News from theory

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SHiP
Search for Hidden Particles

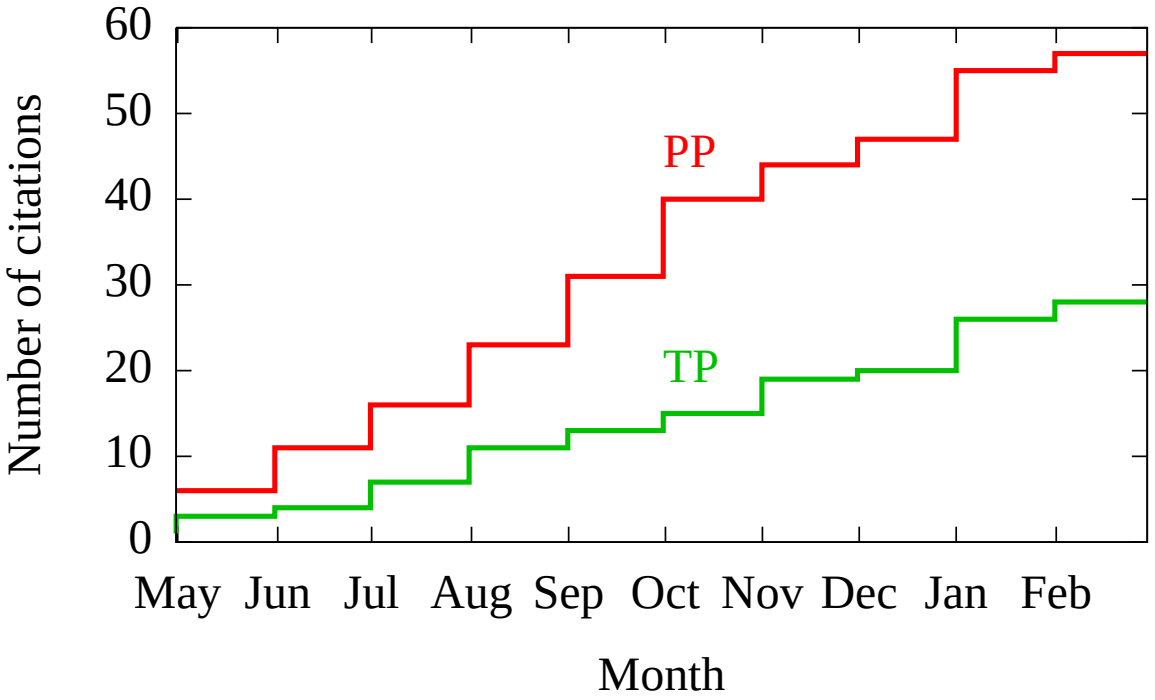
Status of SHiP Physics Paper

[1504.04855]

- SHiP Physics Paper has been accepted to **Reports on Progress in Physics**
- From the referee report: *This is an excellent and timely review, well written. It should be very useful in the search for hidden particles.*
- "Reports on Progress in Physics " (ROPP) is published by the IoP

http://www.iopscience.org/ropp

2014 Impact Factor = 17.062



Goal of the talk

Below we overview some of the recent papers that expanded, corrected or updated SHiP sensitivity estimates presented in the Physics Paper.

One can think about these papers as part of **SHiP Physics Paper 2.0**

Types of models with light feebly interacting particles

Reminder from the SHiP PP

I. Intermediate scale models

There is a wider theory with a new (maybe even TeV) energy scale. The particle, responsible for BSM phenomena exist at this scale or above, but there are light particles in the spectrum. **SUSY** is an example of such a model

II. High scale models

New physics is at very high scale. Light mediators, that couple it to SM via "portals", are the only particles that one can probe in a foreseeable future. **Axion-like particles** are examples of such models

III. No-new-scale models

Standard Model plus some light particles is valid up to very high energies. Light particles (for example, **HNLs**) are responsible for all BSM phenomena. No new physics between Fermi and Planck scale. **νMSM** is an example of such a model

Outline

Scalar portal and light dark matter

Based on **G. Krnjaic** **[1512.04119]**

"Probing Light Thermal Dark-Matter With a Higgs Portal Mediator"

This is an example of the situation I

SHiP is not finding light dark matter particle directly, but it can find a **mediator**, *connecting dark matter to the SM sector.*

Main message

In models with light dark matter interacting with the SM via scalar mediator the complimentarity between direct detection experiment and SHiP will remain for the next decades. We may well end up in the situation when SHiP discovers a mediator and DM direct detection experiments still see nothing

Scalar portal

- Scalar particle Φ that interacts with SM sector via renormalizable interactions

$$\mathcal{L}_{\text{scalar portal}} = (A_{\Phi H}\Phi + \lambda_{\Phi H}\Phi^2)H^\dagger H$$

- Because of the Higgs-Φ mixing along with the Higgs boson h, there is a **scalar state** ϕ that couples to all SM fermions ψ as

$$\mathcal{L}_{\text{mediator-SM coupling}} = \phi \sin\theta \frac{m}{v}\bar{\psi}\psi, \qquad \sin\theta \ll 1$$

- This interaction allows the scalar particles to be produced and detected at SHiP

Why relation between the scalar portal and (light) dark matter?

Reminder: Weakly interacting massive particles

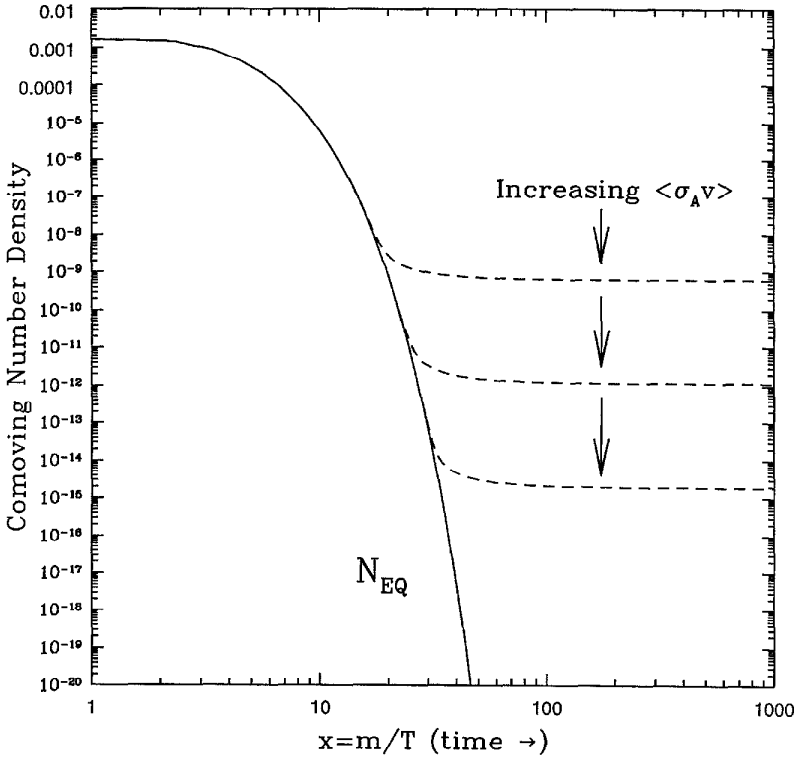
- Original idea of Weakly Interacting Massive Particles (**WIMP** dark matter) goes back to **Lee & Weinberg (Phys. Rev. Lett. 1977)**
- Their paper was titled *"Cosmological lower bound on heavy-neutrino masses"*

- Assume a new **weakly** interacting stable particle (called "heavy neutrino" in the original paper)
- These particles were in thermal equilibrium in the early Universe so, their concentration is given by Boltzmann distribution (for $m_\chi \gg T$)

$$n_\chi(T) = \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$$

- They keep the equilibrium number density via annihilation $\chi + \bar{\chi} \to \mathrm{SM} + \mathrm{SM}$
- At some moment their **annihilation rate** is not enough to maintain the equilibrium number density $\Rightarrow$ **freeze out**

WIMP freeze out



- The weaker you interact the larger is your number density

$$\Omega_\chi h^2 \sim \frac{3 \cdot 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_A v \rangle}$$

