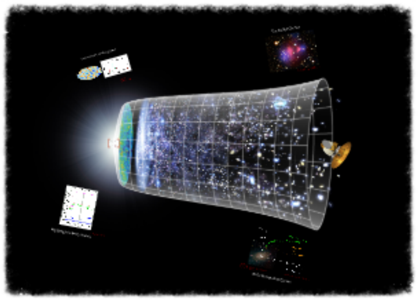
Conclusions

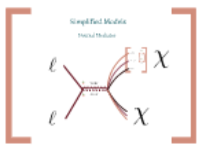
Leptophilic dark matter has novel phenomenology

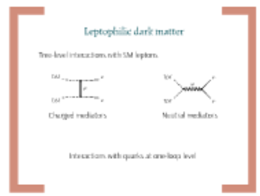
Can potentially explain the anomalous magnetic moment of the muon

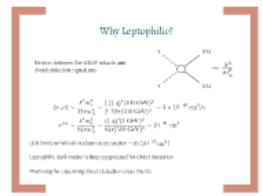
For chiral couplings, new physics scale is O(100) GeV

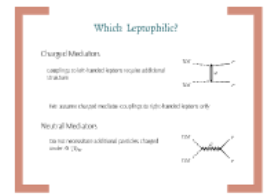
Under tension from direct detection and collider constraints

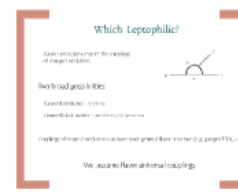




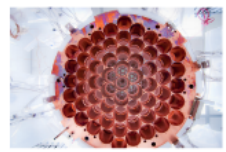








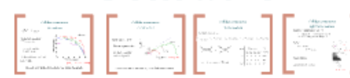
Direct



Detection

g-2

Colliders

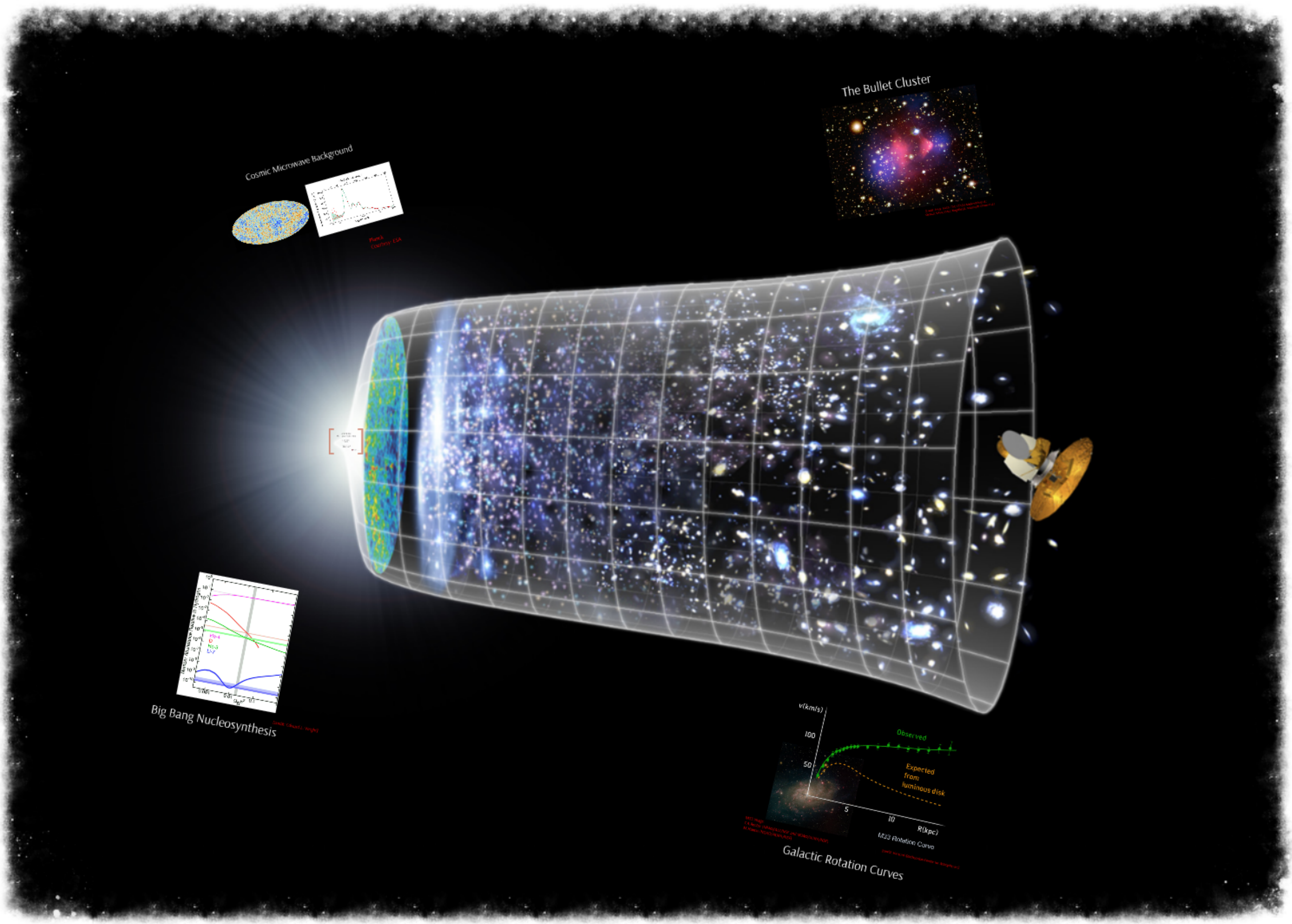


Dark Matter: The Lepton Connection

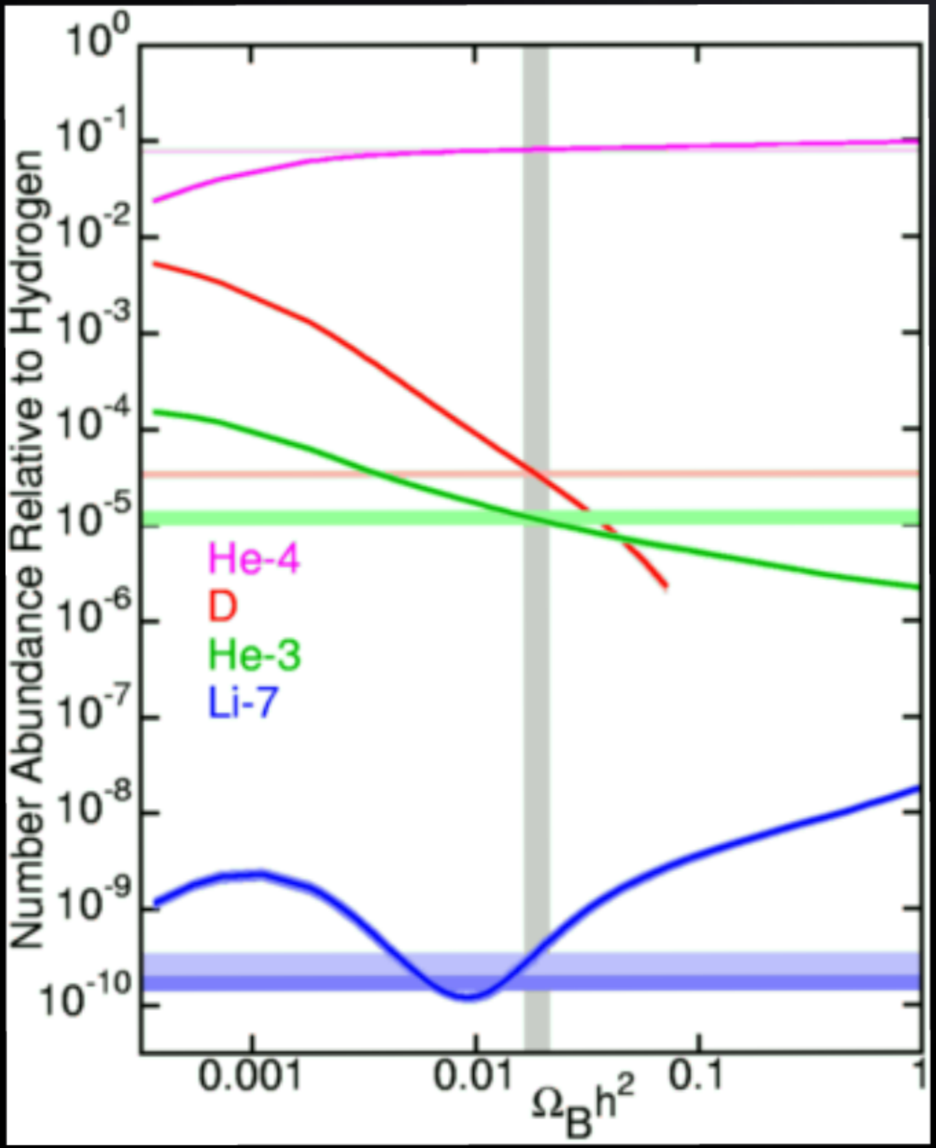
Prateek Agrawal
Fermilab

Rutgers University
April 29, 2014

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



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



[credit: Edward L. Wright]

Big Bang Nucleosynthesis

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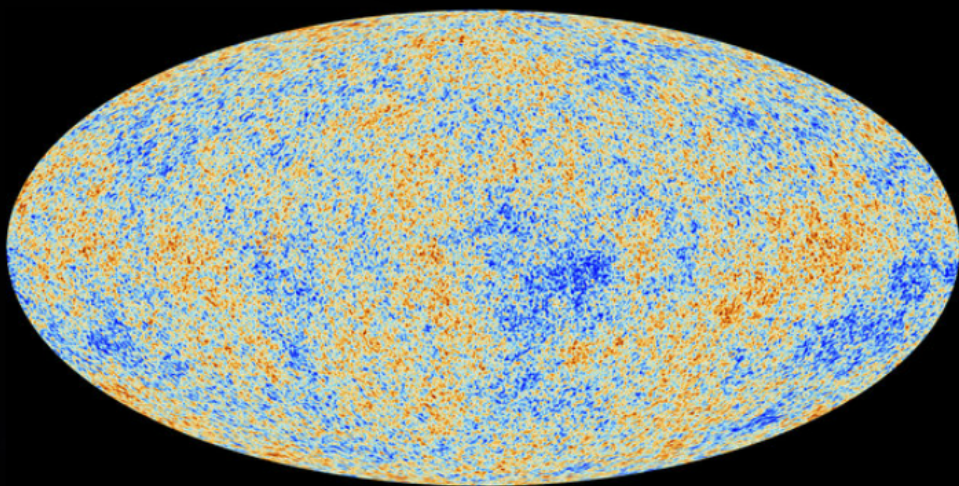
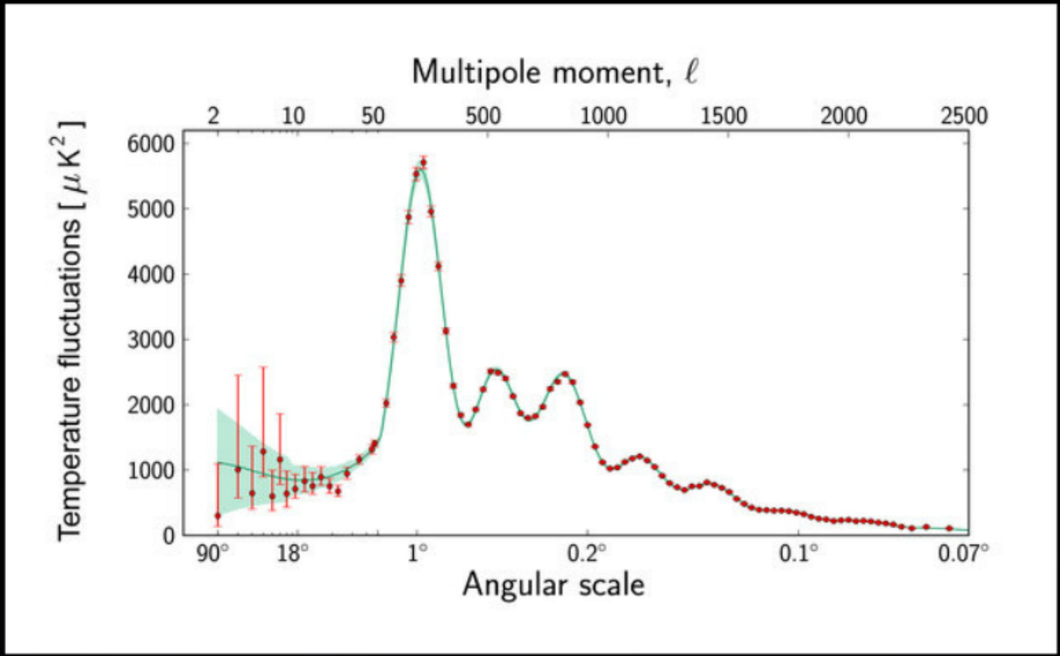
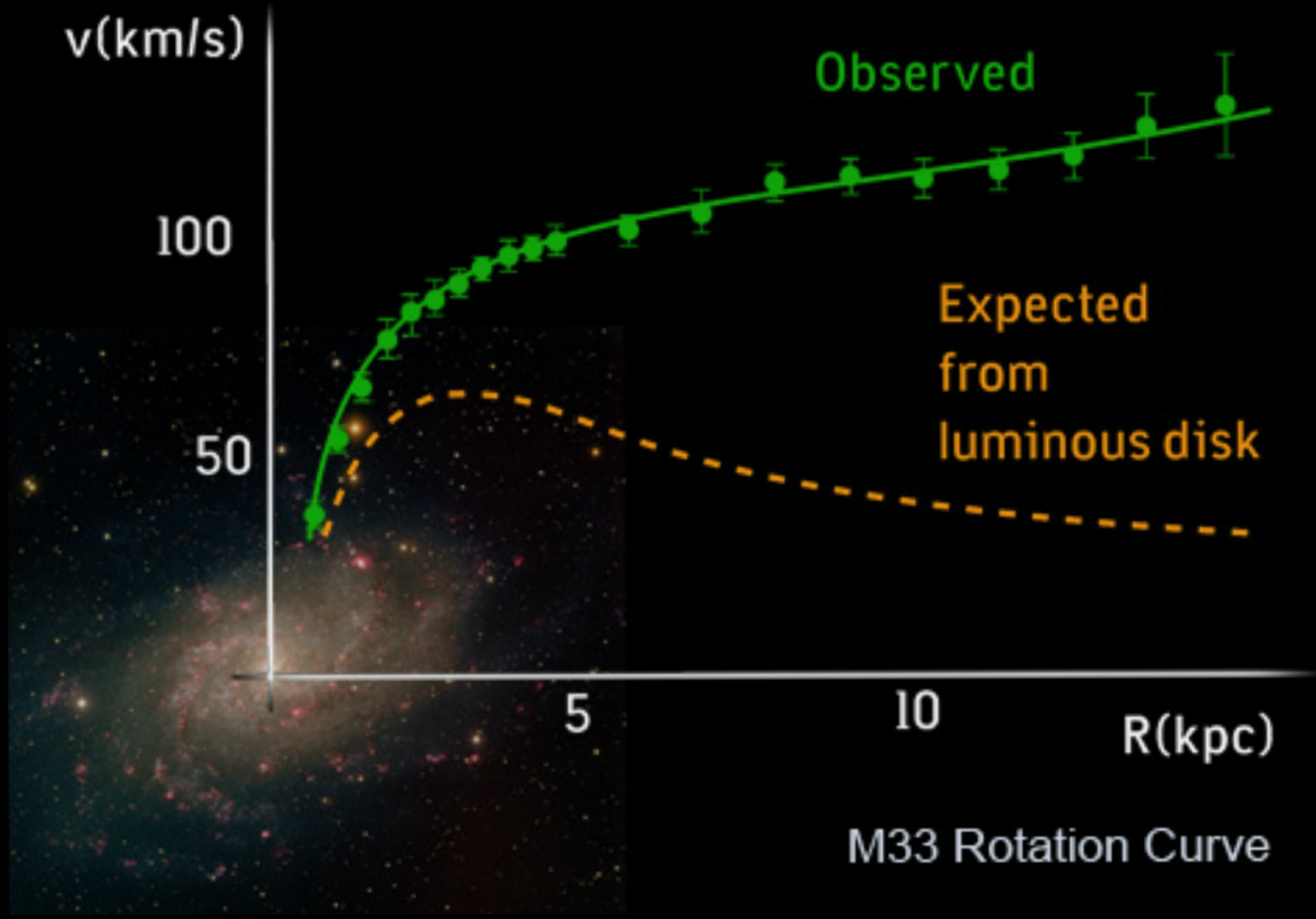




