MU Tag 2015 FZJülich

Cross-Topic

Nature of Dark Matter

Theory overview	Geraldine Servant, DESY-HH
ALPS	Axel Lindner, DESY-HH
Direct DM search with Ge	Klaus Eitel, KIT
Indirect DM search with gamma rays and neutrinos	Johannes Knapp, DESY-Zeuthen
CASPEr and GNOME	Arne Wickenbrock and Dmitry Budker, HI Mainz

MU Tag 2016 HIM

Cross-Topic

Nature of Dark Matter

Studying generalized dark matter interactions with extended halo-independent methods F. Kahlhoefer, DESY-HH

Axion dark matter from topological defects K. Saikawa, DESY-HH

FUNK dark photon search: status and perspectives D. Verberic, KIT

Dark photon searches at MAMI and MESA A. Denig, JGU & HIMainz

Dark matter models with two mediators M. Duerr, DESY-HH

Phenomenology of flavoured dark matter S. Kast, KIT

Studying generalised dark matter interactions with extended halo-independent methods.

Felix Kahlhoefer
MUTAG2016
Helmholtz Institute Mainz
12-13 December 2016

Based on
arXiv:1607.04418 with Sebastian Wild

HELMHOLTZ
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DESY

Motivation

- Differential event rates in direct detection experiments are given by

$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{R}} = \frac{\rho}{m_T\, m_\chi} \int_{v_\mathrm{min}}^{\infty} v f(\boldsymbol{v} + \boldsymbol{v}_\mathrm{E}(t)) \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{R}} \mathrm{d}^3 v \quad \text{with} \quad v_\mathrm{min}(E_\mathrm{R}) = \sqrt{\frac{m_T E_\mathrm{R}}{2\,\mu_{T\chi}^2}}$$

Dark matter (DM) mass and scattering cross section: This is what we (particle physicists) would like to find out

Local DM density and velocity distribution: These are uncertainties that enter experimental predictions in a complicated way

- How reliably can we get to the particle physics properties of DM from future direct detection signals in the face of astrophysical uncertainties?

There are many models of DM

- There are many plausible models for the interactions of DM beyond standard spin-independent (SI) and spin-dependent (SD) scattering:

  - DM with an Anapole moment (AM):

    $$\mathcal{A}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

    This is the only possible interaction of Majorana fermions with photons.

  - DM with a magnetic dipole moment (MDM):

    $$\mathcal{D}_{\mathrm{magn}}\,\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

    This leads to long-range interactions due to the massless photon exchange.

  - DM with a dark magnetic dipole moment (DMDM):

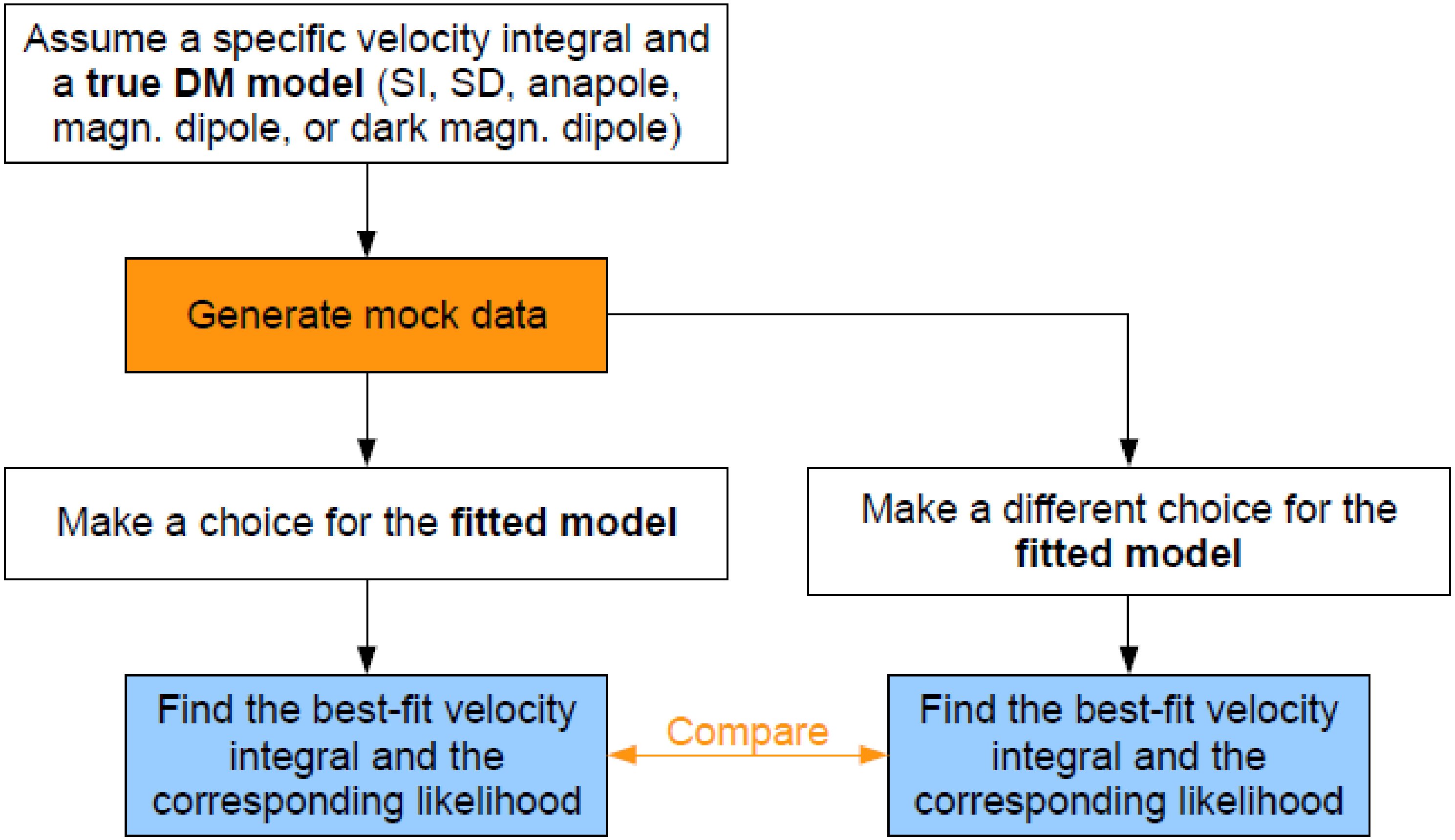
    $$\mathcal{D}_{\mathrm{magn}}\,\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu}$$

    Same as the the MDM but for a massive hidden photon ($1/q^2 \to 1/M^2$).

One can then construct a matrix D_{ij}, such that the expected number of events in bin i (R_i) is given by a simple matrix multiplication:

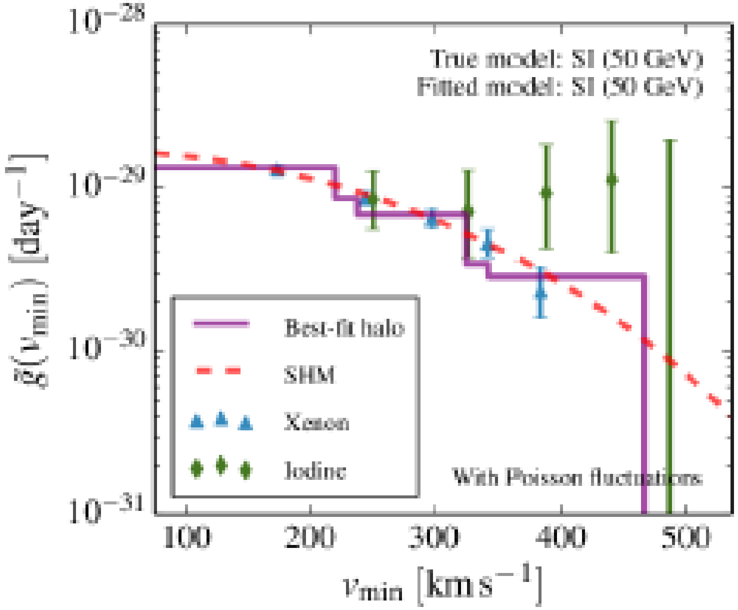
$$R_i = \sum_j D_{ij} g_j$$

Best-fit velocity integrals

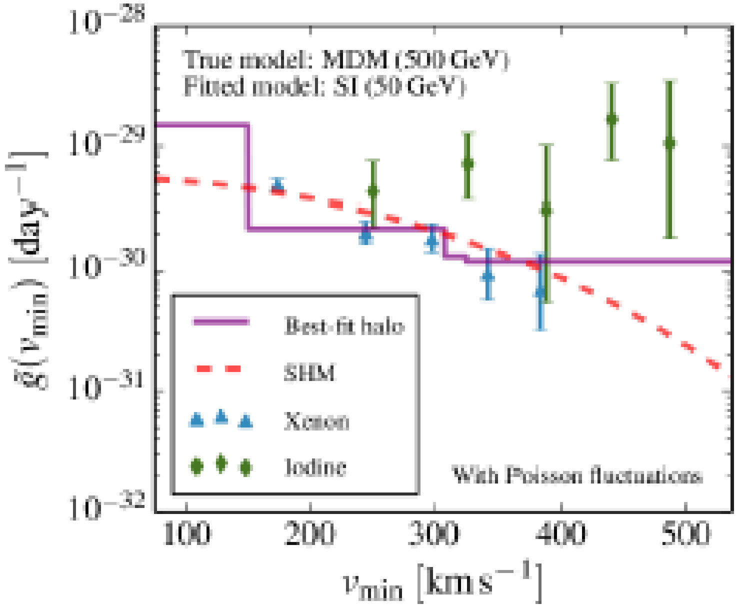


DM toy model

Xenon & Iodine

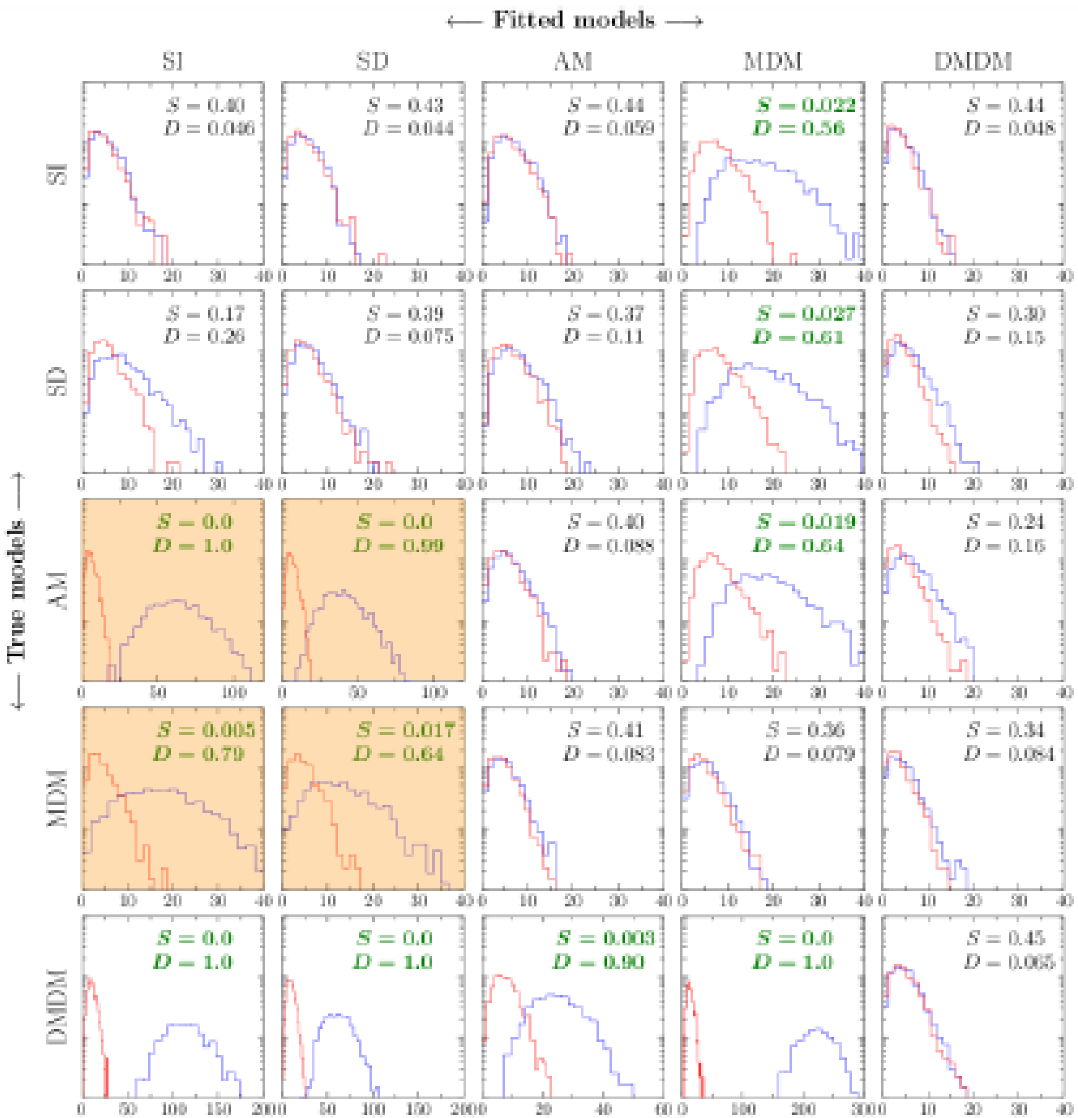


true model
=
fitted model



true model
≠
fitted model

Results for xenon+iodine experiments



S: p-value of a typical realisation

D: fraction of realisations that are excluded at 95% CL

- The presence of a second experiment with an iodine target makes it possible to rule out SI or SD interactions if DM has an anapole moment or a magnetic dipole moment.
- The reason is that iodine has a much higher sensitivity to anapole and dipole interactions.

arXiv:1607.04418

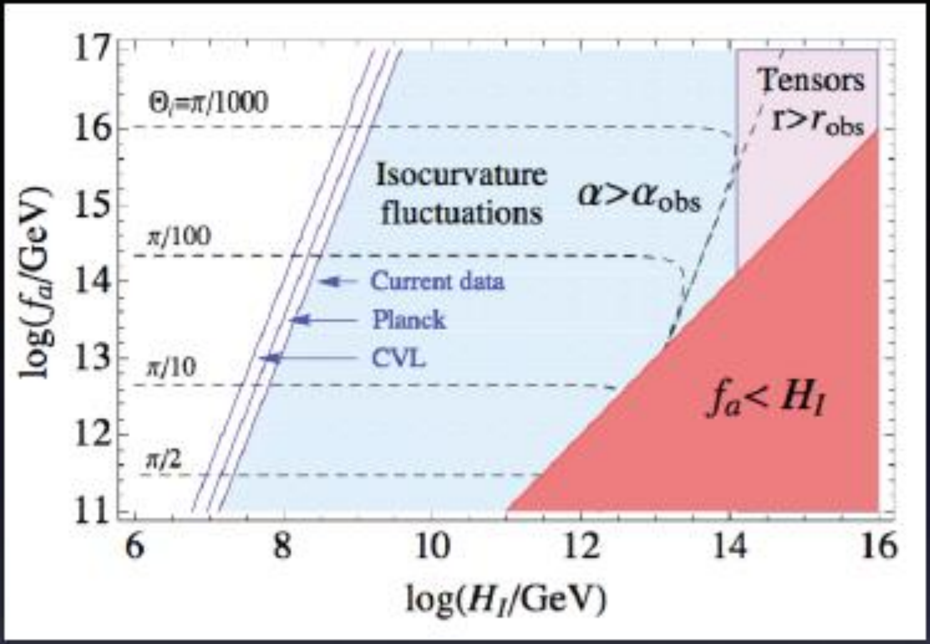
Axion dark matter from topological defects

Ken'ichi Saikawa (DESY)

Based on

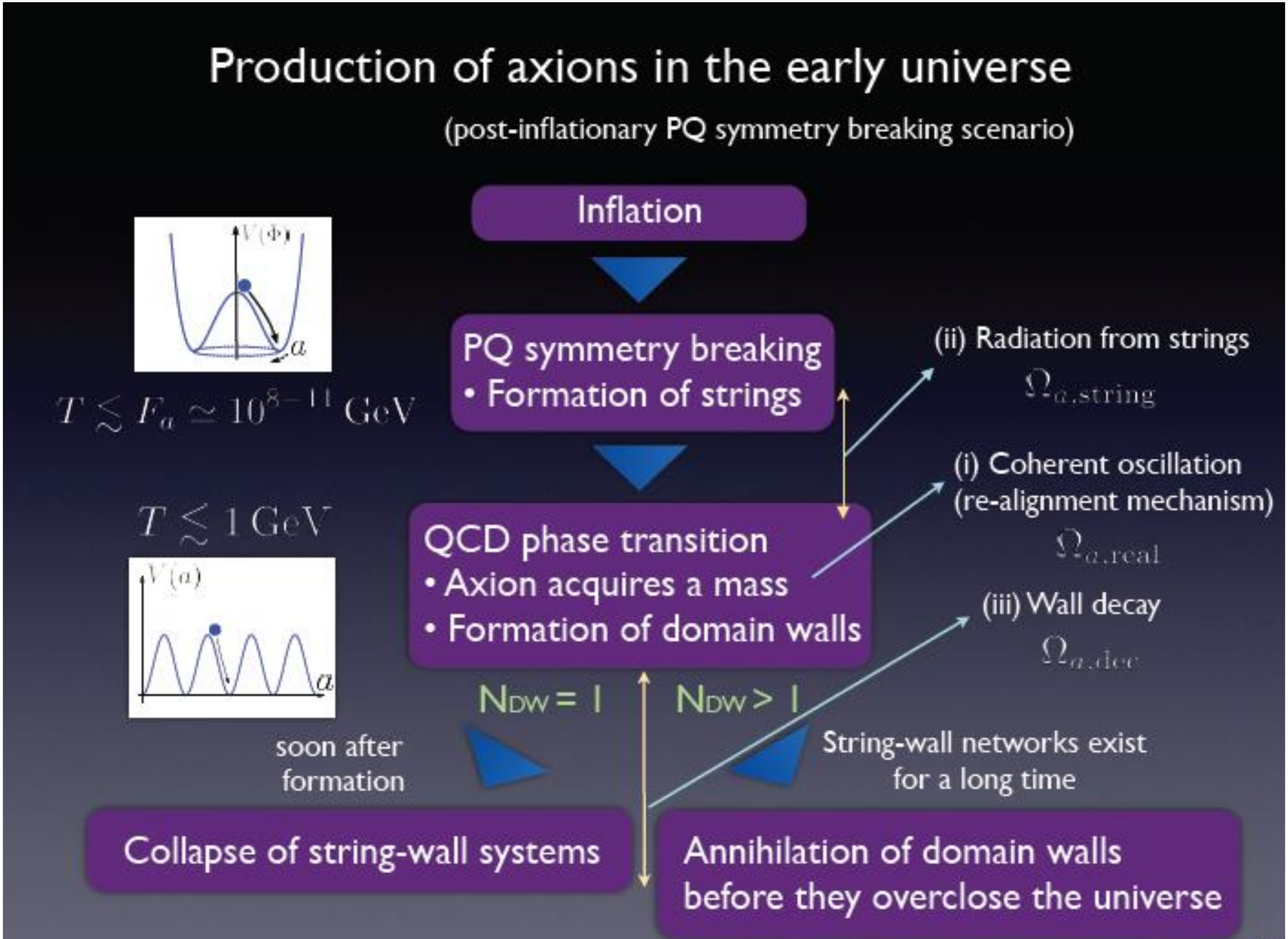
T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, PRD85, 105020 (2012) [1202.5851]
T. Hiramatsu, M. Kawasaki, KS, T. Sekiguchi, JCAP01, 001 (2013) [1207.3166]
M. Kawasaki, KS, T. Sekiguchi, PRD91, 065014 (2015) [1412.0789]
A. Ringwald, KS, PRD93, 085031 (2016) [1512.06436]

Axions in the inflationary universe: two scenarios



Hamann, Hannestad, Raffelt and Wong (2009)

