Heavy Photons, Axions, and WISPs

(+ sub-GeV dark matter)

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8th Patras Workshop on Axions, WIMPs, and WISPs

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What motivates a new particle/interaction?

- Deep (real) puzzles

Examples:

- mechanism of EWSB?

major progress with LHC discovery of
a new boson at ~125 GeV!
SM Higgs!?

What motivates a new particle/interaction?

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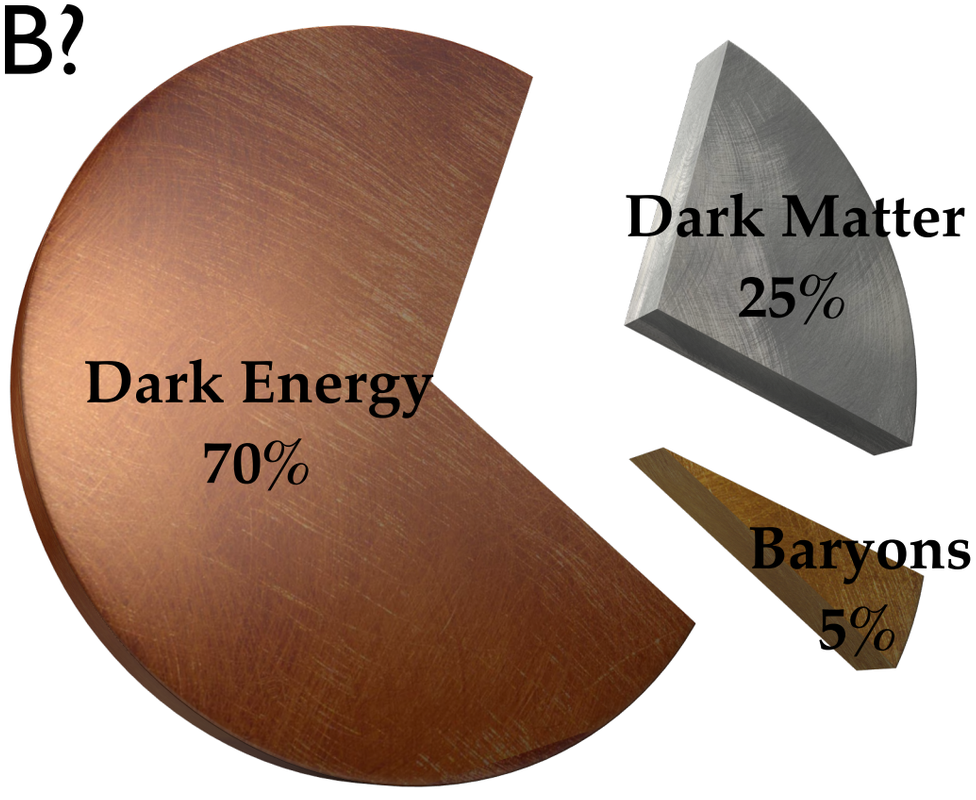
Examples:

- mechanism of EWSB?
- dark matter?
- dark energy?



What motivates a new particle/interaction?

- Deep (real) puzzles

Examples:

- mechanism of EWSB?
- dark matter?
- dark energy?
- hierarchy problem/naturalness

e.g. Supersymmetry

No evidence currently that Weak scale is “natural”

What motivates a new particle/interaction?

- Deep (real) puzzles

Examples:

- mechanism of EWSB?
- dark matter?
- dark energy?
- hierarchy problem/naturalness
- strong CP problem

(more later)

What motivates a new particle/interaction?

- Deep (real) puzzles
- Intriguing observations

Example:

- WIMP miracle + hierarchy problem

main motivation for direct, indirect,
and collider searches for DM

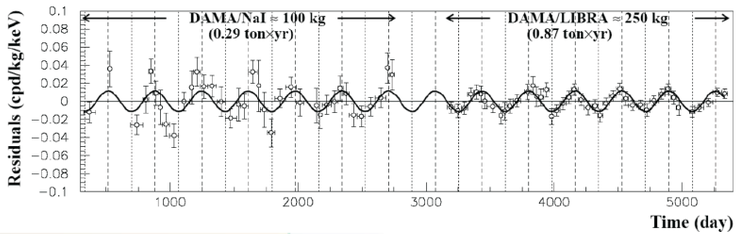
(but may be totally misleading us!)

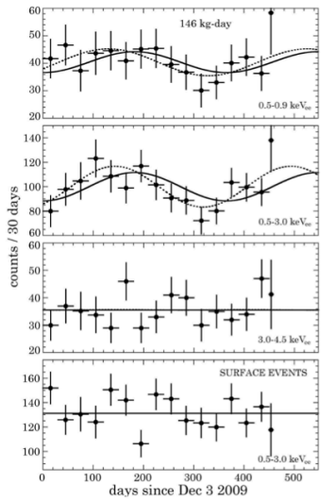
What motivates a new particle/interaction?

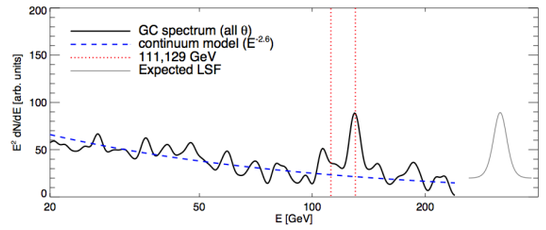
- Deep (real) puzzles
- Intriguing observations
- data anomalies

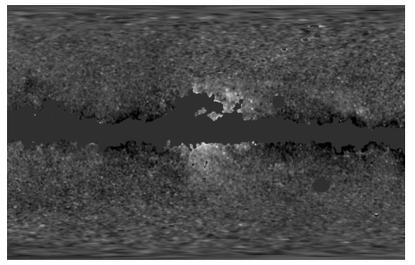
Examples:

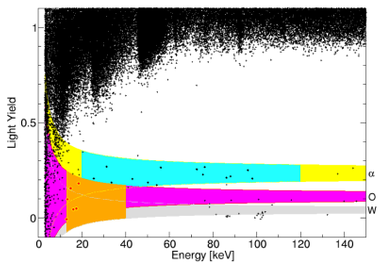
- many!

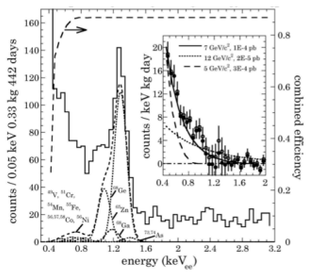


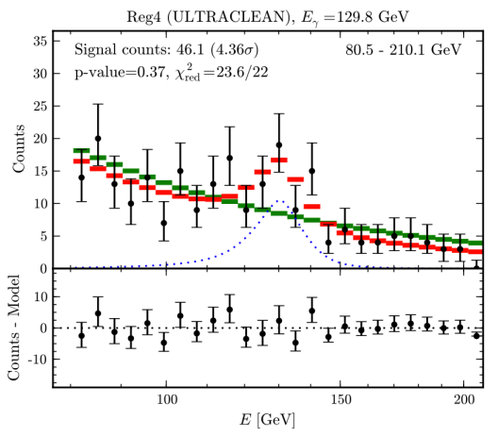


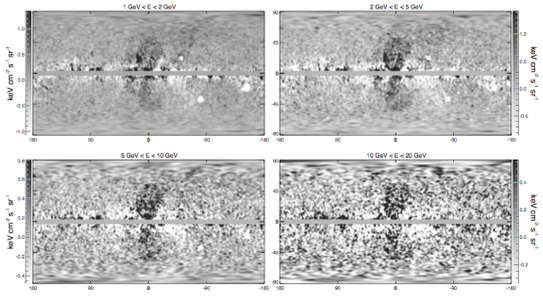


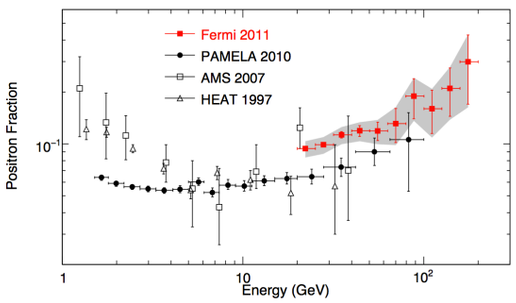


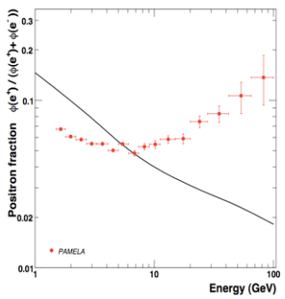


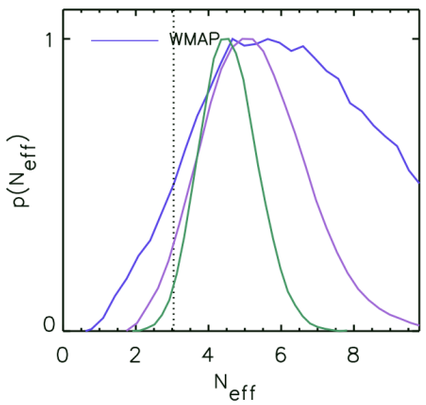


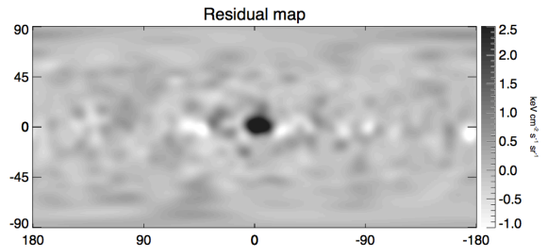


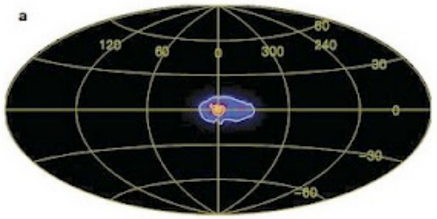


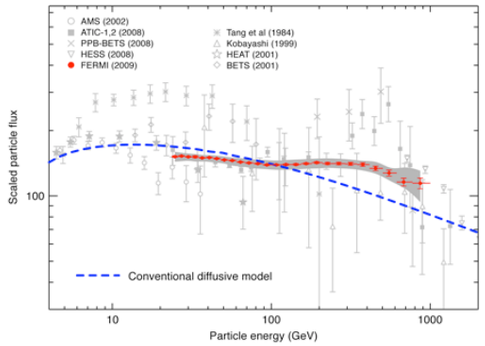


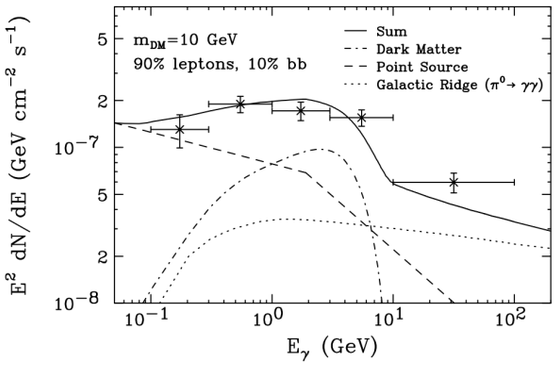


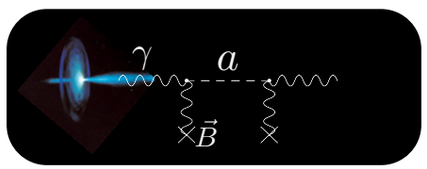


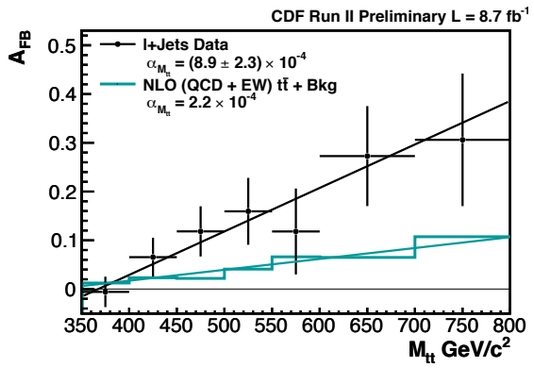


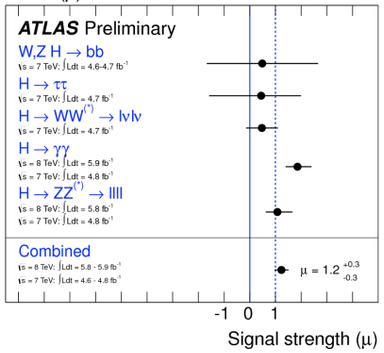


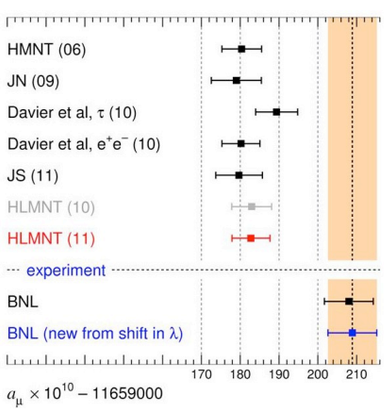




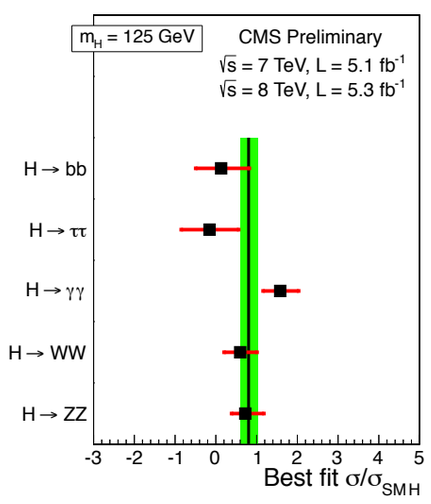








I'm >5σ confident that not all these are real…



What motivates a new particle/interaction?

- Deep (real) puzzles
- Intriguing observations
- data anomalies
- theoretically viable

theorists have a lot of imagination…

sometimes, exploring a new experimental frontier can lead to amazing discoveries

Heavy Photons, Axions, and WISPs

strongly motivated from theory, strong CP problem,
dark matter, dark energy, muon g-2,
and/or various astrophysics anomalies

"WISPs"

Weakly **I**nteracting "**S**ub-eV" (or "**S**lim") **P**articles

- heavy photons — $\mathrm{mass} < \mathrm{MeV}$
- axion-like particles
- chameleons
- mini charged particles

etc.

