Dark matter at a crossroads

Leszek Roszkowski

Astrocent, Nicolaus Copernicus Astronomical Center of PAS
and
National Centre for Nuclear Research
Poland

AstroCeNT:
Particle Astrophysics Center for Science and Technology, https://astrocent.camk.edu.pl/

ASTROCENT

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480

Dark Wave

European Funds | Republic of Poland | FNP Foundation for Polish Science | European Union


This way
That way
Who knows?
over there
over yonder
over here
?

Outline

- ✧ Introduction
- ✧ main strands in DM models
  - ✧ Some DM candidates and DM production mechanisms
  - ✧ Standard thermal WIMP:
    - ✧ (too) many possibilities
    - ✧ my favourite choice: 1 TeV higgsino of SUSY
  - ✧ Comments on light DM (~1 MeV - ~1 GeV)
- ✧ Axion DM in non-standard cosmologies
- ✧ Summary

Where is the DM?

- **Mass range: at least 30 orders of magnitude**

- **Interaction range: some 32 orders of magnitude**

What is DM?

- **Many different approaches, many include additional, light dark sector**

Impeded DM
1609.02147,…

Co-scattering DM
1705.08450, 1705.09292,…

iDM
hep-ph/0101138, …

Secluded DM
0711.4866, …

Selfish DM
1504.00361,…

Co-decaying DM
1607.03110, …

Forbidden DM
Griest-Seckel, 1505.07107, …

Cannibal DM
1602.04219, …

Semi-annihilating DM
1003.5912, …

Boosted DM
1405.7370, 1503.02669…

… and many other

<Your choice> DM
1811.xxxx

→Seemingly only limited by our ability to invent new names …

Darme

TOM GAULD for NEW SCIENTIST

Three main strands in DM models

❖ Particle theory-driven

- DM candidate is part of a more complete, and more motivated, framework…
- Solves more than one (DM) problem
- Provides promising framework for Big Bang physics
- Is compatible with data

• Gauge hierarchy problem
• Unification of SM forces (+gravity?)
• Unification of SM matter, …
• Strong CP problem
• Naturalness of some sort?
• …

❖ Mapping-driven

- Any interactions allowed by basic principles and data
- Not necessarily complete models
- Usually not addressing other issues
  - Simplified models
  - Effective theory models
- …

Mapping out the landscape
of possible models and interactions

❖ Data-driven

- Fit one or more data result

Classes of DM candidates

Stable, cold, cosmic relic with $\Omega h^2 \sim 0.1$

WIMP: weakly interacting massive particle

Two prime *classes* of candidates:

- WIMP
- axion

← strongly motivated

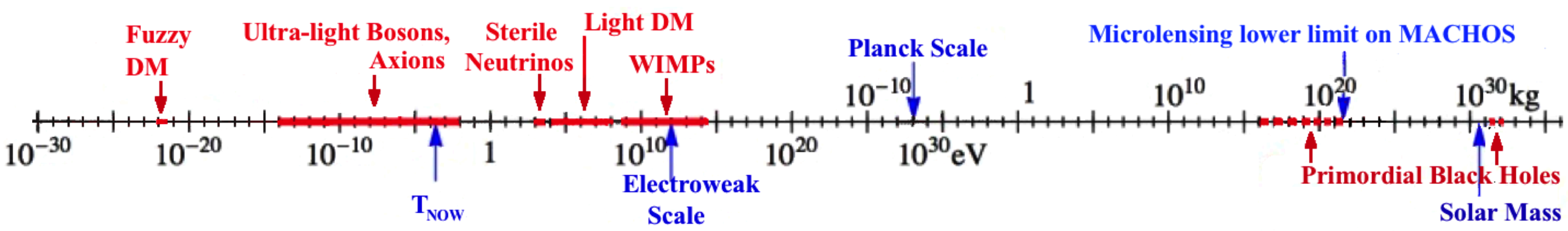
They have not been invented to solve DM problem
- WIMP: predicted in many beyond SM (BSM) frameworks
- Axion: by-product of PQ solution to strong CP problem

(Some) other possibilities:

- Asymmetric DM
- Sterile (s)neutrino
- Exotica:
  - gravitino, axino of SUSY
  - Fuzzy DM
  - Other extremely-weekly coupled DM
  - …
- PBHs (not particles)

Often non-detectable…

…much creative activity in the field



Gelmini, Rept. Prog. Phys. (2017)

Ultimate criterion: DM Detection

The WIMP is more than the``standard" thermal WIMP

cosmic relic with $\Omega h^2 \sim 0.1$

- **standard (thermal) WIMP**

  mass: ~GeV to TeV, int's: ~(sub)EW

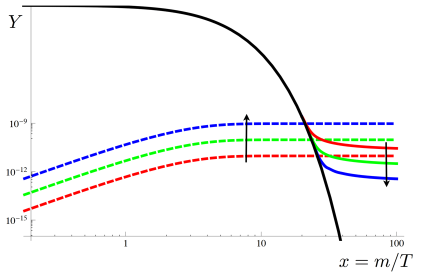
- **general (thermal) WIMP**

  mass: ~eV to ~100 TeV, ints: ***not only*** (sub)EW

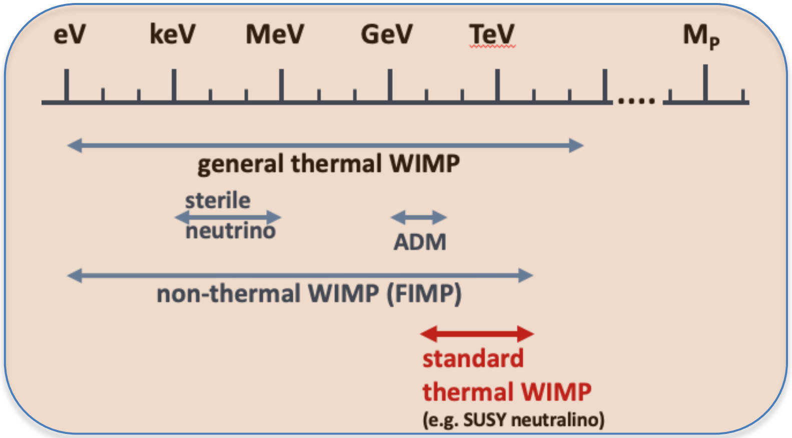
- **non-thermal WIMP (FIMP)**

  mass: ~eV to ~100 TeV, int's: usually << thermal WIMP

thermal: thermally produced via freeze-out



non-thermal: DM from freeze-in, etc



Direct Detection of Dark Matter
-- APPEC Committee Report 2104.07634 (→ ROPP)

(many) DM experimentalists:

- any ``theory WIMP"-like particle that can be searched for in ug detectors

Huge challenge for experimental DM search to probe the WIMP

Claims of WIMP's death have been grossly exaggerated

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group ⓘ

Science

The Universe is out there, waiting for you to discover it.

WIMPs on Death Row

Posted on July 21, 2016 by woit

``Standard" thermal WIMP

few GeV < mass < few TeV

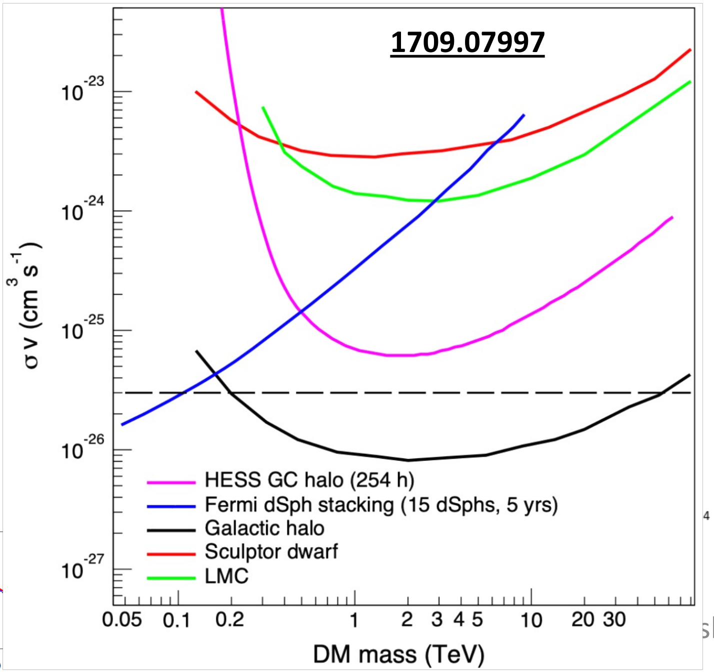
Part of some BSM framework (e.g. SUSY)

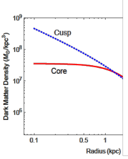
- electroweak interactions involved in production in early Universe
- Freeze-out:
  Omega*h^2=0.1 → <sigma_{ann} v> ~ $3\text{x}10^{-26}$ cm^3/s

$$\Omega h^2 \simeq \frac{0.1}{\frac{\langle \sigma_{\rm ann} v \rangle}{3\times 10^{-26}{\rm cm}^3/{\rm s}}}$$

Within ~order of magnitude

- sigma*v of $3\text{x}10^{-26}$ cm^3/s – natural target for ID searches





Still large astrophysical uncertainties:

- Halo profiles
- Galactic center (+foreground)
- Size and distribution of DM clumps
- …