- Annihilation cross-section depends on the interaction strength and on the number of final states

$$\sigma_A \sim G_F^2 \; m_\chi^2 \; N_{\text{channels}}$$

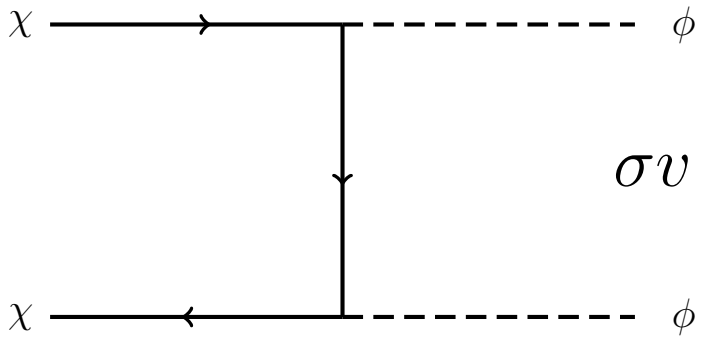
For mass $m_\chi \sim \mathcal{O}(1)$ GeV annihilation into the SM channels leads to a **too small** cross-section $\Rightarrow$ **too large** DM abundance

Lee & Weinberg took G_F as an interaction strength and got the lower bound $m_\chi > 5$ GeV

Light WIMP $\Rightarrow$ extra light states

- Light DM requires more **light** states to annihilate to (scalars, vectors)
- Consider scalar portal coupled to DM fermion χ

$$\mathcal{L}_{\text{DM-mediator coupling}} = \phi g_\chi \bar{\chi}\chi$$

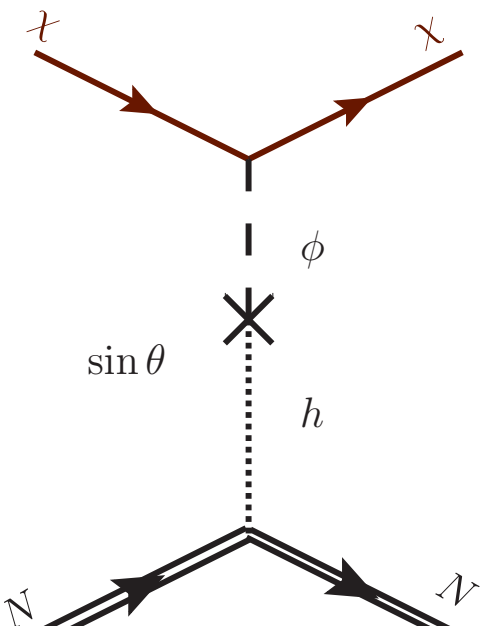


$$\sigma v \propto g_\chi^4$$

$$(m_\phi < m_\chi)$$

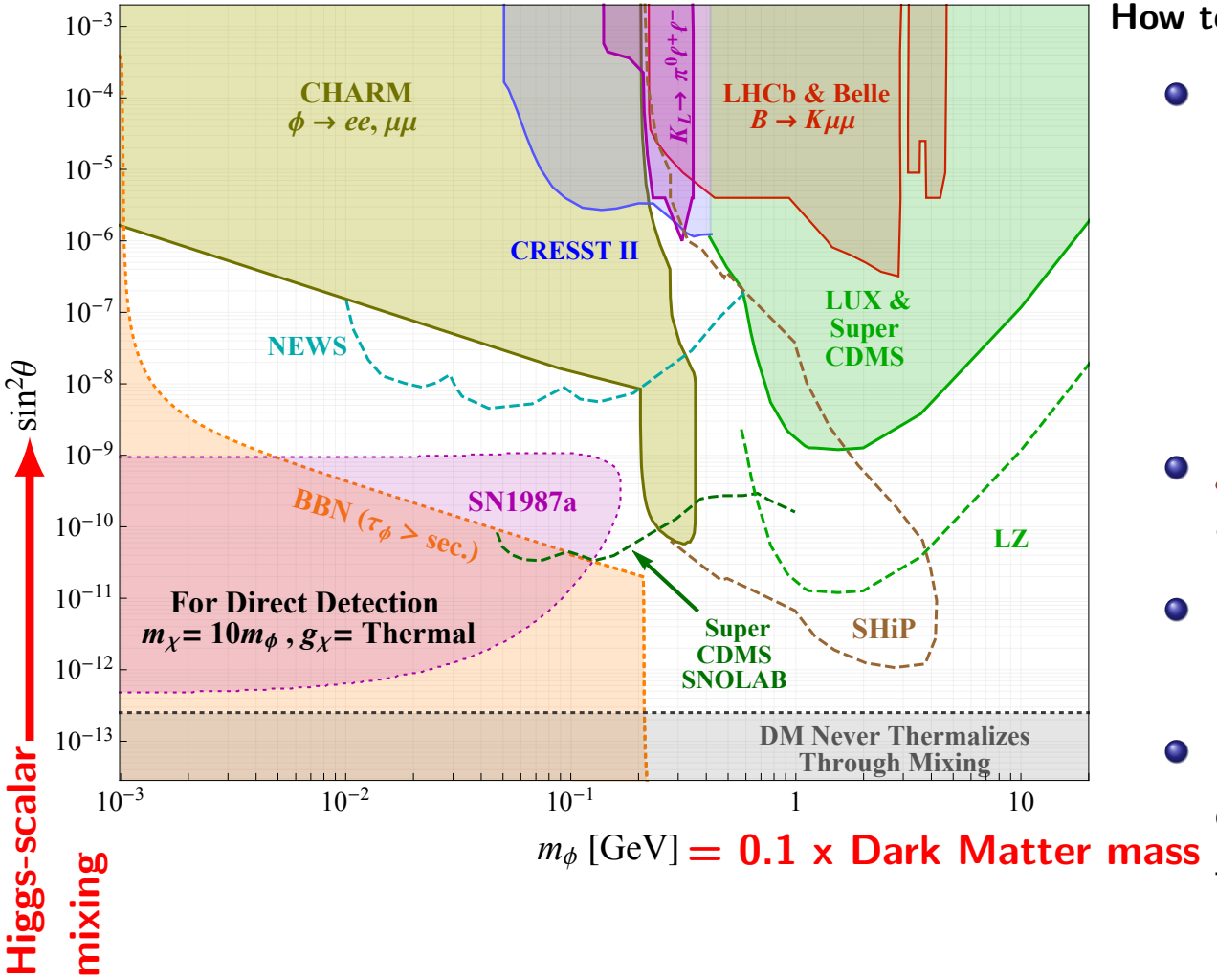
- Mediator ϕ couples WIMP to SM fermions via $\sin\theta$ determines **DM-nucleon cross-section** for direct detection experiments

$$\sigma_{\chi N} \propto \sin^2\theta \frac{g_\chi^2}{m_\phi^4}$$



SHiP vs. direct detection experiments

[1512.04119]



How to read this figure:

- Direct detection exps. probe DM-nucleon cross-section:

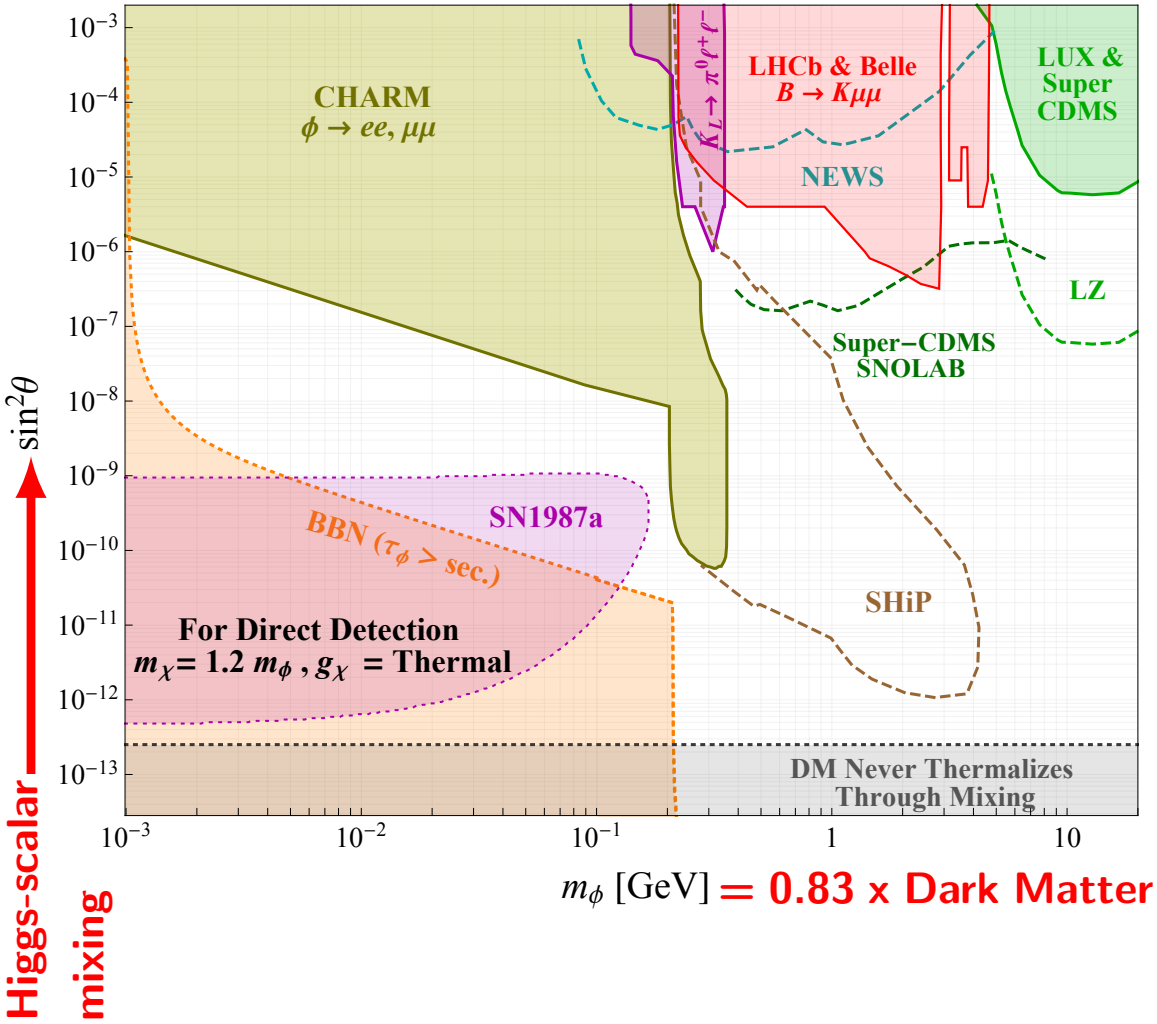
$$\sigma_{\chi N} \propto \sin^2\theta g_\chi^2$$

- g_χ is fixed by requiring correct DM abundance, Ω_χ
- $\Rightarrow$ can translate $\sigma_{\chi N}$ bound into $\sin^2\theta$
- Lower bound for $\sin\theta$ exists – dark matter never thermalises in the early Universe

dashed lines – future direction detection experiments

SHiP vs. direct detection experiments

[1512.04119]



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dashed lines – future direction detection experiments

Outline

Axion-like particles at SHiP

Based on **B. Döbrich, J. Jaeckel, F. Kahlhoefer, A. Ringwald, K. Schmidt-Hoberg**
ALPtraum: ALP production in proton beam dump experiments **[1512.03069]**

This is an example of the situation II

New physics is very heavy (well beyond the reach of accelerators) but there are some light particles (pseudo-Nambu-Goldstone bosons)

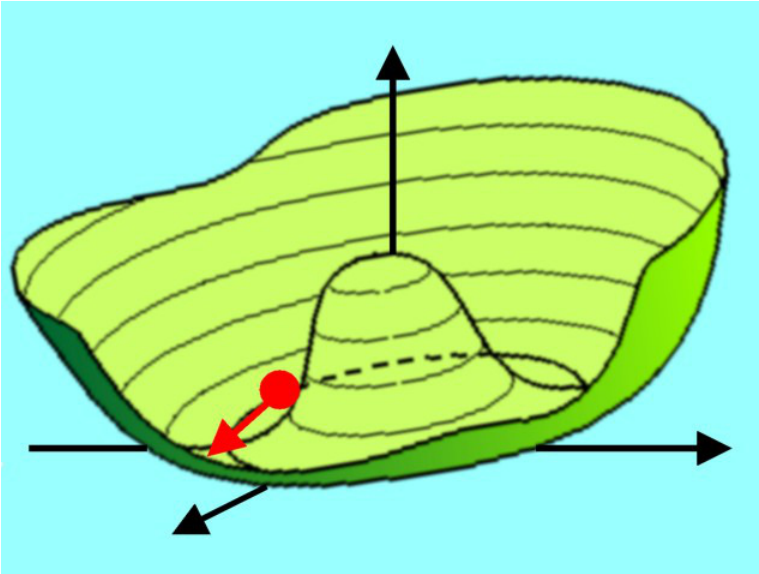
Main message

A dominant production channel for axion-like particles has been overlooked previously. Coherent Primakoff scattering of the whole proton off the nucleus increases production of ALPs in the fixed-target experiments. The updated SHiP sensitivity curves are presented in **[1512.03069]**

Reminder: axions

- Complex scalar field $\Phi = (f + \phi)e^{\frac{ia}{f}}$ with a "Mexican hat"-type potential

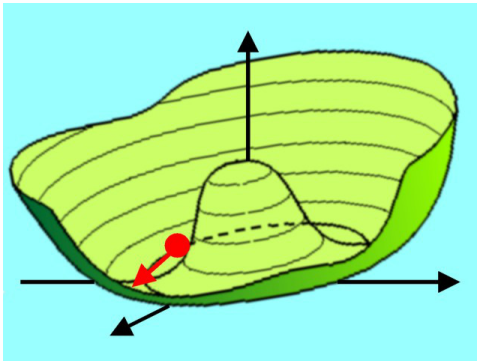
$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - f^2)^2$$



- The symmetry is **spontaneously broken** at high energies $\langle\Phi\rangle \sim f \gg \mathrm{TeV}$
- Spontaneously broken symmetry leaves behind a **Goldstone boson** a
- if the symmetry was not exact these pseudo-Goldstone bosons will be massive. But generically axion mass $m_a \ll f$

ALP = axion-like particle

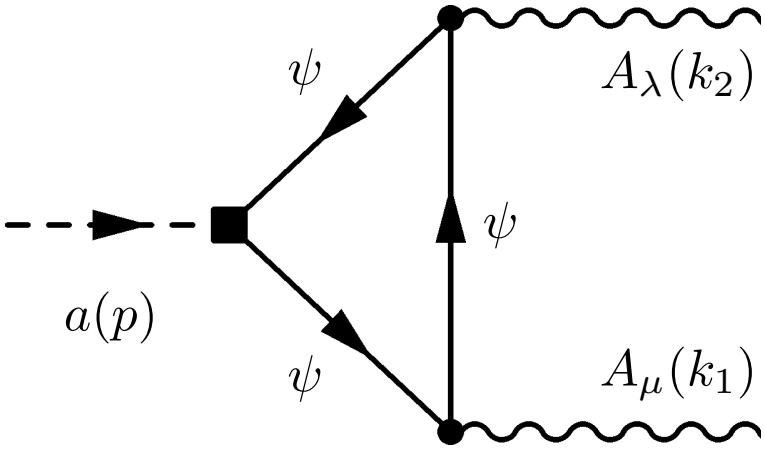
$$\mathcal{L}_{\text{axion}} = \frac{(\partial a)^2}{2} - \frac{m_a^2 a^2}{2} - \frac{g_{a\gamma}}{4} a F \tilde{F}$$



More possibilities exist if axion couples to quarks. But often consider only this model as the most conservative. Two parameters: **mass** m_a and **interaction strength** $g_{a\gamma}$