Heavy Photons, Axions, and WISPs

strongly motivated from theory, strong CP problem,
dark matter, dark energy, muon g-2,
and/or various astrophysics anomalies

light particles, with weak coupling to ordinary matter

probe with high intensity beams of electrons,
protons, or photons, and sensitive detectors

experiments are *much* smaller scale than LHC

offer incredible pay-off if they find something,
for relatively small investment

Outline

- axions & axion-like particles
- heavy photons
- direct detection of sub-GeV DM

What are they?
Motivation?
Opportunities?

no time to talk about chameleons,
but see talks by A. Upadhye and K. Zioutas

Axions: solve strong CP problem

theoretically, QCD should violate CP: $\mathcal{L} \supset \dfrac{\alpha_s}{4\pi}\,\theta\,\mathrm{tr}\,\mathrm{G}\tilde{\mathrm{G}}$

experimentally, no CP violation: $\theta \lesssim 6 \times 10^{-10}$

$\Longrightarrow$ strong CP problem

Solution: set $\theta = \dfrac{a}{f_a}$ with new symmetry, U(1)$_{\mathrm{PQ}}$,
spontaneously broken at high scale f_a

$\Longrightarrow$ new particle (axion) and $\theta \to 0$

$$m_a \sim \frac{\Lambda^2_{\mathrm{QCD}}}{f_a} \simeq 0.6\ \mathrm{meV}\ \frac{10^{10}\,\mathrm{GeV}}{\mathrm{f_a}}$$

naturally light

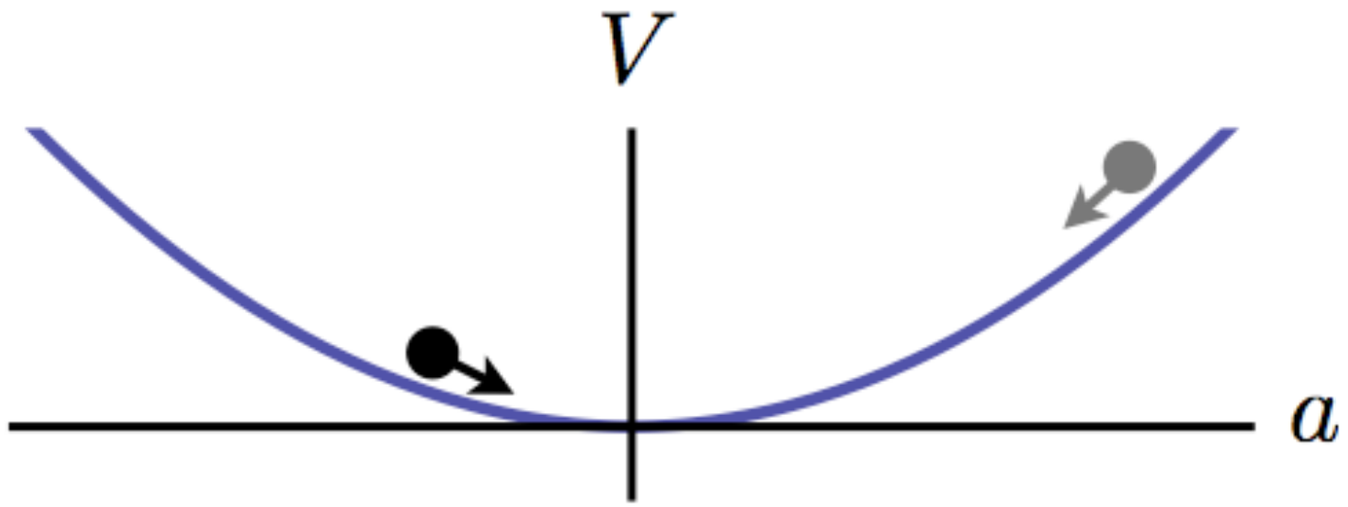
Axion-Like Particles (ALPs)

breaking of PQ symmetry gives axion…

general: breaking of symmetry at high scale can give Axion-Like Particles with small masses

generic in many well-motivated extensions of Standard Model, and top-down approaches (string theory)

Axions & ALPs can be dark matter



QCD effects provide a potential to axion field,
driving it to CP conserving minimum

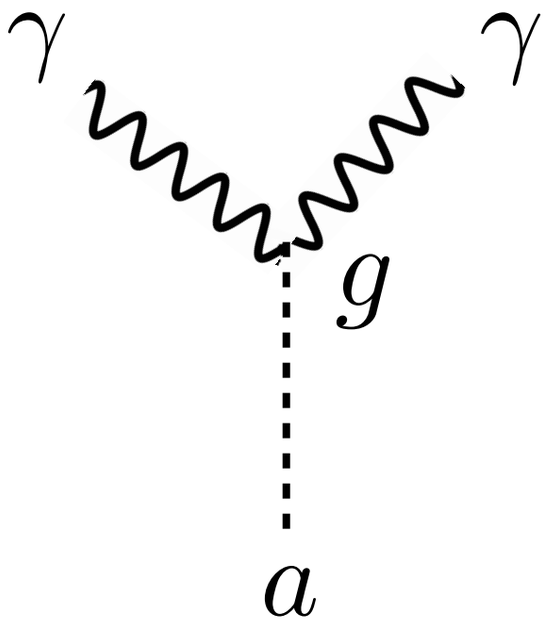
oscillations of axion field around
minimum act as cold DM

see talks by J. Redondo, Q. Yang, E. Mielke

Couplings to ordinary matter

axions couple to fermions & photons

e.g. coupling to photons:

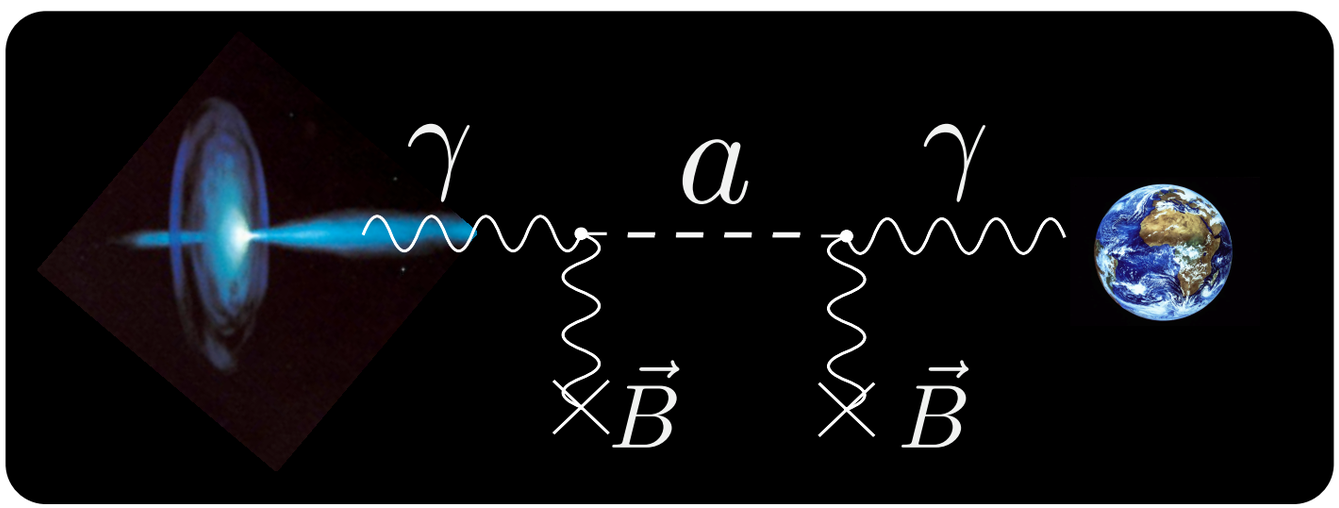


$$g \sim 10^{-13}\,\mathrm{GeV}^{-1}\left(\frac{10^{10}\,\mathrm{GeV}}{\mathrm{f_a}}\right)$$

coupling suppressed by f_a

for ALPs, coupling to photons
can be different (even zero)

Axion/ALPs can solve astro puzzles

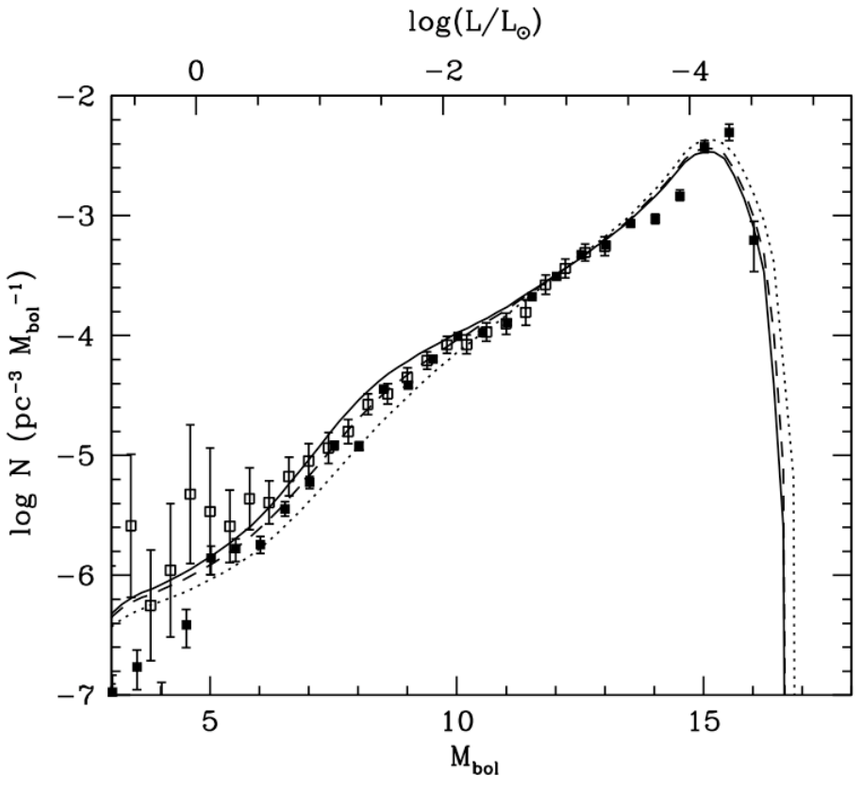


Roncadelli, de Angelis, …

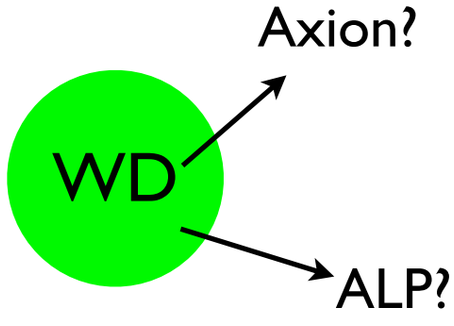
Is universe more transparent than expected to high energy γ-rays?

γ-ALP conversion?

see talks by M. Meyer



Isern, Garcia–Berro, Torres, Catalan



Do white dwarf stars cool faster than expected?

cooling enhanced by axion/ALP radiation?

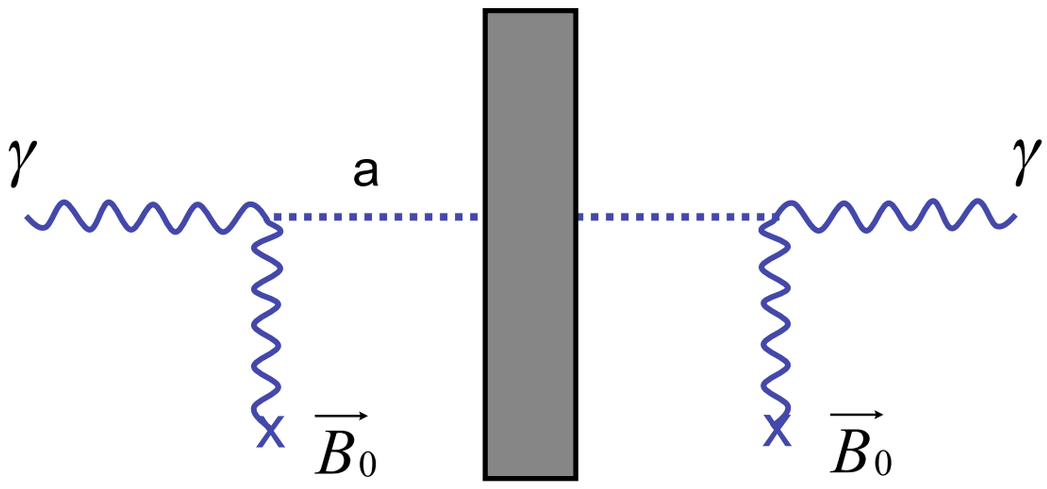
see talks by J. Isern & R. Gill

How to look for Axion and ALPs?

Best probes from γ-axion/ALP conversion

"Light-shining-through-walls"

Okun; Sikivie; Anselm; van Bibber;



LIPSS (Jlab) , BFRT (BNL), BMV (LULI), GammeV (Fermilab),
ALPS (DESY), OSQAR (CERN), PVLAS (INFN), ...

Need large magnets, powerful lasers, optical cavities

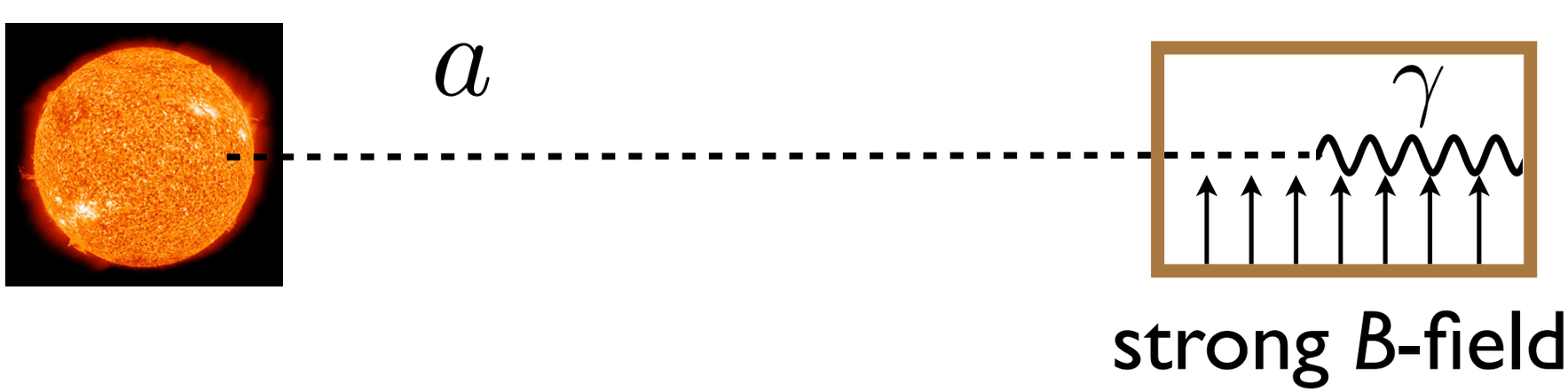
see talks by R. Baehre, M. Betz, M. Sulc

How to look for Axion and ALPs?

Best probes from γ-axion/ALP conversion

Helioscopes: stare at the sun

Sikivie; ….



SHIPS, CAST, SUMICO, IAXO, …

Need large magnets, sensitive detectors

see talks by J. Vogel (IAXO) & J. Ruz Armendariz (CAST)

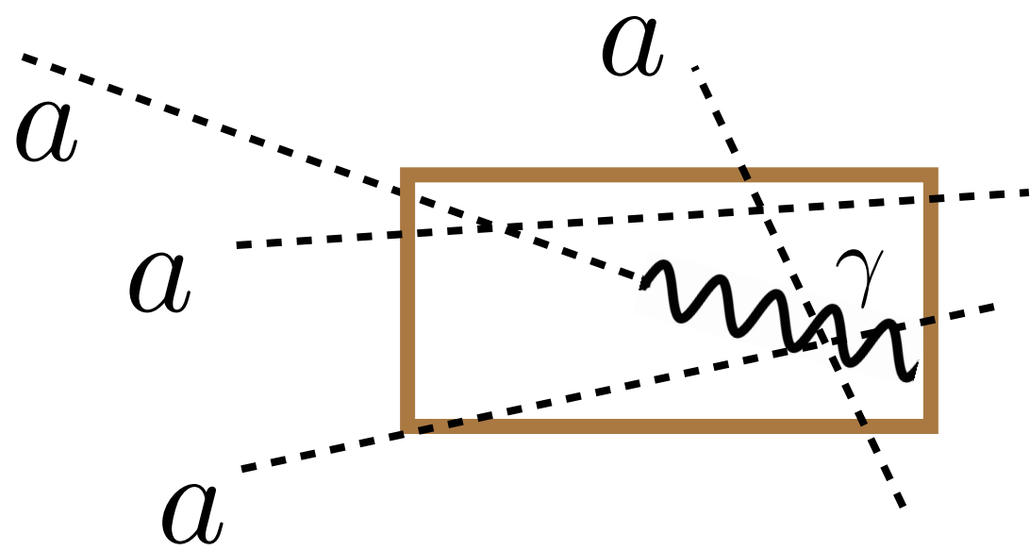
How to look for Axion and ALPs?