Planck
Courtesy: ESA

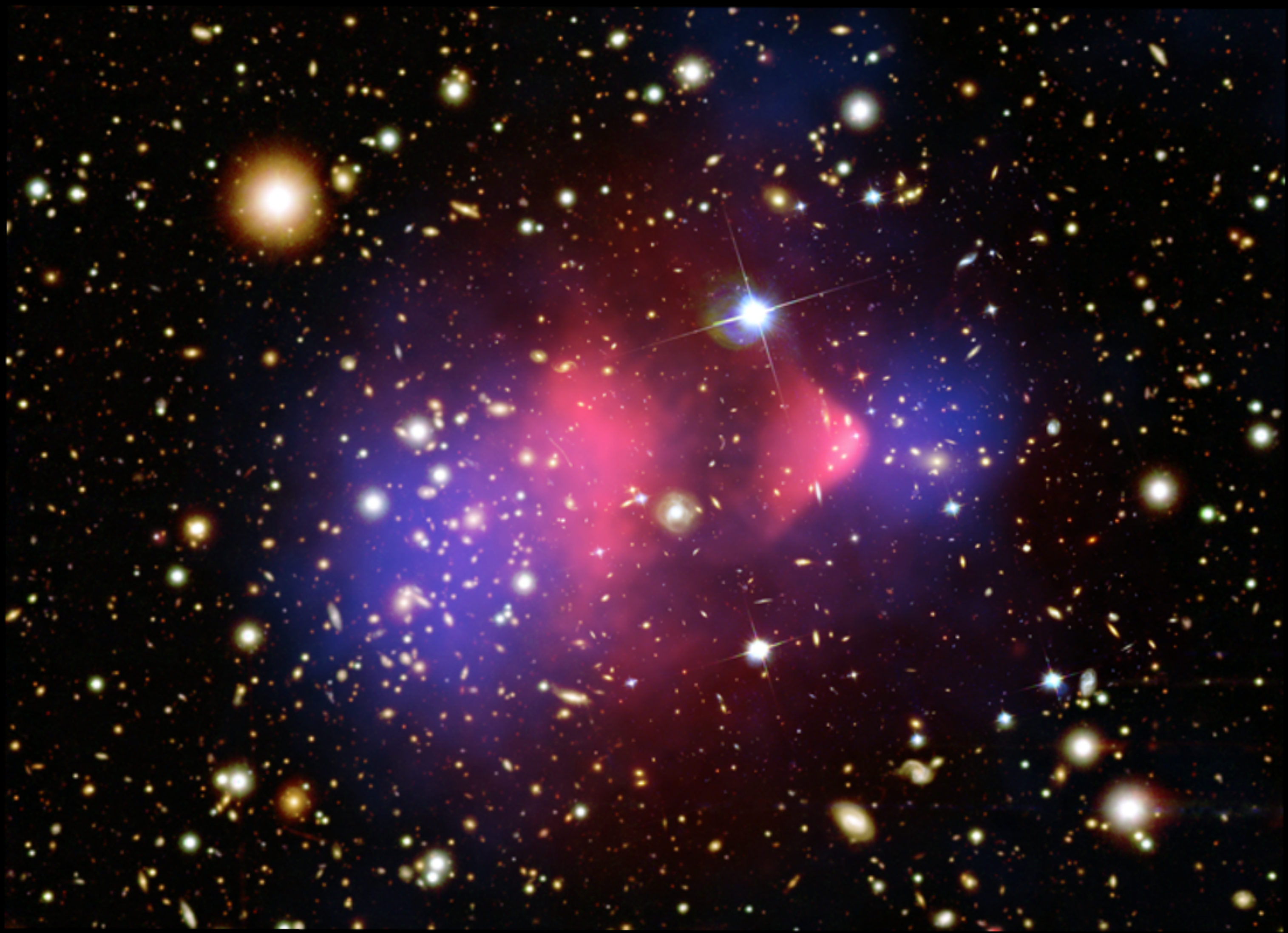


M33 image:
T.A.Rector (NRAO/AUI/NSF and NOAO/AURA/NSF)
M.Hanna (NOAO/AURA/NSF)

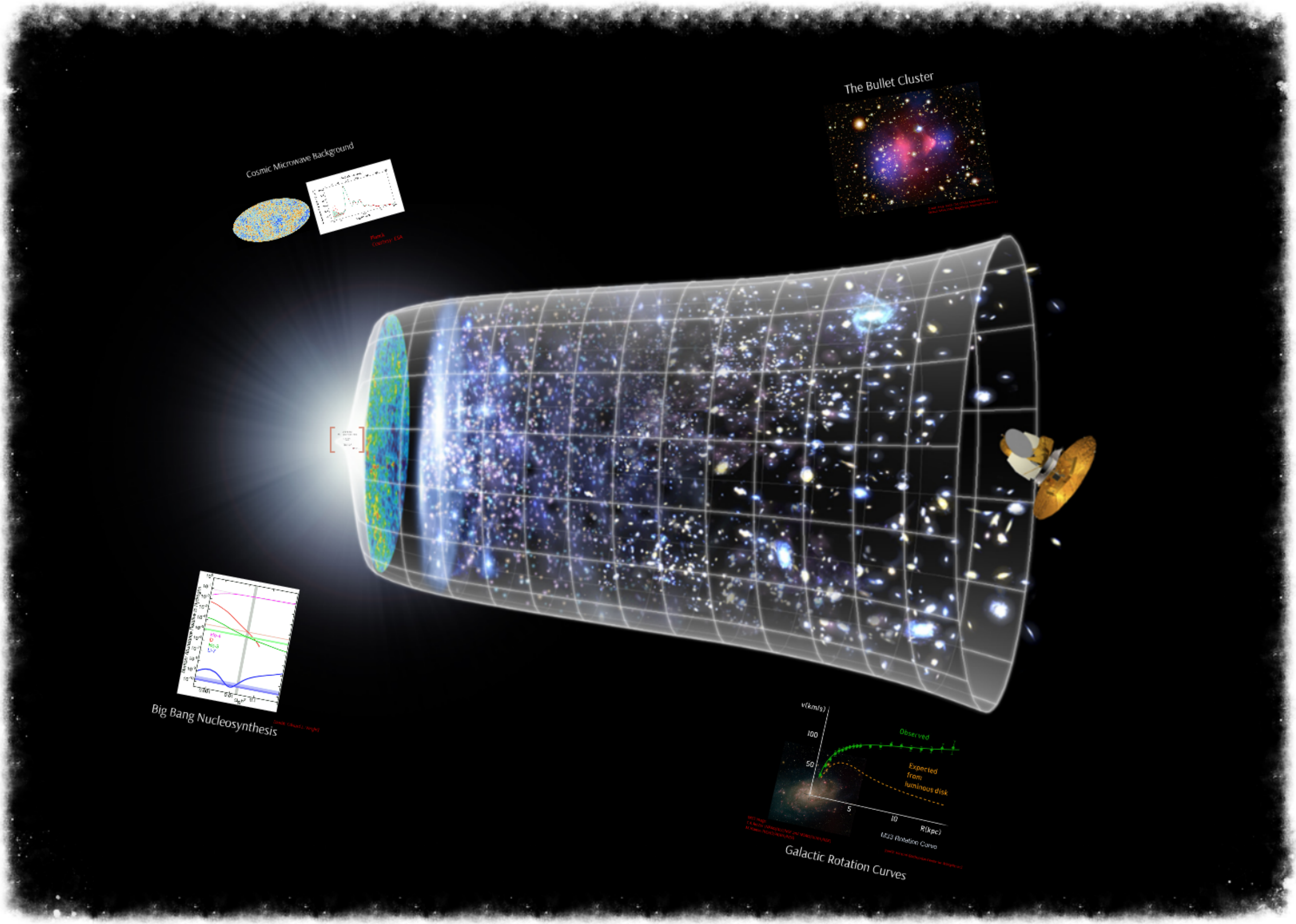
[credit: Harvard-Smithsonian Center for Astrophysics]

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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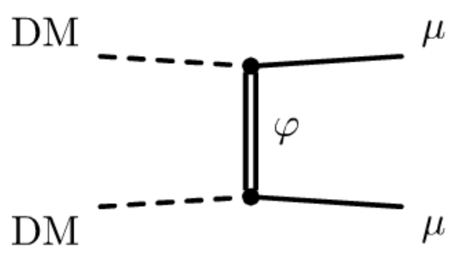
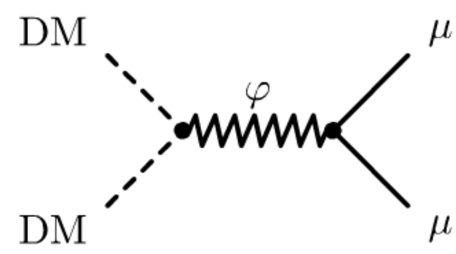
Leptophilic dark matter

Tree-level interactions with SM leptons



Charged mediators

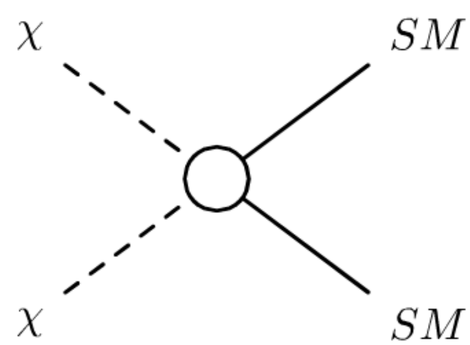


Neutral mediators

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 $[10^{-45}\mathrm{cm}^2]$

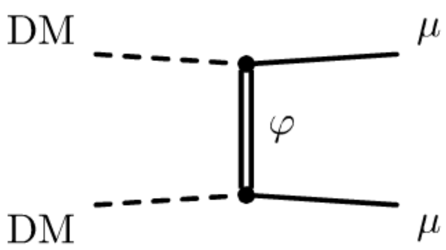
Leptophilic dark matter is loop suppressed for direct detection

Promising for upcoming direct detection experiments

Which Leptophilic?

Charged Mediators

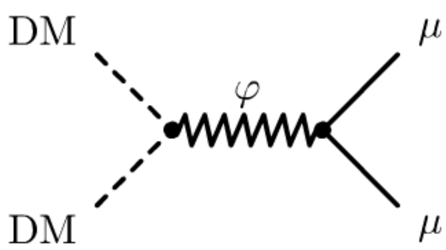
Couplings to left-handed leptons require additional structure



We assume charged mediator couplings to right-handed leptons only

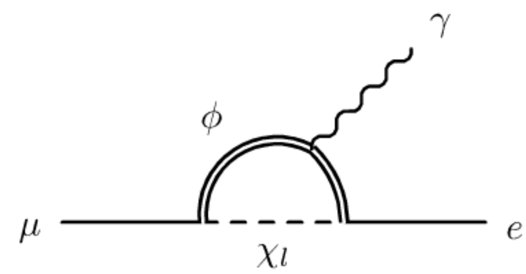
Neutral Mediators

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



Which Leptophilic?

Flavor constraints restrict the couplings
of charged mediators



Two broad possibilities

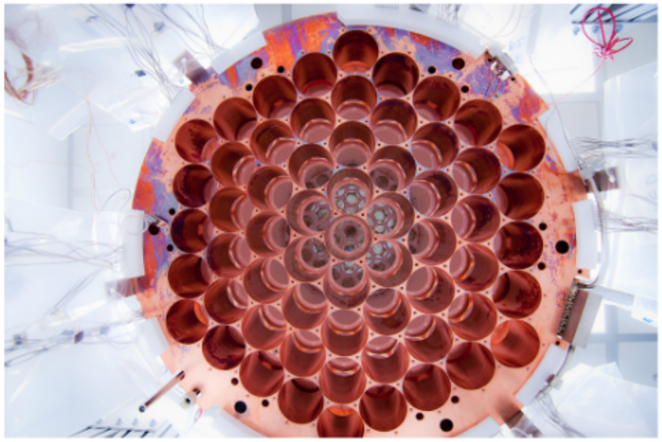
Flavored mediator - sleptons

Flavored dark matter - sneutrino, KK neutrino

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

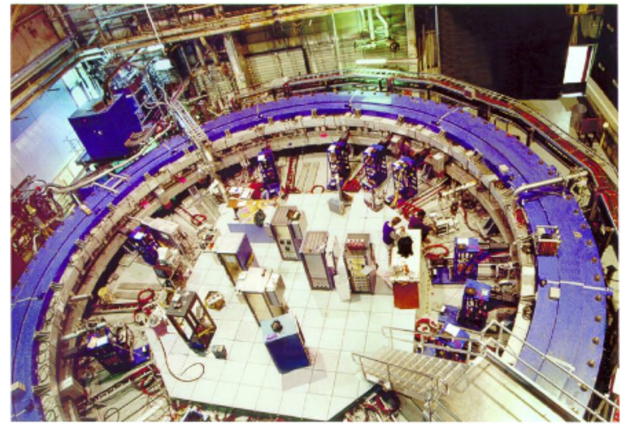
We assume flavor universal couplings

Direct



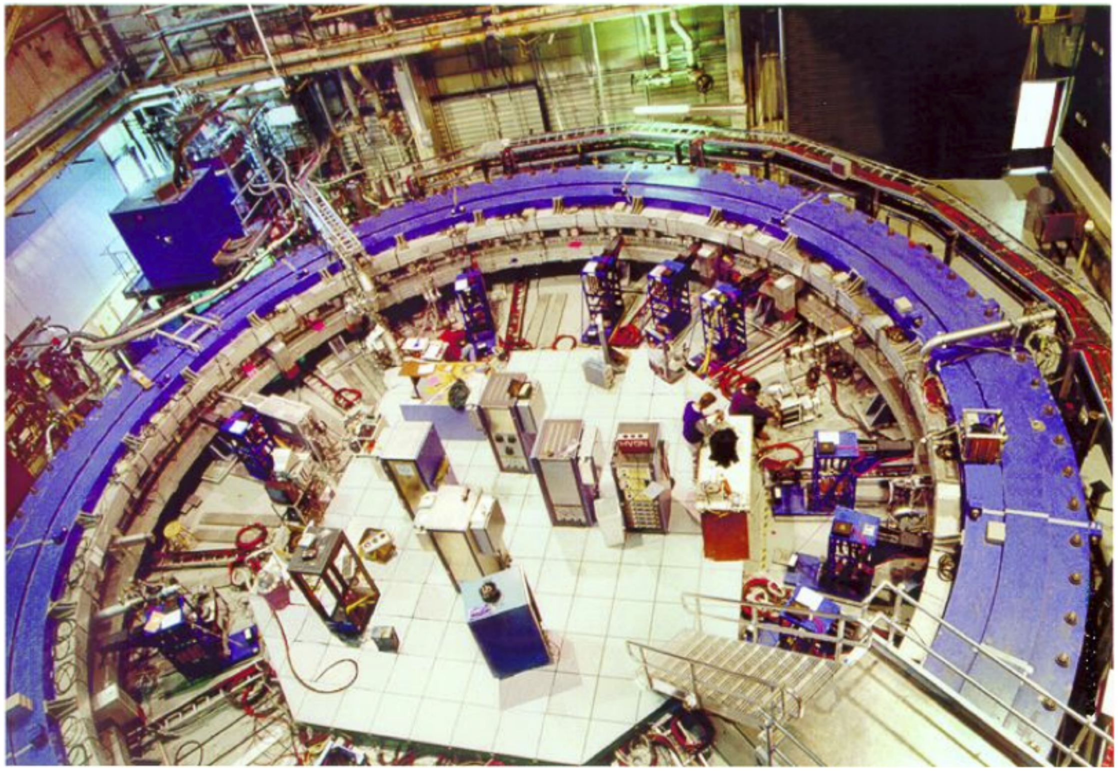
Detection

g-2



Colliders

g-2



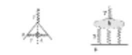
g - 2

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

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

experimental (6.3); theoretical (4.9)

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



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

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

[Czarnecki, Marciano 2001]

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

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

g - 2

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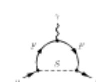

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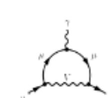

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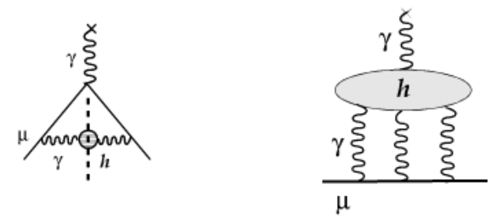

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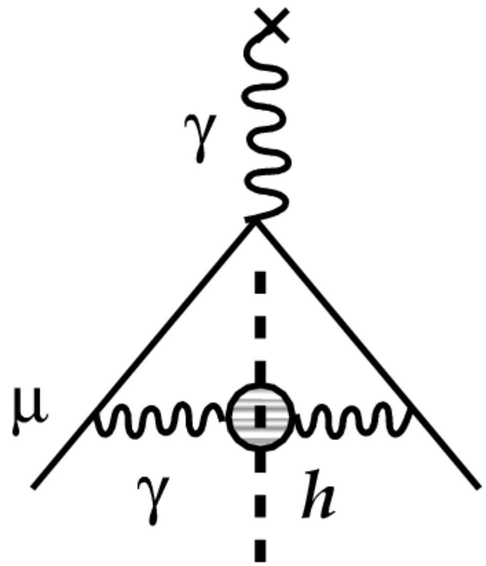

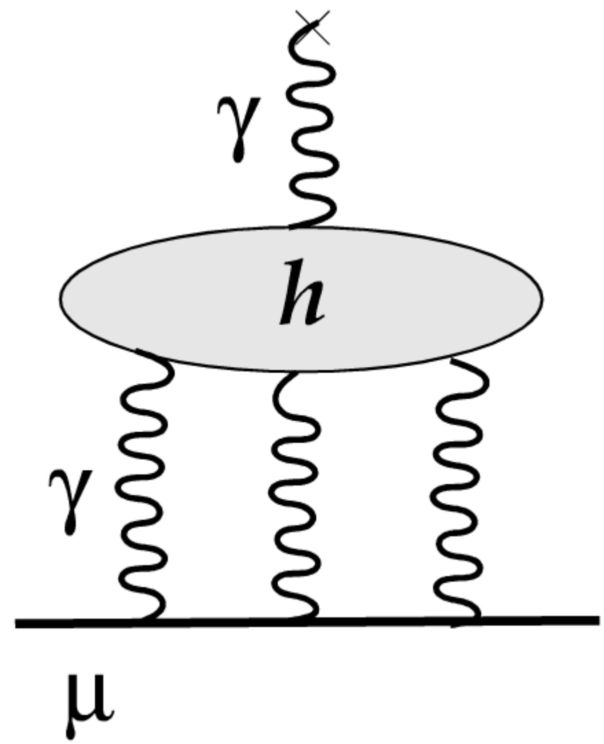

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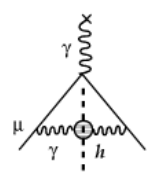

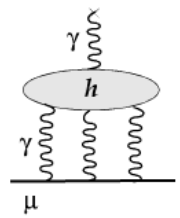

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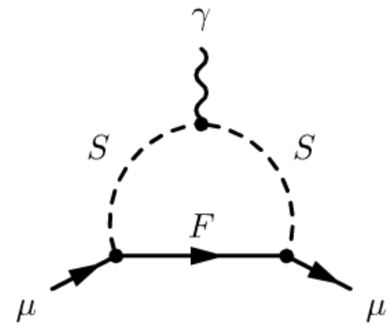

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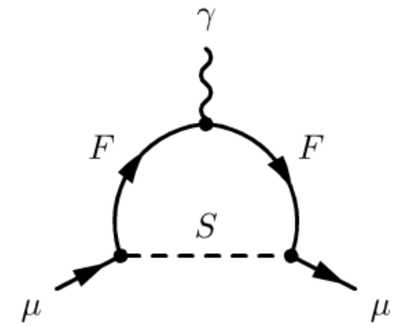

g - 2

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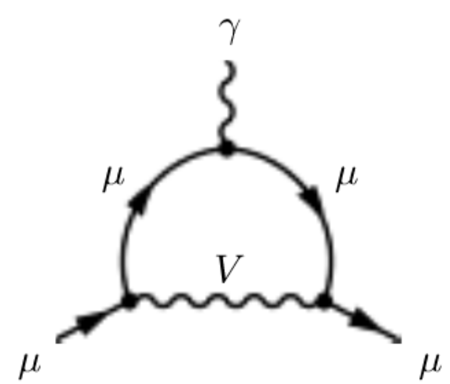

