Cosmology and particle physics: current status

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Outline

Issues of interest to (current) particle physics

- Dark matter
  - Astrophysics
  - Candidates

    Historical order of personal prejudice:
    - Thermal WIMPs (in brief)
    - Sterile neutrino
    - Axions and ALPs
- Baryon asymmetry
- Instead of conclusion

Dark matter

- Cold dark matter, CDM: non-relativistic already at very early cosmological epoch (“always”)
- Weakly interacting CDM: currently most popular option
- ΛCDM: Universe filled with cold dark matter, cosmological constant Λ and usual matter + zero spatial curvature.

Standard Model of cosmology.

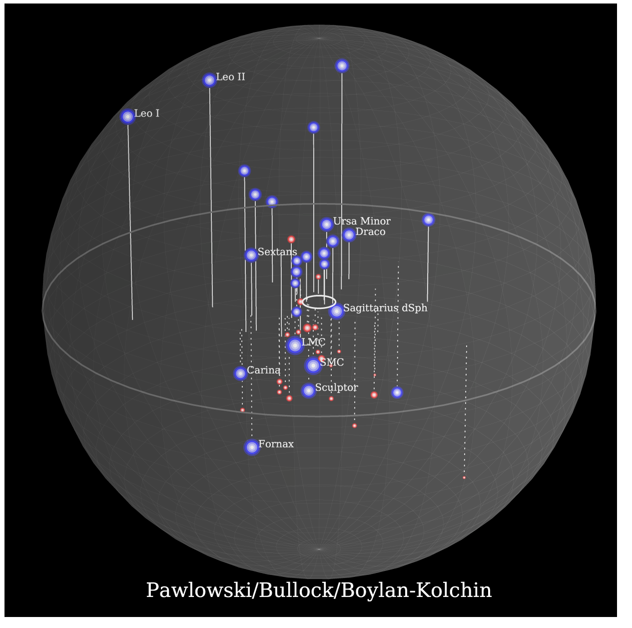
- ΛCDM consistent with all we know about the Universe from 15 Gpc (size of visible Universe) to 100 kpc (size of a galaxy like ours).

NB: Di Valentino, Melchiorri, Silk, Nov. 2019, claim that spatial curvature is non-zero. Too premature, likely systematic effects.

Dark matter: Astrophysics

Clouds over weakly interacting CDM?

- Missing satellite problem
  CDM simulations show hundreds of smaller halos around Milky Way, while not so many dwarf galaxies are observed



Bullock, Boylan-Kolchin' 17
250 kpc around Milky Way

- Astrophysical solution
  - Observed number is no longer very small
    Dozen faint satellite galaxies until several years ago $\Longrightarrow$ about 60 today $\Longrightarrow$ complete sample will have 150 – 300.
  - Small halos, $M \lesssim 10^9 M_\odot$, are inefficient in forming luminous component. Confirmed by simulations.

  If so

  - Numerous ultra-faint galaxies $M \gtrsim 10^8 M_\odot$
  - Dark small halos $M \gtrsim 10^6 - 10^7 M_\odot \Longrightarrow$ strong gravitational lensing, stellar streams

  To be decided in $\sim$ 10 years,
  especially with LSST (Large synoptic survey telescope)

- Particle physics solution: Warm dark matter
  e.g. relic of mass $m_\chi \sim$ a few keV in kinetic equilibrium in early Universe. Decouples relativistic, free streams until $T \sim m_\chi \Longrightarrow$ perturbations of comoving size smaller than horizon at $T \sim m_\chi$ are smoothed out. Candidate: sterile neutrino (later on).

More clouds over weakly interacting CDM?

- Core-cusp problem
  CDM simulations show singular density at centers of galaxies (cusps, $\rho \propto 1/r$) while observations show smooth cores.

Astrophysical solutions: Effects due to baryons.
Particle physics solution: Strongly interacting dark matter, SIMP.
Mean free path $l \sim 1$ kpc, mass density $\rho \sim \mathrm{GeV/cm^3}$ $\Longrightarrow$

$$\frac{\sigma_{\chi\chi}}{m_\chi} \sim 10^{-24}\mathrm{cm}^2/\mathrm{GeV}$$

t-channel exchange of light mediator V: $m_V \sim 10 - 100$ MeV. It must decay into e^+e^-, $\gamma\gamma$ (mixing with γ, Z or Higgs) $\Longrightarrow$ SHiP.

Yet another particle physics solution: Fuzzy dark matter.

Hu, Barkana, Gruzinov' 00

Hui, Ostriker, Tremain, Witten' 17

Boson of mass $m_\chi \sim 10^{-22}$ eV

Oversimplified picture:

De Broglie wavelength ~ 1 kpc at $v_\chi \sim 10$ km/s $\Longrightarrow$ structures of small sizes suppressed.

Non-thermal production: coherently oscillating scalar field.

In principle detectable through pulsar timing!

Khmelnitsky, VR' 14

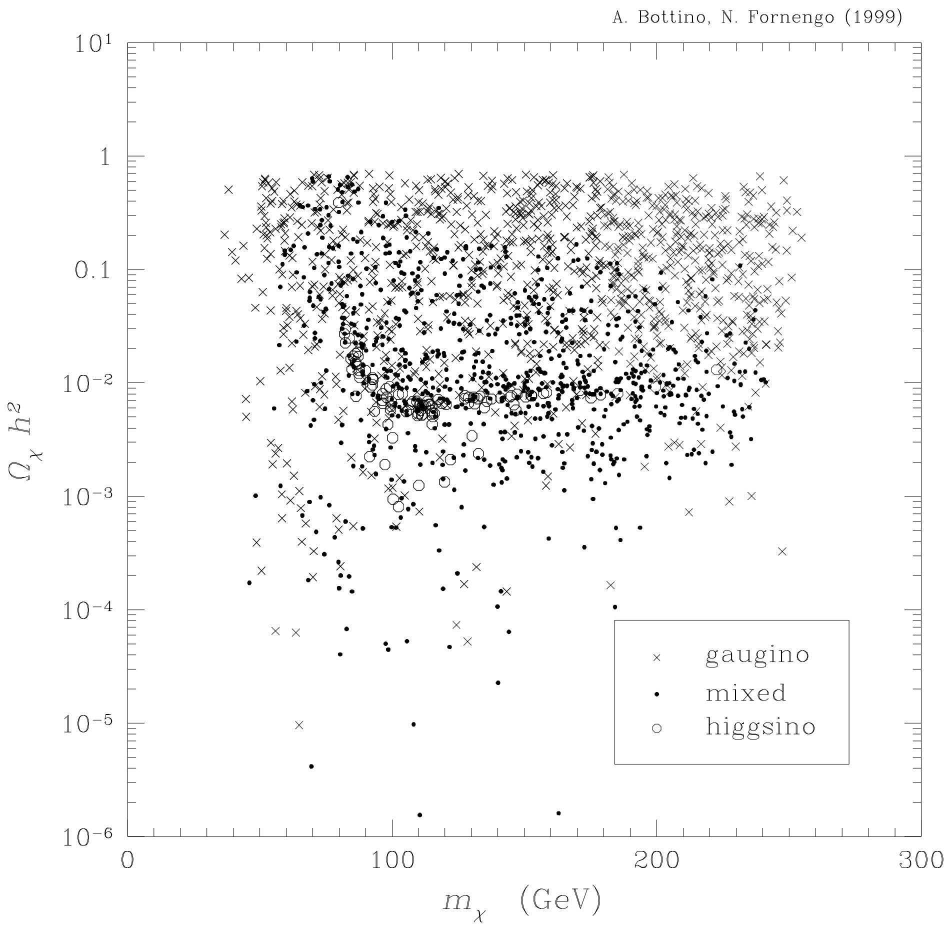
Summary of astrophysics

- It will soon become clear whether small scale "anomalies" are real or not.
  - If real: need particle physics solutions. Least contrived: WDM
  - If not: confirmation of weakly interacting CDM (especially by observing small non-luminous clumps $M \sim 10^5 - 10^7 M_\odot$).

