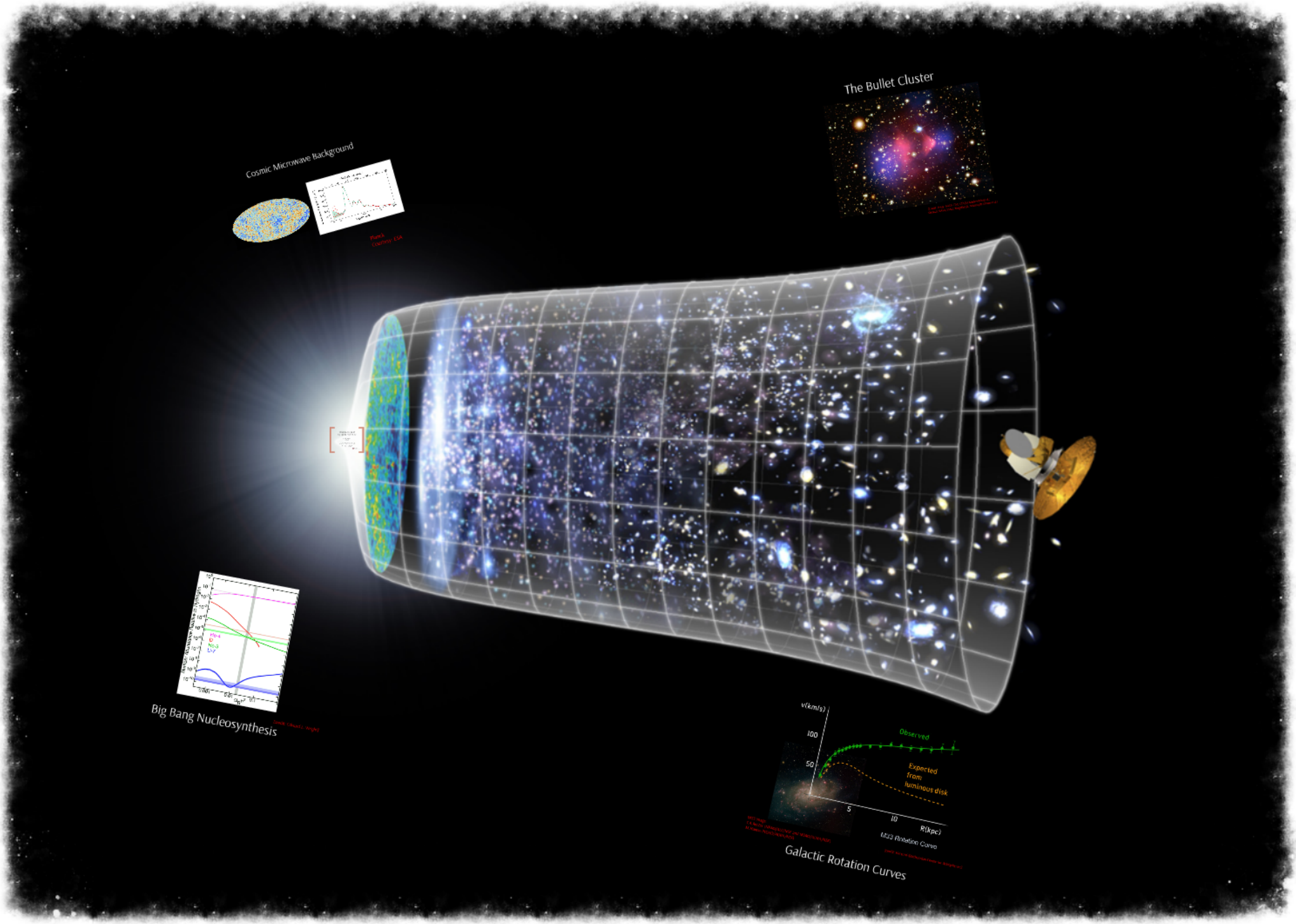
Phenomenology of Leptophilic Dark Matter

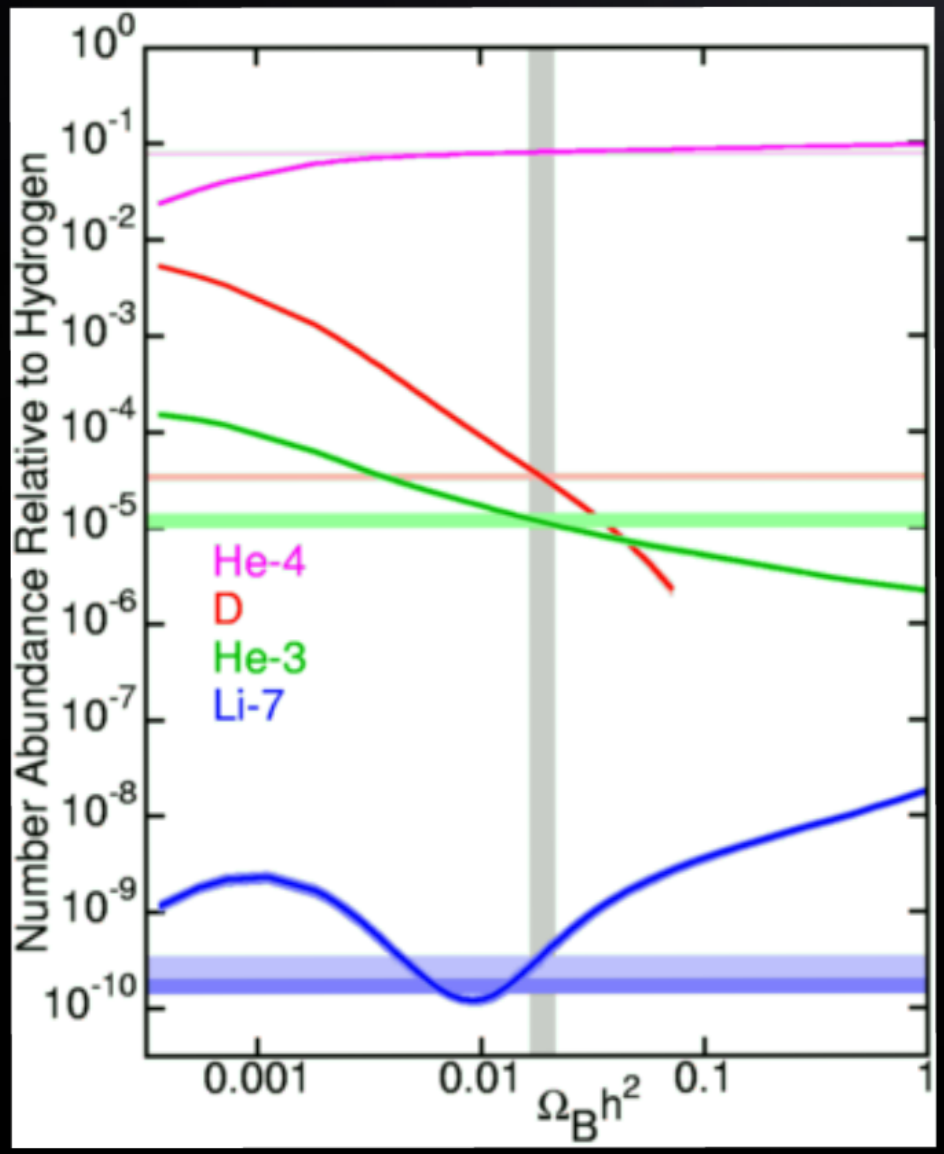
Prateek Agrawal
Fermilab

Santa Fe 2014 Summer Workshop

"LHC After the Higgs"

arXiv:1402.7369
PA, Z. Chacko, C. Verhaaren


Cosmic Microwave Background
Planck
Courtesy ESA
The Bullet Cluster
Big Bang Nucleosynthesis
Observed
Expected from luminous disk
v(km/s)
100
50
5
10
R(kpc)
M33 Rotation Curve
Galactic Rotation Curves



[credit: Edward L. Wright]

Big Bang Nucleosynthesis

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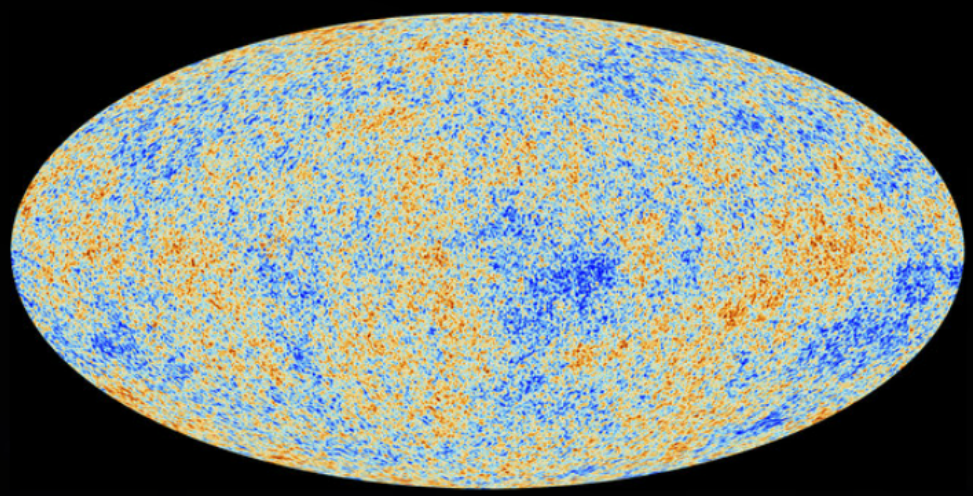

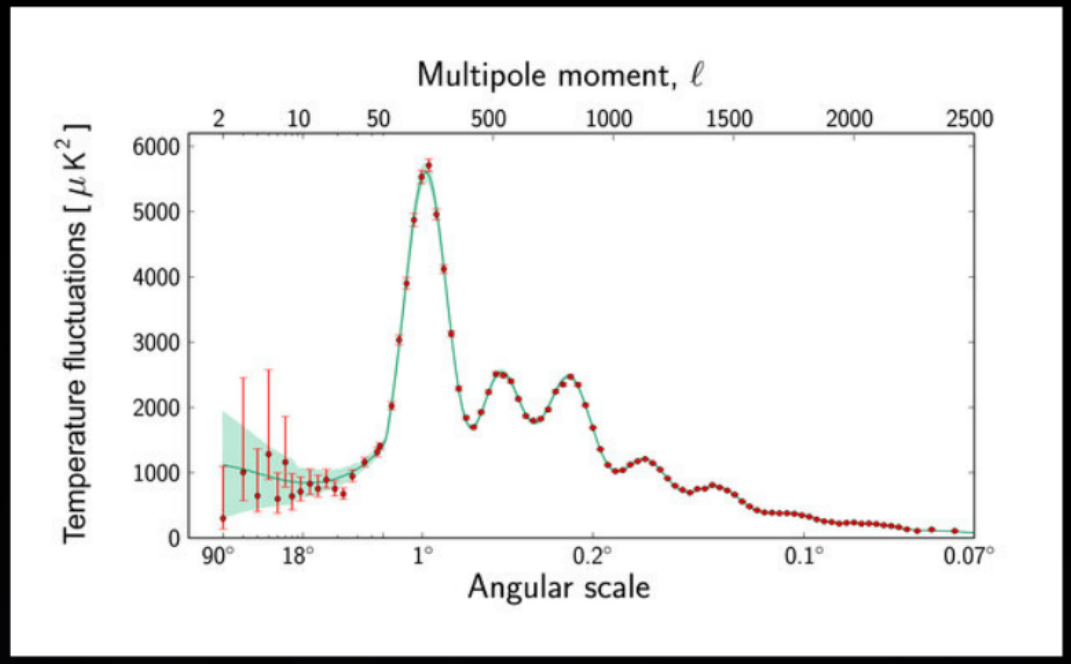

Planck
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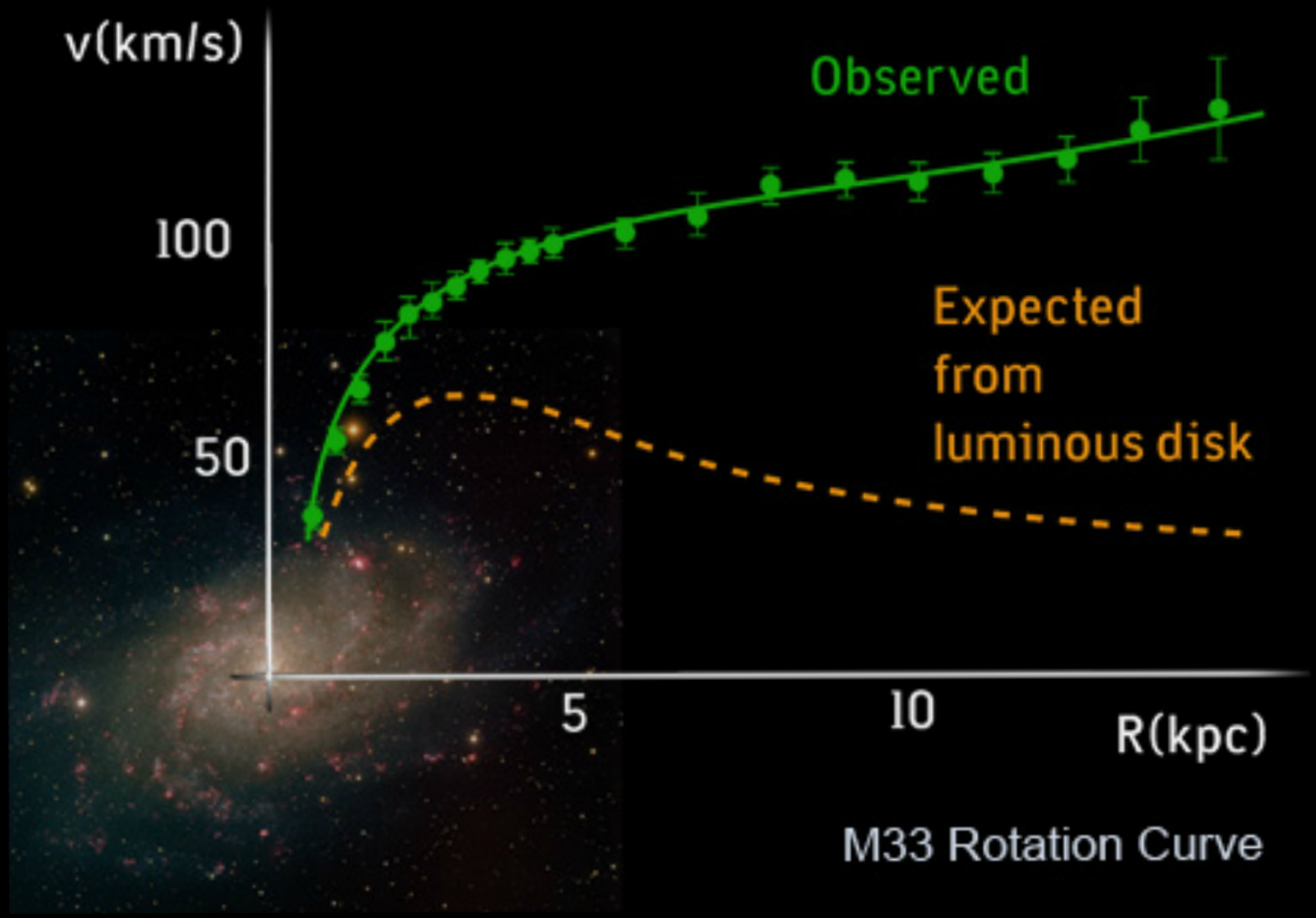