Once the ``thermal benchmark" region is explored, then the WIMP hypothesis will become ``disfavoured"

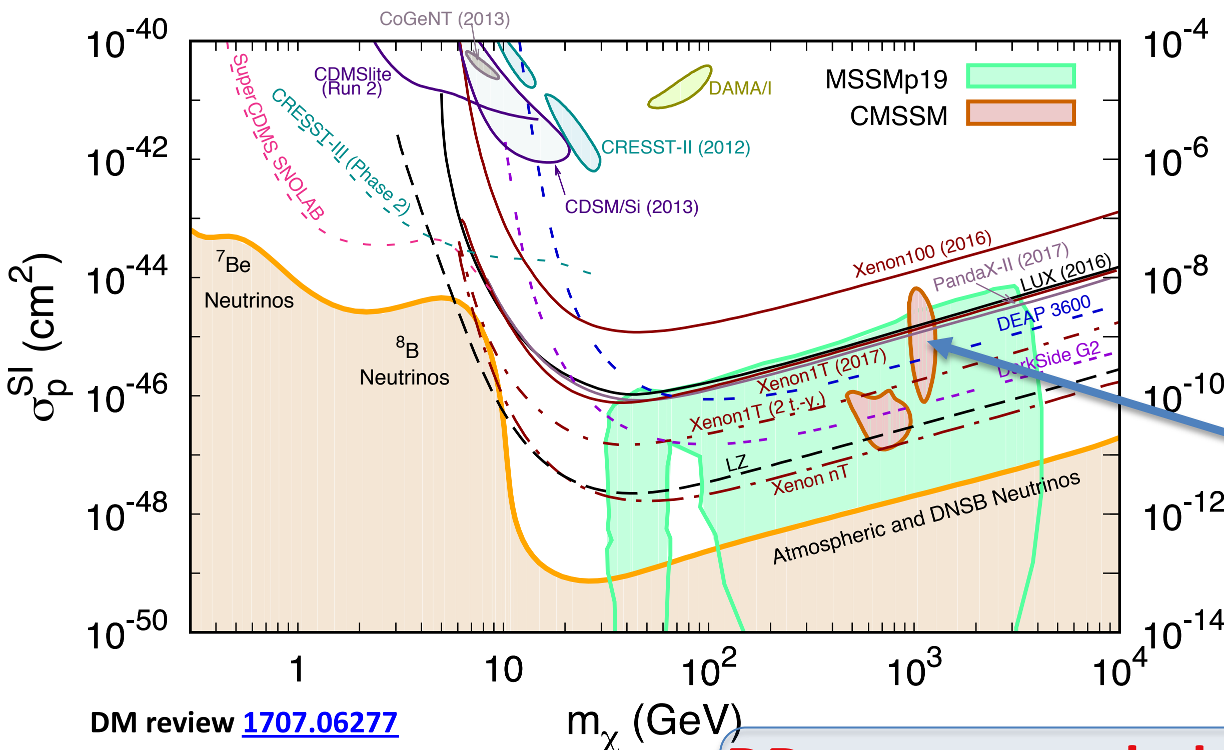
(except for ADM)

Is there a ``benchmark" cross section for DD searches?

NO!

Theoretical predictions:

- are model dependent
- predicted ranges depend on theoretical expectations/assumptions
- are known to have ``blind spots" of vanishing DD c.s.



Claims that the standard WIMP is ``disfavored" lack scientific basis.

My favourite: ~1TeV higgsino

DM review [1707.06277](1707.06277)
LR, Sessolo, Trojanowski

DD target: reach down to ``neutrino floor" and expand towards lower mass range

~125 GeV Higgs and DM in unified SUSY

- **Take only m_h~125 GeV and lower limits from direct SUSY searches**

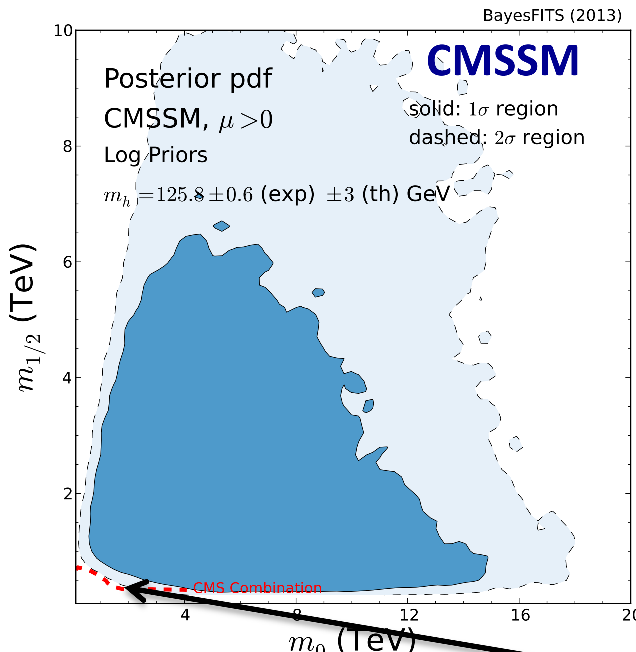
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)\right]$$

$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\,\mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

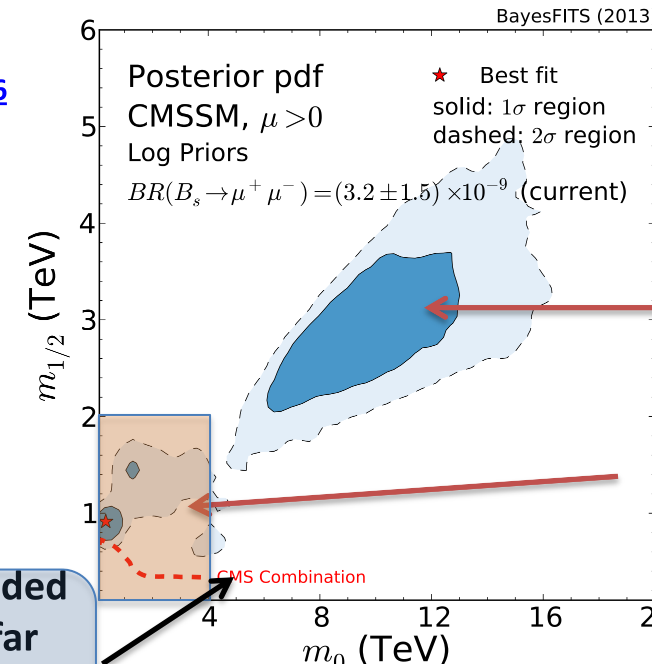
$$M_{SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \qquad X_t = A_t - \mu \cot\beta$$

$$\sigma = 0.6\ \mathrm{GeV}, \tau = 2\ \mathrm{GeV}$$

- **Add relic abundance** $\Omega_{DM} h^2 \simeq 0.12$



1302.5956



~1 TeV higgsino DM (``new")

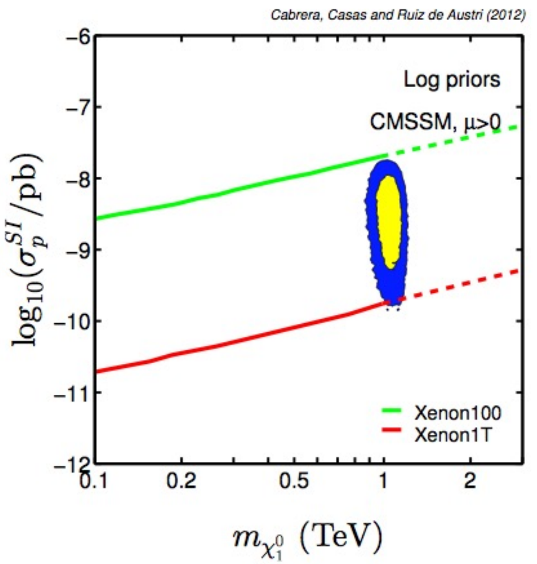
bino DM (previously favored)

Excluded so far by LHC searches

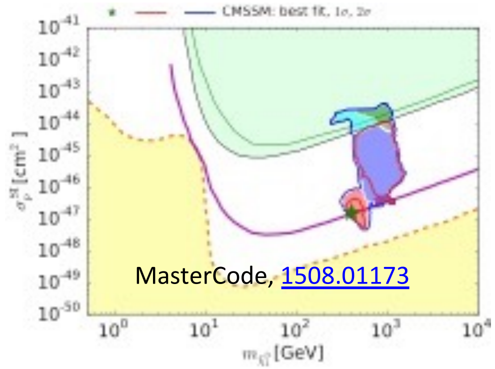
~125 GeV Higgs mass implies multi-TeV scale for SUSY