- Fermions Ψ interact with a scalar and get mass ($m_\Psi \sim f \gg \text{TeV}$)
- Via loops they induce interactions between **light** particles (photons γ and axion a):

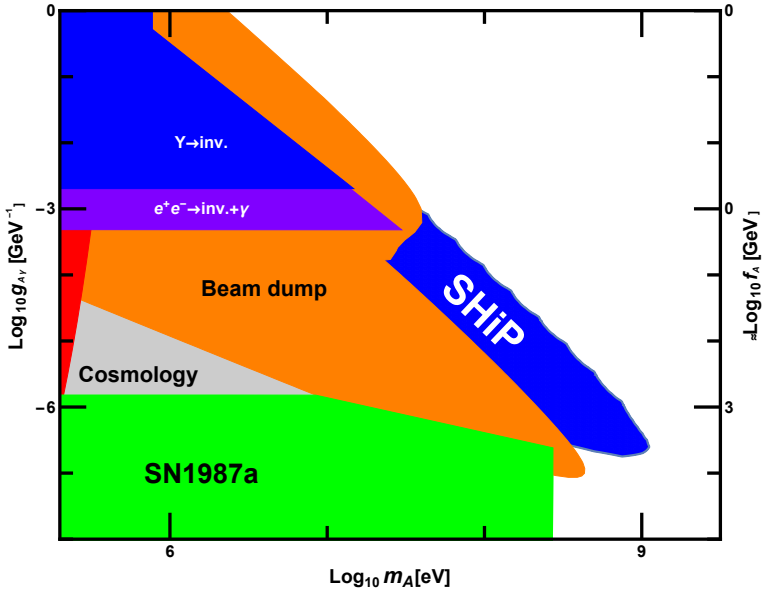
$$g_{a\gamma} \sim \frac{\alpha}{2\pi} \frac{1}{f}$$



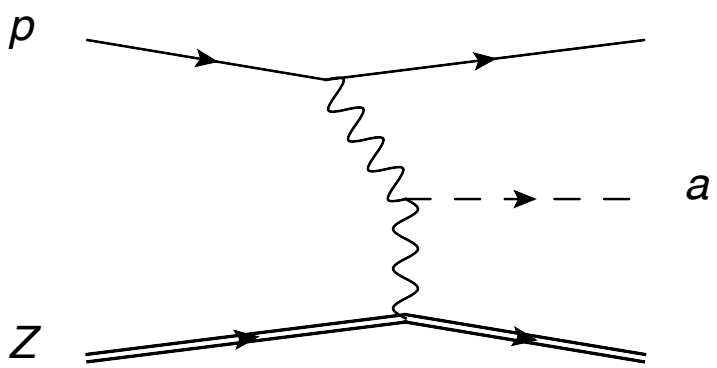
Coherent Primakoff production

B. Döbrich, J. Jaeckel, F. Kahlhoefer, A. Ringwald, K. Schmidt-Hoberg *"ALPtraum: ALP production in proton beam dump experiments"* **[1512.03069], accepted to JHEP**

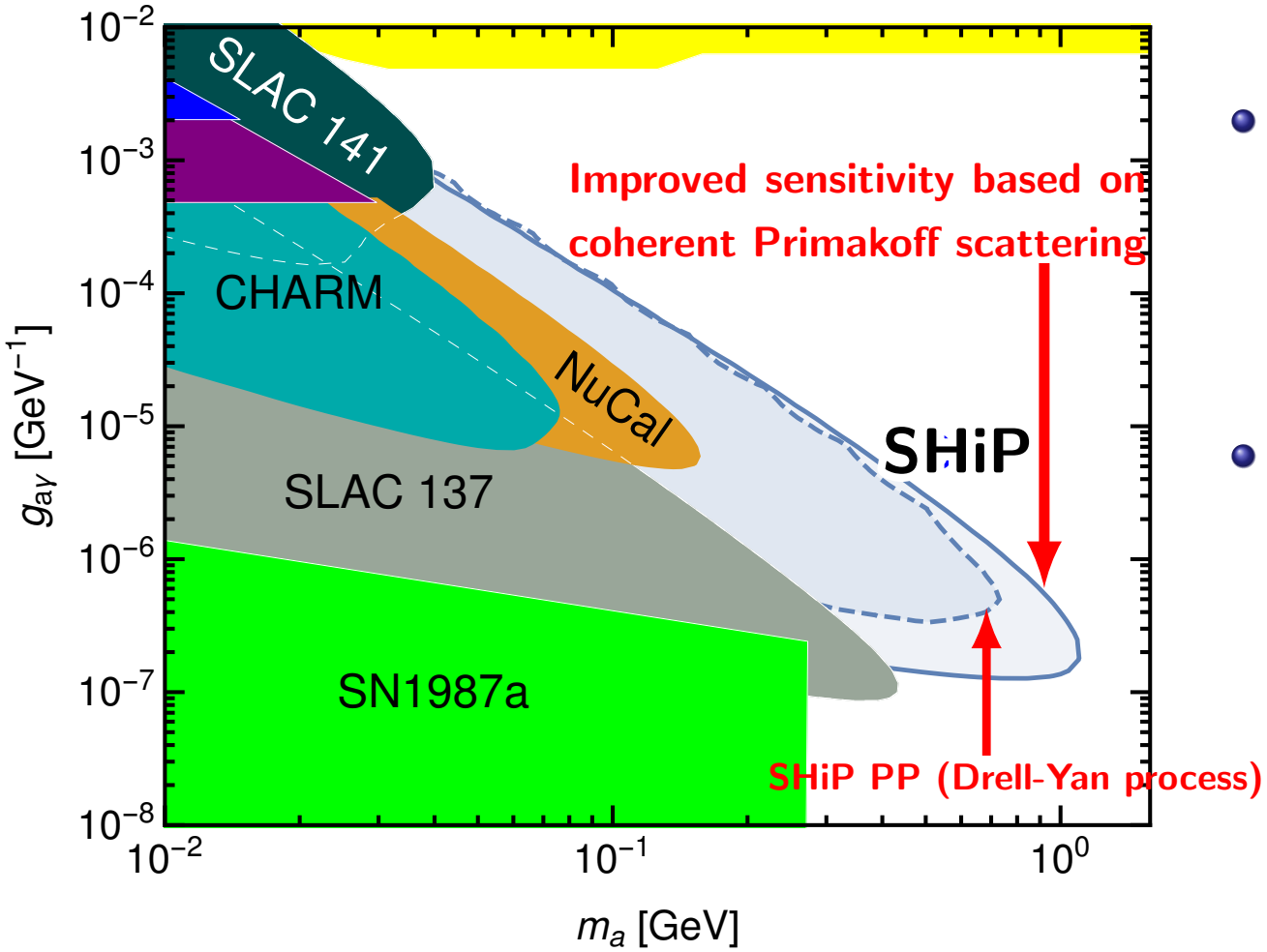
- In SHiP PP production was estimated as quark-antiquark Drell-Yan process – incoherent Primakoff effect
- SHiP PP sensitivity estimates and previous bounds are based on this calculation



- **New result:** at SHiP energies photons from the whole proton "feel" the electric field of the **whole** nucleus
- Cross-section goes as Z^2 for heavy nuclei
- For SHiP energies it wins over Drell-Yan



How much did coherent production improve things?