Best probes from γ-axion/ALP conversion

Resonant Cavities with Large Magnetic Field

Sikivie; ….

assume axions are dark matter



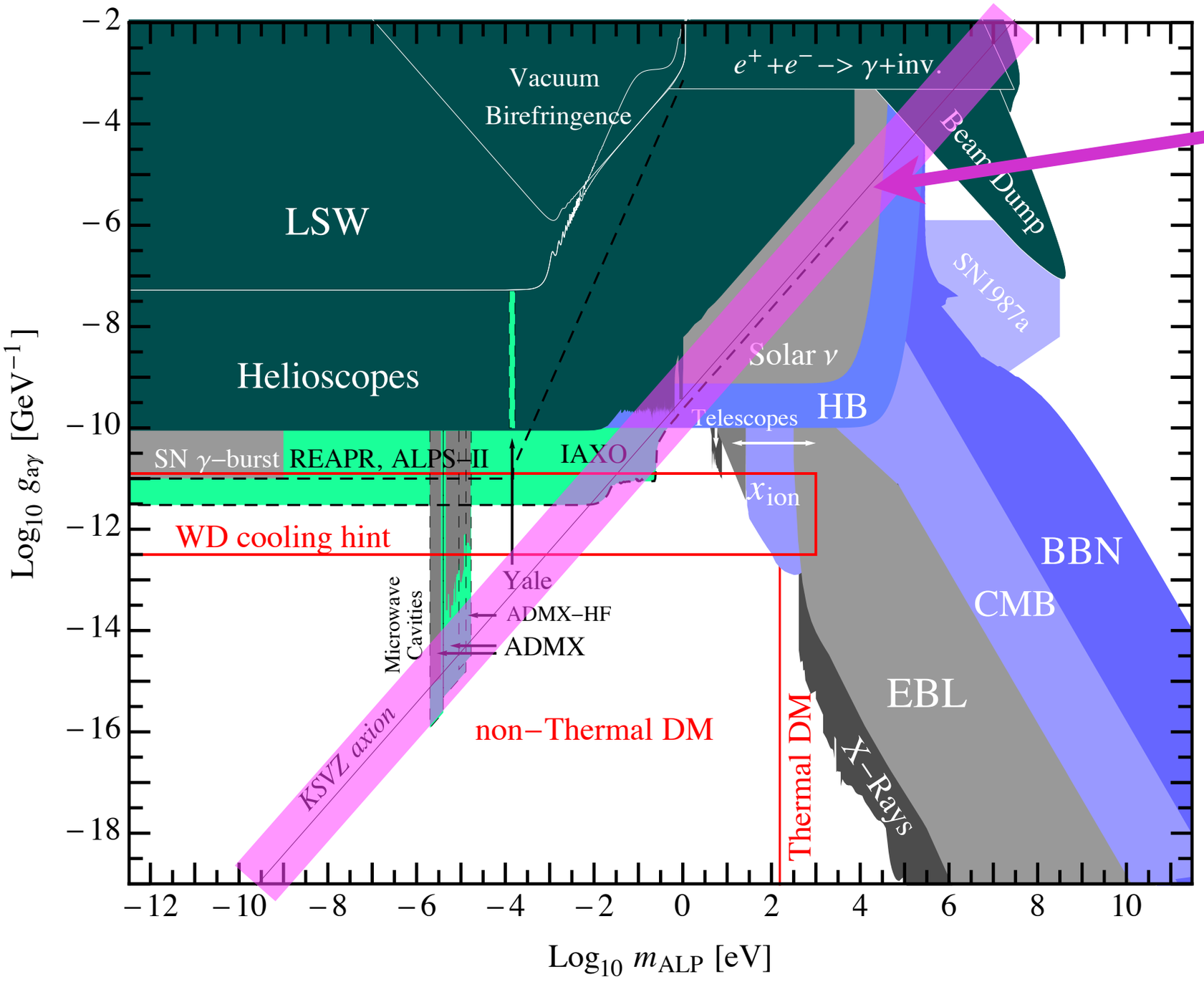
tunable Resonant Cavity

ADMX, ADMX-HF, …

see talk by K. van Bibber on ADMX

Current Limits & Opportunities

Axions & ALPs



axion band

Jaeckel, Redondo, Ringwald, …

Outline

- axions & axion-like particles
- heavy photons
- direct detection of sub-GeV DM

Heavy Photons

dark matter?

?

Standard Model

g $W^{\pm}, Z$ γ

Hidden Sector

A' (massive)

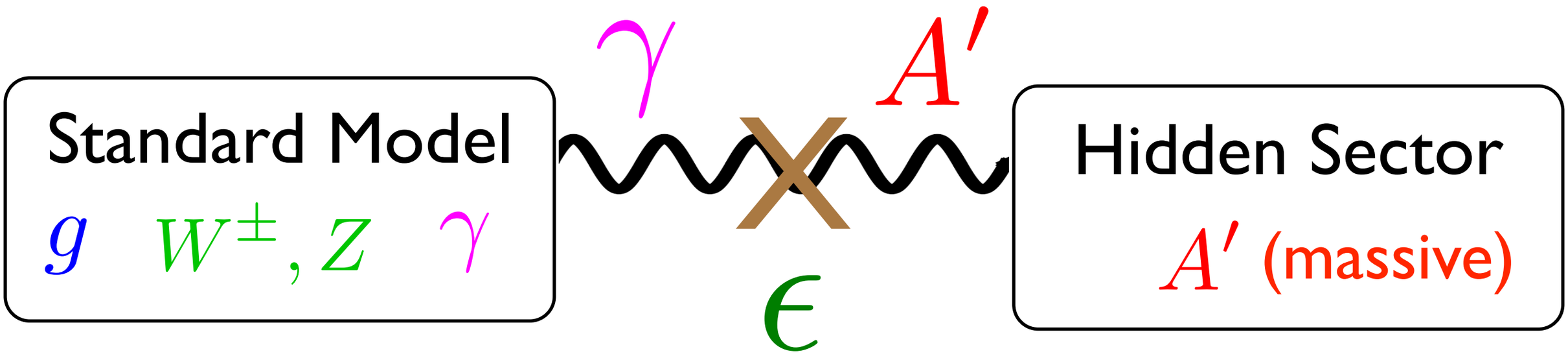
Known Forces

New force: *U(1)*

"Hidden Valleys" Strassler, Zurek, et.al.

Heavy Photons

ordinary photon & A' can mix



$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing"

see talk by B. Batell for this & other possibilities

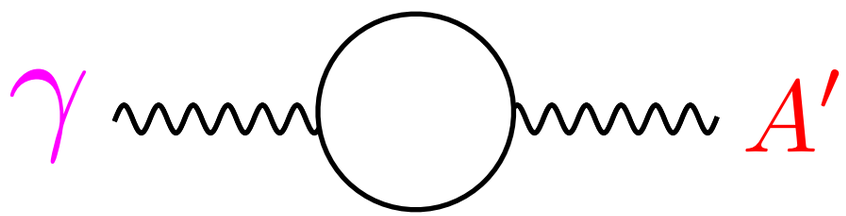
Holdom

Galison, Manohar

Generating Kinetic Mixing

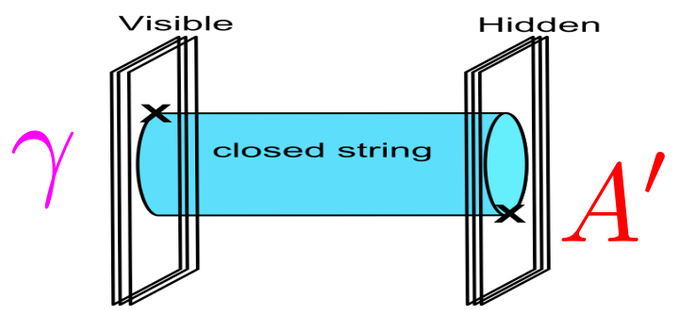
Examples:

loops of heavy particles



$$\epsilon \sim 10^{-8} - 10^{-2}$$

string theory



ϵ much smaller is possible

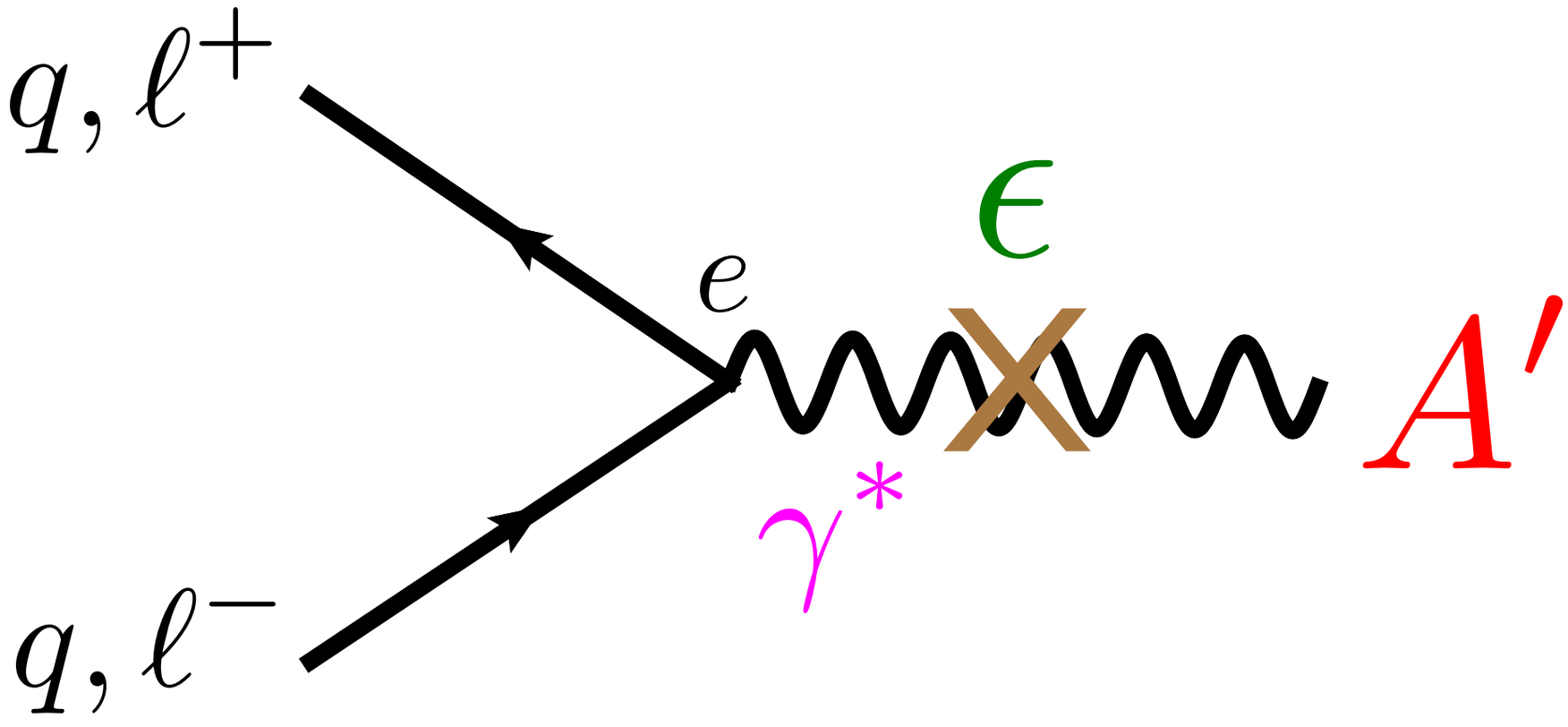
e.g. Goodsell, Jaeckel, Redondo, Ringwald

Mixing with photon allows:

$$A' \leftrightarrow \gamma \text{ “oscillation”}$$

and

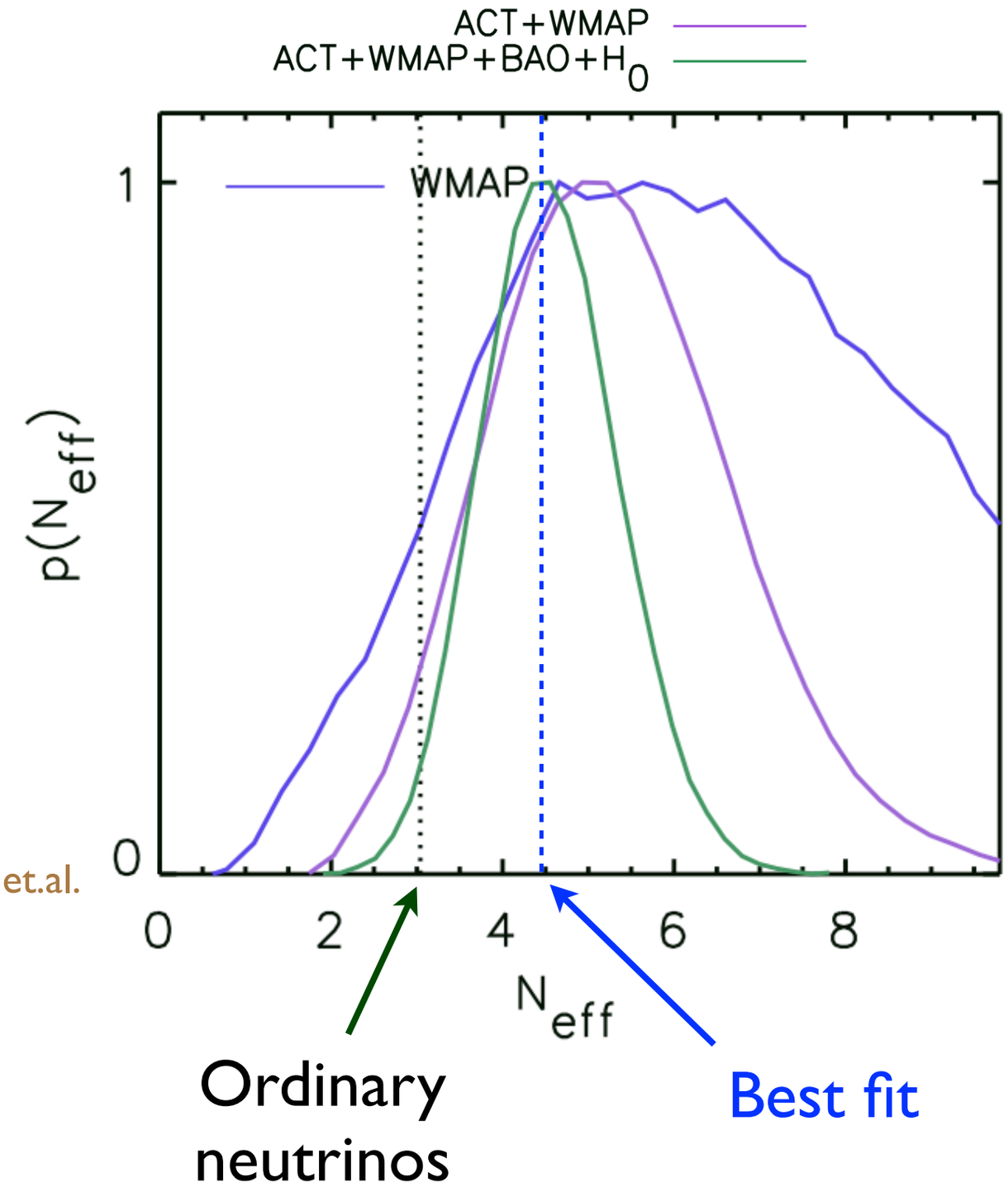
A′ coupling to quarks and charged leptons:



A′ WISP:

mass < $2m_e$ ~MeV

A′ WISP hints from N_{eff} from CMB?



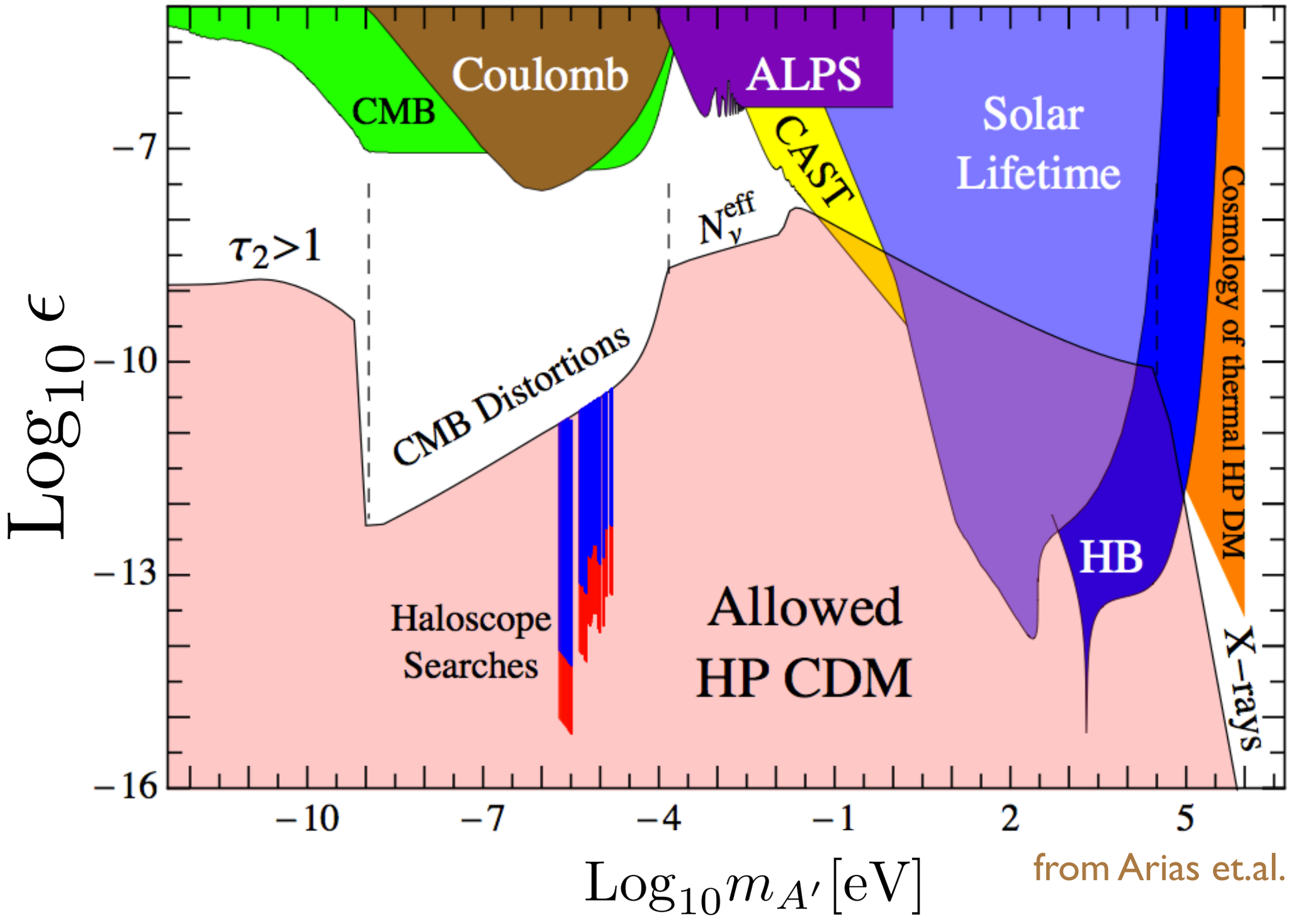
Dunkley et.al. (ACT)

suggestive of additional relativistic degrees of freedom (N_{eff})?