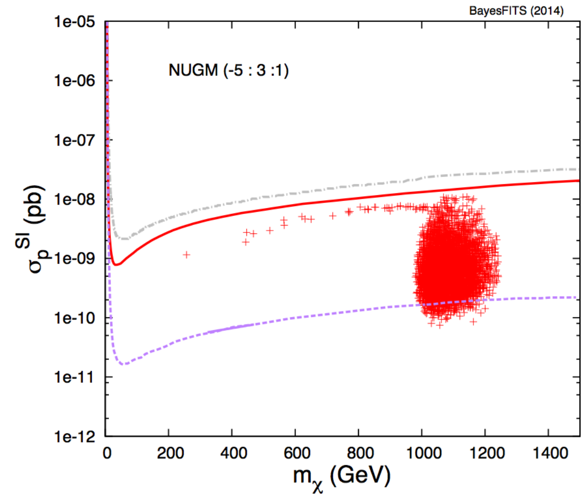
Simple unified SUSY: NO other solutions

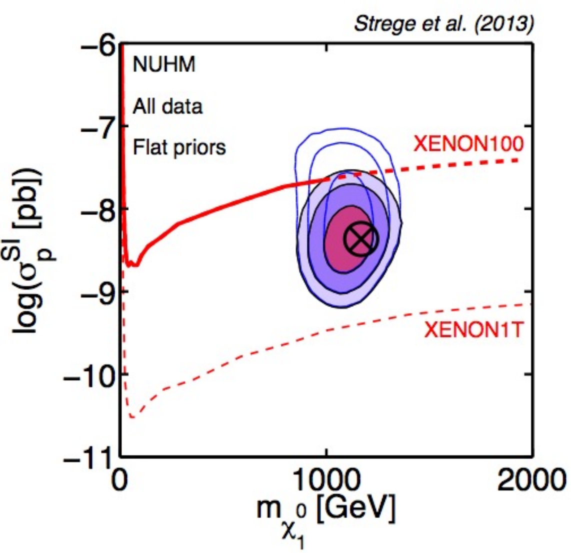
~1 TeV higgsino DM is robust

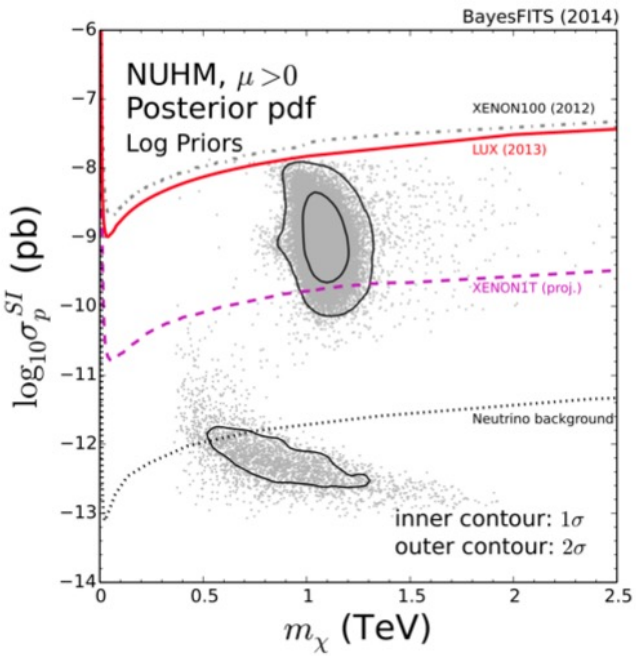


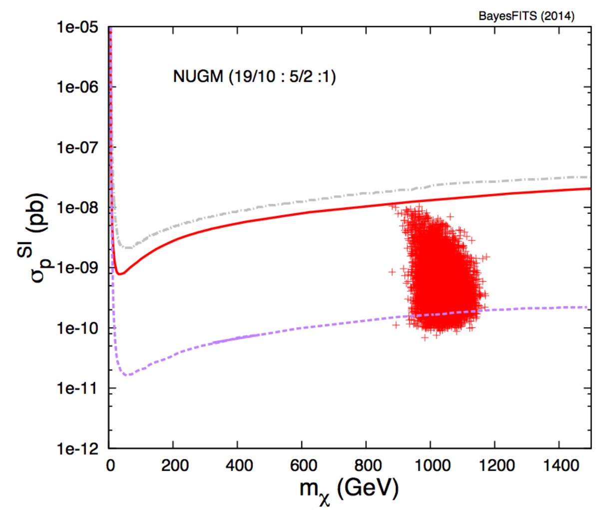
Present in both unified and pheno SUSY models











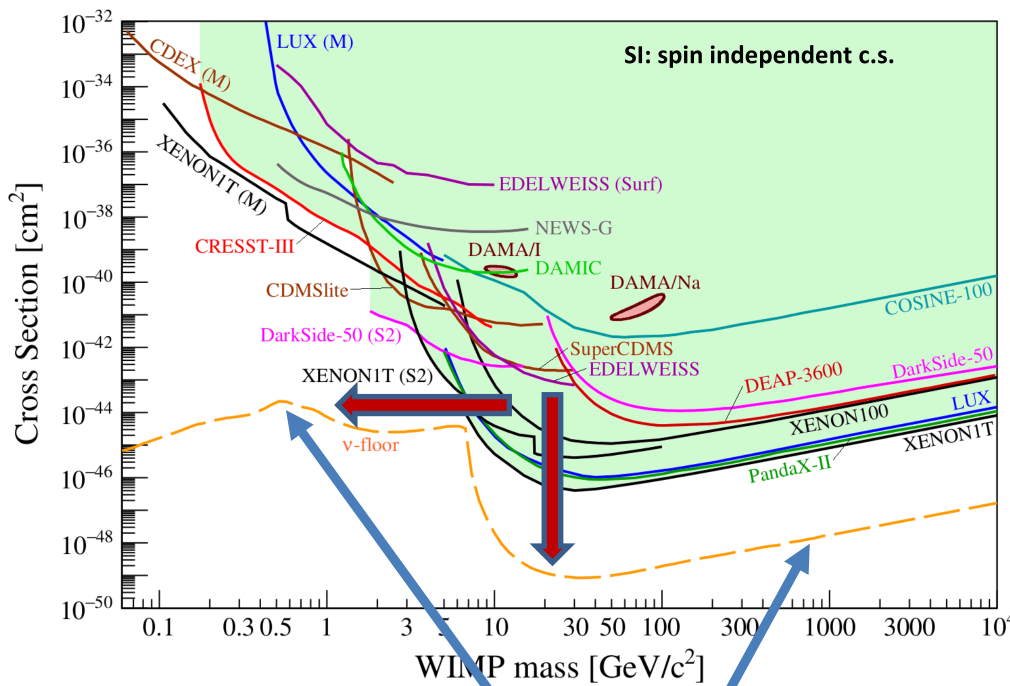
Watch prior dependence and chi2 vs Bayesian

WIMP Search Program

Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2@ GeV/c^2]	Exposure [t× year]	Timescale
Cryogenic bolometers (Section 4.6.1)							
EDELWEISS-subGeV	LSM	Ge	20	SI	10^{-43} @ 2	0.14	in prep.
SuperCDMS	SNOLAB	Ge, Si	24	SI	4×10^{-44} @ 2	0.11	constr.
CRESST-III	LNGS	$CaWO_4$+	2.5	SI	6×10^{-43} @ 1	3×10^{-3}	running
LXe detectors (Section 4.6.2)							
LZ	SURF	LXe	7.0 t	SI	1.5×10^{-48} @ 40	15.3	comm.
PandaX-4T	CJPL	LXe	4.0 t	SI	6×10^{-48} @ 40	5.6	constr.
XENONnT	LNGS	LXe	5.9 t	SI	1.4×10^{-48} @ 50	20	comm.
DARWIN	LNGS*	LXe	40 t	SI	2×10^{-49} @ 40	200	~2026
LAr detectors (Section 4.6.3)							
DarkSide-50	LNGS	LAr	46.4	SI	1×10^{-44} @ 100	0.05	running
DEAP-3600	SNOLAB	LAr	3.6 t	SI	1×10^{-46} @ 100	3	running
DarkSide-20k	LNGS	LAr	40 t	SI	2×10^{-48} @ 100	200	2023
ARGO	SNOLAB	LAr	400 t	SI	3×10^{-49} @ 100	3000	TBD
NaI(Tl) scintillators (Section 4.6.4.1)							
DAMA/LIBRA	LNGS	NaI	250	AM		2.46	running
COSINE-100	Y2L	NaI	106	AM	3×10^{-42} @ 30	0.212	running
ANAIS-112	LSC	NaI	112	AM	1.6×10^{-42} @ 40	0.560	running
SABRE	LNGS	NaI	50	AM	2×10^{-42} @ 40	0.150	in prep.
COSINUS-1π	LNGS	NaI	~1	AM	1×10^{-43} @ 40	3×10^{-4}	2022
Ionisation detectors (Section 4.6.4.2)							
DAMIC	SNOLAB	Si	0.04	SI	2×10^{-41} @ 3-10	4×10^{-5}	running
DAMIC-M	LSM	Si	~0.7	SI	3×10^{-43} @ 3	0.001	2023
CDEX	CJPL	Ge	10	SI	2×10^{-43} @ 5	0.01	running
NEWS-G	SNOLAB	Ne,He		SI			comm.
TREX-DM	LSC	Ne	0.16	SI	2×10^{-39} @ 0.7	0.01	comm.
Bubble chambers (Section 4.6.4.3)							
PICO-40L	SNOLAB	C_3F_8	59	SD	5×10^{-42} @ 25	0.044	running
PICO-500	SNOLAB	C_3F_8	1 t	SD	$\sim 1 \times 10^{-42}$ @ 50		in prep.
Directional detectors (Section 4.6.5)							
CYGNUS	Several	He:SF_6	10^3 m^3	SD	3×10^{-43} @ 45	6 y	R&D
NEWSdm	LNGS	Ag,Br,C,...		SI	8×10^{-43} @ 200	0.1	R&D

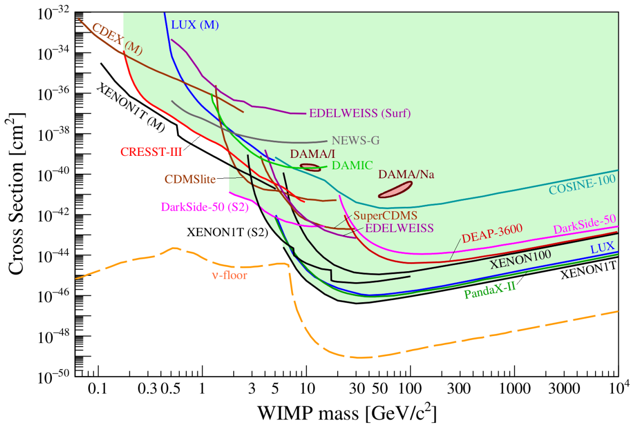
Table 1: Current, upcoming and proposed experiments for the direct detection of WIMPs. Mass is given in kg unless explicitly specified. The experiments' main detection channel (Ch) is abbreviated as: SI (spin independent WIMP-nucleon interactions), SD (spin dependent), AM (annual modulation). The sensitivity is reported for this channel, assuming the quoted exposure. Note that many projects have several detection channels. comm. = experiment under commissioning.
*No decision yet. A CDR for LNGS is being prepared.