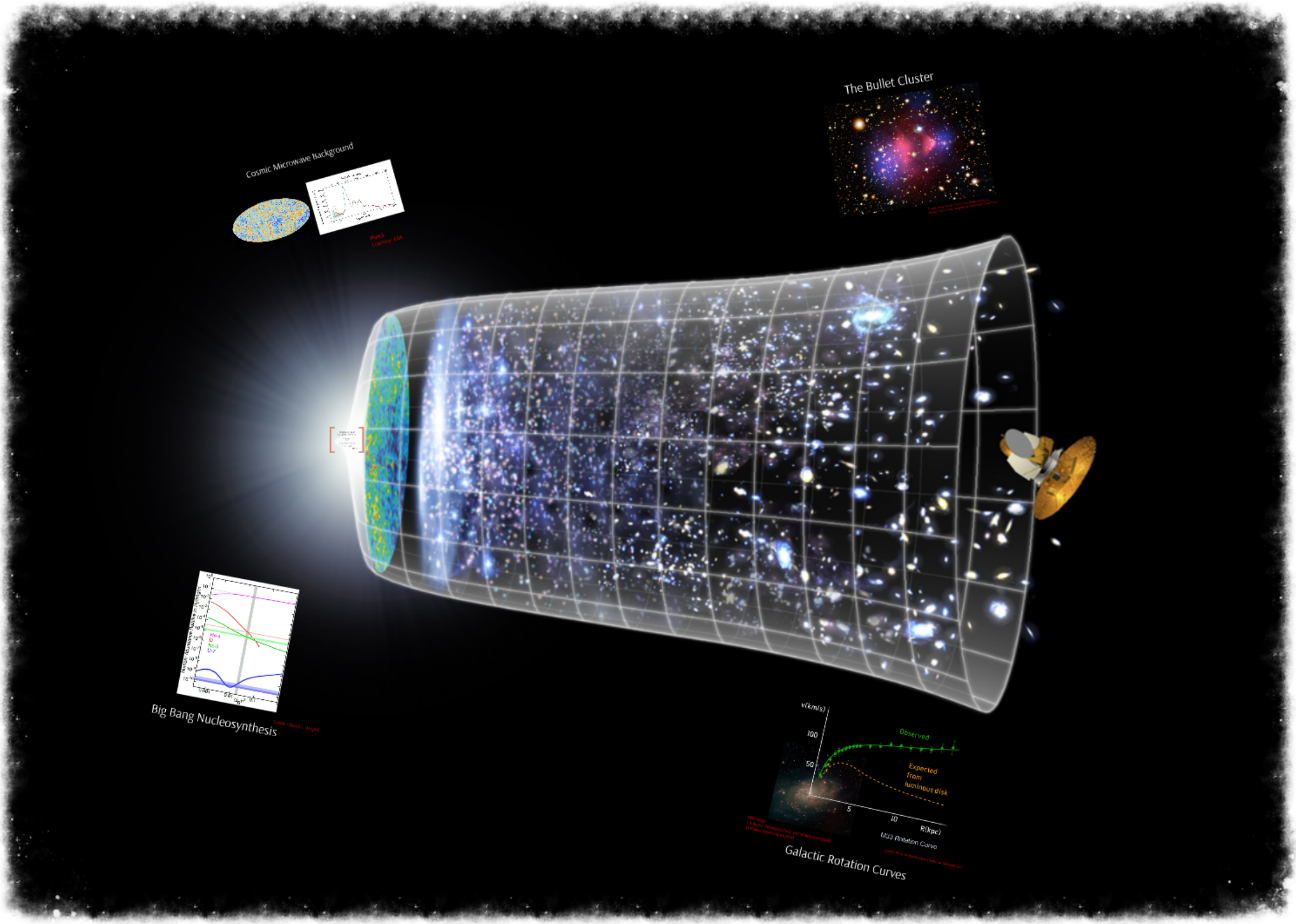
M33 image:
T.A.Rector (NRAO/AUI/NSF and NOAO/AURA/NSF)
M.Hanna (NOAO/AURA/NSF)

[credit: Harvard-Smithsonian Center for Astrophysics]

Galactic Rotation Curves

The Bullet Cluster

[Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.]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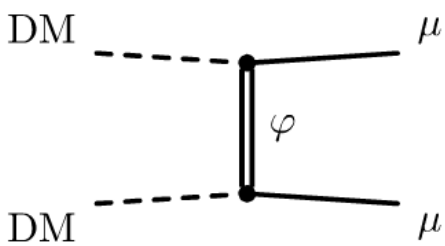
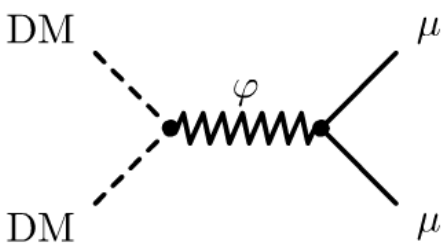
Leptophilic dark matter

Tree-level interactions with SM leptons



Charged mediators

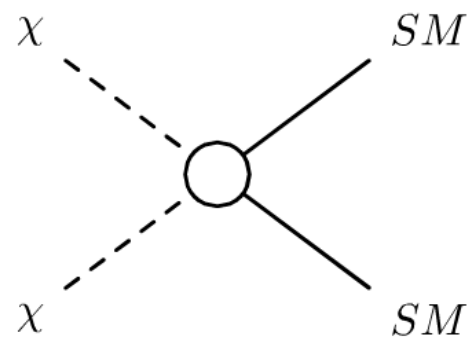


Neutral mediators

Interactions with quarks at one-loop level

Why Leptophilic?

Tension between the WIMP miracle and direct detection signatures



$$\sim \frac{\lambda^2}{m_\phi^2}$$

$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{1}{2}\frac{(1.4)^4(100\ \mathrm{GeV})^2}{32\pi(500\ \mathrm{GeV})^4} \sim 3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$\sigma^{(n)} \sim \frac{\lambda^4 m_n^2}{64\pi m_\phi^4} \sim \frac{(1.4)^4(1\ \mathrm{GeV})^2}{64\pi(500\ \mathrm{GeV})^4} \sim 10^{-40}\ \mathrm{cm}^2$$

LUX limits on WIMP-nucleon cross section ~ zb [$10^{-45}\mathrm{cm}^2$]

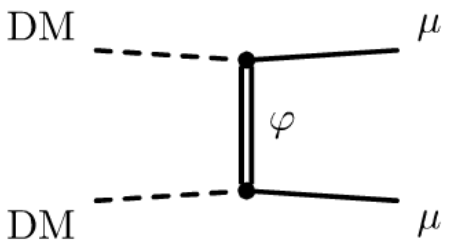
Leptophilic dark matter is loop suppressed for direct detection

Promising for upcoming direct detection experiments

Which Leptophilic?

Charged Mediators

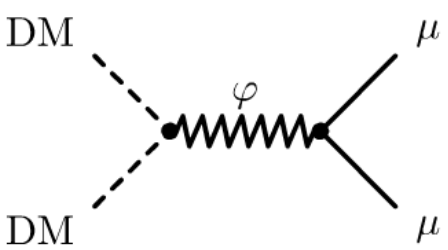
Couplings to left-handed leptons require additional structure



We assume charged mediator couplings to right-handed leptons only

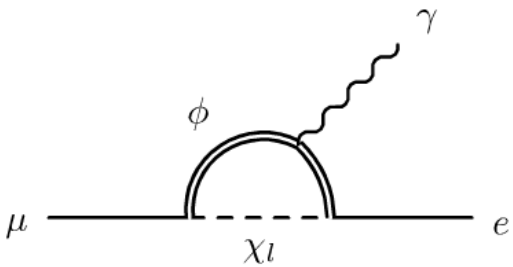
Neutral Mediators

Do not necessitate additional particles charged under $SU(2)_W$



Which Leptophilic?

Flavor constraints restrict the couplings of charged mediators



Two broad possibilities

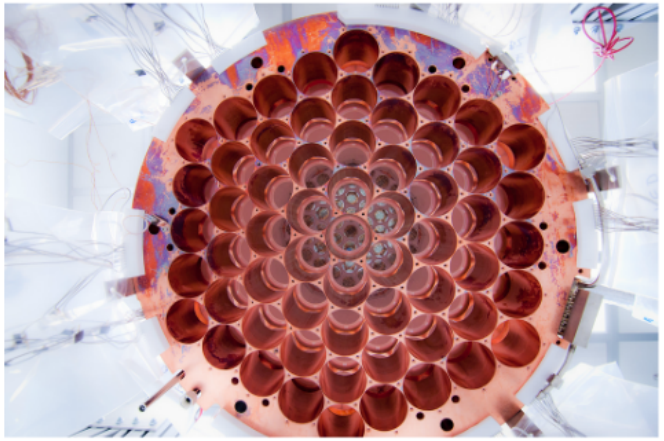
Flavored mediator - sleptons

Flavored dark matter - sneutrino, KK neutrino

Couplings of neutral mediators can have more general flavor structure (e.g. gauged $U(1)_{\mu-\tau}$)

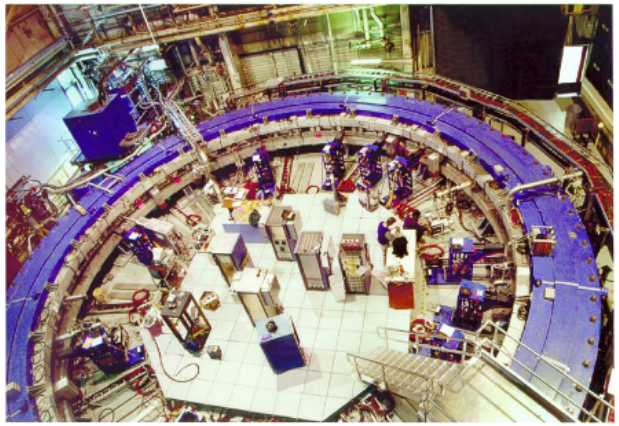
We assume flavor universal couplings

Direct



Detection

g-2



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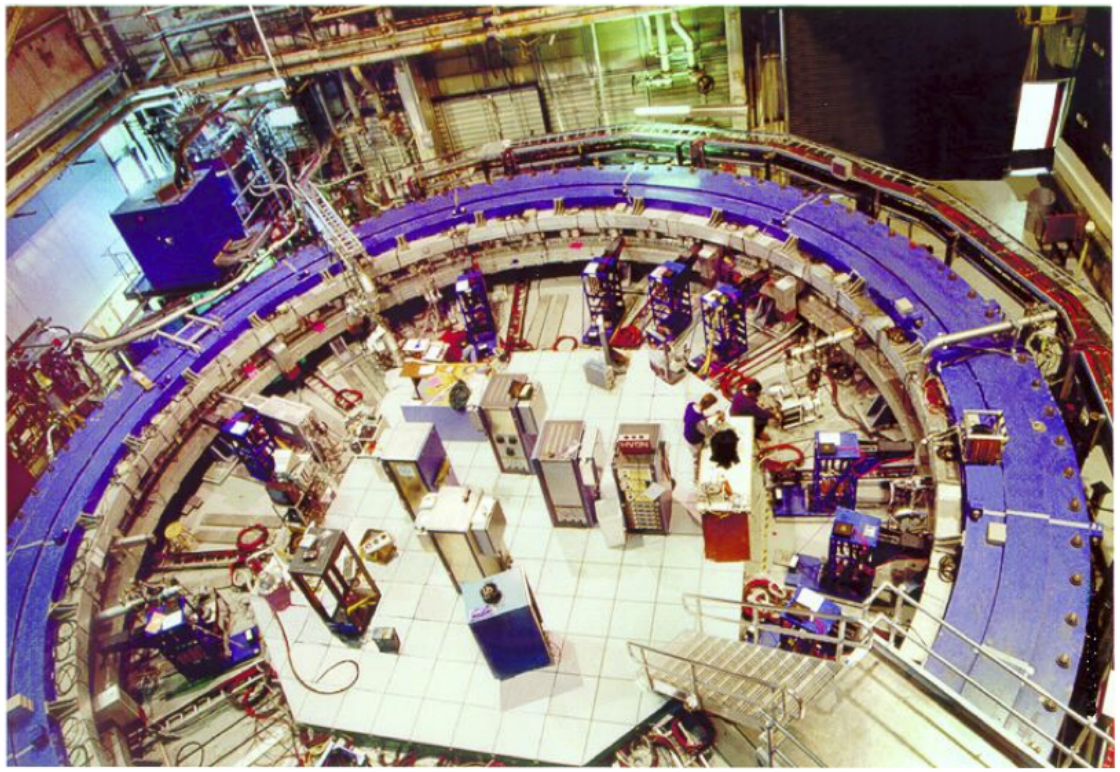

g - 2

$$a_\mu = \frac{g-2}{2}$$

experimental

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = 28.7(6.3)(4.9) \times 10^{-10}$$

theoretical

$$\delta a_\mu \equiv 8.0 \times 10^{-10}$$

Hadronic uncertainty

g - 2

Finite effect, cannot capture by an effective field theory

$$\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu}$$

Chiral symmetry breaking effect

$$\delta_\mu \simeq \left[\frac{m_\mu^2}{\Lambda^2}\right]\frac{\delta m_\mu}{m_\mu} \qquad \frac{\delta m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} \longrightarrow \delta m_\mu \bar{\mu}\mu$$

[Czarnecki, Marciano 2001]

Electron g-2 is a less sensitive probe of new physics

$$\frac{\delta_e/\delta_e}{\delta_\mu/\delta_\mu} \sim \frac{\delta_\mu}{\delta_e} \times \frac{m_e^2}{m_\mu^2} \sim 0.02$$

g - 2

$$\mathcal{L}_{\rm scalar} = \bar{\mu}\left(a + b\gamma^5\right) FS + {\rm h.c.} \qquad r \equiv m_{\rm DM}/m_{\rm Med} \qquad z = m_\mu/m_{\rm Med}$$

Charged scalar mediator

$$\delta_\mu^{S,r} = -\frac{z}{16\pi^2}\left\{\frac{z(|a|^2+|b|^2)}{2(1-r^2)^2}\left[1-6r^2+3r^4+2r^6-6r^4\ln(r^2)\right] + \frac{r(|a|^2-|b|^2)}{(1-r^2)^2}\left[-r^4+2r^2\ln(r^2)\right]\right\} + \mathcal{O}(z^3),$$

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g - 2

Neutral vector mediator

$$\mathcal{L}_{\rm vector} = \bar{\mu}\gamma^\nu\left(a + b\gamma^5\right)\mu V_\nu + {\rm h.c.} \qquad z = m_\mu/m_{\rm Med}$$