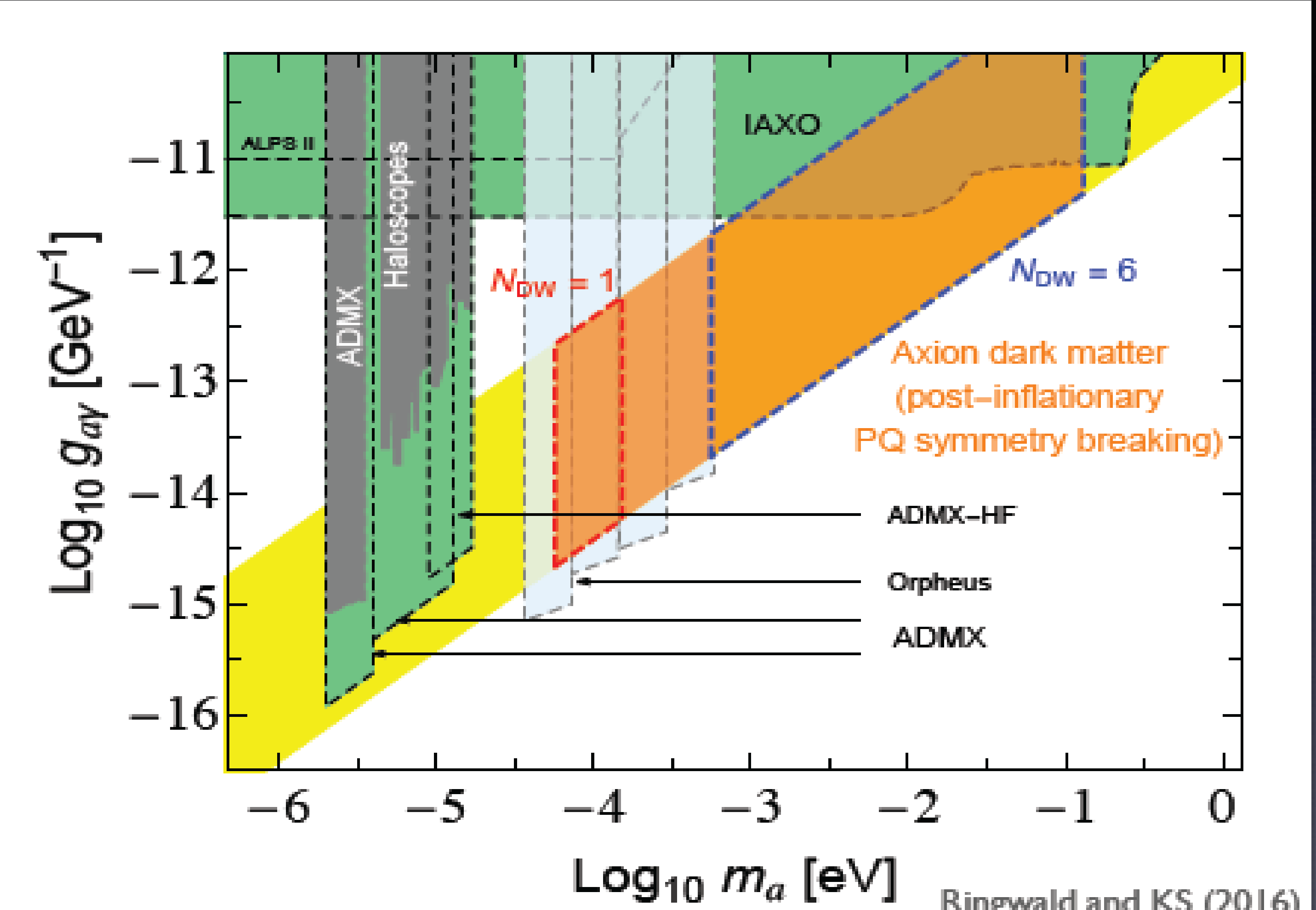
- Pre-inflationary PQ symmetry breaking
  - Severe isocurvature constraints
  - Tuning of the initial field value ("anthropic window")
- Post-inflationary PQ symmetry breaking ← this talk
  - Formation of topological defects



Production of axions in the early universe
(post-inflationary PQ symmetry breaking scenario)
Inflation
$V(\Phi)$
a
$T \lesssim F_a \simeq 10^{8-11}$ GeV
PQ symmetry breaking
• Formation of strings
(ii) Radiation from strings
$\Omega_{a,\mathrm{string}}$
(i) Coherent oscillation
(re-alignment mechanism)
$\Omega_{a,\mathrm{real}}$
$T \lesssim 1$ GeV
$V(a)$
a
QCD phase transition
• Axion acquires a mass
• Formation of domain walls
(iii) Wall decay
$\Omega_{a,\mathrm{dec}}$
$N_{DW} = 1$
$N_{DW} > 1$
soon after formation
String-wall networks exist for a long time
Collapse of string-wall systems
Annihilation of domain walls before they overclose the universe

Search for axion dark matter

Search space in photon coupling $g_{a\gamma} \sim \alpha/(2\pi F_a)$ vs. mass m_a



Ringwald and KS (2016)

Search for Hiden-Photon Dark Matter

Status & Perspectives

K. Daumiller, B. Döbrich, R. Engel, L. Gastaldo, J. Jaeckel, M. Kowalski,
A. Lindner, H.-J. Mathes, A.-S. Müller, J. Redondo, M. Roth, C. Schäfer,
T. Schwetz-Mangold, R. Ulrich, D. Veberic

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KIT
Karlsruher Institut für Technologie

MUTAG 2016

Hidden Photons

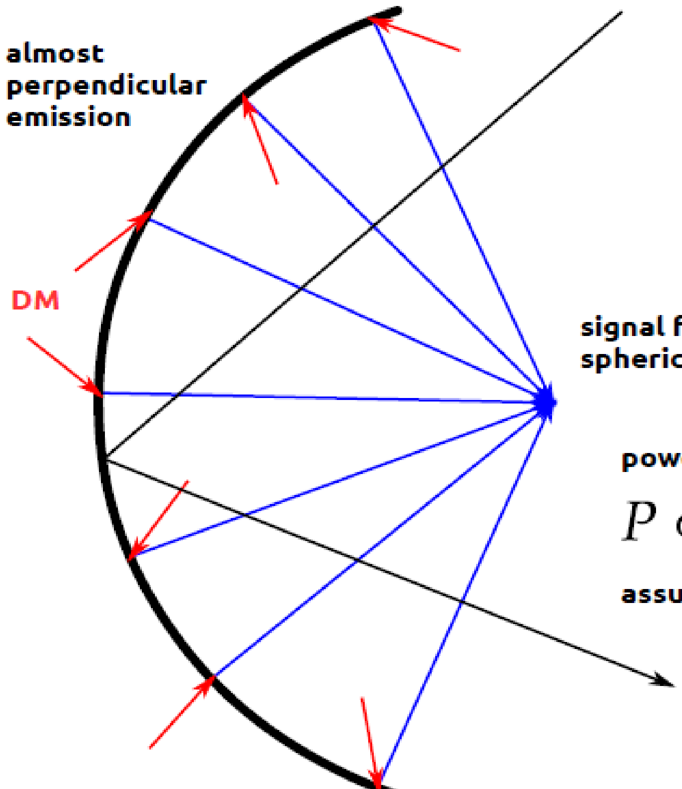
$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + \tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu}) - \frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m^2}{2}\tilde{X}_\mu\tilde{X}^\mu + J^\mu A_\mu$$

light extra U(1) gauge boson: hidden photon

kinetic mixing coupling

mass term

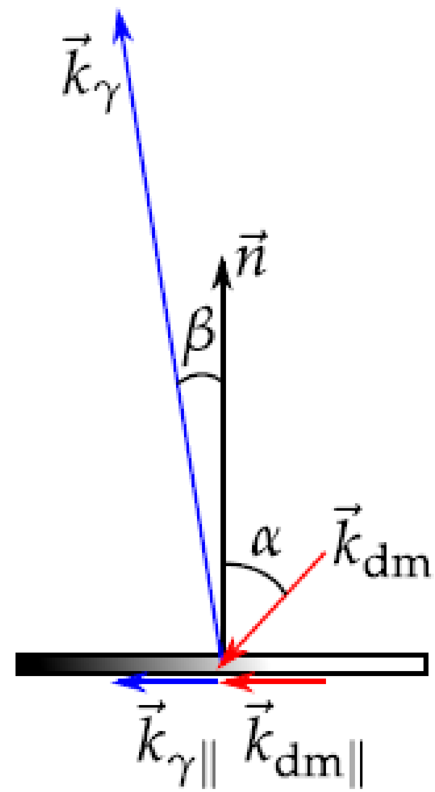
Horns *et al.*, JCAP 04 (2013) 016



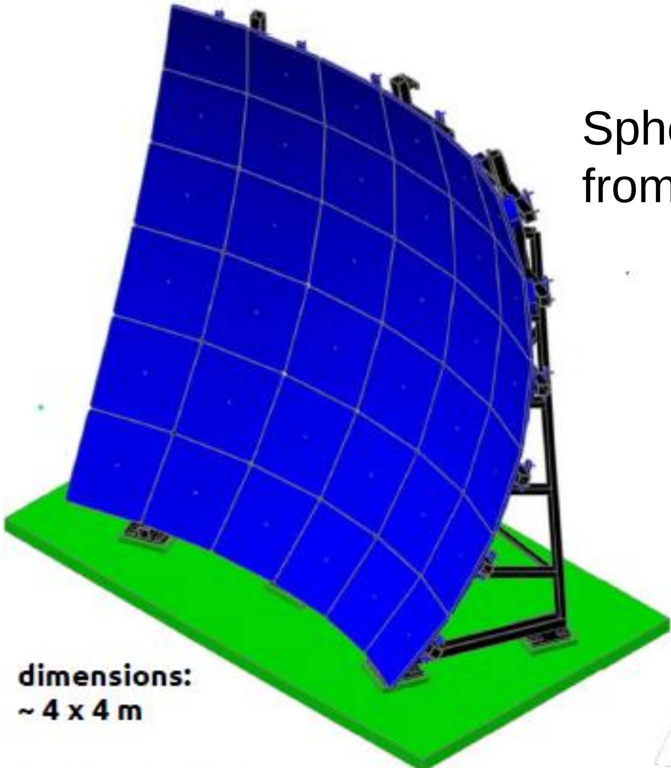
power from spherical mirror scales with area