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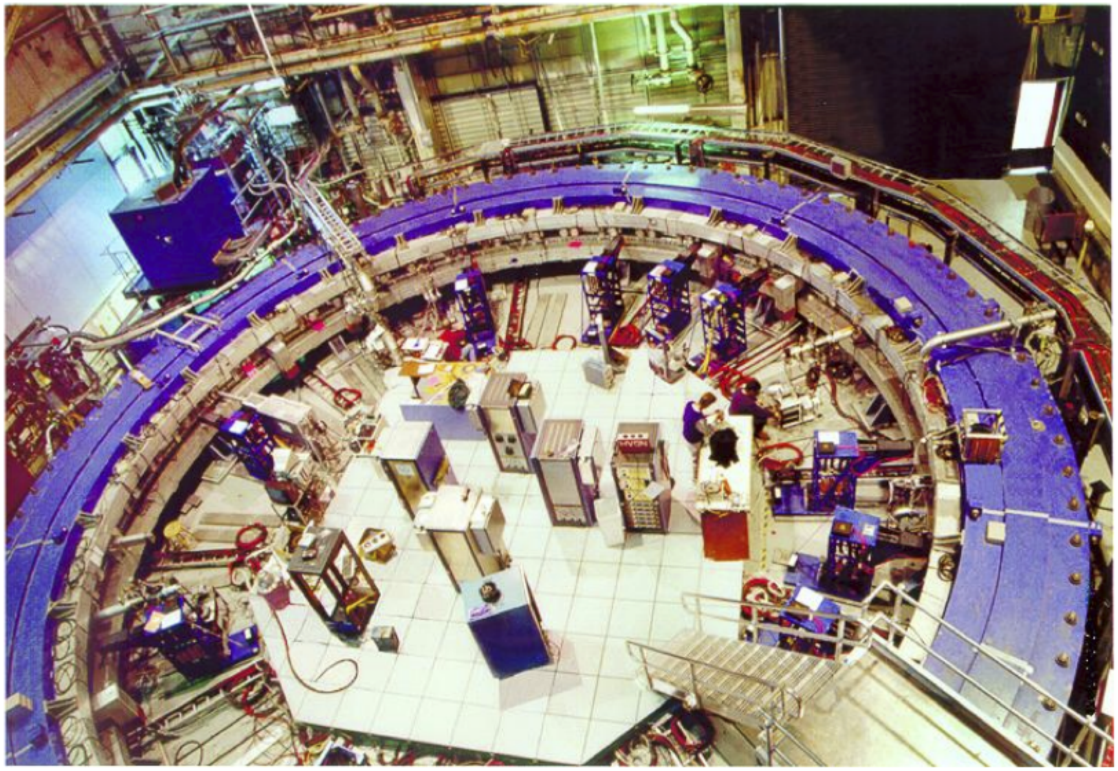

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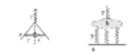

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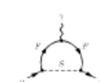

g - 2

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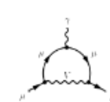
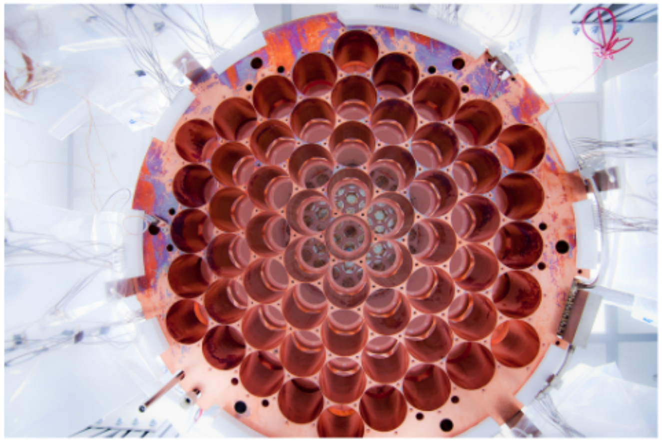


Direct



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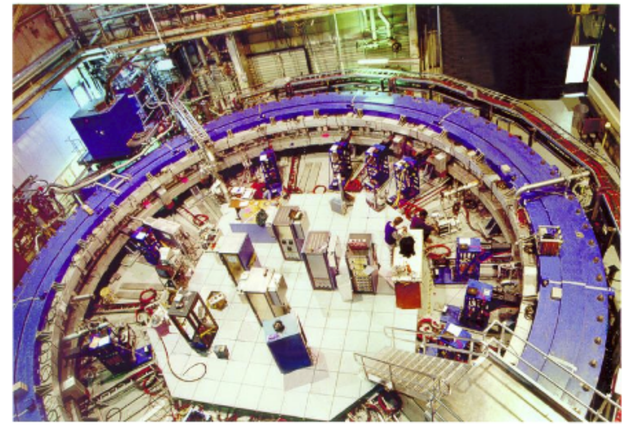
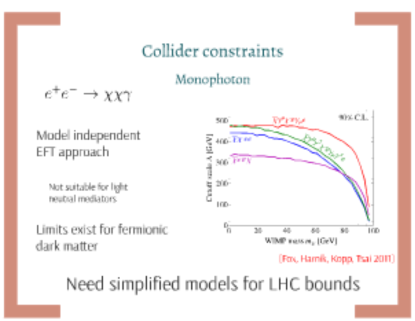
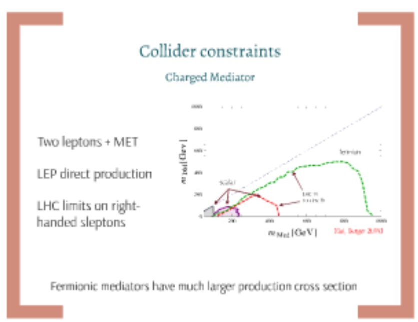
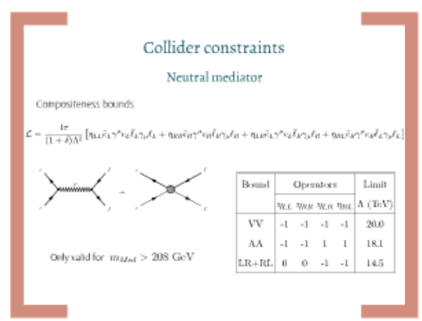


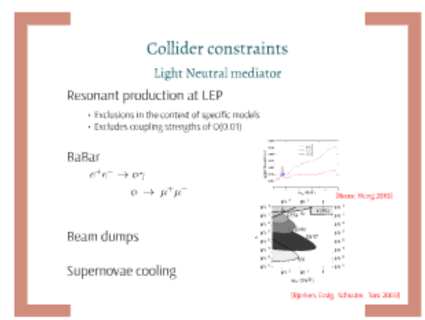
Colliders

Colliders


Collider constraints
Monophoton
Model independent EFT approach
Not suitable for light neutral mediators
Limits exist for fermionic dark matter
Need simplified models for LHC bounds


Collider constraints
Charged Mediator
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


Collider constraints
Light Neutral mediator
Resonant production at LEP
BaBar
Beam dumps
Supernovae cooling

Collider constraints

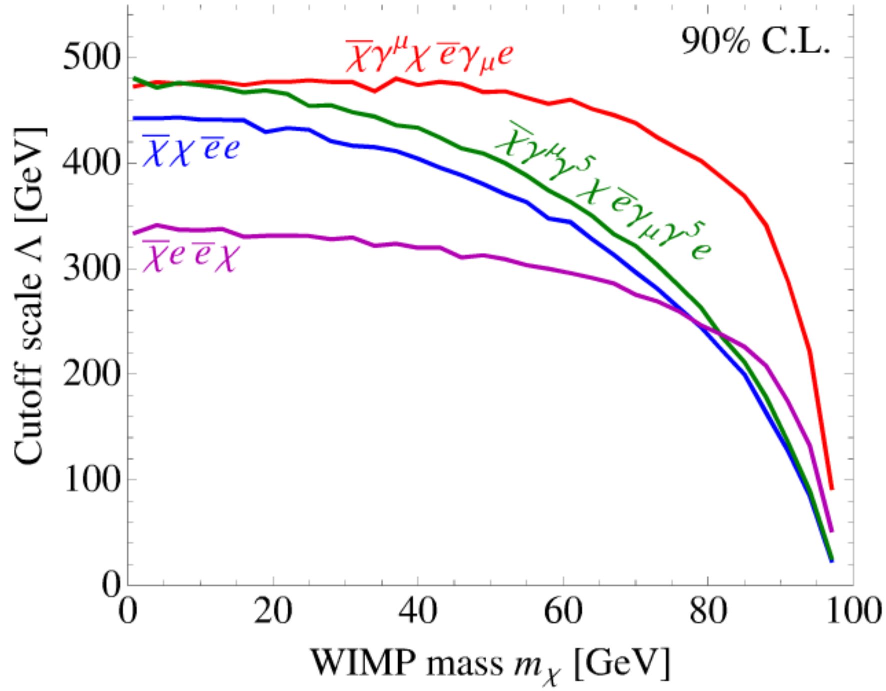
Monophoton

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

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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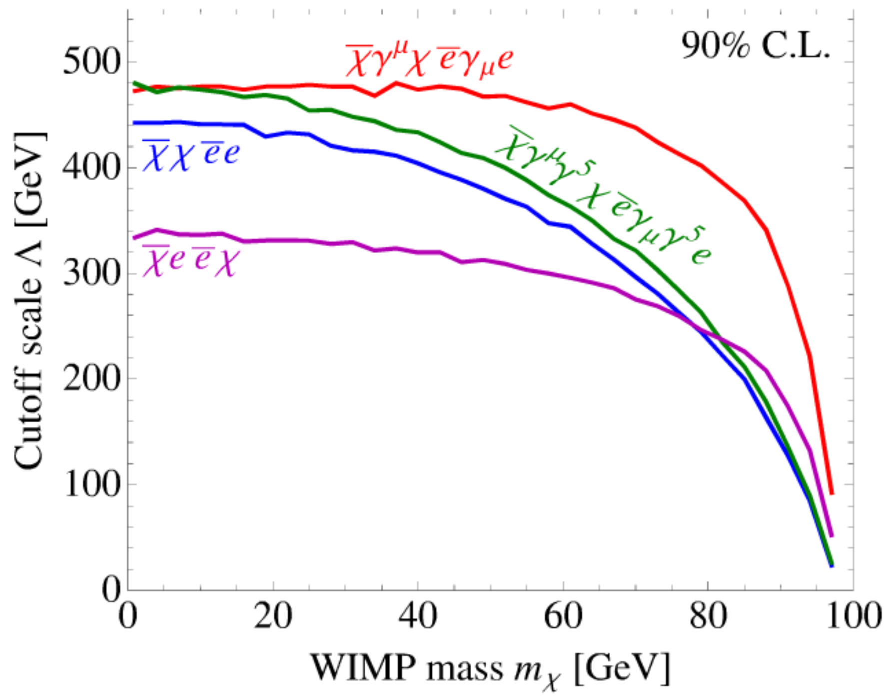

[Fox, Harnik, Kopp, Tsai 2011]

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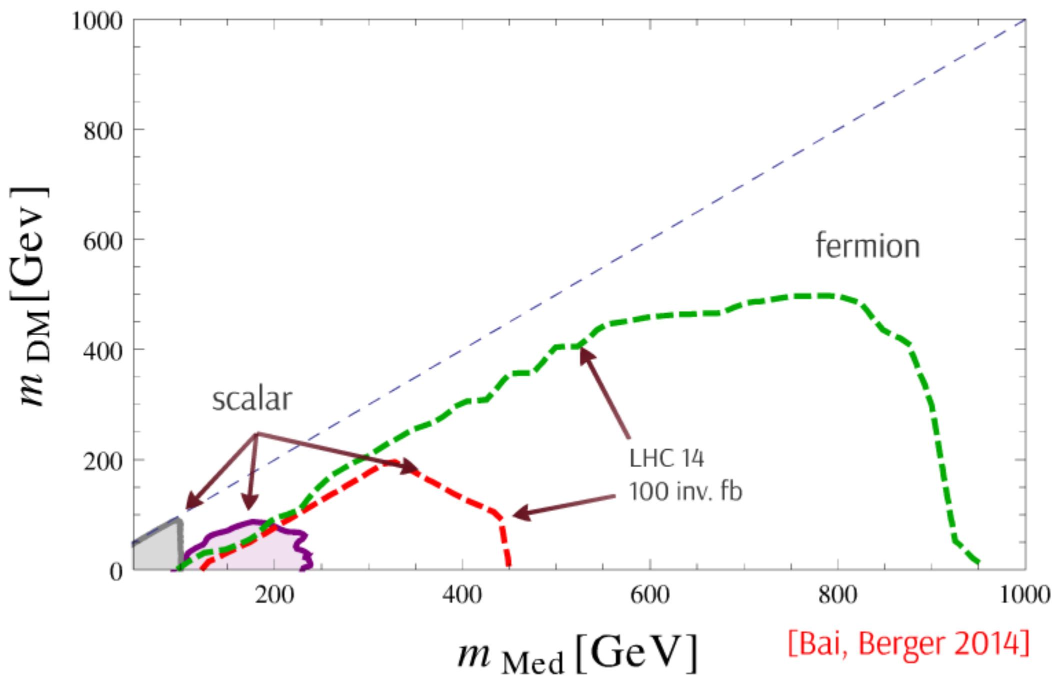
Collider constraints

Charged Mediator

Two leptons + MET

LEP direct production

LHC limits on right-handed sleptons



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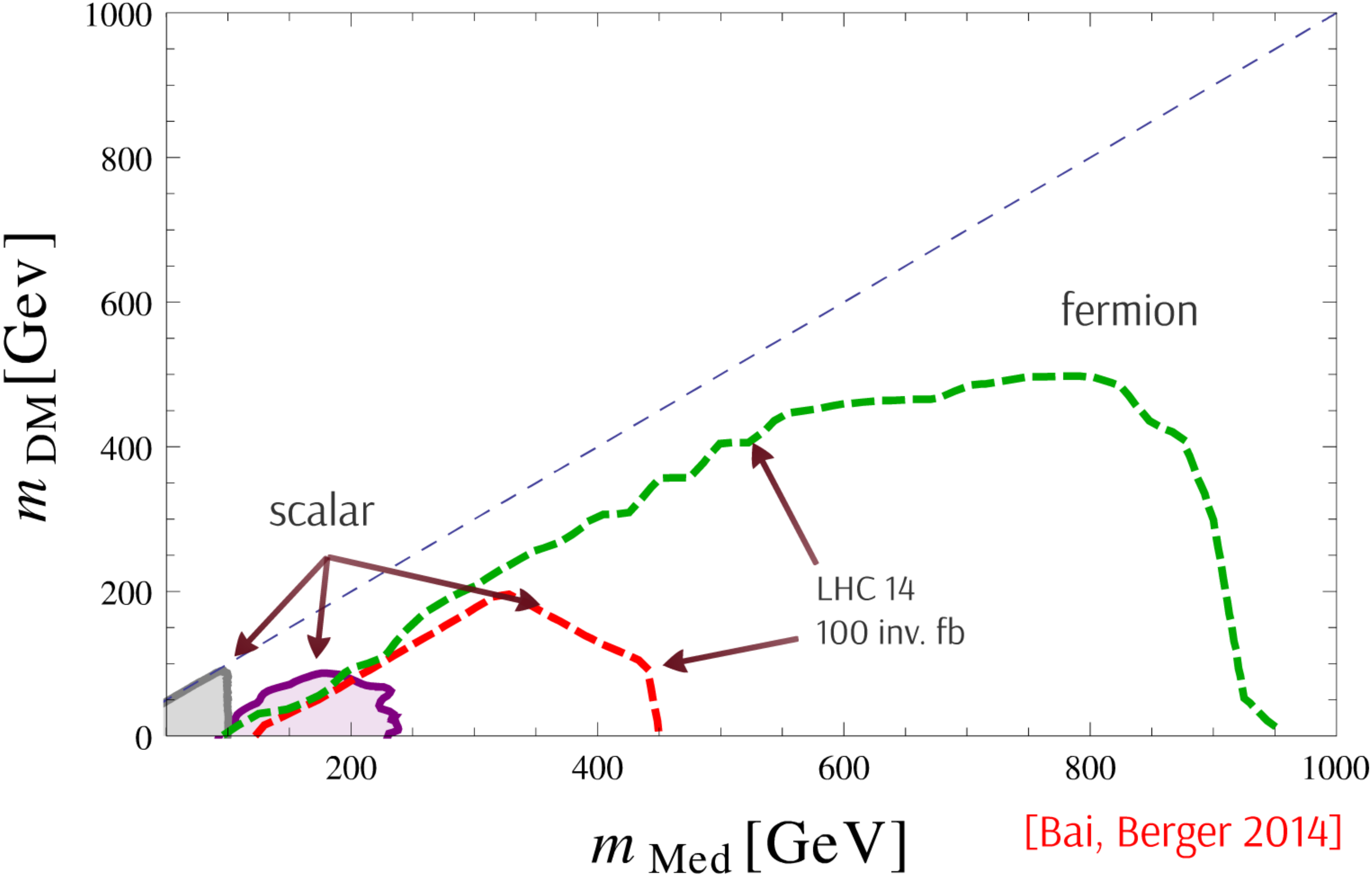

1000
800
600
400
200
0
200
400
600
800
1000
m_{DM} [Gev]
m_{Med} [GeV]
fermion
scalar
LHC 14
100 inv. fb
[Bai, Berger 2014]

Collider constraints

Charged Mediator

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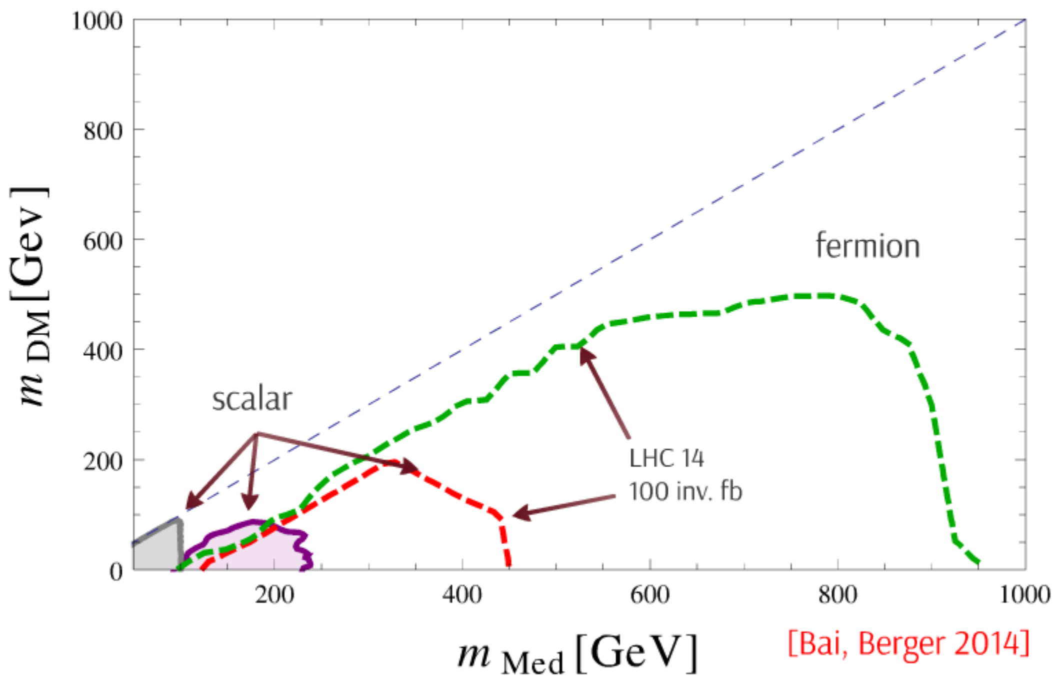
LEP direct production

