

Implications of Naturalness for Light Hidden Sectors

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TRIUMF

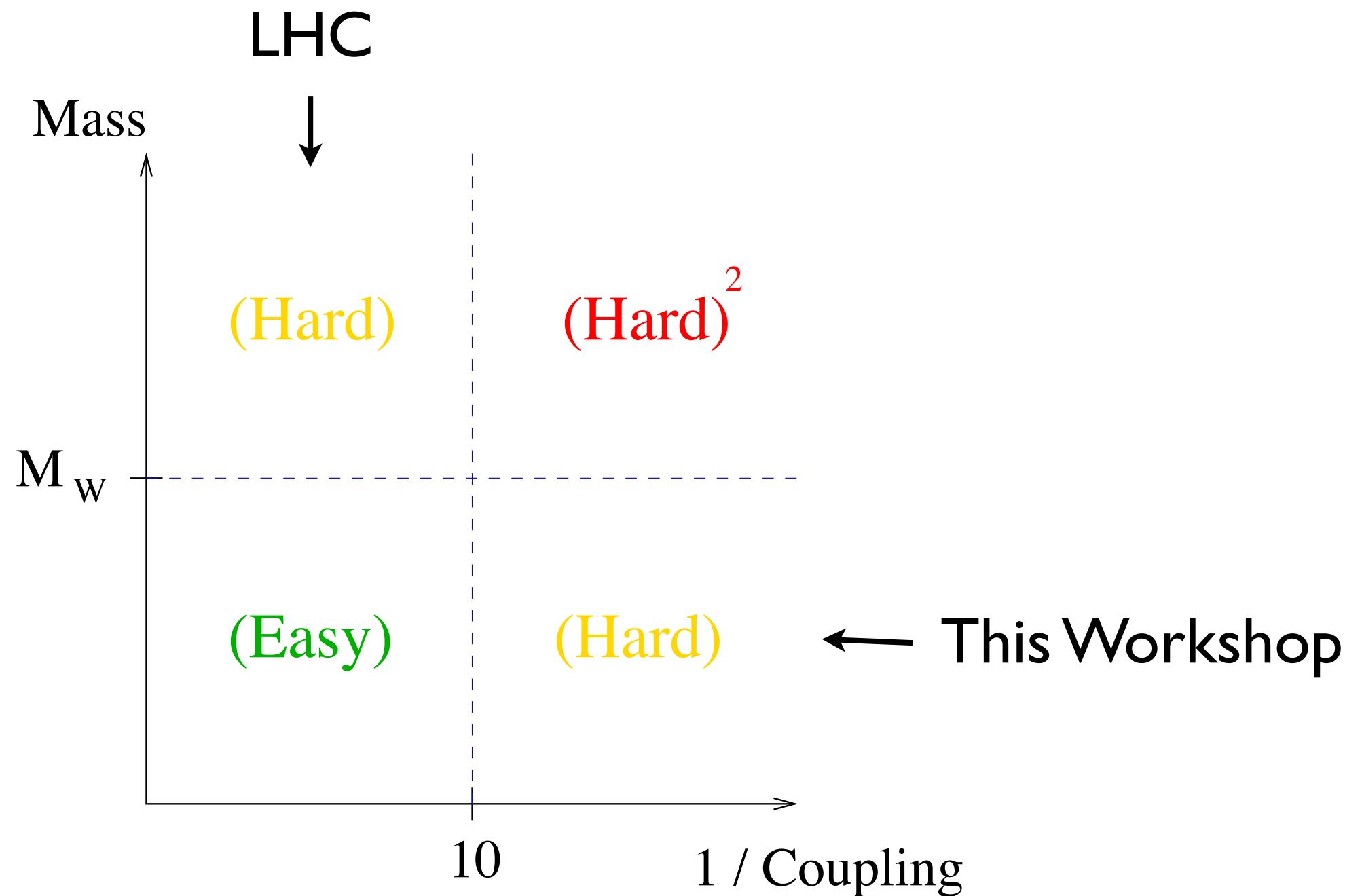
with

Patrick Chan, Lindsay Forestell, Matthew Low,
Kristian McDonald, Kris Sigurdson, Andrew Spray

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Light Dark World 2016, IBS CTPU

Searching for New Phenomena

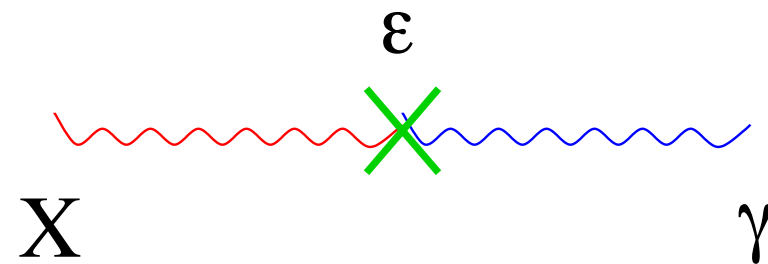


Portals to Hidden Physics

- Two nice ways for new hidden physics to couple:

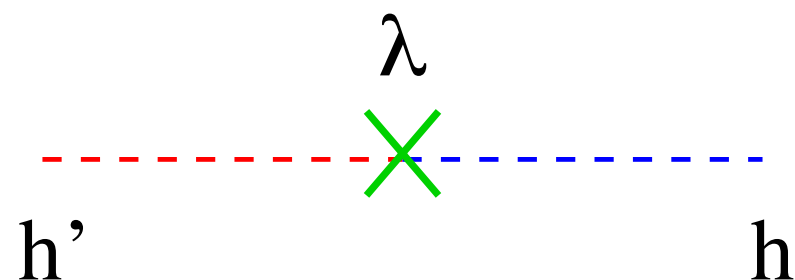
- Vector Portal
(X = “hidden vector”)

$$\epsilon X_{\mu\nu} F^{\mu\nu}$$



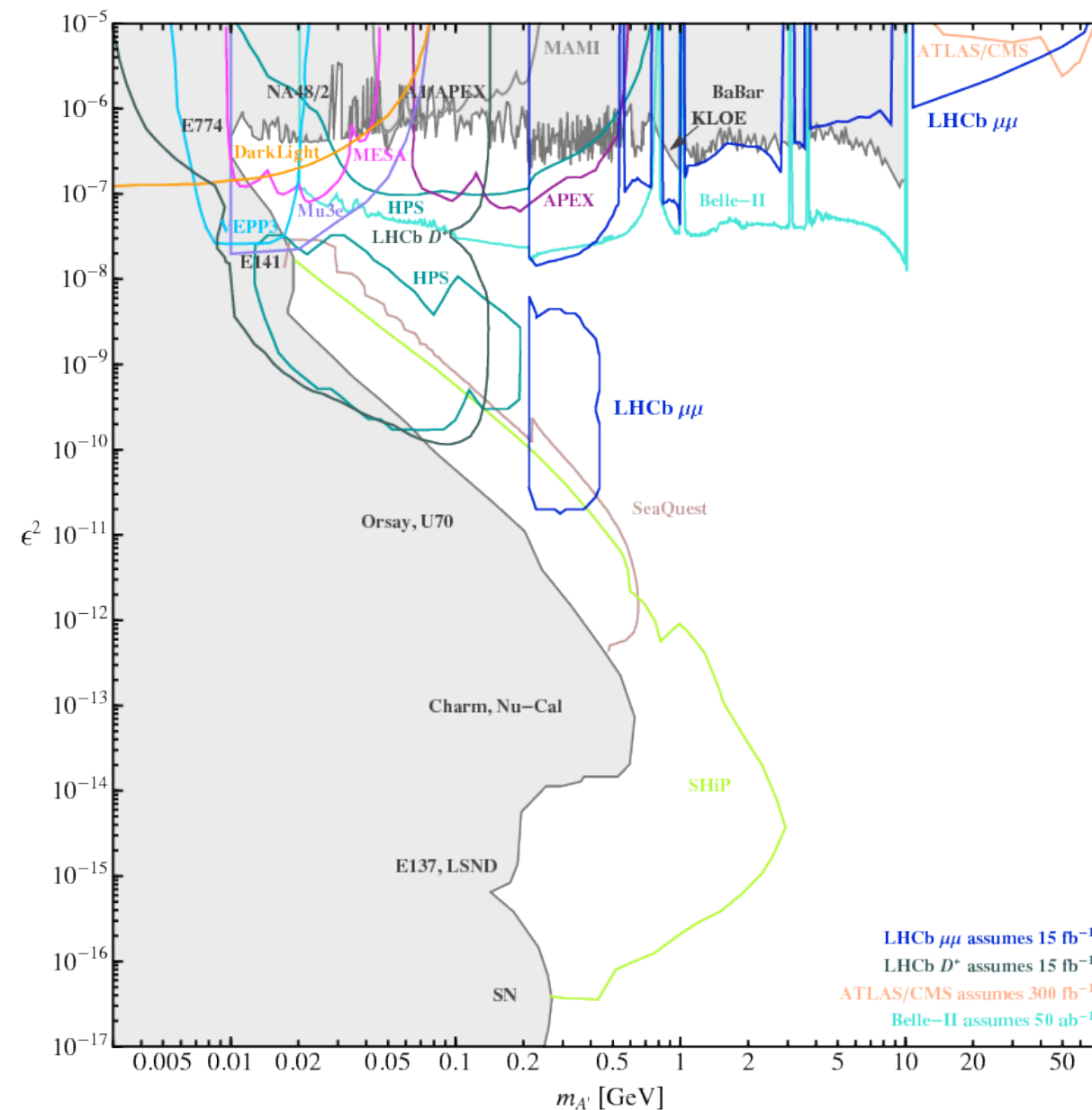
- Higgs Portal
(H' = “hidden Higgs”)

$$\lambda |H'|^2 |H|^2$$



Minimal Vector Portal: Combined Limits

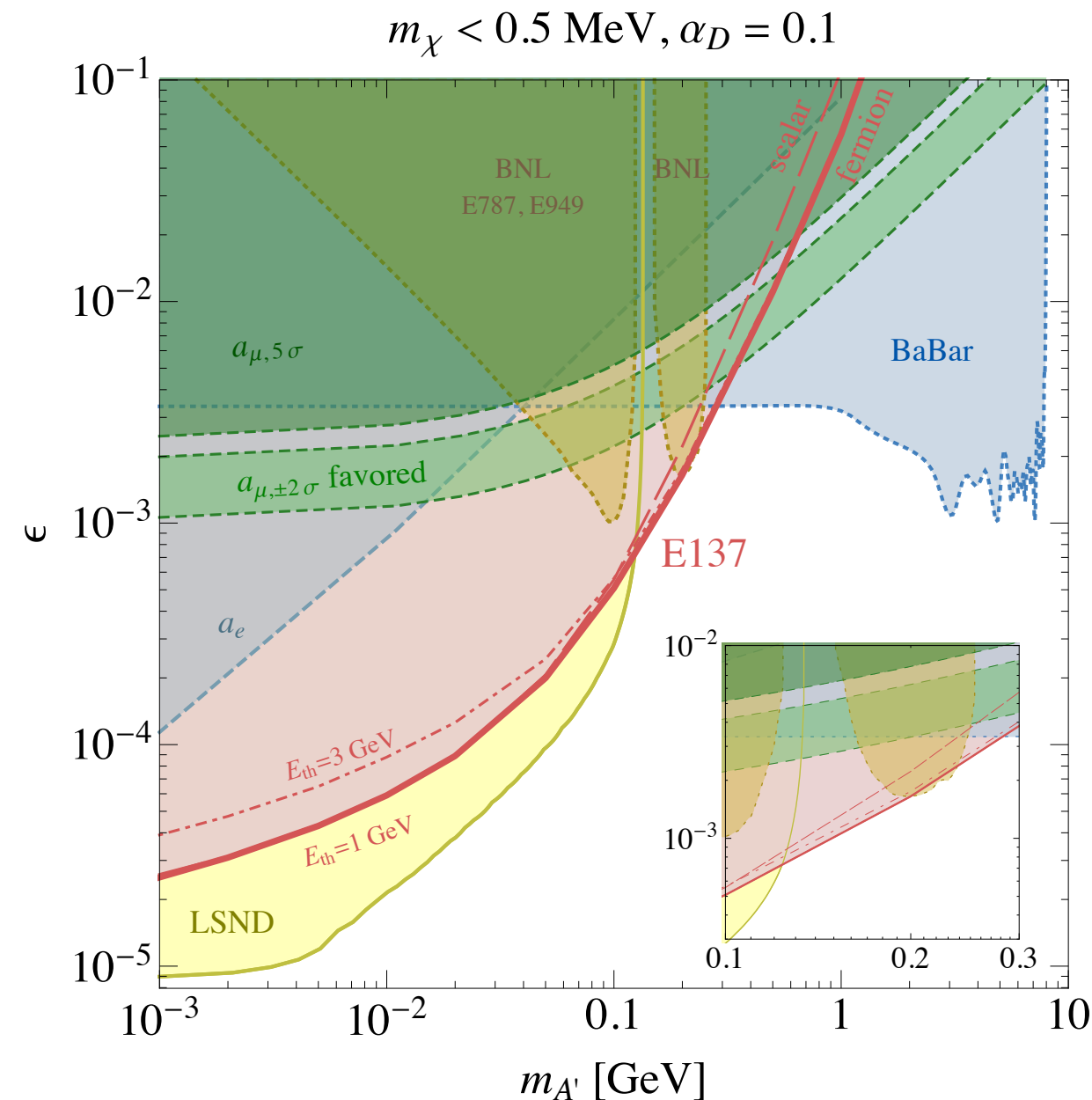
- Hidden vector X^μ , mass $m_x > 2m_e$, decays $X^\mu \rightarrow SM$:



[Bjorken, Essig, Schuster, Toro 2009; ...; **Ilten et al. 2016**]

Minimal Vector Portal: Combined Limits

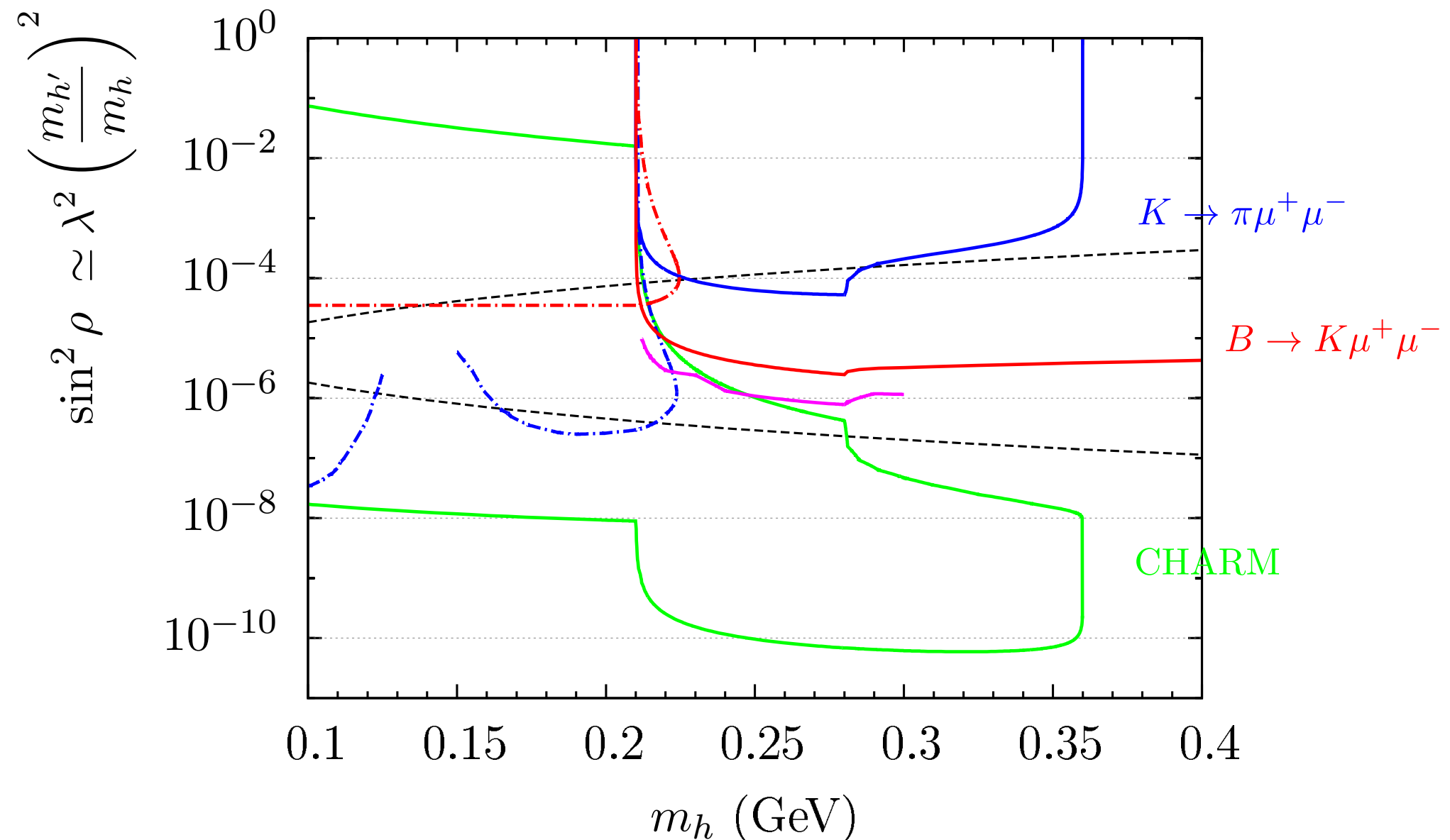
- Hidden vector X^μ , mass $m_x > 2m_e$, decays $X^\mu \rightarrow DM$:



[de Niverville et al. 2011, Essig et al. 2013; Batell et al. 2014; ...]

Minimal Higgs Portal: Combined Limits

- Hidden Higgs h' , mass $m_{h'}$, decays $h' \rightarrow SM$:



[...; Batell, Pospelov, Ritz 2009; Bezrukov+Gorbunov 2013; **Clarke, Foot, Volkas 2013**;...]

Beyond Minimal

- Hidden sectors can be more complicated than minimal.
- Motivation:
 1. Origin of light mass and naturalness?
 2. Dark matter: Majorana, ADM, iDM, xDM, SIDM, ...
 3. Nature is Complicated!
- What do these considerations imply for new signals?
 - three examples motivated by naturalness

Non-Minimal #1: SUSY Hidden Vector

SUSY Hidden Vector

- Hidden $U(1)_x$ mixes kinetically with $U(1)_Y$.
Hidden Higgs multiplets to spontaneously break $U(1)_x$.

$$\mathcal{L} \supset \int d^2\theta \left(\underbrace{\frac{\epsilon}{2c_w} B^\alpha X_\alpha}_{\text{vector portal}} + \underbrace{\mu' H H'}_{\text{hidden Higgs fields}} \right) + (h.c.)$$

- Assumptions:
 - SUSY breaking is suppressed in the hidden sector.
 - $U(1)_x$ breaking occurs at or below the GeV scale.
 - Conserved R-parity (MSSM + hidden).
 - $\alpha_x = \alpha$

Hidden Masses: D-Terms

- SUSY kinetic mixing: $\epsilon D_x D_Y \supset \int d^2\theta \frac{\epsilon}{2} X^\alpha B_\alpha$
- This gives:

$$V_{D_x} = \frac{g_x^2}{2} \left(\sum_i x_i |\phi_i|^2 + \frac{\epsilon}{2} \frac{g_Y}{g_x} v^2 \cos 2\beta \right)^2$$

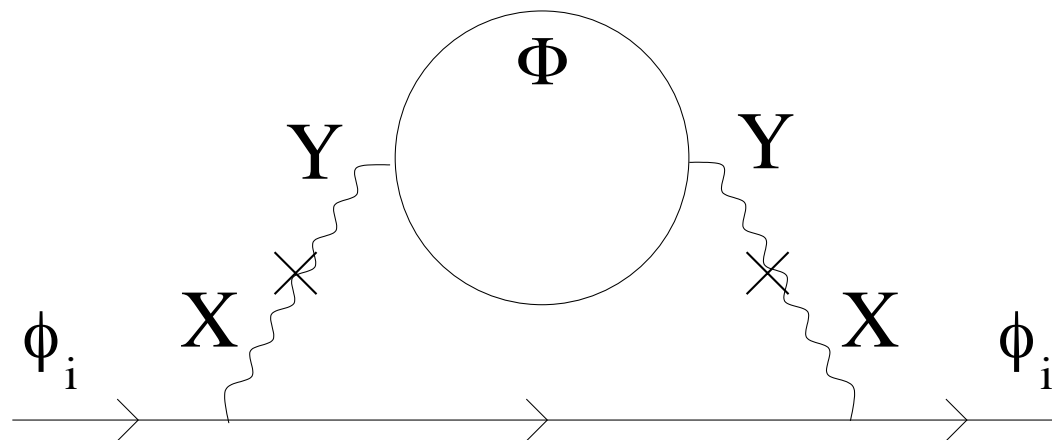
An effective Fayet-Iliopoulos term! [Baumgart *et al.* 2009]

- Contributes to $U(1)_x$ breaking:

$$\langle \phi_i \rangle = \sqrt{\epsilon \frac{g_Y}{g_x} \frac{|\cos 2\beta|}{2|x_i|}} v \sim \sqrt{\epsilon} v$$

Hidden Masses: Residual Gauge Mediation

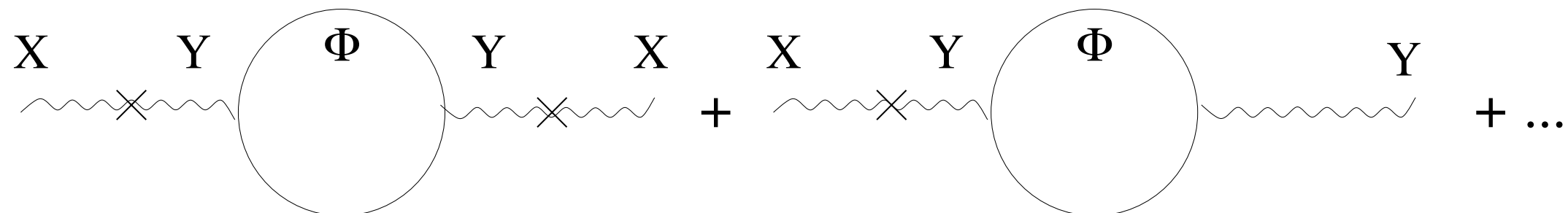
- Hidden scalar soft masses:



$$m_i^2 = \epsilon^2 \left(\frac{g_x x_i^2}{g_Y} \right) m_{Ec}^2$$

[DM, Poland, Zurek 2009]

- Hidden gaugino soft mass:



$$M_x < \epsilon^2 M_1 \quad (\text{Gaugino Screening})$$

SUSY Hidden Vector Spectrum

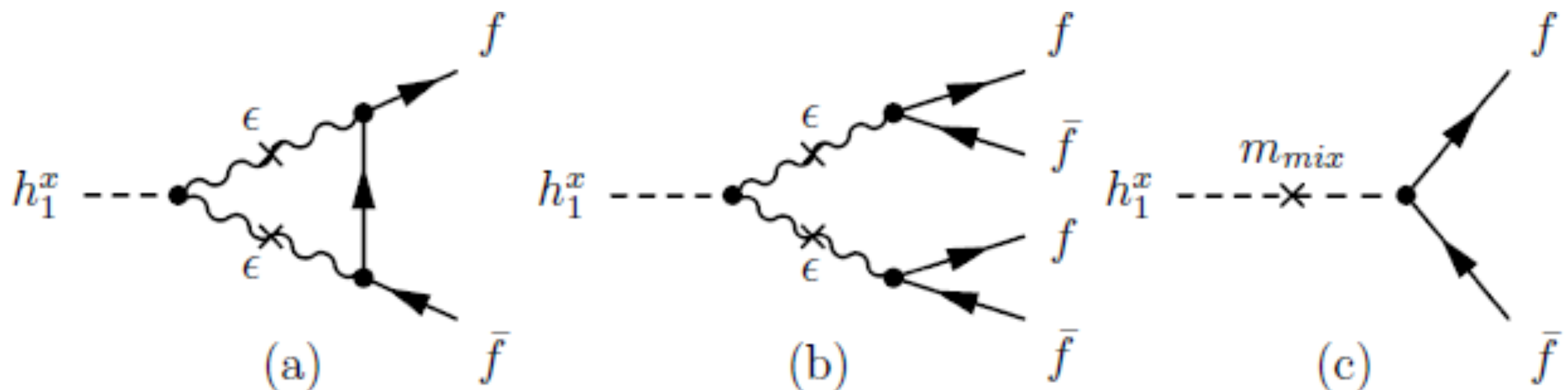
- Hidden states:
 - 1 X^μ massive hidden photon
 - 3 $\chi_{1,2,3}^x$ hidden fermion “neutralinos” (lightest is stable)
 - 2 $h_{1,2}^x$ hidden scalar Higgs bosons
 - 1 a^x hidden pseudoscalar Higgs boson
- Many mass orderings are possible.
Set all masses as ratios of m_x .
Vary m_x and ϵ .