$$m_{A'} \sim \mathrm{meV} \ ?$$

Jaeckel, Redondo, Ringwald

A′ WISPs as Dark Matter

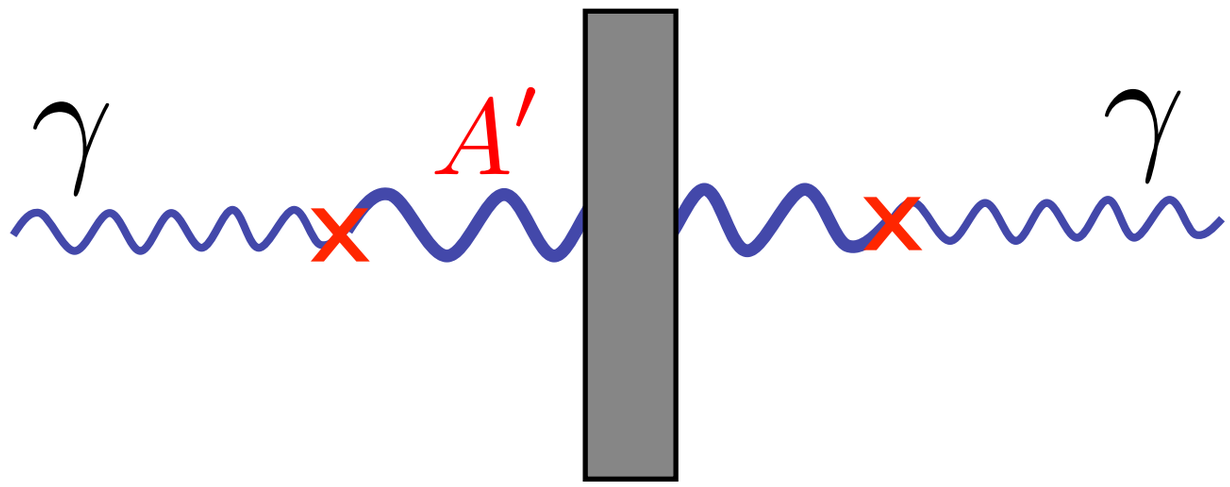


from Arias et.al.

see talk by J. Redondo

How look for A′ WISPs?

"Light-shining-through-walls" (cf. axions)



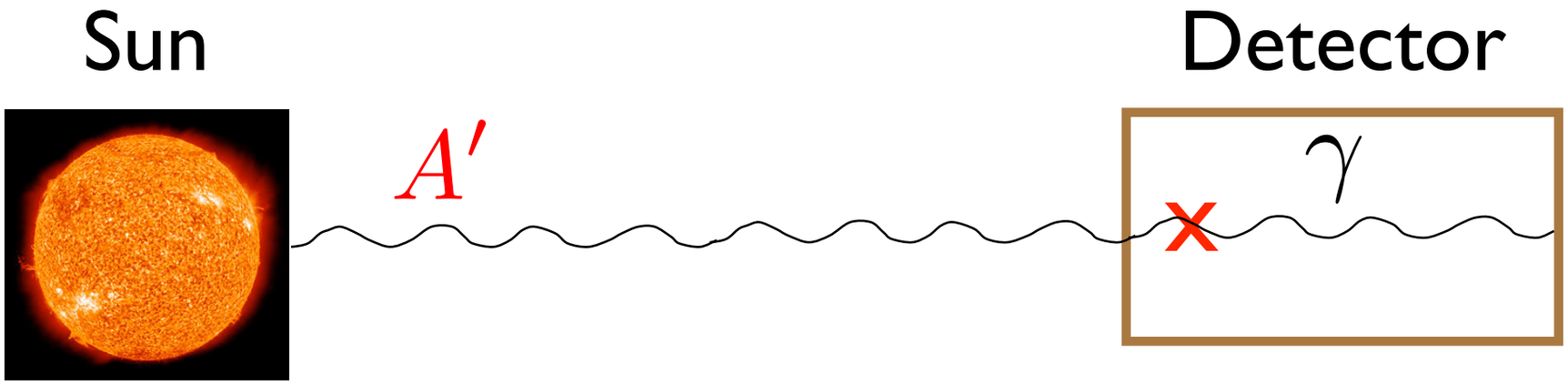
LIPSS (Jlab) , BFRT (BNL), BMV (LULI), GammeV (Fermilab),
ALPS (DESY), OSQAR (CERN), PVLAS (INFN), ...

Need powerful lasers but no magnets

How look for A′ WISPs?

Helioscopes: stare at the sun (cf. axions)

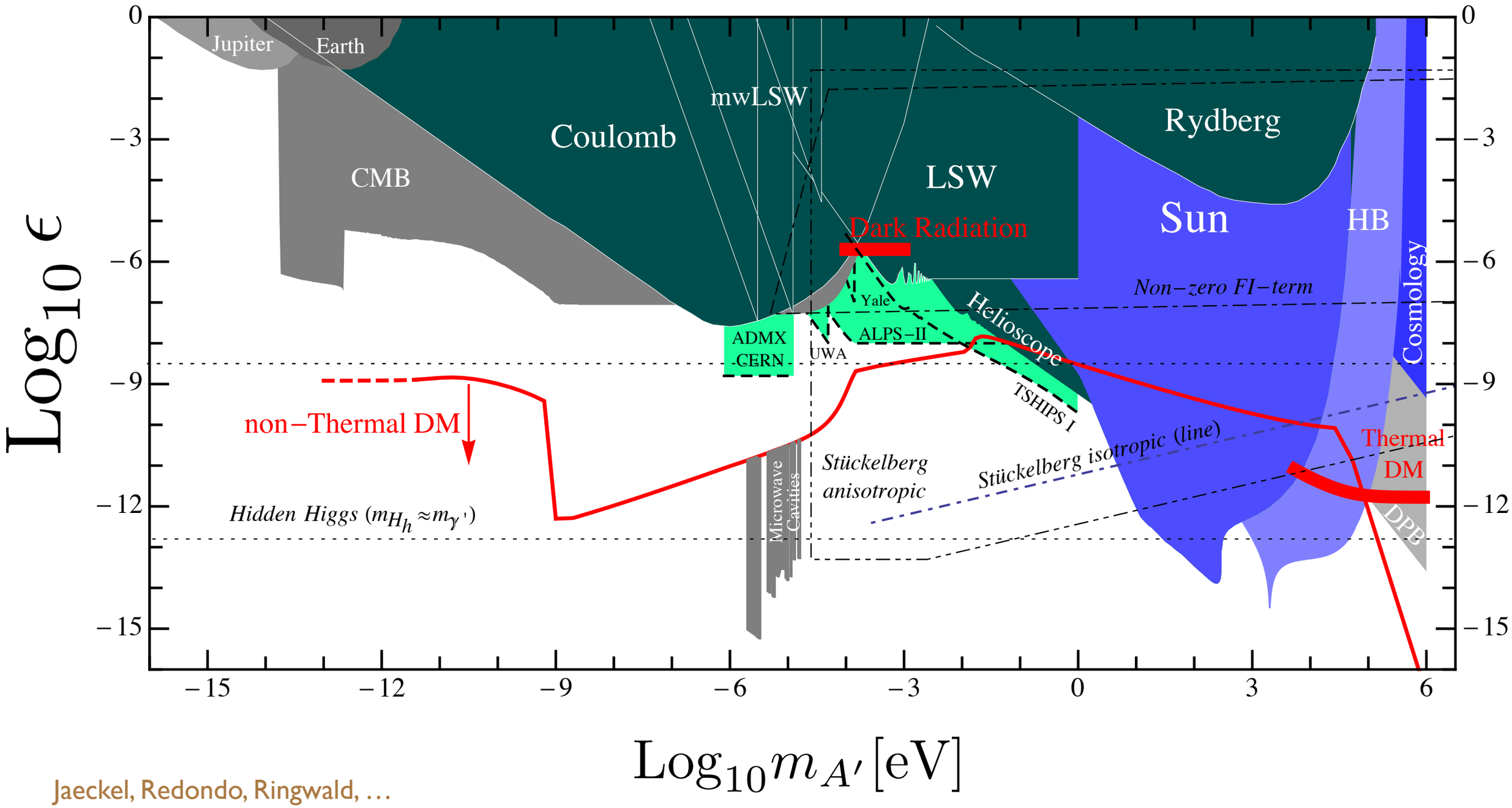
Okun, …



TSHIPS, CAST, SUMICO, IAXO, …

see talk by M. Schwarz

A′ WISP parameter space



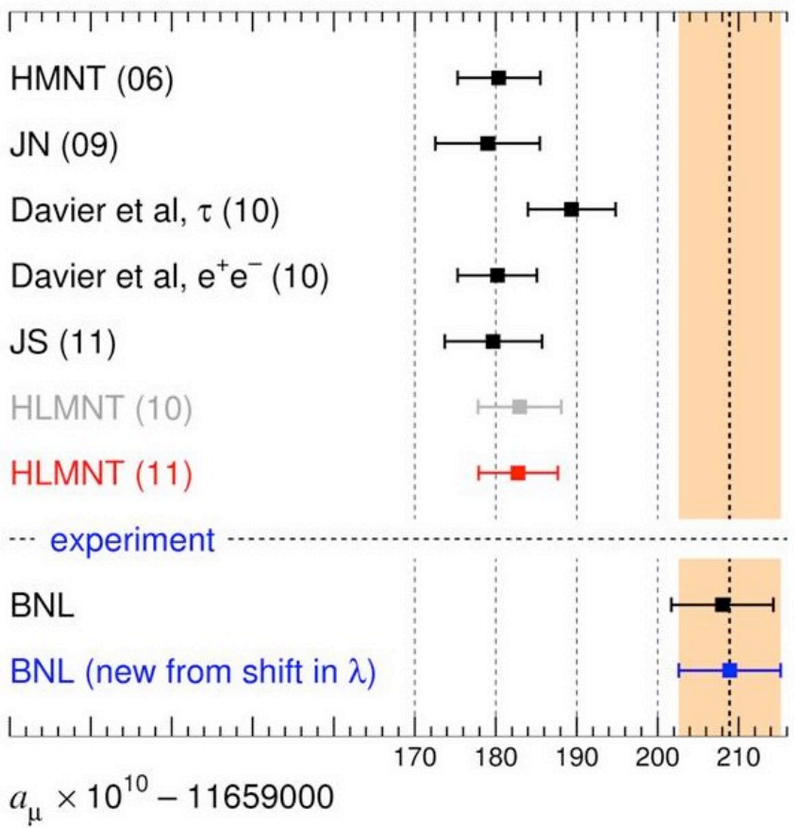
Jaeckel, Redondo, Ringwald, …

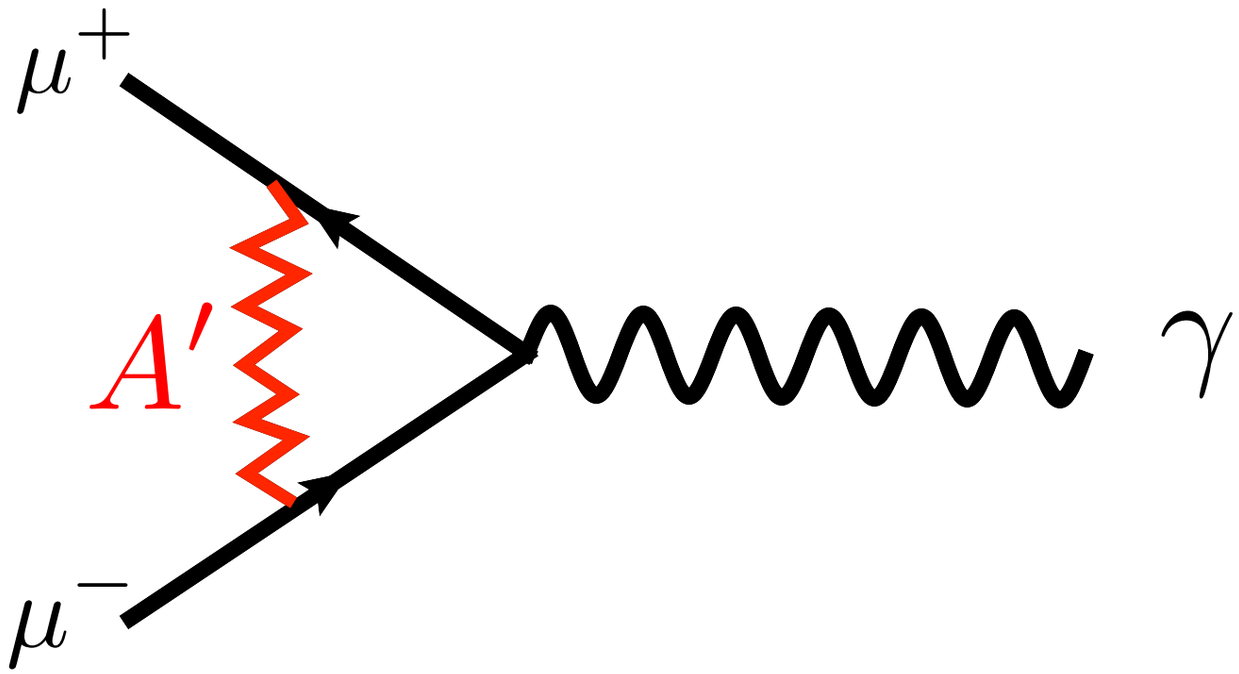
A′:
mass ~ MeV-GeV

Hints for A′ with MeV-GeV mass?

anomalous muon g-2 ?