LHC limits on right-handed sleptons



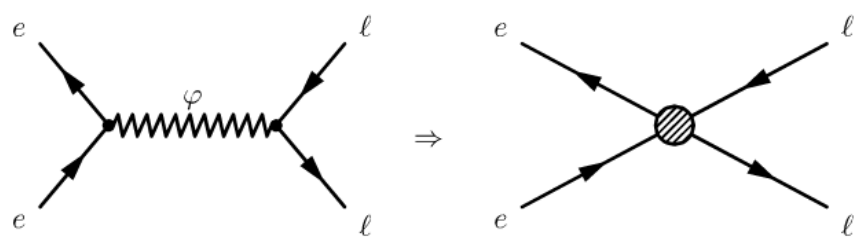
Fermionic mediators have much larger production cross section

Collider constraints

Neutral mediator

Compositeness bounds

$$\mathcal{L} = \frac{4\pi}{(1+\delta)\Lambda^2}\left[\eta_{LL}\bar{e}_L\gamma^\mu e_L\bar{\ell}_L\gamma_\mu\ell_L + \eta_{RR}\bar{e}_R\gamma^\mu e_R\bar{\ell}_R\gamma_\mu\ell_R + \eta_{LR}\bar{e}_L\gamma^\mu e_L\bar{\ell}_R\gamma_\mu\ell_R + \eta_{RL}\bar{e}_R\gamma^\mu e_R\bar{\ell}_L\gamma_\mu\ell_L\right]$$



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

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

Collider constraints

Light Neutral mediator

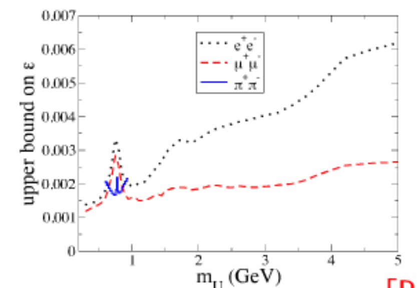
Resonant production at LEP

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

BaBar

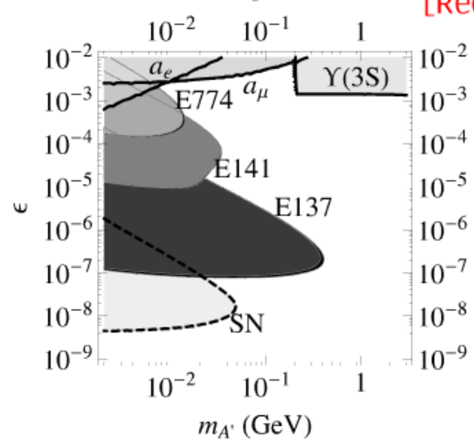
$$e^+e^- \to \phi\gamma$$

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



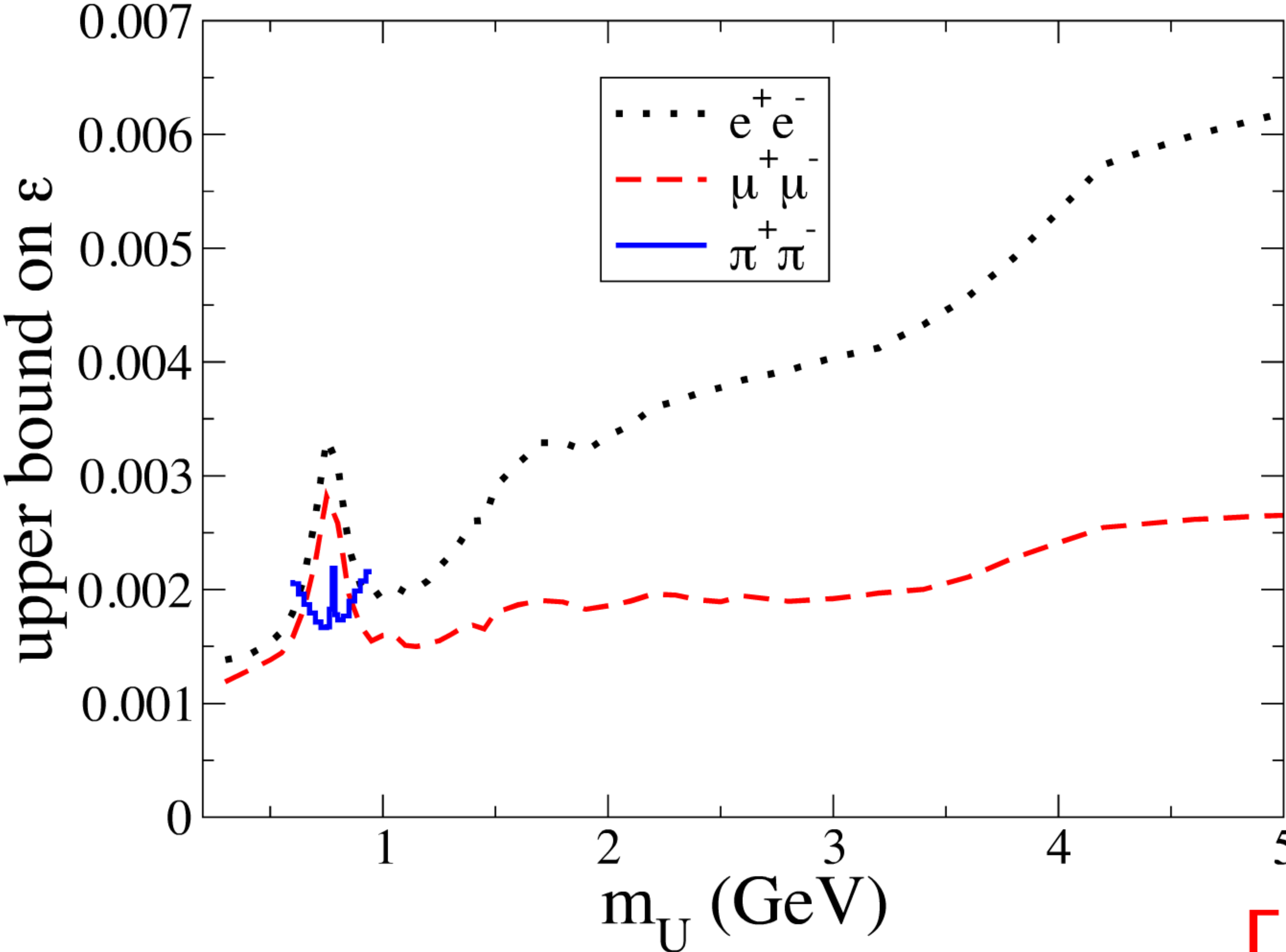
[Reece, Wang 2010]

Beam dumps



Supernovae cooling

[Bjorken, Essig, Schuster, Toro 2009]


upper bound on ε
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
1
2
3
4
5
m_U (GeV)
e^+e^-
$\mu^+\mu^-$
$\pi^+\pi^-$

[Re

Collider constraints

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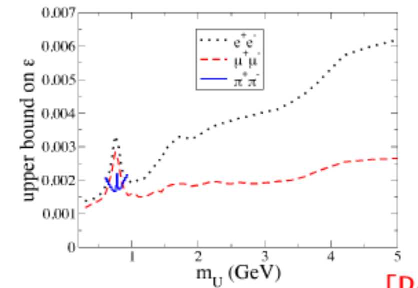

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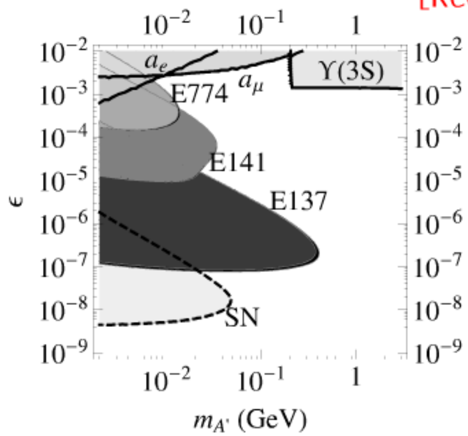

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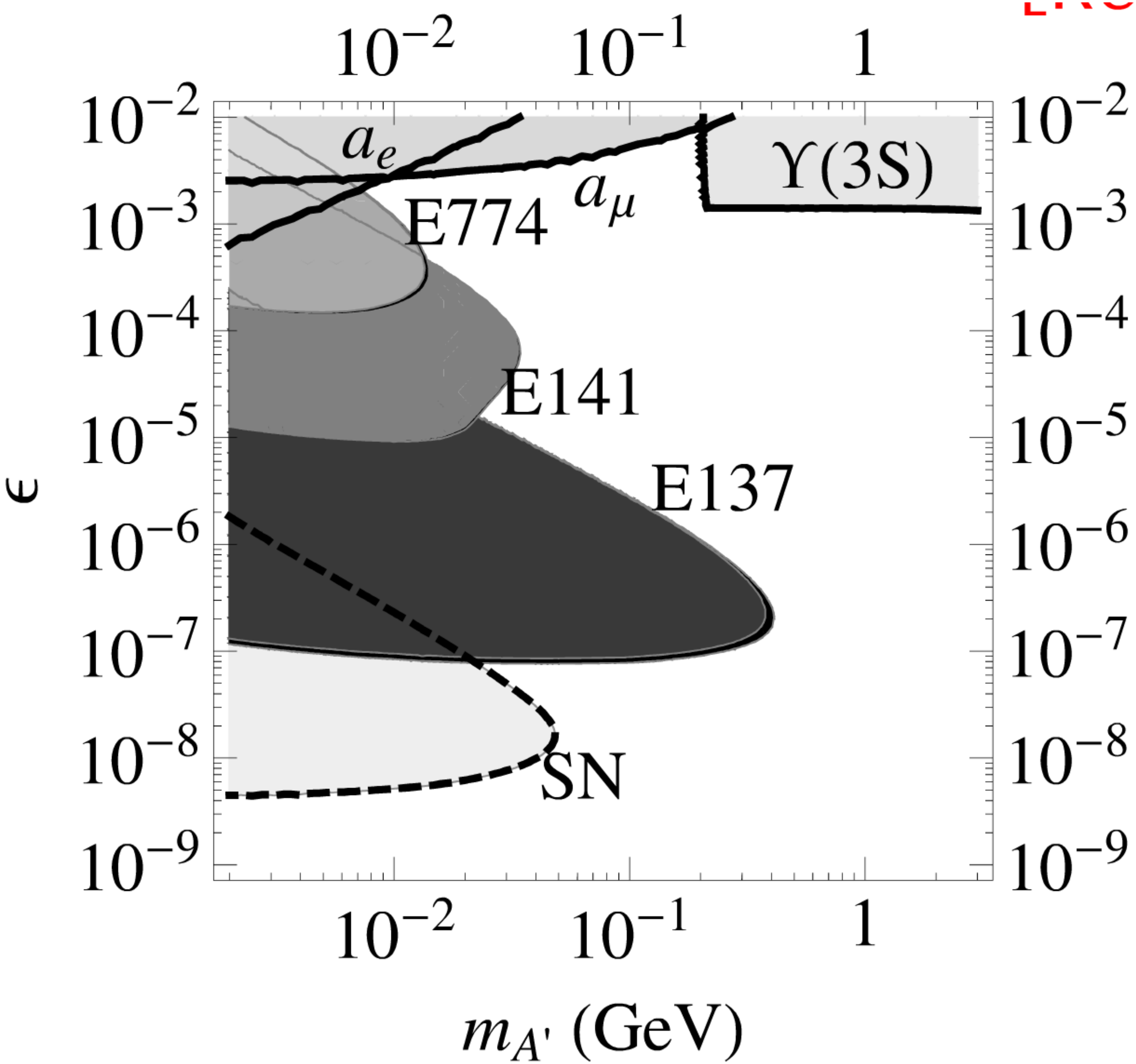

a_e
a_μ
E774
E141
E137
SN
Υ(3S)
ϵ
$m_{A'}$ (GeV)
10^{-2}
10^{-1}
1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}

Collider constraints

Light Neutral mediator

Resonant production at LEP

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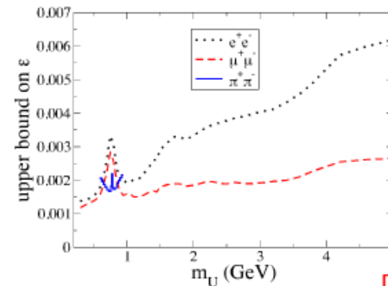

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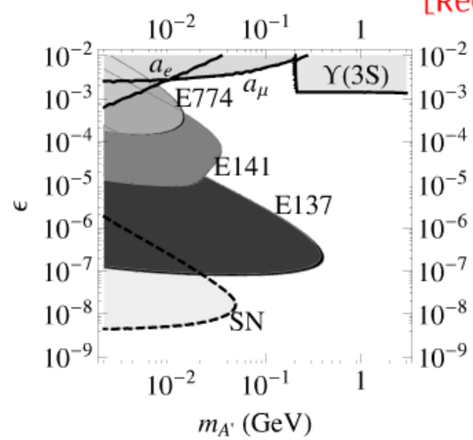

Beam dumps

Supernovae cooling

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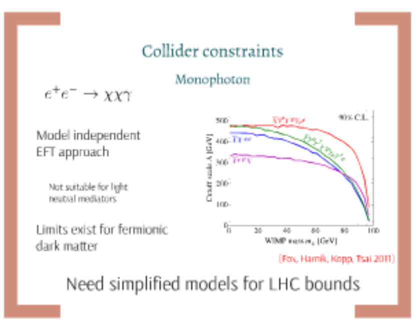
Colliders



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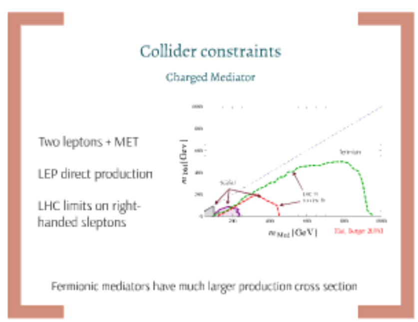

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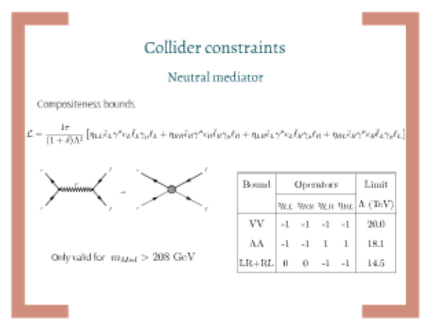
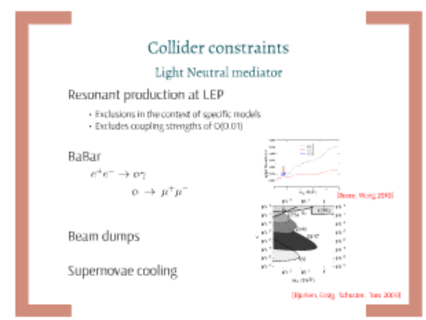
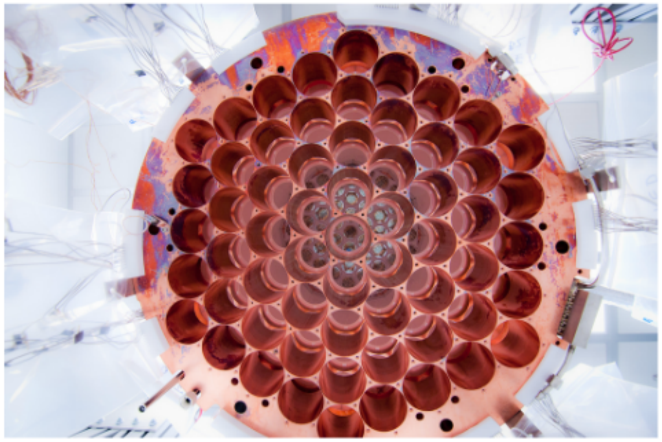


Collider constraints
Neutral mediator
Compositeness bounds



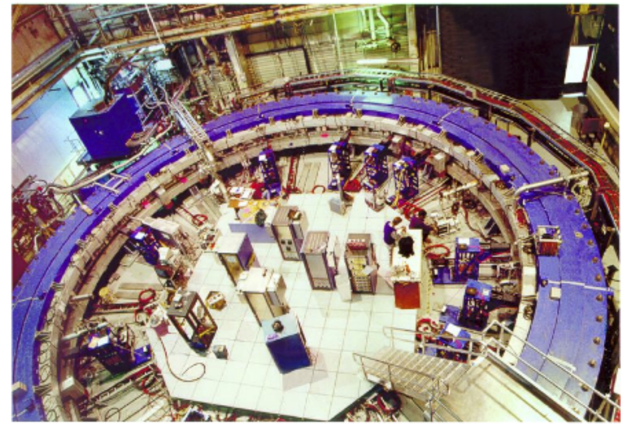
Collider constraints
Light Neutral mediator
Resonant production at LEP
BaBar
Beam dumps
Supernovae cooling