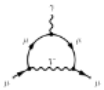
$$\delta_\mu^V = \frac{z^2}{4\pi^2}\left[-\frac{2}{3}(|a|^2+|b|^2) + (|a|^2-|b|^2)\right] + \mathcal{O}(z^3)$$

Independent of dark matter couplings

For $m_V \ll 100$ MeV

$$(g-2)_\mu \to const.$$

$(g-2)_e$ constraints start being relevant



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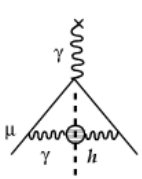
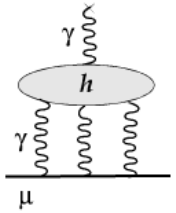
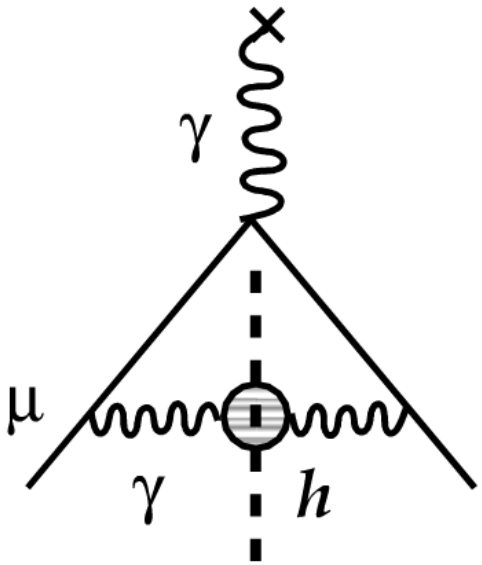
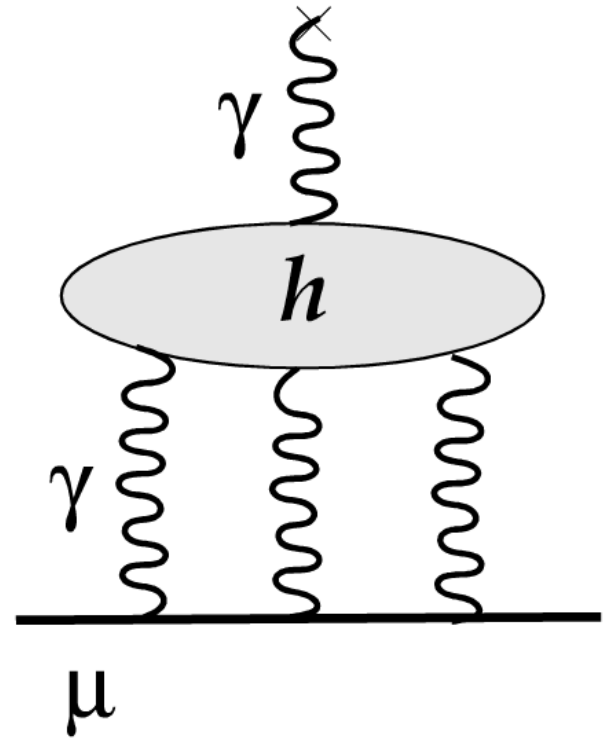




Hadronic uncertainty





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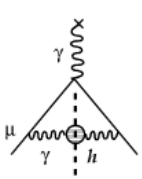

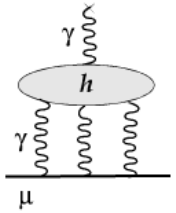

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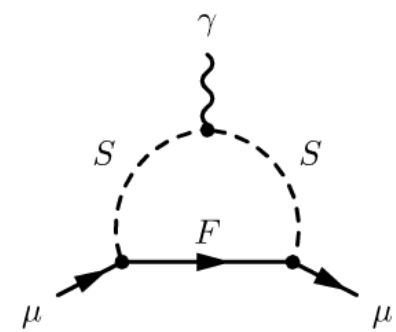

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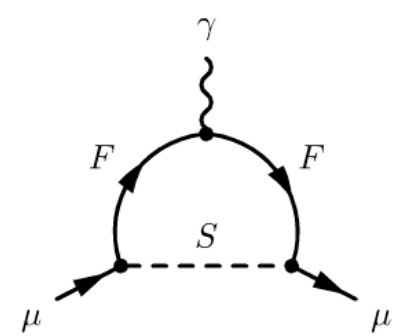

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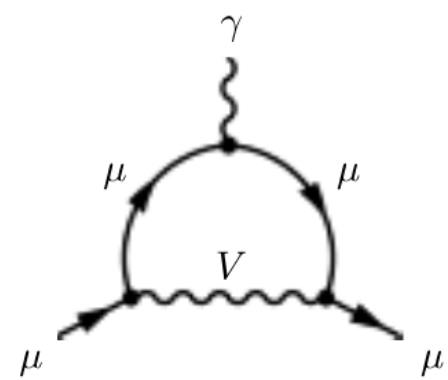


Colliders

Collider constraints

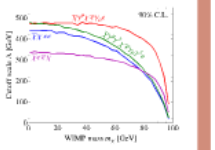
Monophoton

$e^+e^- \to \chi\chi\gamma$

Model independent EFT approach

Not suitable for light neutral mediators

Limits exist for fermionic dark matter



(Fox, Harnik, Kopp, Tsai 2011)

Need simplified models for LHC bounds

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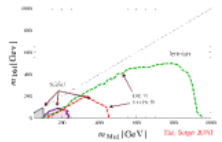
Two leptons + MET

LEP direct production

LHC limits on right-handed sleptons



Fermionic mediators have much larger production cross section

Collider constraints

Neutral mediator

Compositeness bounds

$$\mathcal{L} = \frac{1\pi}{(1+\delta)\Lambda^2}\left[\eta_{LL}\bar{e}_L\gamma^\mu e_L\bar{f}_L\gamma_\mu f_L + \eta_{RR}\bar{e}_R\gamma^\mu e_R\bar{f}_R\gamma_\mu f_R + \eta_{LR}\bar{e}_L\gamma^\mu e_L\bar{f}_R\gamma_\mu f_R + \eta_{RL}\bar{e}_R\gamma^\mu e_R\bar{f}_L\gamma_\mu f_L\right]$$

Only valid for $m_{Med} > 208$ GeV

Bound	Operators				Limit
	η_{LL}	η_{RR}	η_{LR}	η_{RL}	Λ (TeV)
VV	-1	-1	-1	-1	20.0
AA	-1	-1	1	1	18.1
LR+RL	0	0	-1	-1	14.5

Collider constraints

Light Neutral mediator

Resonant production at LEP

- Exclusions in the context of specific models
- Excludes coupling strengths of O(0.01)

BaBar

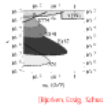
$e^+e^- \to e\gamma$

$e \to \mu^+\mu^-$

(BaBar 2014)

Beam dumps

Supernovae cooling



(Bjorken, Essig, Schuster, Toro 2009)

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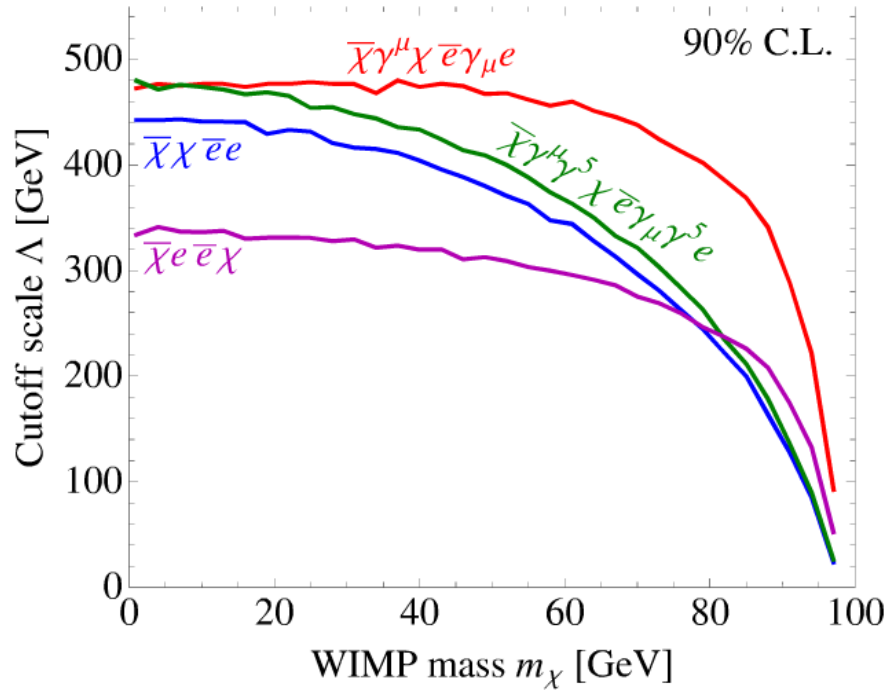

[Fox, Harnik, Kopp, Tsai 2011]

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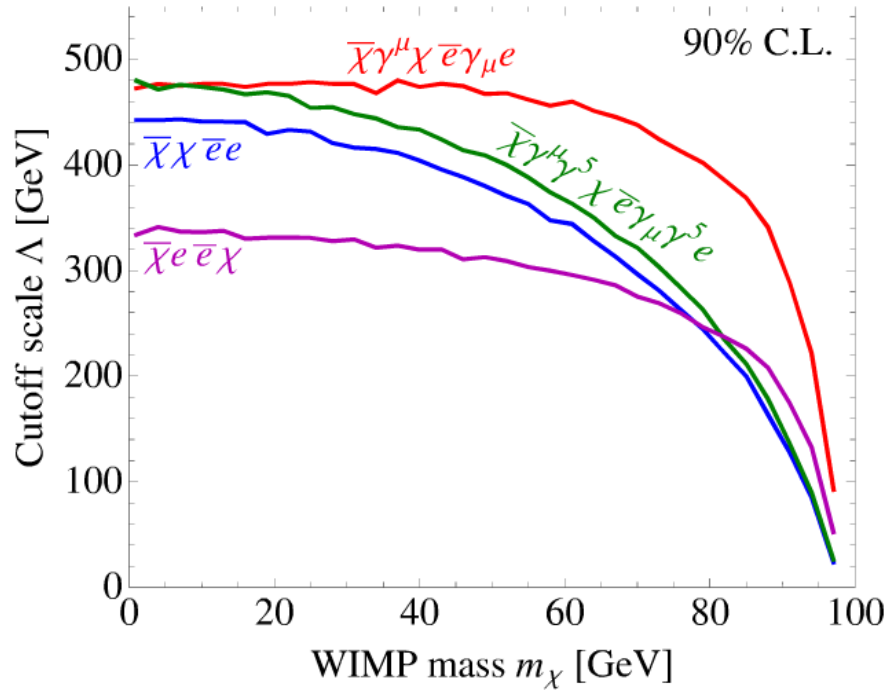

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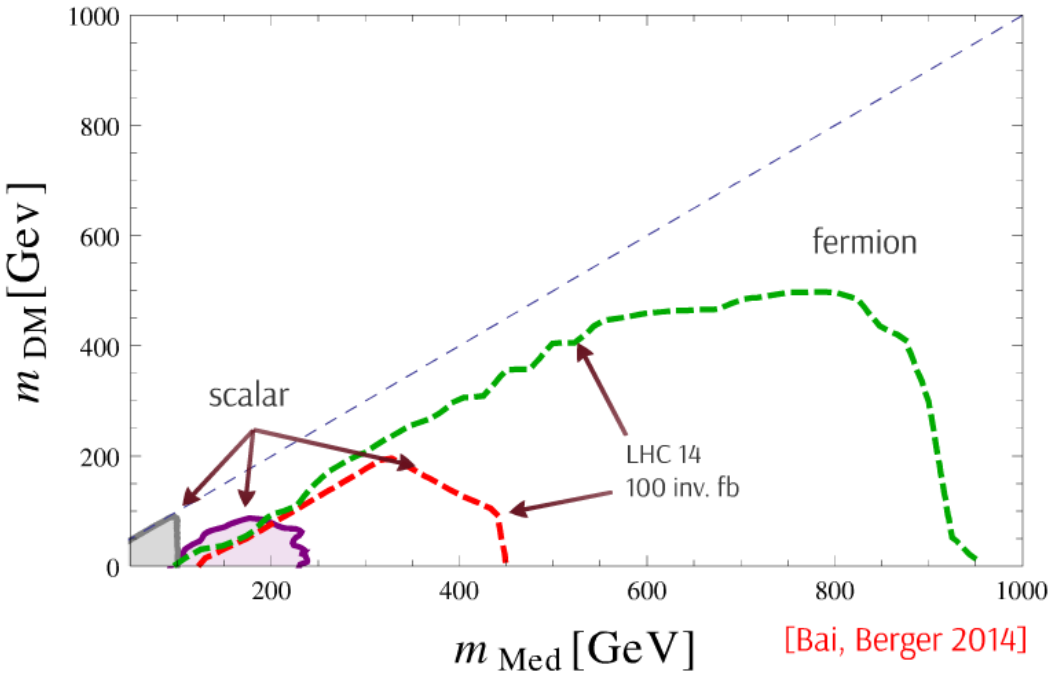
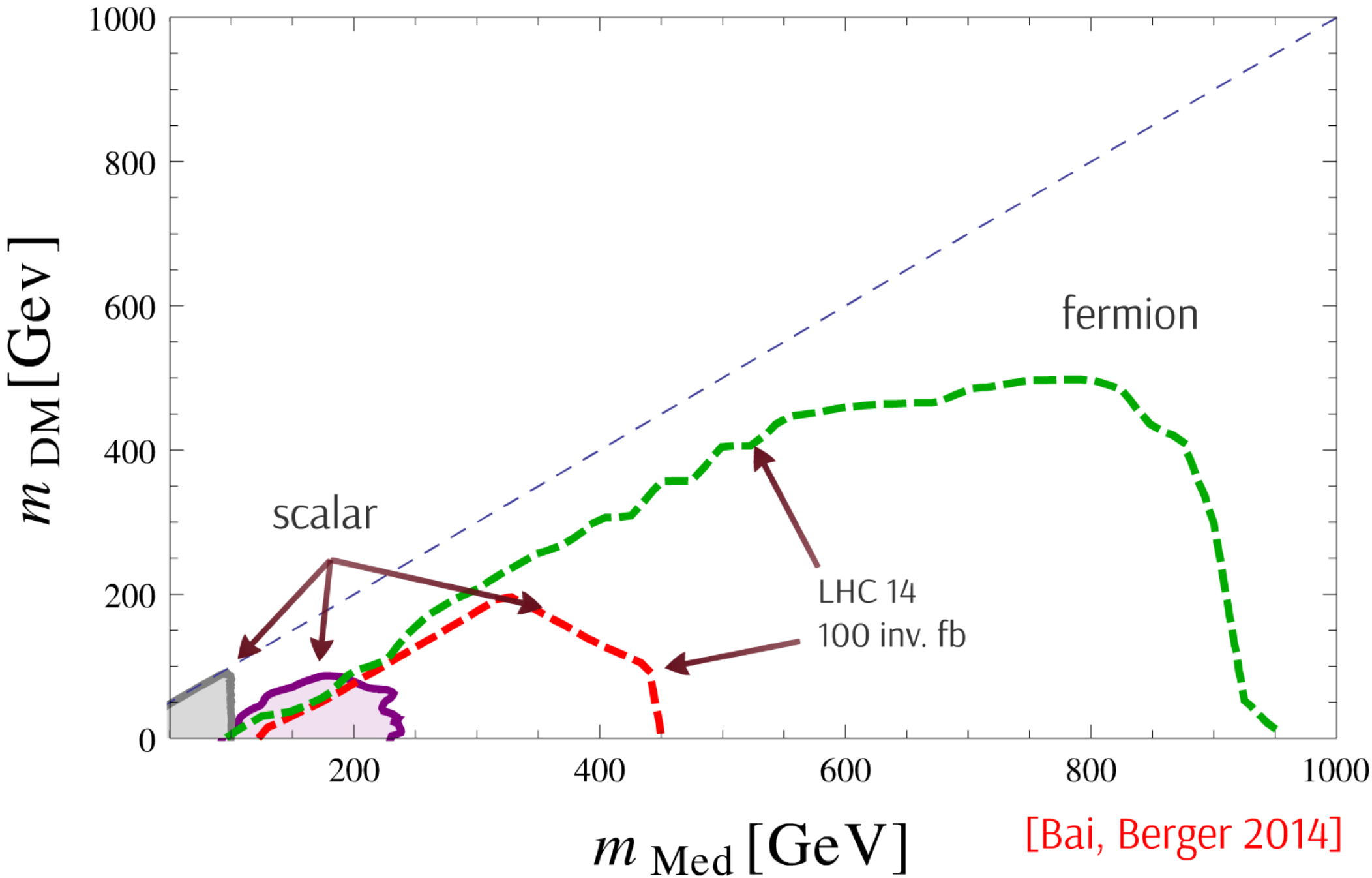