Pospelov
Boehm, Fayet



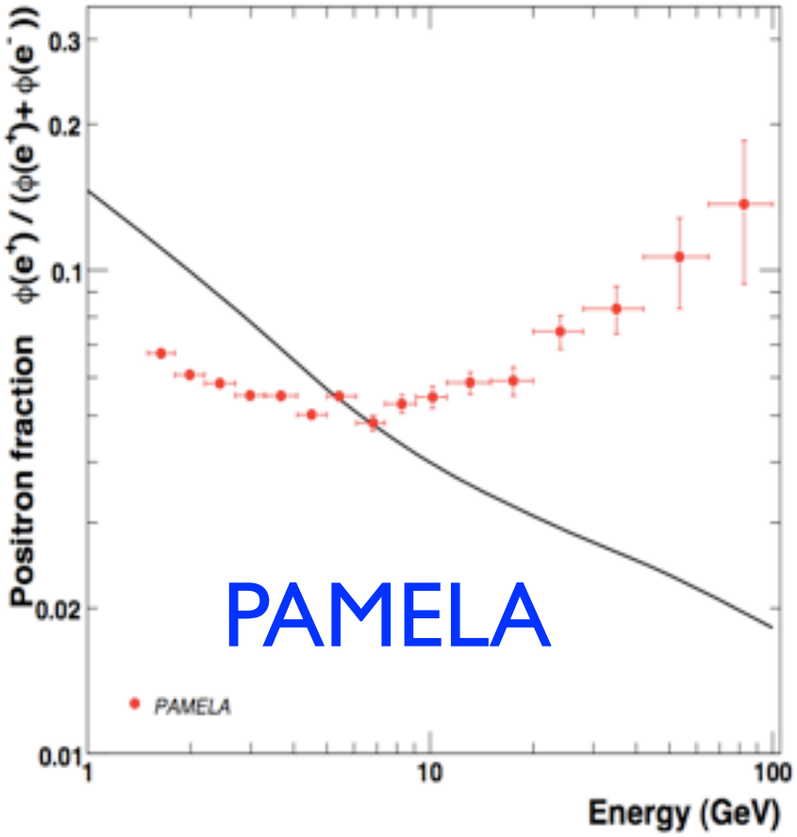


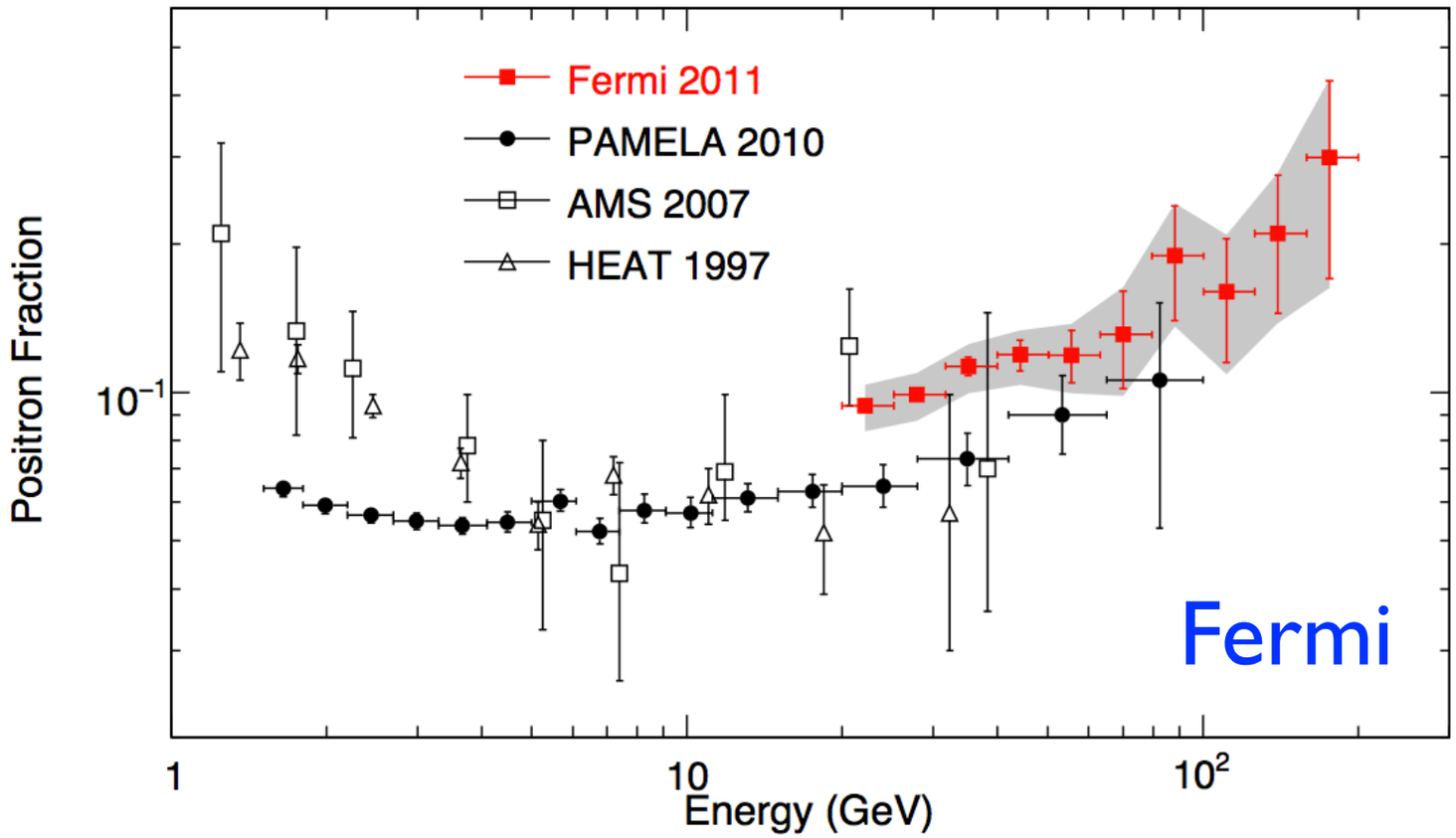
A′ may explain observed $(g_s - 2)_\mu$!

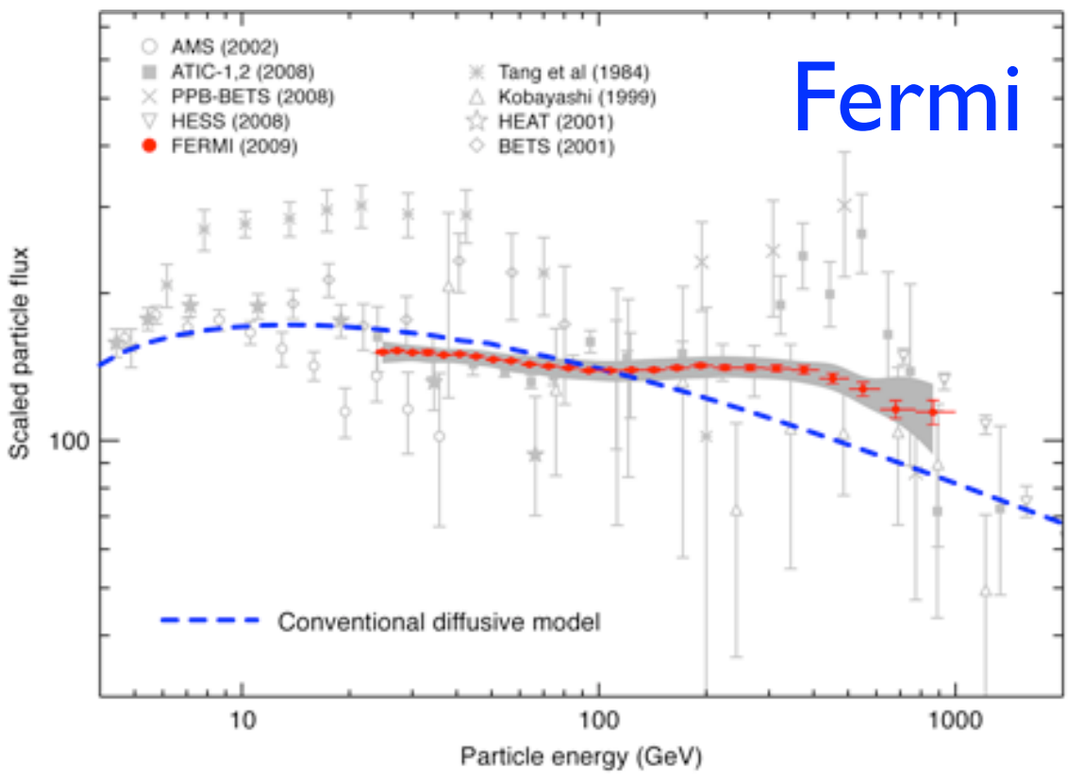
Hints for A′ with MeV-GeV mass?

New dark matter interactions?

Many, many DM related anomalies



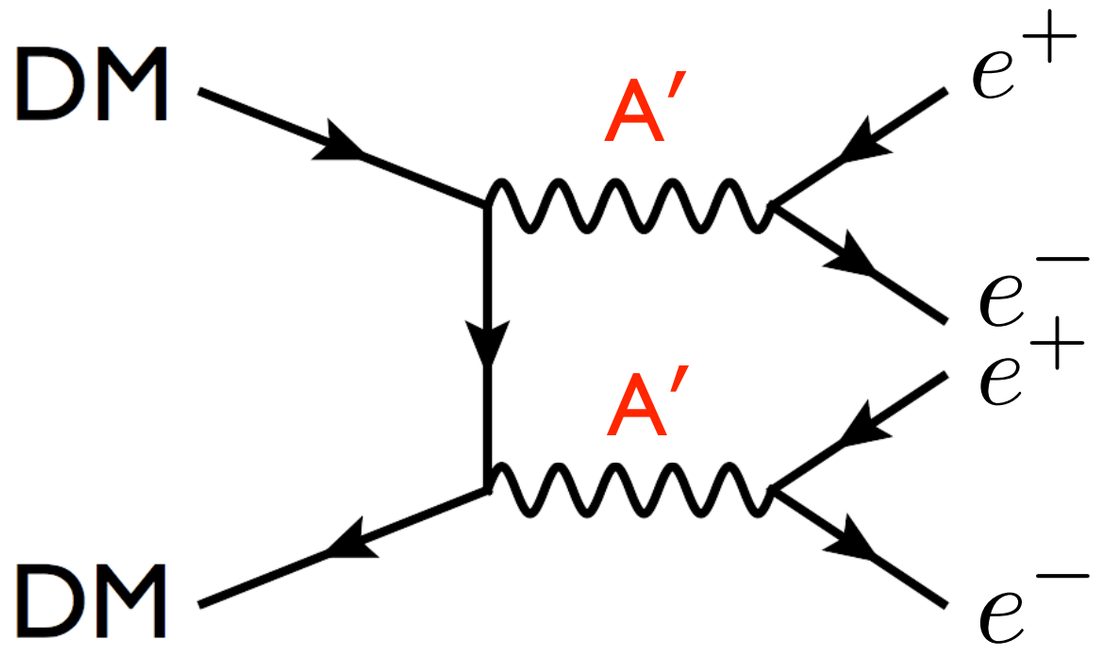




cosmic-ray e^+ & e^- excess

but no anti-proton excess
(restricts DM interactions)

100 GeV - 1 TeV

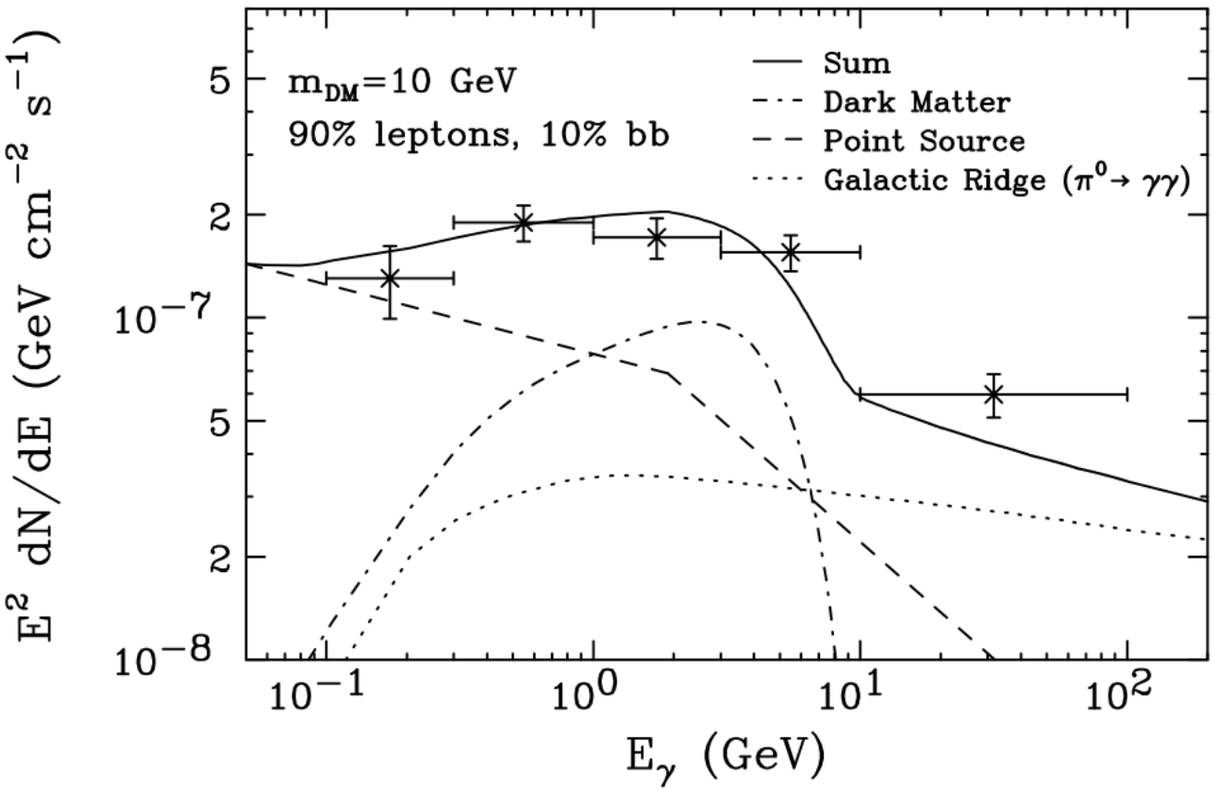


produces e^+, no $\bar{p}$

Finkbeiner, Weiner; Pospelov, Ritz, Voloshin; Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Pospelov & Ritz; Nomura & Thaler