Direct



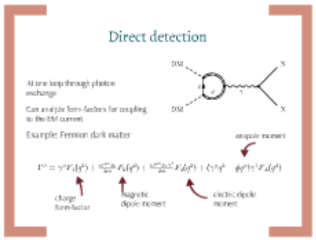
Detection

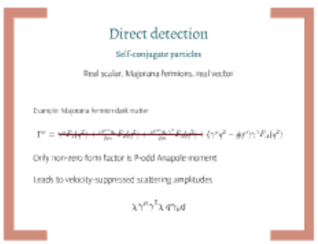
g-2

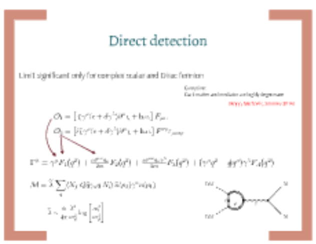


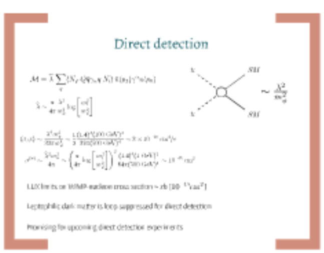
Colliders

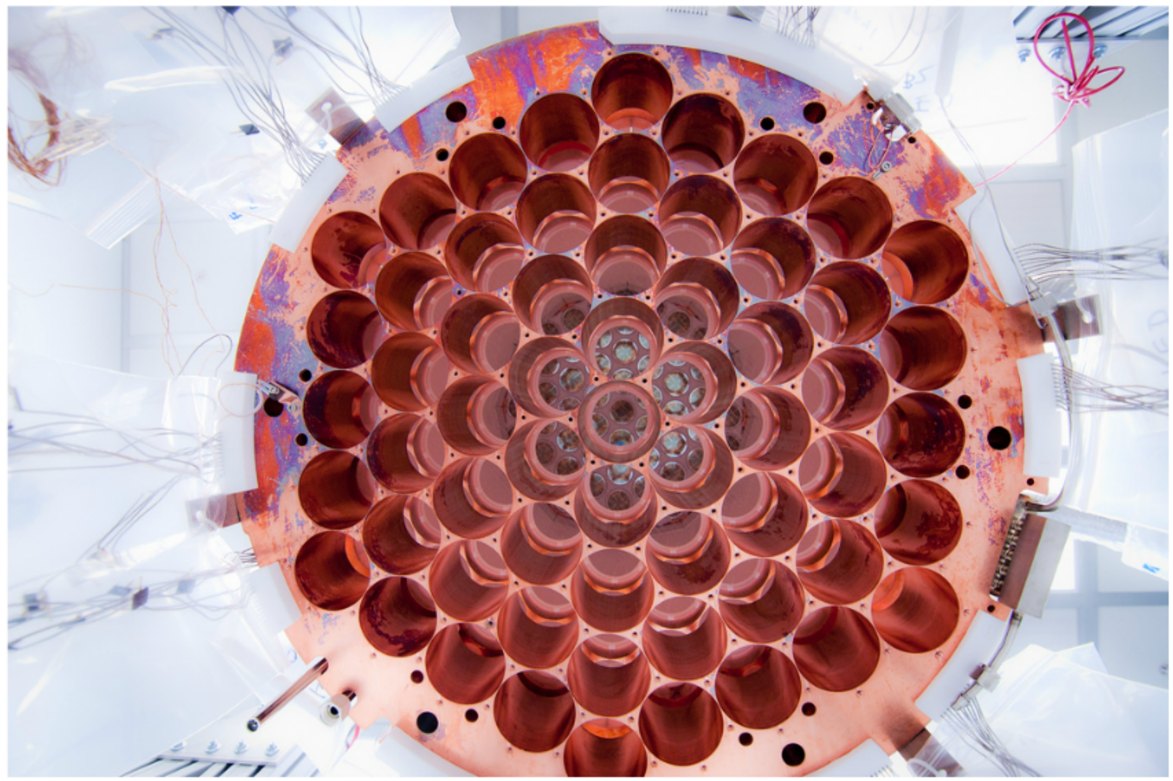
Direct











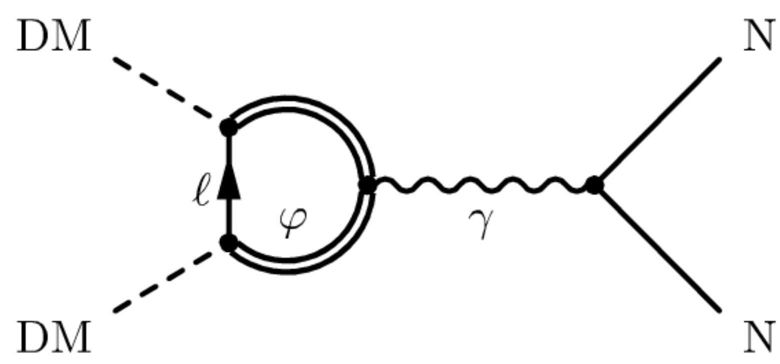
Detection

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

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

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]

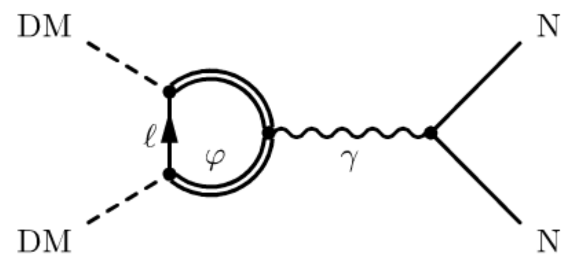
$$\mathcal{O}_1 = \left[\bar{\chi}\gamma^\mu(c + d\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F_{\mu\nu},$$

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

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

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

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



Direct detection

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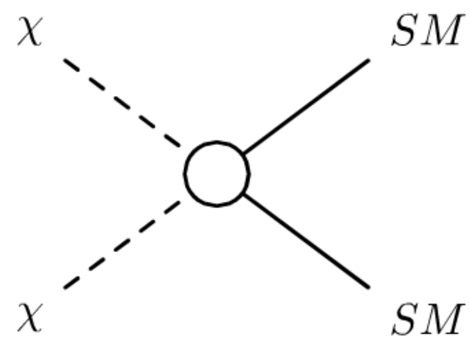


$$\sim \frac{\lambda^2}{m_\phi^2}$$

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

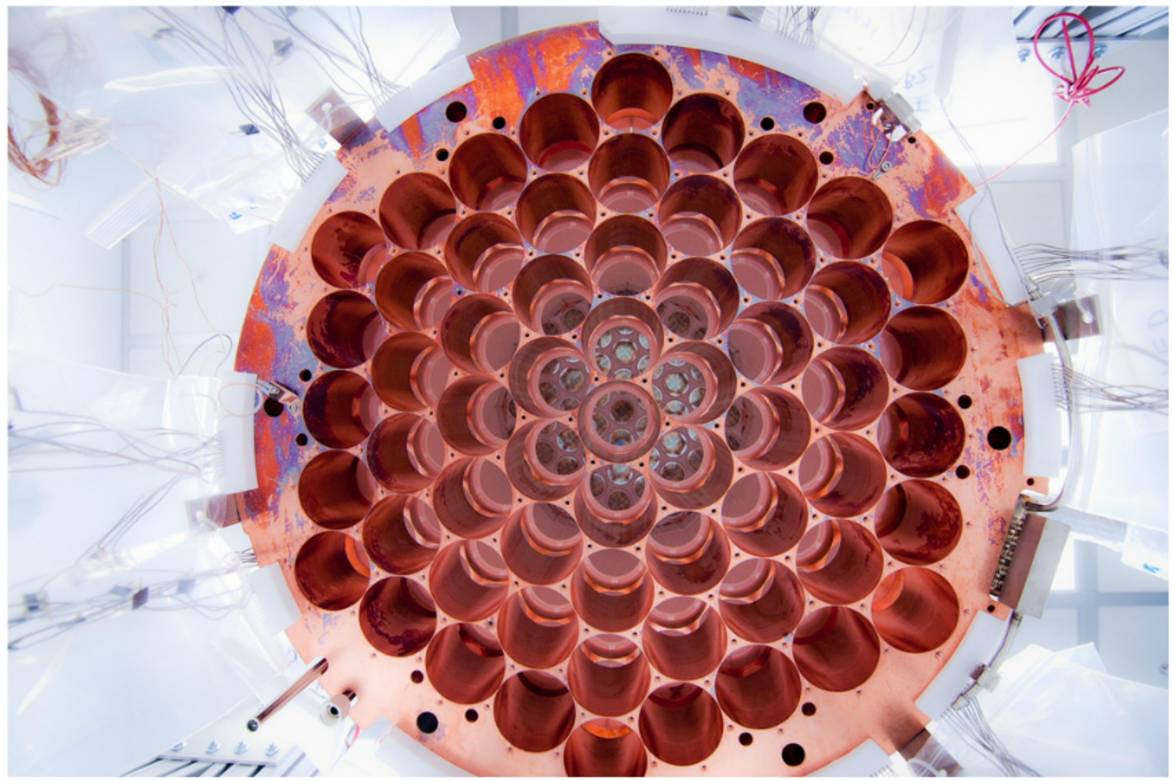
$$\sigma^{(n)} \sim \frac{\widetilde{\lambda}^2 m_n^2}{4\pi} \sim \left(\frac{\alpha}{4\pi}\log\left[\frac{m_l^2}{m_\phi^2}\right]\right)^2 \frac{(1.4)^4(1\text{ GeV})^2}{64\pi(500\text{ GeV})^4} \sim 10^{-45}\text{ cm}^2$$

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

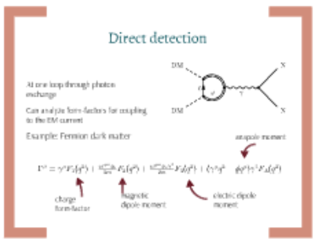
Leptophilic dark matter is loop suppressed for direct detection

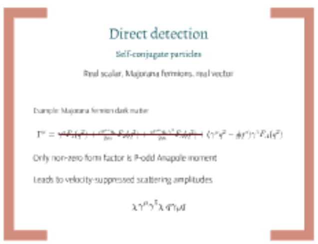
Promising for upcoming direct detection experiments