[Bai, Berger 2014]

Fermionic mediators have much larger production cross section



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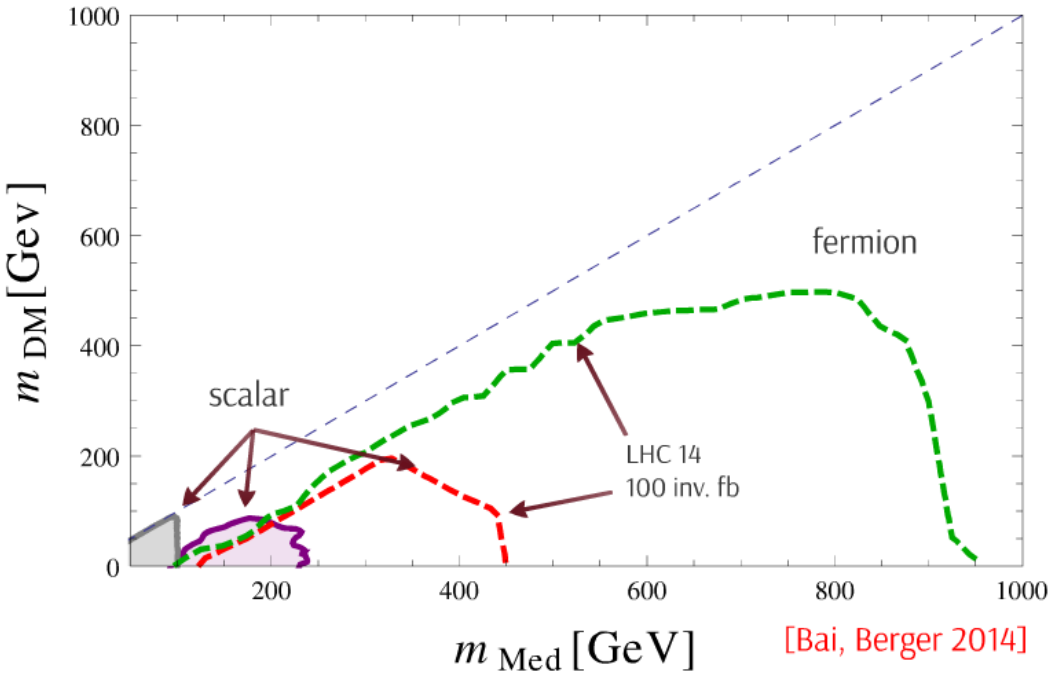

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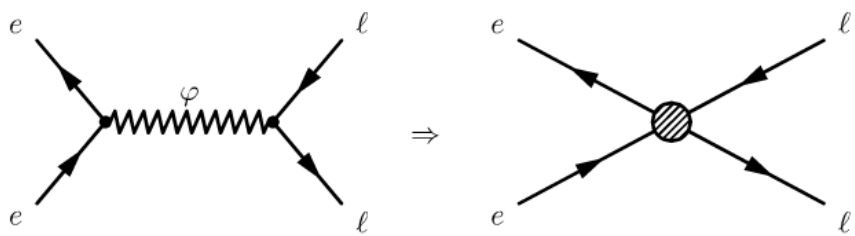

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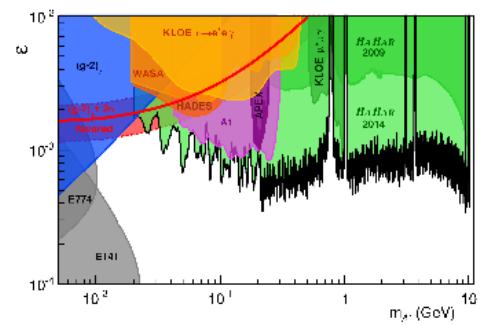
BaBar

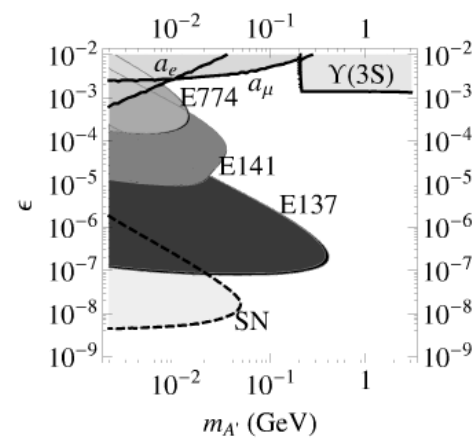
$$e^+e^- \to \phi\gamma$$
$$\phi \to \mu^+\mu^-$$



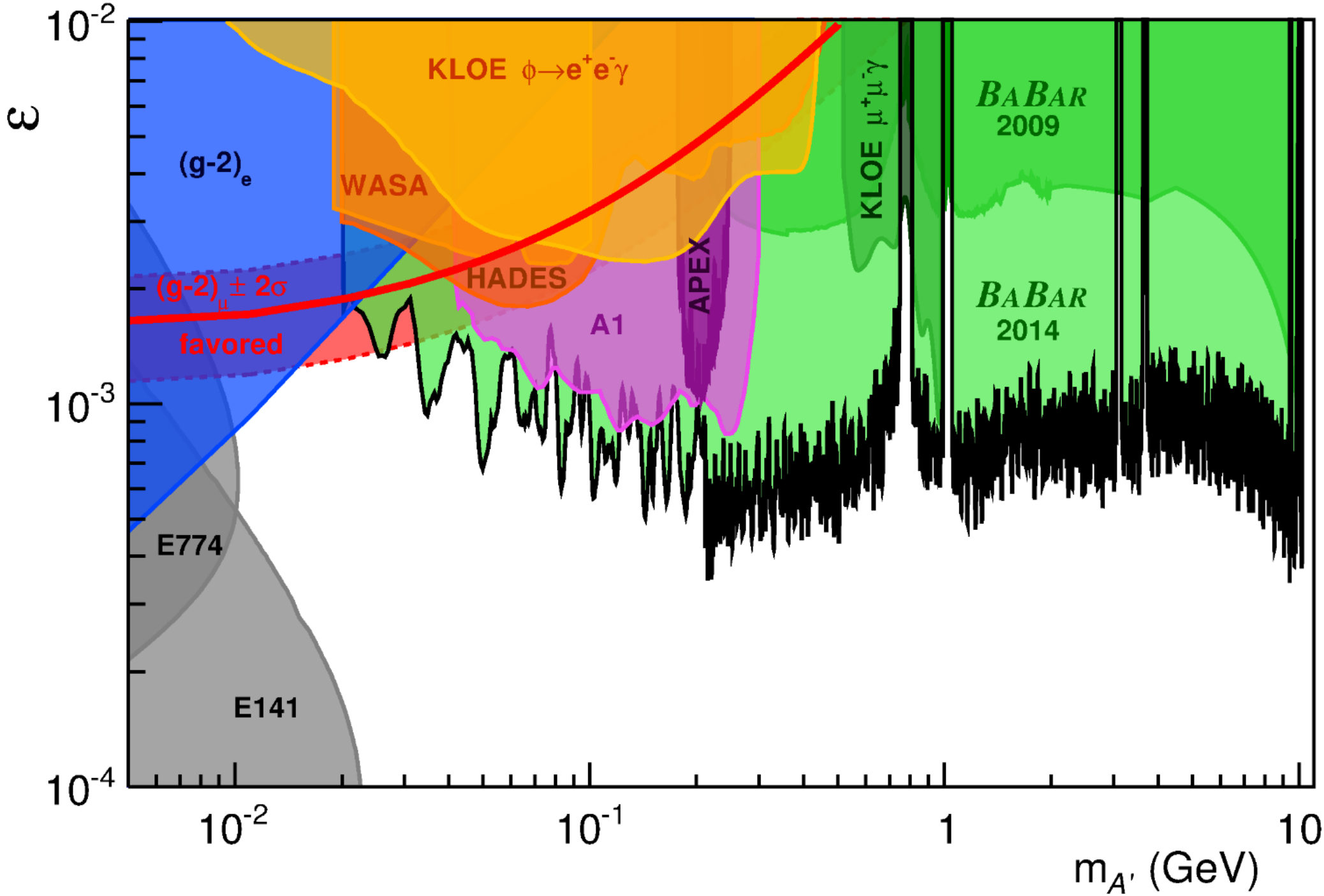
[BaBar 2014]

Beam dumps

Supernovae cooling



[Bjorken, Essig, Schuster, Toro 2009]


ε
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
10
$m_{A'}$ (GeV)
KLOE $\phi \to e^+e^-\gamma$
$(g-2)_e$
WASA
$(g-2)_\mu \pm 2\sigma$
favored
HADES
A1
APEX
KLOE $\mu^+\mu^-\gamma$
BABAR 2009
BABAR 2014
E774
E141

Collider constraints

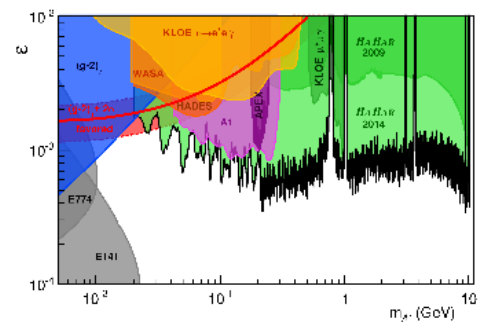
Light Neutral mediator

Resonant production at LEP

- Exclusions in the context of specific models
- Excludes coupling strengths of O(0.01)

BaBar

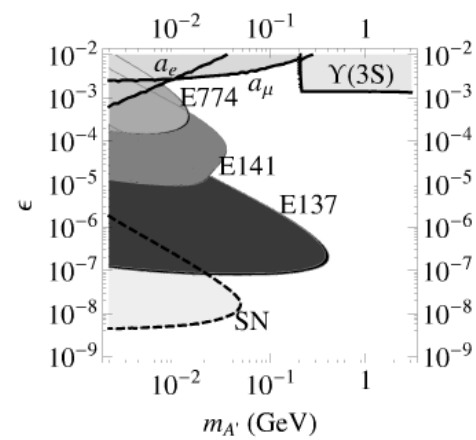
$$e^+e^- \to \phi\gamma$$
$$\phi \to \mu^+\mu^-$$



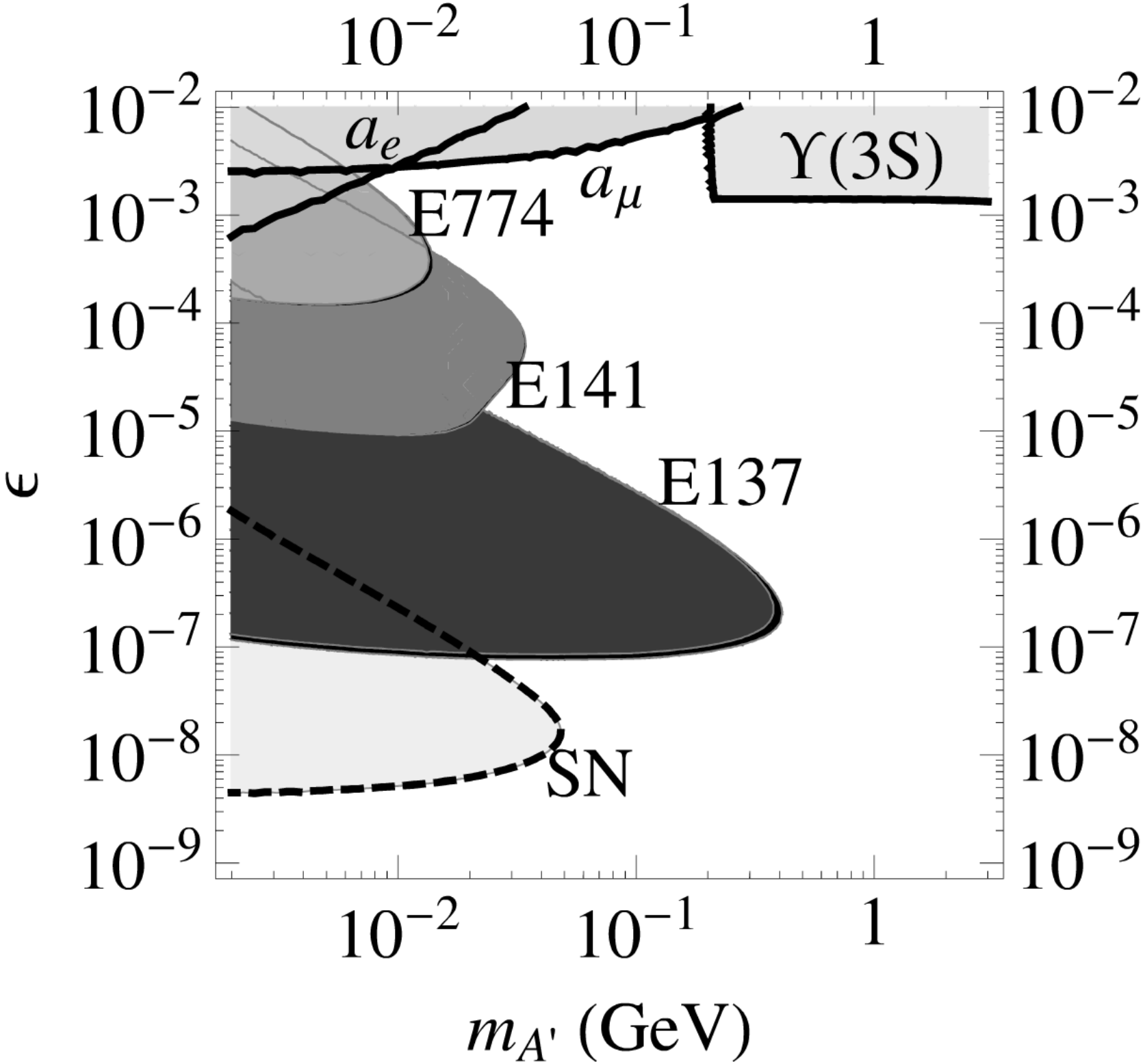
[BaBar 2014]