(2021):

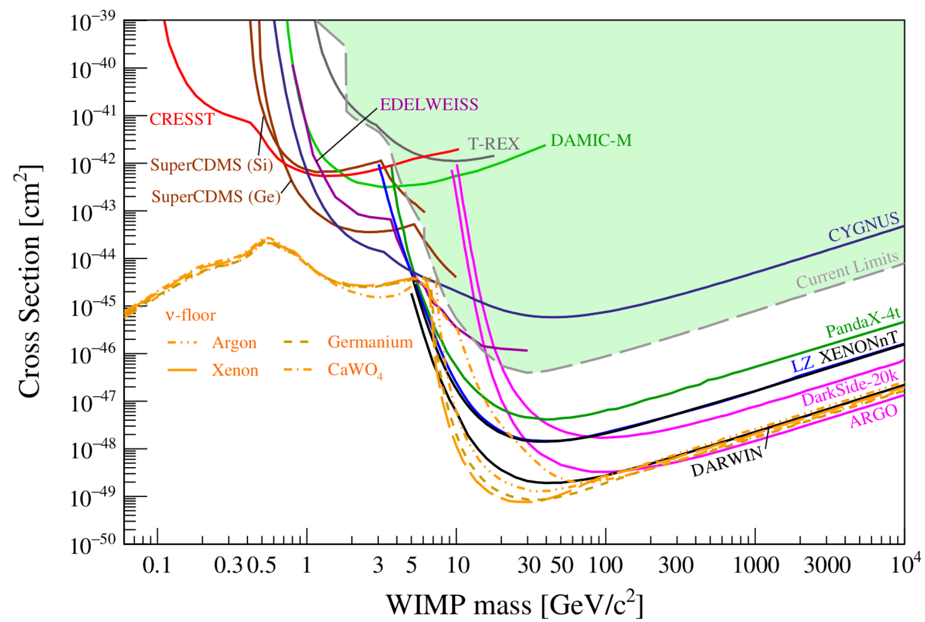


Neutrino floor:
Coherent interactions of solar or atmospheric neutrinos with nuclei

Present

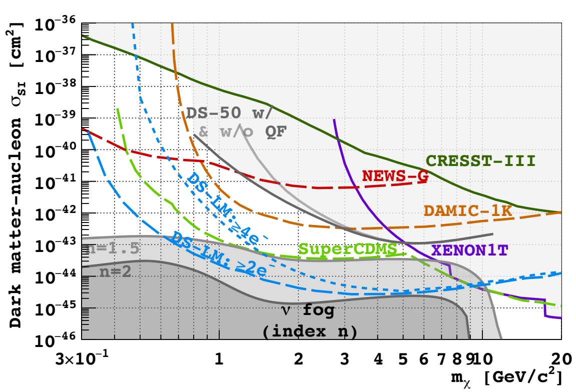


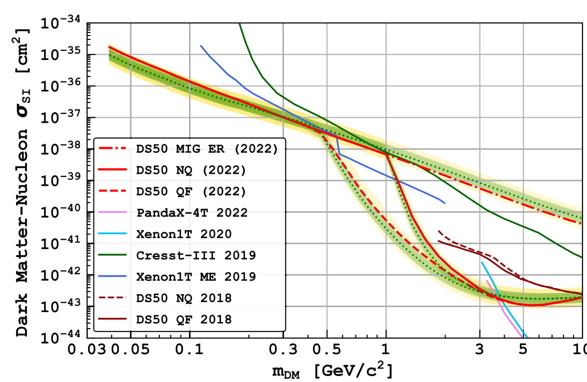
Next decade(+)



Low mass WIMP search

no Migdal effect





Assuming Migdal effect

[DarkSide Low-Mass Study 2209.01177]

[DarkSide Low-Mass 2207.11967] (*Phys.Rev.Lett.* 130 (2023) 10, 101001

← Will reach down to solar neutrino floor

Mapping-driven approach

- **Minimal set of assumptions (renormalizability, gauge invariance)**
- **Reduced set of parameters**
- **Limits from Planck, DD, LHC Mono-X (jet/photon/...), etc**
- **Allows for bound comparison (with care)**

Cao, Chen, Li, Zhang, 0912.4511 (JHEP), Beltran *et al.* 1002.4137 (JHEP), Goodman, Tait *et al.* 1005.3797 (PLB), 1009.0008 (NPB), Bai, Fox, Harnik *et al.* 1005.3797 (JHEP), 1109.4398 (PRD).... many more

- **Effective field theory approach**

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \qquad \mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3} \qquad \mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R)$$

Busoni, De Simone, Riotto *et al.* 1307.2253 (PLB), 1402.1275 (JCAP), 1405.3101 (JCAP), ….

Low mass regime:
Sub-MeV to sub-GeV

- **Portals and simplified models, e.g.**

Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu}B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}^{\mu\nu}_i$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS}S^2)H^\dagger H$
Heavy Neutral Lepton, N	$y_N LHN$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi}\gamma_\mu\chi$

(From review 2102.12143)

Patt, Wilczek hep-ph/0605188, March-Russel *et al.* 0801.3440 (JHEP), Andreas *et al.* 0808.0255 (JCAP), Djouadi, Lebedev, Mambrini *et al.* 1108.0671 (PRD), 1112.3299 (PLB), 1205.3169 (EPJ), 1411.2985 (JCAP), An *et al.* 1202.2894 (JHEP), Frandsen *et al.* 1204.3839 (JHEP), Bai and Berger 1308.0612 (JHEP), DiFranzo *et al.* 1308.2679 (JHEP).... many more

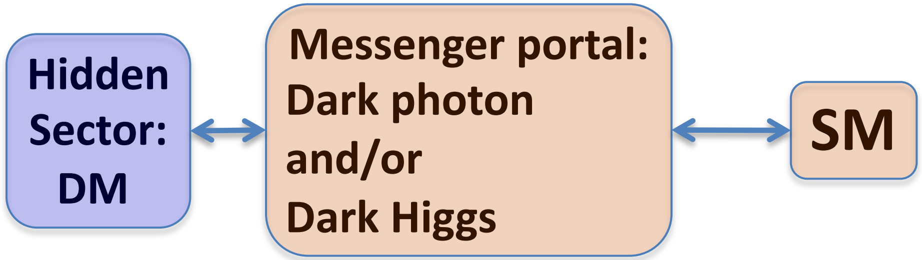
Typical scheme:

Fairly well-studied case

Dark photon, dark Higgs portal

Sub-GeV DM

- extra ``dark photon" *V*
- extra ``dark" gauge U(1)
- dark Higgs mechanism + boson S
- DM particle: scalar or fermion

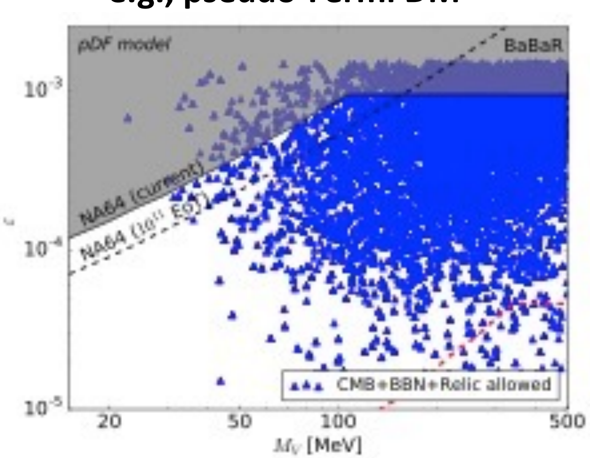


$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \boxed{\frac{1}{2}\frac{\varepsilon}{\cos\theta_w}B_{\mu\nu}F'^{\mu\nu}}$$
$$\boxed{+ (D^\mu S)^*(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4}$$