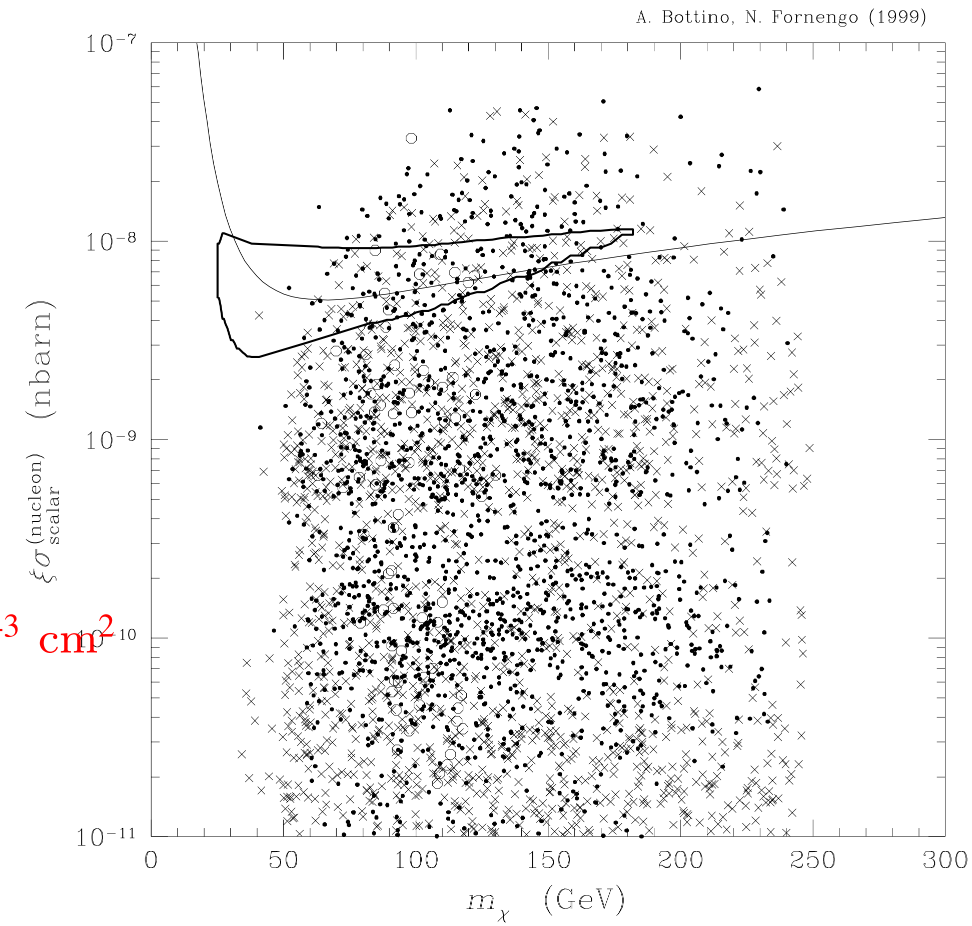
Thermal WIMPs: still an option, BUT

SUSY WIMPs 20 years ago

Direct detection (spin independent) expectations and limits



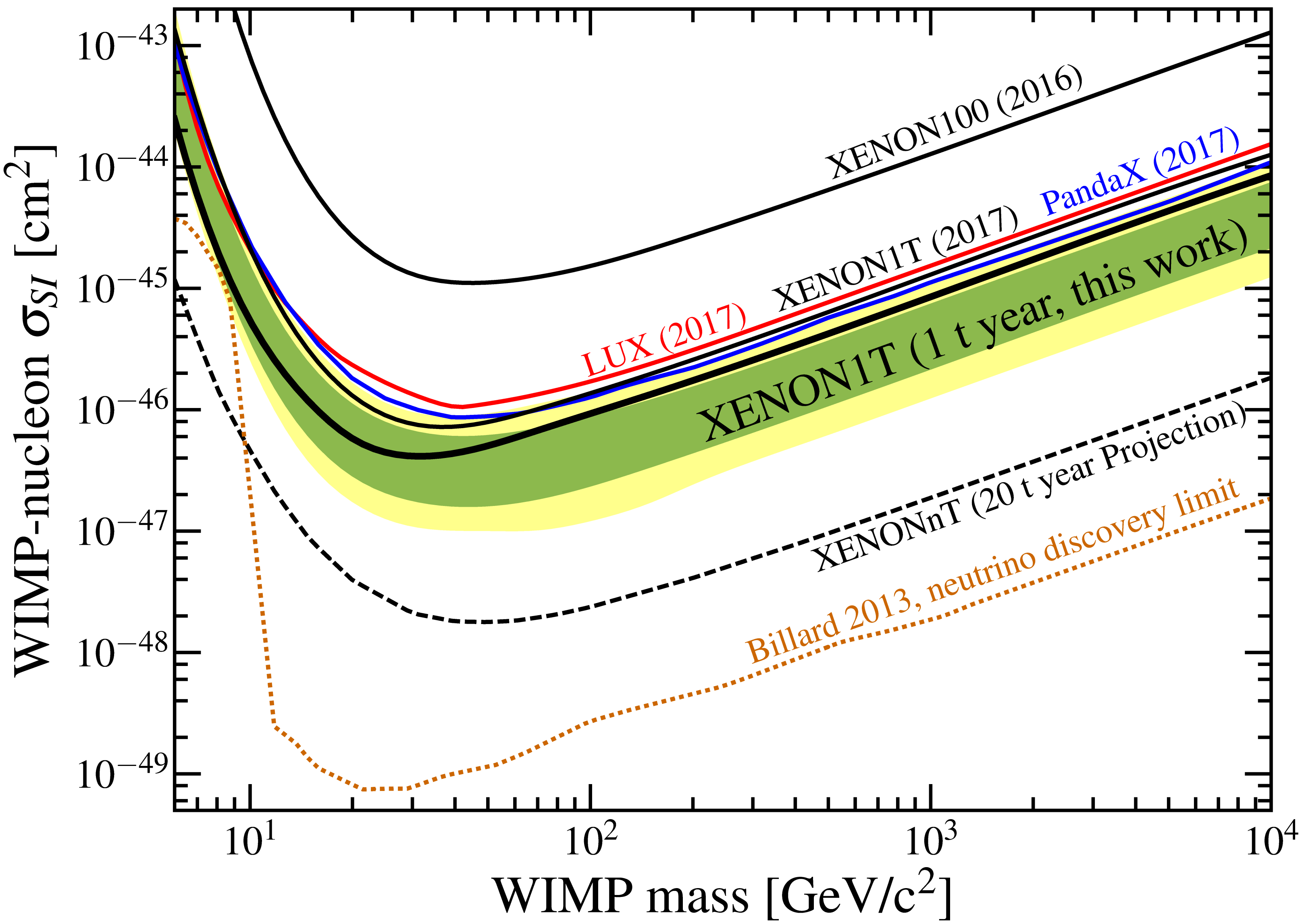
10^{-43} cm^2



Bottino, Fornengo' 1999

Today: Xenon-1T, PandaX, LUX

Spin-independent, direct detection



Conclusion on WIMPs

- More constraints:
  - indirect searches for WIMP annihilation in center of Sun, Earth

    $X\bar{X} \to \pi^{\pm}, K^{\pm}, \cdots \to \nu\bar{\nu}$

    Baikal GVD, IceCube
  - Search for high energy gammas from WIMP annihilation is cosmos

    Fermi-LAT, Magic, HESS
- Today: WIMP option squeezed.

  Parameter space in concrete models is often strongly constrained.

  This does not mean much: we are after one point in the parameter space of one theory.
- Perspective: Hunt continues, but options other than thermal WIMP become more and more interesting.

Sterile neutrinos

- Needed to give masses to ordinary neutrinos
- One sterile neutrino species may be light.
  Seemingly, nothing wrong with m_{ν_s} = a few keV − a few MeV
  - Not well motivated by see-saw
- Production in early Universe through mixing with ordinary neutrinos (say, ν_e), mixing angle θ_s.

  Lifetime longer than age of Universe $\nu_s \to 3\nu$:

$$\theta_s^2 \lesssim 10^{-7} \left(\frac{50 \text{ keV}}{m_{\nu_s}} \right)^5$$

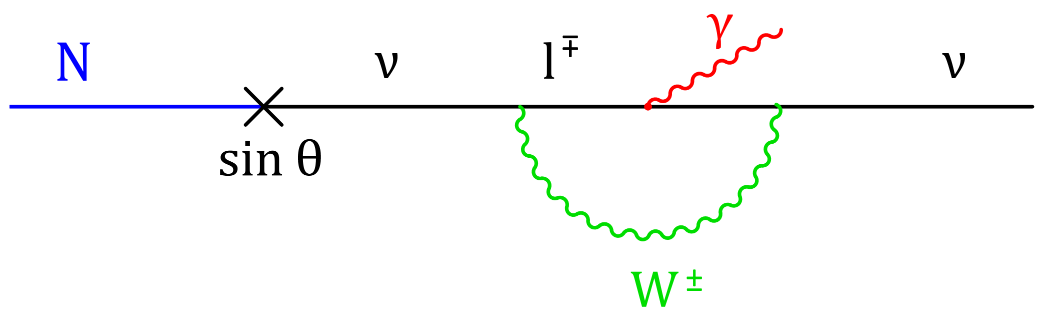
  This is why ν_s must be light.