Experimental Signals of the Theory

- Depend mainly on how the hidden vector decays. This is determined mostly by the mass spectrum.
- Four main cases: [DM, Spray 2014]
 - A: $X^\mu \rightarrow SM + SM$
 - B: $X^\mu \rightarrow \chi_1^x + \chi_1^x$
 - C: $X^\mu \rightarrow h_1^x + a^x$
 - D: $X^\mu \rightarrow \chi_1^x + \chi_2^x$
- Cases A and B are similar to minimal vector scenarios. Concentrate on cases C and D.

Case C: $X^\mu \rightarrow h_1^x + a^x$

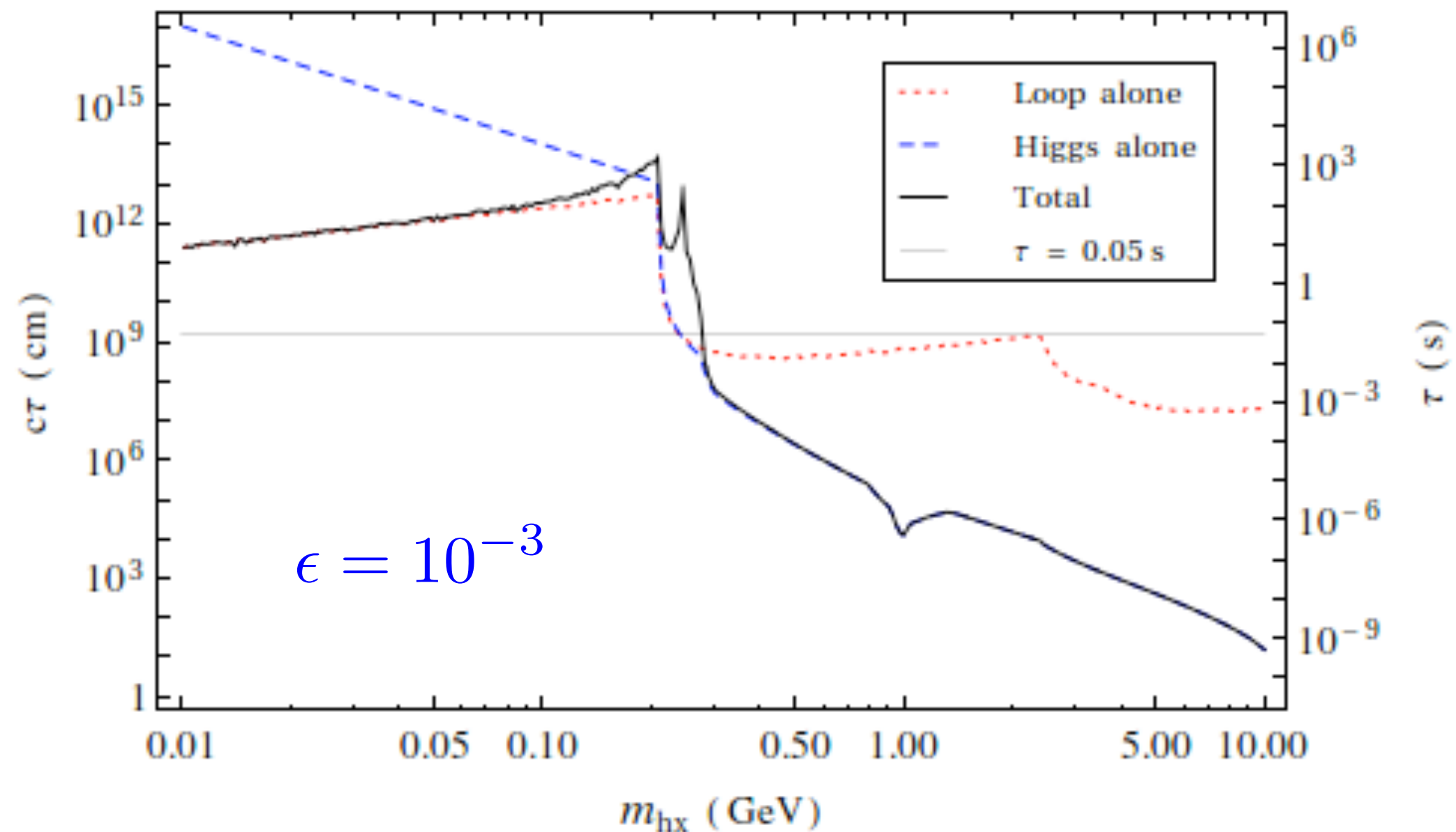
- Usually dominates over SM modes for $\alpha_x > \epsilon^2 \alpha$.
- Both h_1^x and a^x tend to be long-lived.
- Decays of h_1^x :



- Higgs portal coupling from: $\epsilon D_x D_Y \supset \int d^2\theta \frac{\epsilon}{2} X^\alpha B_\alpha$

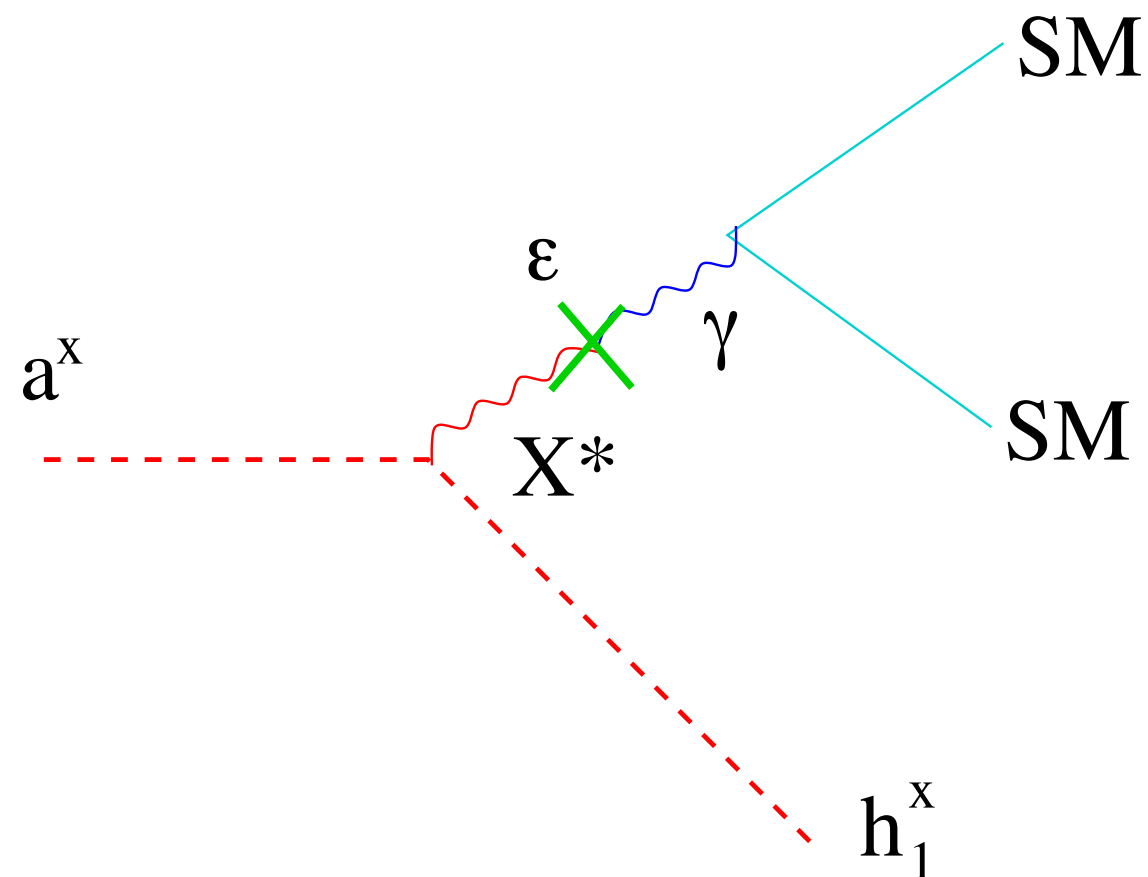
Case C: $X^\mu \rightarrow h_1^x + a^x$

- Lifetime of h_1^x : [Chan, Low, DM, Spray 2011]



Case C: $X^\mu \rightarrow h_1^x + a^x$

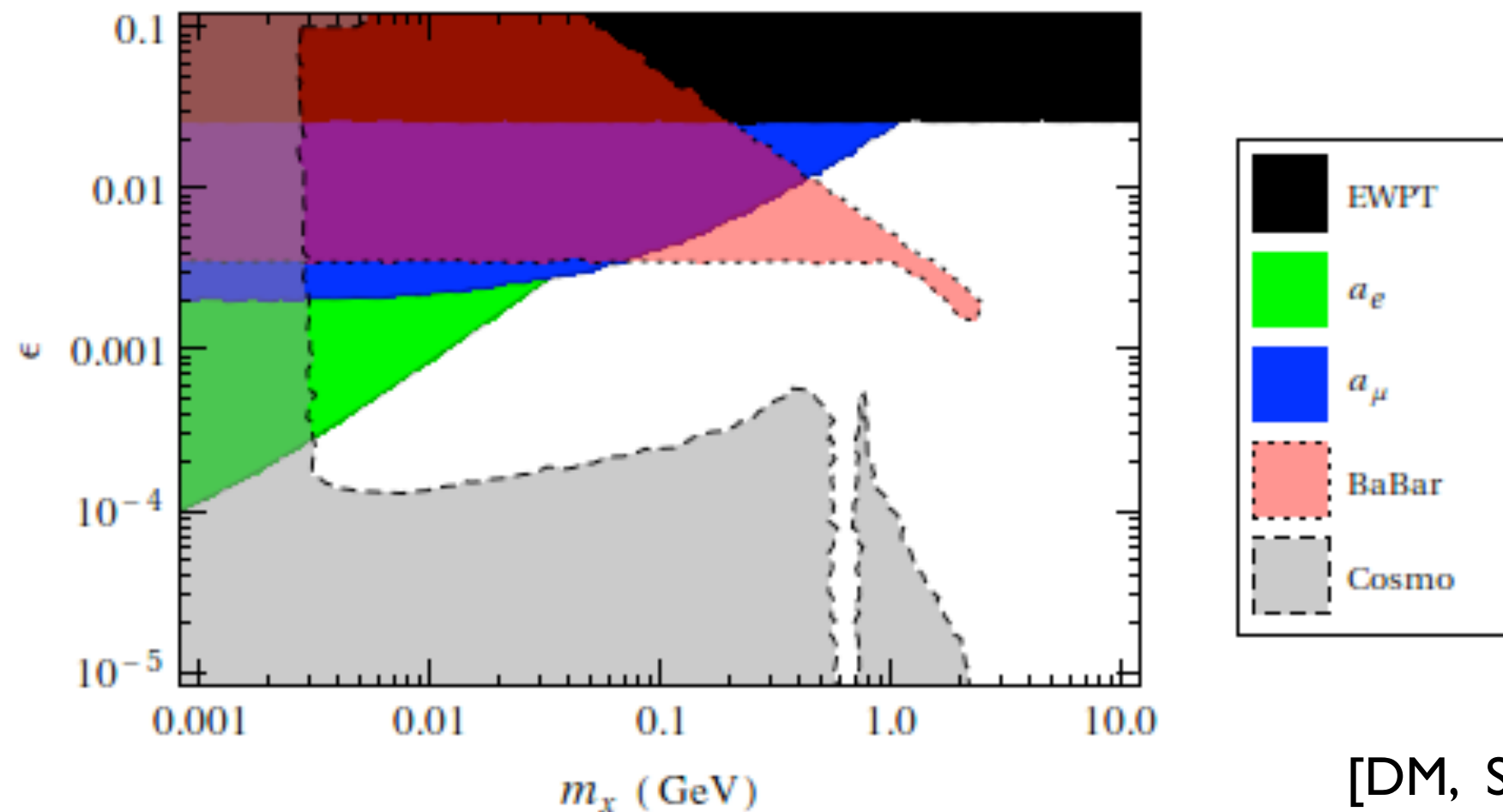
- Decays of a^x :



- Lifetime depends on relative a^x and X^μ masses.

Case C: Bounds from Meson Factories and ...

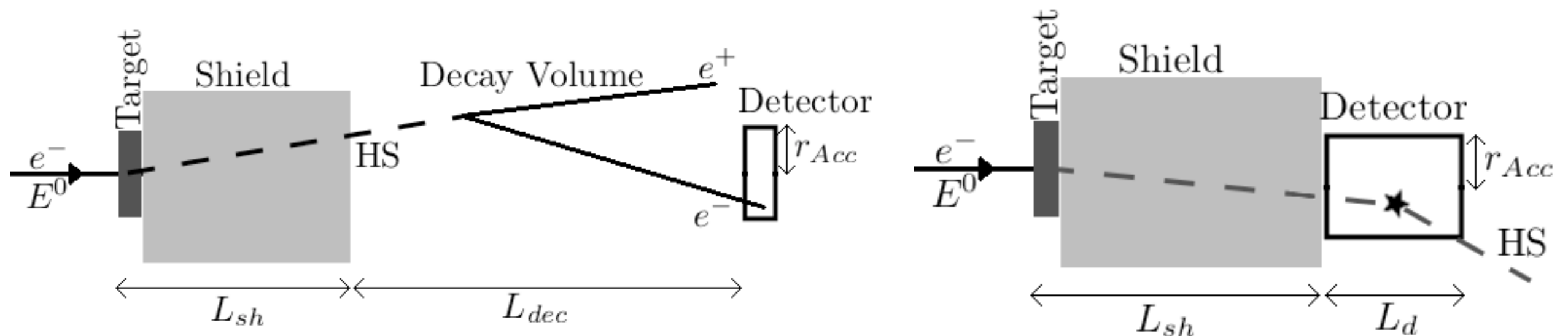
- Meson factories: BaBar $\Upsilon(ns) \rightarrow \gamma + (invisible)$
Relevant for $\gamma c\tau \gtrsim 100 \text{ cm}$, other searches not sensitive.



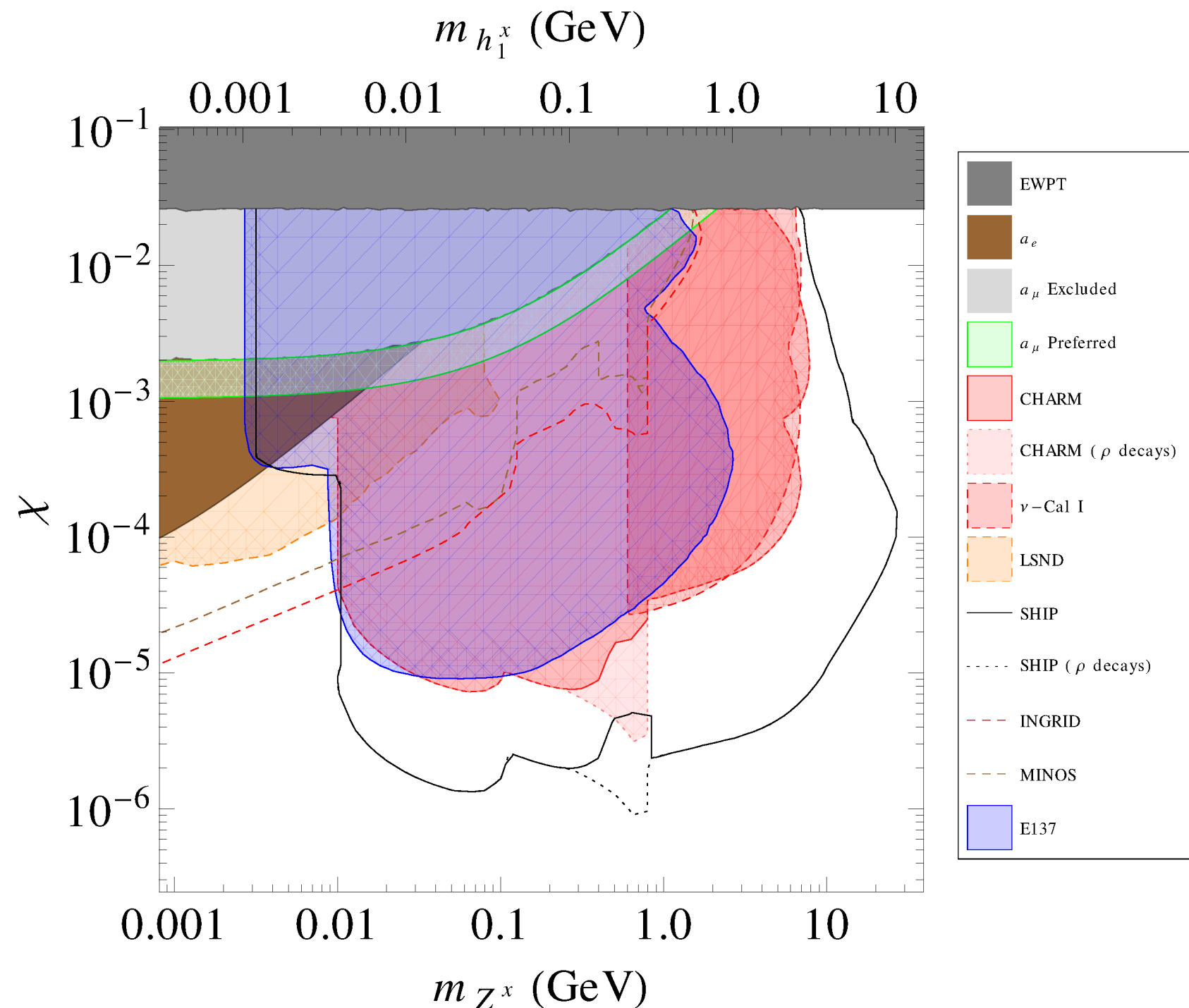
- (Cosmo: remnant h_1^x and a^x decay after BBN starts.)

Case C: Bounds from Fixed Targets

- X^μ is produced relatively efficiently, either directly or from meson decays.
- Two sources of signals:
 1. decay products of h_1^x or a^x are seen in the detector.
 2. h_1^x or a^x scatters quasi-elastically in the detector.



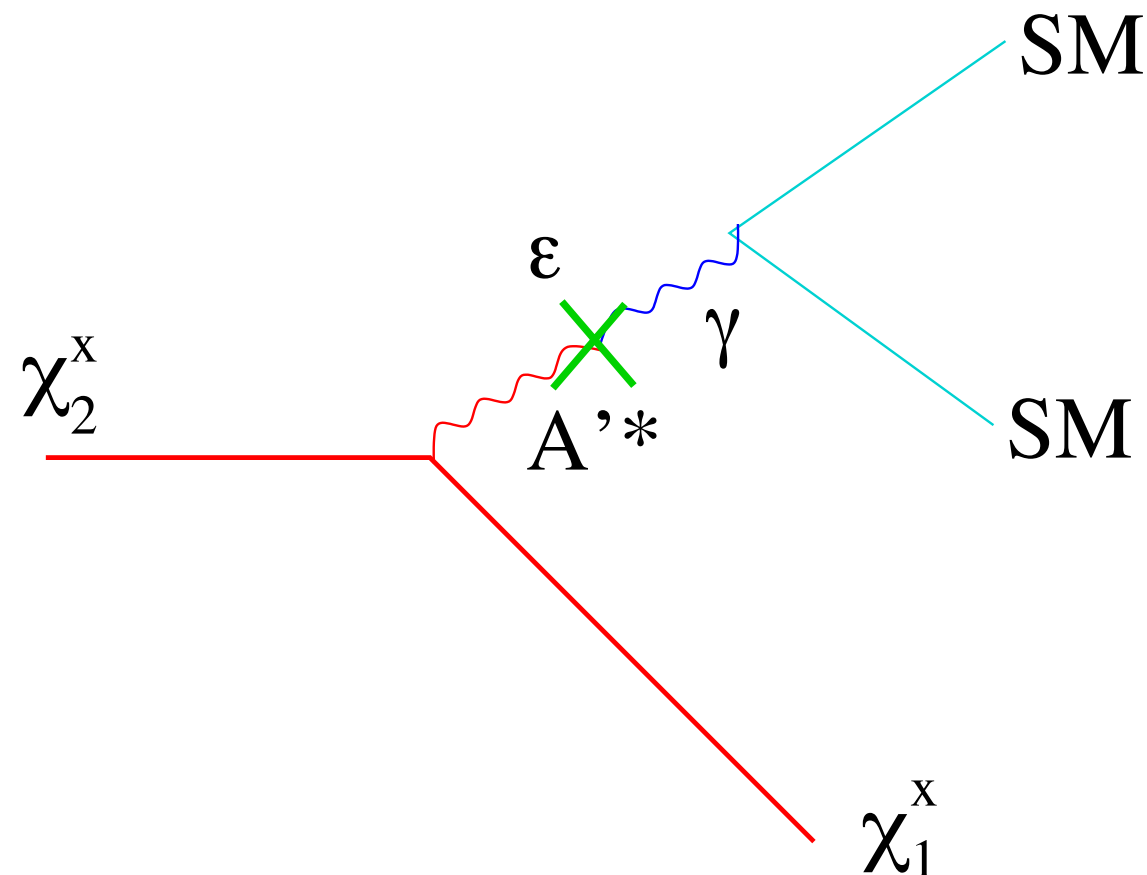
Case C: Bounds from Fixed Targets



[SHiP Physics, Alekhin, ..., DM, Spray, ... 2015]

Case D: $A' \rightarrow \chi_1^x + \chi_2^x$

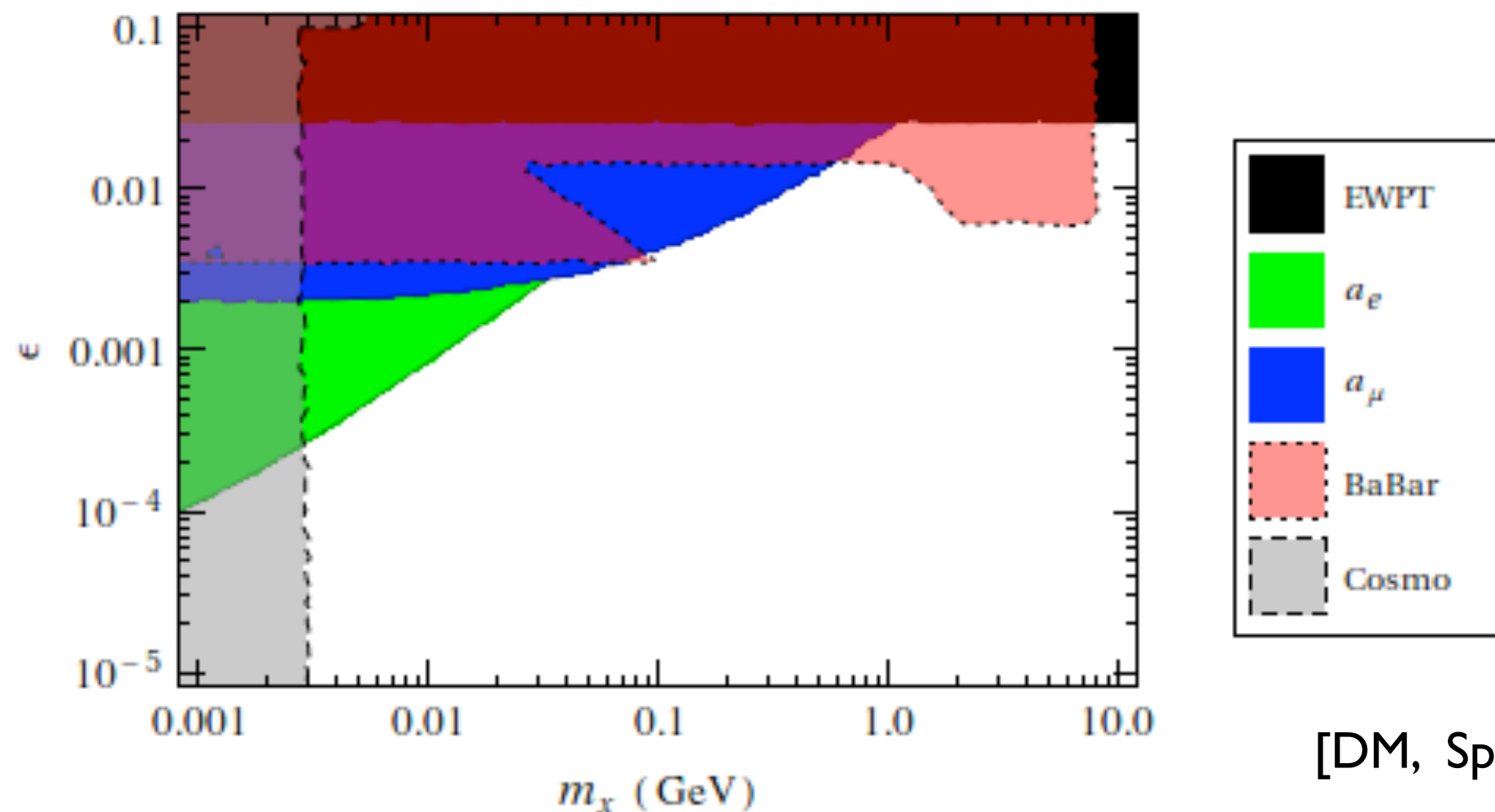
- Decays of χ_2^x :



- Lifetime depends on relative $\chi_{1,2}^x$ and X^μ masses.
- Choose parameters with $BR(X^\mu \rightarrow \chi_1^x \chi_2^x) = 0.9$.