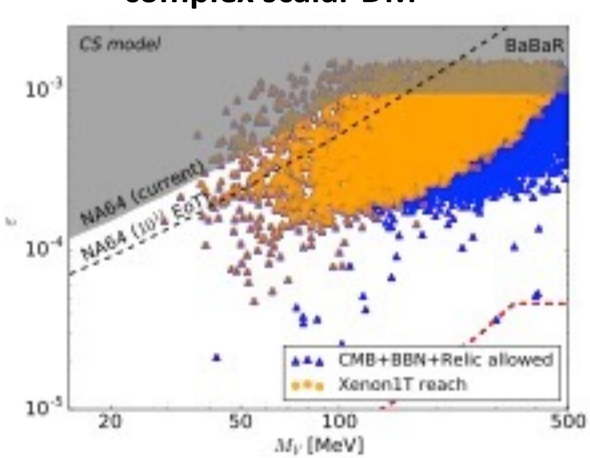
epsilon: kinetic mixing

- DM produced via freeze-out

e.g., pseudo-Fermi DM



complex scalar DM



Constraints from:

- CMB, BBN, relic density
- BaBar, NA64 (→ LDMX)…
- Beam dump expts
- DM searches
- …

Darme et al, 1710.08430

Types of accelerator-based searches for light (MeV-~GeV) thermal DM

(S. Trojanowski)

- **Missing energy/momentum/ mass in beam-dump**

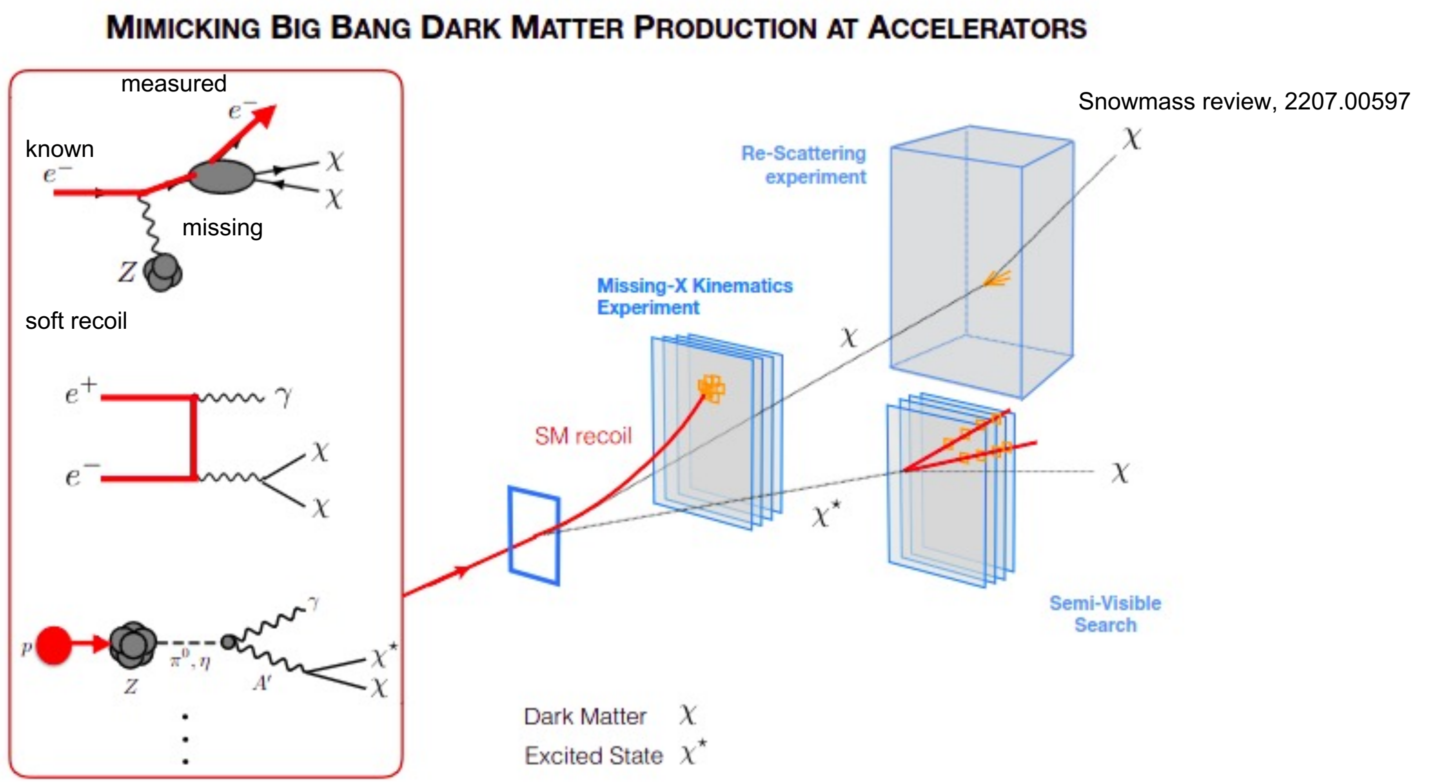
examples: NA64, LDMX

- **Missing energy in colliders**

Examples: B factories (BaBaR, Belle-II)

- **Production +**

- rescattering
e.g., MiniBooNE, SND@SHiP, FLArE, COHERENT, CCM
or
- semi-visible decay
e.g., NA62, SHiP, FASER



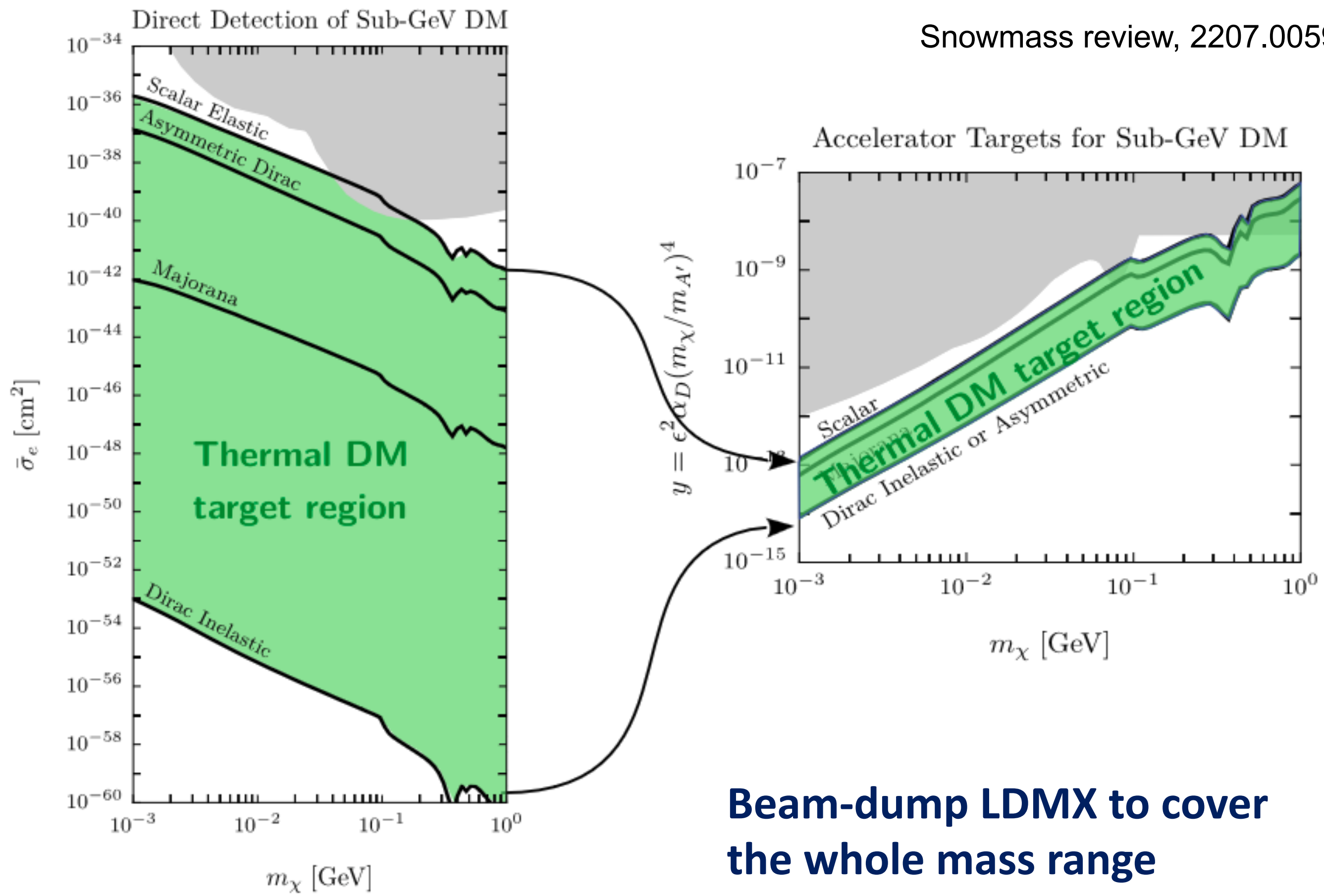
Going beyond direct detection of DM

Relativistic regime of DM interactions corresponds to conditions in the early Universe

- **dark photon mediator (kinetic mixing)**

Rates for DD very low (p-wave suppressed)