- Particularly interesting case: m_{ν_s} = a few keV:
  Warm Dark Matter

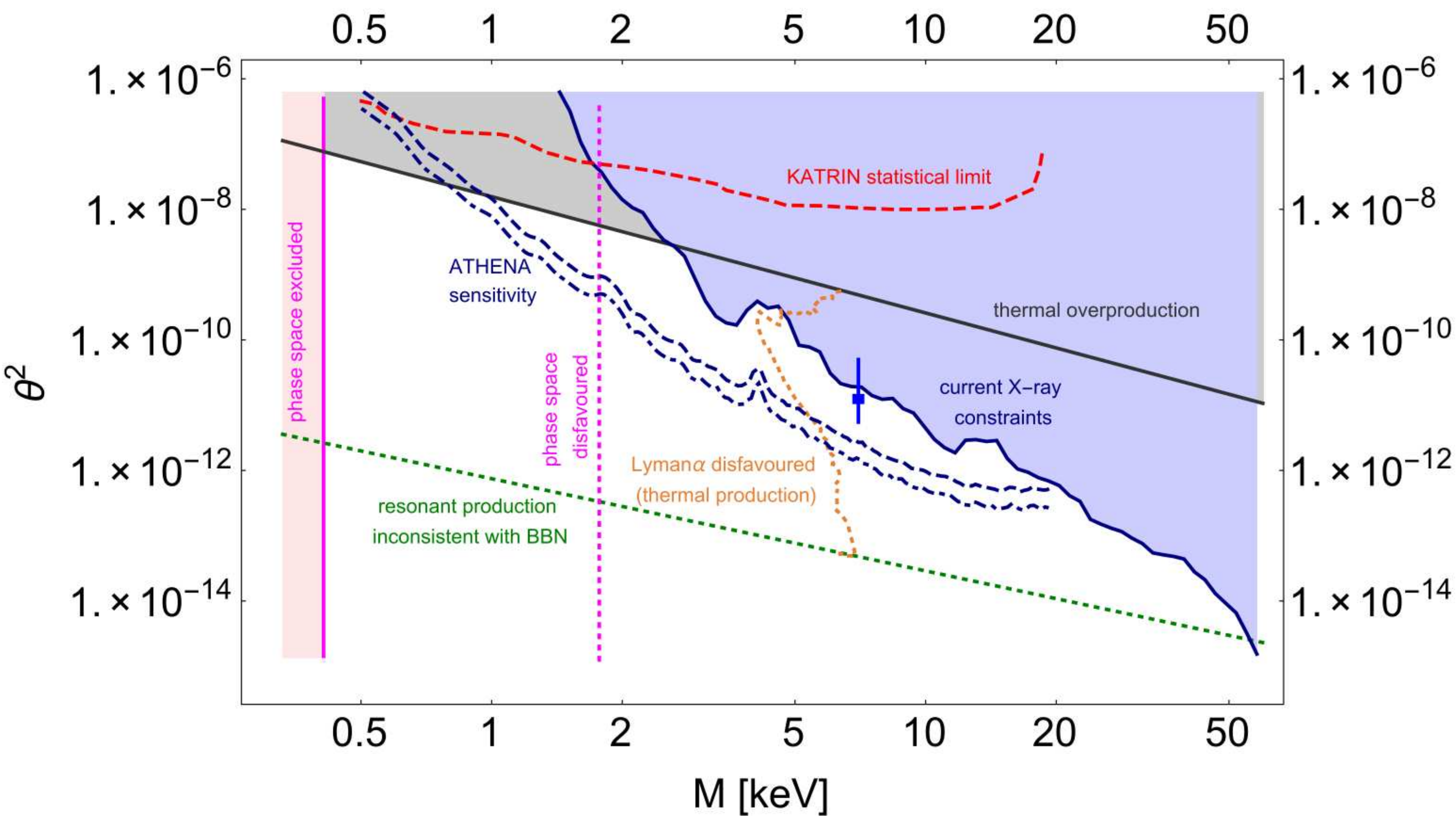
Non-resonant thermal production mechansim,
$\nu \to \nu_s$ in early Universe:

$$\Omega_s \simeq 0.2 \cdot \left(\frac{\sin 2\theta_s}{10^{-4}} \right)^2 \cdot \left(\frac{m_{\nu_s}}{1 \text{ keV}} \right)$$

But $\nu_s \to \nu\gamma \Longrightarrow$ Search for photons with $E = m_{\nu_s}/2$ from sky.

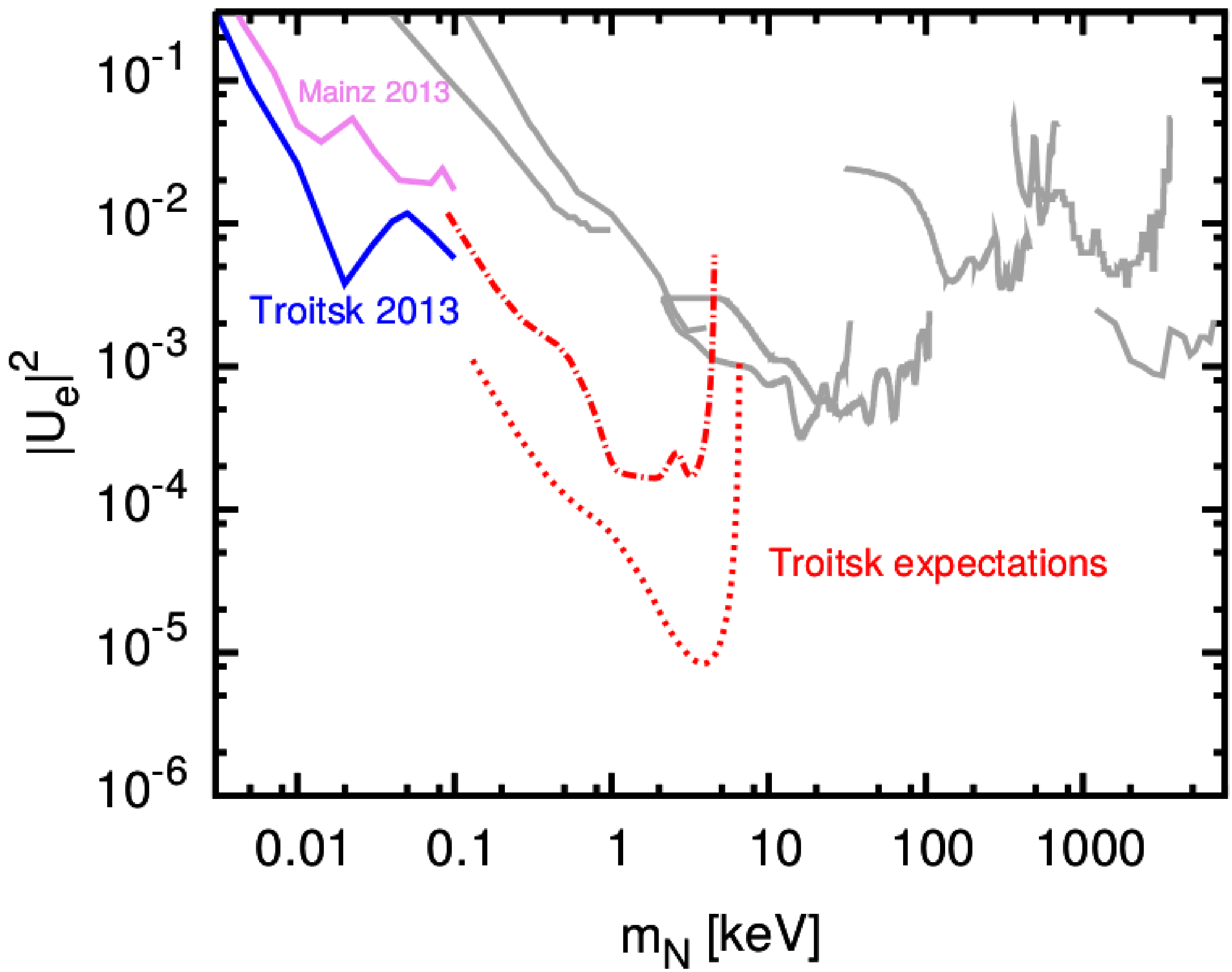


Search for photons with $E = m_{\nu_s}/2$



Straightforward version of scenario ruled out
But more contrived (assuming lepton asymmetry or phase transition) does not

Laboratory search: long way to go



Conclusion on sterile neutrinos

- Fairly contrived (small m_{ν_s}, complicated production mechanism), but not impossible.
- Search in terrestrial experiments notorously difficult.
- Possible signal: gamma-line with $E = m_{\nu_s}/2$ from the sky.
  NB: 3.5 keV gamma-line controversy unresolved.
- Will gain support if small-scale astrophysical anomalies are confirmed.

Axions

- Reasonably well motivated: solution to strong CP-problem.
  - NB: Light axion is no longer a must: heavy (GeV – TeV) axion may do the job as well

- Light axion: one unknown parameter, axion decay constant = PQ scale, f_{PQ},

$$m_a f_{PQ} = (m_\pi f_\pi)/2 = 6 \cdot 10^{-3}\ \text{GeV}^2 \implies m_a = 6\,\mu\text{eV} \cdot \left(\frac{10^{12}\ \text{GeV}}{f_{PQ}} \right)$$

- Non-thermal production $\Longleftrightarrow$ cold dark matter even for very light axion.

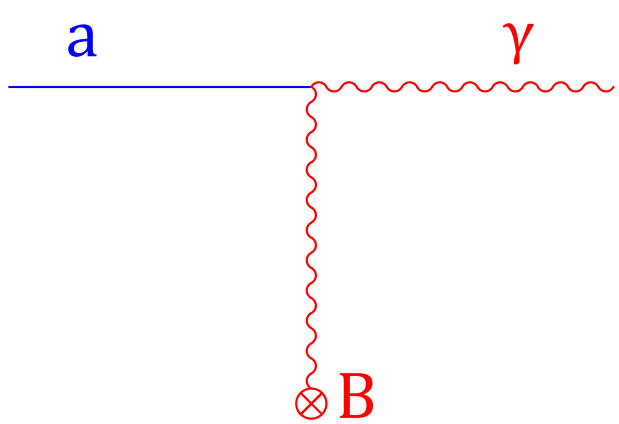
- Axion production just right for $m_a = 10^{-4} - 10^{-6}$ eV.

  NB: Precise input from theory missing!

Search

$a\gamma\gamma$ interaction $\quad C_{a\gamma\gamma}\dfrac{\alpha}{2\pi}\dfrac{a(x)}{f_{PQ}}(\vec{E}\cdot\vec{H})$

Conversion of DM axion into photon in magnetic field in a resonant cavity. 10^{-6} eV$/2\pi = 240$ MHz.