$$P \propto \chi^2 \rho_{\mathrm{dm}} A \approx 10^5\,\mathrm{W}\,\chi^2$$

assuming all DM is HP



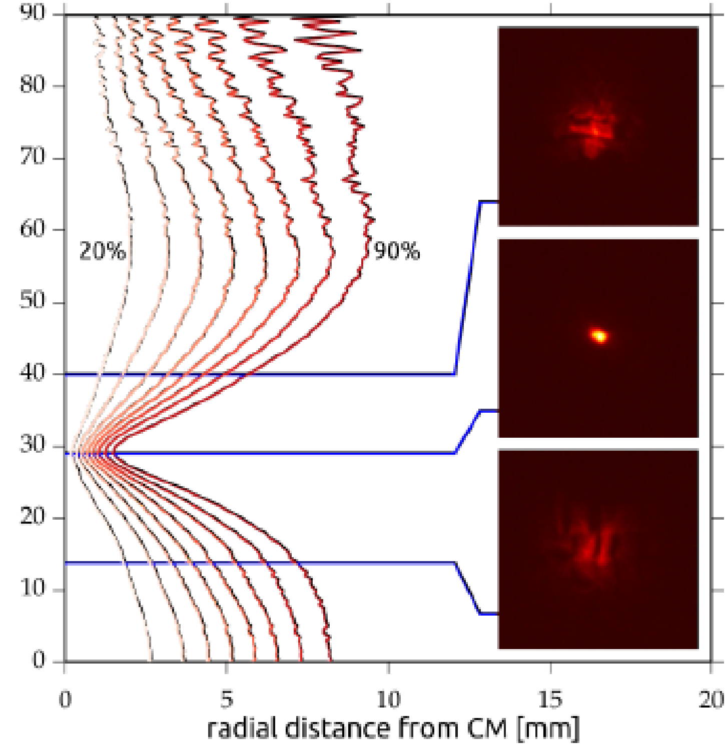
Spherical mirror
from PAO



dimensions:
~ 4 x 4 m

6 x 6 segments

only 3 unique shapes



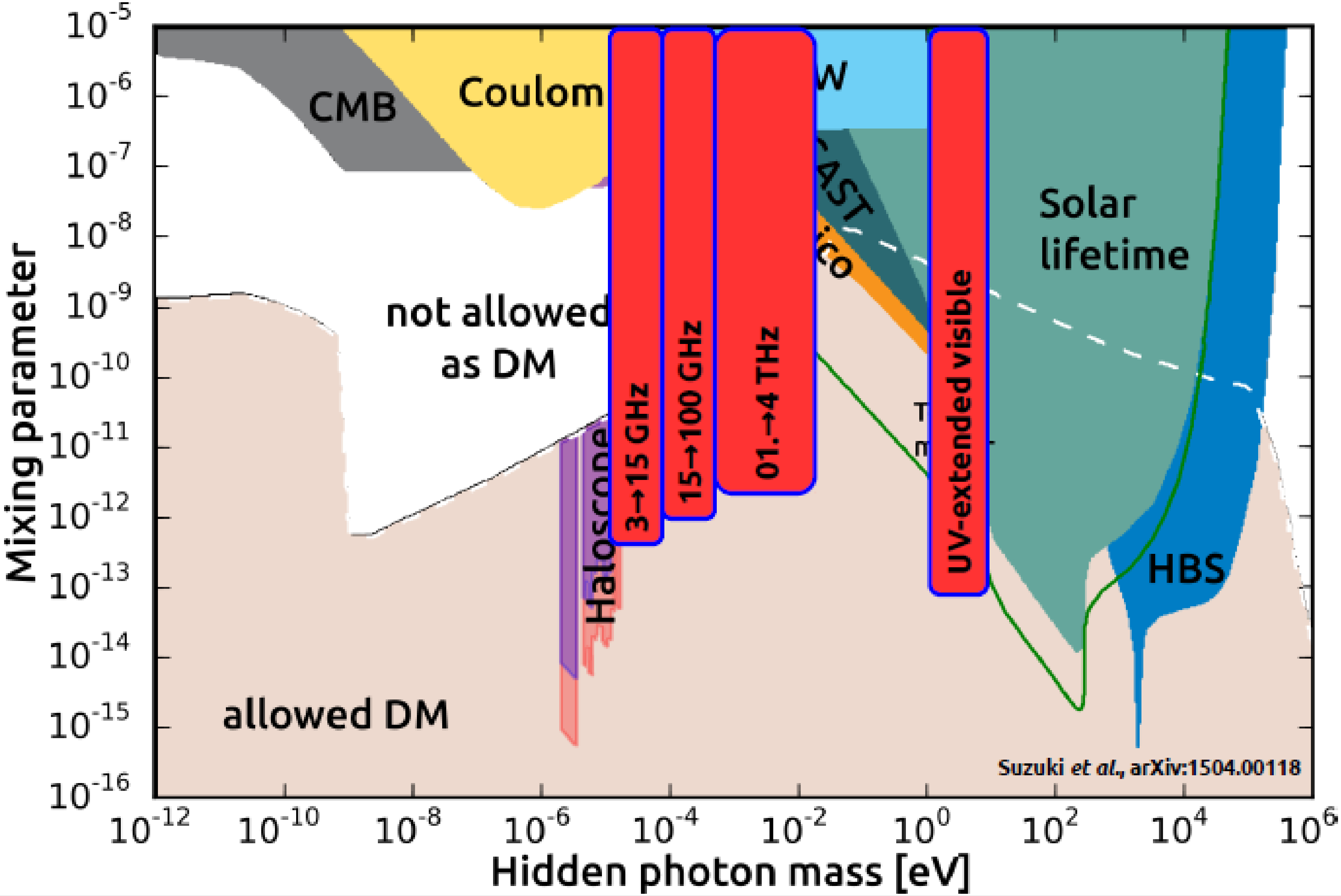
spot size ~2 mm

PCO Sensicam VGA
640x480 pixel CCD
internally Peltier cooled to -15°C

1. test: CCD camera

curent: PMT 160-630 nm

Outlook and Future Plans



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Helmholtz Institute Mainz

Dark Photon Searches at MAMI and MESA

Achim Denig, Mainz

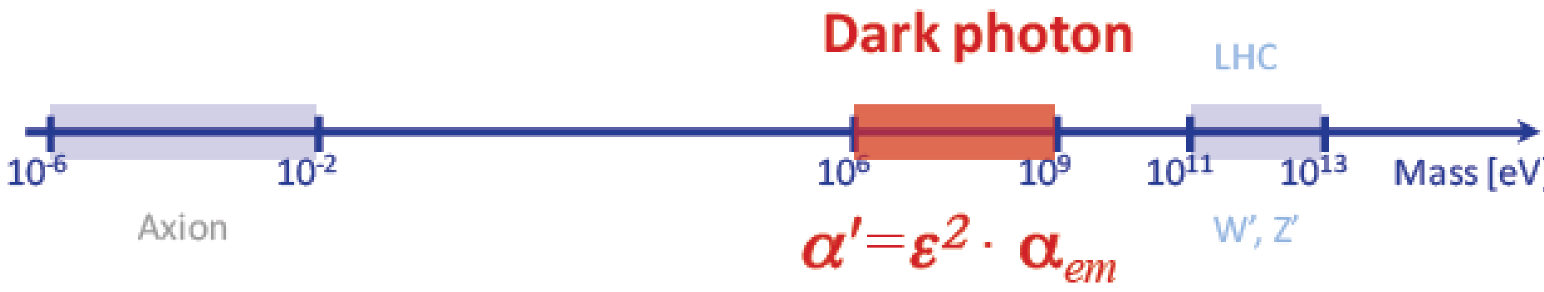
Cluster of Excellence PRISMA
Precision Physics, Fundamental Interactions and Structure of Matter

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

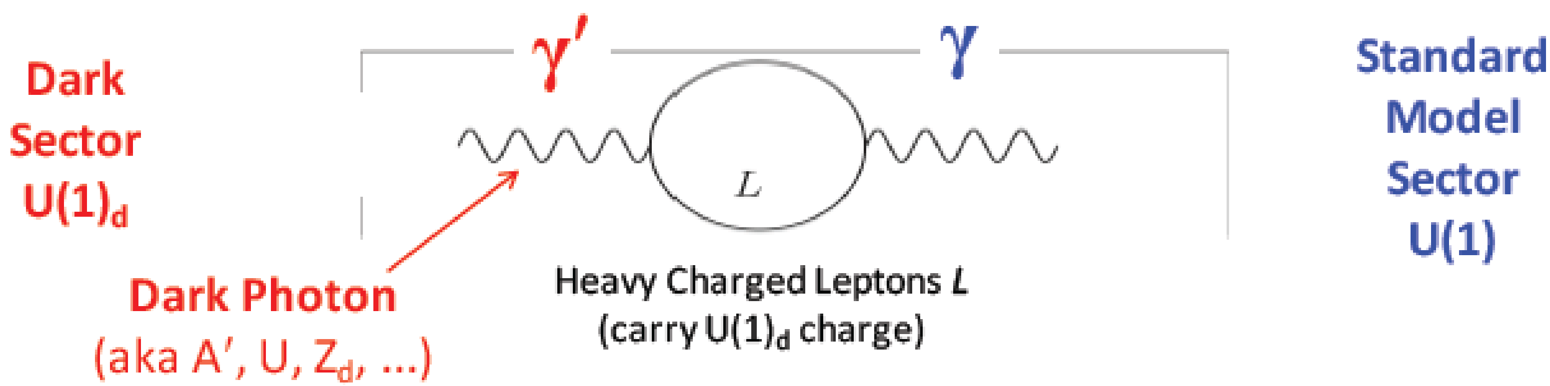
HIM
Helmholtz-Institut Mainz

JG|U

New massive force carrier of extra $U(1)_d$ gauge group; predicted in almost all string compactifications



A way to relate the dark sector to the SM (coupling ~ ε^2)

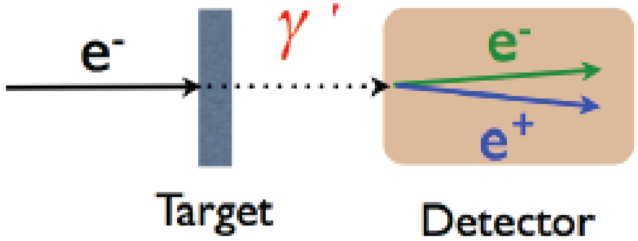


Results from A1 Pilot Run (2011)

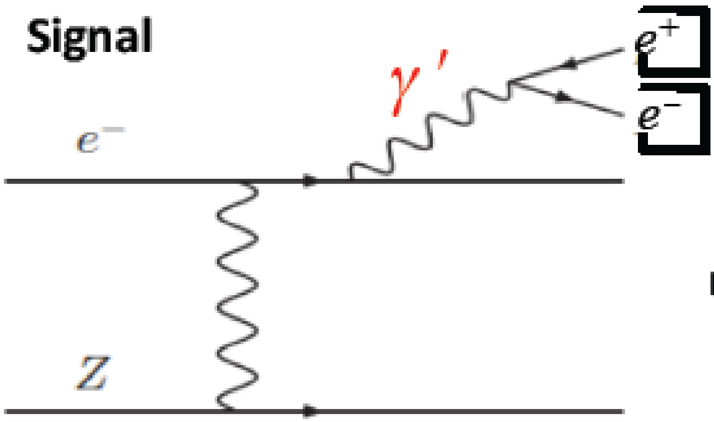
Low-Energy Electron Acceler. with high intensity suited for DP search

3 days @ MAMI

Bjorken, Essig, Schuster, Toro (2009)

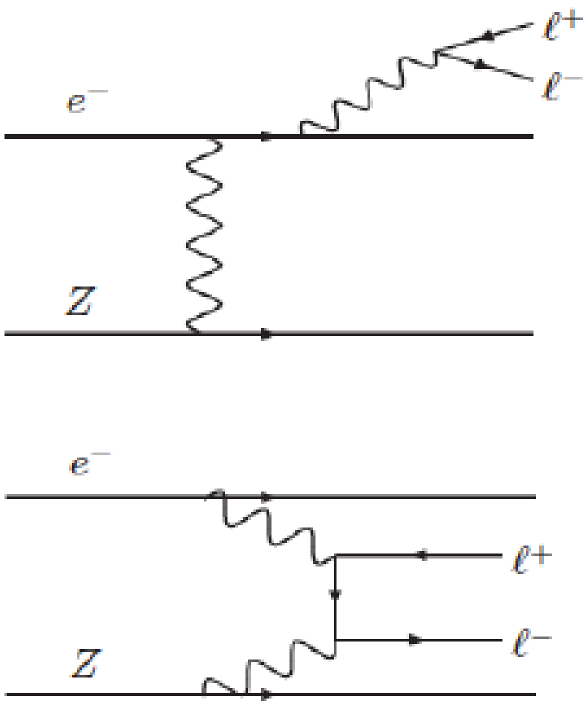


Signal



Bump search!