Snowmass review, 2207.00597



Beam-dump LDMX to cover the whole mass range

DM axions
in non-standard cosmological scenarios

- *New opportunities for axion dark matter searches in nonstandard cosmological models*, P. Arias, N. Bernal, A. Narino, D. Karamitros, C. Maldonado, LR, M. Venegas, JCAP 11 No 11 (2021) 003
- *Dark Matter Axions in the Early Universe with a Period of Increasing Temperature,* P. Arias, N. Bernal, J.K. Osiński, LR, e-Print: 2207.07677 → JCAP 05 (2023) 028
- *Frozen-in fermionic singlet dark matter in non-standard cosmology with a decaying fluid,* P. Arias, D. Karamitros, LR, JCAP 05 (2021) 041

Outline

- **Brief introduction:**
  - **Standard cosmology (SC) of the Big Bang**
  - **Nonstandard cosmology (NSC) alternatives**
- **Axion dark matter (DM) in SC and NSC with early matter domination (EMD) period**
  - **EMD with a period of increasing temperature**
- **Summary**

➢ Standard Cosmology (SC) of the early Universe:

- Period of inflation, reheating
- Radiation domination (RD) follows until BBN
  (and later, until radiation-matter EQ)
- Dark matter (DM) production takes place between inflation and BBN
  - Axion: misalignment mechanism
  - WIMP: freeze-out or freeze-in

➢ **Most studies of DM production, properties and prospects for discovery assume SC**

- **Simplest assumption, but no observational evidence**
- **There are many possible alternatives to SC, called nonstandard cosmology (NSC)**

Examples:

- **early matter domination (EMD),**
- **kination**
- **…**
- **PBH evaporation**

How do results for DM change in NSCs?

Much work in the literature (see bibliography)

(Many slides from J. Osiński)

Nonstandard Cosmologies (NSCs)

- Domination by energy density other than radiation before BBN
- General equation of state of dominating component: $p = \omega\rho$

$\boldsymbol{\omega = 0}$ **matter**	$\boldsymbol{\omega = 1/3}$ **radiation**	$\boldsymbol{\omega = 1}$ **kination**
$\rho \propto a^{-3}$	$\rho \propto a^{-4}$	$\rho \propto a^{-6}$
$a \propto t^{2/3}$	$a \propto t^{1/2}$	$a \propto t^{1/3}$

Faster redshift, slower expansion

Matter-like: $\omega < 1/3$
- can be initially subdominant
- should decay to end NSC
- (oscillating scalar field)

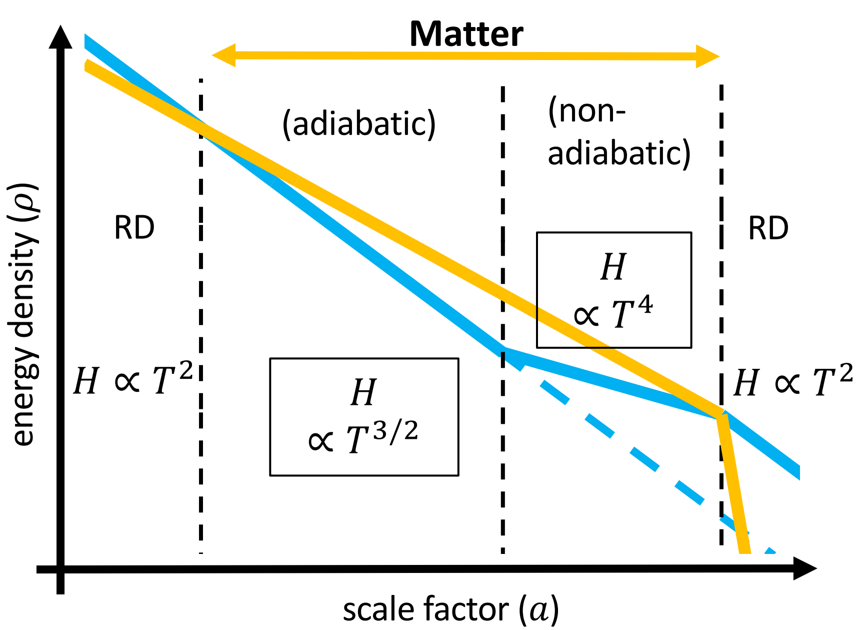
Kination-like: $\omega > 1/3$
- should begin dominant
- can be stable
- (fast-rolling scalar field)

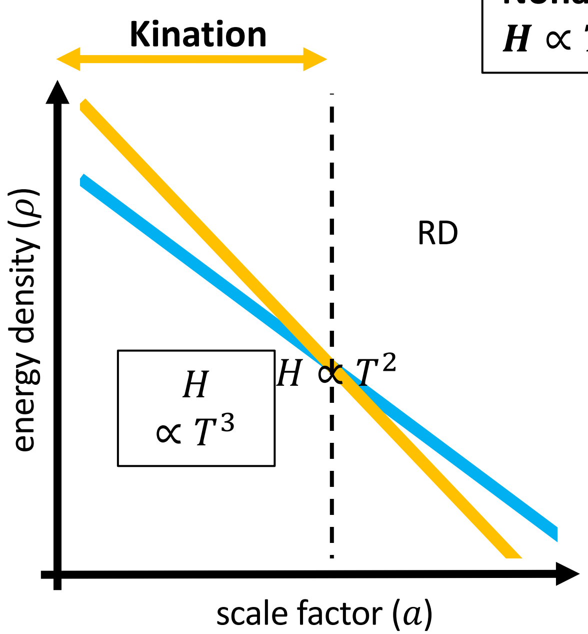
Examples of NSC

Standard RD:
$H \propto T^2$

Adiab. NSC:
$H \propto T^{3(1+\omega)/2}$

Nonad. NSC:
$H \propto T^4$





NSC field
Radiation

Consequences of NSC

- Two main effects:

1. Change evolution of expansion rate H and temperature T

   → processes happen at different times and temperatures than in SC

2. Entropy injection if dominant component decays to SM, mostly in matter-like cases

   → Dilution of other energy densities

→ NSC affects DM production

(and other processes, too)

DM production

Thermal

- DM can be produced directly from thermal bath (many possible interactions with either freeze-out or freeze-in)

Nonthermal

- Does not originate from thermal bath (out-of-equilibrium decay, primordial black holes, scalar oscillations, topological sources)

  → focus on axions from misalignment

Axion misalignment mechanism

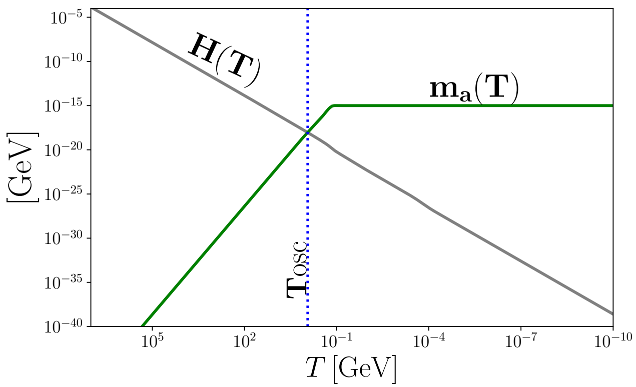
- Initial value of angle θ fixed after Peccei-Quinn (PQ) breaking at a high scale f_a
- Axion field a frozen as long as Hubble rate > axion mass

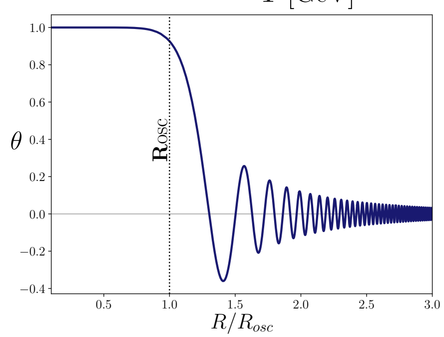
$$\theta(t) \equiv \frac{a(t)}{f_a}$$

(zero-temp. axion mass)

$$m_a \approx 5.7\ \text{meV} \left(\frac{10^9\ GeV}{f_a}\right)$$

$$T_{QCD} \approx 150\ \text{MeV}$$





Hubble rate:

$$H(T) \propto \frac{T^2}{M_P}$$

(radiation domination)

Axion mass:

$$m(T) \approx m_a \begin{cases} \left(\frac{T_{QCD}}{T}\right)^4 & T > T_{QCD} \\ 1 & T < T_{QCD} \end{cases}$$

Axion misalignment mechanism

- **As temperature of Universe cools,**
  axion mass increases while Hubble rate drops
- **Axion oscillation begins when**

$$3\,H(T_{\mathrm{osc}}) \approx m(T_{\mathrm{osc}})$$

- **"standard mass window" for correct DM relic abundance assuming standard RD history:**

$$10^{-6}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-5}\ \mathrm{eV} \quad \text{for} \quad 0.5 \lesssim \theta_{\mathrm{i}} \lesssim \pi/\sqrt{3}$$

- **Notice that this mechanism depends on thermal history**
  → nonstandard cosmologies (NSCs) can alter axion production