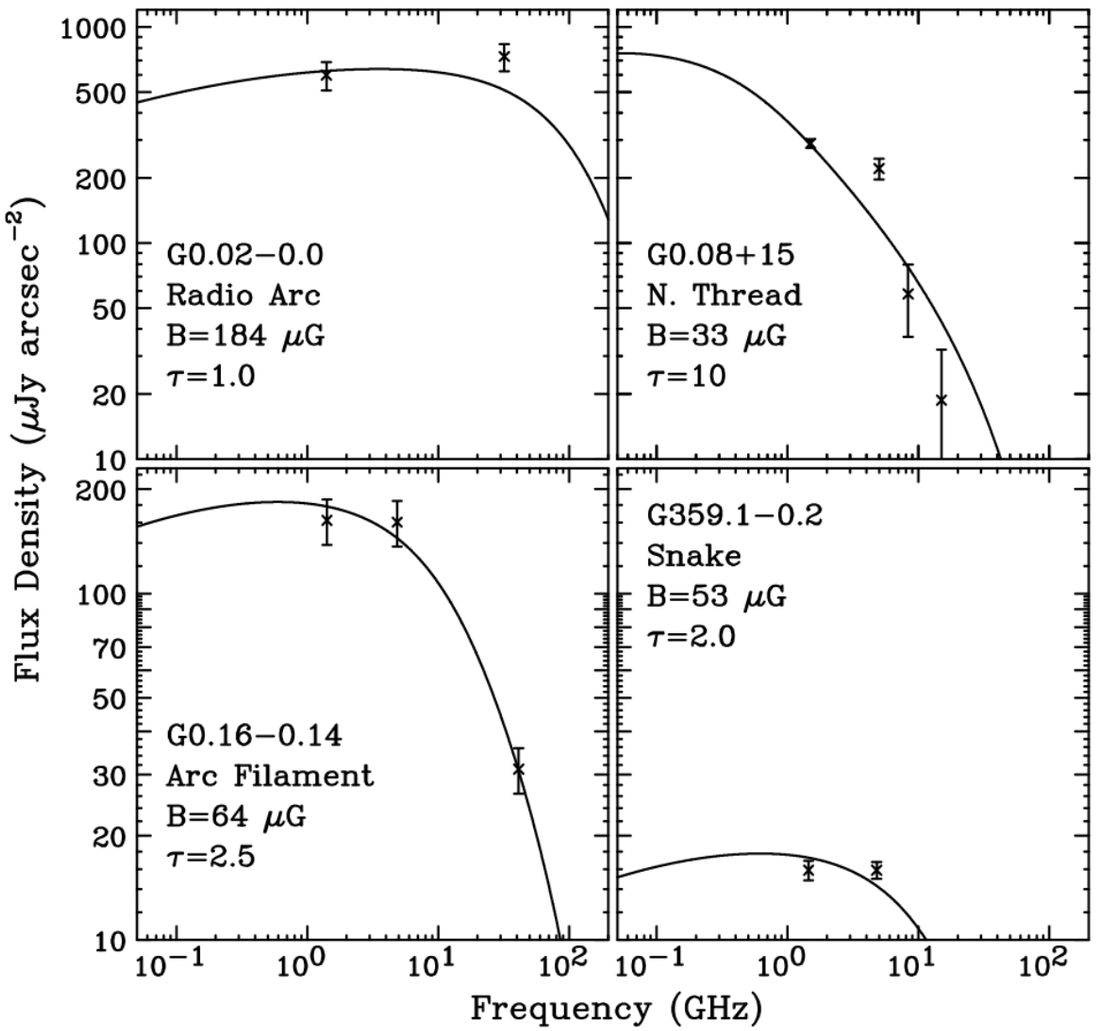
Many, many DM related anomalies

Fermi photon spectrum near GC

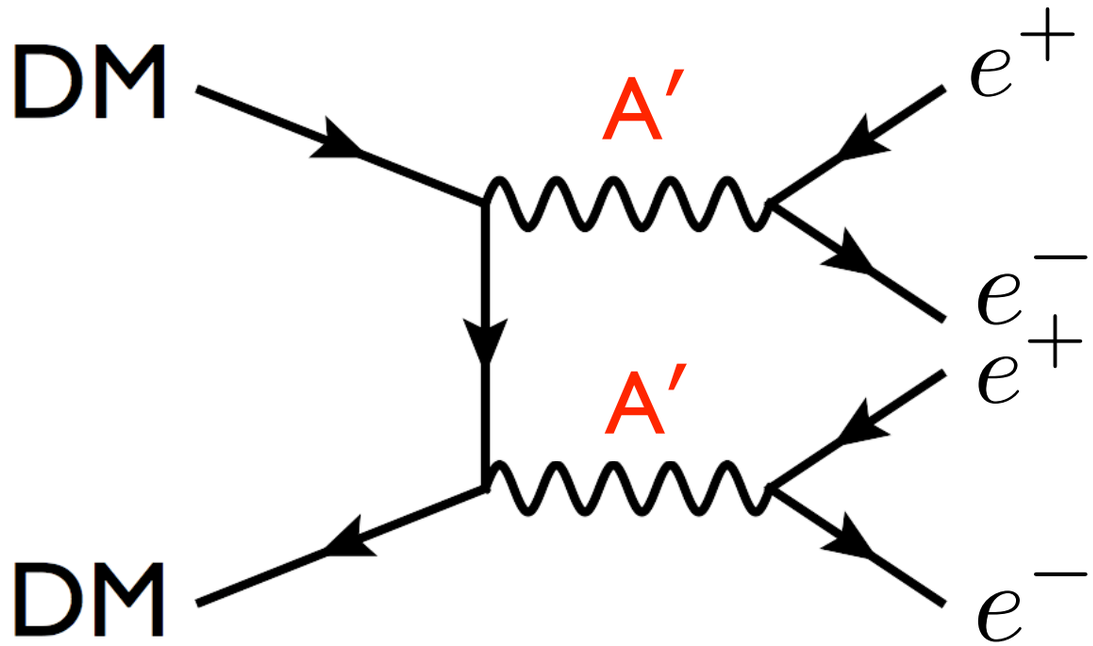


see talk by D. Hooper

Synchrotron emission from inner galaxy's radio Filaments



~10 GeV



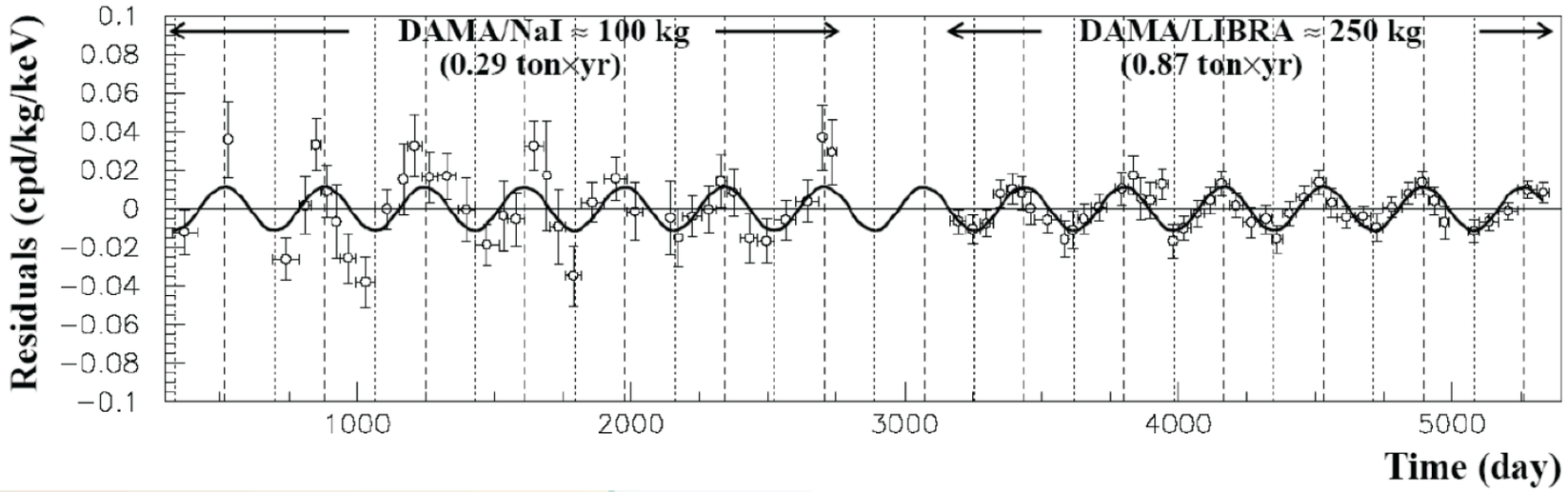
produces e^+

Hooper, Weiner, Xue

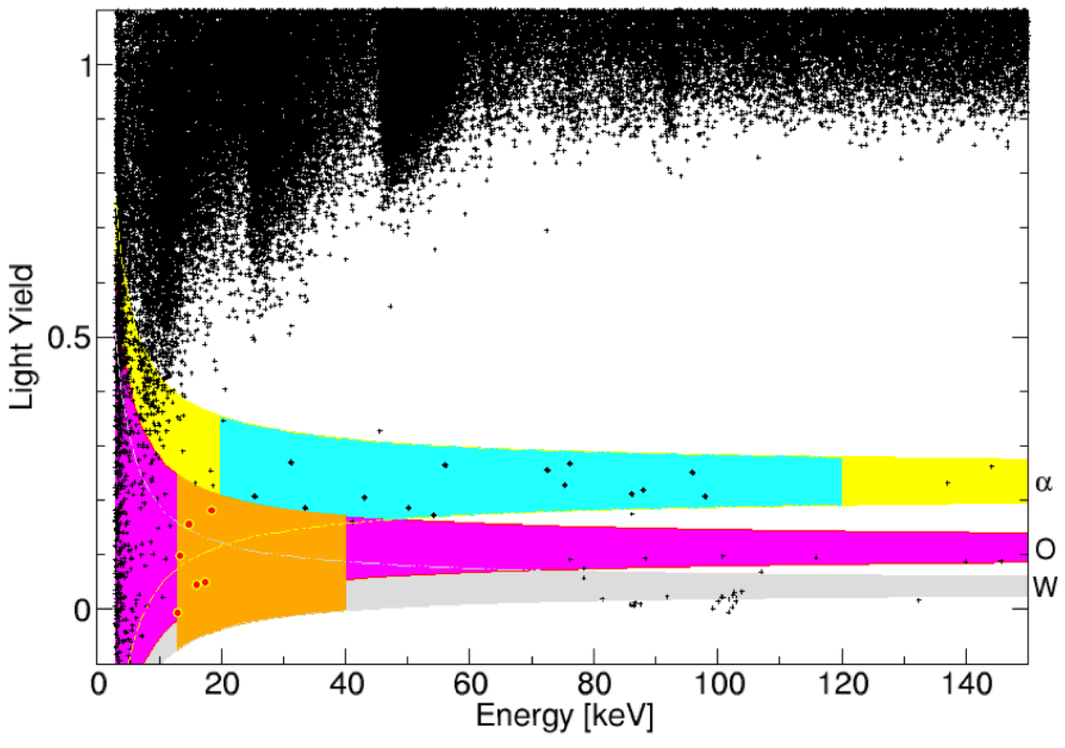
see talk by D. Hooper

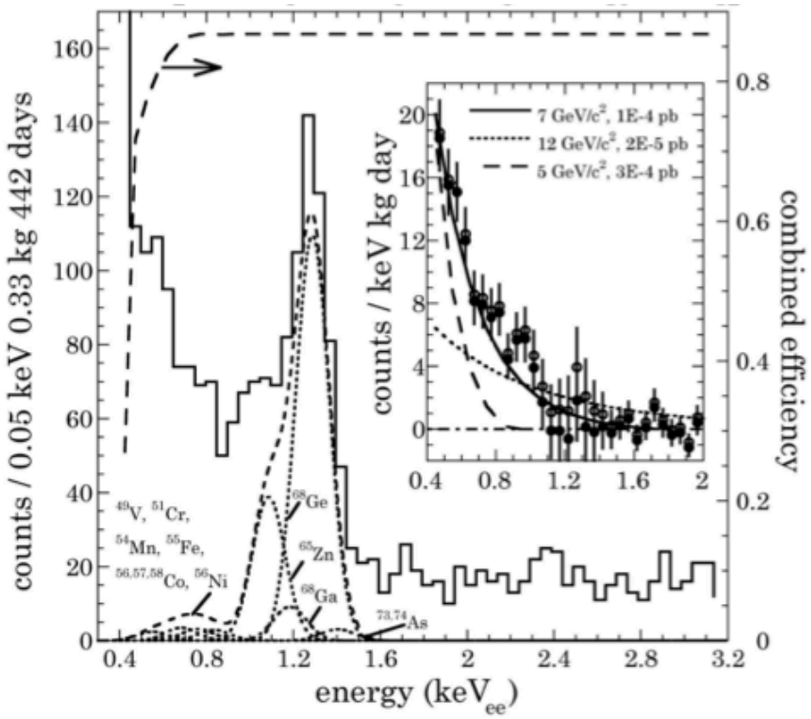
Many, many DM related anomalies

DAMA



CRESST



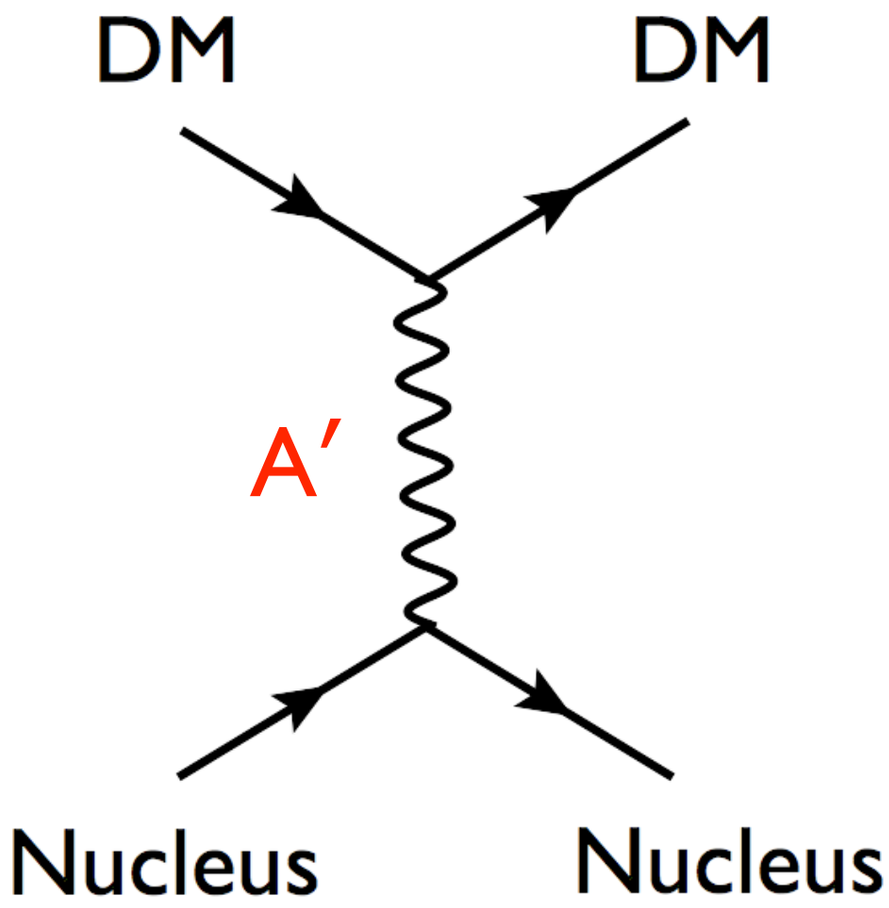


CoGeNT

see talk by J. Collar

direct detection anomalies

~10 GeV



e.g.

Arkani-Hamed et.al.;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;
Cline, Frey;
Hooper, Weiner, Xue
RE, Kaplan, Schuster, Toro;

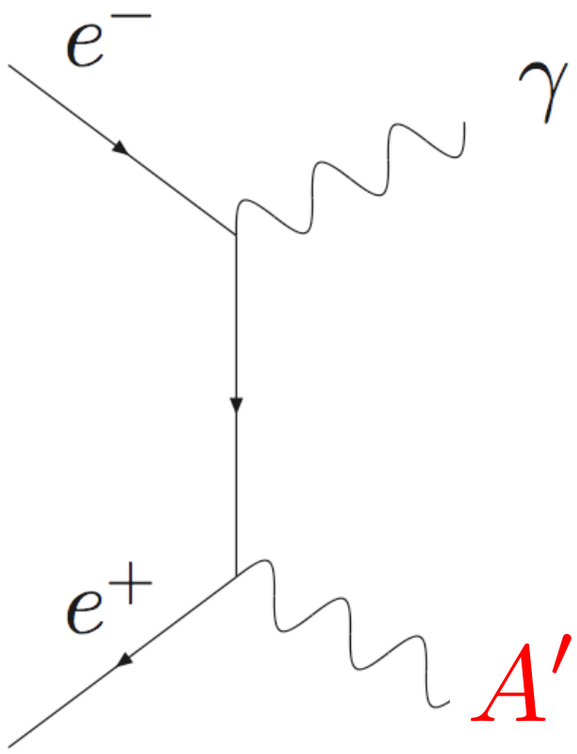
direct detection hints?

see talks by S. Andreas, D. Hooper

How look for A′ with MeV-GeV mass?

e^+e^- colliders

RE, Schuster, Toro
Batell, Pospelov, Ritz
Reece, Wang
Borodatchenkova et.al.
Fayet



Rare meson decays

$$\phi \to \eta A'$$

$$\pi^0 \to \gamma A'$$

B-factories, Phi-factories

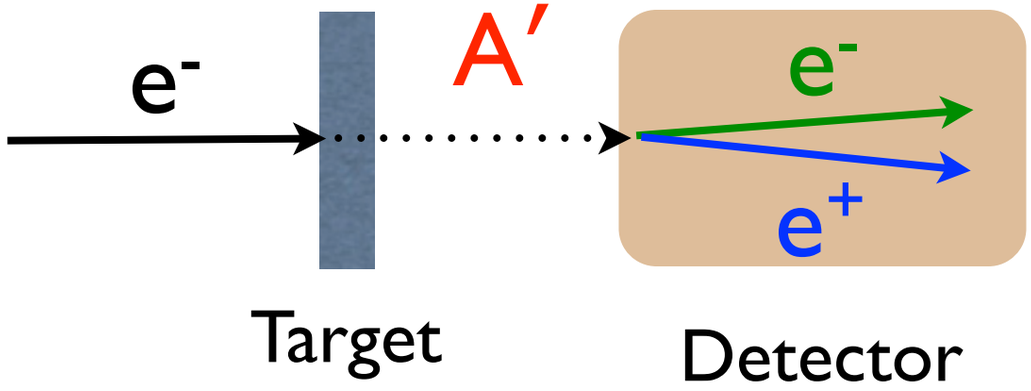
Searches ongoing

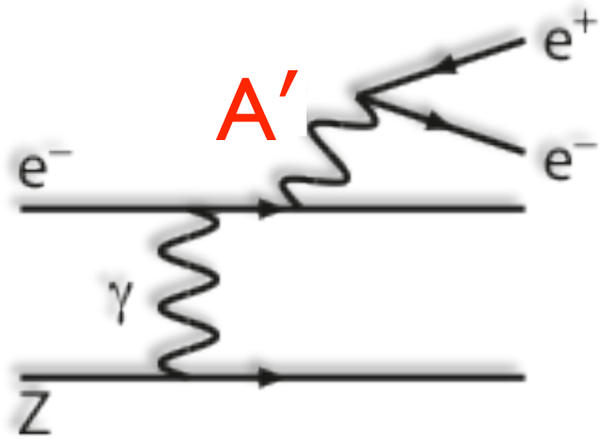
see talks by B. Echenard, Y. Liu

How look for A′ with MeV-GeV mass?

New e⁻ fixed target experiments

Bjorken, RE, Schuster, Toro
Freytsis, Ovanesyan, Thaler
Reece & Wang





Experiments done/planned at

- Jefferson Lab (APEX, HPS, DarkLight)
- Mainz
- VEPP-3

see talks by
J. Beacham (APEX)
P. Hanssen (HPS)
J. Boyce (JLab)

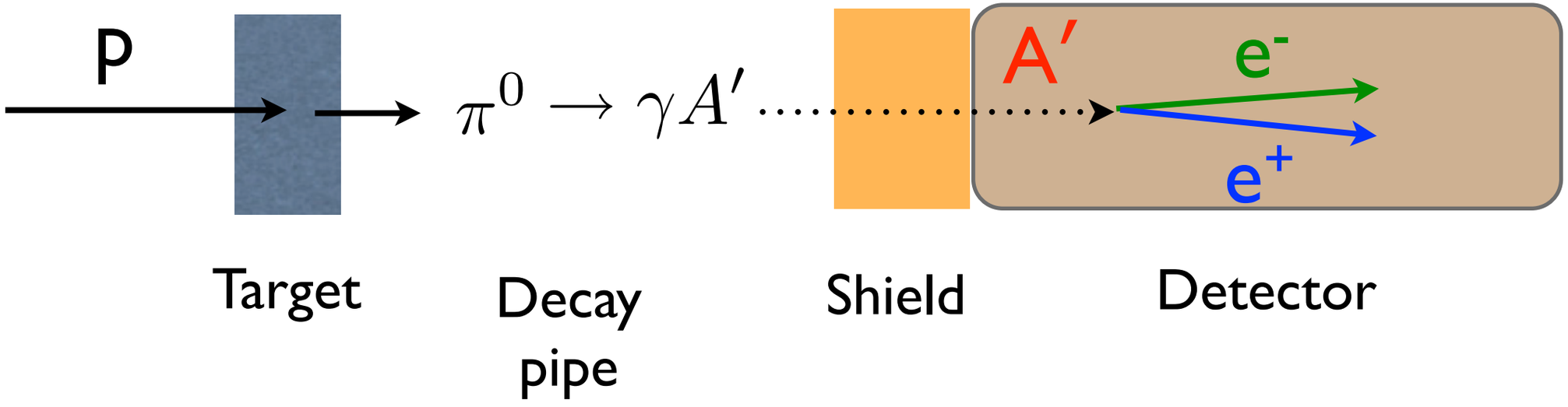
How look for A′ with MeV-GeV mass?