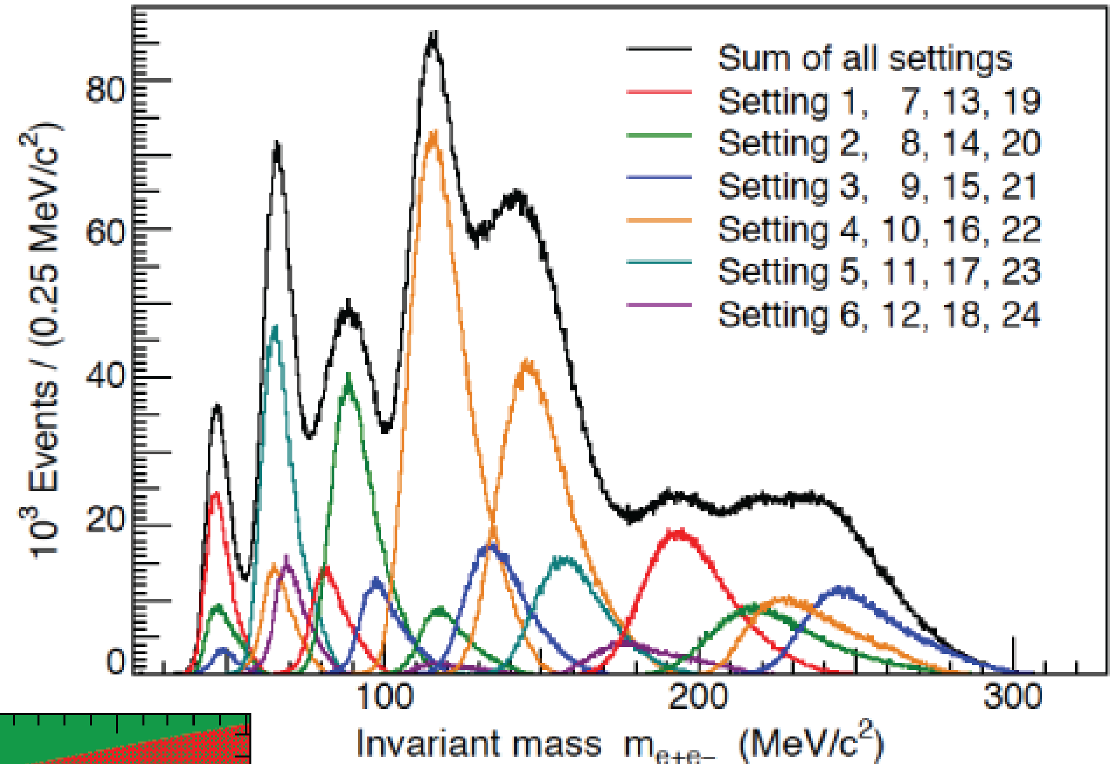
Backgroud

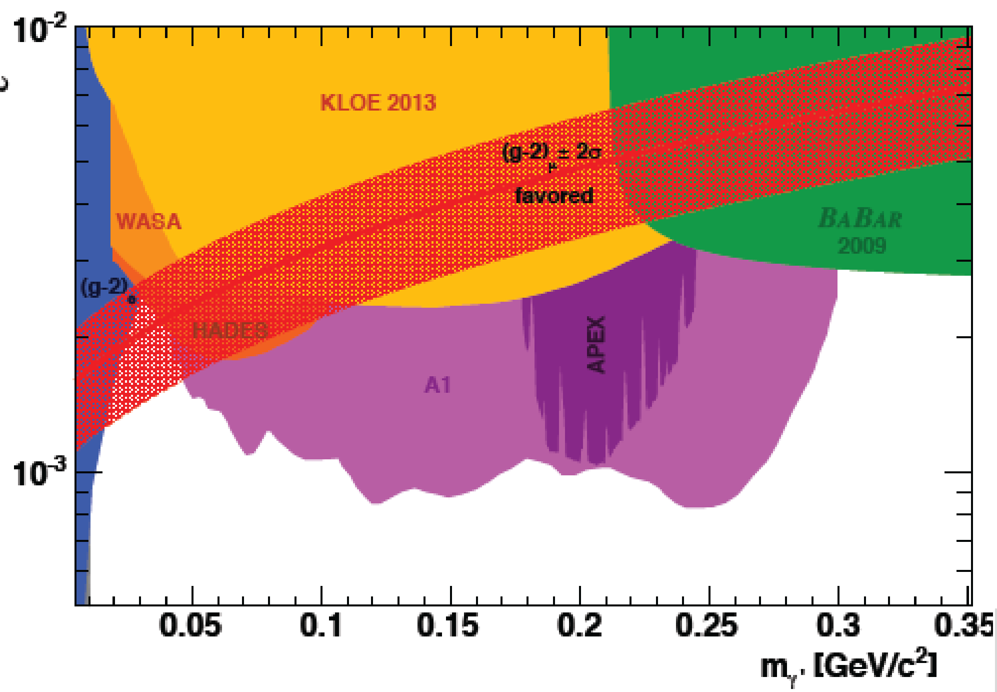


Merkel et al. [A1]
PRL '11
PRL '14

4 weeks @ MAMI

- E_{beam} 180 - 855 MeV
- 100 μA beam current
- Stack of Ta targets
- 22 kinematic settings
- O(1 month) of beam time





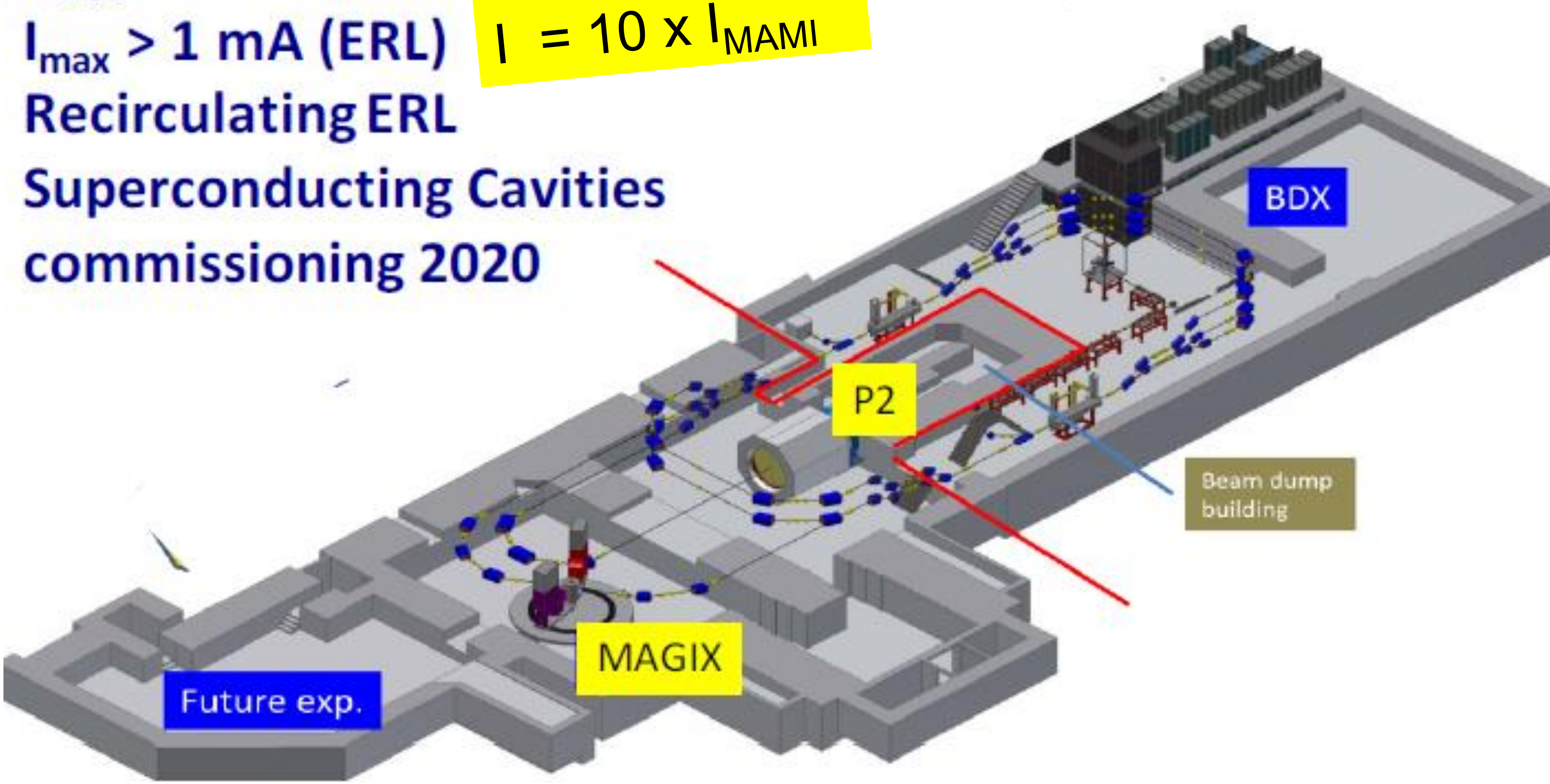
at time of publication most stringent limit ruling out major part of the parameter range motivated by $(g\text{-}2)_\mu$