- Dashed line: Drell-Yan based production. Did not take into account calorimeter acceptance! (Slightly updated version of the PP)
- Solid line: improvement based on coherent production (includes the requirement that both ALP produced photons hit the detector and that the separation between them is large enough)

Figure courtesy of Felix Kahlhoefer

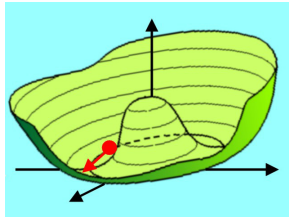
SHiP and di-photon excess

Based on **L. Aparicio, A. Azatov, E. Hardy, A. Romanino** *Diphotons from Diaxions* **[1602.00949]**

It has been proposed that the di-photon excess may be due to two **axions** mistaken for photons

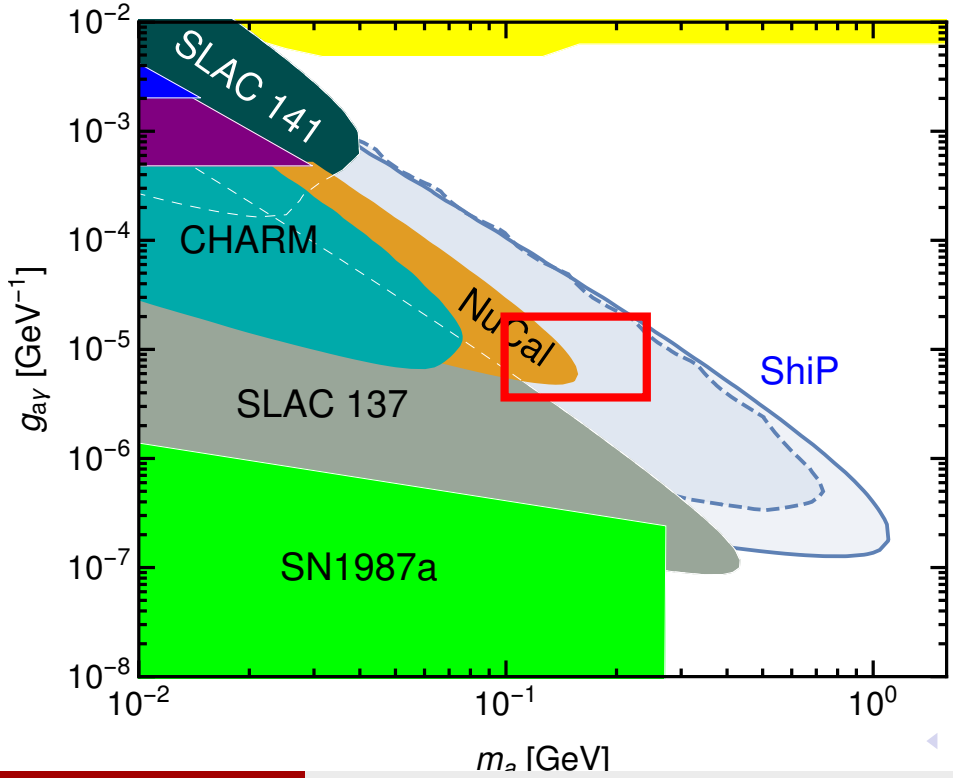
- Gluon fusion $gg \to s$ to scalar with mass $M_s = 750$ GeV
- Scalar decays to two axions: $s \to aa$ with $m_a \sim (100 - 200)$ MeV
- Each axion decays to $a \to \gamma\gamma$. γ's are highly boosted
- Each pair of photons is misidentified as a single photon

Origin and parameters of the model



- There exists a new scalar field Φ with Mexican-hat potential
- The symmetry is **spontaneously broken** at high energies

  $\langle\Phi\rangle = f$: $\Phi = (f + s)\exp\left(\frac{ia}{f}\right)$
  - s – heavy scalar, $M_s = 750$ GeV, width $\Gamma_s \simeq 40$ GeV
  - a – axion field, $m_a \sim \mathcal{O}(200)$ MeV (for photons to be collimated)



Outline

Light decaying neutralinos at SHiP

Based on **J. de Vries, H. Dreiner, D. Schmeier** **[1511.07436]**
R-Parity Violation and Light Neutralllinos at SHiP and the LHC
D. Gorbunov, I. Timiryasov **[1508.01780]**
Decaying light particles in the SHiP experiment. II. Signal rate estimates for light neutralinos

This is again an example of the situation I

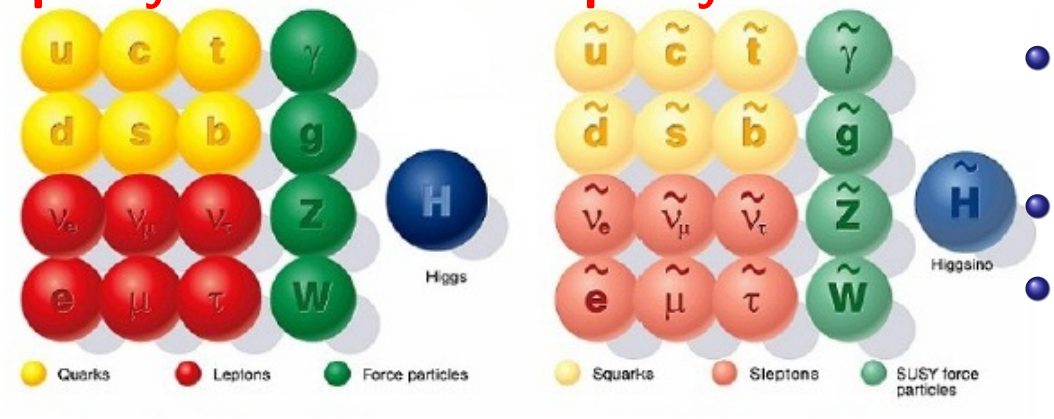
Supersymmetry exists and SHiP is finding the lightest superpartner

Main message

Even within the Minimal Supersymmetric Standard Model (MSSM) light (even massless) neutralinos are experimentally **allowed** and theoretically **possible**. Cosmology tells us that GeV-mass neutralinos should necessarily be **decaying**. SHiP can probe for their decays.

Reminder: Minimal Supersymmetric Standard Model (MSSM)

R-parity even states **R-parity odd states**



- Doubles the number of particles (plus there are two Higgs doublets).
- $R = (-1)^{3(B-L)+2S}$
- Without R-parity **proton is unstable**

Neutralino $\tilde{\chi}_1^0$ – **lightest supersymmetric particle**

- Majorana fermion
- Mixture of superpartners of $SU(2) \times U(1)$ gauge bosons and Higgses
- If R-parity is exact – $\tilde{\chi}_1^0$ is stable (lightest carrier of R-charge) $\Rightarrow$ WIMP

What is known about neutralino?

- PDG LEP bound ($m_{\tilde{\chi}_1^0} > 46$ GeV) is indirect
  and relies on specific assumptions about the type of GUT in the MSSM
- Neutralino can be light and even **massless** within the MSSM framework
  satisfying all laboratory/accelerator bounds **[0901.3485, SHiP PP]**
- Stable neutralino is WIMP
- Produced in the early Universe $\Rightarrow$ Lee & Weinberg bound again:
  $m_{\tilde{\chi}_1^0} > 24$ GeV (otherwise too much DM is produced)
- Lighter neutralino should be **decaying**
- Decay of neutralino means **R-parity violation** or **RPV**

Decaying (or RPV) neutralinos

- RPV – 96 **trilinear** couplings mixing quarks, leptons and sfermions (squarks or sleptons):

$$\mathcal{L}_{\text{RPV}} = -\lambda'_{ijk}\Big(\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^{\star}_{kR}\bar{\nu}^{c}_{iR}d_{jL}$$
$$-\tilde{l}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}l_{iL} - \tilde{d}^{\star}_{kR}\bar{l}^{c}_{iR}u_{jL}\Big) + \text{ h.c. },$$

there are more terms, but not relevant for SHiP

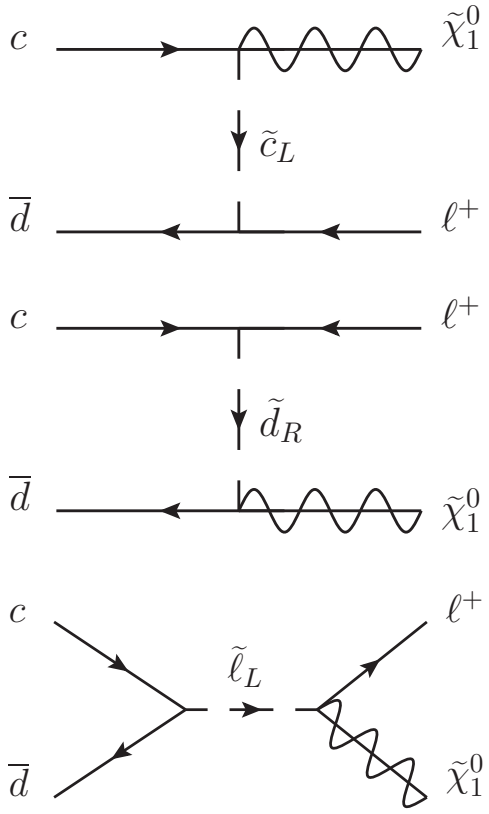
- $p + p \to \tilde{\chi}^0_1 + \tilde{\chi}^0_1 + X$ – negligible contribution
- Dominant production: Meson $\to \tilde{\chi}^0_1 + \ell$
  - $D^{\pm} \to \tilde{\chi}^0_1 + \ell^{\pm}$
  - $D^0 \to \tilde{\chi}^0_1 + \nu$
  - $B^0_d \to \tilde{\chi}^0_1 + \nu$
  - $B^{\pm} \to \tilde{\chi}^0_1 + \tau^{\pm}$