Case D: Bounds from Meson Factories and ...

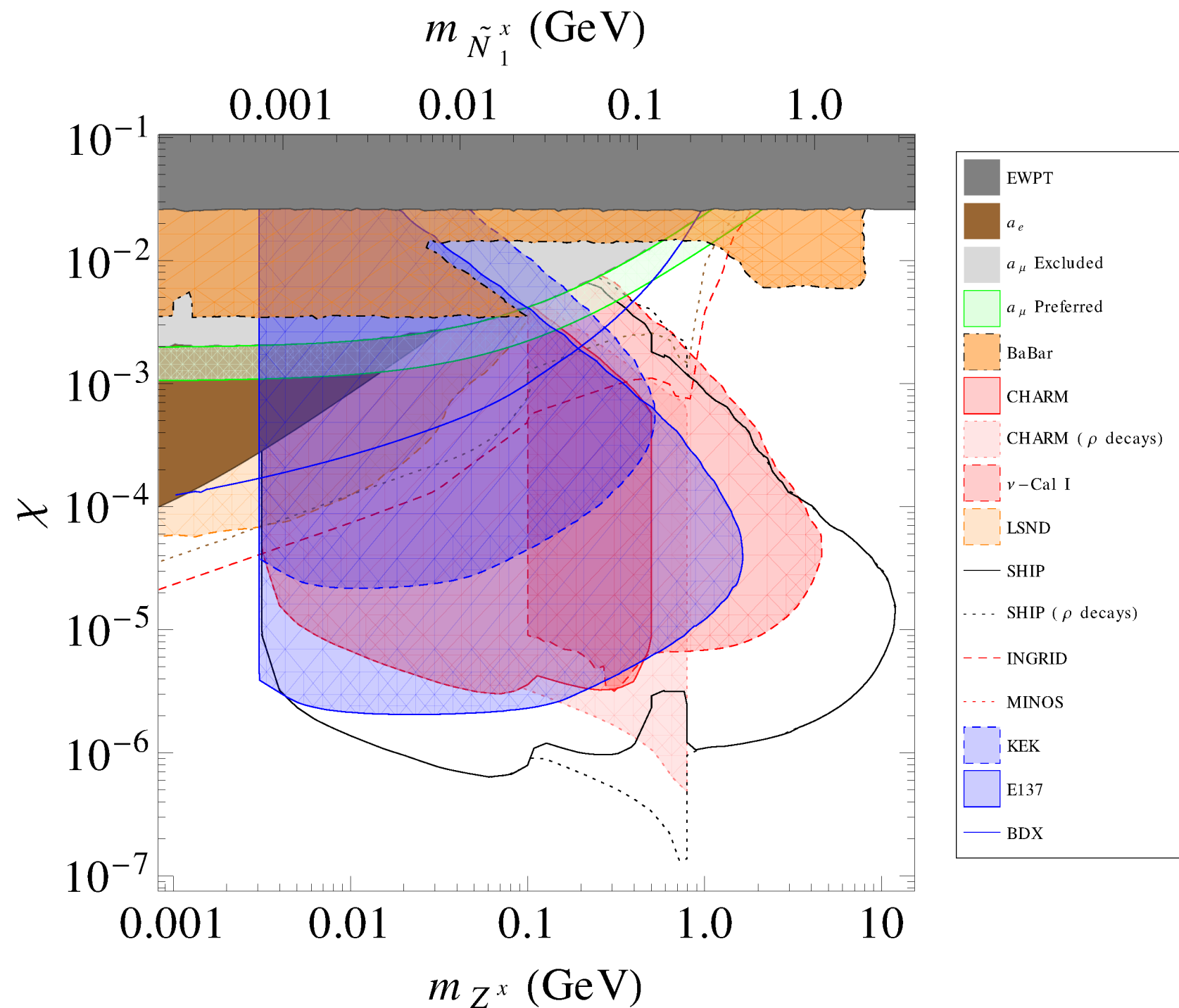
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Case D: Bounds from Fixed Targets



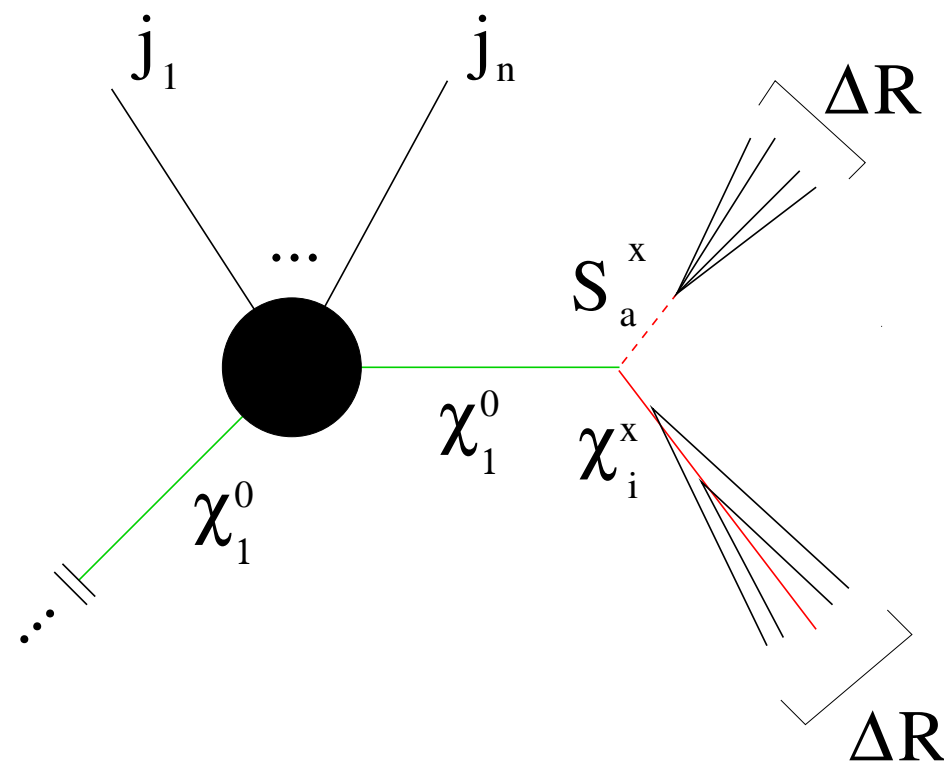
[SHiP Physics, Alekhin, ..., DM, Spray, ... 2015]

Signals at the LHC

- SUSY kinetic mixing:

$$\int d^2\theta \, \epsilon B^\alpha X_\alpha \supset \epsilon \tilde{B}^\dagger \sigma \cdot \partial \tilde{X}$$

- Allows $\chi_1^0 \rightarrow \chi_i^x + S^x$, ($S^x = X^\mu, h_{1,2}^x, a^x$)



[Arkani-Hamed + Weiner 2008, Baumgart *et al.* 2009, Chan, Low, DM, Spray 2011, ...]

Signals at the LHC

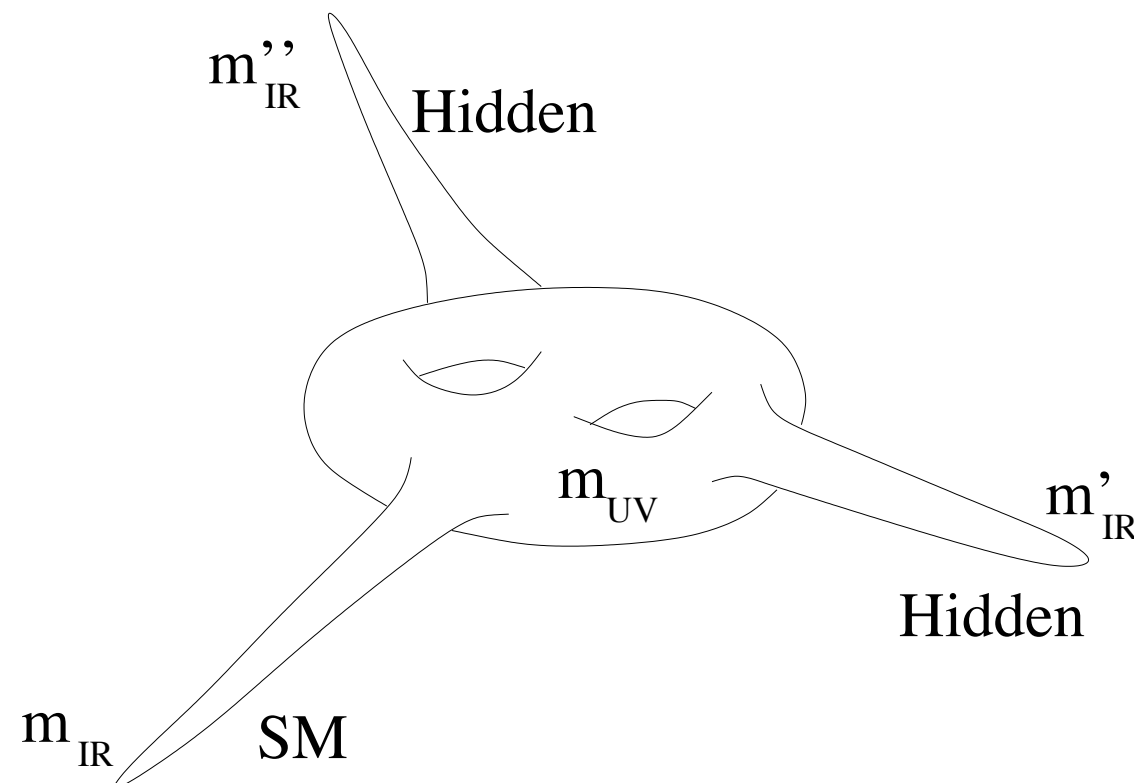
- MSSM superpartners are created as usual.
- Cascade decays to the lightest MSSM superpartner (χ_1^0).
- Further cascades in the hidden sector.
- New visible decay products (mainly) for Case A only.
Vector decay products $X^\mu \rightarrow SM + SM$ are boosted.
 $\Rightarrow$ “lepton jets” [Arkani-Hamed + Weiner 2008]
- Cases B-D give mostly missing energy, very few lepton jets.

Non-Minimal #2: Warped Hidden Vector

Motivation

- Multiple stringy warped throats:

[e.g. Giddings, Kachru, Polchinski 2001; ...; von Harling, Hebeker, Noguchi 2007; ...]

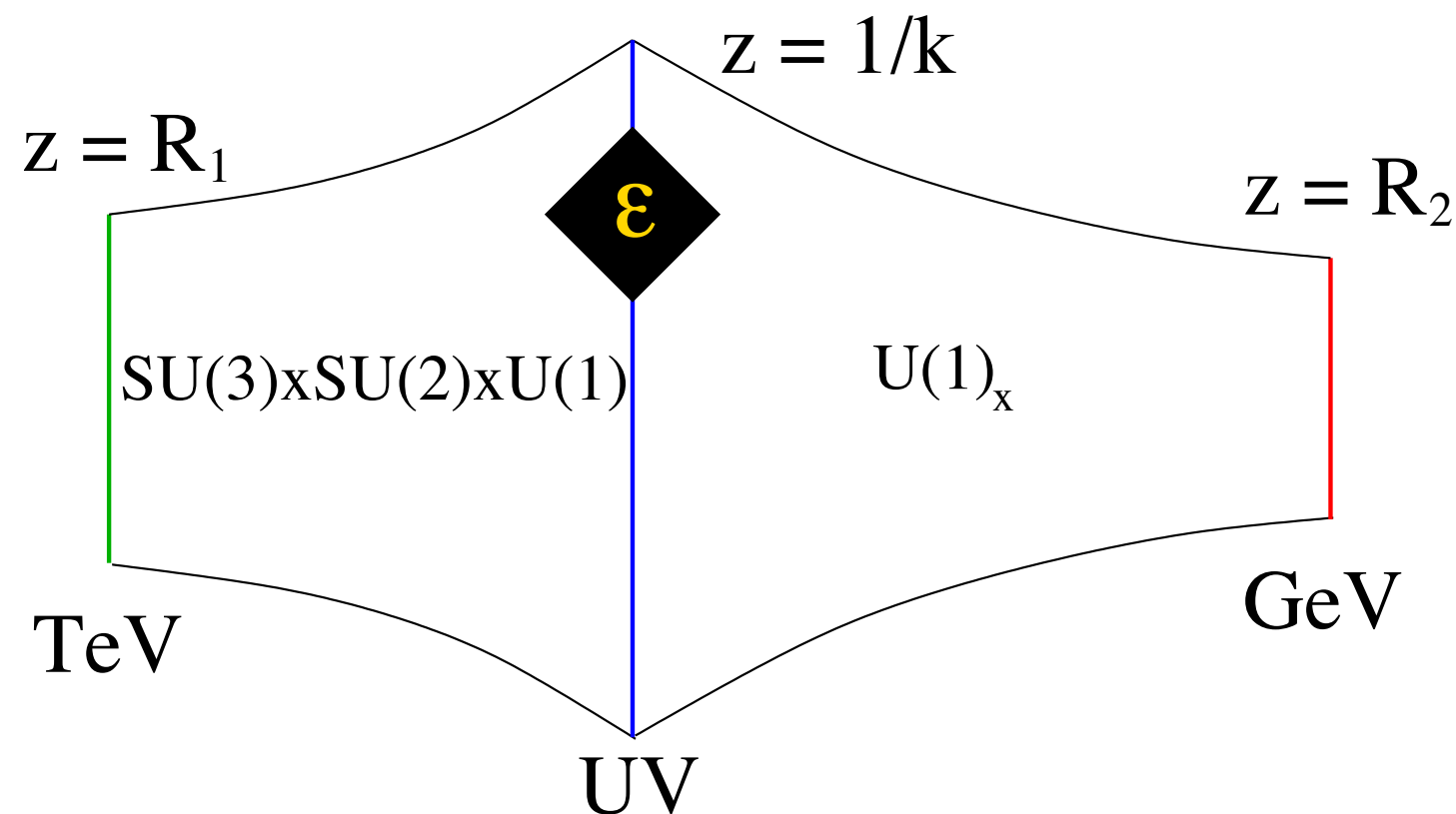


- Some throats may have low IR scales. These could be observable.

Warped Hidden Vector

- Toy Model: multiple Randall-Sundrum warped bulks:

[DM + McDonald 2010]



- Throat metrics: $ds^2 = (kz)^{-2} (\eta^{\mu\nu} dx^\mu dx^\nu - dz^2)$
- Dual to a hidden (approximate) CFT.

Warped Hidden Vector: Gauge Kinetic Mixing

- Local gauge kinetic mixing on the shared UV brane:

$$\frac{\epsilon_*}{2M_*} \int_{UV} d^4x \sqrt{-g} g^{\mu\alpha} g^{\nu\beta} B_{\mu\nu} X_{\alpha\beta}$$

- Get multiple hidden vector KK modes:

$$\mathcal{L}_{eff} \supset -\frac{1}{2} \sum_n \epsilon_n X_n^{\mu\nu} (c_w F_{\mu\nu} - s_w Z_{\mu\nu})$$

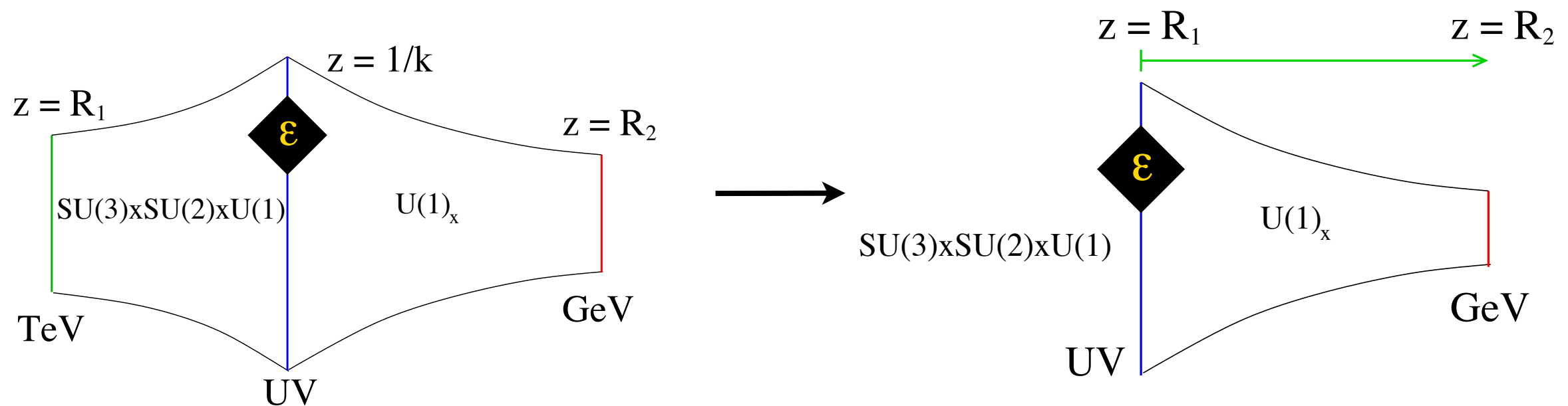
with

$$\epsilon_0 \simeq \epsilon_* \frac{k}{M_*} \frac{1}{\sqrt{\log(kR_1) \log(kR_2)}}$$

$$\epsilon_n \simeq \epsilon_0 \frac{n^{-1/2}}{\sqrt{\log(k/m_n)}} , \quad m_n \simeq n\pi/R_2$$

Hidden Warped Sector

- For low-energy tests, integrate out the visible bulk:



- Hidden vector KK modes:

$$m_n \simeq \frac{\pi}{R_2} (n \mp 1/4)$$

$$\epsilon_n \simeq \epsilon_0 \frac{n^{-1/2}}{\sqrt{\log(k/m_n)}}$$

- Hidden graviton KK modes:

$$m_a \simeq \frac{\pi}{R_2} (n + 1/4) \quad (\text{IR localized})$$

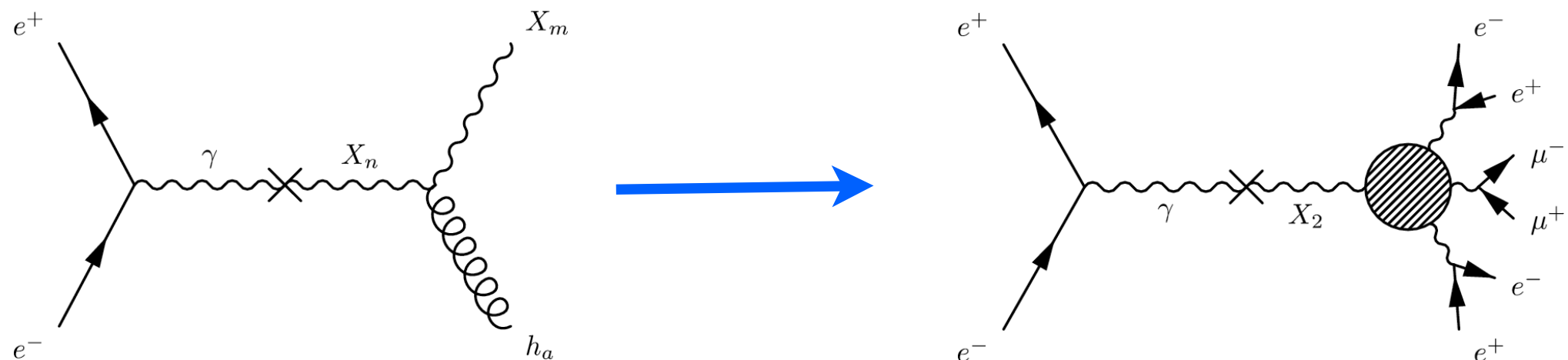
Warped Dark Vector: Signals

- Higher vector modes can decay to lower vector modes, or to KK graviton excitations.

e.g. $X_2 \rightarrow X_0 + G_1$

$$G_1 \rightarrow X_0 + X_0$$

$$\Rightarrow (X_0 \rightarrow SM + SM)^3$$

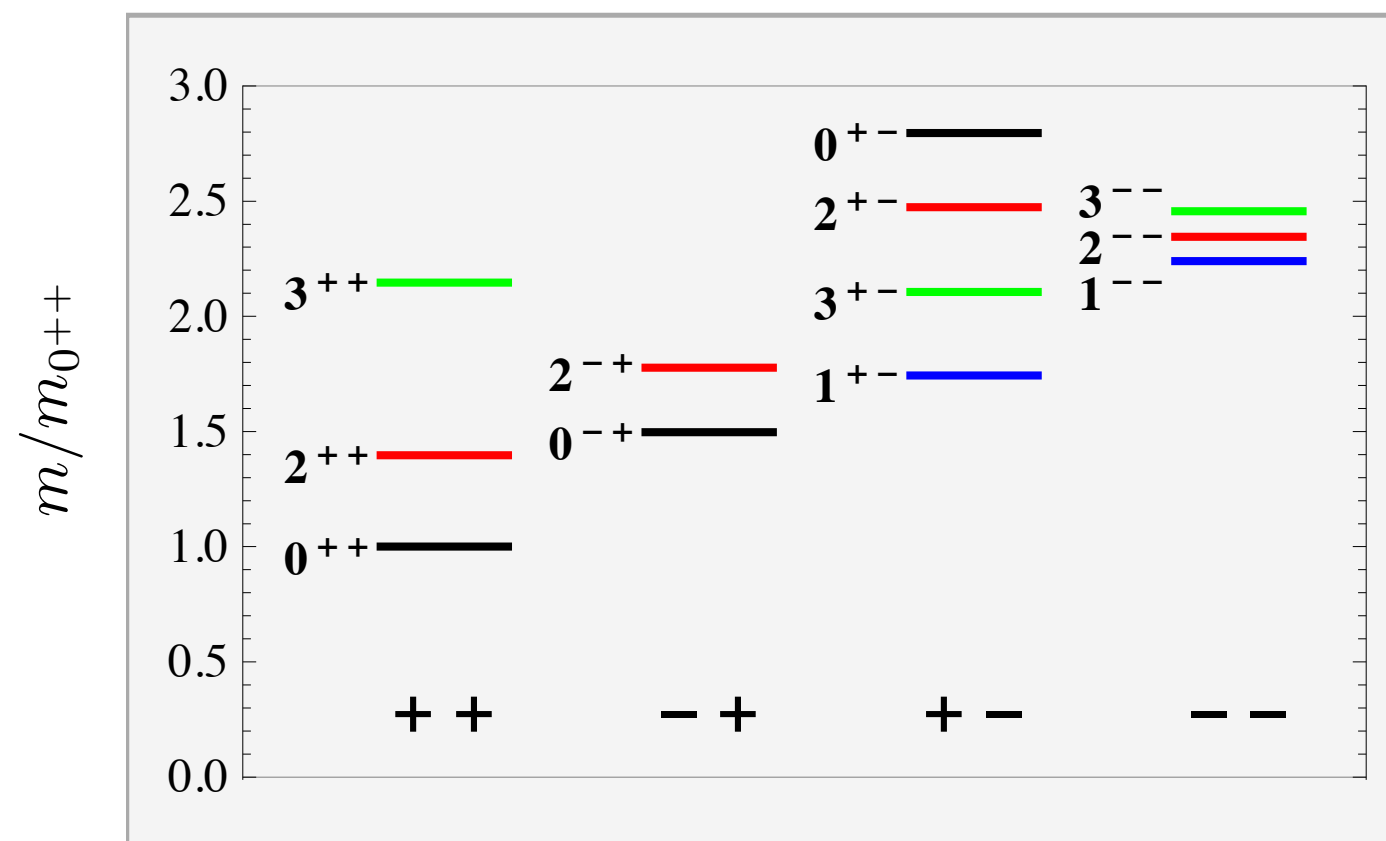


- Higher KK modes become very broad, KK picture breaks, expect soft multi-particle final states (RS2). [Strassler 2008]

Non-Minimal #3: Non-Abelian Dark Vector

Non-Abelian Dark Vector

- Minimal: pure dark Yang-Mills with simple group G_x .
- Expect confinement to glueballs at scale Λ_x , naturally!
For $G_x = SU(3)$:



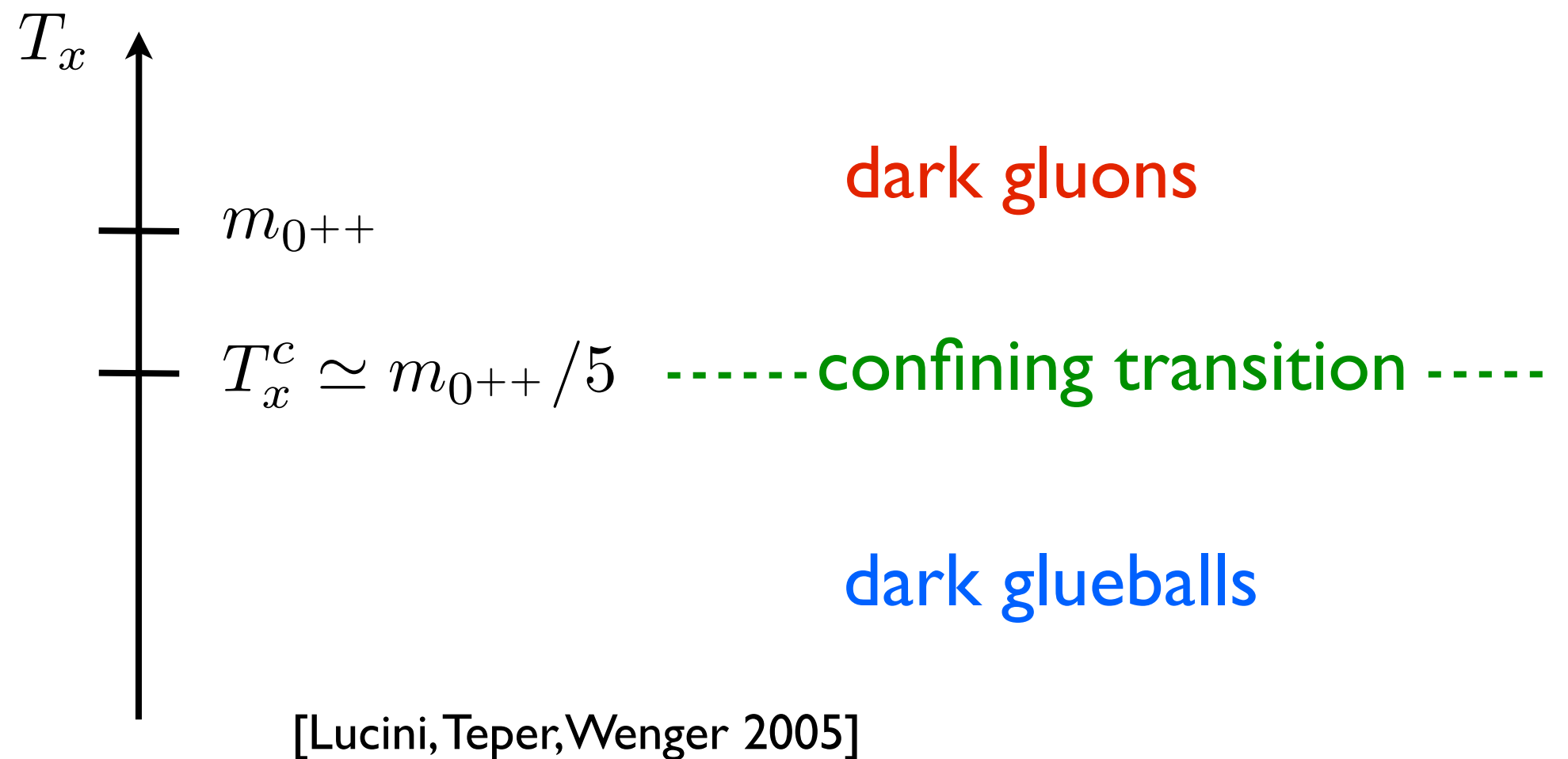
$$m_{0^{++}} \simeq 7 \Lambda_x$$

[Morningstar+Peardon 1999,
via Juknevich *et al.* 2009]

- Similar spectrum for $SU(N)$, $N > 3$.