New Tool for Low-Precision Physics: MESA

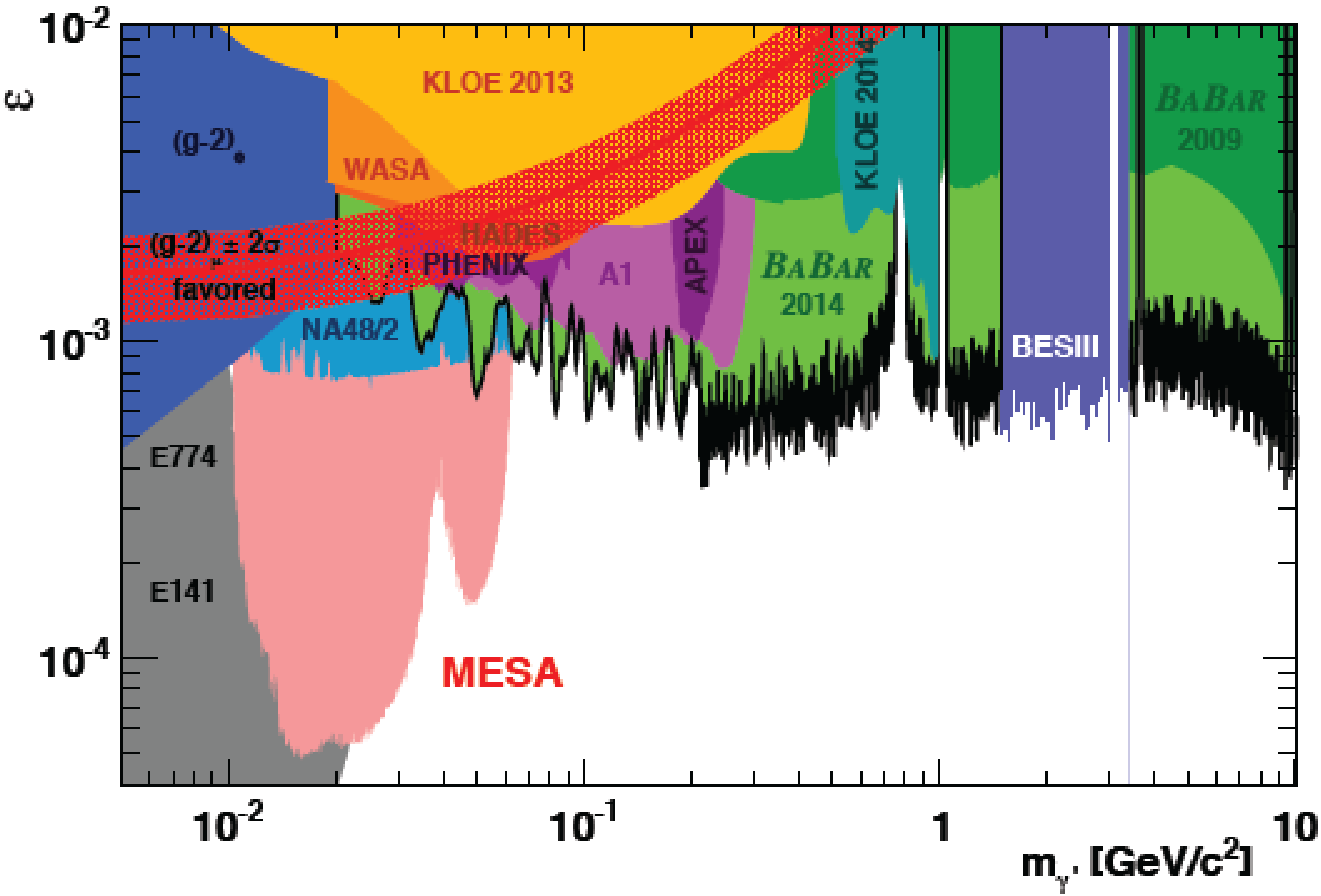
Mainz Energy-Recovering Superconducting Accelerator

E_{max} = 155 MeV
I_{max} > 1 mA (ERL)
Recirculating ERL
Superconducting Cavities
commissioning 2020

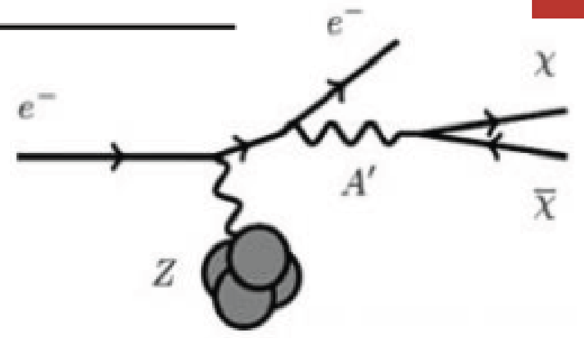
$E = 1/10\ E_{MAMI}$
$I\ = 10 \times I_{MAMI}$



Potential of MESA w/ MAGIX after 6 months data taking



Invisible Decay of Dark Photon



So far Kinetic Mixing: M(γ') < 2M(χ)

Consider now: M(χ) < 0.5M(γ')

Dark Photon decays dominantly into

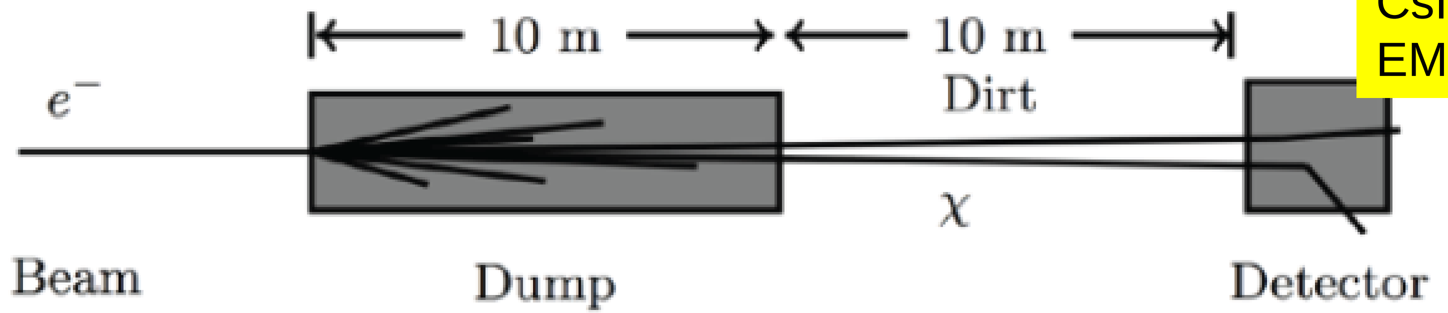
Light Dark Matter (LDM), which is not yet constraint experimentally!

Beam Dump Experiment (BDX)

Electron Scattering on Beam Dump

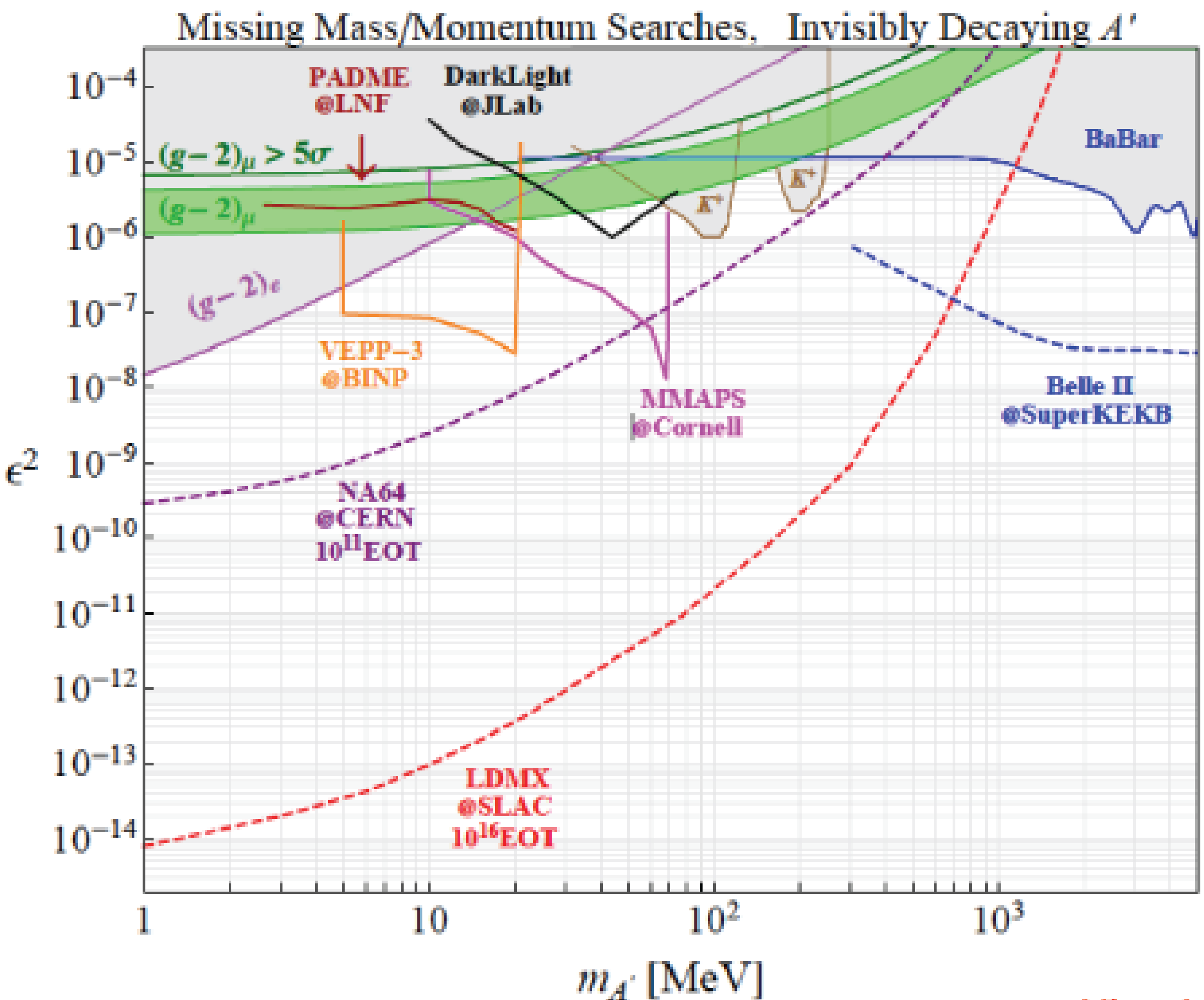
→ Collimated and boosed (!) pair of Dark Matter particles

$1m^3$(1-5t)
CsI(Tl)
EM shower det.