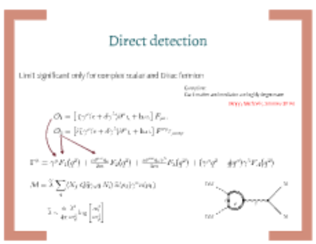
Direct

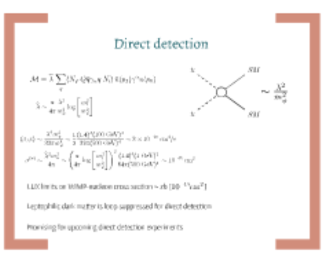


Detection

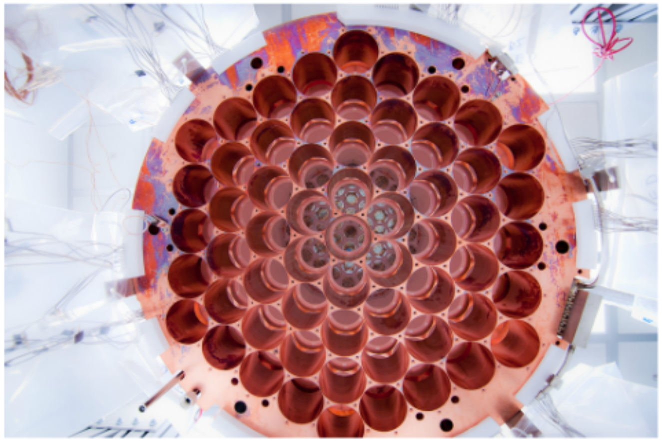






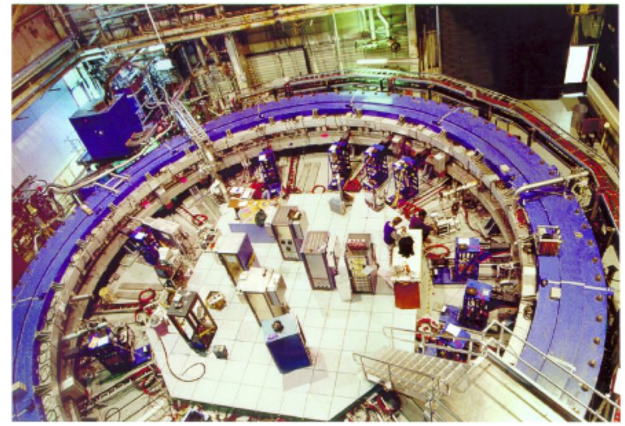


Direct



Detection

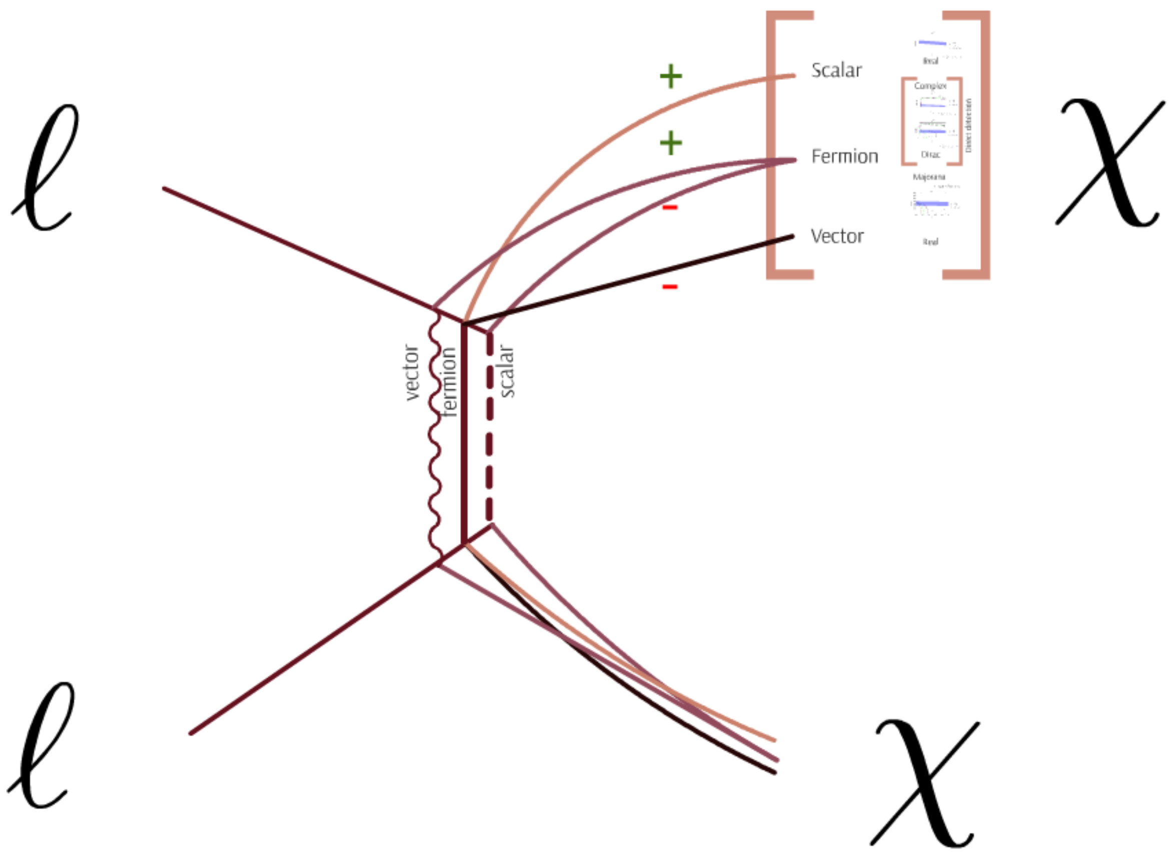
g-2

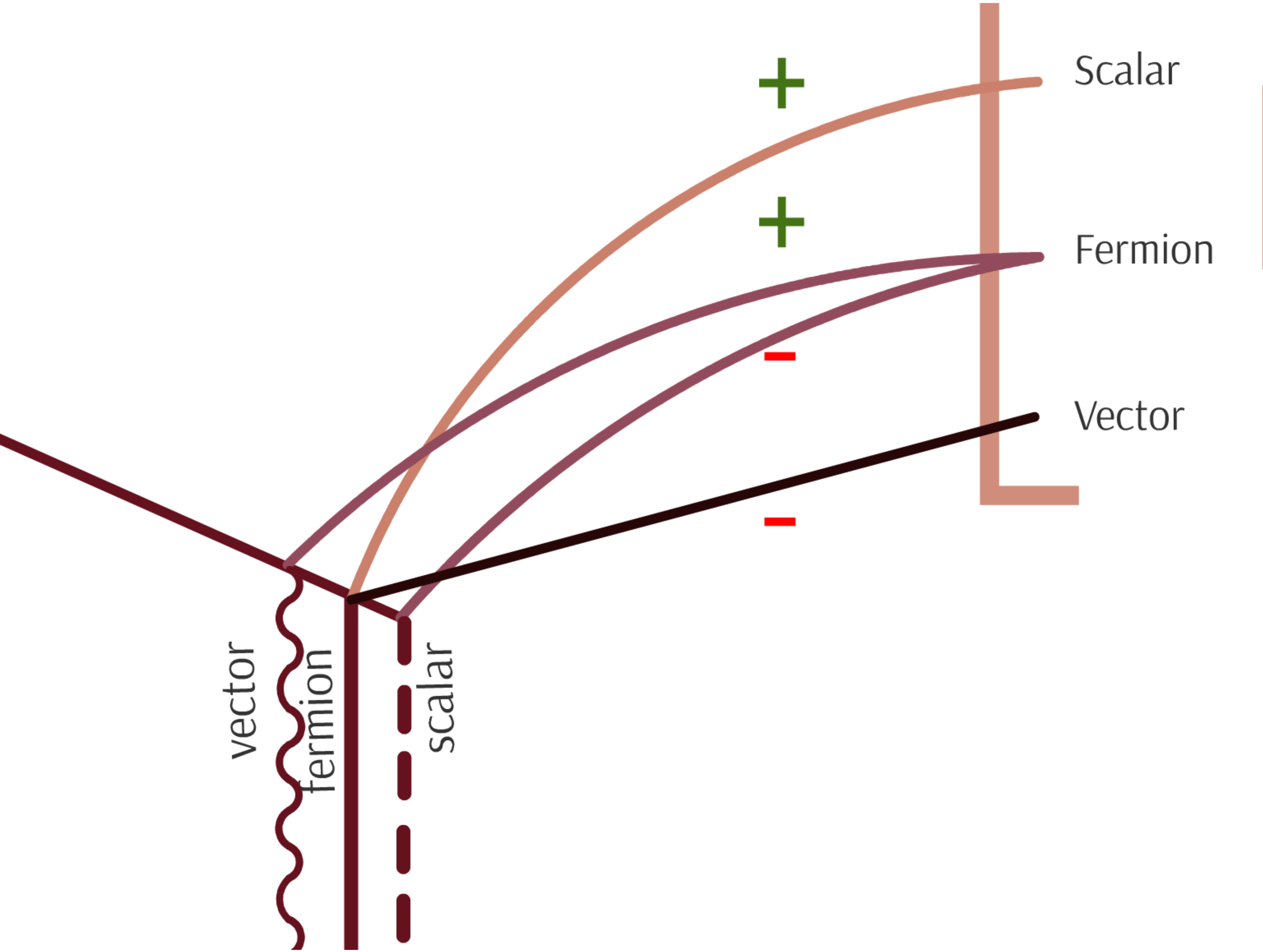


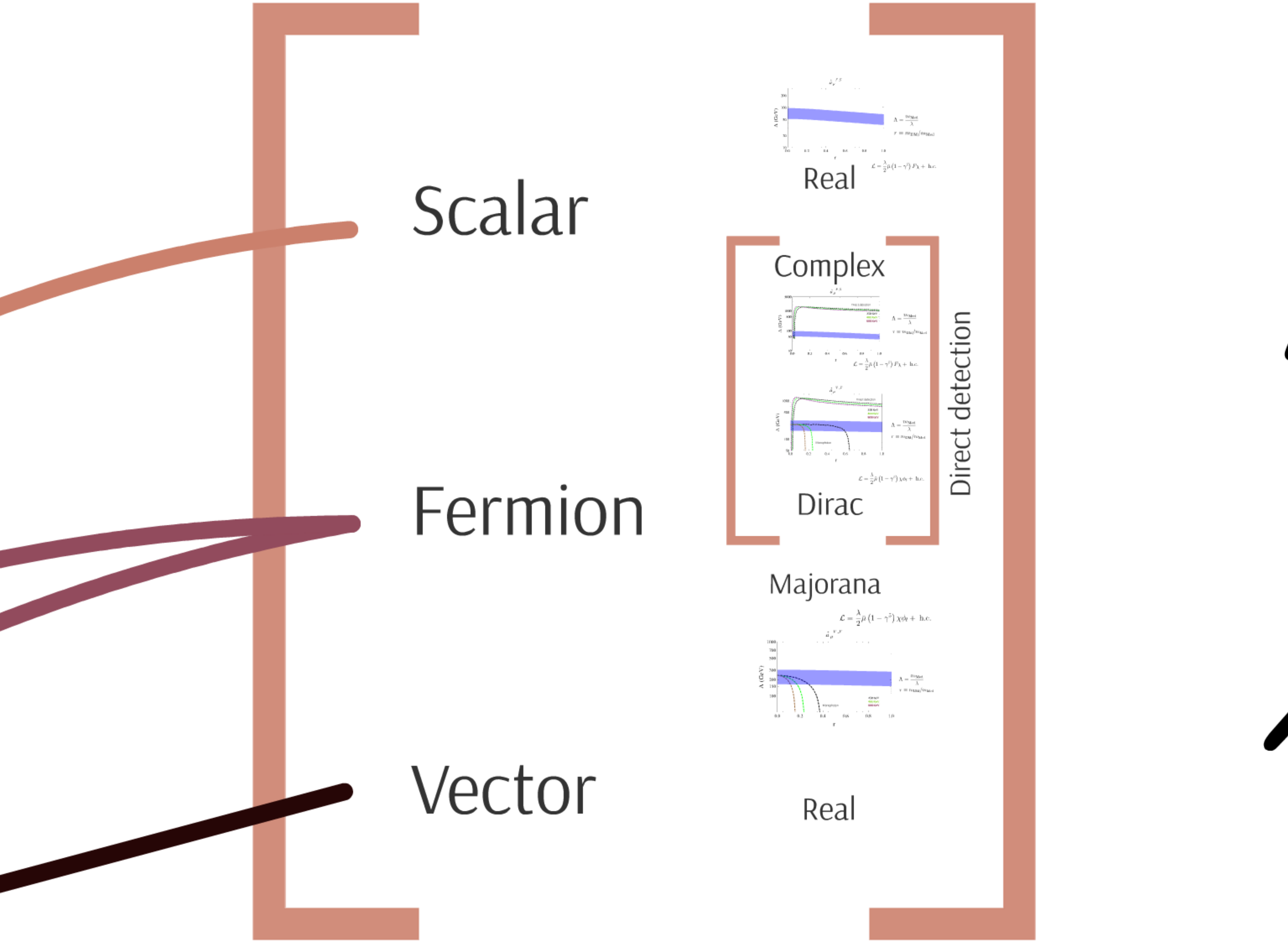
Colliders

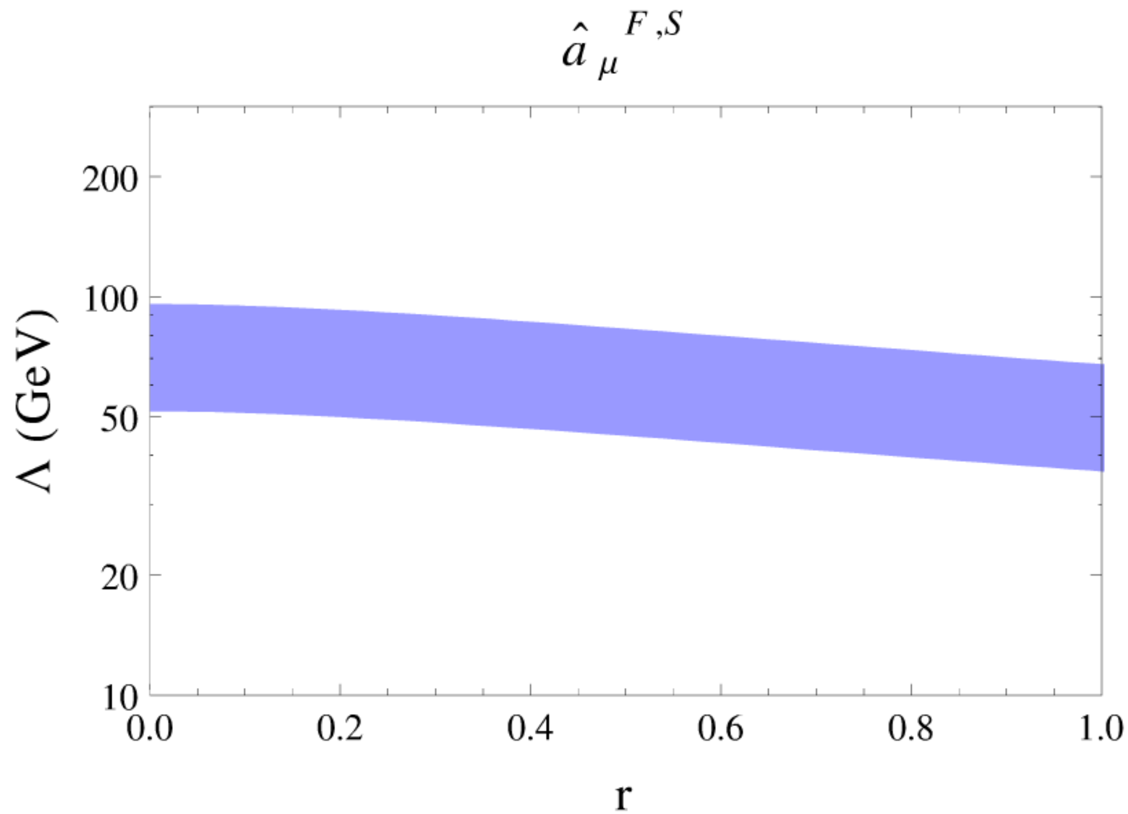
Simplified Models

Charged Mediator




Scalar
Fermion
Vector
+
+
-
-
vector
fermion
scalar


Scalar
Fermion
Vector
Real
Complex
Dirac
Majorana
Real
Direct detection



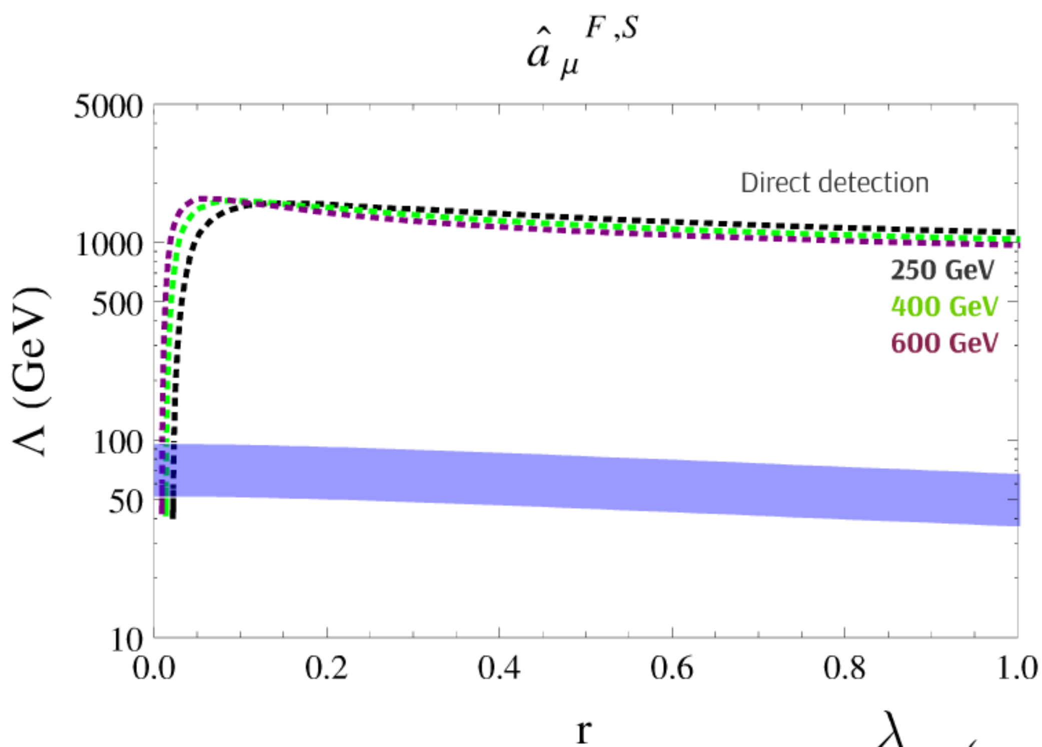
$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

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

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

Real

Complex



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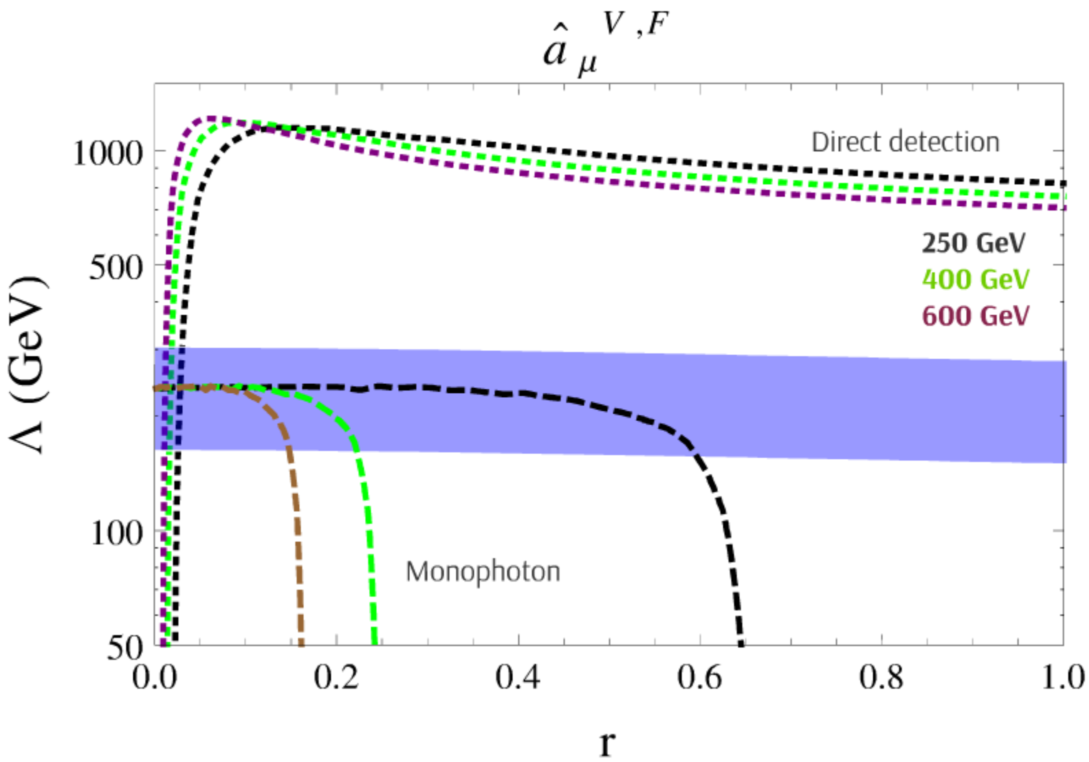

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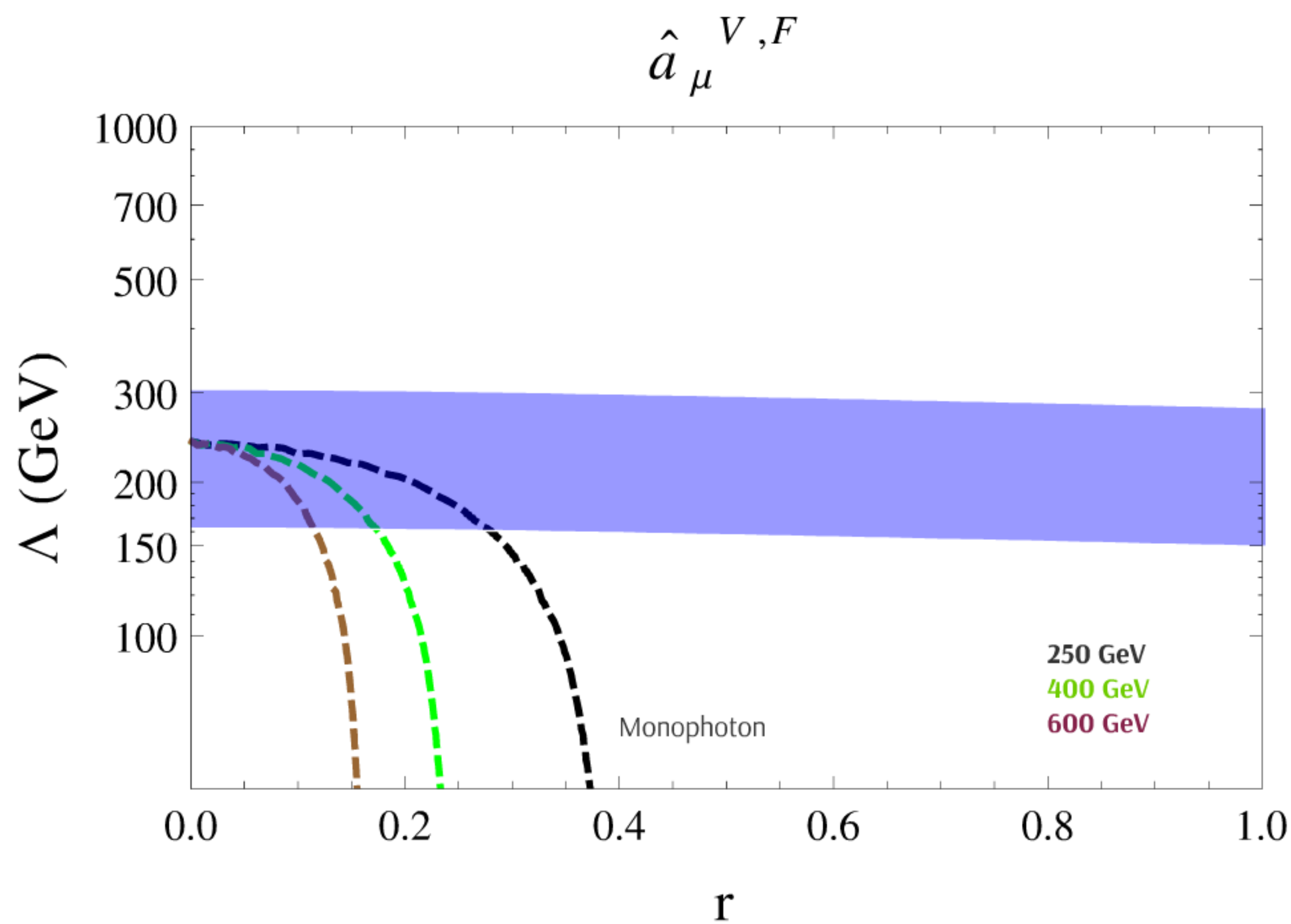
$$\mathcal{L} = \frac{\lambda}{2}\bar{\mu}\left(1-\gamma^5\right)\chi\phi_l + \text{ h.c.}$$