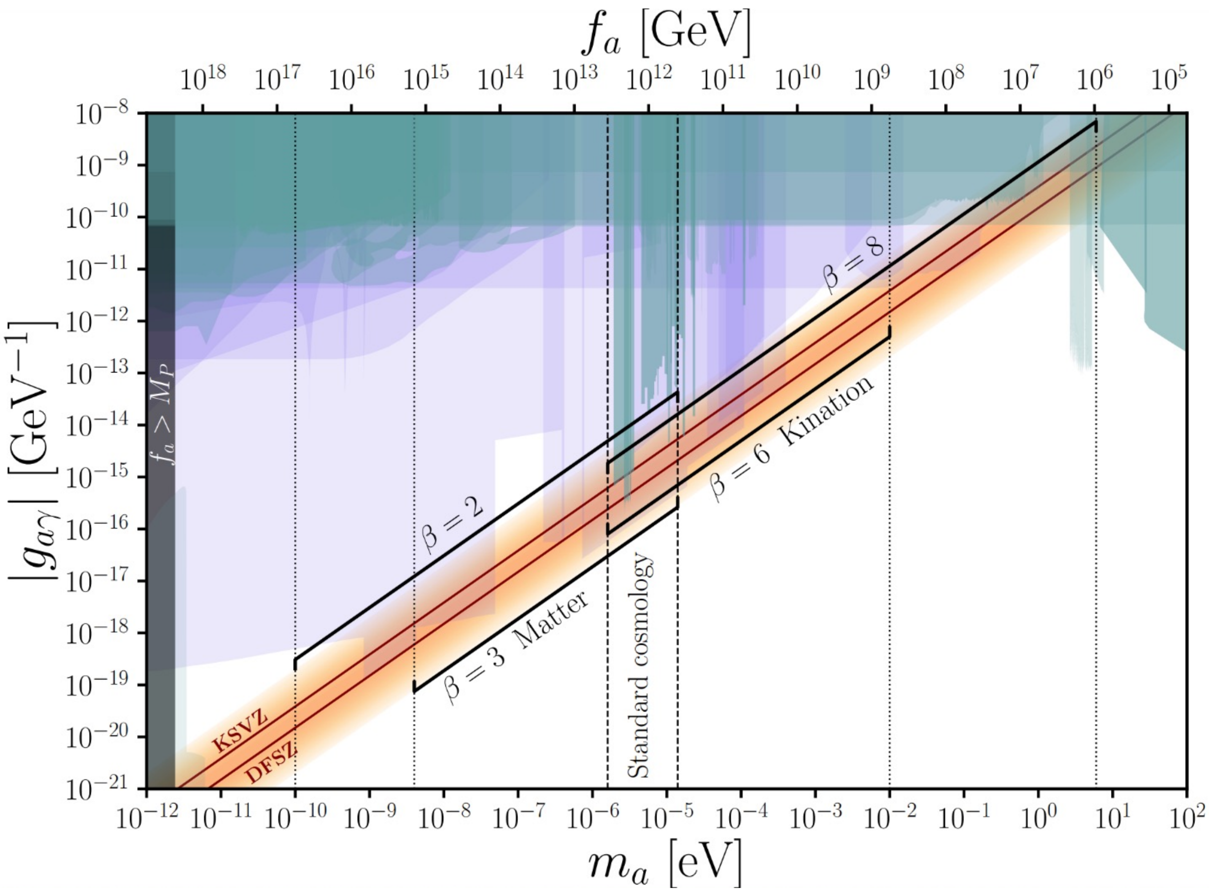
Axions in NSC

- Extended mass window for axion DM
- Matter-like NSC: smaller mass
- Kination-like NSC: larger mass

(no dilution here for kination, but still large effect!)

(for $0.5 \lesssim \theta_\mathrm{i} \lesssim \pi/\sqrt{3}$)

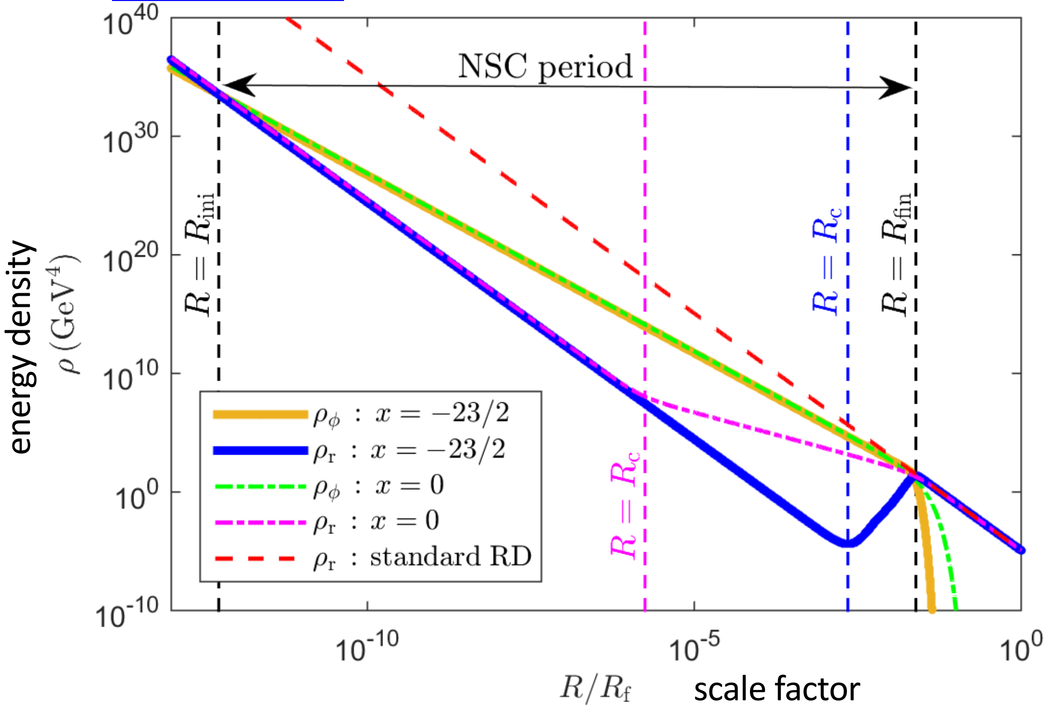
$$\beta = 3(1+\omega)$$



P. Arias, N. Bernal, D. Karamitros, C. Maldonado, L. Roszkowski, M. Venegas, 2107.13588 → JCAP

Axions with increasing-temperature EMD

P. Arias, N. Bernal, J.K. Osiński, L. Roszkowski, 2207.07677



- **Consider early matter domination by scalar field**
- **Decay rate of dominating field increases with time (set by x, constant for $x = 0$)**
- **$\Gamma = \Gamma(T,R) \sim R^k T^n$**
- **Nonadiabatic phase is altered to $H \propto T^{12/(3+2x)}$**

$$x \equiv \frac{3\,n - 8\,k}{2\,(4-n)}$$

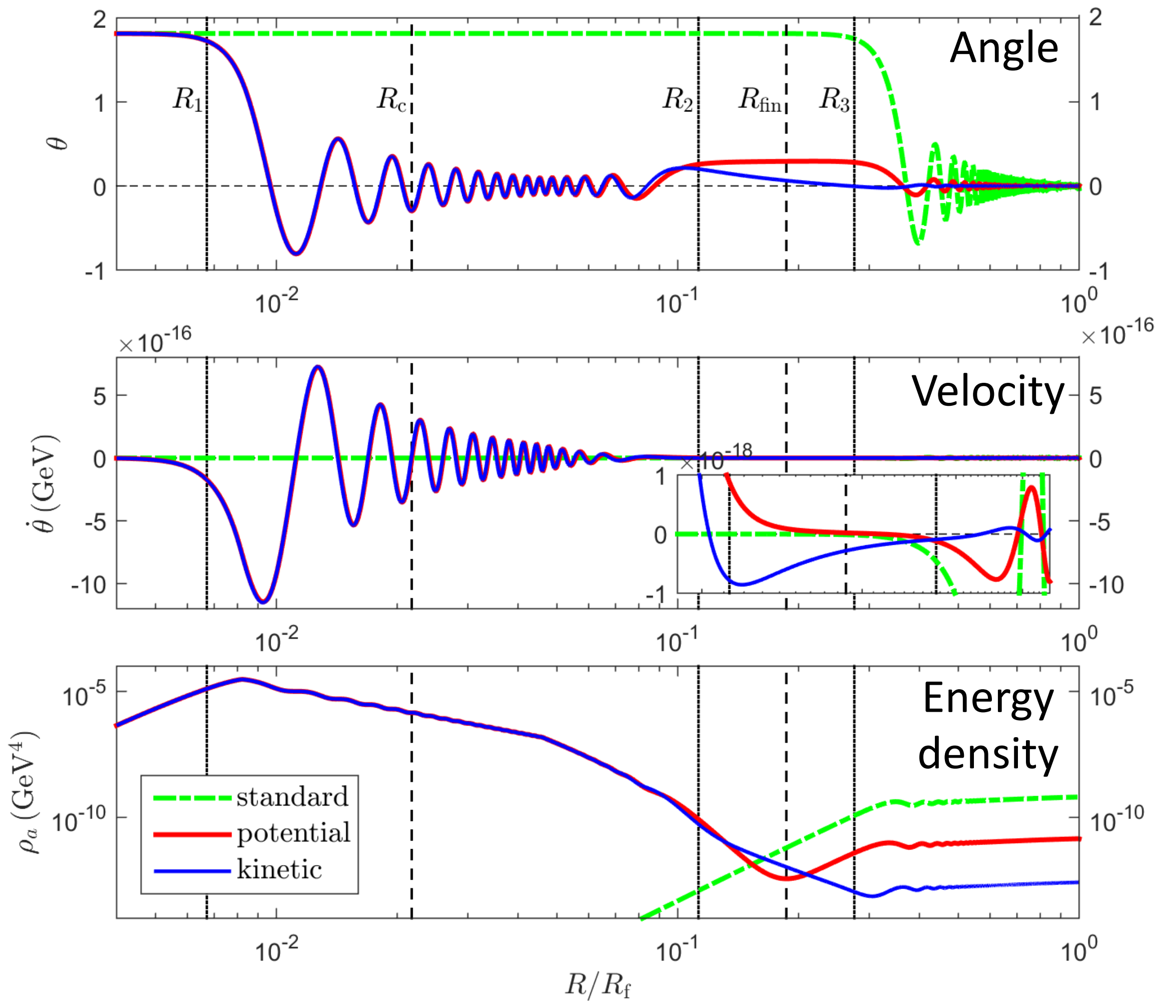
- **Same temperature can occur multiple times**