Beam dumps

Supernovae cooling



[Bjorken, Essig, Schuster, Toro 2009]


10^{-2}
10^{-1}
1
a_e
a_μ
$\Upsilon(3S)$
E774
E141
E137
SN
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$m_{A'}$ (GeV)

Collider constraints

Light Neutral mediator

Resonant production at LEP

- Exclusions in the context of specific models
- Excludes coupling strengths of O(0.01)

BaBar

$$e^+e^- \to \phi\gamma$$
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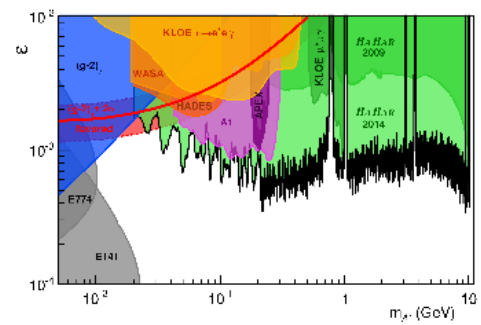
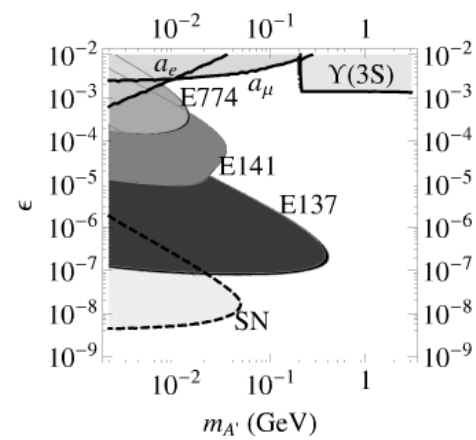


[BaBar 2014]

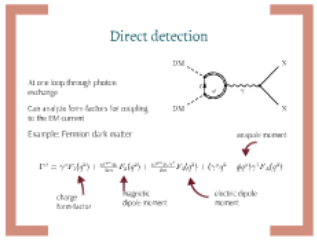
Beam dumps

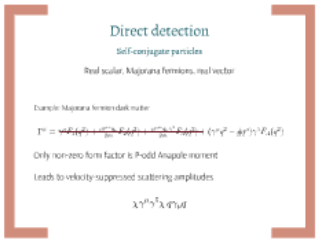
Supernovae cooling

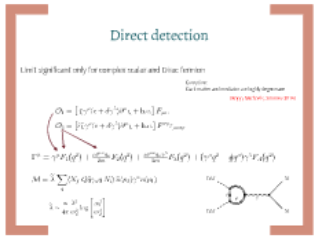


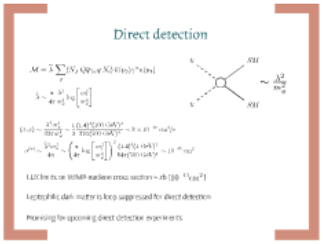
[Bjorken, Essig, Schuster, Toro 2009]

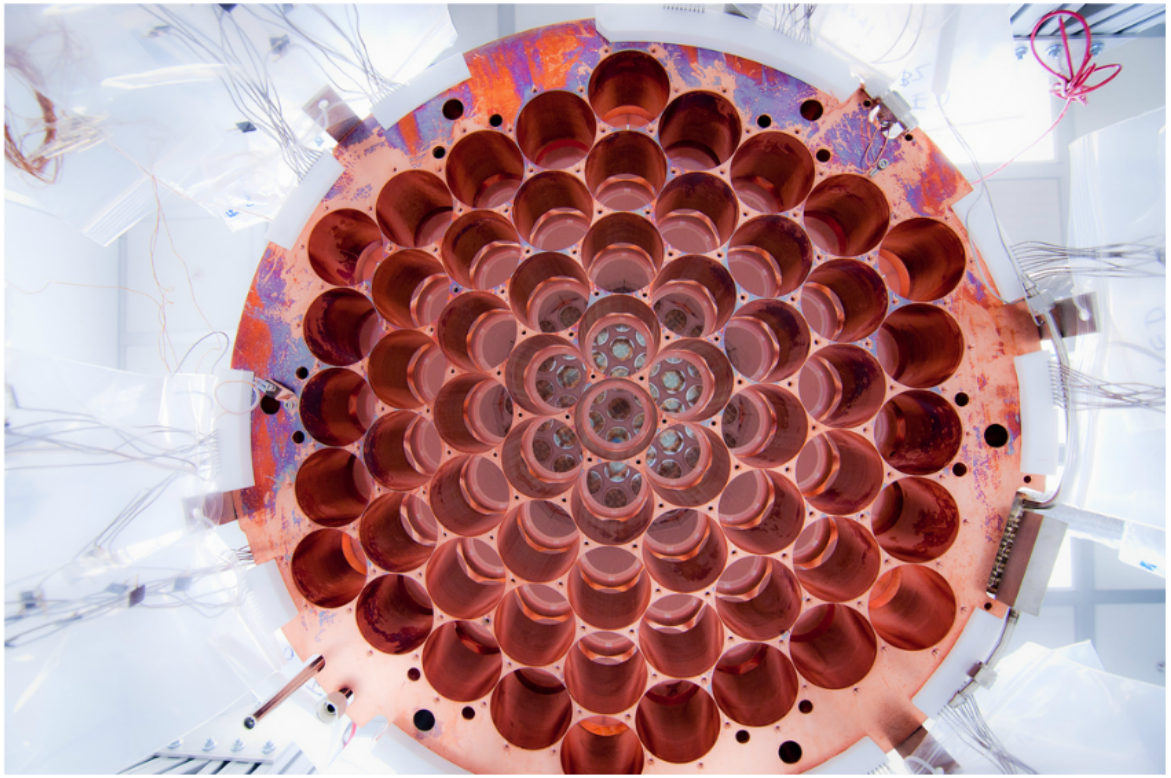
Direct





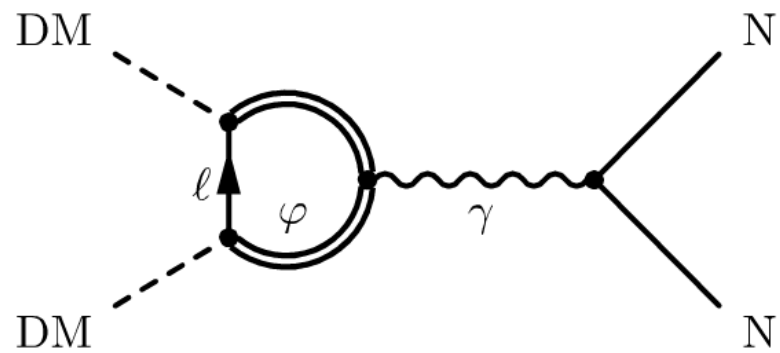






Detection

Direct detection



At one loop through photon exchange

Can analyze form-factors for coupling to the EM current

Example: Fermion dark matter

anapole moment

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu\gamma^5}{2m}F_3(q^2) + (\gamma^\mu q^2 - \not{q}q^\mu)\gamma^5 F_A(q^2)$$

charge form-factor

magnetic dipole moment

electric dipole moment

Direct detection

Self-conjugate particles

Real scalar, Majorana fermions, real vector

Example: Majorana fermion dark matter

$$\Gamma^\mu = \cancel{\gamma^\mu F_1(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu\gamma^5}{2m}F_3(q^2) +} (\gamma^\mu q^2 - \not{q}q^\mu)\gamma^5 F_A(q^2)$$

Only non-zero form factor is P-odd Anapole moment

Leads to velocity-suppressed scattering amplitudes

$$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$$

Direct detection

Limit significant only for complex scalar and Dirac fermion

Exception:
Dark matter and mediator are highly degenerate

[Kopp, Michaels, Smirnov 2014]

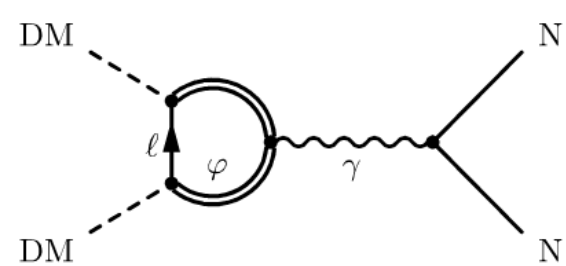
$$\mathcal{O}_1 = \left[\bar{\chi}\gamma^\mu(c + d\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F_{\mu\nu},$$

$$\mathcal{O}_2 = \left[i\bar{\chi}\gamma^\mu(c + d\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F^{\sigma\rho}\varepsilon_{\mu\nu\sigma\rho}$$

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{\imath\sigma^{\mu\nu}q_\nu\gamma^5}{2m}F_3(q^2) + (\gamma^\mu q^2 - \not{q}q^\mu)\gamma^5 F_A(q^2)$$

$$\mathcal{M} = \widetilde{\lambda}\sum_q \langle N_f|Q\bar{q}\gamma_\alpha q|N_i\rangle\,\bar{u}(p_2)\gamma^\alpha u(p_1)$$

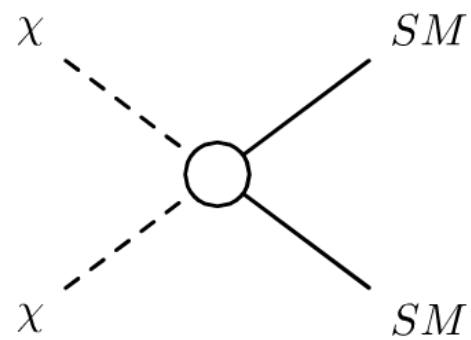
$$\widetilde{\lambda} \sim \frac{\alpha}{4\pi}\frac{\lambda^2}{m_\phi^2}\log\left[\frac{m_l^2}{m_\phi^2}\right]$$



Direct detection

$$\mathcal{M} = \widetilde{\lambda} \sum_q \langle N_f | Q\bar{q}\gamma_\alpha q | N_i \rangle \, \bar{u}(p_2)\gamma^\alpha u(p_1)$$

$$\widetilde{\lambda} \sim \frac{\alpha}{4\pi} \frac{\lambda^2}{m_\phi^2} \log\left[\frac{m_l^2}{m_\phi^2}\right]$$



$$\sim \frac{\lambda^2}{m_\phi^2}$$

$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{1}{2} \frac{(1.4)^4 (100 \text{ GeV})^2}{32\pi (500 \text{ GeV})^4} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

$$\sigma^{(n)} \sim \frac{\widetilde{\lambda}^2 m_n^2}{4\pi} \sim \left(\frac{\alpha}{4\pi} \log\left[\frac{m_l^2}{m_\phi^2}\right]\right)^2 \frac{(1.4)^4 (1 \text{ GeV})^2}{64\pi (500 \text{ GeV})^4} \sim 10^{-45} \text{ cm}^2$$

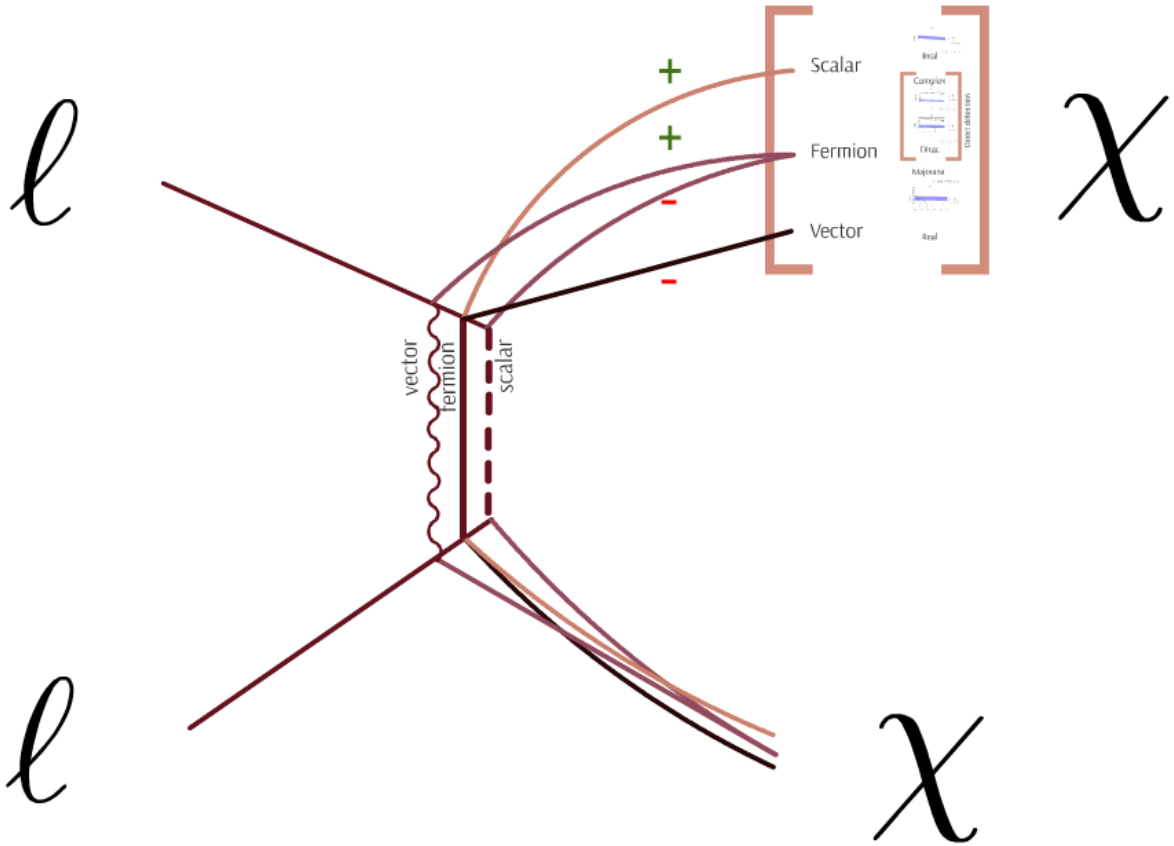
LUX limits on WIMP-nucleon cross section ~ zb [10^{-45}cm^2]