Dark Glueballs in the Early Universe

- Assume thermal decoupling of dark and SM sectors.
 $\Rightarrow$ independent temperatures and entropies



- Weakly first-order for $N = 3$, stronger for larger N .

Dark Glueball Freezeout (SU(N))

- Heavier glueballs can annihilate to the lighter modes.
Lightest 0^{++} glueball reduces density by $3 \rightarrow 2$ reactions.
- Estimate using glueball EFT based on NDA and large-N:

$$\mathcal{L} \simeq \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{1}{3!} \left(\frac{4\pi}{N} \right) \phi^3 - \frac{1}{4!} \left(\frac{4\pi}{N} \right)^2 \phi^4 - \dots$$

- Implies:

$$\langle \sigma_{3 \rightarrow 2} v^2 \rangle \simeq \frac{1}{(4\pi)^3} \left(\frac{4\pi}{N} \right)^6 \frac{1}{m_{0^{++}}^5}$$

$$\langle \sigma_{2 \rightarrow 2}^{el} v \rangle \simeq \frac{1}{(4\pi)} \left(\frac{4\pi}{N} \right)^4 \frac{1}{m_{0^{++}}^2}$$

Dark Glueball Freezeout

- Annihilation by $3 \rightarrow 2$ heats the remaining glueballs!
- Track using adiabaticity: $R \equiv \frac{s_x}{s} = \text{constant}$
- Since $T_x s_x \simeq m_x n_x$ while in equilibrium:

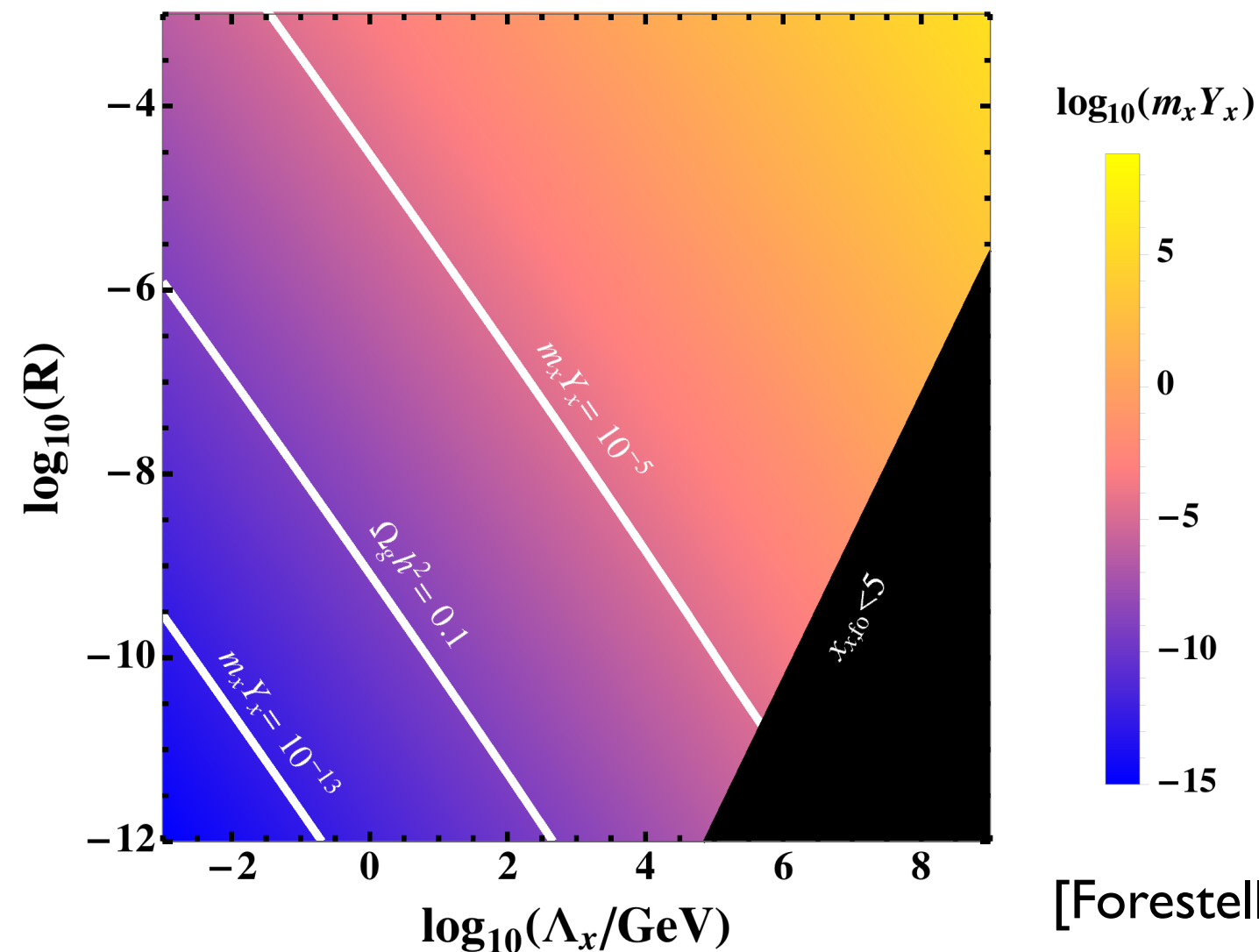
$$Y_x \equiv \frac{n_x}{s} \simeq x_x^{f^o} R$$

- Solve for $x_x^{f^o} = m_x / T_x^{f^o}$ using freezeout condition:

$$3H \simeq x_x^{f^o} \langle \sigma_{32} v^2 \rangle n_x^2$$

Dark Glueball Relic Density

- 0^{++} relic density for SU(3):

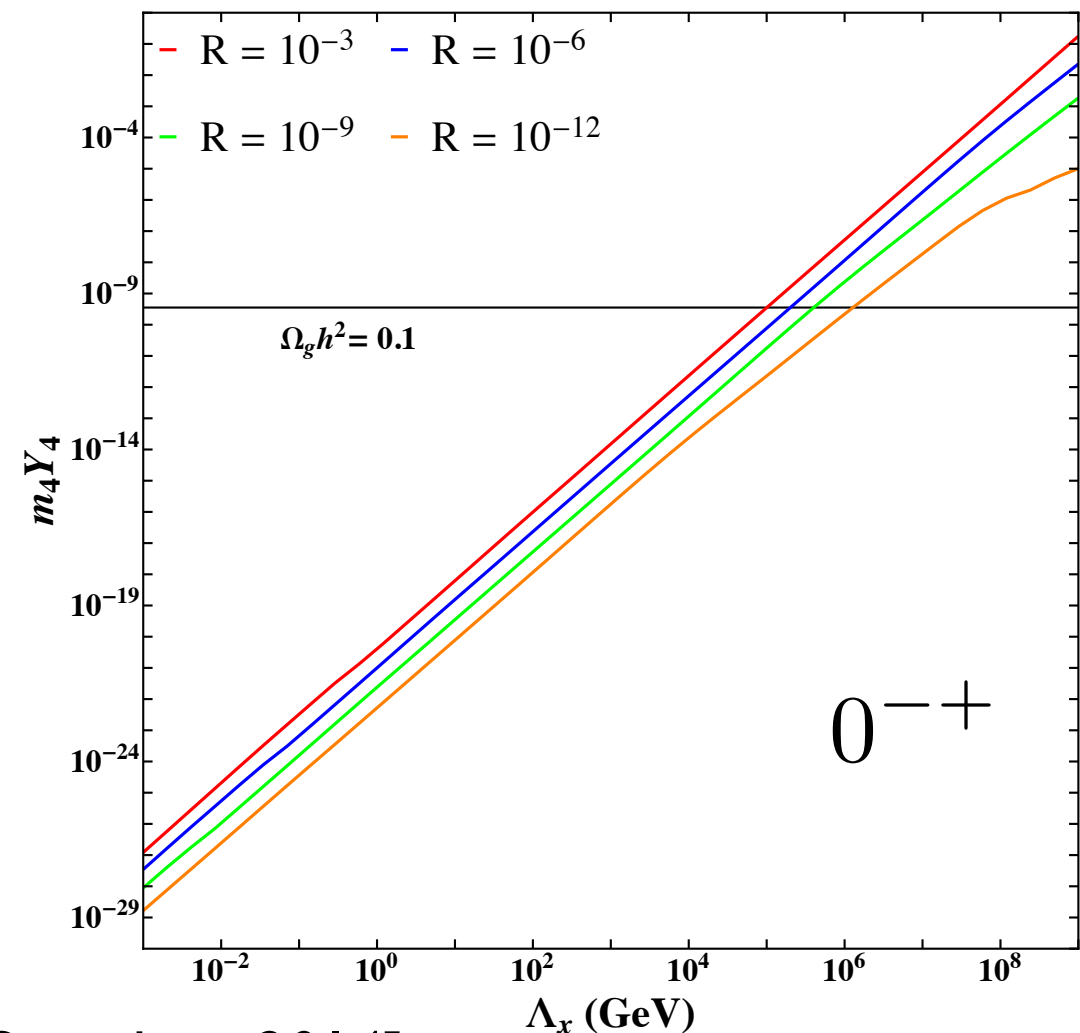
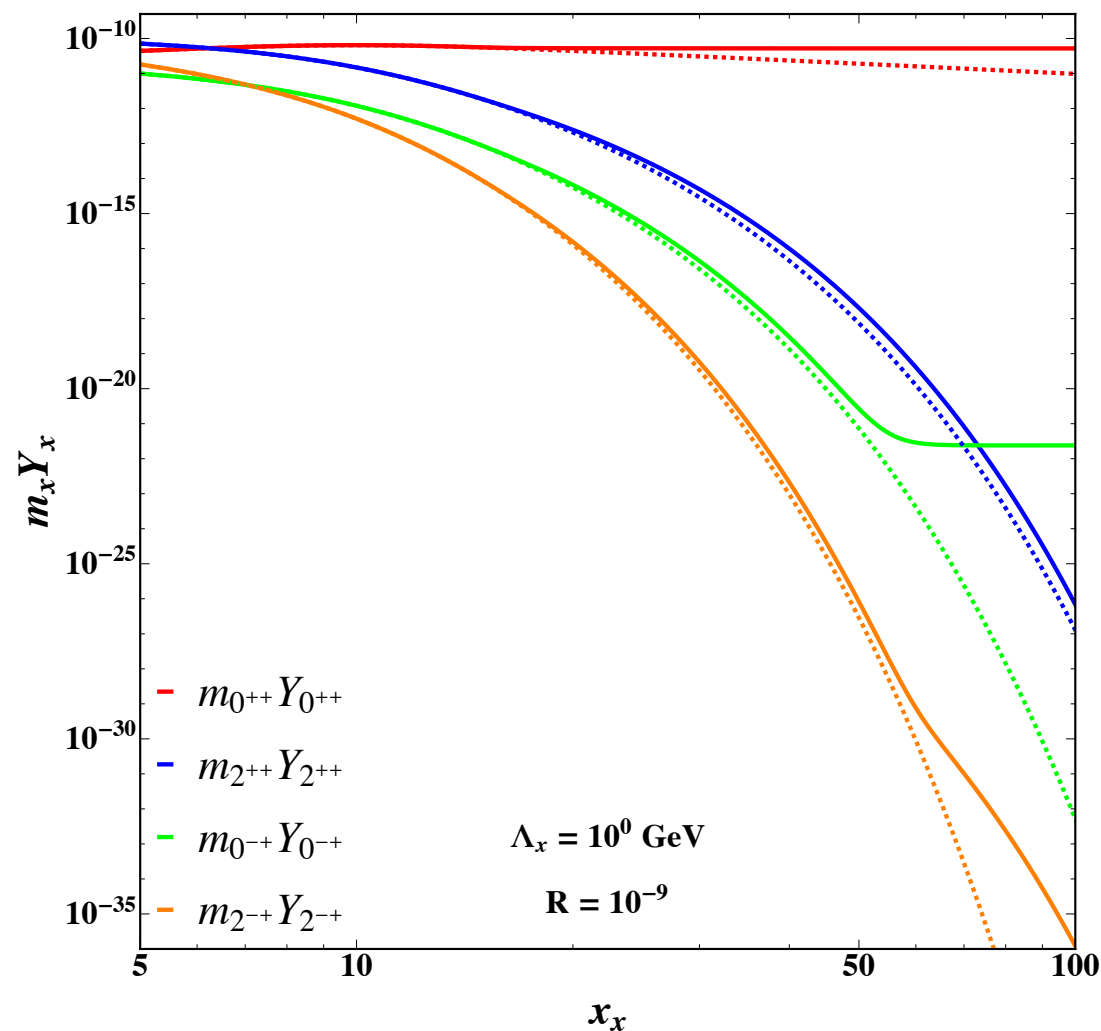


[Forestell, DM, Sigurdson 2014]

- Larger N produces (slightly) larger densities. [Soni+Zhang 2016]

Heavier Glueball Relic Densities

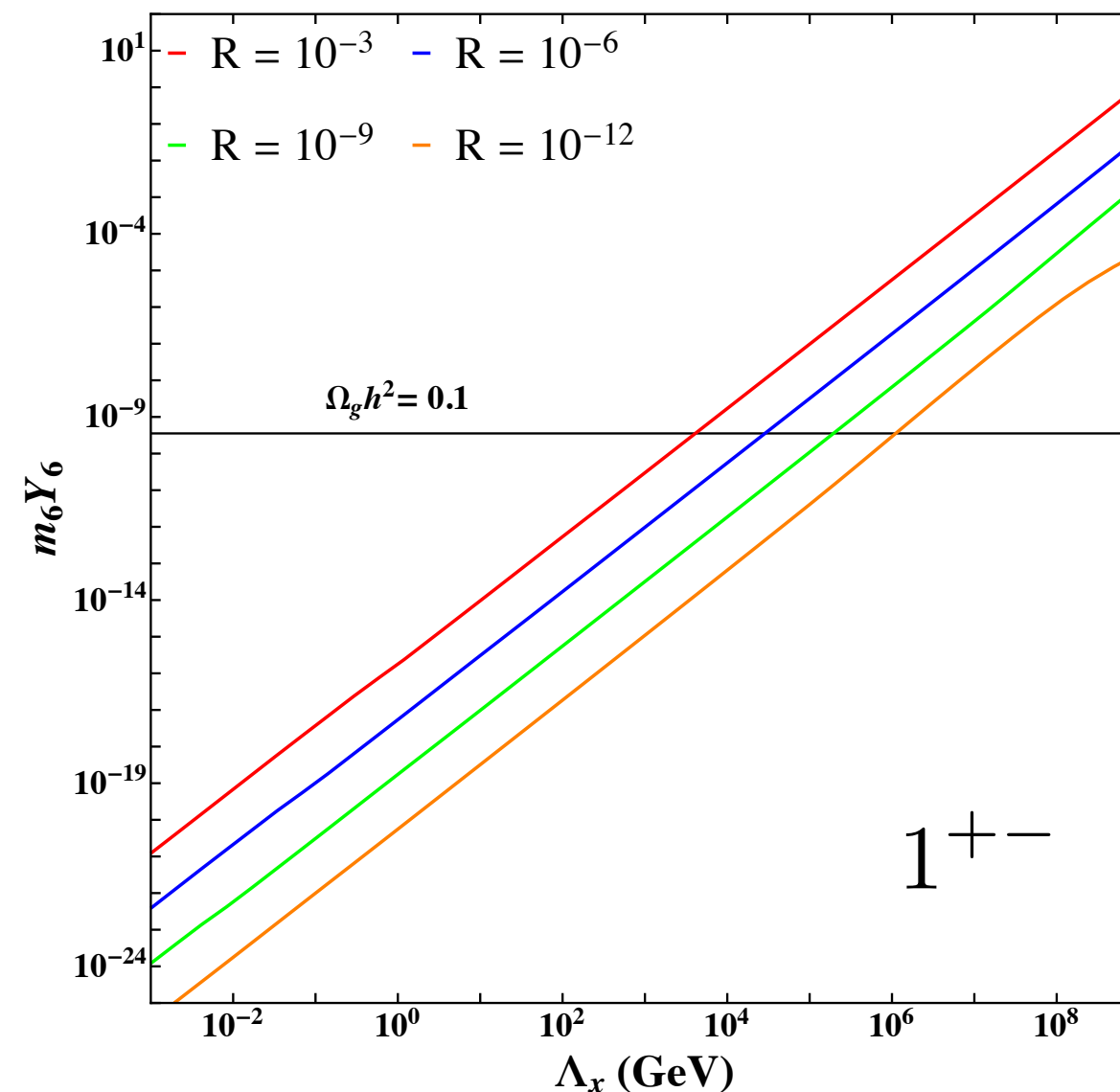
- Use reaction networks with all $2 \rightarrow 2$ for other glueballs.
- C-even modes reduced by coannihilation with 0^{++} :



[Forestell, DM, Sigurdson 2014]

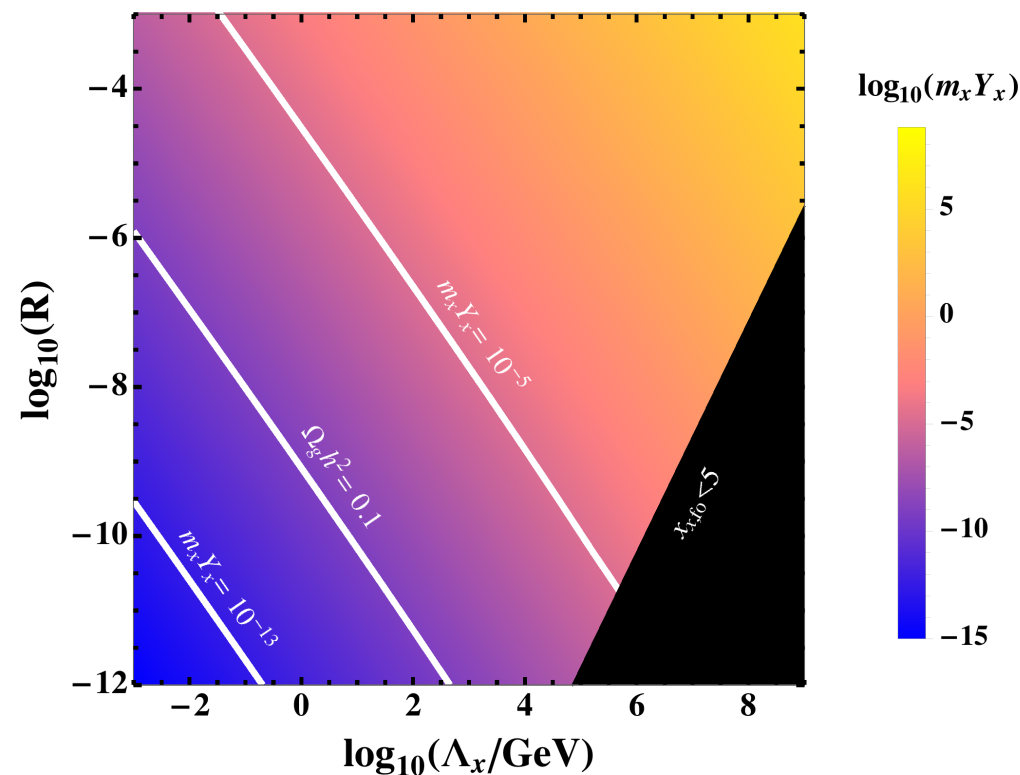
Heavier Glueball Relic Densities

- Use reaction networks with all $2 \rightarrow 2$ for other glueballs.
- C-odd modes are dominated by 1^{+-} :



Cosmological Implications

- Dark glueballs can easily overclose the Universe:



$$R = \frac{s_x}{s} \sim \left(\frac{T_x}{T} \right)^3$$

- Dark glueball self interactions:

$$\sigma_{2 \rightarrow 2}/m < 10 \text{ cm}^2/\text{g} \quad \Rightarrow \quad \Lambda_x \gtrsim 100 \text{ MeV} \left(\frac{3}{N} \right)^{4/3}$$

[Boddy, Feng, Tait 2014; Soni+Zhang 2016]

Connecting to the SM

- Connecting dark glueballs to the SM changes the story!

$$\mathcal{L} \supset \frac{1}{M^4} \text{tr}(F_{SM} F_{SM}) \text{tr}(G_x G_x) + \frac{1}{M^4} B_{\mu\nu} \text{tr}(G_x G_x G_x)^{\mu\nu} \rightarrow \text{vector portal with } 1^{+-} + \frac{\lambda}{M^2} |H|^2 \text{tr}(G_x G_x) \rightarrow \text{Higgs portal with } 0^{++}$$

- Confinement:** $\text{tr}(G_x G_x) \rightarrow \left(\frac{N}{4\pi}\right) \Lambda_x^3 \phi_{0^{++}} + \dots$
 $\text{tr}(G_x G_x G_x)^{\mu\nu} \rightarrow \left(\frac{N}{4\pi}\right) \Lambda_x^4 \tilde{\rho}_{1^{+-}}^{\mu\nu} + \dots$

Dark Glueball Decays

- Width via d=6 operator:

$$\Gamma_6 \sim \lambda^2 N^2 \frac{\Lambda_x^6}{v^2 M^4} \Gamma_h(m_h = \Delta m_x)$$

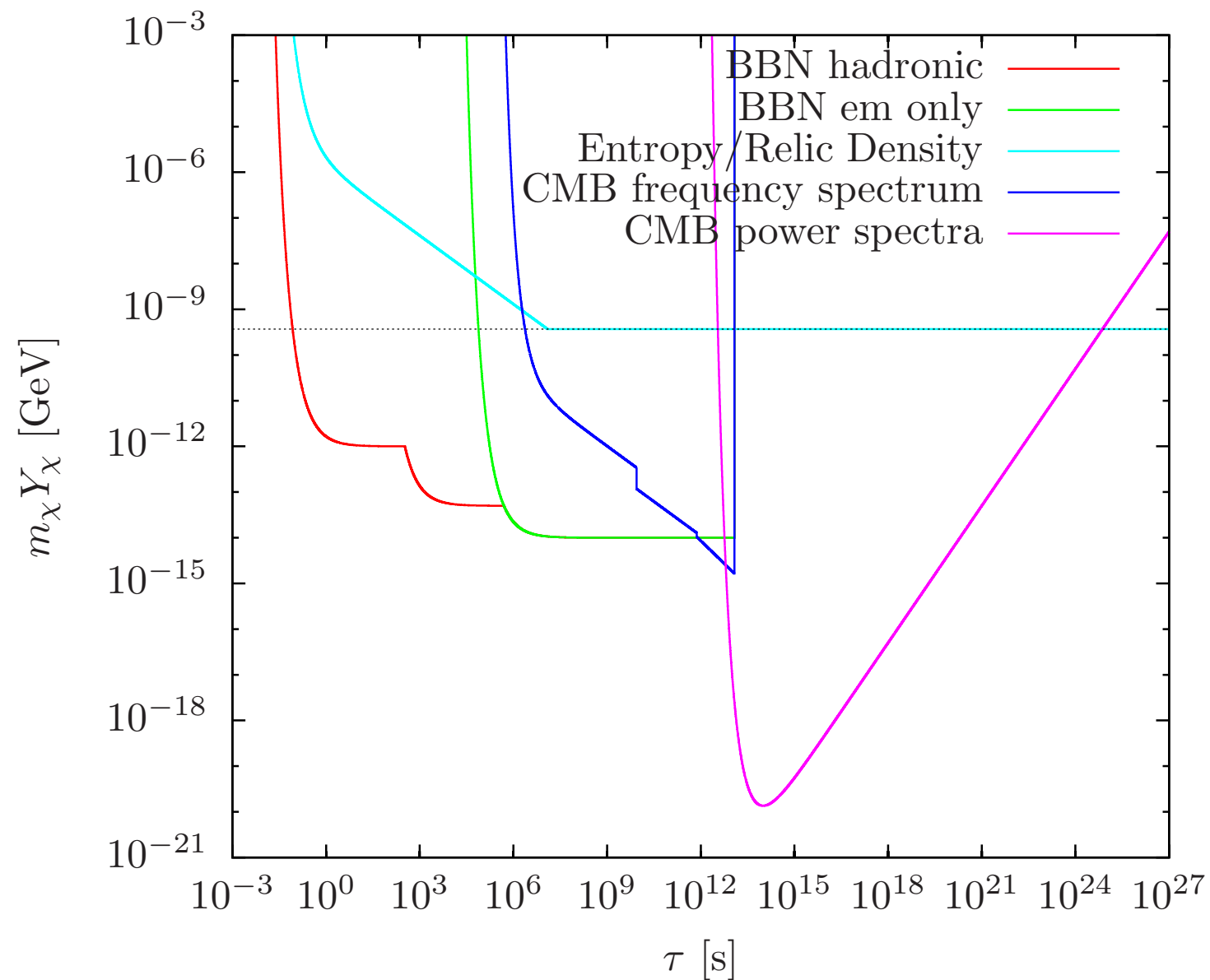
- Width via d=8 operator:

$$\Gamma_8 \sim N^2 \frac{\Lambda_x^9}{M^8}$$

- All states except 1^{+-} , 0^{-+} can decay by d=6.
(0^{-+} can decay by d=6 with P violation.)
- Long-lived 1^{+-} can give strongest constraints or be DM.