→ $3\,H \approx m$ can occur up to three times (provided that $x < -3$)

Axions with increasing-temperature EMD

- **Axion misalignment altered by restoration of Hubble friction**
- **Second period of oscillation with new configuration**
- **Resultant axion energy density is smaller due to entropy injection and smaller amplitude**

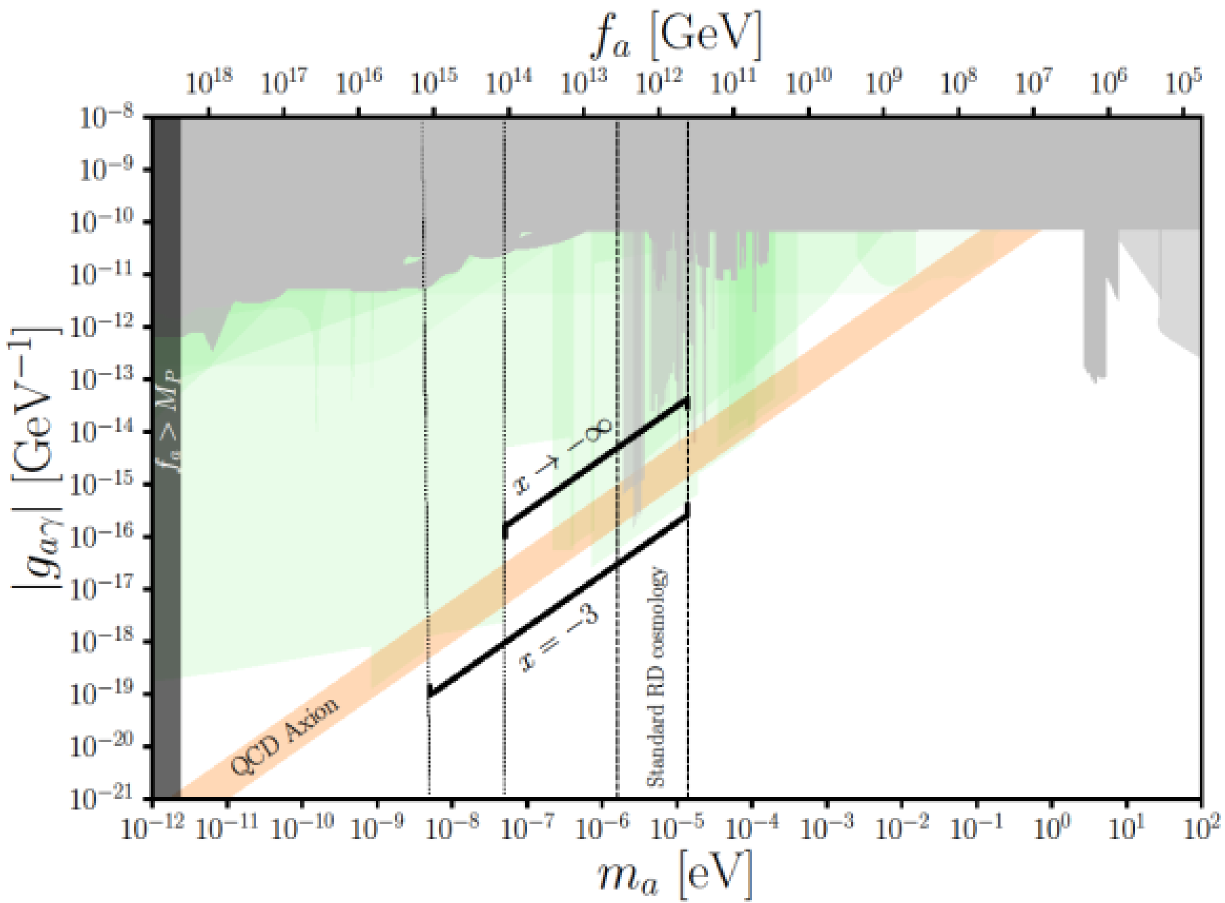
→ Smaller mass for axion DM



P. Arias, N. Bernal, J.K. Osiński, L. Roszkowski, 2207.07677 →JCAP

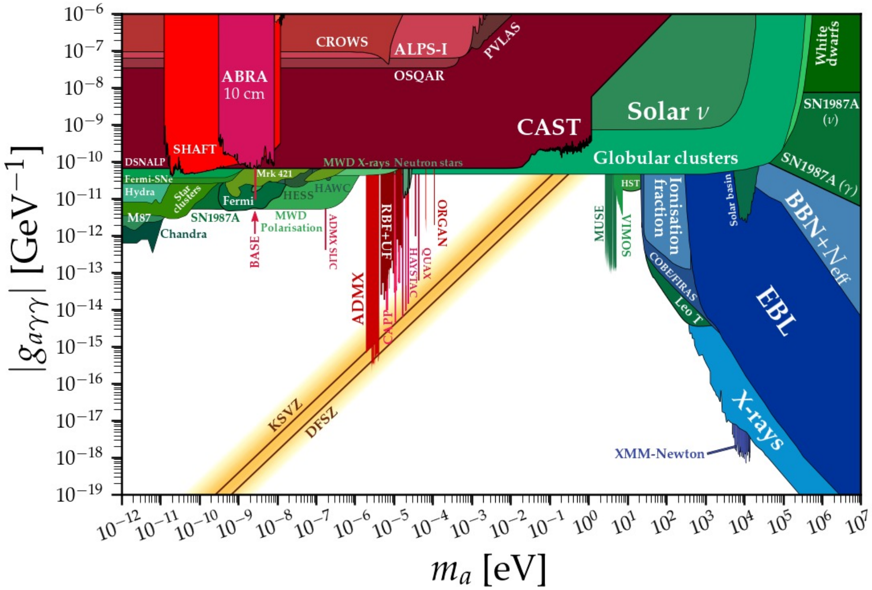
Axions with increasing-temperature EMD

- Extended window toward smaller mass, as before
- NSC histories add to motivation to look out of standard window
- Can probe NSC scenarios in coming years

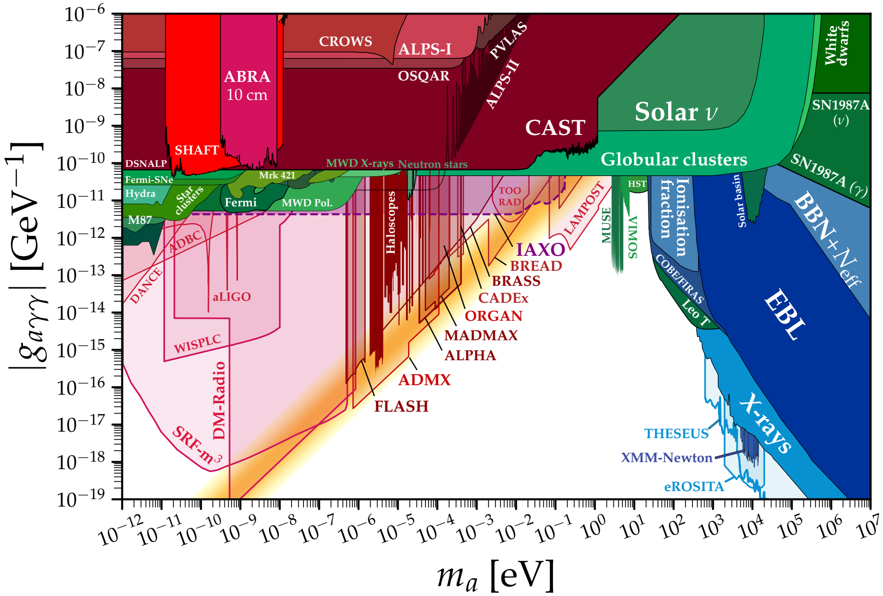


P. Arias, N. Bernal, J.K. Osiński, L. Roszkowski, [2207.07677](2207.07677)

current



future



https://github.com/cajohare/AxionLimits

To take home:

- DM: evidence convincing but nature unknown
- Much theoretical activity, new avenues explored
- A plethora of candidates, few well motivated
- Axion and ~1TeV higgsino are my front-runners
- Steady experimental search progress
- Multi-GeV to TeV range to be eventually explored down to neutrino floor
- ~1 GeV WIMP regime likely to be experimentally covered by low-mass experiments (LM DarkSide, also cryogenic)
- Light O(MeV) WIMPs: hard in DD but LDMX may help
- …
- Axion: intense search in and outside of the standard window
- Non-standard cosmologies: strong motivation to look outside the window