SHiP PP included only D-mesons in the analysis

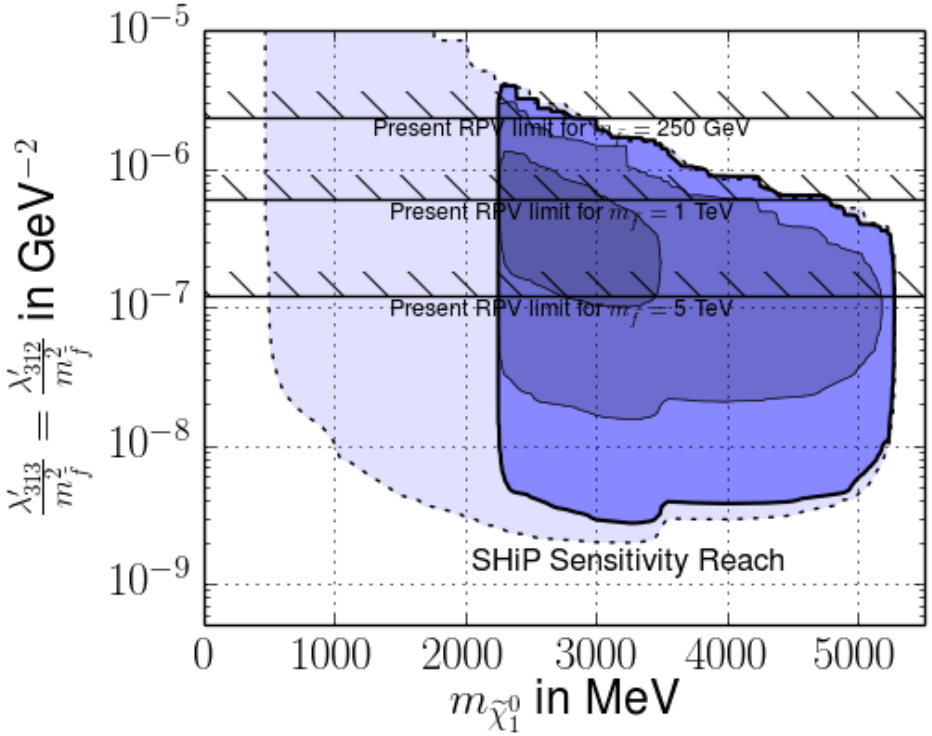
- Decay channels:
  - $\tilde{\chi}^0_1 \to K^{\pm}\ell^{\mp}$
  - $\tilde{\chi}^0_1 \to \pi^{\pm}\ell^{\mp}$
  - ...
  - $\tilde{\chi}^0_1 \to \ell^+_i \nu_j \ell^-_k$
  - $\tilde{\chi}^0_1 \to K^0\nu$ (invisible)
  - ...

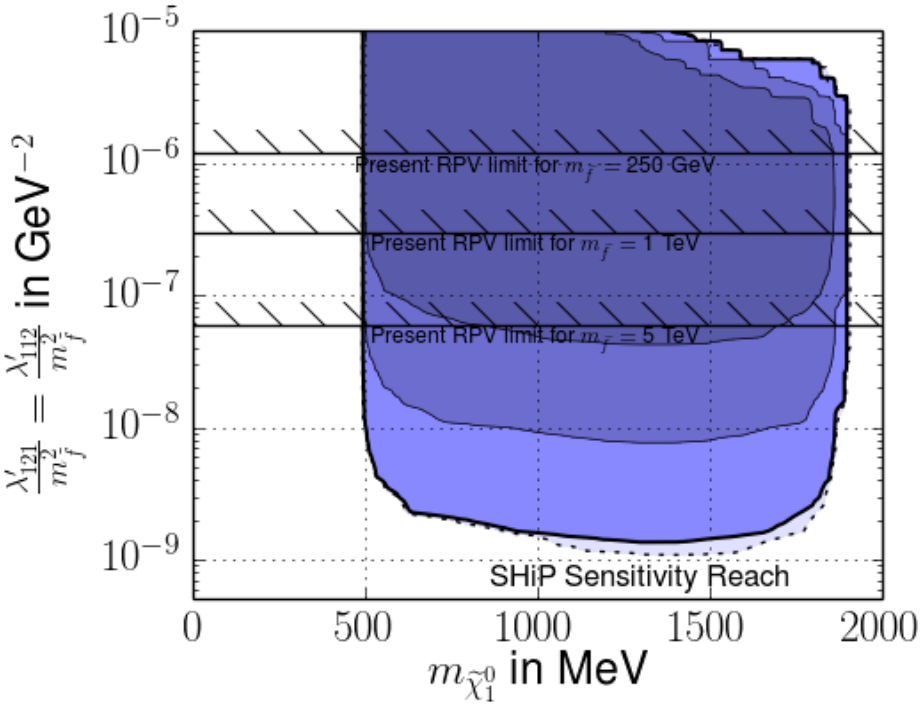
$$D^+ \to \tilde{\chi}^0_1 + \ell^+$$

Four-fermion interaction mediated by sfermions:



Update on decaying neutralino searches at SHiP





- The bound is for $\frac{\text{RPV coupling}}{\text{sfermion mass}^2}$
- Many more updated sensitivity plots for various benchmark models in **[1508.01780, 1511.07436]**
- LHC and SHiP are compatible, but SHiP is still factor ~ 2 better

How to distinguish RPV neutralino HNLs?

- Neutralino production and decay is very similar to HNL:

$$D \to N + \ell$$

$$N \to \ell^+ + \ell^- + \nu \quad ; \quad N \to \mu^\pm + \pi^\mp$$

- ...different momentum spectra of each final state?
- ...different branching ratios of final states?

Outline

Current status of 3.5 keV line

Based on **O. Ruchayskiy, A. Boyarsky et al.** **[1512.07217]**
"Searching for decaying dark matter in deep XMM-Newton observation of the Draco dwarf spheroidal"

This is an example of the situation III

It is possible to resolve BSM phenomena with only light particles. HNLs at SHiP plus a 7 keV HNL dark matter would be an example of such a model.

Main message

The status of 3.5 keV line is still unclear. Dark matter explanation of its origin is the only one that fits **all observations**. Otherwise, one has to assume atomic line in some objects, and systematics/statistical fluctuation at the same energy in the other objects.