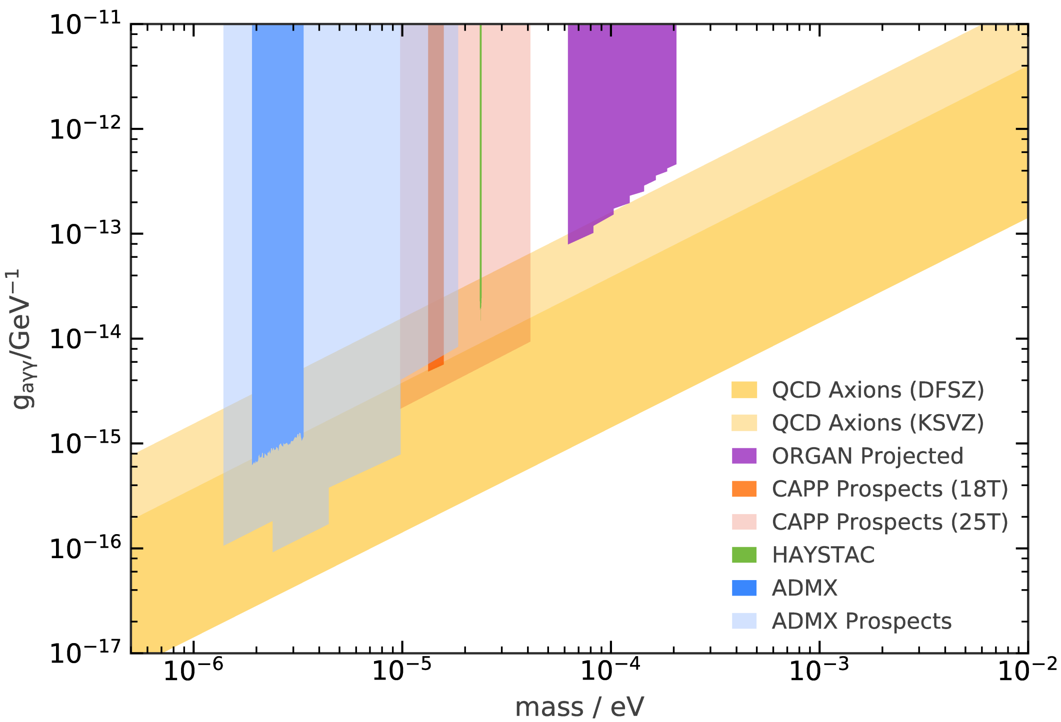


Need high Q resonator to collect photons, narrow bandwidth, go small steps in m_a. Long story. ADMX since 1990's.

New efforts in axion searches:

- CAPP, axion-photon conversion in magnetic field, $m_a = (3 \cdot 10^{-6} - 10^{-4})$ eV;
- MADMAX, axion-photon conversion at boundaries of dielectric discs in magnetic field $m_a \gtrsim 4 \cdot 10^{-5}$ eV
- CASPEr, time-varying EDM of nuclei in oscillating axion background $\Longrightarrow$ spin precession, $m_a \lesssim 10^{-9}$ eV

All aim at dark matter QCD axions



Axion-like particles, ALPs

Axions: $m_a f_a = (m_\pi f_\pi)/2 = 6 \cdot 10^{-3}$ GeV^2

ALPs: No relationship between m_a and f_a.

Possible origin: pseudo-Nambu–Goldstone bosons of approximate global symmetry

Coupling to photons

$$C_{a\gamma\gamma} \frac{\alpha}{2\pi} a(x) (\vec{E} \cdot \vec{H})$$

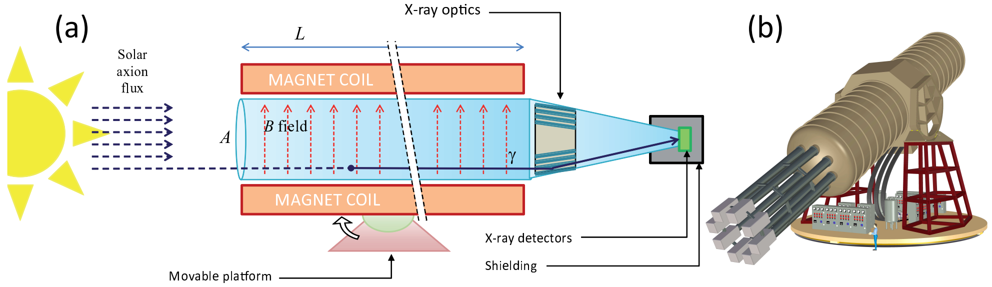
Coupling to SM fermions f through Higgs:

$$C_{aff} a H \bar{f} f \implies C_{aff} \langle H \rangle a \bar{f} f$$

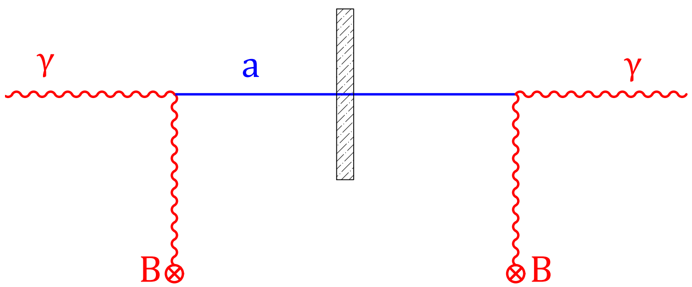
Large symmetry breaking scale $f_a \implies$ small $C_{a\gamma\gamma}, C_{aff} \propto f_a^{-1}$.

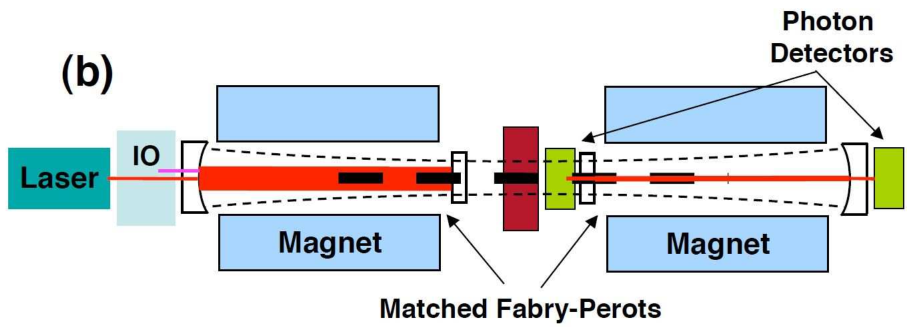
ALP searches, present and future

- Haloscopes – ALPs from dark matter halo: ADMX, CAPP, MADMAX, CASPEr
- Helioscopes – ALPs from the Sun: CAST, IAXO, TASTE



- Light shining through wall, ALPS I, ALPS II





- Beam-dump searches: SHiP

Conclusion on axions

- Axions, ALPs are promising DM candidates.
- Not very constrained for the time being.
- A lot of experimental effort in near future.
- Theory lags behind, despite considerable development.

Dark matter summary

- With exception of axions/ALPs, well-motivated candidates are strongly constrained already.

  This does not mean much: we are after one point in the parameter space of one theory.

- Still, it is worth looking for less-motivated/ad hoc candidates.

  This happens already: NA64, SHiP, Troitsk nu-mass, Katrin, ...

- Astrophysics/cosmology may well give hints towards the nature of DM

- One cannot rule out nightmare: gravitino, Wimpzilla, ...

Baryon asymmetry of the Universe

Q: Can electroweak baryon number non-conservation ("sphalerons") be used to generate baryon asymmetry at $T \lesssim 100$ GeV?

A: Not in the Standard Model

- Sakharov condition # 2: CP-violation. CKM too weak.
- Sakharov condition # 3: departure from thermal equilibrium.

  Universe expands slowly. Expansion time

$$H^{-1} \sim 10^{-10} \text{ s}$$

  Too large to have deviations from thermal equilibrium?

Chance: 1st order phase transition, highly inequilibrium process

Electroweak symmetry is restored, $\langle \phi \rangle_T = 0$ at high temperatures

Just like superconducting state becomes normal at “high” T

Transition may in principle be 1st order

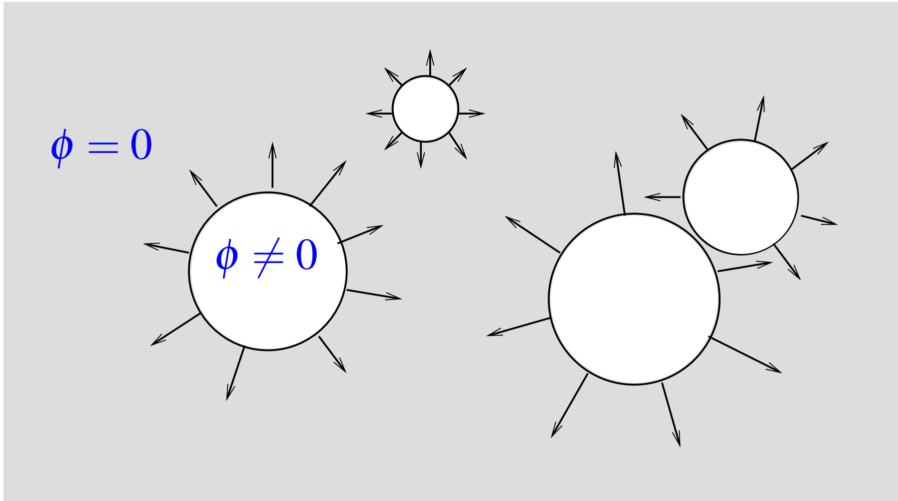
1st order phase transition occurs from supercooled state via spontaneous creation of bubbles of new (broken) phase in old (unbroken) phase.

