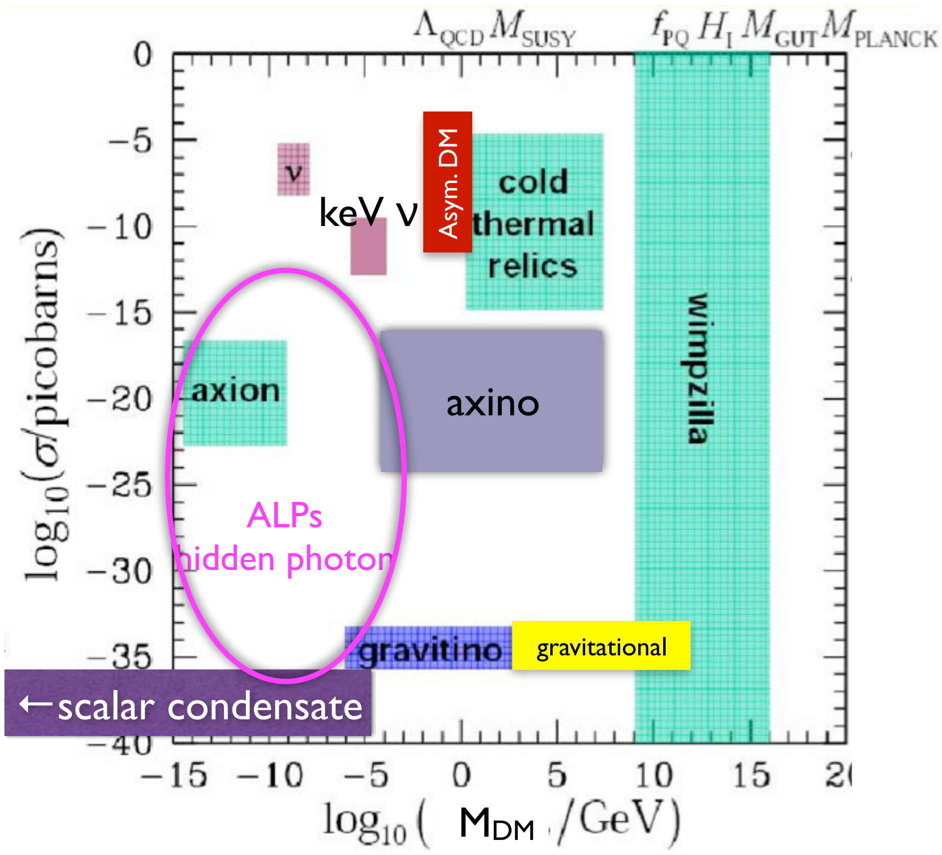
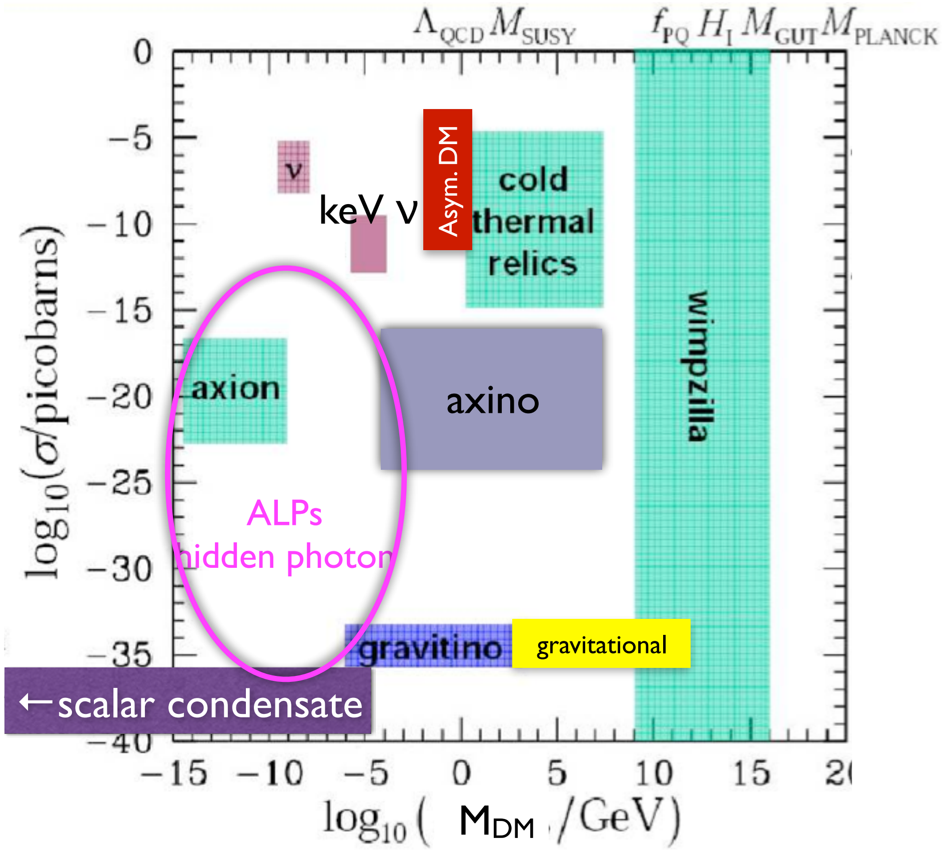
- we don’t need miracles but data!

Conclusions?



- the game is completely open
- no clear preference from theory (some candidates more motivated than others)
- some candidates are getting really cornered→ excellent prospects for discovery

Conclusions?



- the game is completely open
- no clear preference from theory (some candidates more motivated than others)
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If you don't yet know where you're going, any road may take you there. [Lewis Carroll]

John Ellis, Where is particle physics going? 1704.02821