Proton-beam fixed target experiments

Batell, Pospelov, Ritz

RE, Harnik, Kaplan, Toro

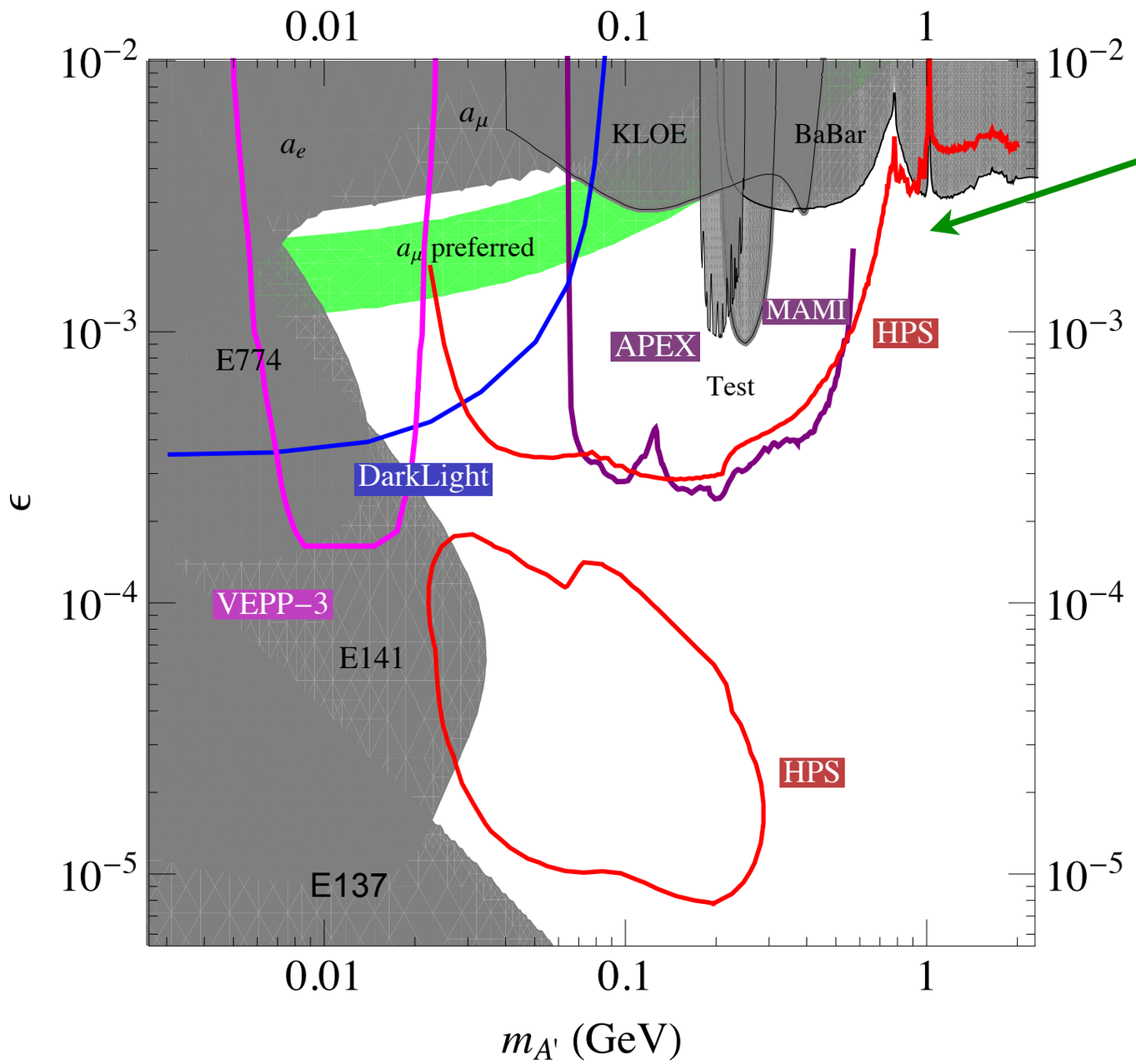
Example: produce A′ from pion decays



e.g. LSND, MINOS, MiniBooNE, Project X

see talks by B. Batell, C. Wallace

MeV-GeV A′ constraints & prospects



B/Phi-factories can significantly extend reach

MAMI has plans to cover similar region to APEX

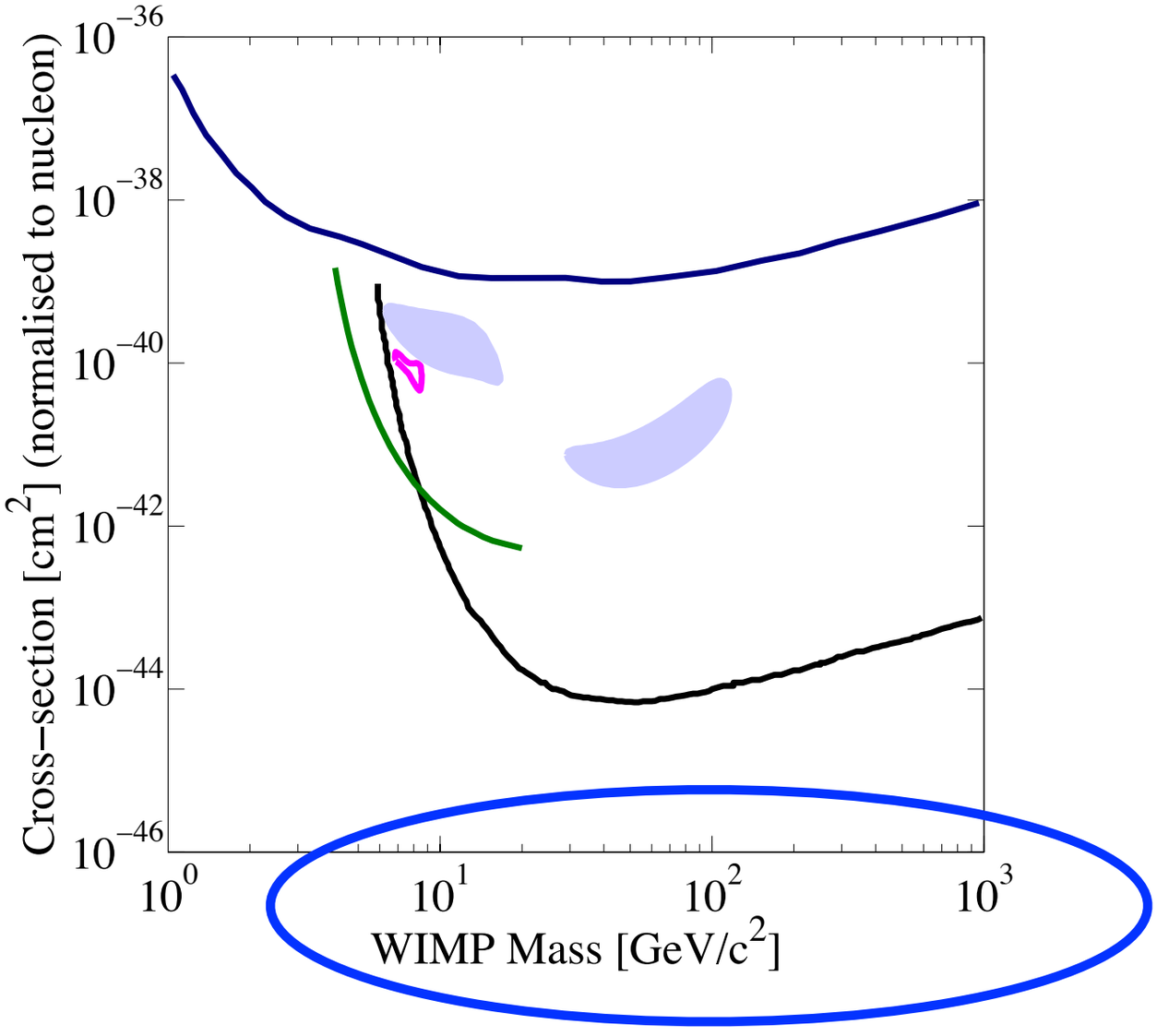
region motivated by theory, dark matter, muon g-2

Outline

- axions & axion-like particles
- heavy photons
- direct detection of sub-GeV DM

see talk by A. Manalaysay

The usual DM direct detection parameter space



well-motivated by the WIMP miracle

Weak-scale

See *many* talks: J. Collar, P. Gondolo, W. Guo, C. Gustavo, K. Hiraide, B. Kilminster, V. Kozlov, B. Loer, D. McKinsey, R. Nelson, U. Oberlack, M. Schumann, E. Vazquez-Jauregui, U. Wichoski

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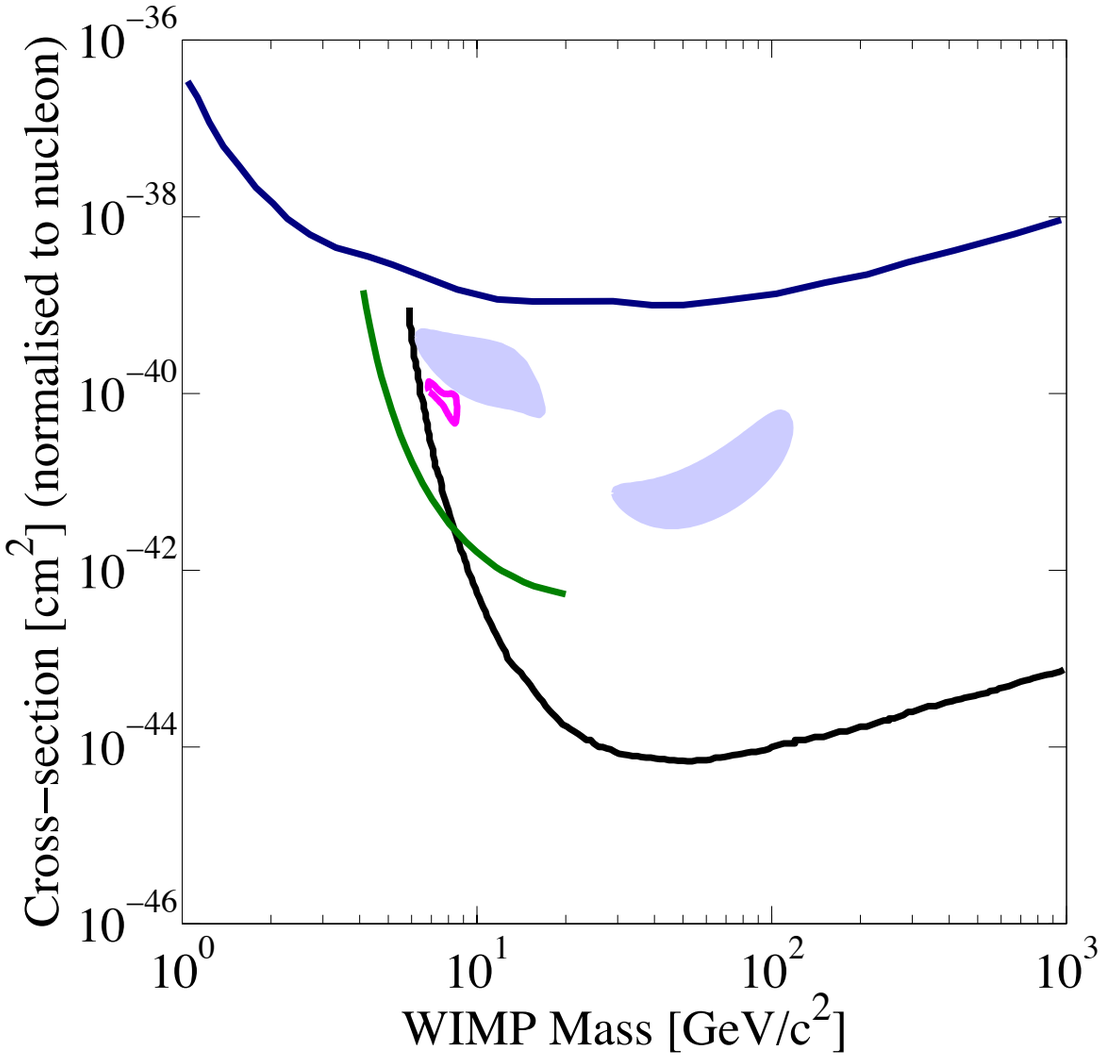