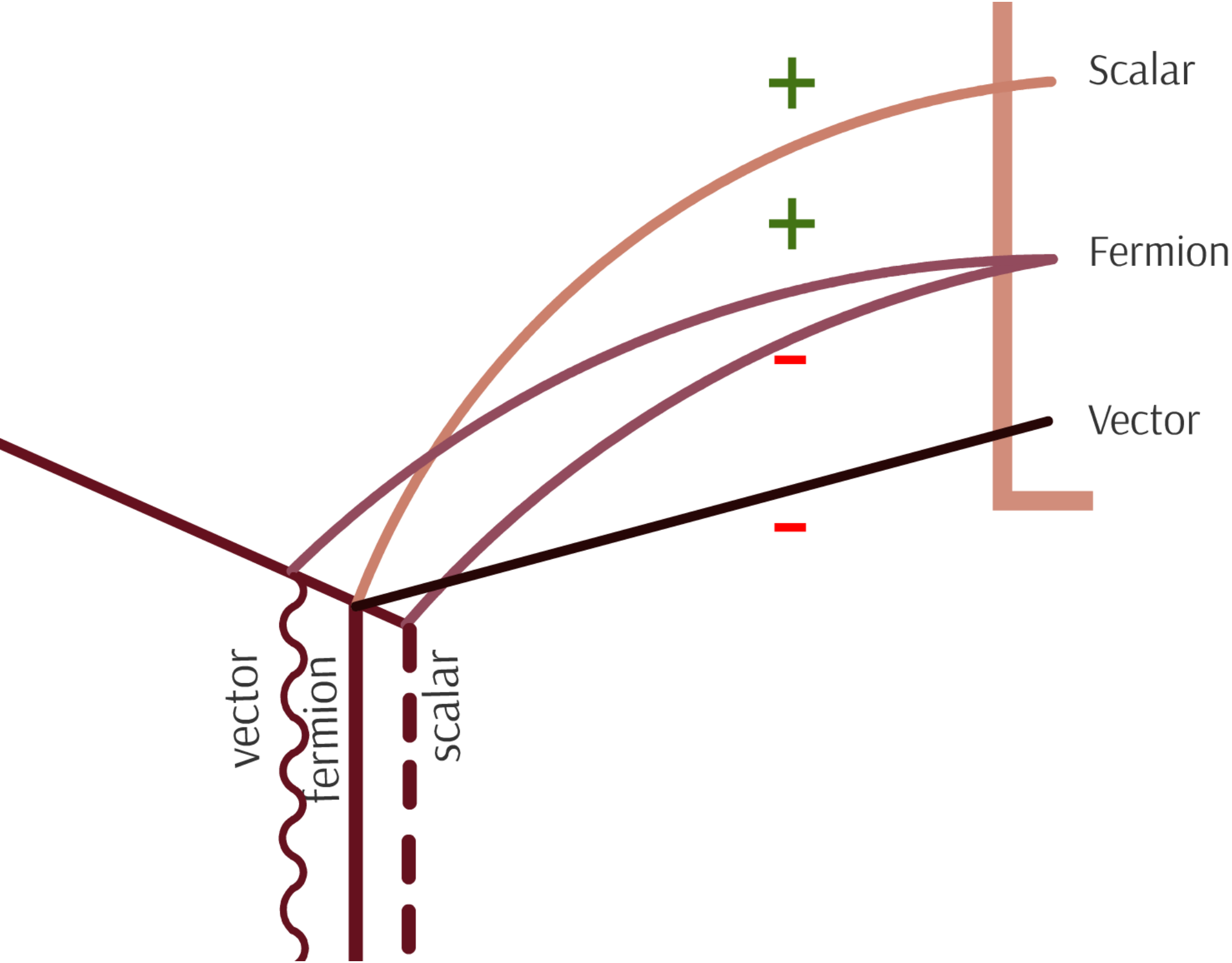
Leptophilic dark matter is loop suppressed for direct detection

Promising for upcoming direct detection experiments

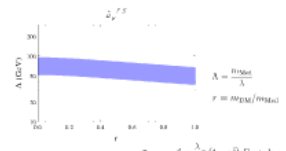
Simplified Models

Charged Mediator



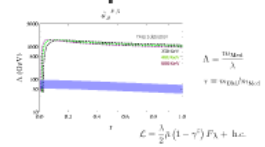

Scalar
+
+
Fermion
-
Vector
-
vector
fermion
scalar

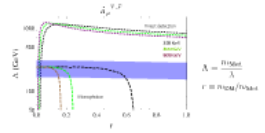
Scalar



Real

Complex



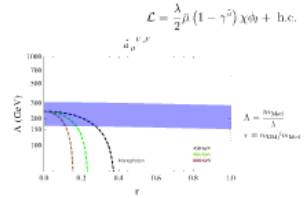


Dirac

Direct detection

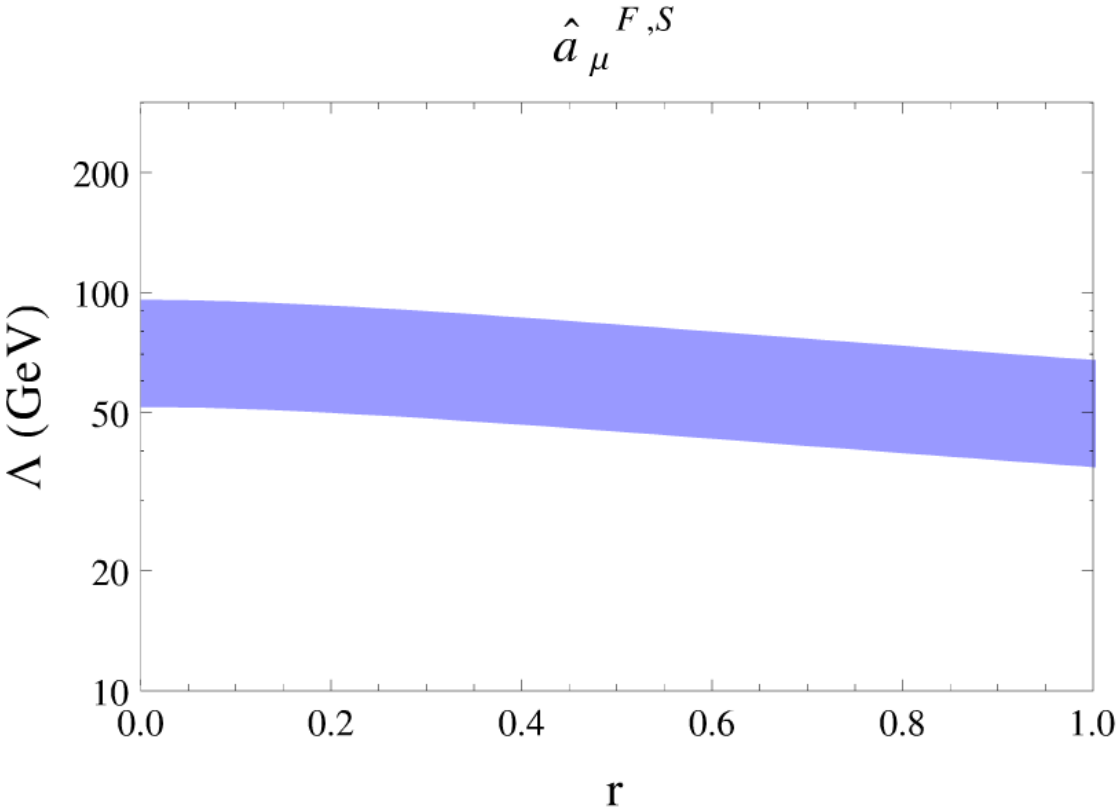
Fermion

Majorana



Vector

Real



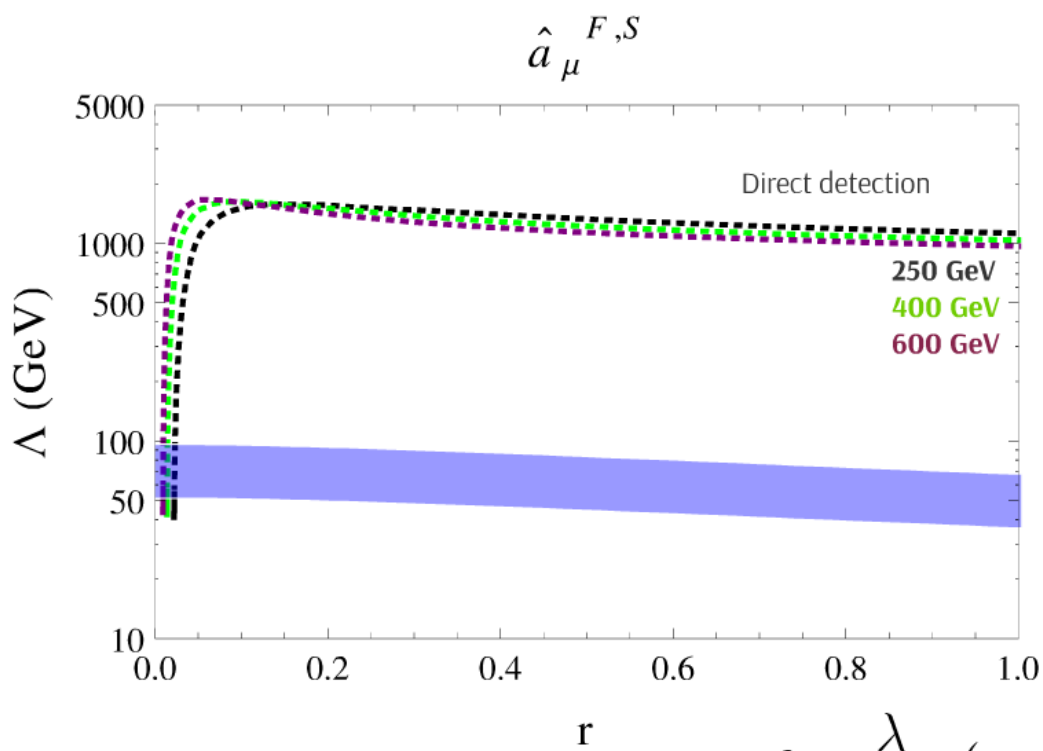
$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

$$r \equiv m_{\rm DM}/m_{\rm Med}$$

$$\mathcal{L} = \frac{\lambda}{2}\bar{\mu}\left(1-\gamma^5\right)F\chi + \text{ h.c.}$$

Real

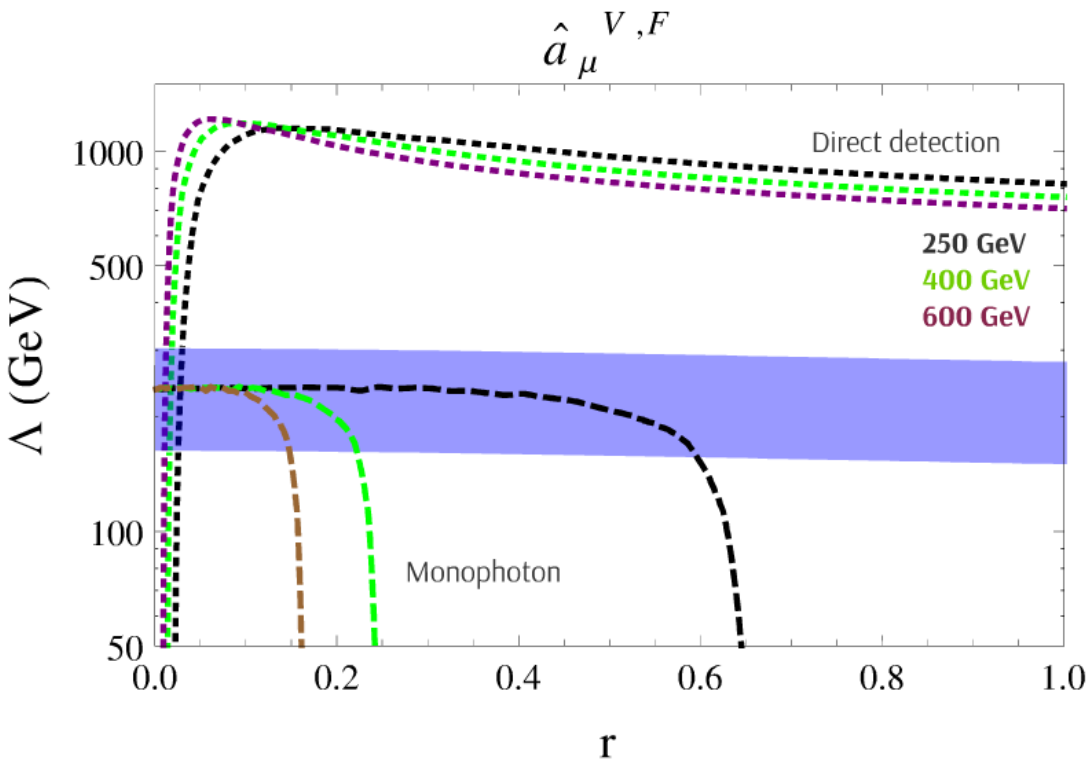
Complex



$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

$$r \equiv m_{\rm DM}/m_{\rm Med}$$

$$\mathcal{L} = \frac{\lambda}{2}\bar{\mu}\left(1-\gamma^5\right)F\chi + \text{ h.c.}$$



$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

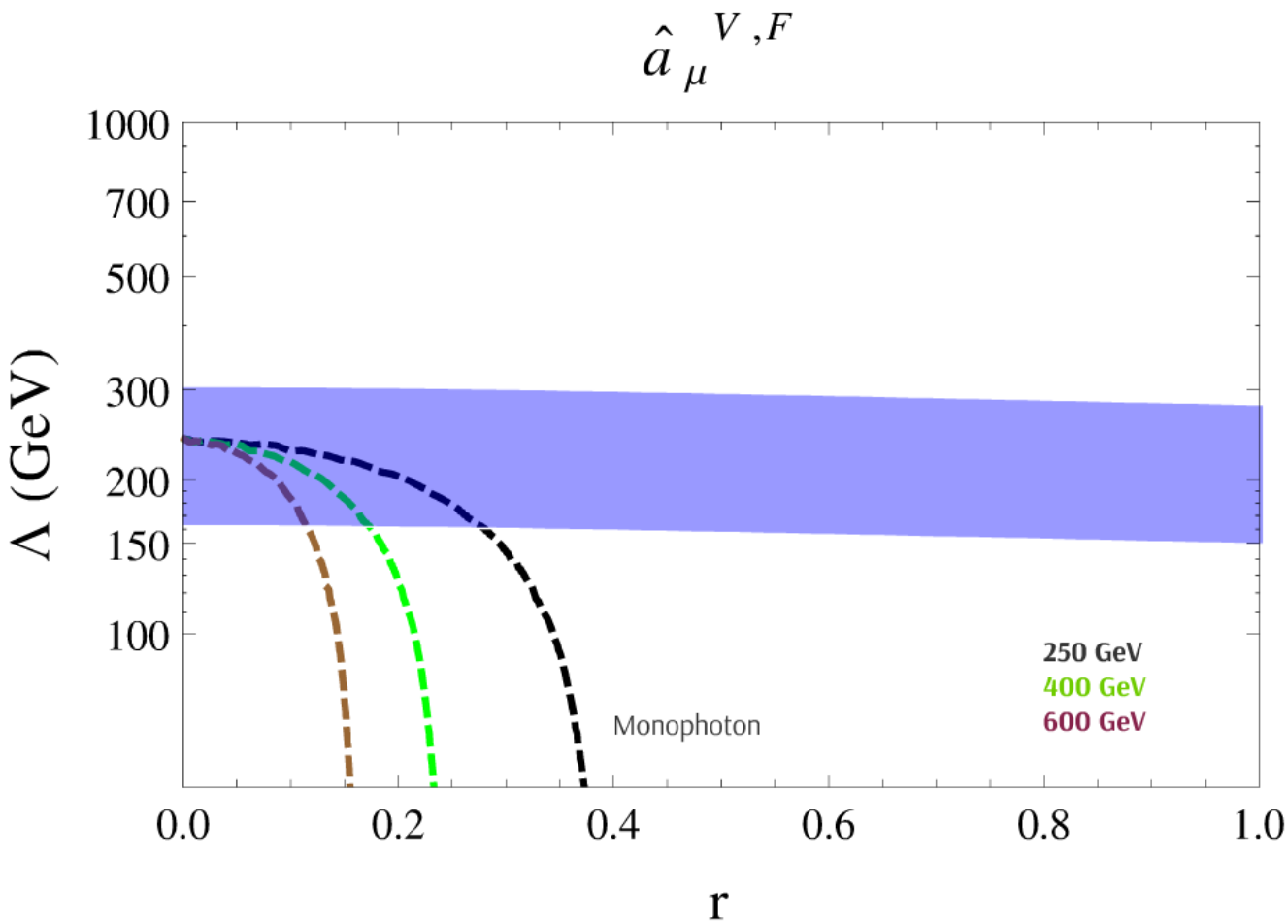
$$r \equiv m_{\rm DM}/m_{\rm Med}$$

$$\mathcal{L} = \frac{\lambda}{2}\bar{\mu}\left(1-\gamma^5\right)\chi\phi_l + \text{ h.c.}$$