Reminder: 3.5 keV line story

Two groups reported an identified feature in the X-ray spectra of dark matter-dominated objets

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

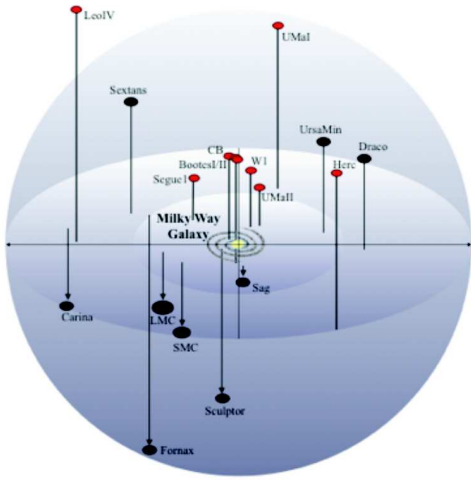
PRL (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay $\mathrm{DM} \to \gamma + \nu$ (fermion) or $\mathrm{DM} \to \gamma + \gamma$ (boson)

Dwarf spheroidal galaxies – smallest DM-dominated objects known

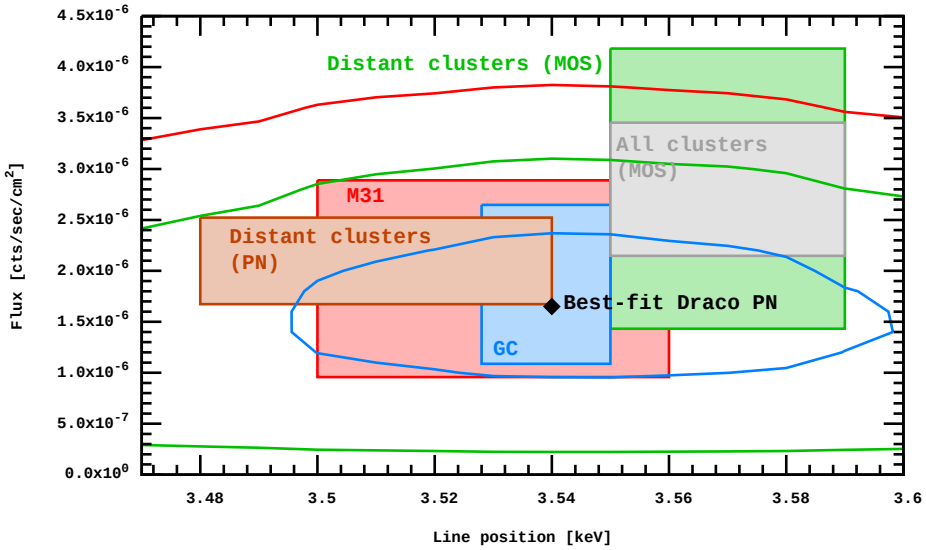
- Dwarf spheroidals are "*galaxies inside our Galaxy*"
- These are ancient galaxies "swallowed" by the Milky Way
- Dwarf spheroidal galaxies are too light and compact to confine X-ray emitting gas ($k_B T \sim G_N \frac{\text{Mass}}{\text{Size}}$)
- The best target (balance between mass and distance) for the current satellite – dwarf galaxy in the constellation of Draco – **Draco dSph galaxy**
- XMM-Newton's time allocation committee granted us 1.4 Mega-seconds (10% of the annual observational budget)

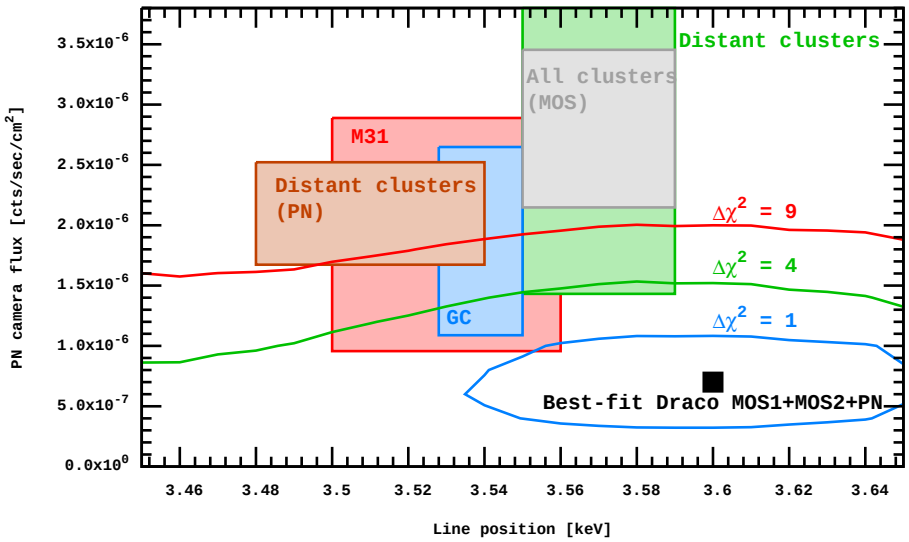
PI: A. Boyarsky



Analysis of Draco dSph

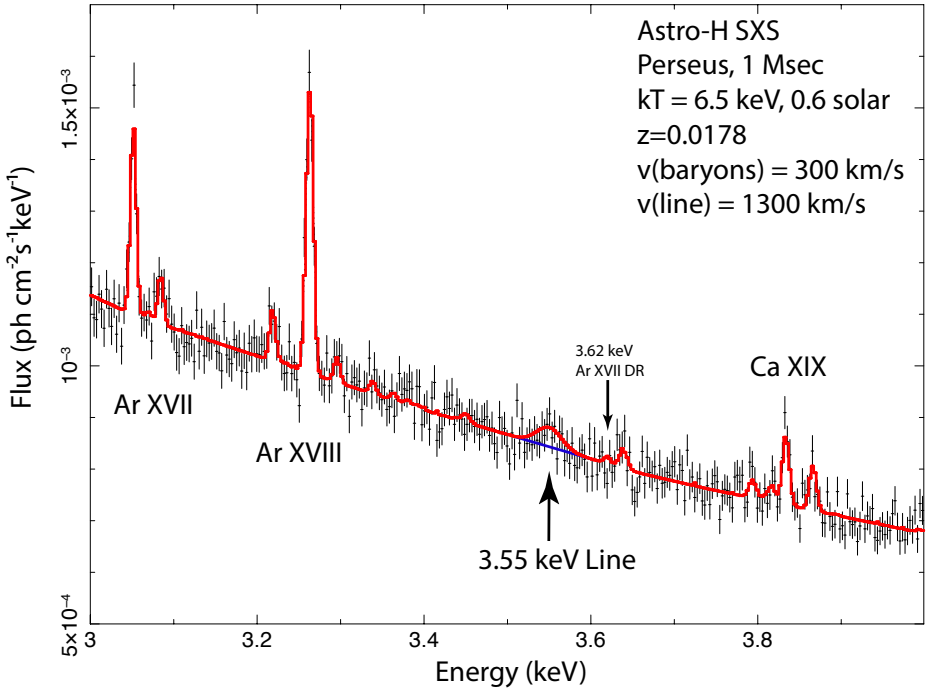
- The line is detected in the spectrum of Draco dSph with low (2σ) significance
- Line flux/position are consistent with previous observations
- There is a shift in position ($\sim 1\sigma$) between two XMM-Newton detectors (which happens for weak lines)
- The data is consistent with DM interpretation for lifetime $\tau > (7{-}9) \times 10^{27}$ sec
- Compared to [1512.01239] we do data processing differently and use a more sophisticated background model.





Next step: Astro-H

- Astro-H – new generation X-ray spectrometer with a superb spectral resolution
- Should be launched in **2 days** (12 February 2016)
- Calibration phase – about 1 year
- First observational/calibration target – Perseus galaxy cluster



- Will be able to confirm the presence of the 3.5 keV line in Perseus and distinguish it from atomic element lines (Potassium, Chlorium, etc.)