Bubbles then expand at $v \sim 0.1c$

Beginning of transition: about one bubble per horizon

Bubbles born microscopic, $r \sim 10^{-16}$ cm, grow to macroscopic size, $r \sim 0.1 H^{-1} \sim 1$ mm, before their walls collide

Boiling Universe, strongly out of equilibrium



Baryon asymmetry may be generated in the course of 1st order phase transition, provided there is enough C- and CP-violation.

This does not happen in SM

- Given the Higgs boson mass $m_H = 125$ GeV
  no phase transition at all; smooth crossover

What can make EW mechanism work?

- Extra bosons
  - Should interact fairly strongly with Higgs(es)
  - Should be present in plasma at EW epoch

  $\Longrightarrow$ physics at or below TeV scale

- Plus extra source of CP-violation.

  Better in Englert–Brout–Higgs sector $\Longrightarrow$ Several scalar fields
  - Electric dipole moments of neutron and electron.
  - Recent limit $d_e < 1.1 \cdot 10^{-29}$ e cm (ACME) kills many concrete models

More generally, EW baryogenesis requires
complex dynamics in EW symmetry breaking sector
at $E \sim (\text{a few}) \cdot 100$ GeV

COLLIDER'S FINAL WORD

Another possibility

Baryon asymmetry generated in production and oscillations of sterile neutrinos m_{ν_s} in GeV range.

Until a few years ago this was considered contrived: nearly degenerate sterile neutrinos,

$$\frac{M_1 - M_2}{M_1 + M_2} \lesssim 10^{-3}$$

Now it is understood that with 3 sterile neutrino species, all in GeV range, degeneracy is not needed.

Viable models $\Longrightarrow$ fairly large $\nu_s - \nu_\mu$ mixing $\Longrightarrow$ ν_s production in D-, B-decays.

Chance for BELLE-II, LHC-B and especially SHiP.

Summary of baryogenesis

- It is likely that baryogenesis is due to physics at scales well above $1 - 10$ TeV.

  Very hard/impossible to probe directly.

  Indirect evidence will be inconclusive. In particular, CP-violation in active neutrino sector or elsewhere at achievable energies will not be directly relevant.

- There remains a (slim?) chance that physics behind baryogenesis can be discovered in terrestrial experiments.

  At least in the case of electroweak baryogenesis, studies at energy frontier are crucial.

Instead of conclusion

Astrophysics and cosmology
posed profound questions to particle physics.

Result of persistent effort during more than 25 years:

CONFUSION

Adequate approach today:

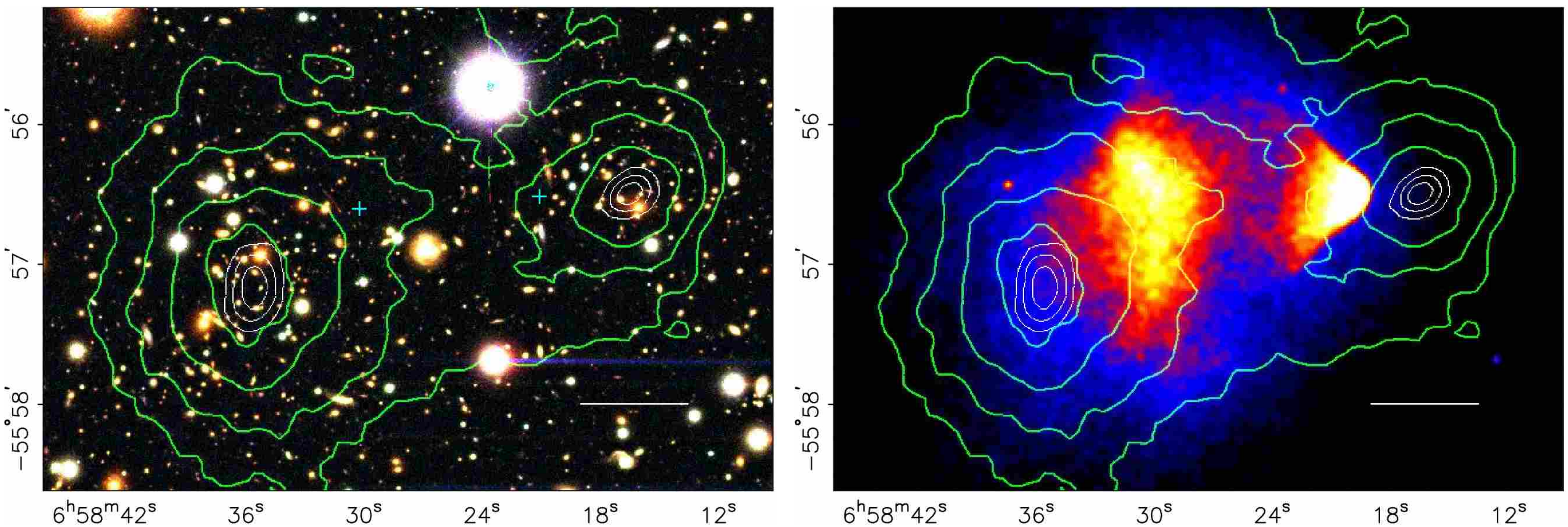
DIVERSITY

At most handful of discoveries for entire community.

But the questions are worth the effort.

Backup slides

SIMP: tension with Bullet cluster



Contours: distribution of mass.
Color: distribution of baryons, hot gas
Dark matter scattering cross section

$$\sigma_{\chi\chi} < 10^{-24}\ \mathrm{cm}^2$$

Direct detection limits, LHC limits on SUSY $\Longrightarrow$
SUSY WIMP is even less attractive option than before.

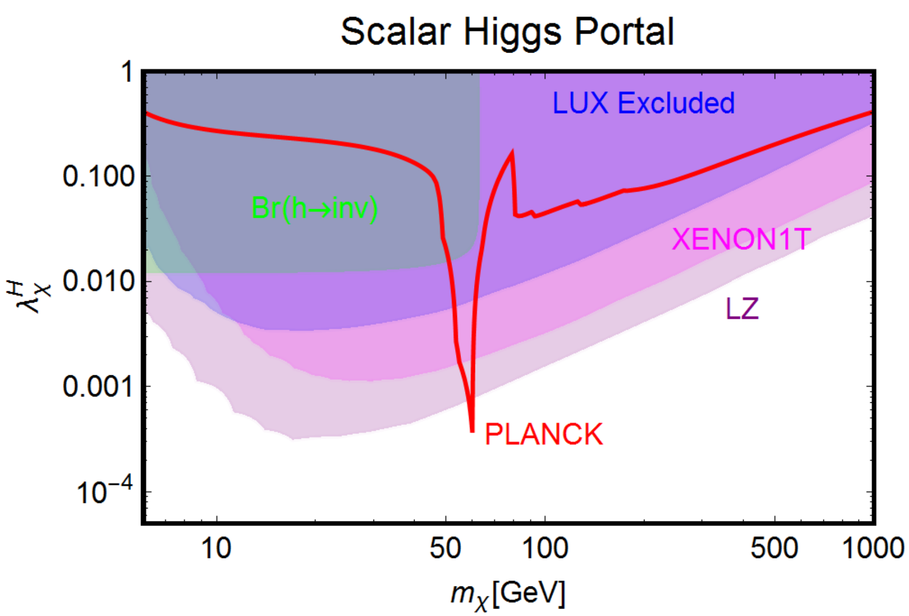
Ad hoc wimps. Main annihilation channels $\Longleftrightarrow$ portals.

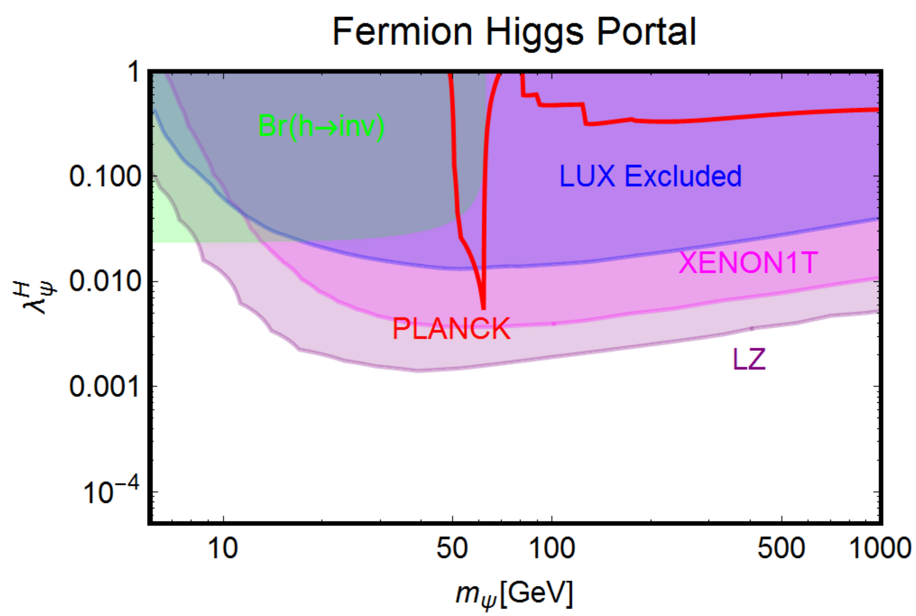
Many are ruled out or strongly constrained.
Example: Higgs portal