Dirac

Majorana

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



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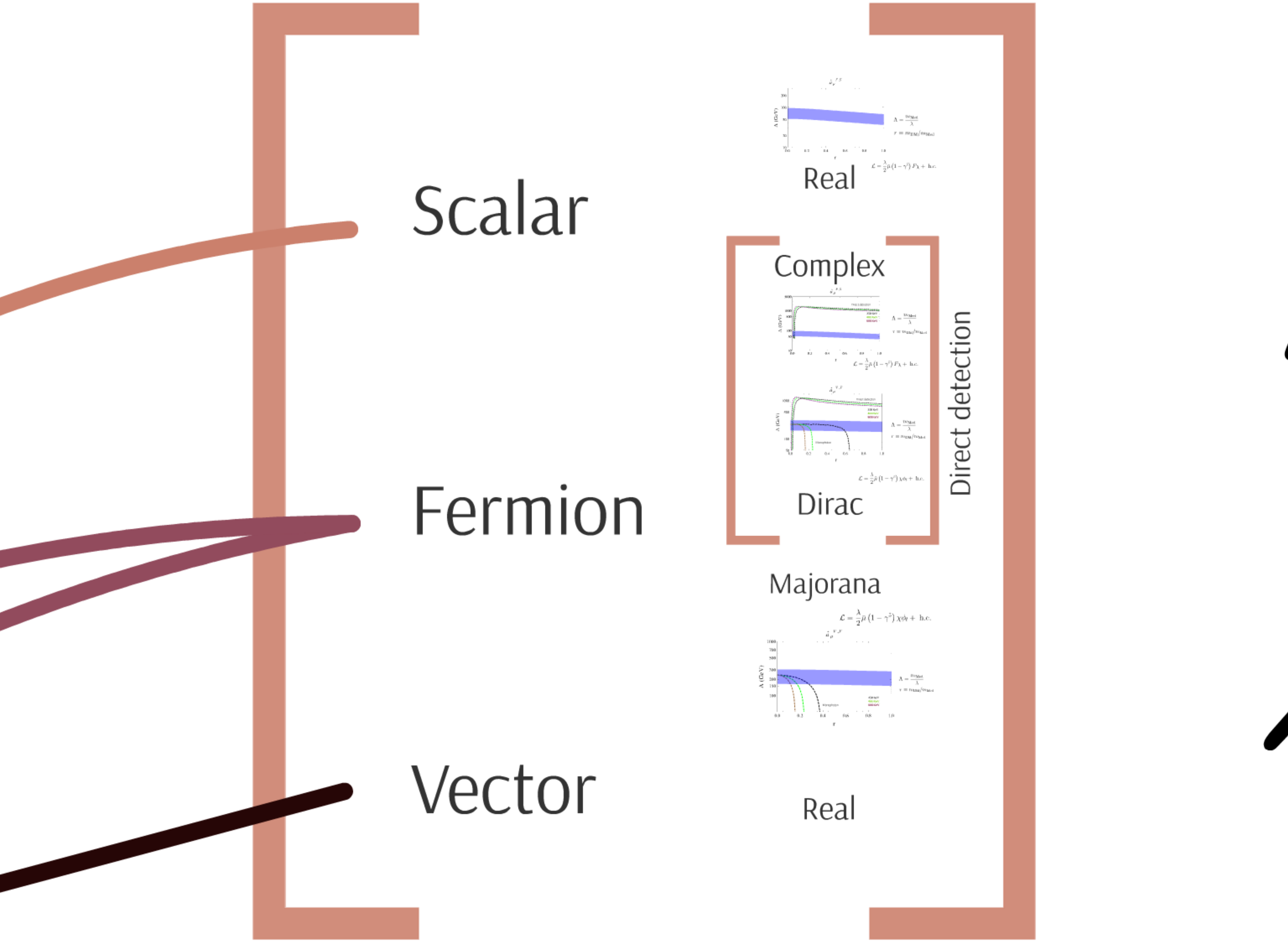
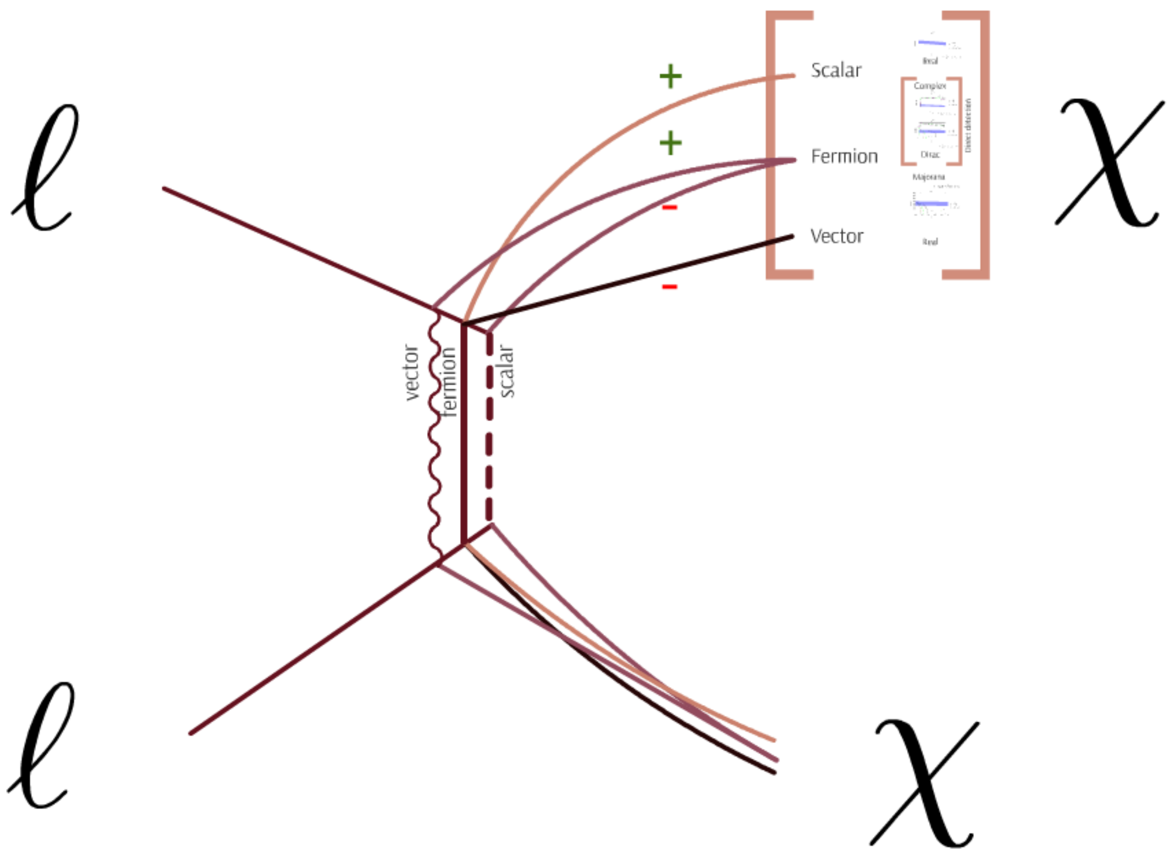