Cosmological Bounds on Late Decays

- Approximate for $m_\chi \gtrsim 10 \text{ MeV}$:



[e.g. Kawasaki *et al.* 2004; Hu+Silk 1993; Fradette *et al.* 2014]

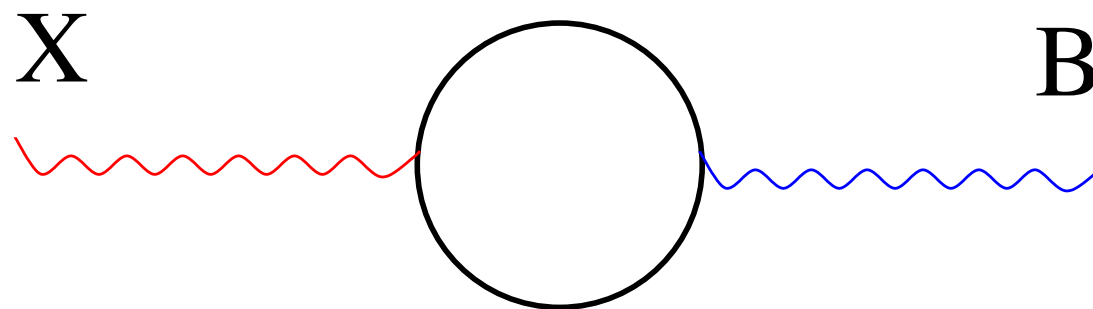
Summary

- Naturalness motivates new states and new searches.
 - e.g.1. SUSY dark vector with Cases A, B, C, D
 - e.g.2. multiple warped throats with KK dark states
 - e.g.3. dark glueballs from dark Yang-Mills
- New signals to look for:
 - long-lived states produced by dark vectors
 - events with multiple final states
 - deviations from minimal Λ CDM cosmology

Extra Slides: Massive Hidden Vector

Vector Portal: ϵ

- Can arise from loops of heavy matter M that is charged under both $U(1)_X$ and $U(1)_Y$. [Okun 1982; Holdom 1986]



$$\epsilon \sim \frac{g_X g_Y}{(4\pi)^2} \ln \left(\frac{M}{\mu} \right) \sim 10^{-2} - 10^{-4}$$

- Can be further suppressed for many reasons.

Vector Portal: Couplings

- $SU(2)_L \times U(1)_Y \times U(1)_x$ gauge invariance:

$$\mathcal{L} \supset -\frac{1}{4}(X_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 - \frac{1}{4}(W_{\mu\nu}^a)^2 - \frac{\epsilon}{2c_W} B_{\mu\nu} X^{\mu\nu}$$

$$\rightarrow (\dots) - \frac{\epsilon}{2} X_{\mu\nu} (F^{\mu\nu} - t_W Z^{\mu\nu})$$

- Two Cases:

1. Massive X vector

2. Massless X vector: paraphoton and millicharges

- I will focus on the massive vector case.

Vector Portal: Mixing

- If $U(1)_x$ is spontaneously broken,

$$\mathcal{L} \supset -\frac{\epsilon}{2} X_{\mu\nu} (F^{\mu\nu} - t_W Z^{\mu\nu}) + \frac{1}{2} m_x^2 (X^\mu)^2 + \frac{1}{2} m_Z^2 (Z^\mu)^2$$

- Mixing can be removed by the change of variables:

$$\left\{ \begin{array}{l} A^\mu \rightarrow A^\mu - \epsilon X^\mu \\ Z^\mu \rightarrow Z^\mu - \epsilon t_W \left(\frac{\eta}{1-\eta} \right) X^\mu \\ X^\mu \rightarrow X^\mu + \epsilon t_W \left(\frac{1}{1-\eta} \right) Z^\mu \end{array} \right. , \quad \eta = m_x^2 / m_Z^2$$

Vector Portal: Couplings to Matter

- Putting in the shifted vectors,

$$-\mathcal{L} \supset e j_{em}^\mu A_\mu + g_Z j_Z^\mu Z_\mu + g_x j_x^\mu X^\mu$$

$$\rightarrow e j_{em}^\mu A_\mu$$

$$+ \left[g_x j_x^\mu - \epsilon e j_{em}^\mu - \epsilon t_W \left(\frac{\eta}{1-\eta} \right) g_Z j_Z^\mu \right] X_\mu$$

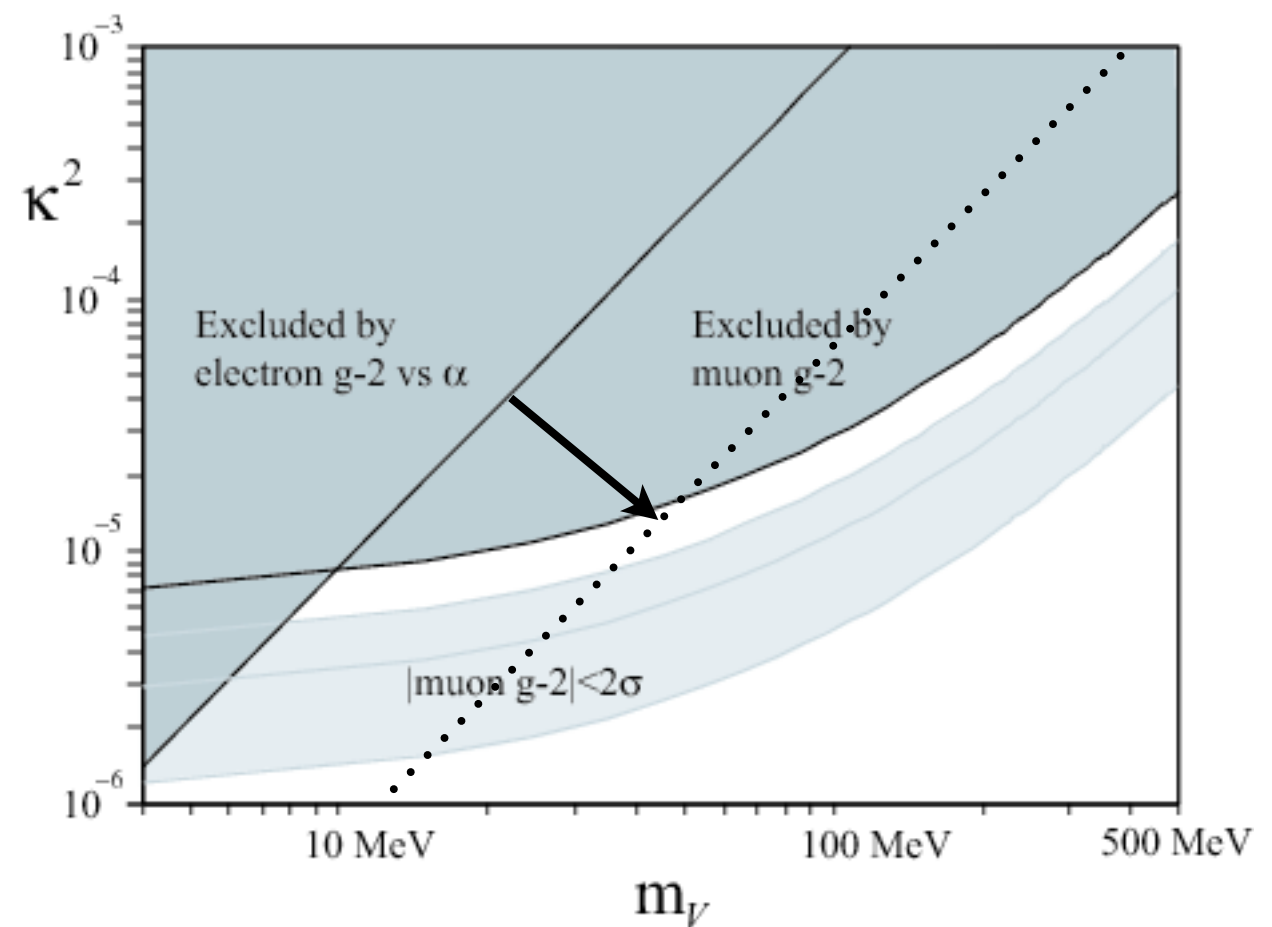
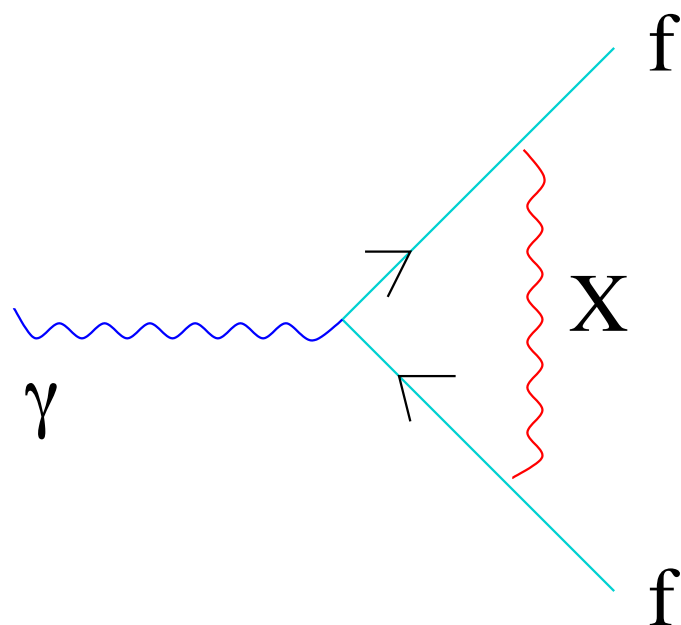
$$+ \left[g_Z j_Z^\mu + \epsilon t_W \left(\frac{1}{1-\eta} \right) g_x j_x^\mu \right] Z_\mu$$

- The hidden vector now couples to SM matter!
 ϵ controls the strength of the interaction.

Vector Portal Bounds: Magnetic Moments

- New contribution from hidden vector:

[Pospelov 2008]

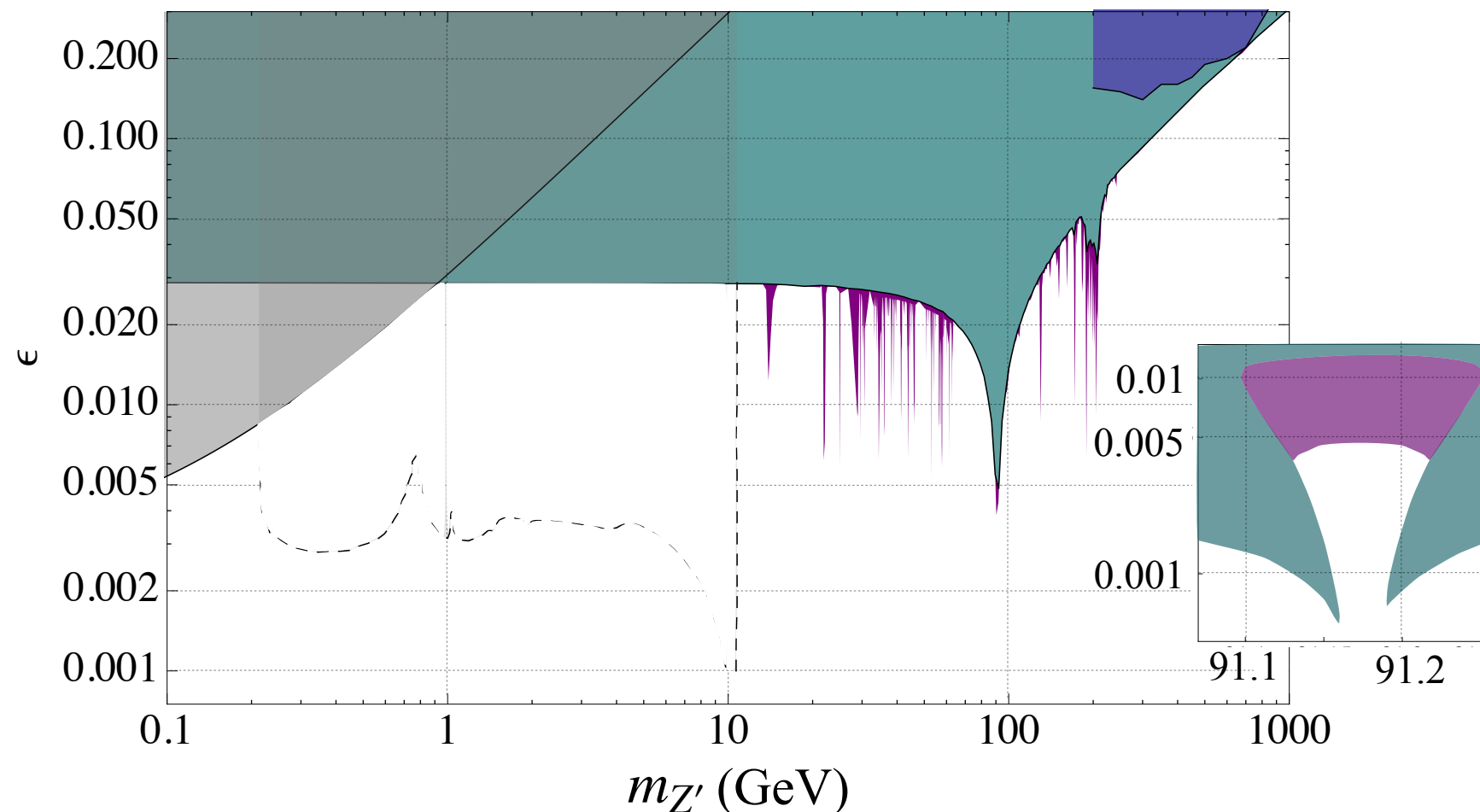


- Can account for the muon discrepancy.

$$a_{\mu} - a_{\mu}^{SM} = (287 \pm 80) \times 10^{-11}$$

Vector Portal Bounds: Precision Electroweak

- Relatively weak due to a cancellation.
Strongest effect is shifting the Z mass.

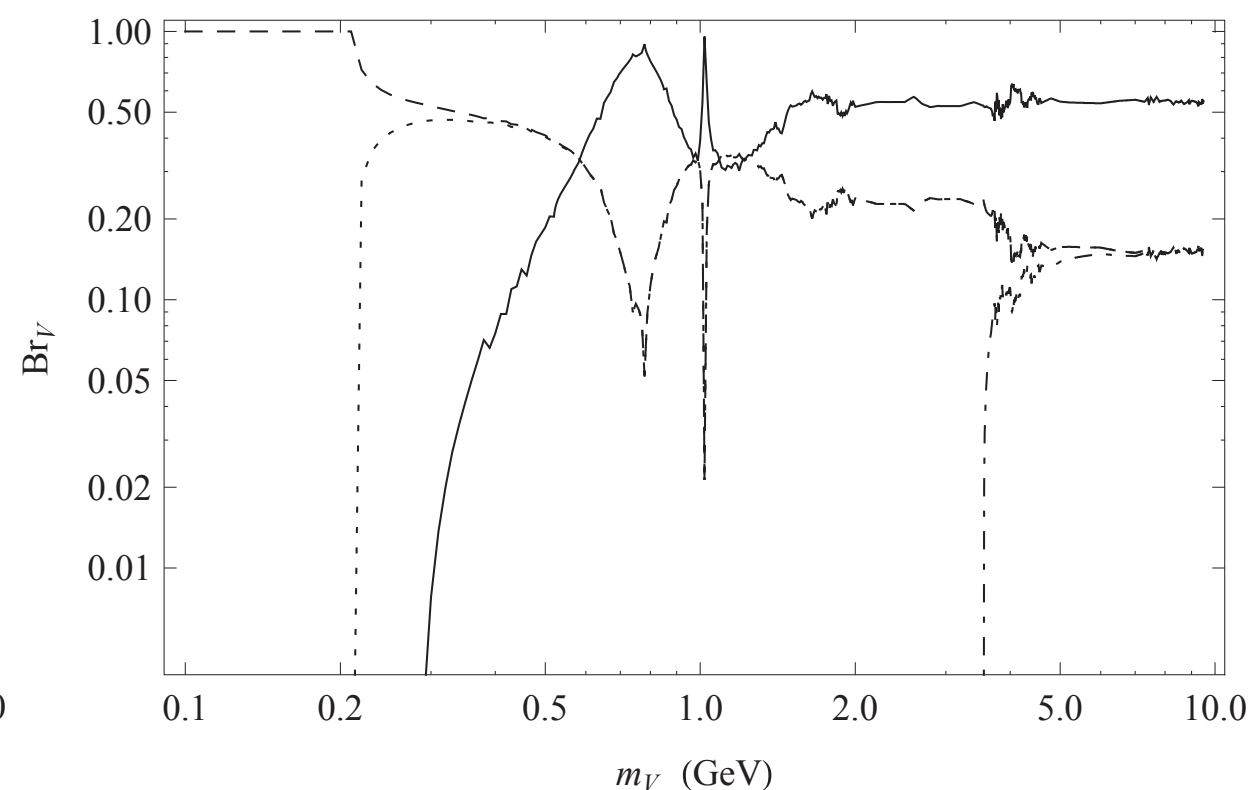
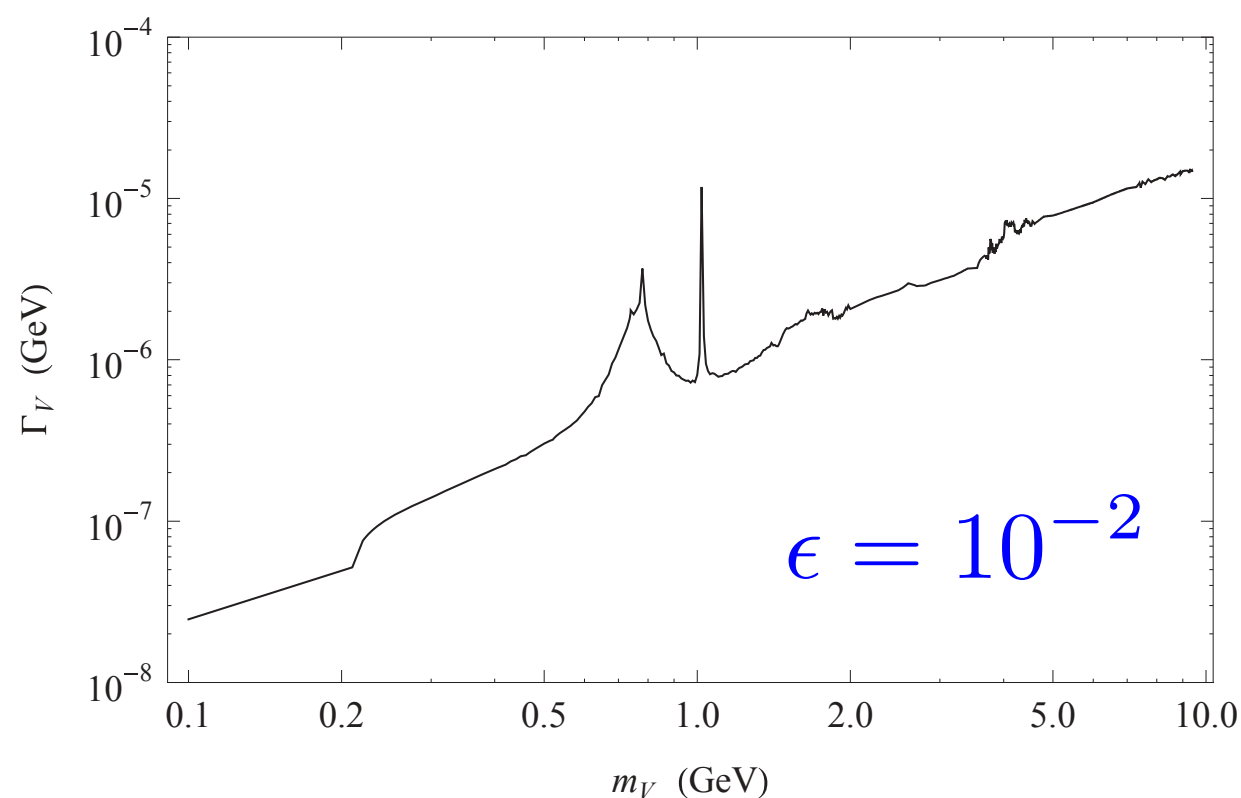


[Hook, Izaguirre, Wacker 2010]

A Minimal Vector Portal (Effective) Theory

- Vector boson of mass m_x , decouple other hidden states.
- Decays:
 - $m_x > 2m_e$: $X^\mu \rightarrow f \bar{f}$

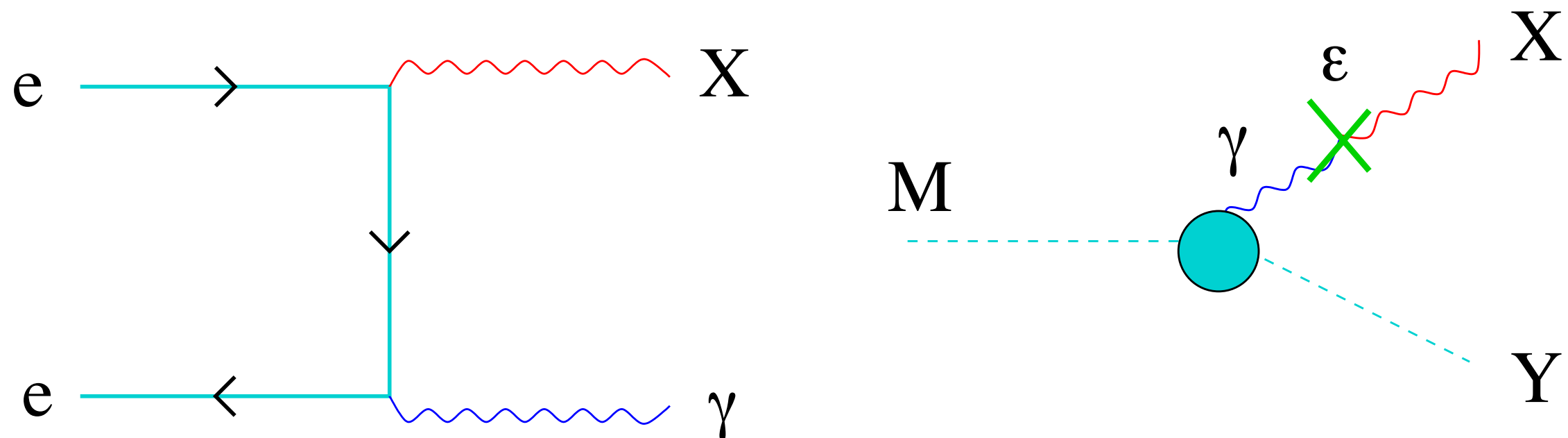
[Batell, Pospelov, Ritz 2009]