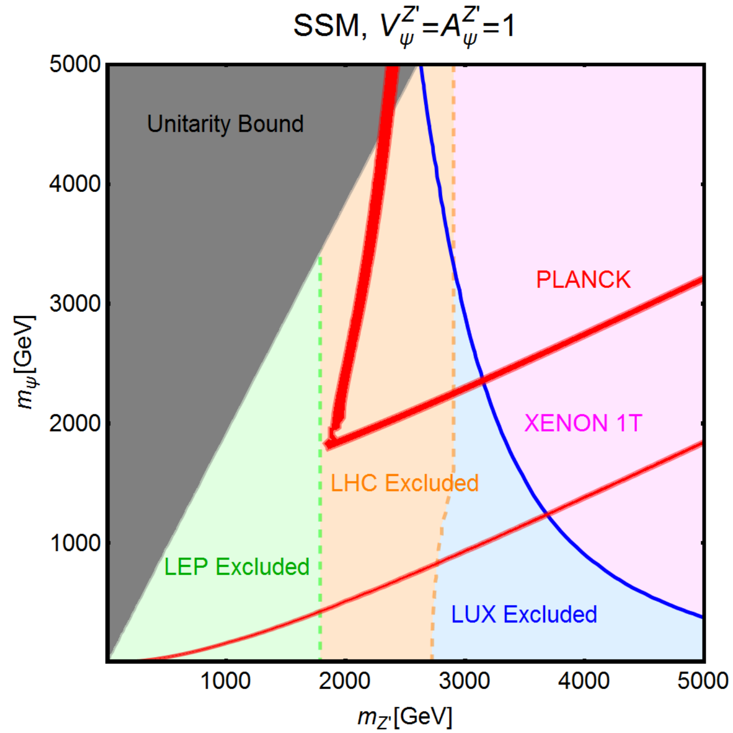
Arcadi et. al.' 17

$$\xi \lambda_\chi^H \chi^* \chi H^\dagger H,$$

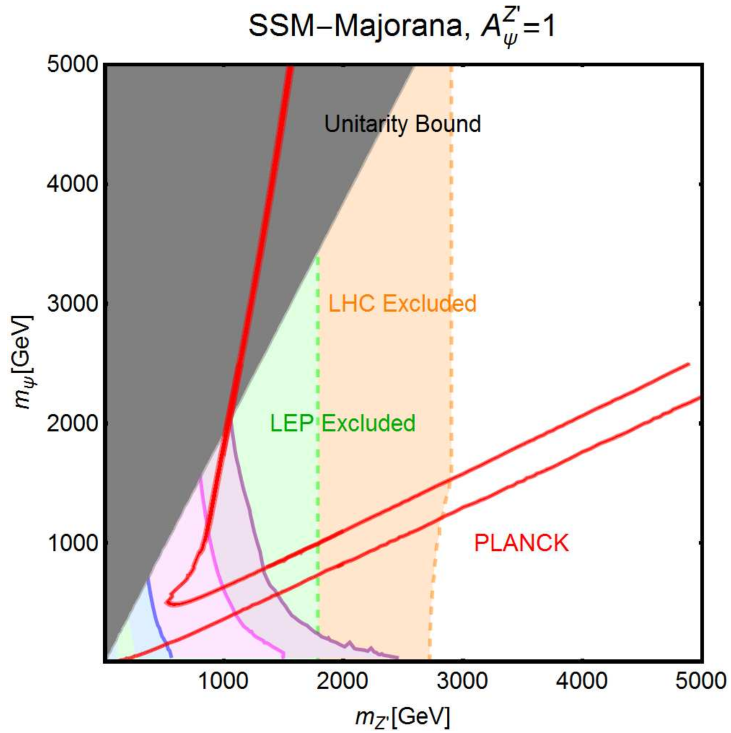
$$\xi \frac{\lambda_\psi^H}{\Lambda} \bar{\psi} \psi H^\dagger H$$







Z'-portal



Axial-vector portal

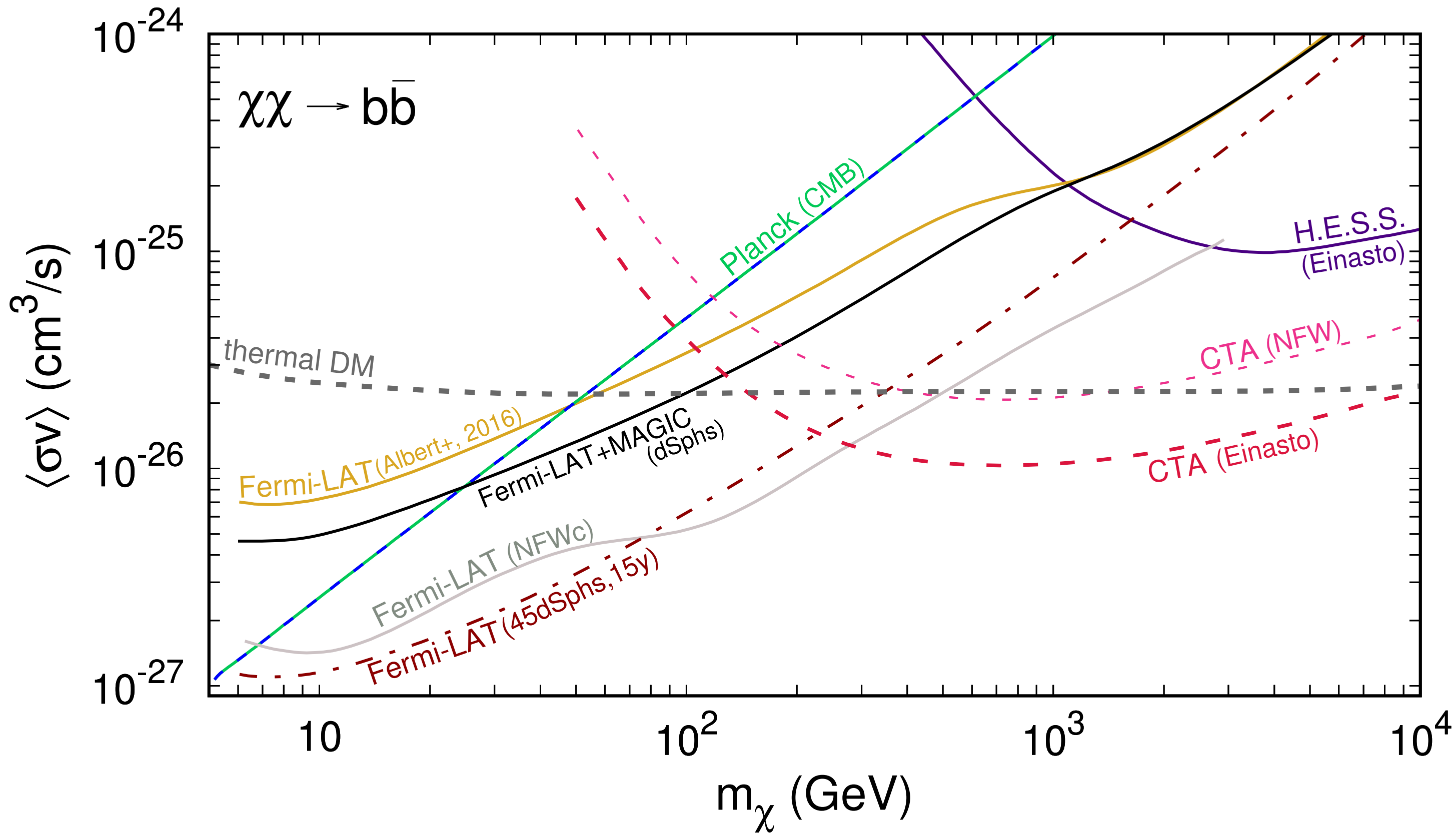
Spin-dependent
interaction with nucleons

$$\bar{X}\gamma_\mu\gamma^5 X \cdot \bar{q}\gamma^\mu\gamma^5 q$$

LHC more sensitive
than direct detection

Limits from annihilation γ's in cosmos

Roszkowski, Sessolo, Trojanowski' 17



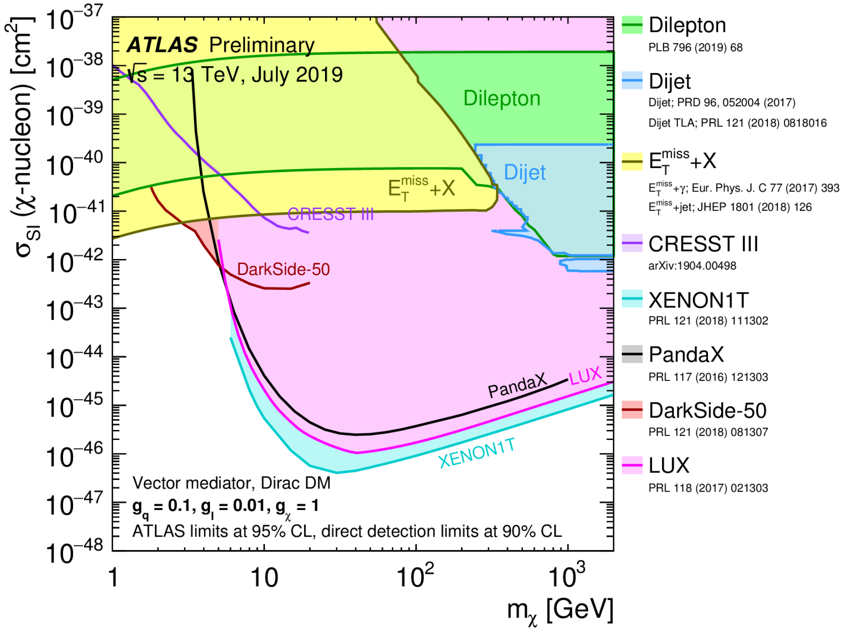
Current limits, solid; projected limits, dashed