Scalar
Fermion
Vector
Real
Complex
Dirac
Majorana
Real
Direct detection

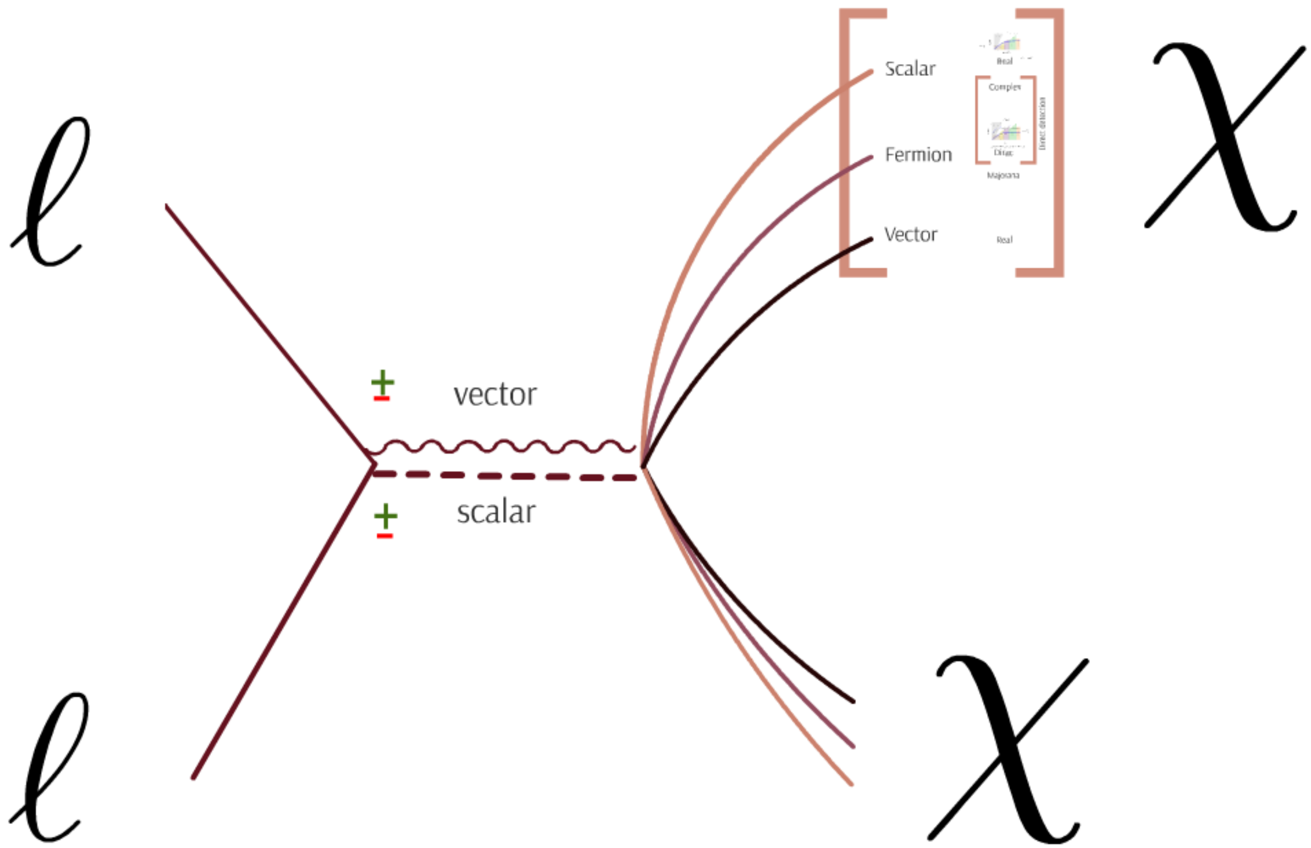
Simplified Models

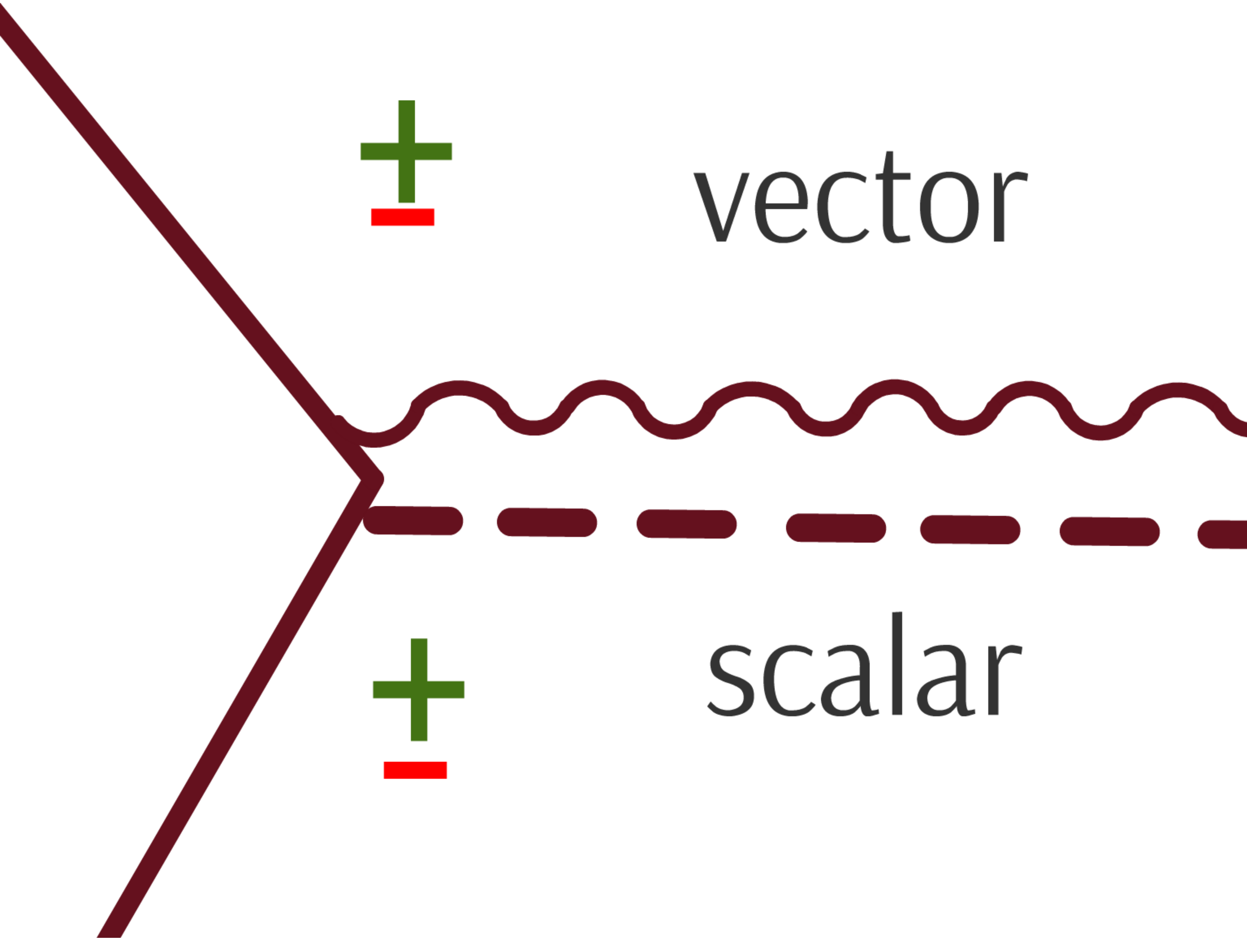
Charged Mediator



Simplified Models

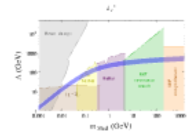
Neutral Mediator




±
vector
±
scalar

Scalar

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

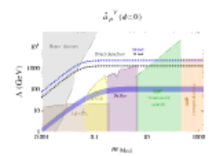


Real

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

Complex

Fermion



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

Dirac

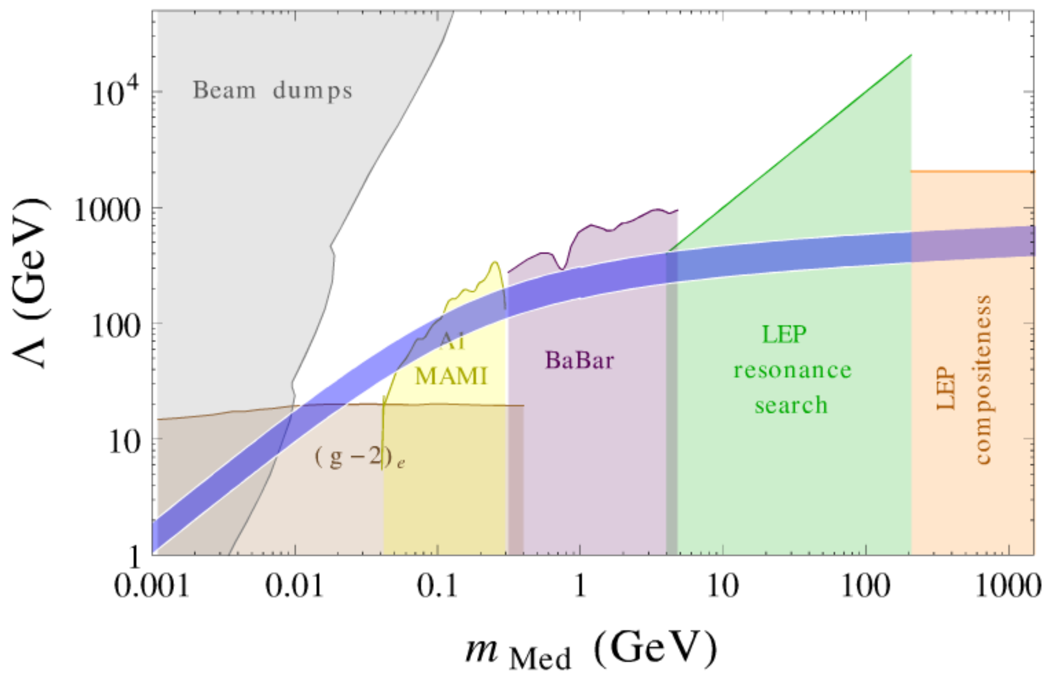
Majorana

Direct detection

Vector

Real

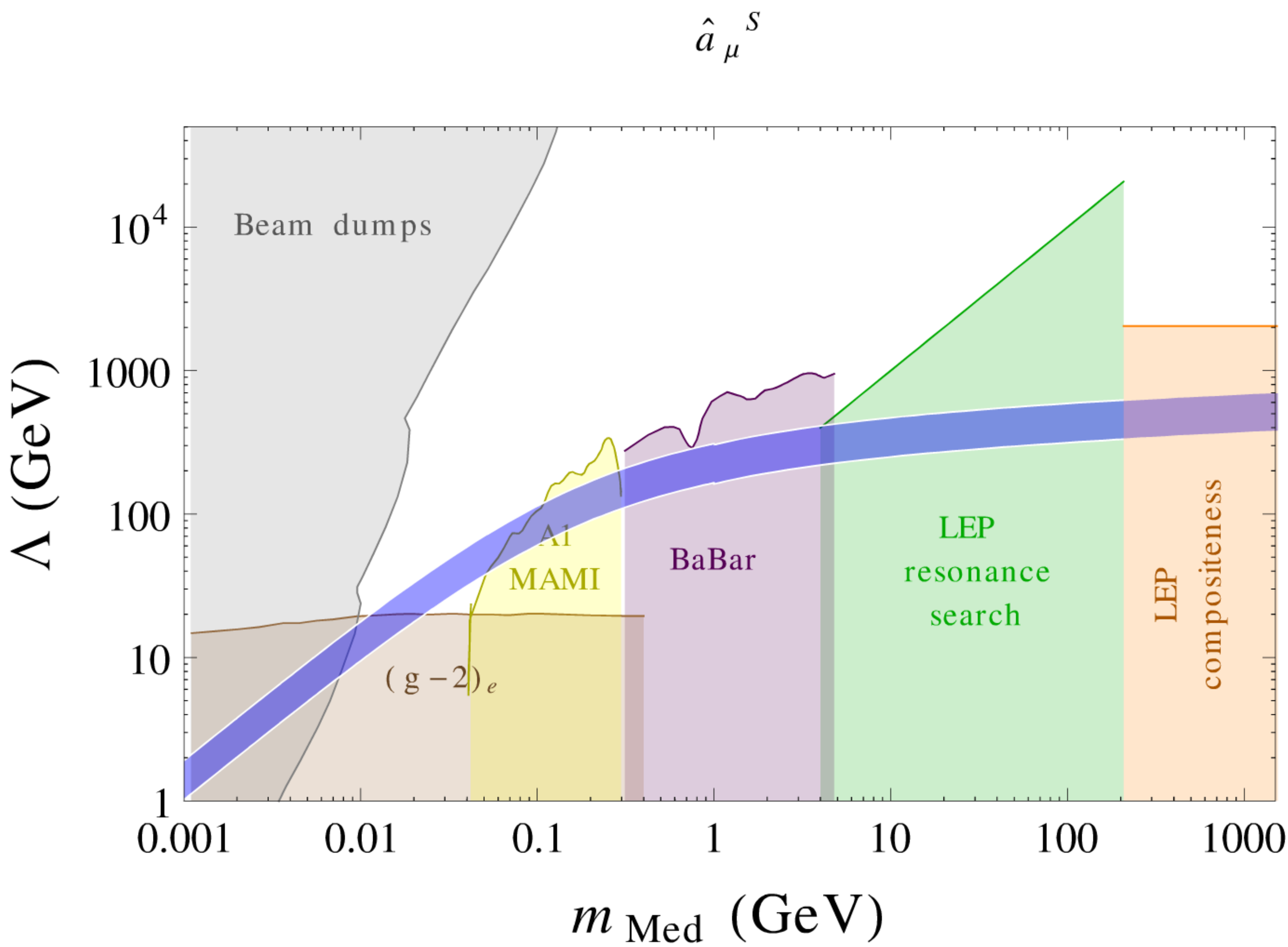
$\hat{a}_\mu{}^S$



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

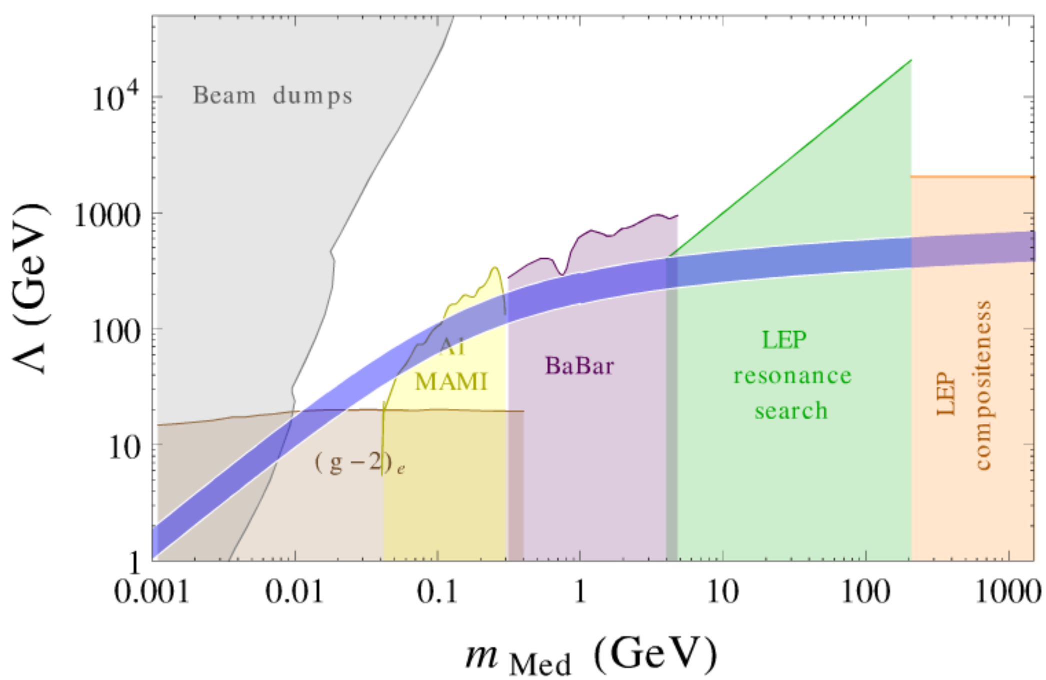
Real

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



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

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

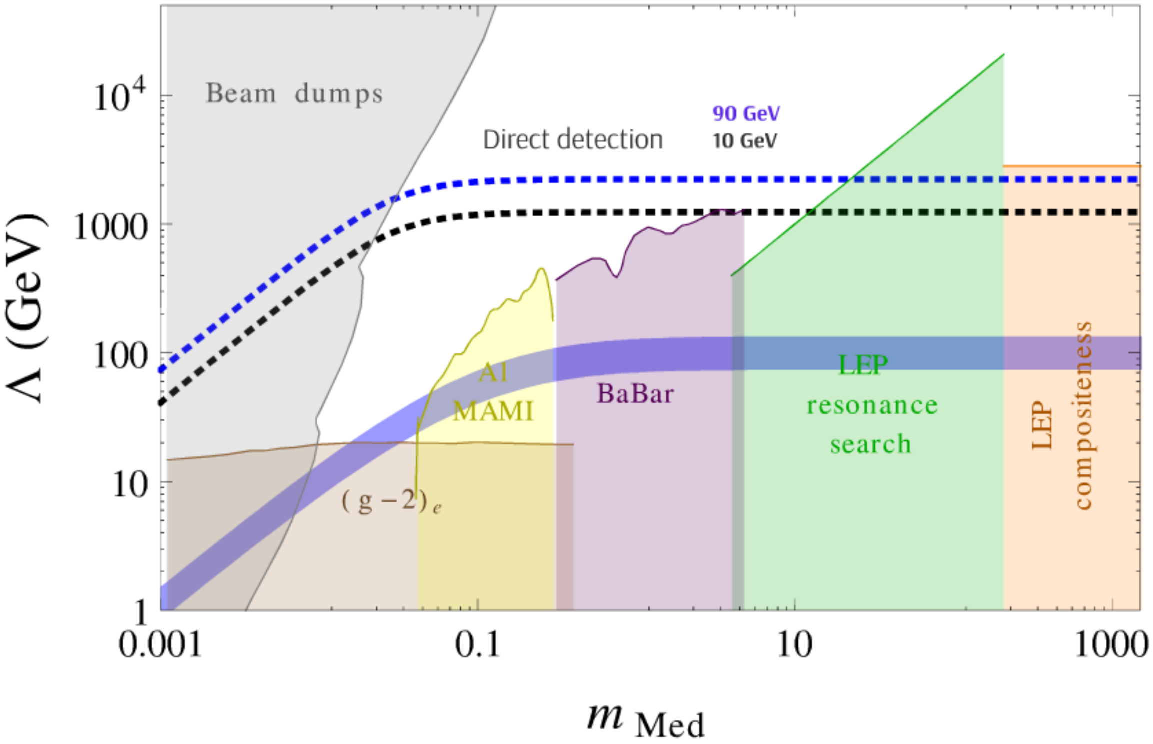


$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

Real

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

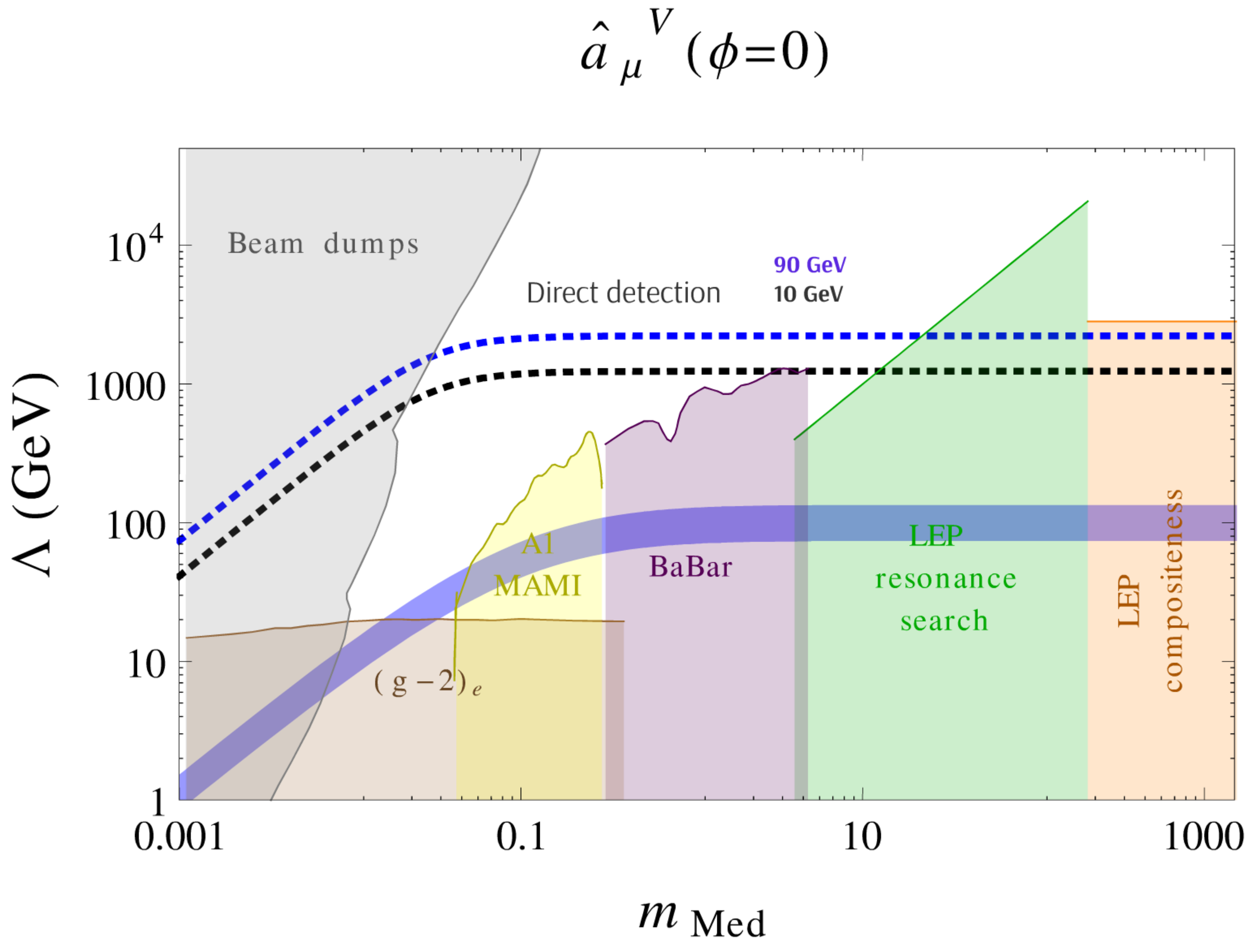
$\hat{a}_\mu^V\ (\phi=0)$



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

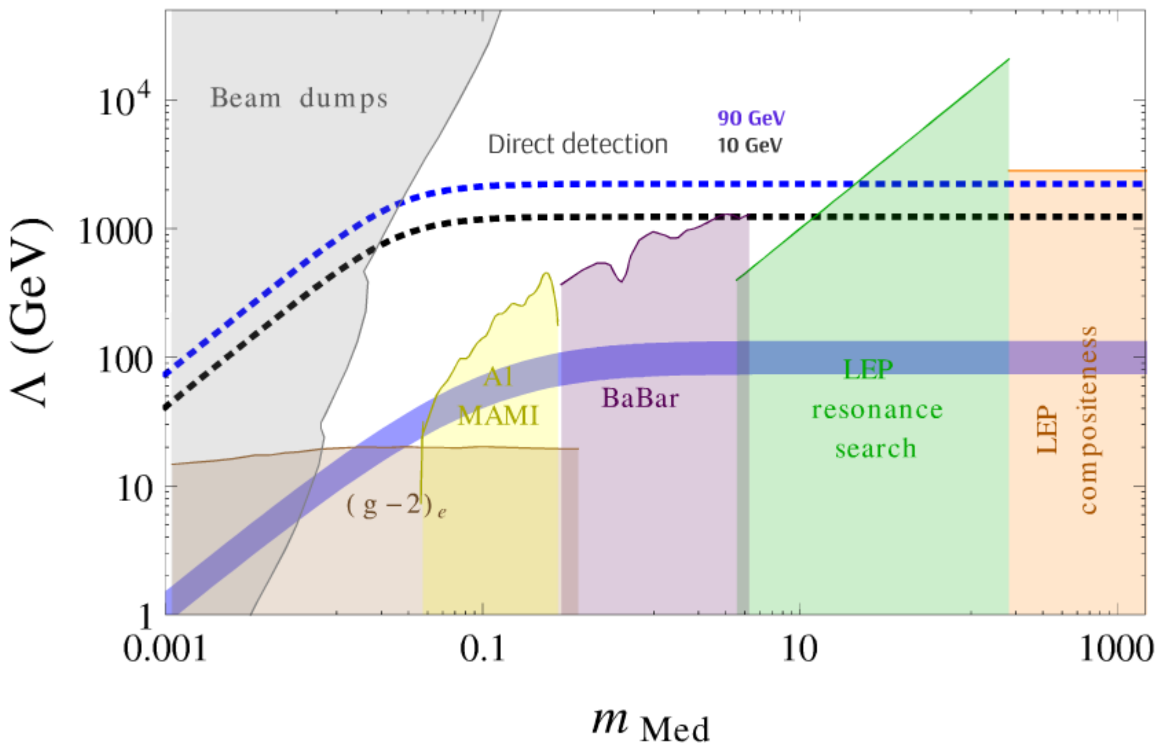
$$\mathcal{L} = \frac{\lambda_\chi}{2}\bar{\chi}\gamma^\nu\left(\cos\theta + \sin\theta\gamma^5\right)\chi V_\nu + \frac{\lambda}{2}\bar{\mu}\gamma^\nu\left(\cos\phi + \sin\phi\gamma^5\right)\mu V_\nu$$

Dirac



$\hat{a}_\mu^V(\phi=0)$
Beam dumps
Direct detection
90 GeV
10 GeV
A1
MAMI
BaBar
LEP
resonance
search
LEP
compositeness
$(g-2)_e$
Λ (GeV)
$m_{\rm Med}$
10^4
1000
100
10
1
0.001
0.1
10
1000

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

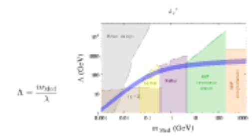


$$\Lambda = \frac{m_{\rm Med}}{\lambda}$$

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

Dirac

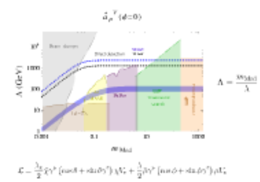
Scalar



Real

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

Complex



Dirac

Majorana

Direct detection

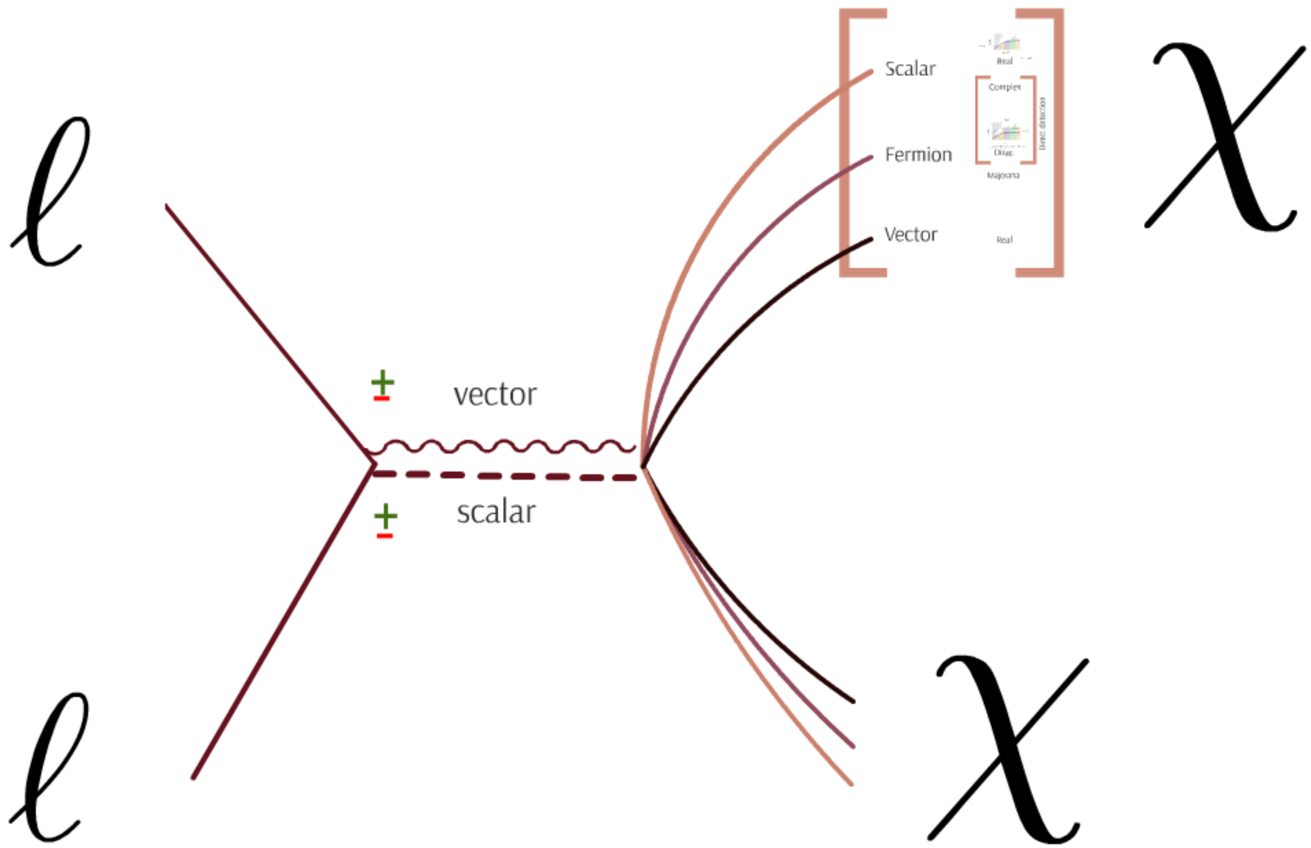
Fermion

Vector

Real

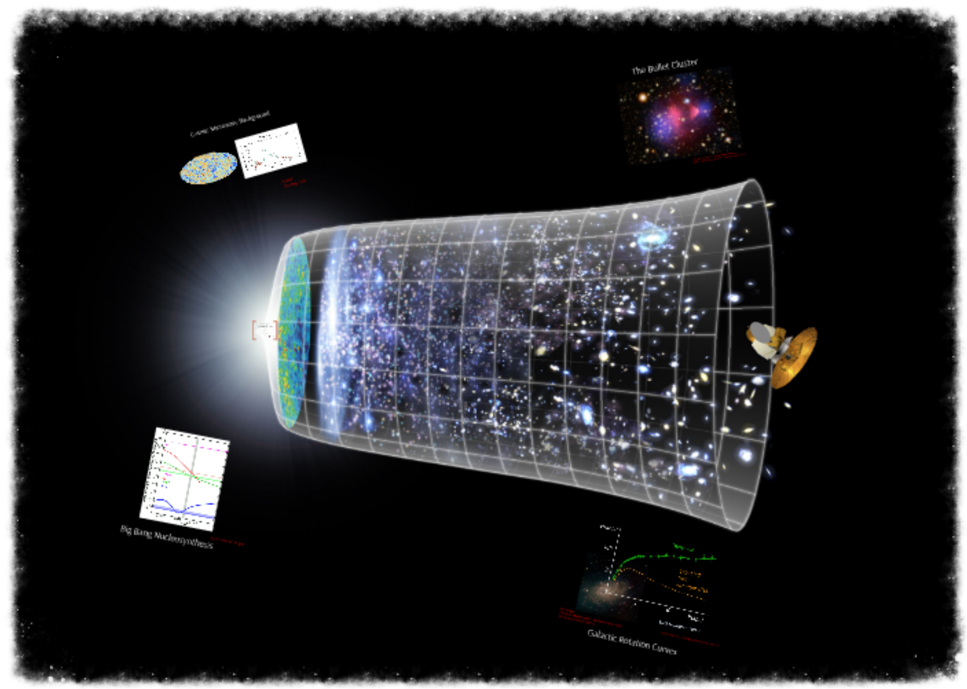
Simplified Models

Neutral Mediator



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