- $m_x < 2m_e$: $X^\mu \rightarrow 3\gamma$ very slow (age of the Universe)

Minimal Vector Portal Bounds: Flavor Factories

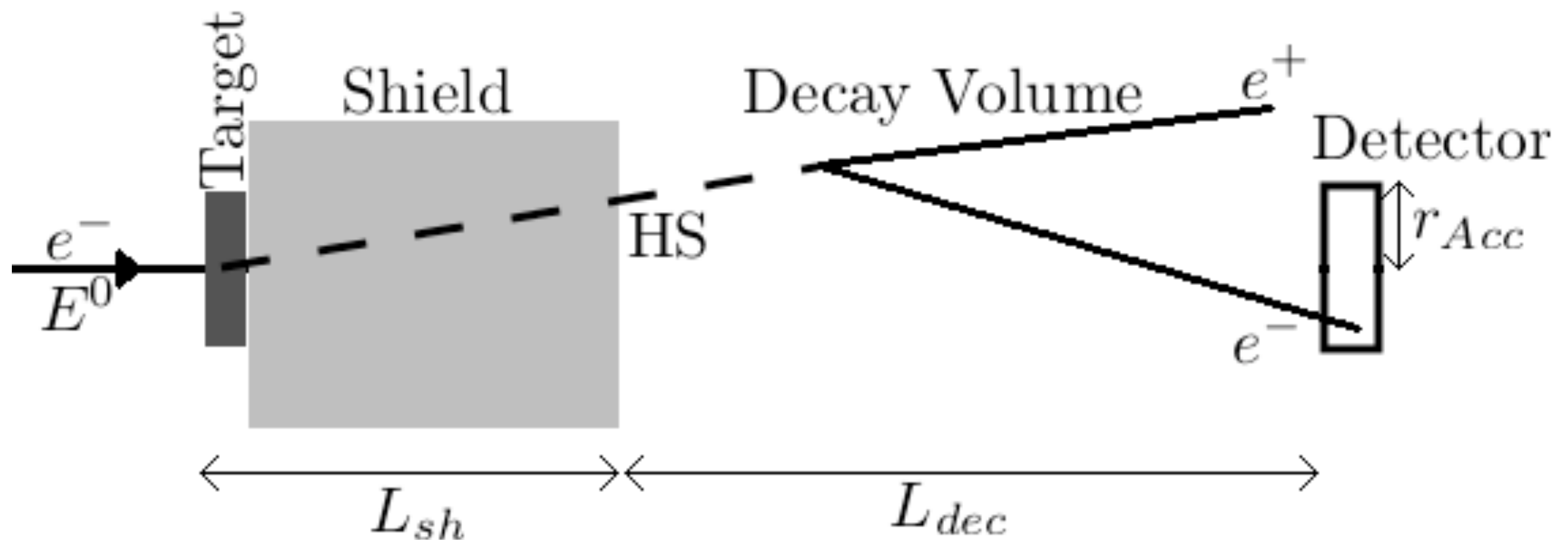
- Continuum production or meson decays:



- Detection: [Bjorken, Essig, Schuster, Toro 2009]
 - BaBar - resonance in $\Upsilon(ns) \rightarrow \gamma \mu^+ \mu^-$ data.
 - KLOE - resonance in $\phi \rightarrow \eta e^+ e^-$.

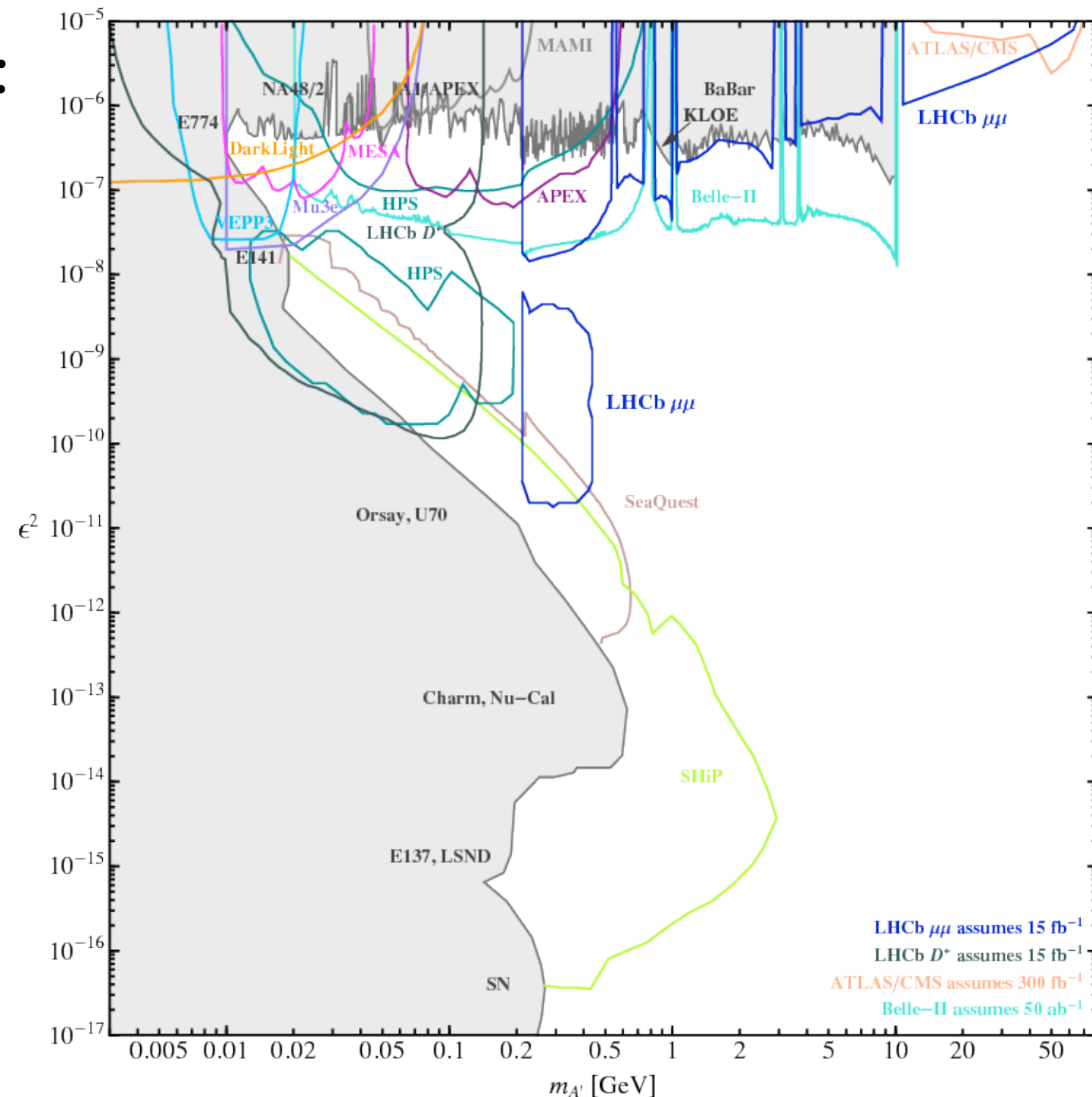
Minimal Vector Portal Bounds: Fixed Targets

- Create a dark vector in the target.
- Look for long-lived decays downstream.



Minimal Vector Portal: Combined Limits

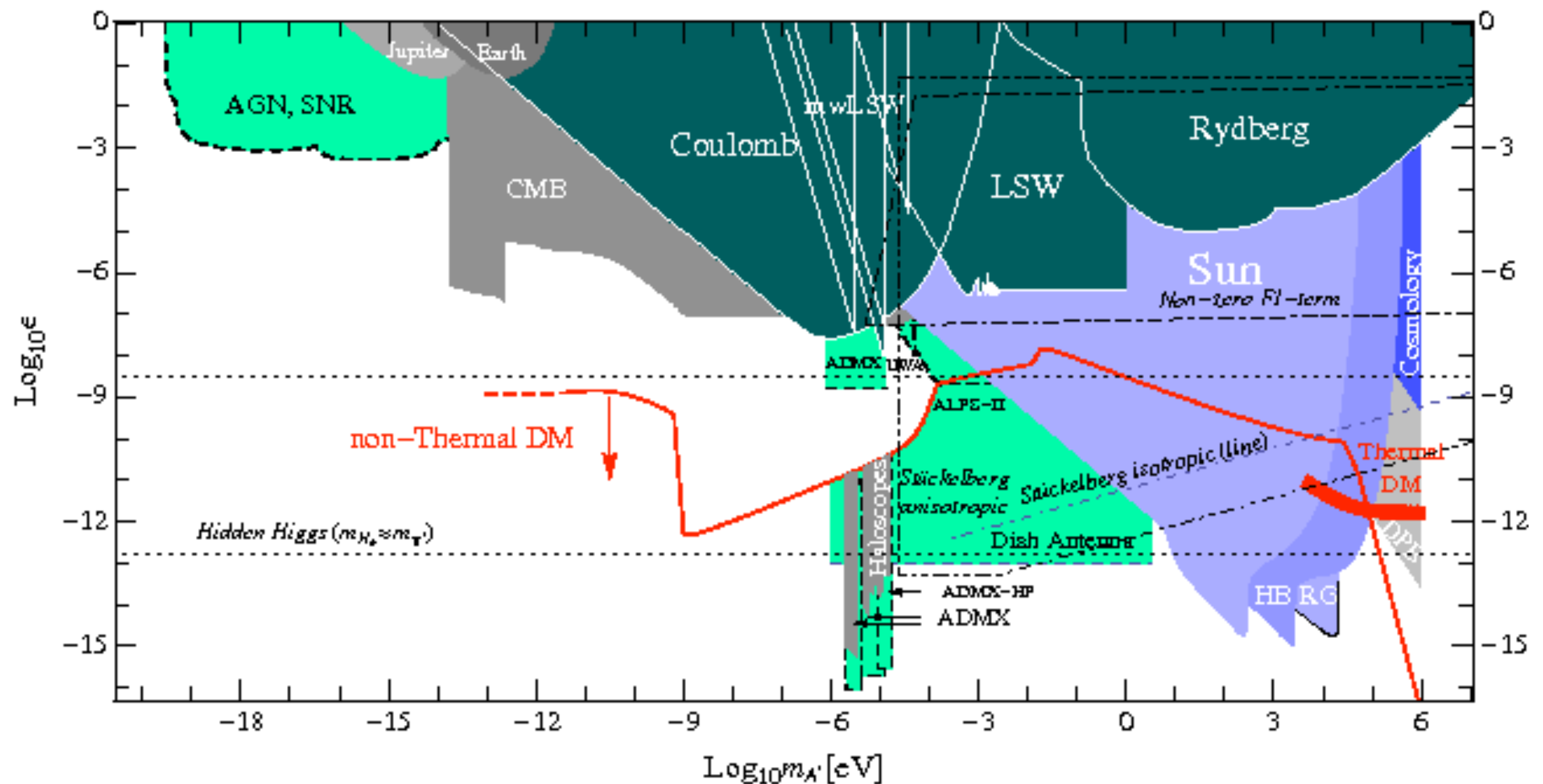
- If $m_x > 2m_e$:



[Bjorken, Essig, Schuster, Toro 2009; ...; **Itten et al. 2016**]

Minimal Vector Portal: Combined Limits

- If $m_x < 2m_e$:



[Jaeckel, Ringwald 2010; Arias et al. 2012; An, Pospelov, Pradler 2013; Essig et al. 2013]

Extra Slides: Massless Hidden Vector

Massless Dark Vector

- Start with massless X and A , massive Z vectors:

$$-\mathcal{L} \supset \frac{\epsilon}{2} X_{\mu\nu} (F^{\mu\nu} - t_W Z^{\mu\nu}) + e A_\mu j_{em}^\mu + g_Z Z_\mu j_Z^\mu + g_x X_\mu j_x^\mu$$

- Remove kinetic mixing with the change of variables

$$\left\{ \begin{array}{lcl} A^\mu & \rightarrow & A^\mu \\ Z^\mu & \rightarrow & Z^\mu \\ X^\mu & \rightarrow & X^\mu - \epsilon A^\mu + \epsilon t_W Z^\mu \end{array} \right.$$

Massless Dark Vector Couplings

- Putting in the shifted vectors,

$$\begin{aligned} -\mathcal{L} \supset & (ej_{em}^\mu - \epsilon g_x j_x^\mu) A_\mu \\ & + (g_Z j_Z^\mu + \epsilon t_W g_x j_x^\mu) Z_\mu \\ & + g_x j_x^\mu X_\mu \end{aligned}$$

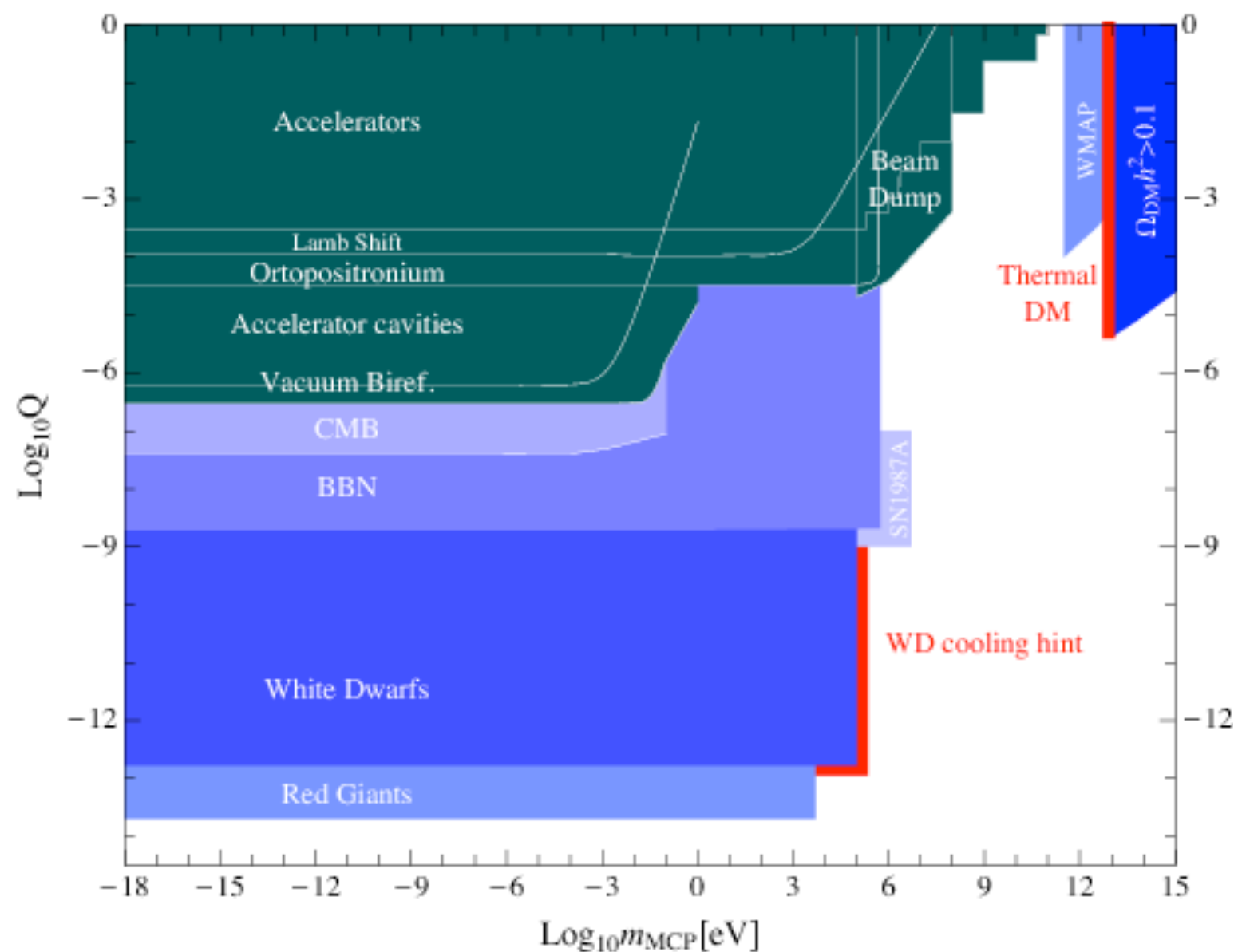
- Dark-sector matter acquires a millicharge:

$$Q_{eff} = -\epsilon \frac{g_x}{e}$$

- The dark photon does not couple to visible matter!

Limits on Millicharged Particles

- Limits are quoted in the $m_{MCP} - Q_{eff}$ plane:

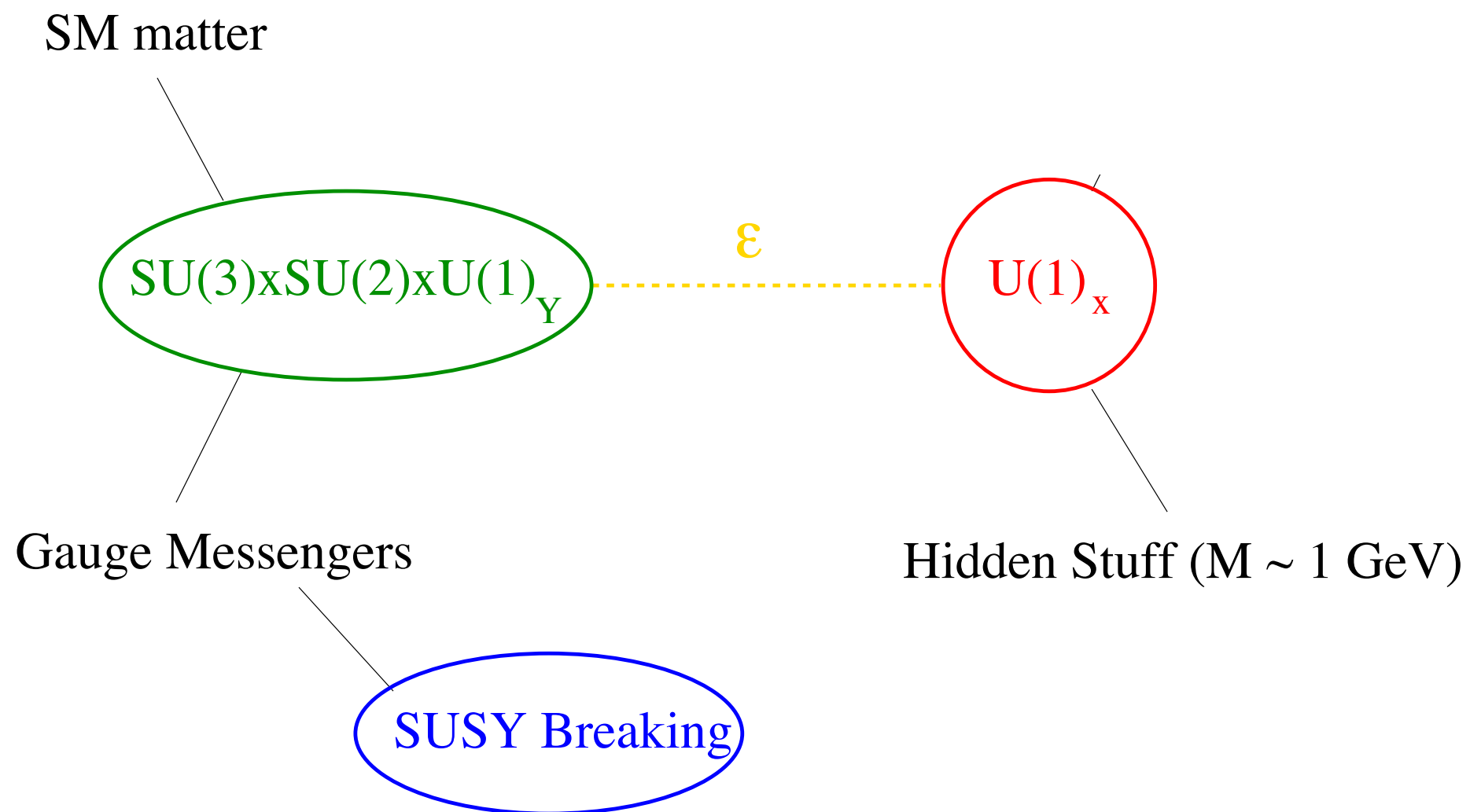


[Goodsell, Jaeckel, Redondo, Ringwald 2009]

Extra Slides: SUSY

Hidden Masses: Little Gauge Mediation

- If gauge mediators only carry MSSM charges:



Electron Fixed-Target Experiments

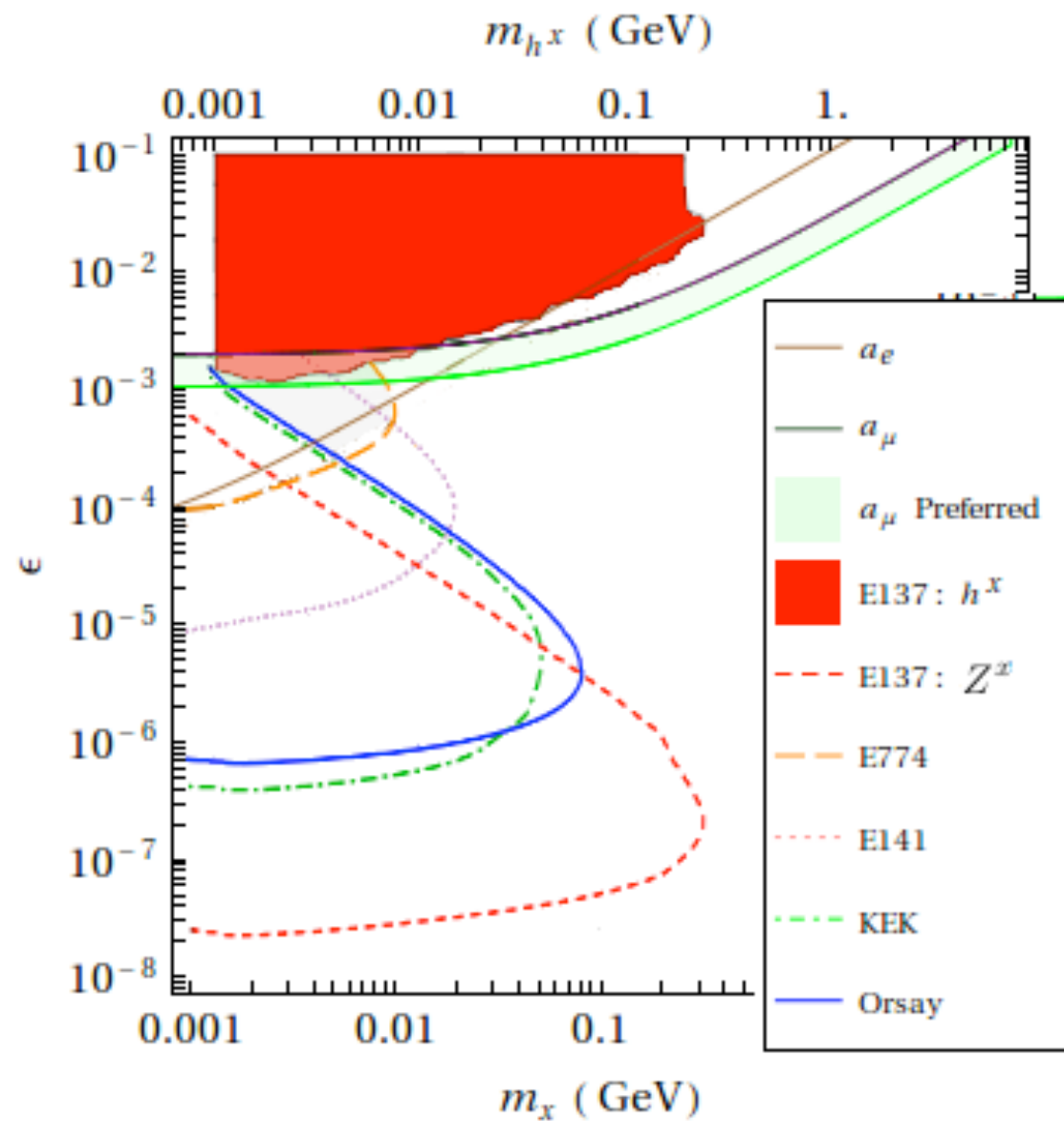
Expt	Target	E (GeV)	$\text{Log}_{10}N_e$	L_{sh}	L_{dec}
E137	Al	20	20	179	204
E141	W	9	15	0.12	35
E774	W	275	9	0.3	2
KEK	W	2.5	17	2.4	2.2
Orsay	W	1.6	16	1	2
JLab	Al	12	20	10	1