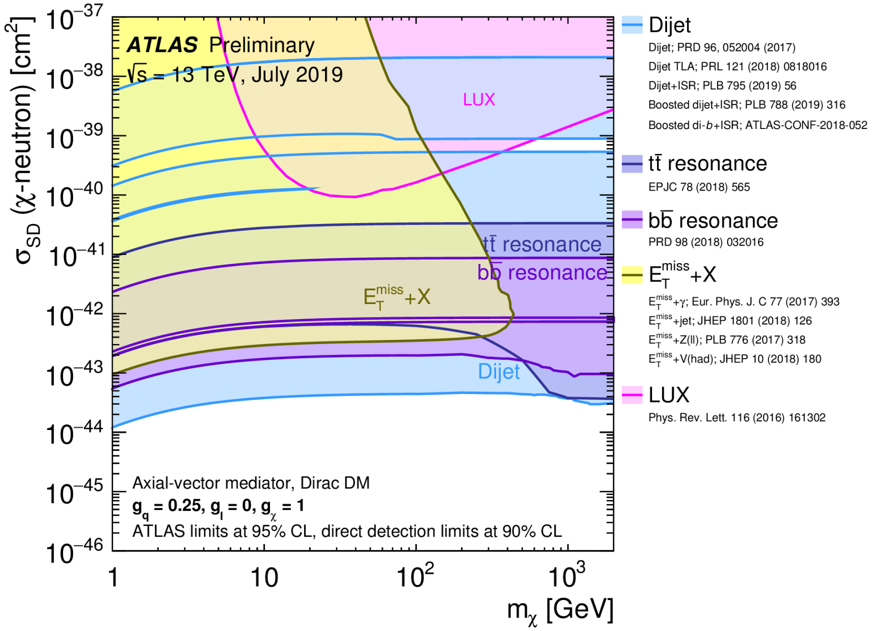
NFW, Einasto: dark matter profiles in galaxies

Thermal DM: <u>s-wave</u> WIMP annihilation, assuming domination of

$X \to b\bar{b}$ $\quad \Longleftrightarrow \quad$ model dependent

The LHC sensitivity to WIMPs





spin-independent

$\bar{X}\gamma_\mu X \cdot \bar{q}\gamma^\mu q$

$\sigma_{AX} \propto A^2$

spin-dependent

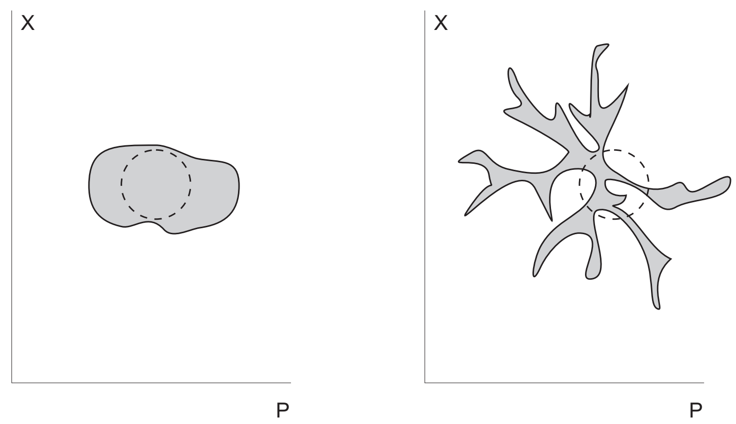
$\bar{X}\gamma_\mu\gamma^5 X \cdot \bar{q}\gamma^\mu\gamma^5 q$

$\sigma_{AX} \propto J_A(J_A+1)$

Bounds on sterile neutrino mass

Mildly depend on production mechanism through initial distribution in momenta; assume thermal

- Must be capable of forming dwarf galaxies, $M \gtrsim 10^9\ M_\odot \implies$ comoving free streaming length $\gtrsim 100$ kpc $\implies m_{\nu_s} \gtrsim 4$ keV
- "Tremaine–Gunn": maximum phase space density (coarse-grained) decreases in time



$$f(p,\vec{x}) = \frac{dN}{d^3x\,d^3p} \simeq \frac{n}{p^3} \simeq \frac{\rho/m}{m^3v^3} \lesssim f_{in}^{max}(p) \quad \implies \quad m_{\nu_s} \gtrsim 5 \text{ keV}$$

- Lyman-α: $m_{\nu_s} \gtrsim 8$ keV.

Axion production

Option 1: misalignment.

If axion field is homogeneous in the beginning of hot epoch,

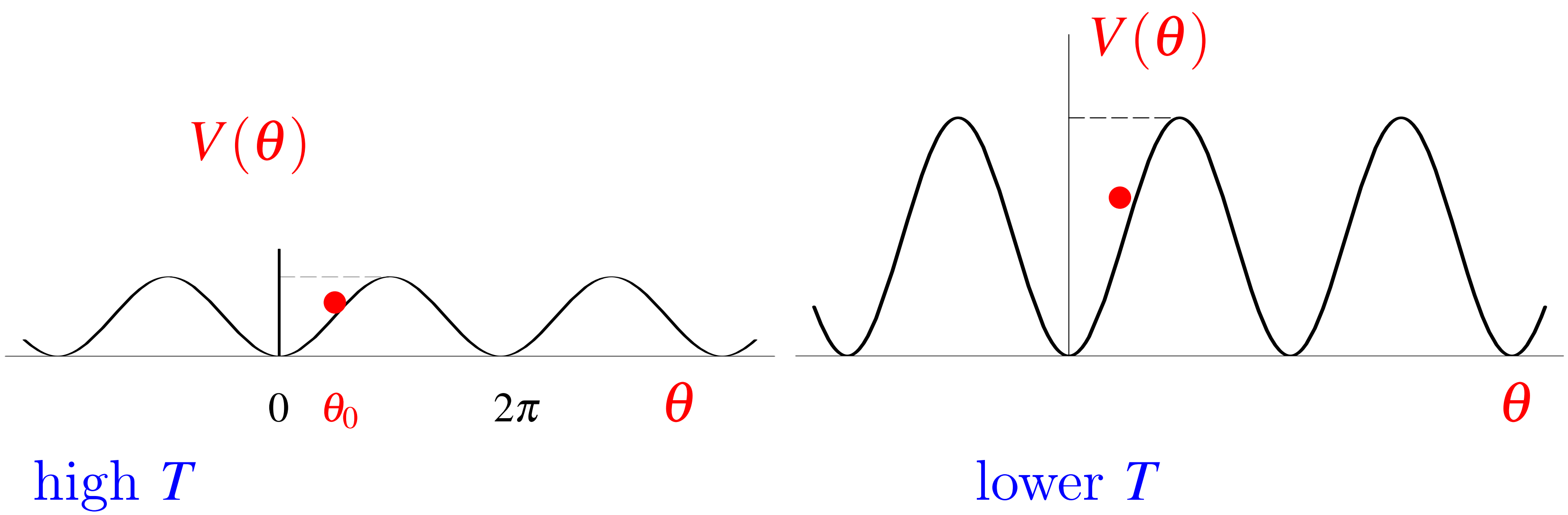
e.g., Peccei–Quinn phase transition before the end of inflation

Axion potential $V(\theta) \simeq -m_q \langle \bar{q} q \rangle \cos\theta$

Early Universe, high T: $\langle \bar{q} q \rangle = 0 \Longrightarrow V(\theta) = 0$.

Initial value θ_0 anywhere between $-\pi$ and π.

At QCD epoch ($T \sim 1$ GeV) potential $V(\theta)$ builds up. θ starts to oscillate $\Longrightarrow$ collection of quanta at rest $\Longrightarrow$ cold dark matter



Axion mass density depends on initial θ_0:

$$\Omega_a \simeq 0.2 \cdot \left(\frac{4 \cdot 10^{-6}\,\text{eV}}{m_a}\right)^{1.2} \cdot \theta_0^2$$

Axion of mass $m_a = 10^{-5} - 10^{-6}$ eV will do the job.
Or lighter, if θ_0 is small (fine tuned).