Outline

Conclusion

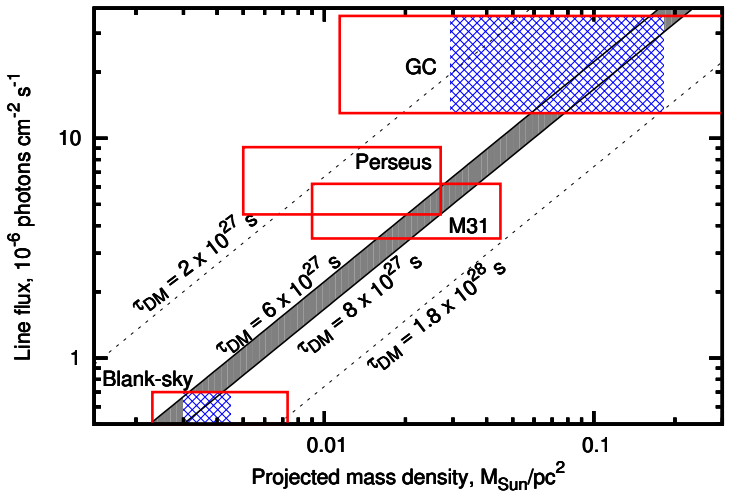
Theoretical community is well aware about the SHiP experiment and continues to work on it after the **SHiP Physics Paper** has been written

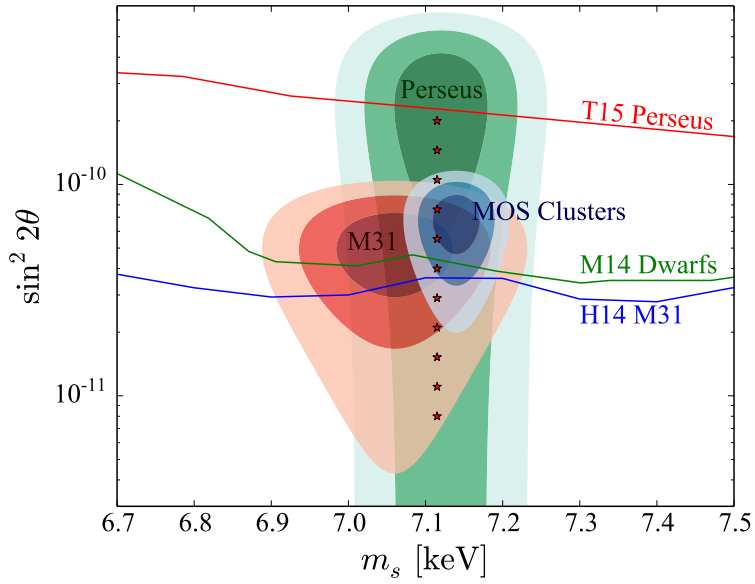
Thank you for your attention!

Outline

Subsequent works

- Subsequent works confirmed the presence of the line in some of the objects (Galactic Center, Perseus galaxy cluster, other galaxy clusters)
- ...challenged it existence in other objects
- ...argued astrophysical origin of the line
- Extensive overview of the subject appears in **[1602.XXXXX] "A White Paper on keV Sterile Neutrino Dark Matter"**





Challenges

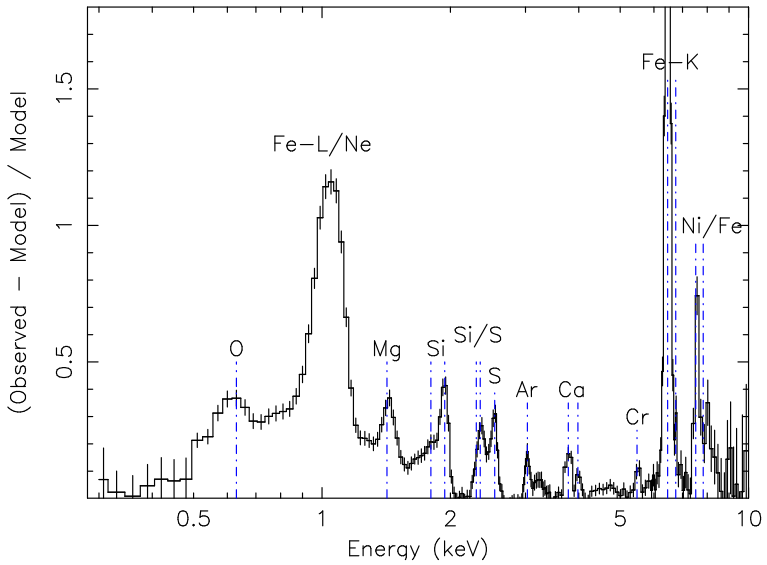
- Dark matter dominated objects (galaxy clusters and big galaxies) are X-ray bright:

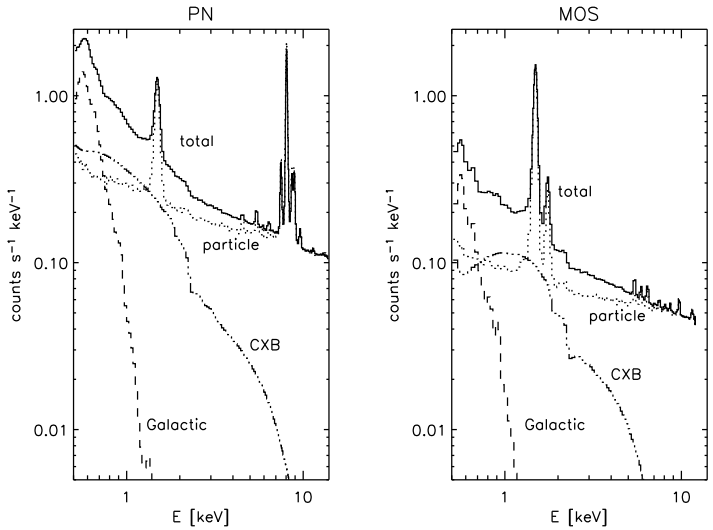
$$k_B T \sim G_N \frac{\text{Mass}}{\text{Size}} \qquad \text{virial theorem}$$

- Spectral resolution does not allow to resolve the individual lines

- X-ray satellites fly in space (above the radiation belt) – heavily bombarded by cosmic rays

$\Rightarrow$

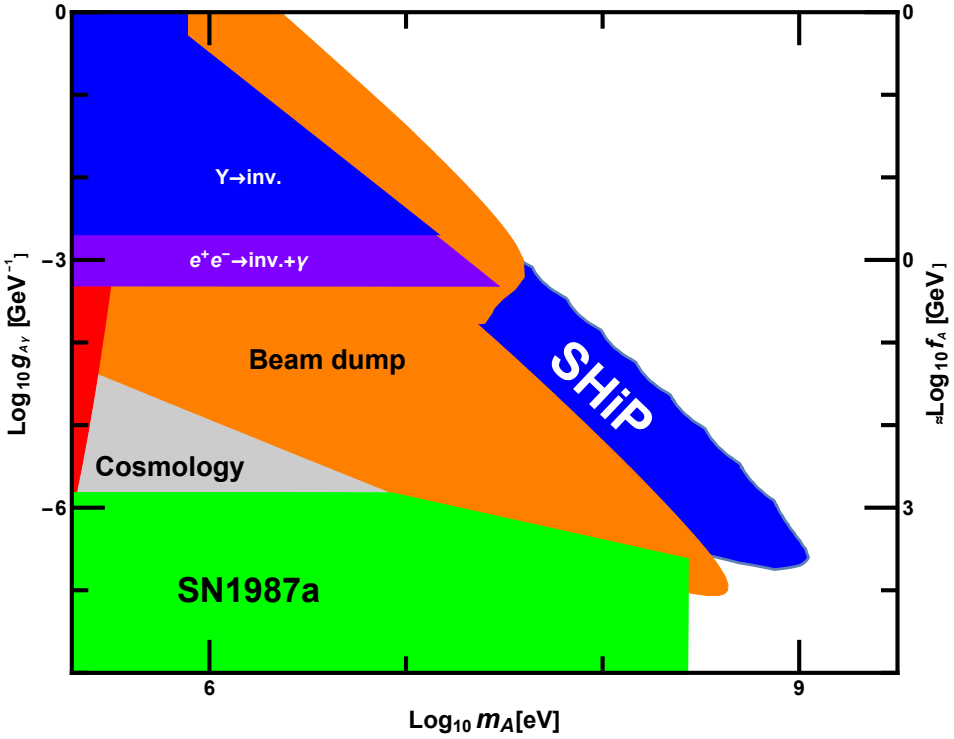




SHiP sensitivity for ALPs

From SHiP Physics Paper

- Small coupling – small number of ALPs produced
- Large coupling short decay length
- Challenging to probe $10^{-6}\mathrm{GeV}^{-1} < g_{a\gamma} < 10^{-3}\mathrm{GeV}^{-1}$



From SHiP PP

$$l_a = 40\,\mathrm{m} \times \frac{E_a}{10\,\mathrm{GeV}} \left(\frac{10^{-5}\,\mathrm{GeV}^{-1}}{g_{a\gamma}}\right)^2 \left(\frac{100\,\mathrm{MeV}}{m_a}\right)^4$$