[Izaguirre, Krnjaic, Schuster, Toro 2013]

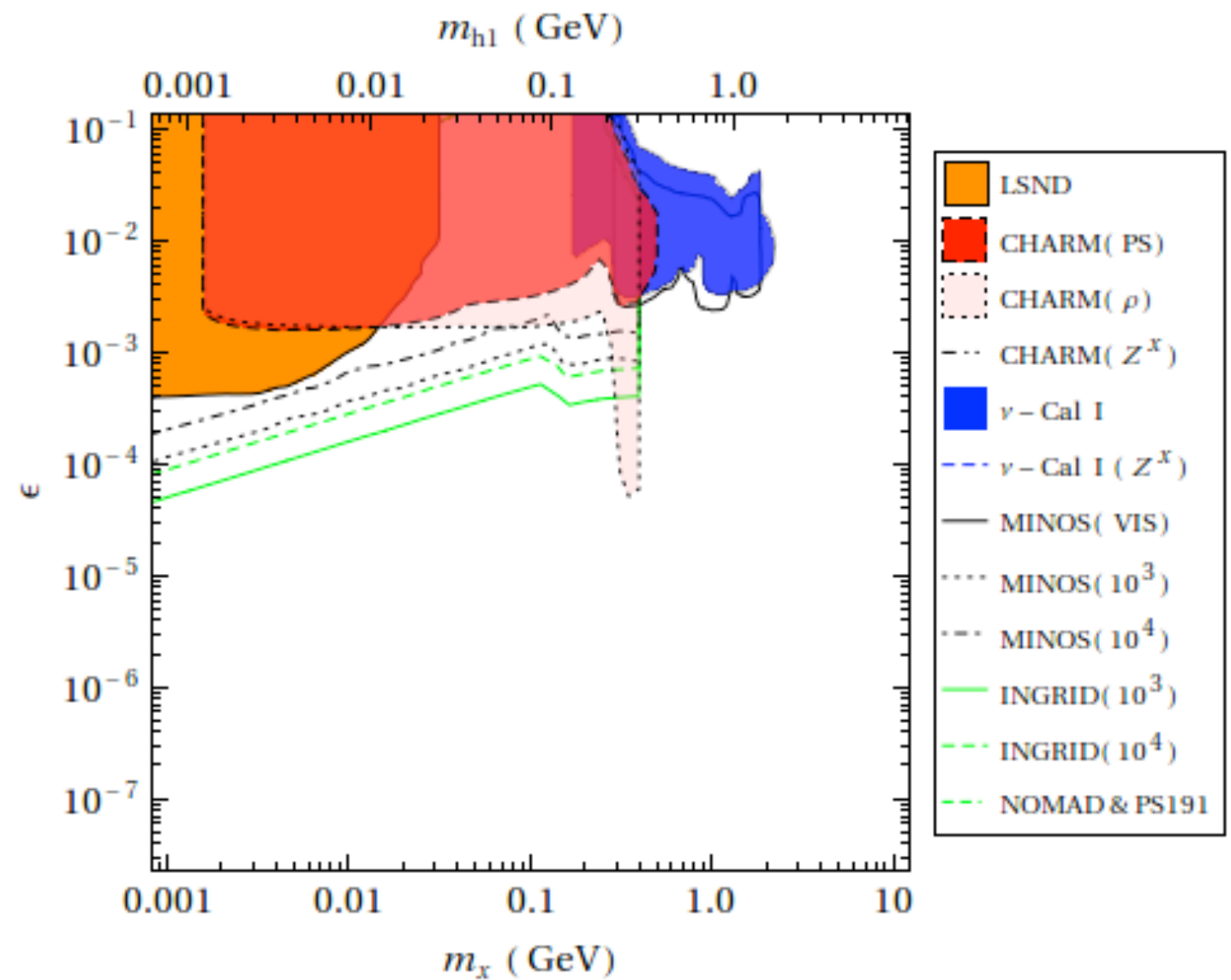
Hadronic Fixed-Target Experiments

Expt	Target	E (GeV)	$\text{Log}_{10}N_p$	L_{sh}	L_{dec}
CHARM	Cu	400	18	480	35
MINOS	C	120	21	1040	1.3
ν -Cal I	Fe	70	18	64	23
INGRID	C	30	21	280	0.585
LSND	...	0.798	...	30	8.3

Case A - Fixed Target

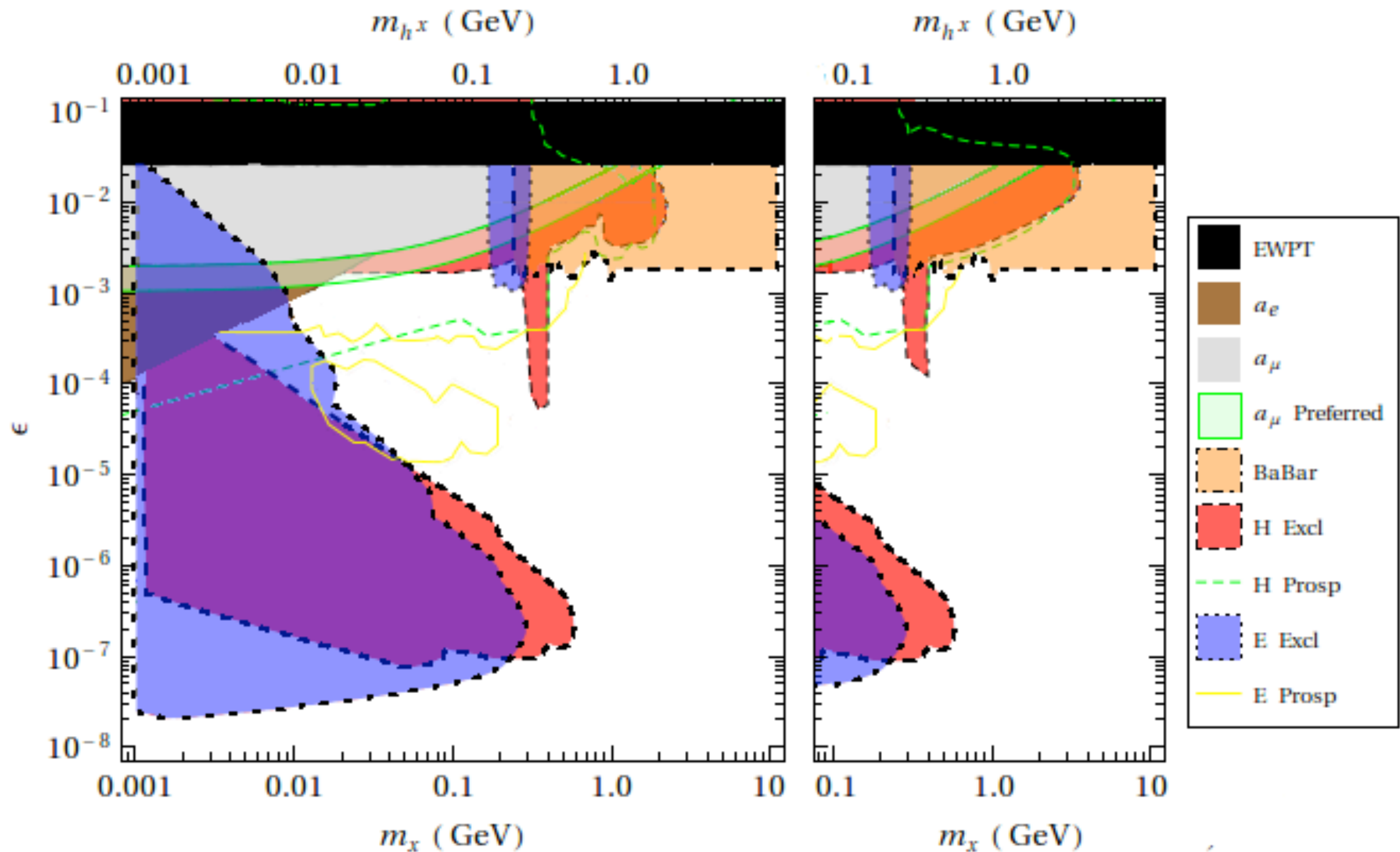


E Beam



H Beam

Case A - Summary

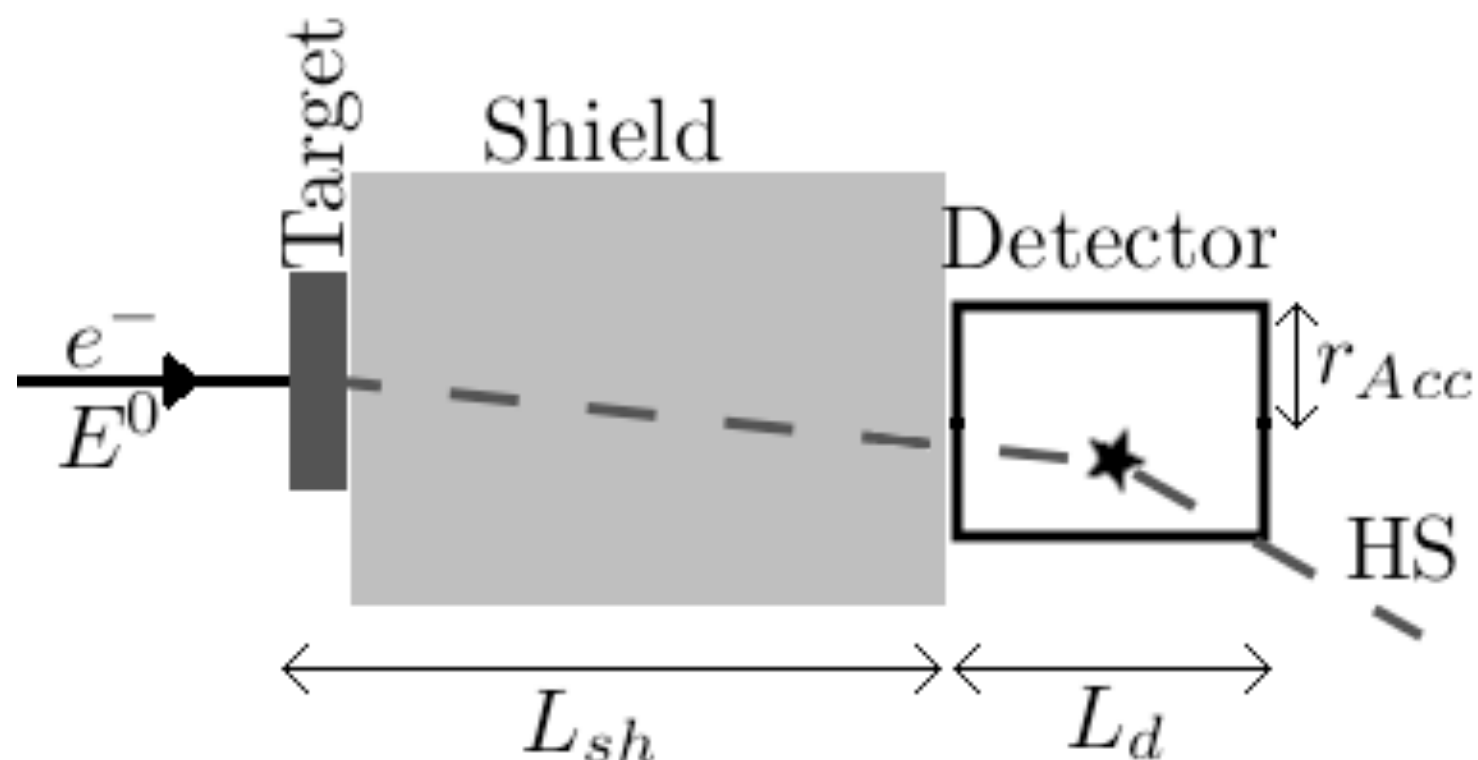


Case B: $X^\mu \rightarrow \chi_1^x + \chi_1^x$

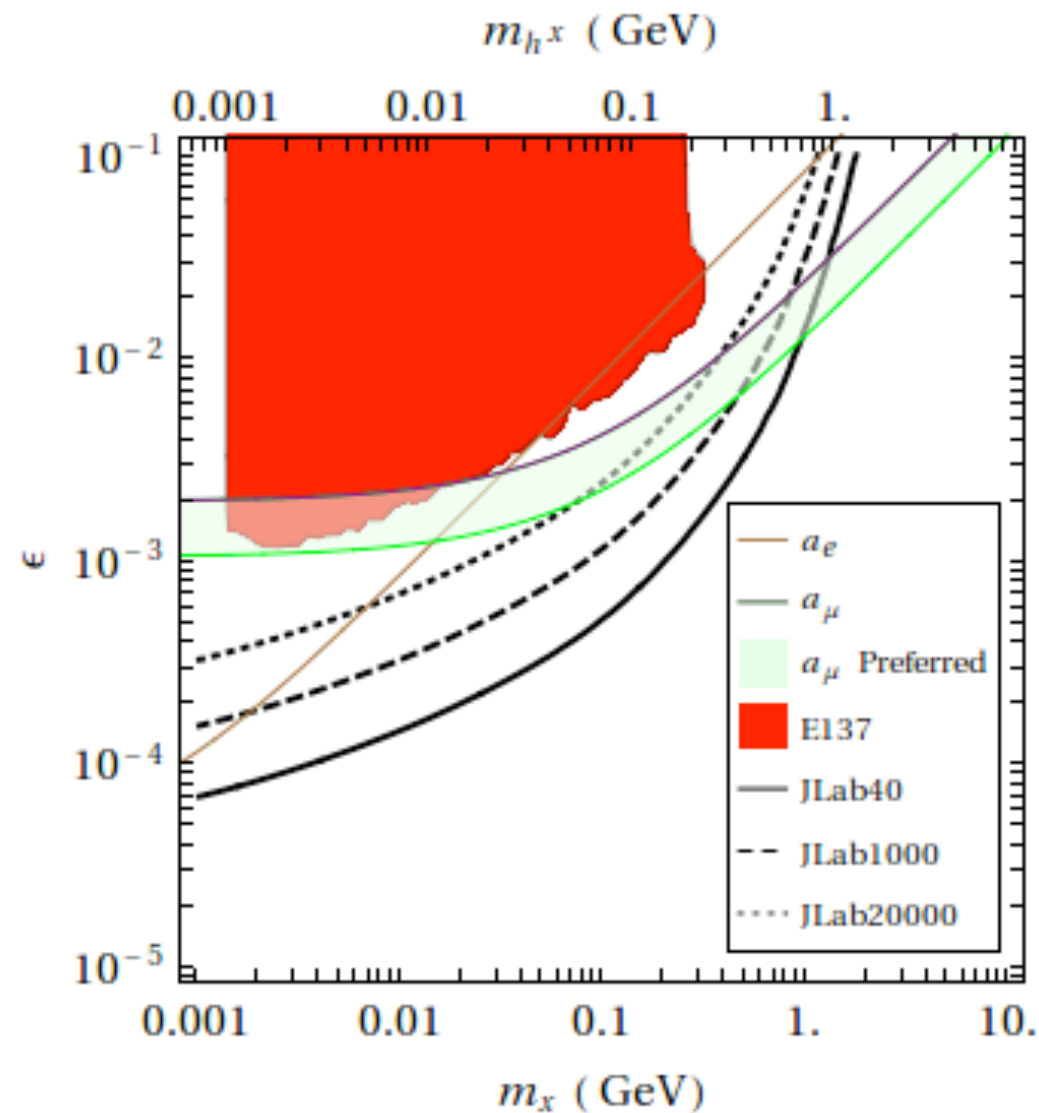
- Dominates over SM modes for $\alpha_x > \epsilon^2 \alpha$.
- χ_1^x is the lightest superpartner (LSP) and is stable.
(Tends to produce too much thermal DM if $m_{\chi_1^x} < m_x$.)
[Pospelov, Ritz, Voloshin 2007]
- Electroweak and (g-2) limits apply here as well.
- Flavor factories: [Izaguirre, Krnjaic, Schuster, Toro 2013]
 - BaBar: $\Upsilon(ns) \rightarrow \gamma + (invisible)$ data.
 - BNL: $K^+ \rightarrow \pi^+ + (invisible)$

Case B: $X^\mu \rightarrow \chi_1^x + \chi_1^x$

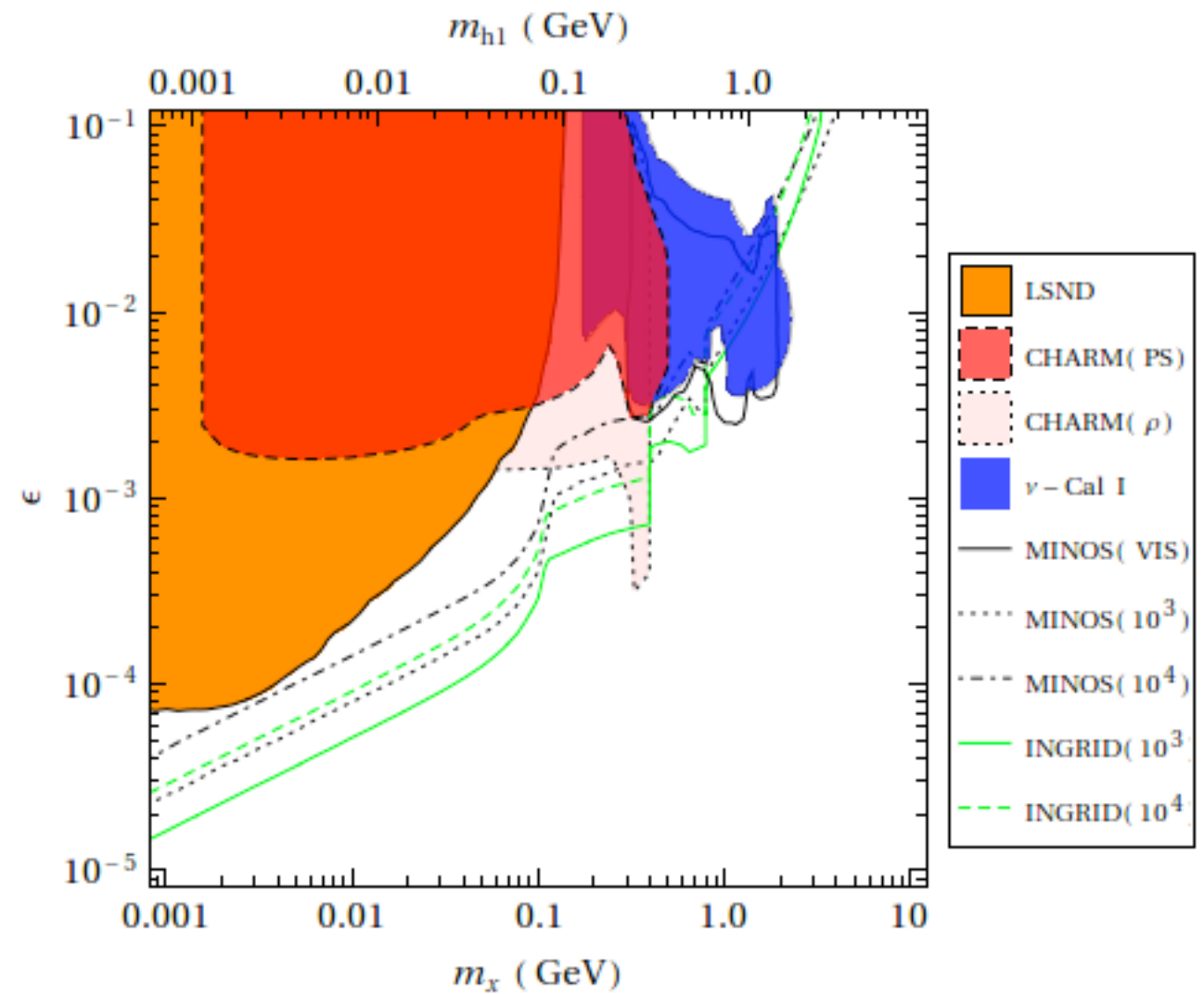
- Fixed-Target experiments: [Batell, Pospelov, Ritz 2009]
- X^μ is created in the target with a large boost.
- Decays to χ_1^x form a collimated hidden neutralino beam.
- Look for quasi-elastic scattering in the detector.