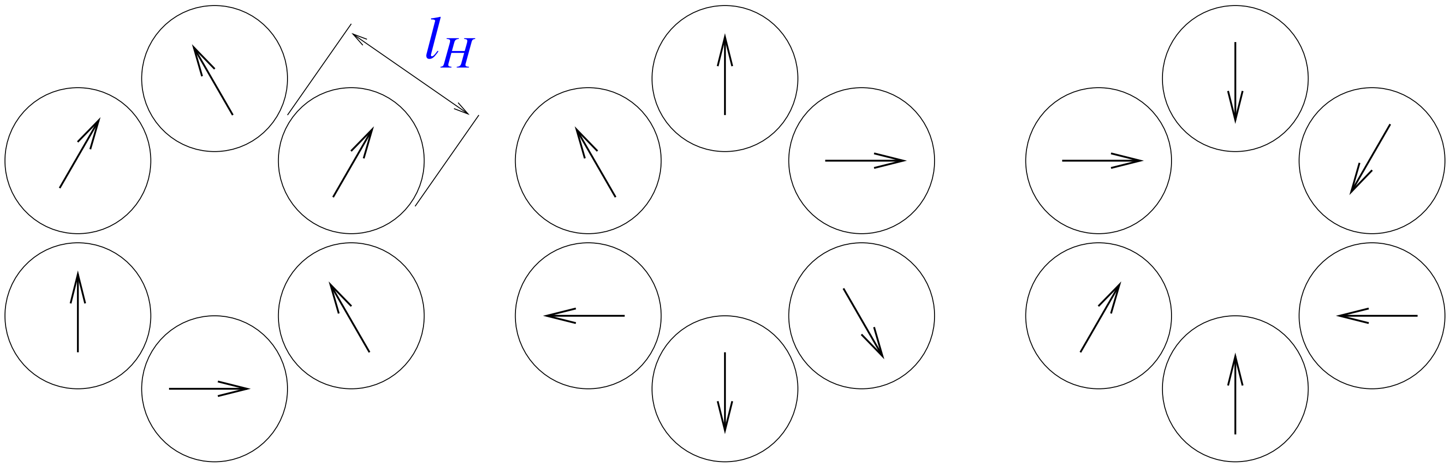
NB: Inflation generates fluctuations of all fields, incluing axion $\Longrightarrow$ entropy mode of density perturbations (perturbations in composition). Not seen in CMB $\Longrightarrow$ low inflation scale $V_{infl}^{1/4} \lesssim 10^{12}$ GeV.

Reversing the argument: discovery of dark matter entropy mode will be an interesting hint towards nature of DM.

Option 2: axion field initially uncorrelated at super-Hubble scale

e.g., Peccei–Quinn phase transition before the end of inflation

No uncertainty due to θ_0. Axion mass density in principle calculable for given m_a. But difficult in practice.

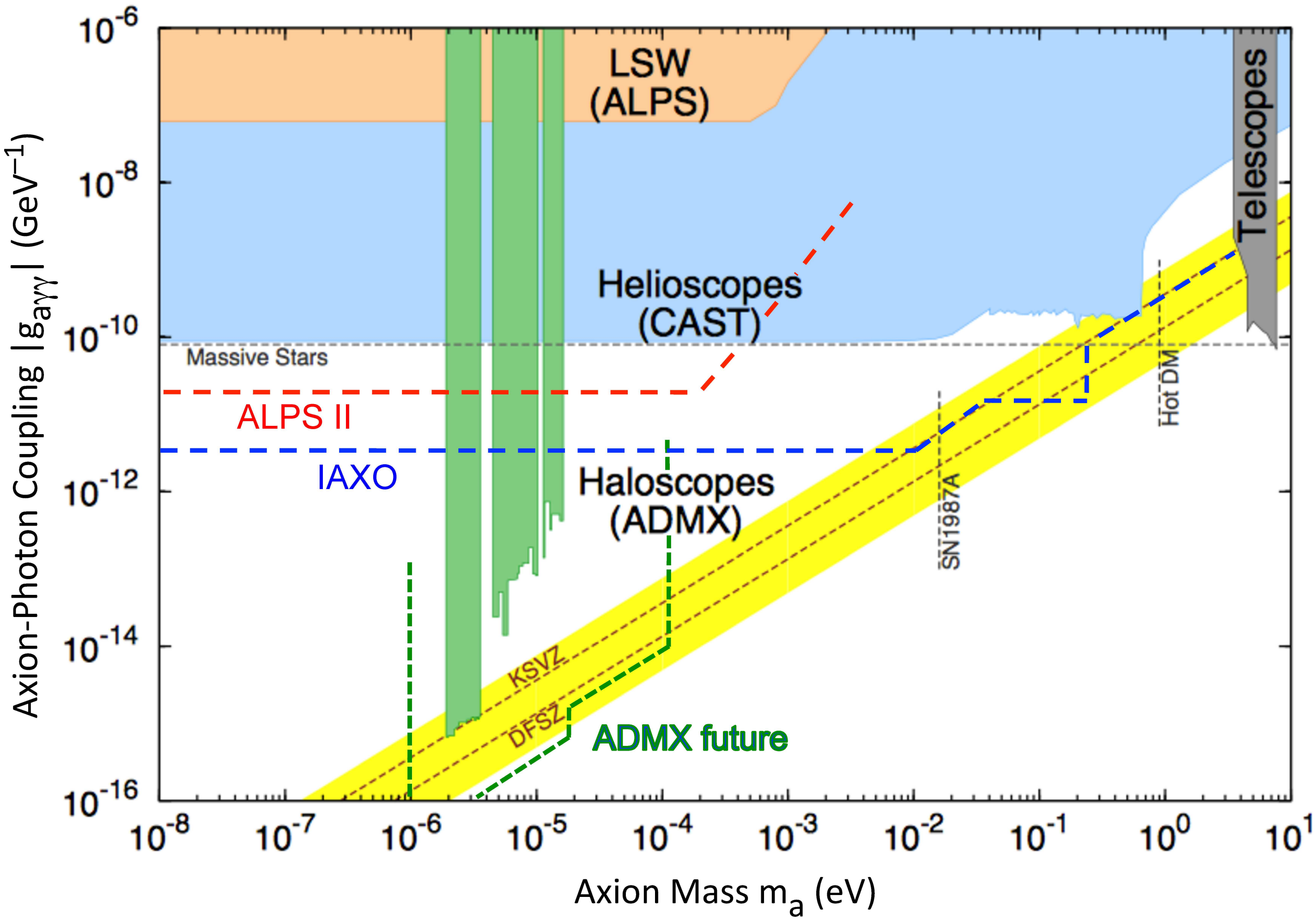


Axion string network, then axion domain walls,...

Existing estimates: $m_a = 10^{-4} - 10^{-5}$ eV

Interesting dynamics both in early Universe and "today":
Axion miniclusters of mass $\sim (10^{-10} - 10^{-12}) M_\odot$, destroyed in Galaxy $\Longrightarrow$ axion streams

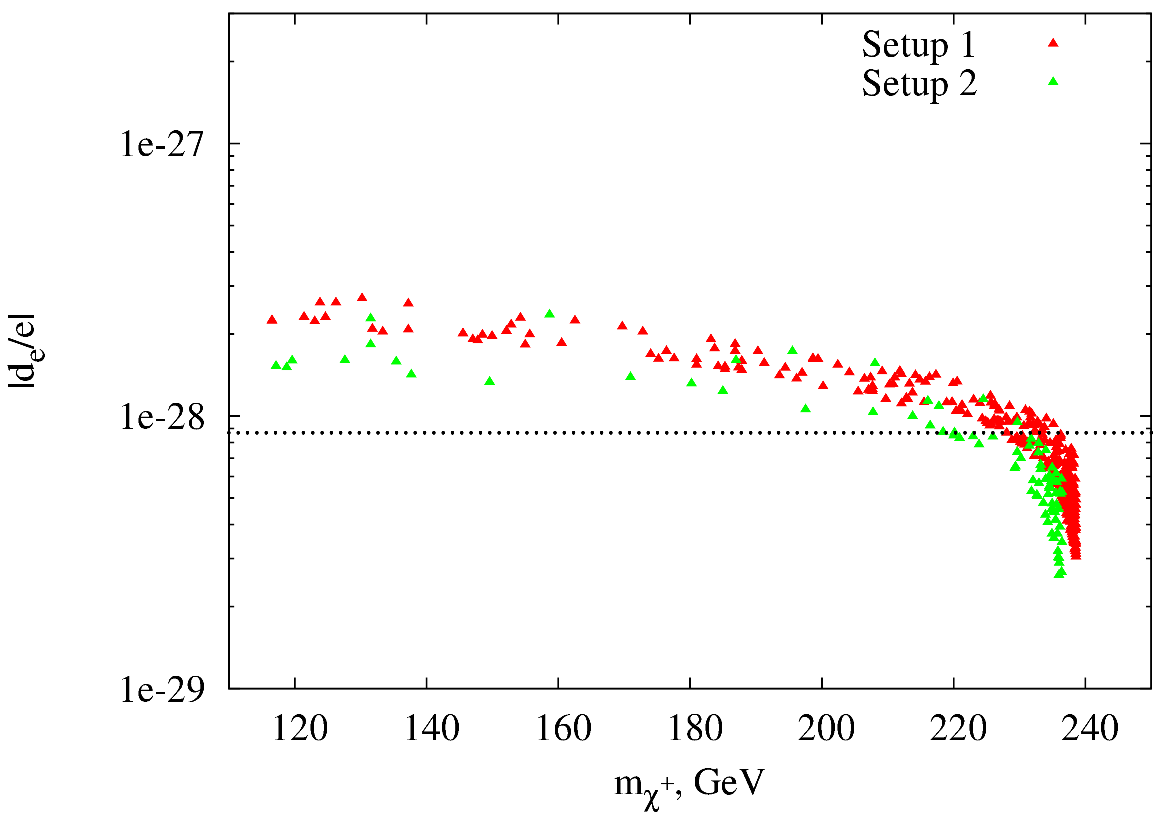
Still a lot of parameter space to explore



Example: NMSSM

Baryon asymmetry can be generated, but requires large electron EDM

Demidov, Gorbunov, Kirpichnikov' 16



ACME: $d_e < 1.1 \cdot 10^{-29} e \cdot \text{cm}$