Dirac

Majorana

$$\mathcal{L} = \frac{\lambda}{2}\bar{\mu}\left(1-\gamma^5\right)\chi\phi_l + \text{ h.c.}$$

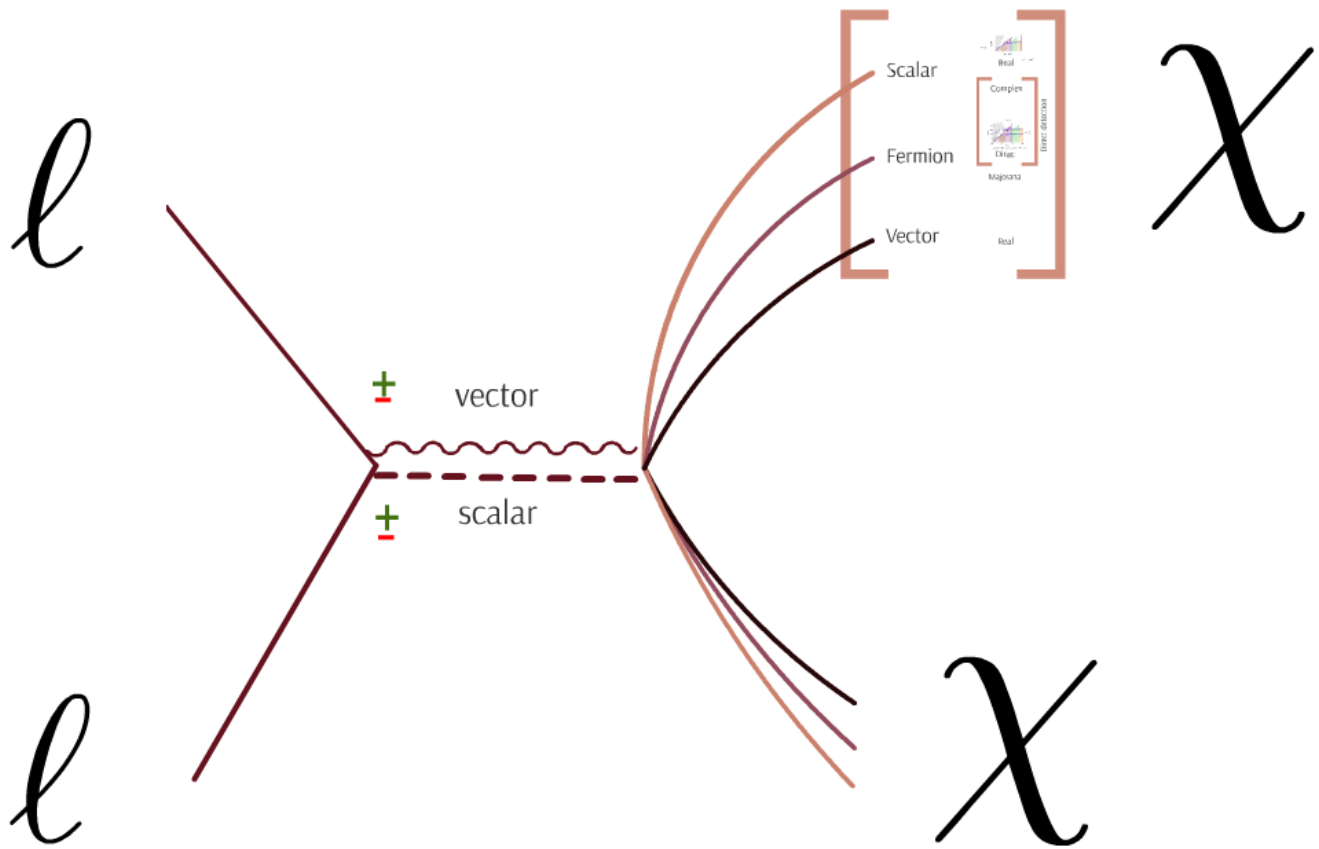


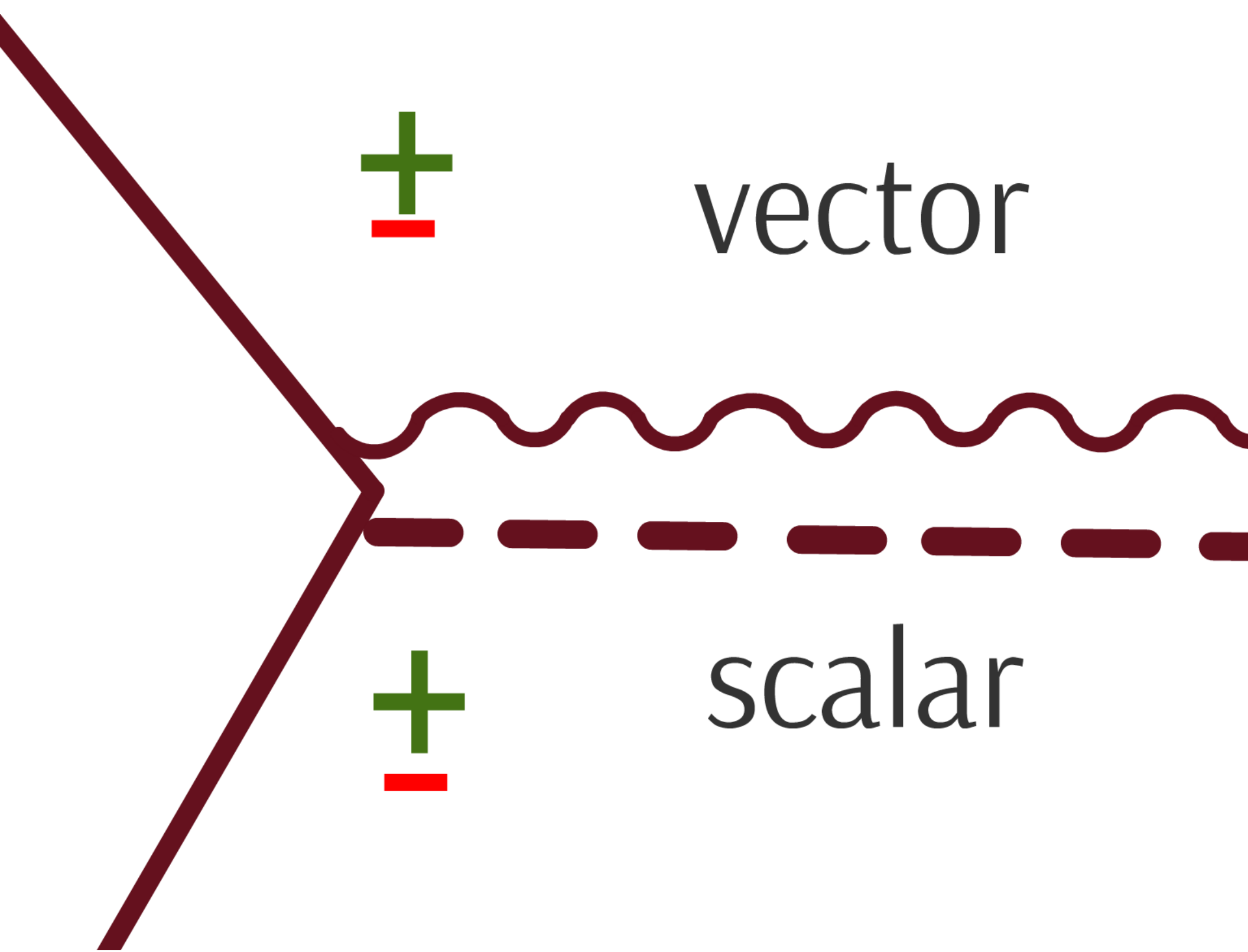
$$\Lambda = \frac{m_{\text{Med}}}{\lambda}$$

$$r \equiv m_{\text{DM}}/m_{\text{Med}}$$

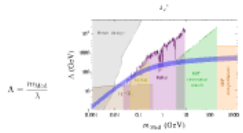
Simplified Models

Neutral Mediator




±
vector
±
scalar

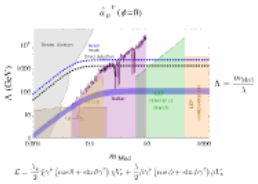
Scalar



Real

$\mathcal{L}_S = \lambda \bar{\psi} \psi S$

Complex



Dirac

Direct detection

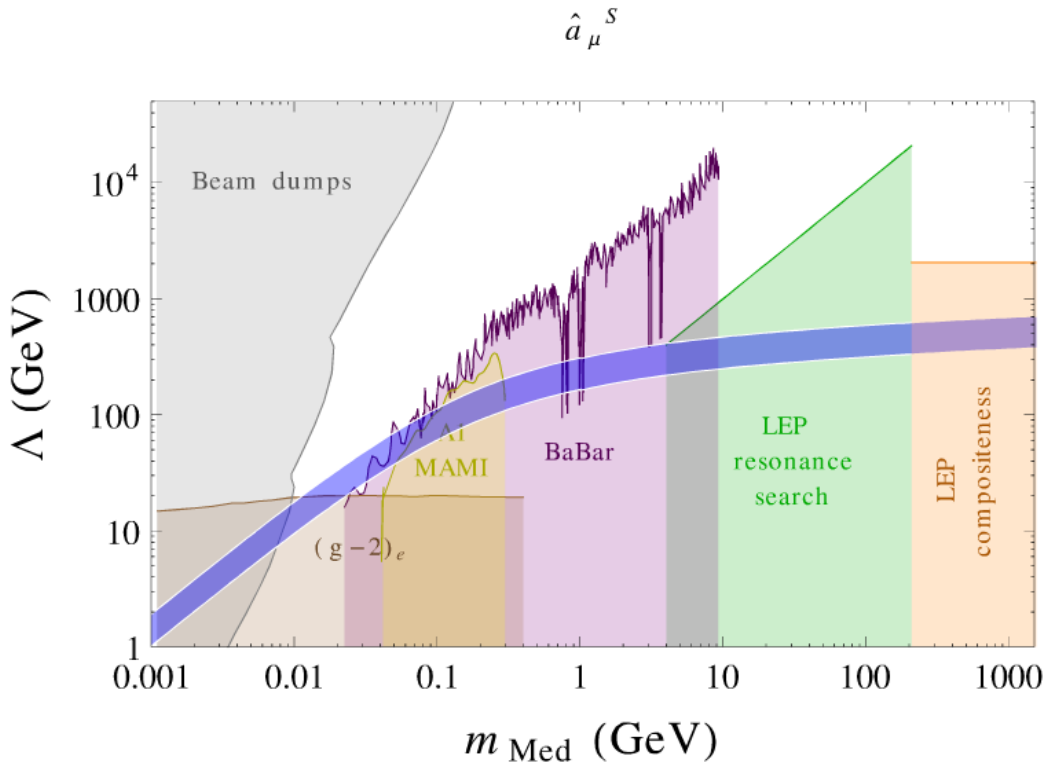
Fermion

Majorana

Vector

Real

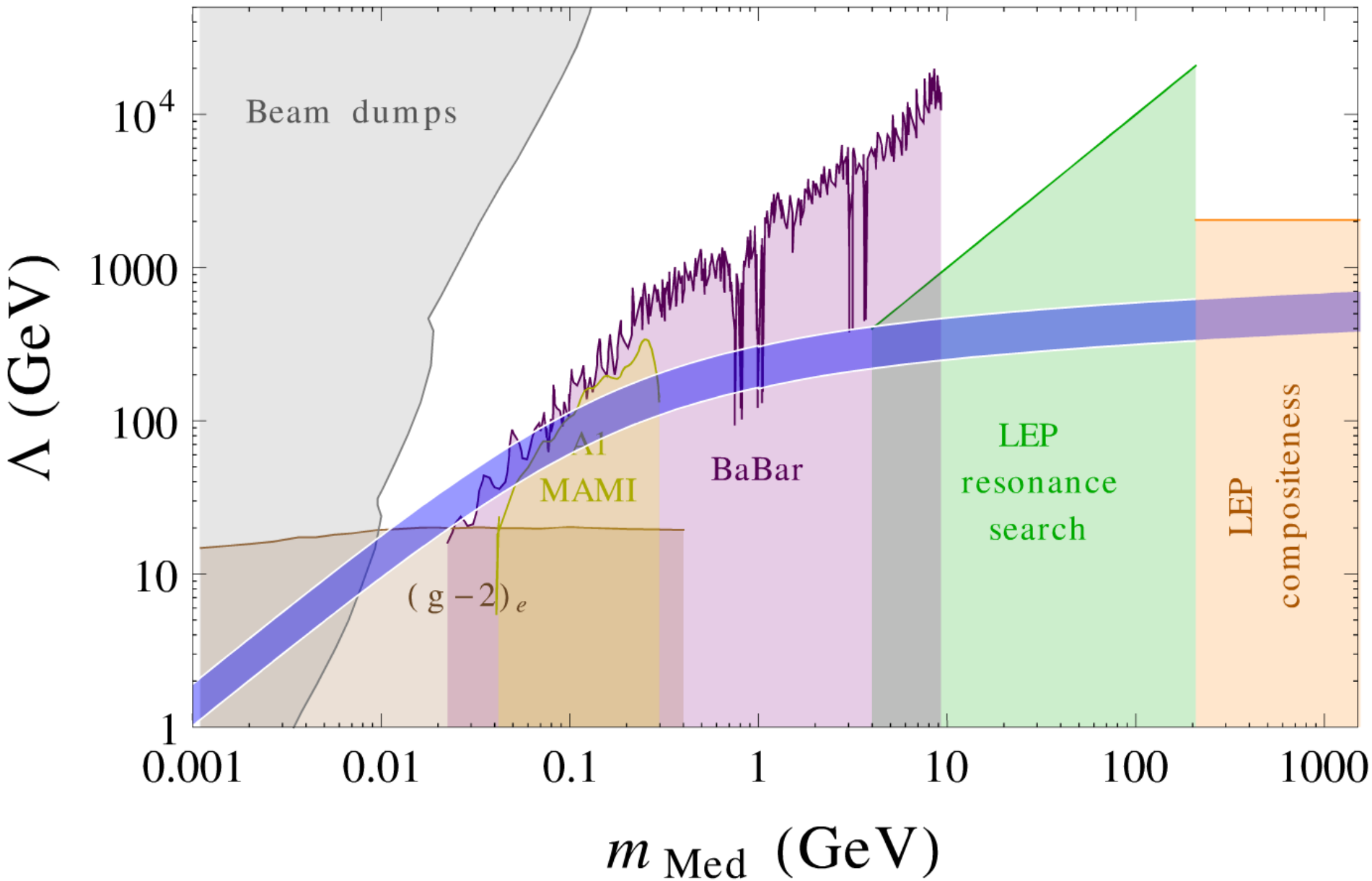
$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$