JLAB, Mainz, SLAC Cornell

Future of Invisible Dark Photon Searches



arXiv: 1608.08632

DM models with two mediators.

How to save the WIMP

© NASA

Michael Duerr
MU Programmtag 2016
Mainz, 12 December 2016

based on:
arXiv:1304.0576, arXiv:1309.3970,
arXiv:1409.8165, arXiv:1508.01425, and
arXiv:1606.07609

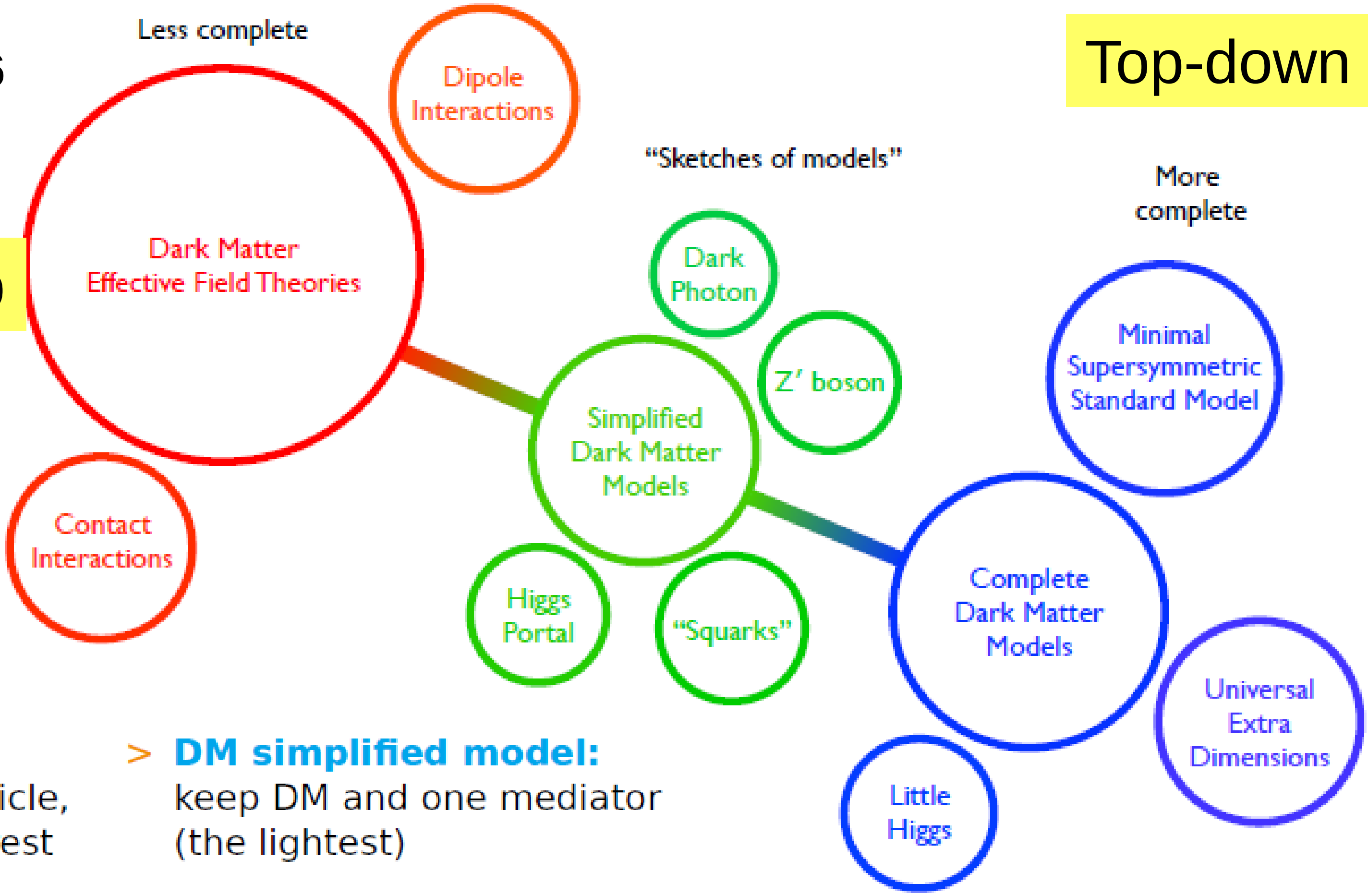
in collaboration with:
P. Fileviez Pérez, F. Kahlhoefer, K. Schmidt-Hoberg,
Th. Schwetz, J. Smirnov, S. Vogl, M. B. Wise

HELMHOLTZ ASSOCIATION

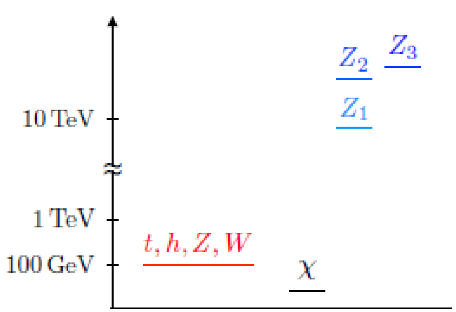
DESY

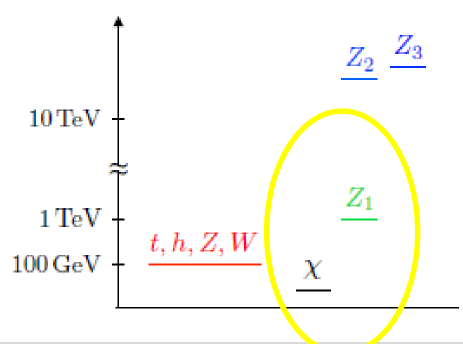
Worm *et al.*,
arXiv:1506.03116

Bottom-up



- **DM EFT:** only keep DM particle, integrate out the rest
- **DM simplified model:** keep DM and one mediator (the lightest)





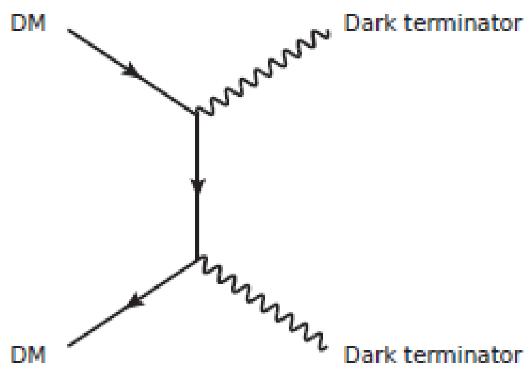
Dark matter model with two mediators.

> 6 independent parameters:

particle masses		coupling constants	
DM mass	m_χ	dark-sector coupling	g_χ or y_χ
Z' mass	$m_{Z'}$	quark–Z' coupling	g_q
dark Higgs mass	m_s	Higgs mixing angle	θ

> A combination of different simplified models:

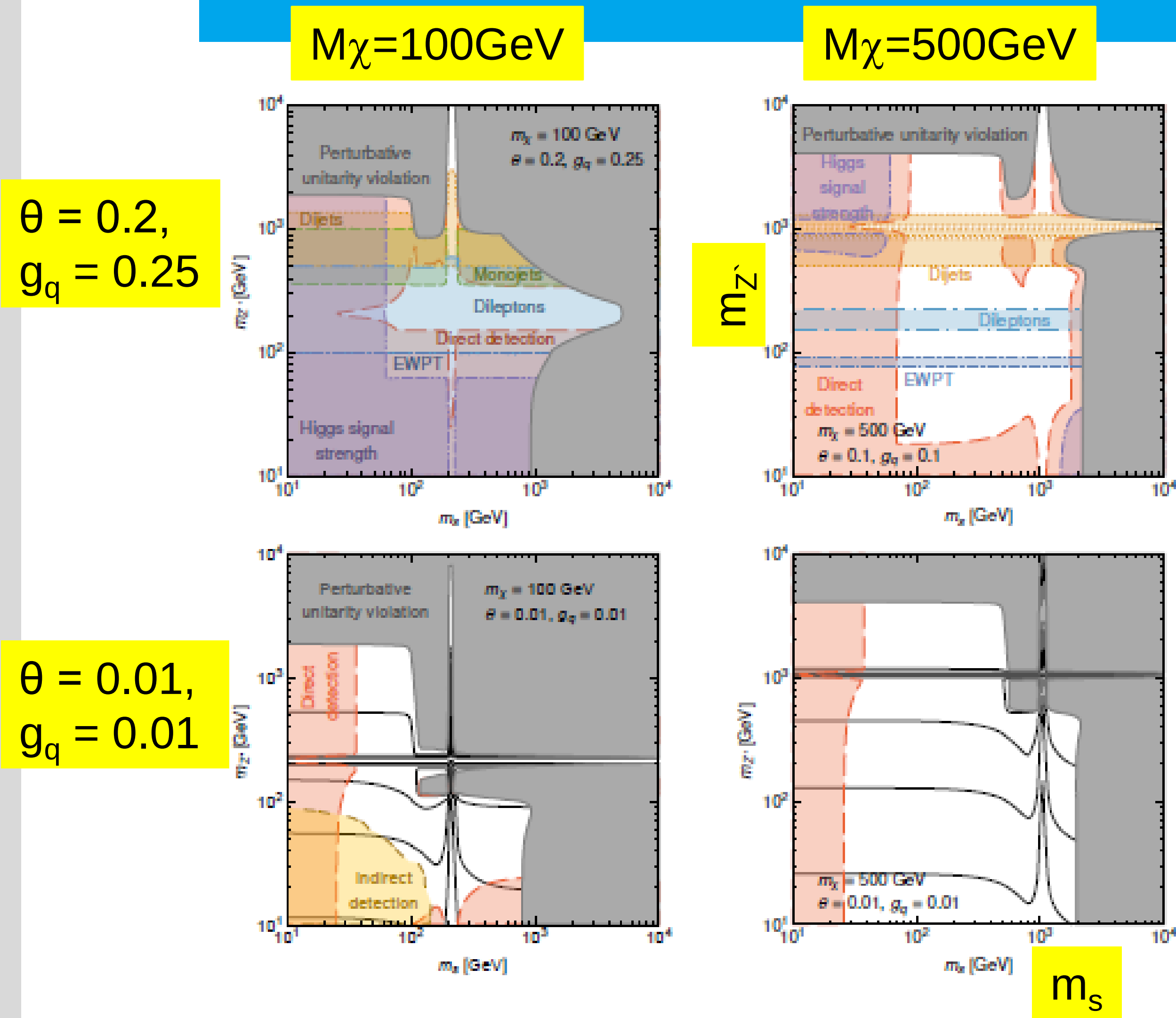
	$g_q \gg \sin\theta$	$g_q \sim \sin\theta$	$\sin\theta \gg g_q$
$m_s \gg m_{Z'}$	Spin-1 mediator simplified model		Spin-0 mediator with spin-1 terminator
$m_{Z'} \sim m_s$		Two-mediator model	
$m_{Z'} \gg m_s$	Spin-1 mediator with spin-0 terminator		Spin-0 mediator simplified model



Dark terminator

new final state for DM annihilation

Two mediators: results.