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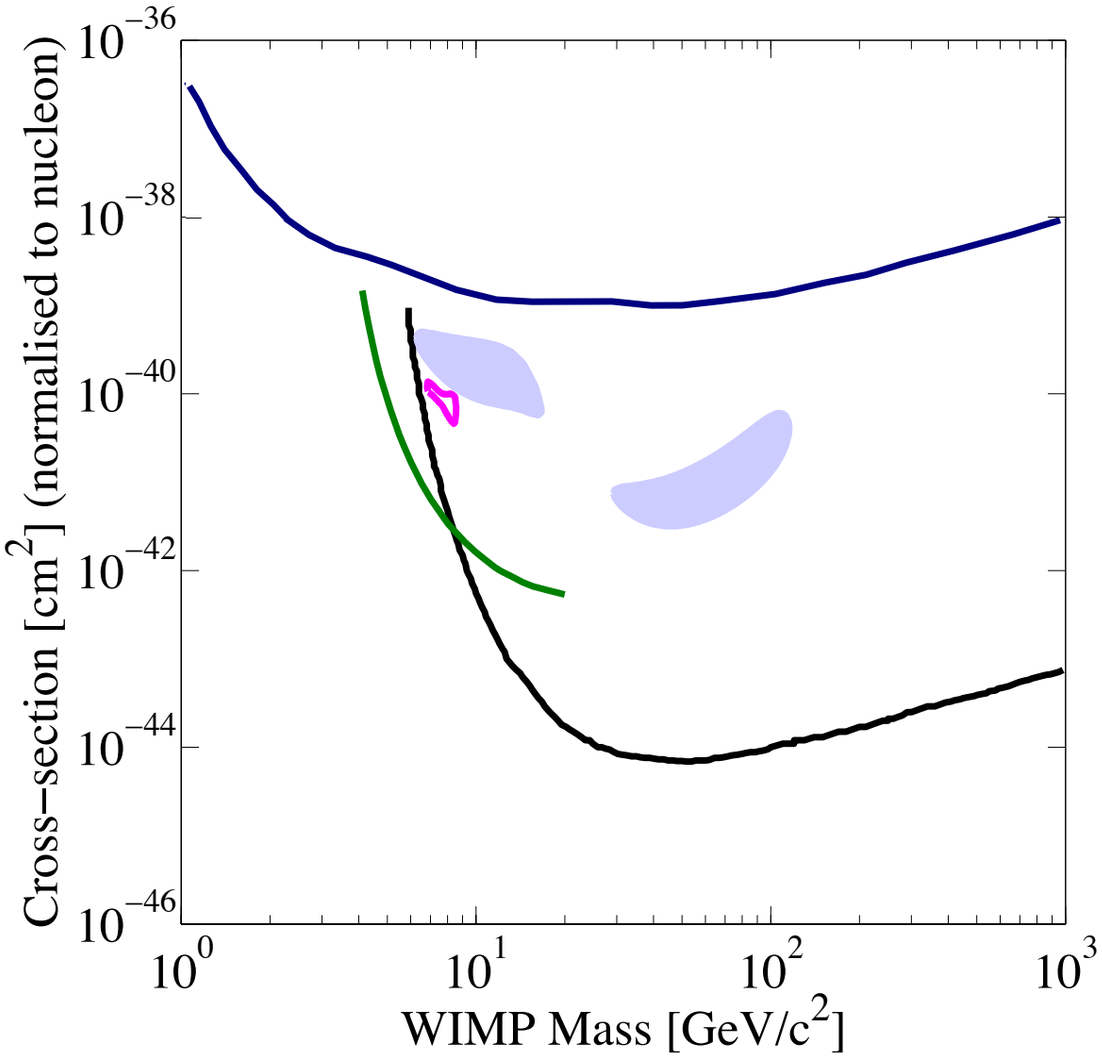
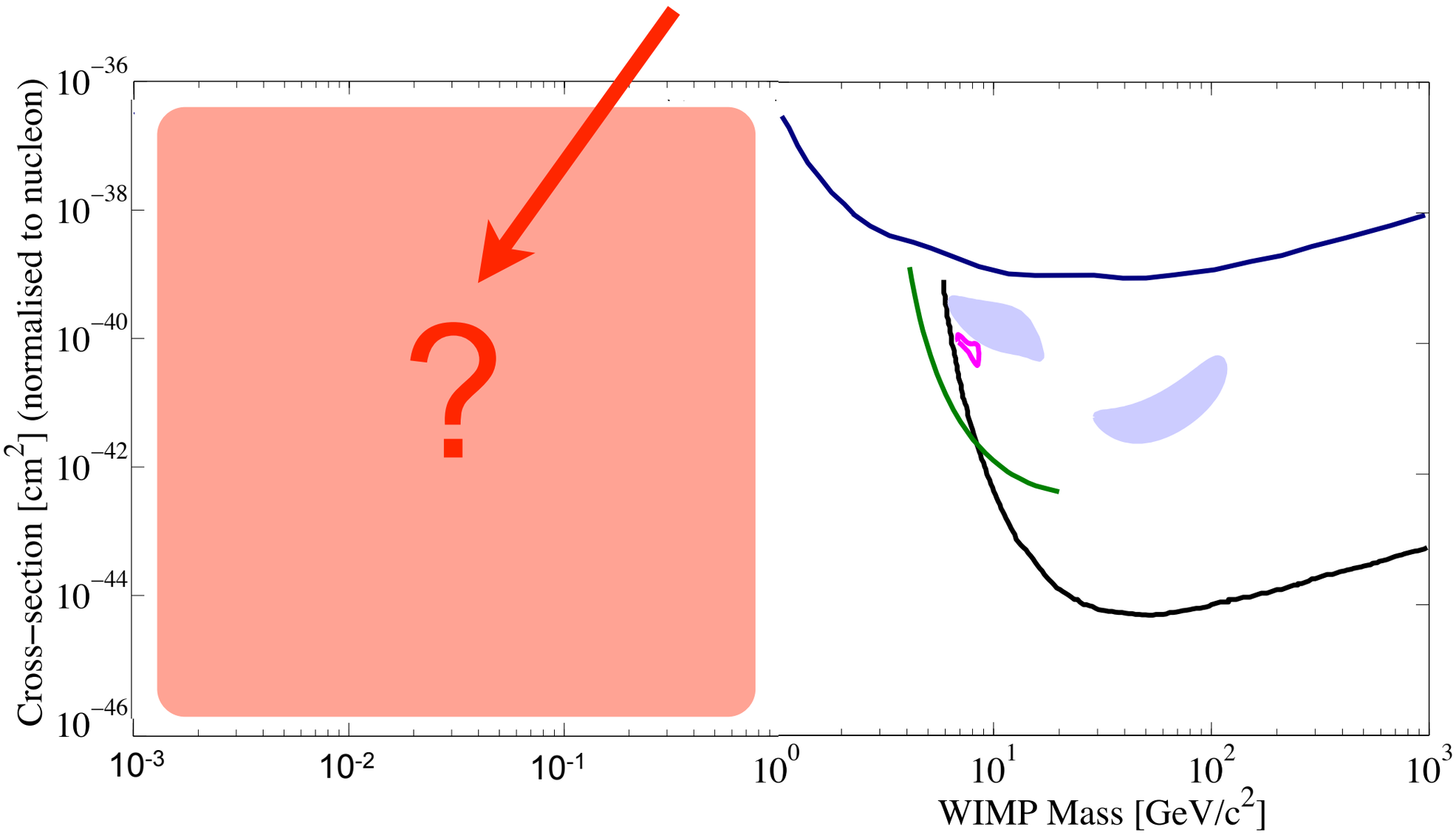
BUT: don't let a paradigm blind you to other experimental opportunities!

Instead of considering only this…



What if DM is here?

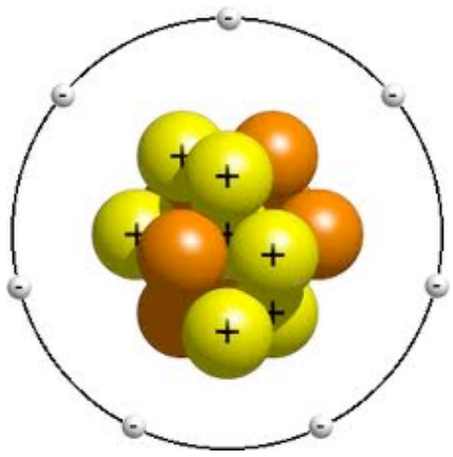


mass ~ MeV - GeV

Easy to build viable DM models
(e.g. interactions through an A′!)

Elastic nuclear recoils don't work

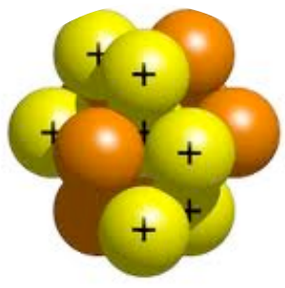
Heavy DM



Atom

Elastic nuclear recoils don't work

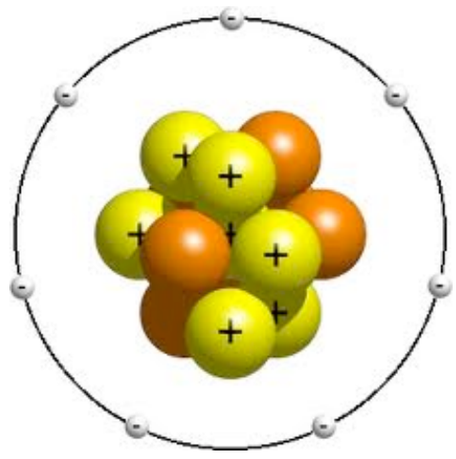
Heavy DM



large recoil…
"no problem"

Elastic nuclear recoils don't work

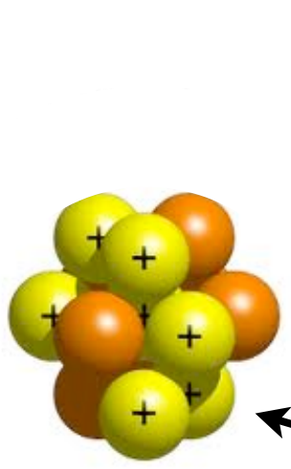
Light DM $\lesssim 1$ GeV



Atom

Elastic nuclear recoils don't work

Light DM $\lesssim 1$ GeV

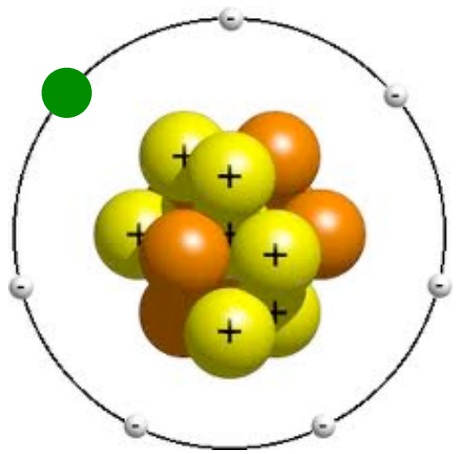


Can't see
recoiling nucleus

But DM could scatter off an electron!

RE, J. Mardon, T. Volansky (1108.5383, PRD)

DM



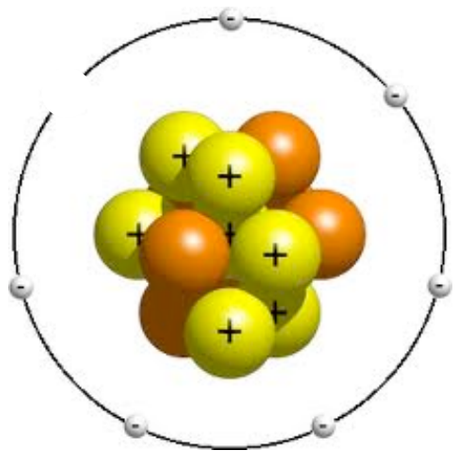
Atom

(only an example)

But DM could scatter off an electron!

RE, J. Mardon, T. Volansky (1108.5383, PRD)

DM



Atom

(only an example)

Ionization

Signal: single (or few) electron events

existing technologies can measure ionization, even of a single electron !

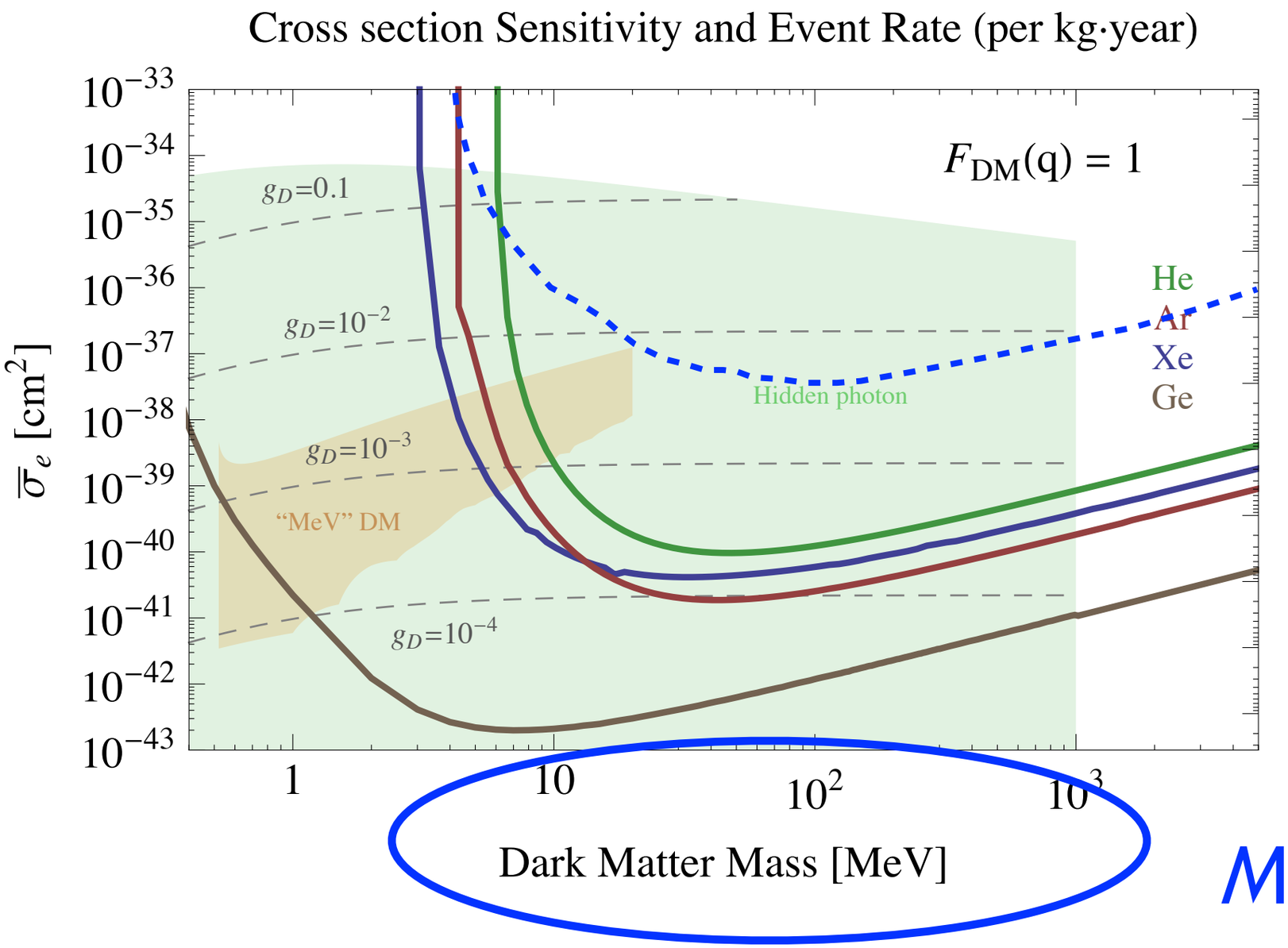
A Proof of Principle

"First direct detection limits on
sub-GeV Dark Matter from XENON10"

RE, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky
(1206.2644, PRL)

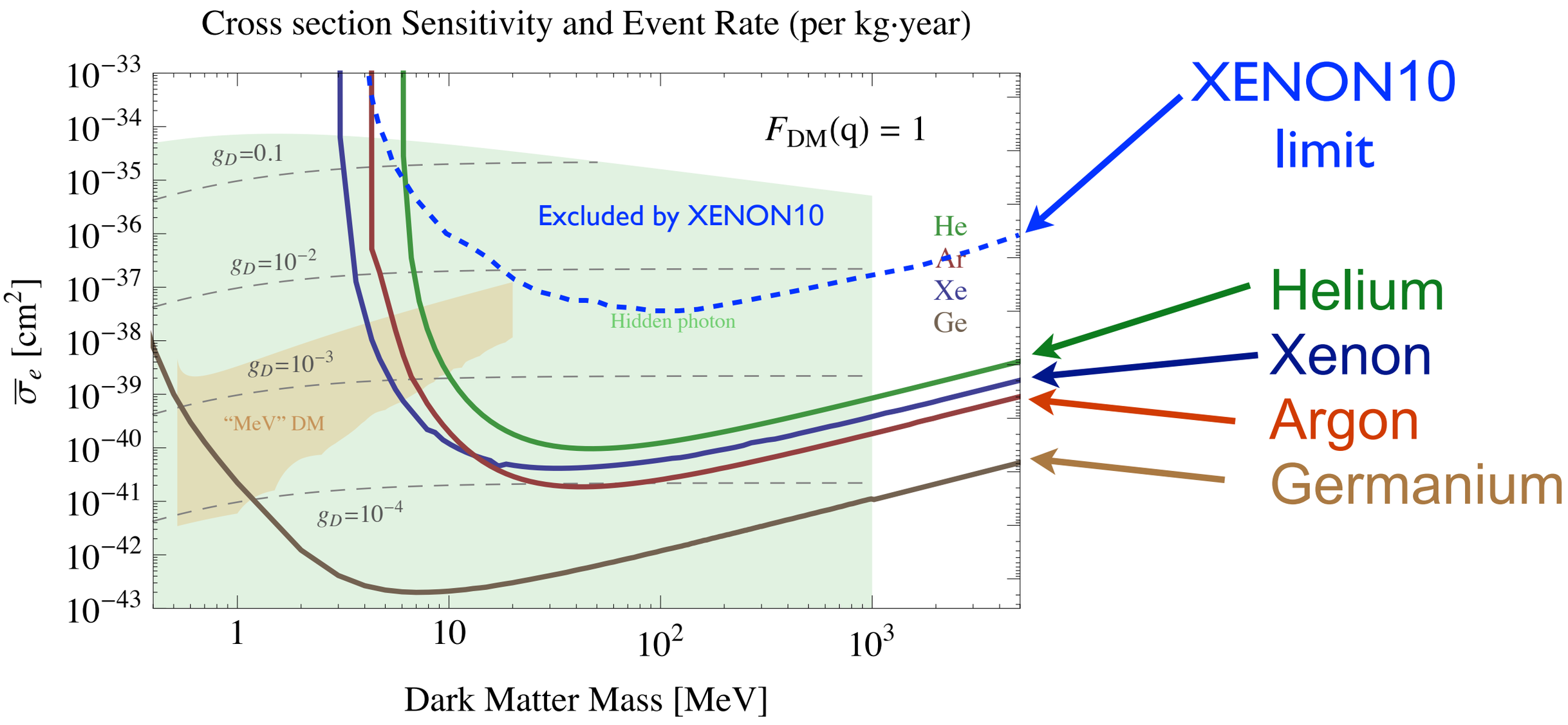
see talk by A. Manalaysay

sub-GeV Dark Matter



MeV-scale!

sub-GeV Dark Matter



already have a limit down to a few MeV!

enormous potential for future experiments

Summary

- Axions and WISPs
  - motivated by strong CP, theory, DM, astro anomalies, …
  - light-shining-through-walls, helioscopes, resonant cavities

- Heavy Photons (> 1 MeV)
  - motivated by theory, muon g-2, DM anomalies, …
  - opportunities at e^+e^- colliders, e^- & p fixed target, LHC, …

- Direct detection of sub-GeV DM
  - beware of WIMP or axion prejudice
  - much more work required to exploit experimental potential