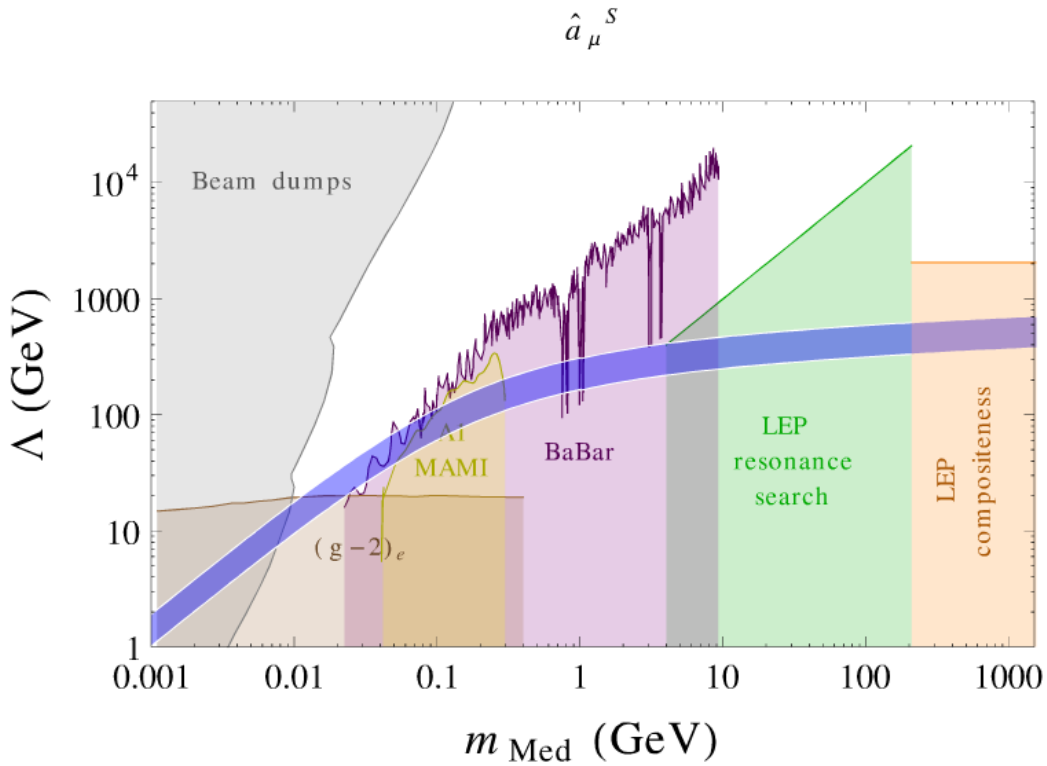
Real

$$\mathcal{L}_S = \lambda \bar{\mu} \mu S$$

$\hat{a}_\mu^S$


Beam dumps
A1
MAMI
BaBar
LEP
resonance
search
LEP
compositeness
$(g-2)_e$
Λ (GeV)
$m_{\rm Med}$ (GeV)
10^4
1000
100
10
1
0.001
0.01
0.1
1
10
100
1000

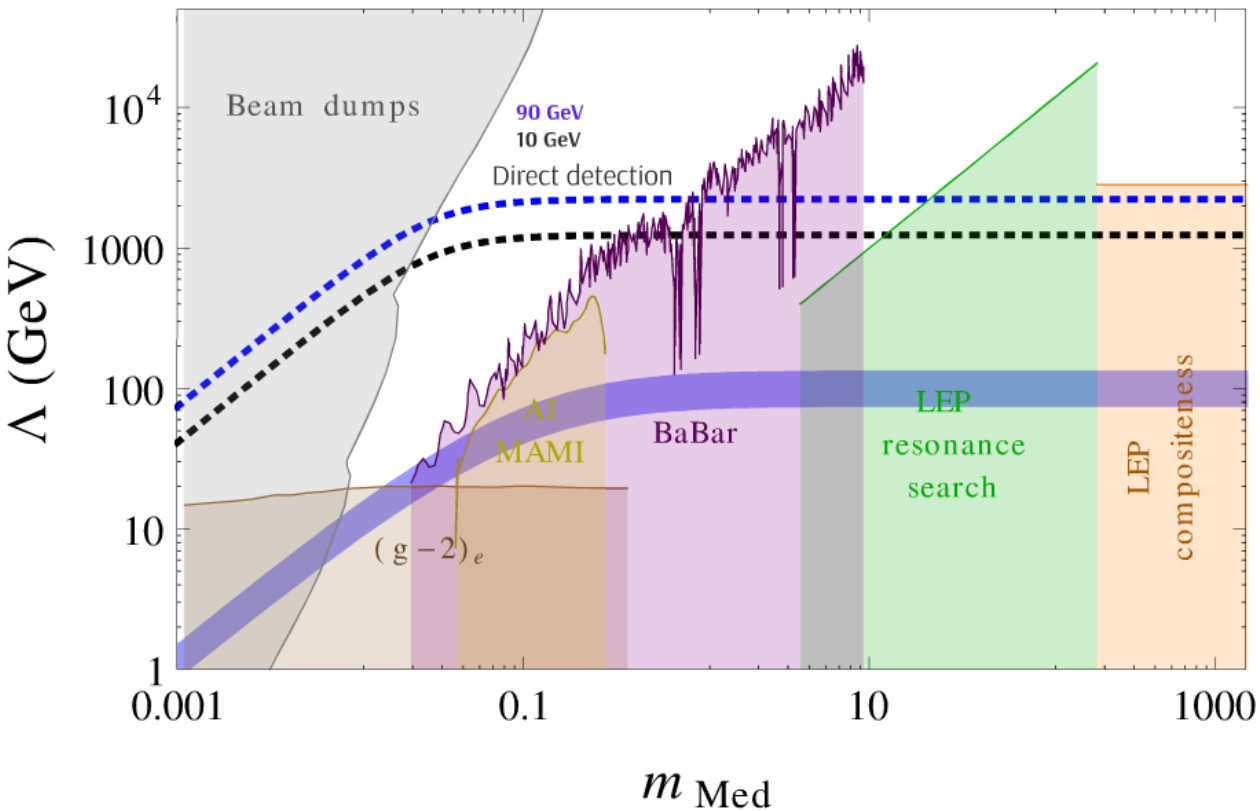
$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$



Real

$$\mathcal{L}_S = \lambda \bar{\mu} \mu S$$

$\hat{a}_\mu{}^V(\phi=0)$

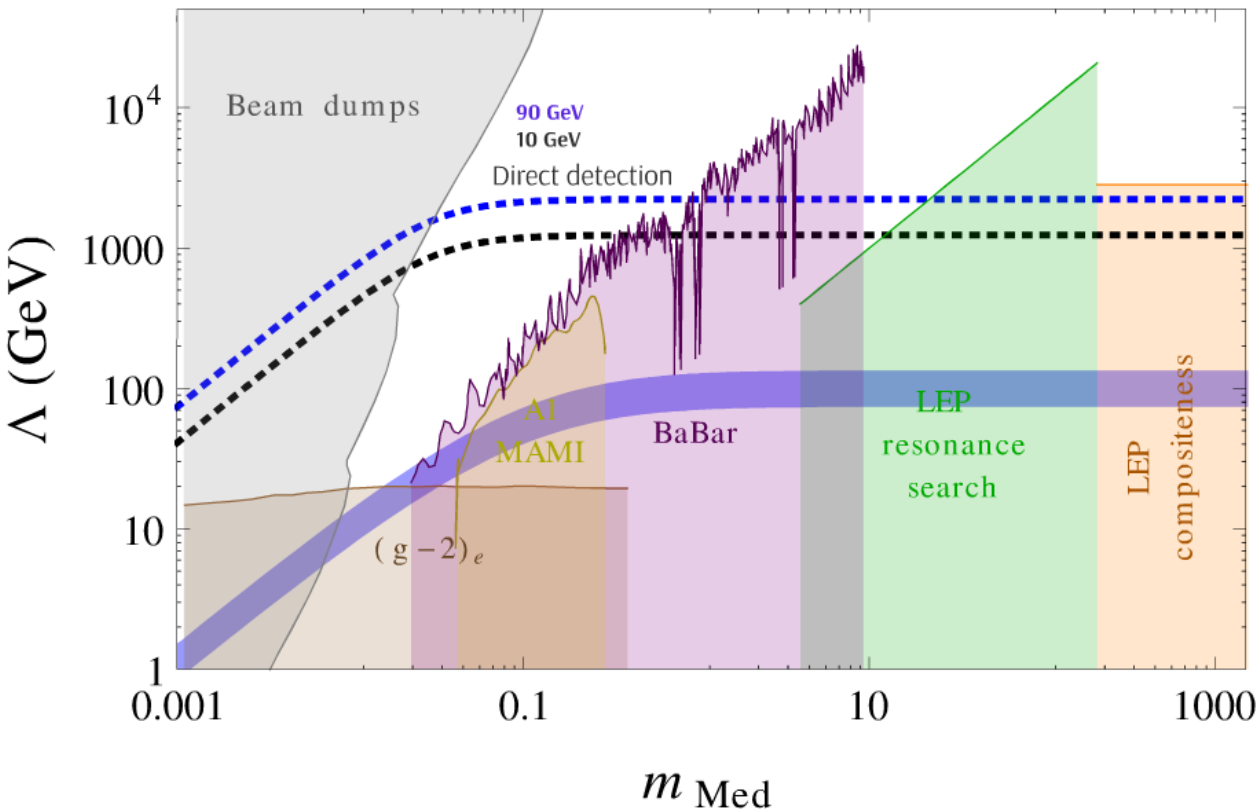


$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

$$\mathcal{L} = \frac{\lambda_\chi}{2}\bar{\chi}\gamma^\nu\left(\cos\theta + \sin\theta\gamma^5\right)\chi V_\nu + \frac{\lambda}{2}\bar{\mu}\gamma^\nu\left(\cos\phi + \sin\phi\gamma^5\right)\mu V_\nu$$

Dirac

$\hat{a}_\mu{}^V(\phi=0)$



$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

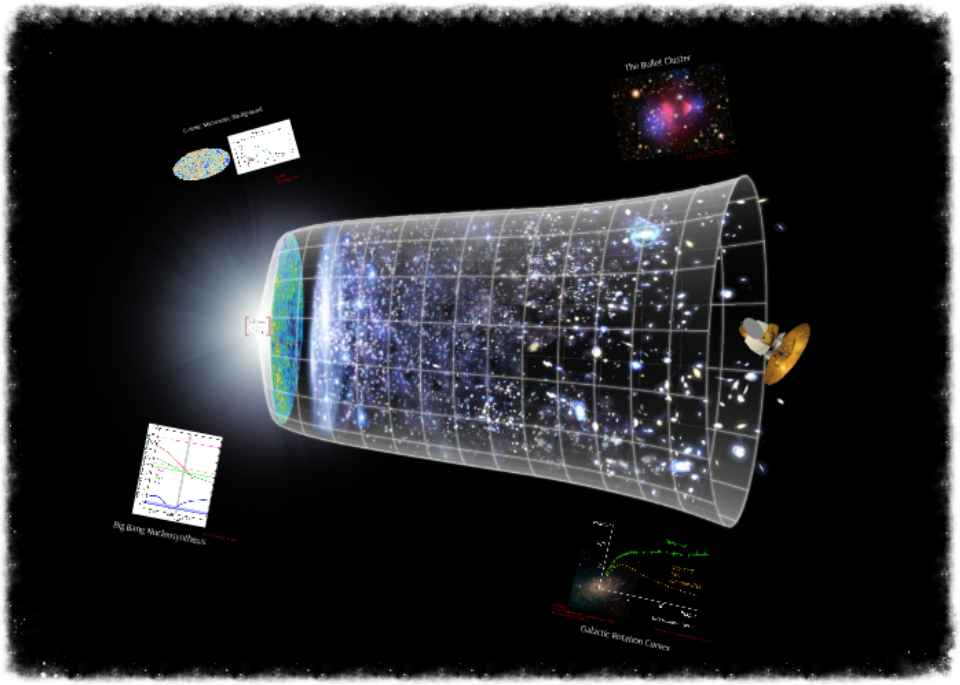
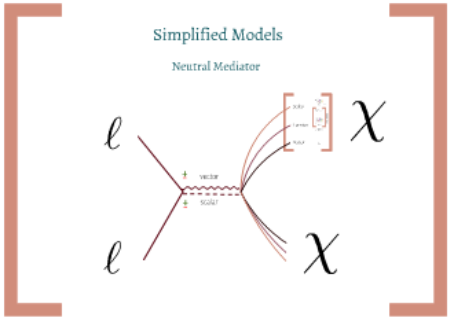
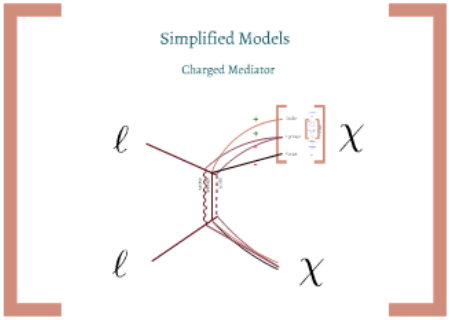
$$\mathcal{L} = \frac{\lambda_\chi}{2}\bar{\chi}\gamma^\nu\left(\cos\theta + \sin\theta\gamma^5\right)\chi V_\nu + \frac{\lambda}{2}\bar{\mu}\gamma^\nu\left(\cos\phi + \sin\phi\gamma^5\right)\mu V_\nu$$

Dirac

Conclusions

Leptophilic dark matter
has novel phenomenology

Can potentially explain the
anomalous magnetic moment
of the muon

For chiral couplings, new physics
scale is O(100) GeV

Under tension from direct
detection and collider constraints