> sizeable g_q and $\sin\theta$:

- for $m_\chi = 100\,\mathrm{GeV}$, only small regions close to the resonances remain viable
- for $m_\chi = 500\,\mathrm{GeV}$, larger regions are allowed because s or Z' can be terminators without being strongly constrained

> secluded from the SM:

- region with $m_{Z'}, m_s > m_\chi$ is tightly constrained because annihilations into SM final states cannot reproduce the relic abundance with perturbative couplings
- for $m_{Z'}, m_s < m_\chi$, annihilation into dark terminators typically dominates
- experimental constraints can be suppressed since g_q and θ can be small → difficult to probe
- for small masses, set-up can still be probed by indirect detection

Karlsruhe Institute of Technology

Institute for Theoretical Particle Physics

Phenomenology of flavoured dark matter

MU Programmtag 2016, Mainz

Monika Blanke, **Simon Kast** | Dez 12, 2016

KARLSRUHE INSTITUTE OF TECHNOLOGY

The Flavour Gate to Dark Matter

Assume an analogy to the SM fermions $\rightarrow$ dark flavour triplet χ_i.

Flavoured Dark Matter coupling to SM right-handed up-quark triplet:

$$\mathcal{L}_{\text{NP,int}} = -\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + h.c.$$

Dark Minimal Flavour Violation

[Agrawal, Blanke, Gemmler '14]

Flavour Symmetry

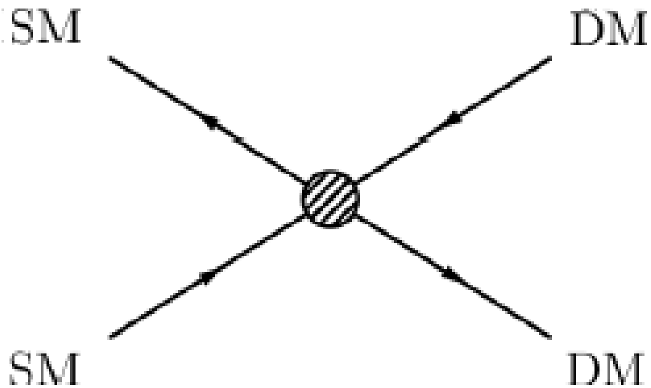
$$U(3)_u \times U(3)_d \times U(3)_q \times U(3)_\chi$$

is only broken by SM Yukawa couplings and the DM-quark coupling λ_{ij} (Dark Minimal Flavour Violation).

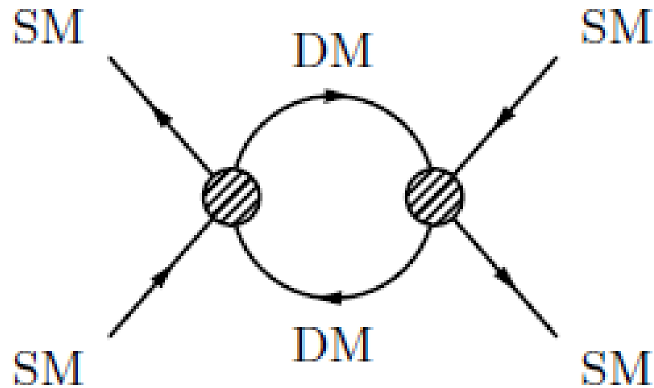
$\Rightarrow$ only DM mass splitting comes from RG running:

$$m_{ij} = m_\chi(\mathbb{1} + \eta\lambda^\dagger\lambda + \ldots)_{ij}.$$

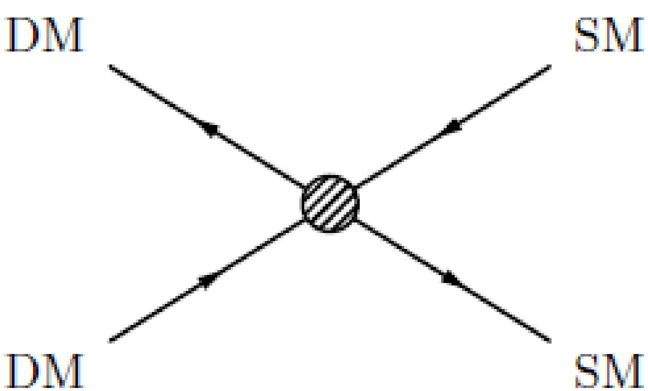
How to Detect Flavoured Dark Datter?



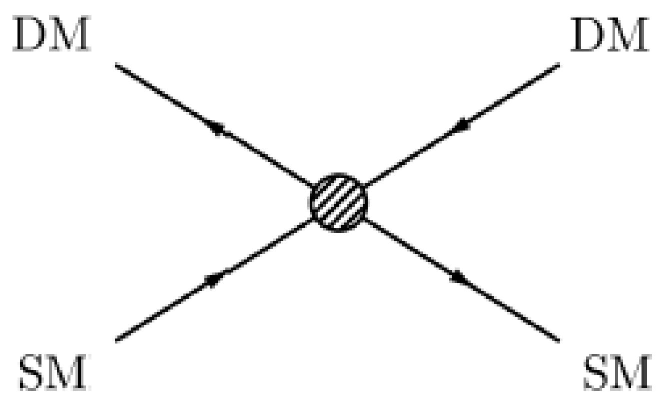
collider searches



precision flavour data



indirect detection / freeze-out



direct detection

DM Bounds from Direct Detection Experiments

[LUX collaboration '16]

- Many contributions to total WIMP-nucleon cross section, only Z-penguin with neutron is negative.
  $\Rightarrow$ saves the day
- Tree level and neutron Z-penguin have to nearly cancel each other.
  $\Rightarrow$ serious constraints on Θ_{13}
- For too large couplings the cancellation is no longer possible $\rightarrow$ excluded.
- Top-flavoured DM is the natural choice.

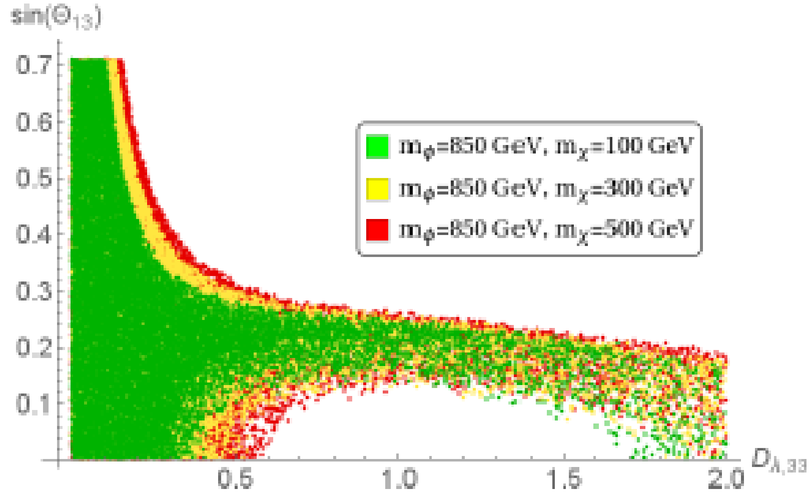


Figure : Valid mixing angle Θ_{13} vs $D_{\lambda,33}$.

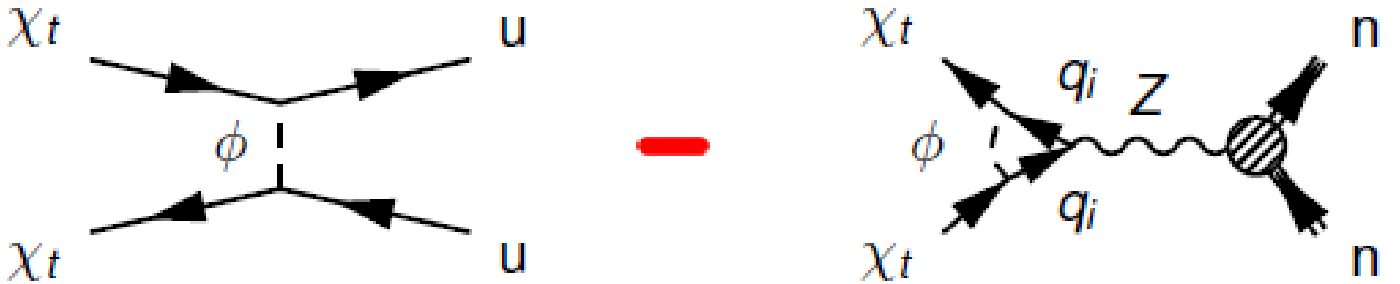


Figure : Cancellation of tree-level and neutron Z-penguin contributions (symbolic).

Conclusion and Outlook

- All kinds of different constraints $\rightarrow$ multitude of effects and interesting interplay.
- Especially interesting effect on mixing angle θ_{13} due to DD and RA constraints.
  $\Rightarrow$ Future measurements of direct detection experiments will test a large part of the parameter space.
  $\Rightarrow$ Ongoing Xenon experiments or experiments with other noble gases well motivated.
- Simplified models are powerful tool to study diversity of constraints.
- Going beyond Minimal Flavour Violation is worth the effort.
  $\rightarrow$ Dark Minimal Flavour Violation as guidance.

Cross-Topic Nature of Dark Matter

Studying generalized dark matter interactions with extended halo-independent methods	F. Kahlhoefer, DESY-HH
Axion dark matter from topological defects	K. Saikawa, DESY-HH
FUNK dark photon search: status and perspectives	D. Verberic, KIT
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Phenomenology of flavoured dark matter	S. Kast, KIT

- large variety of activities (theory & experiments)
- lively discussion, science-driven
- large attendance
- no PoF structural discussions, but

„MUTag very interesting exchange of ideas"