Case B - Fixed Target

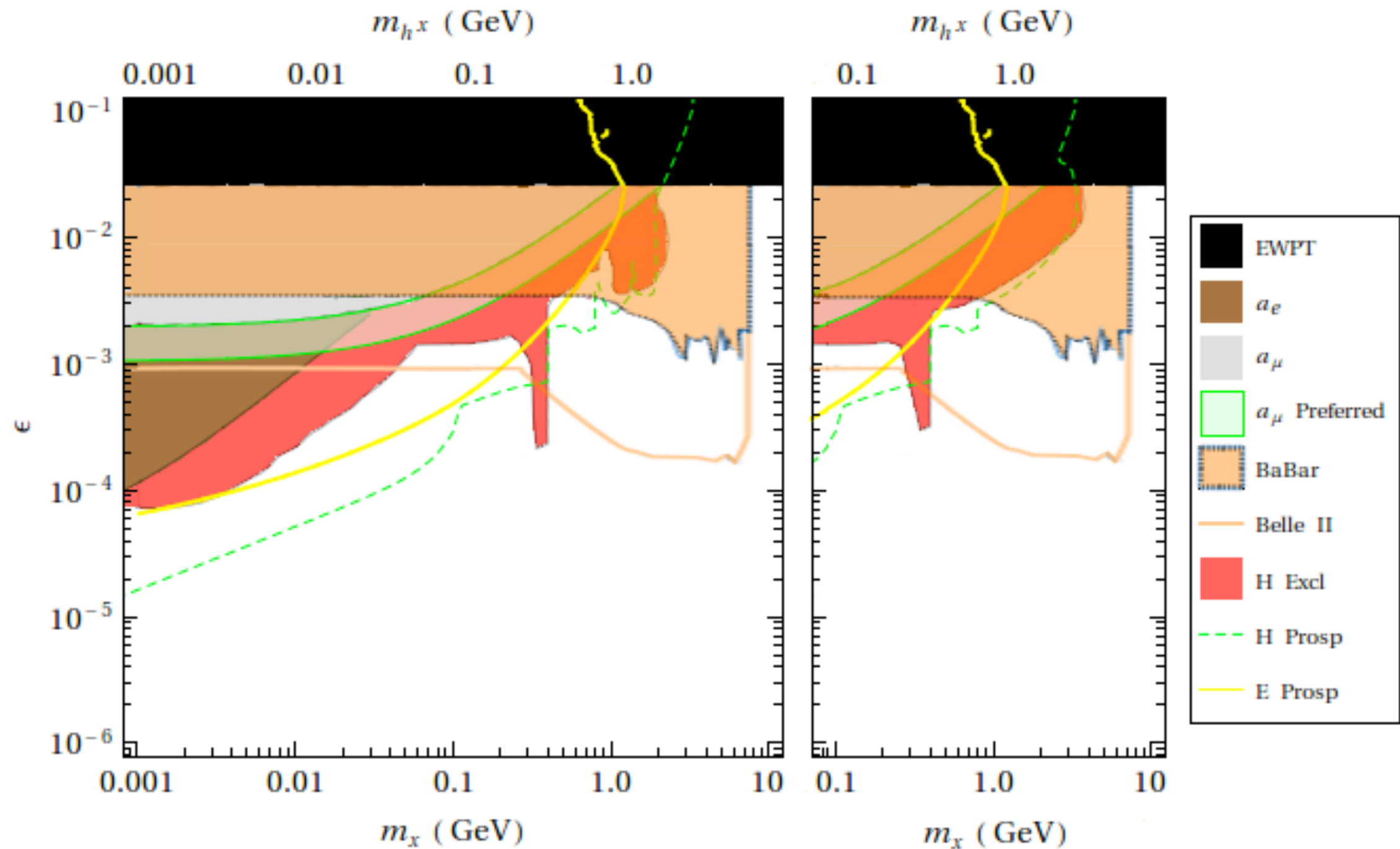


E Beam

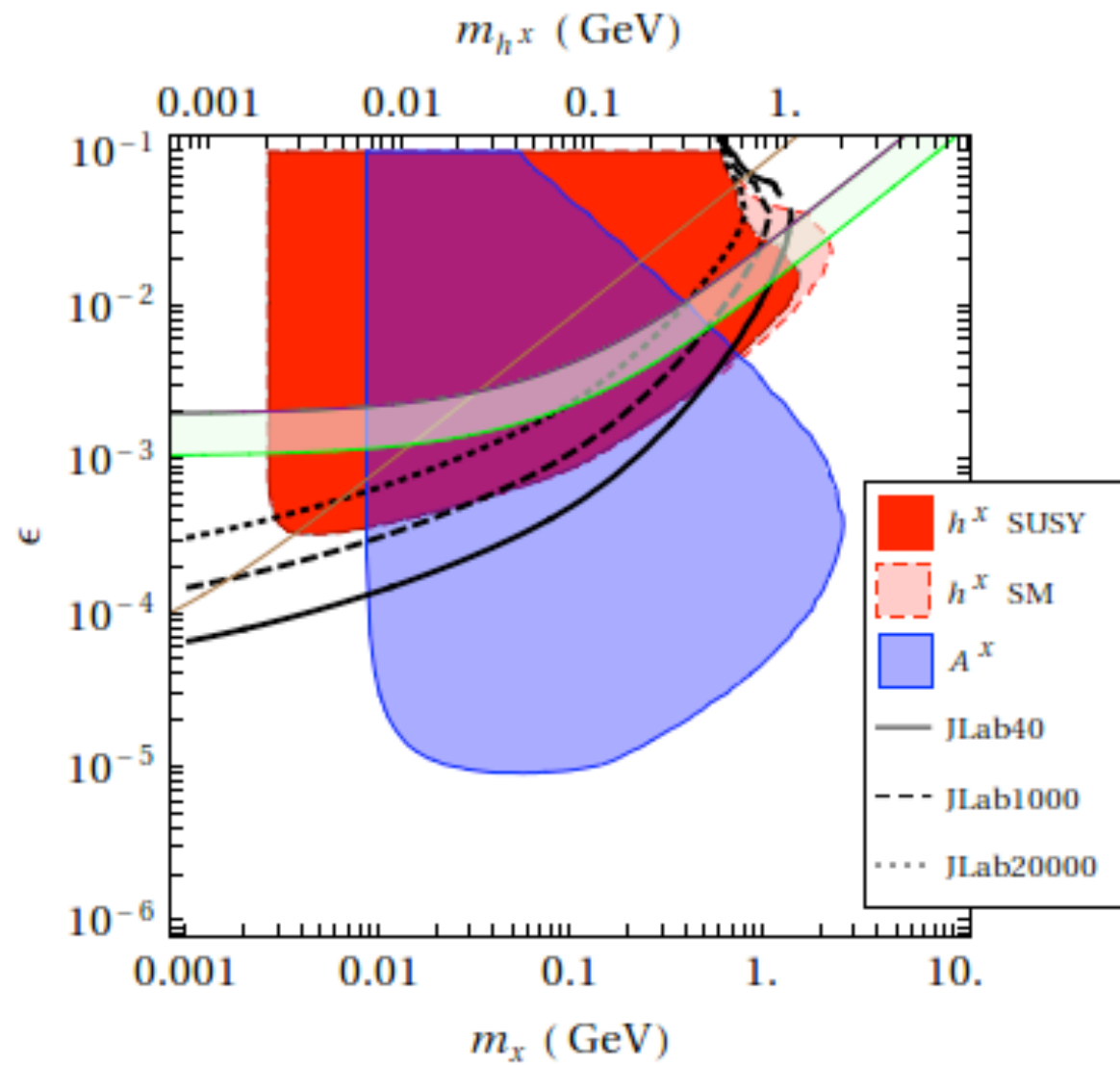


H Beam

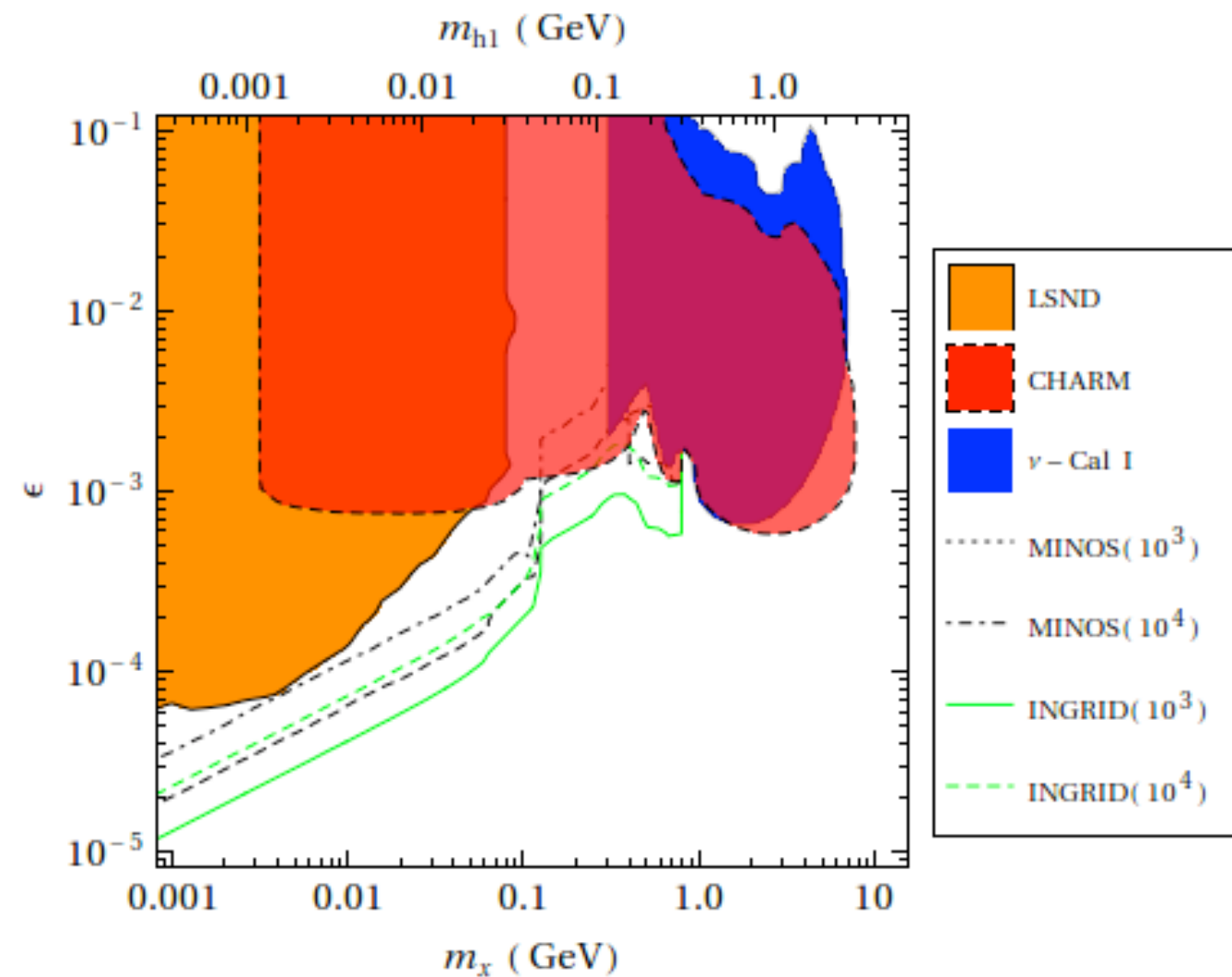
Case B - Summary



Case C - Fixed Target



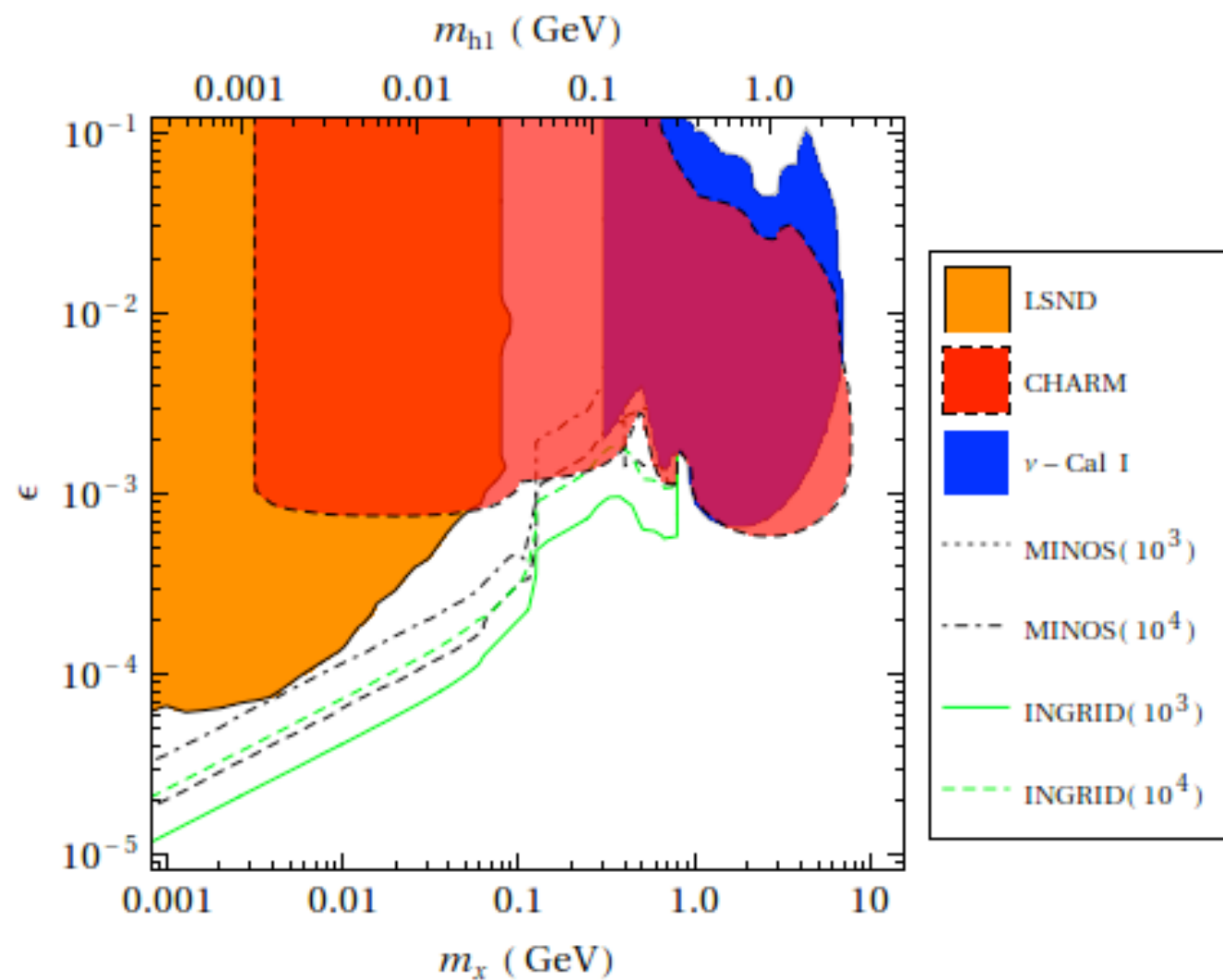
E Beam



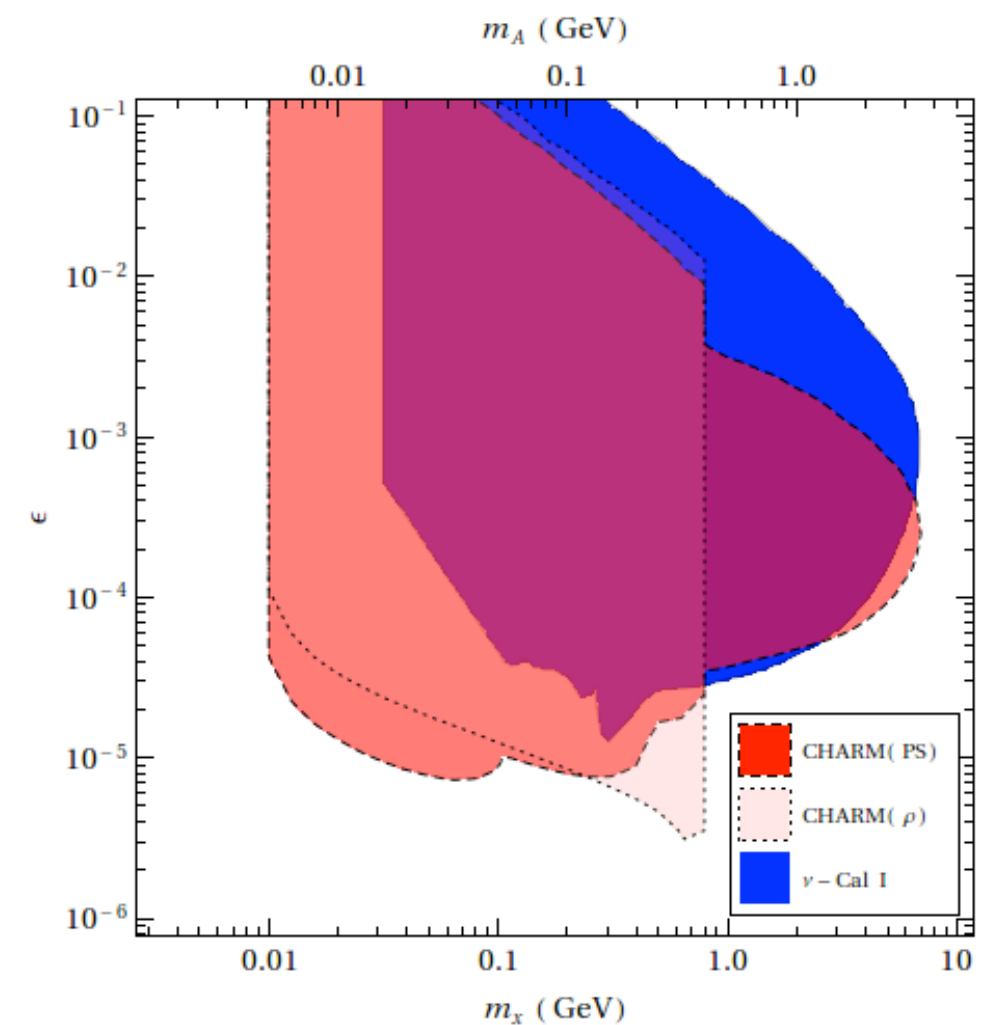
H Beam

Case C: Hadronic Fixed Target Limits

- Best limits come from CHARM, LSND, and ν -Cal I.

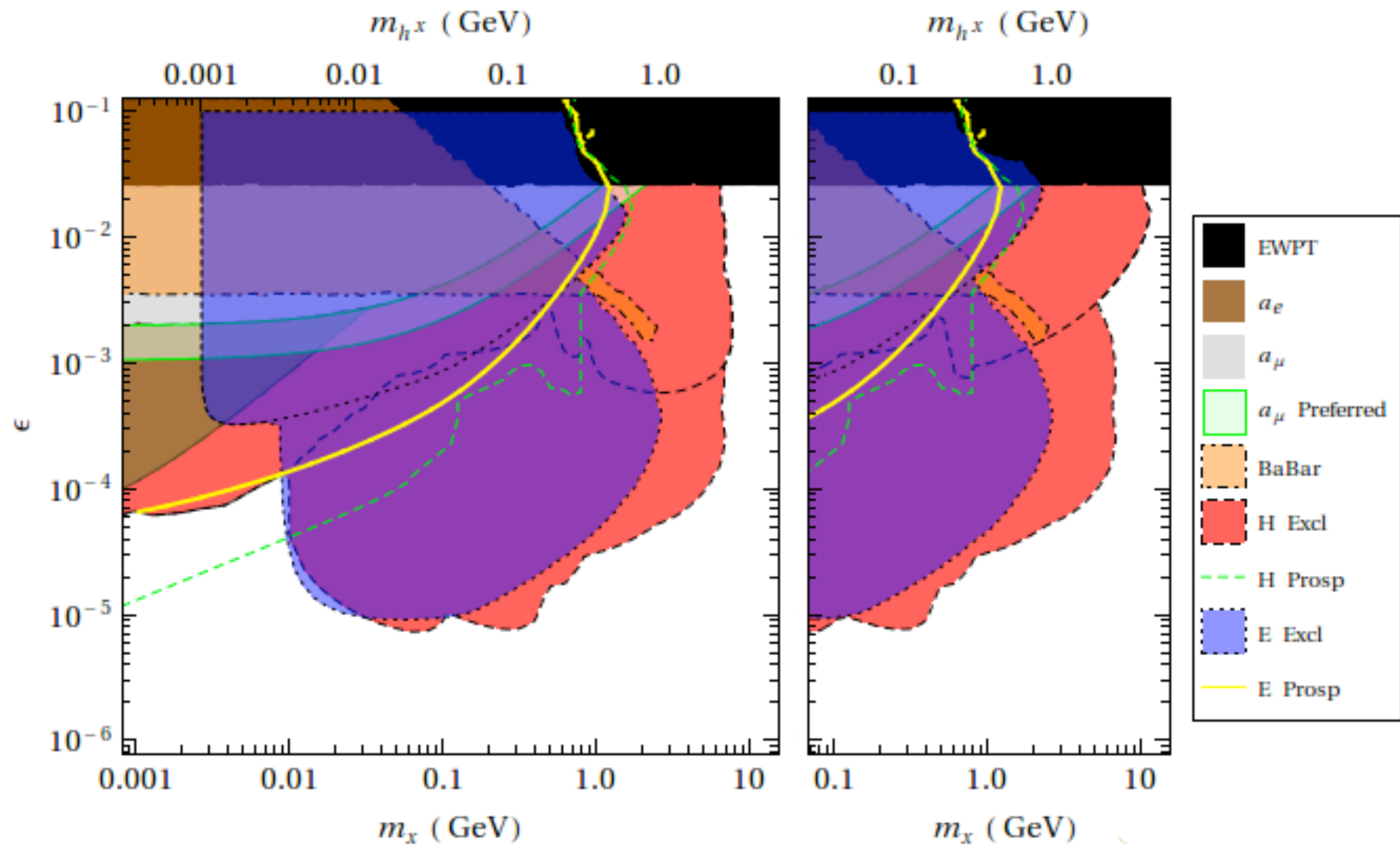


$h_1^x + \text{invisible}$

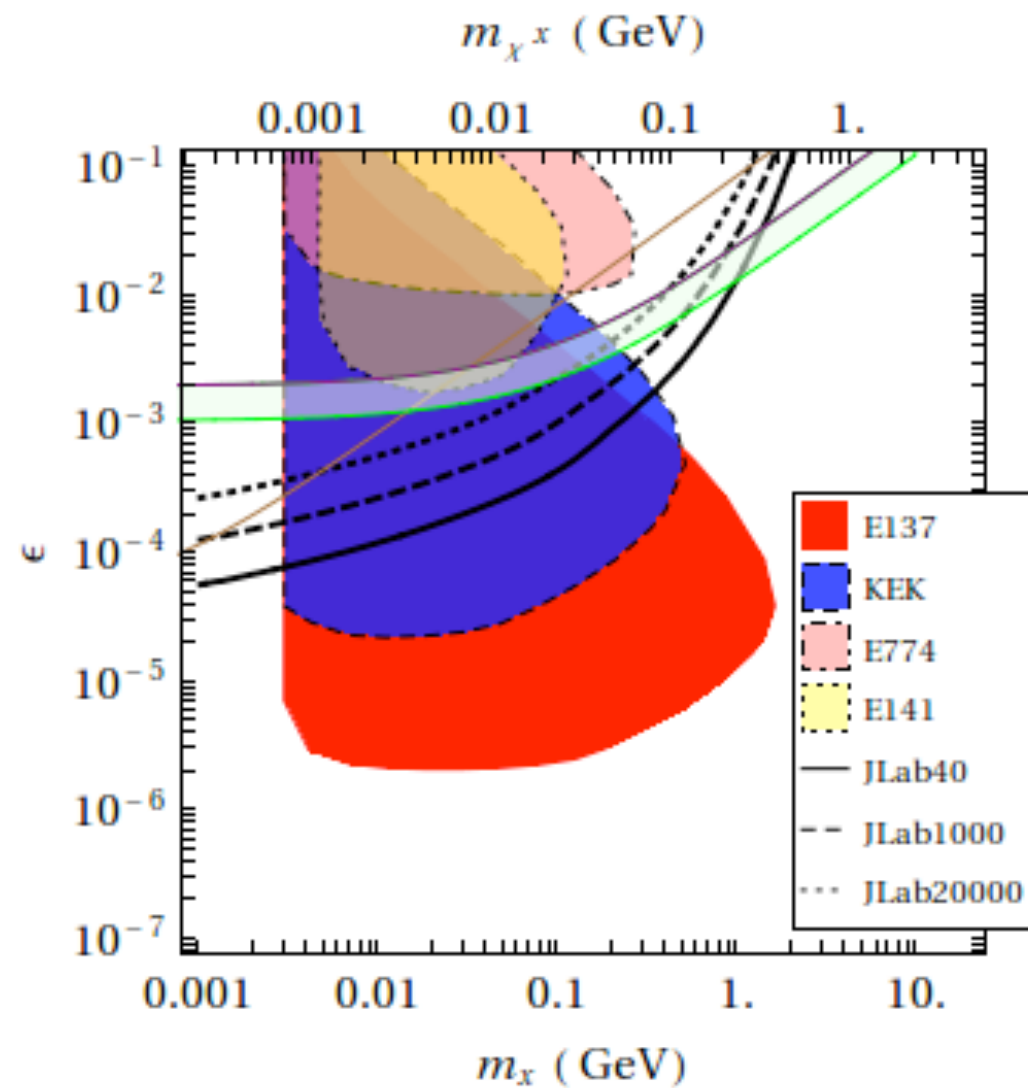


a^x

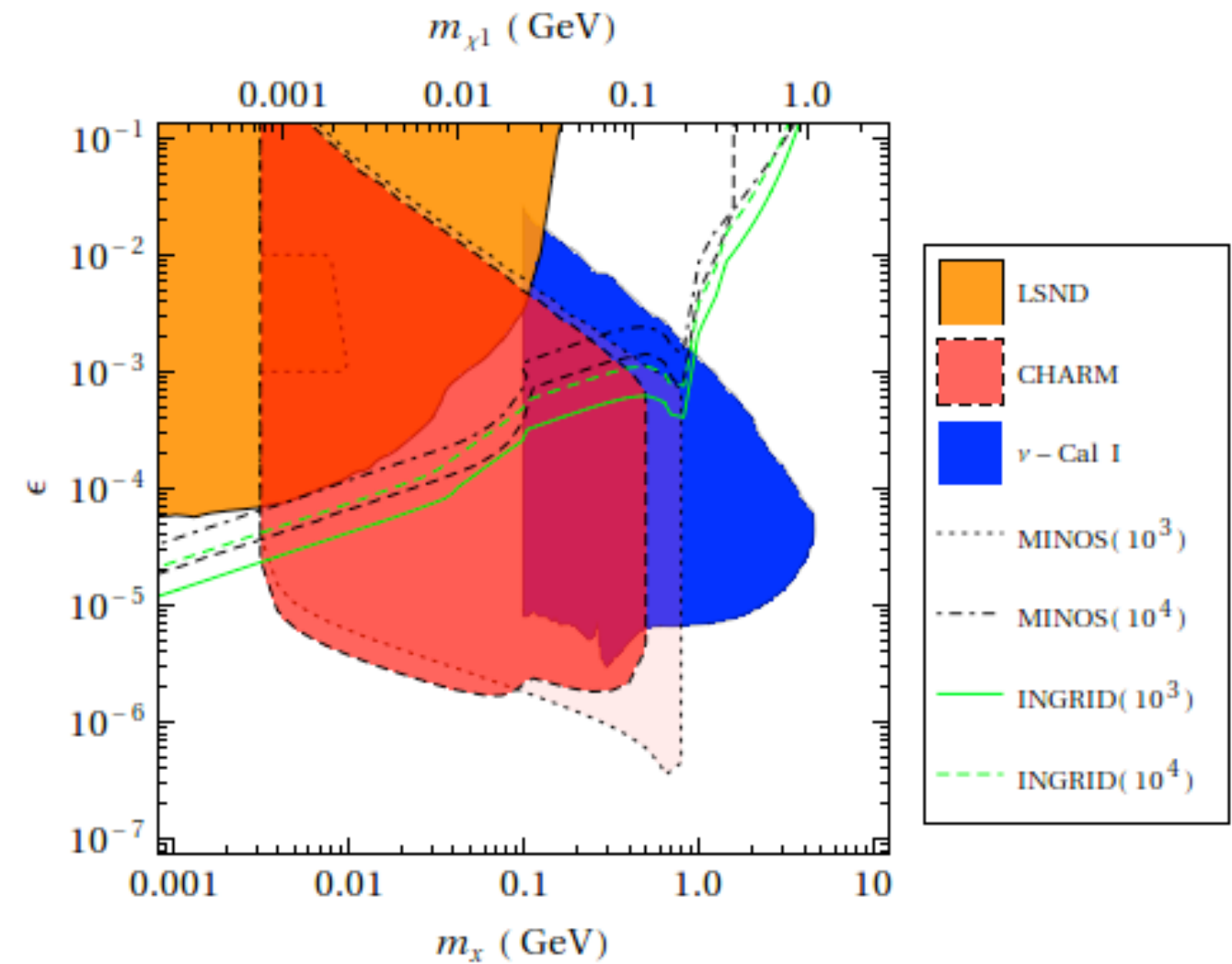
Case C - Summary



Case D - Fixed Target

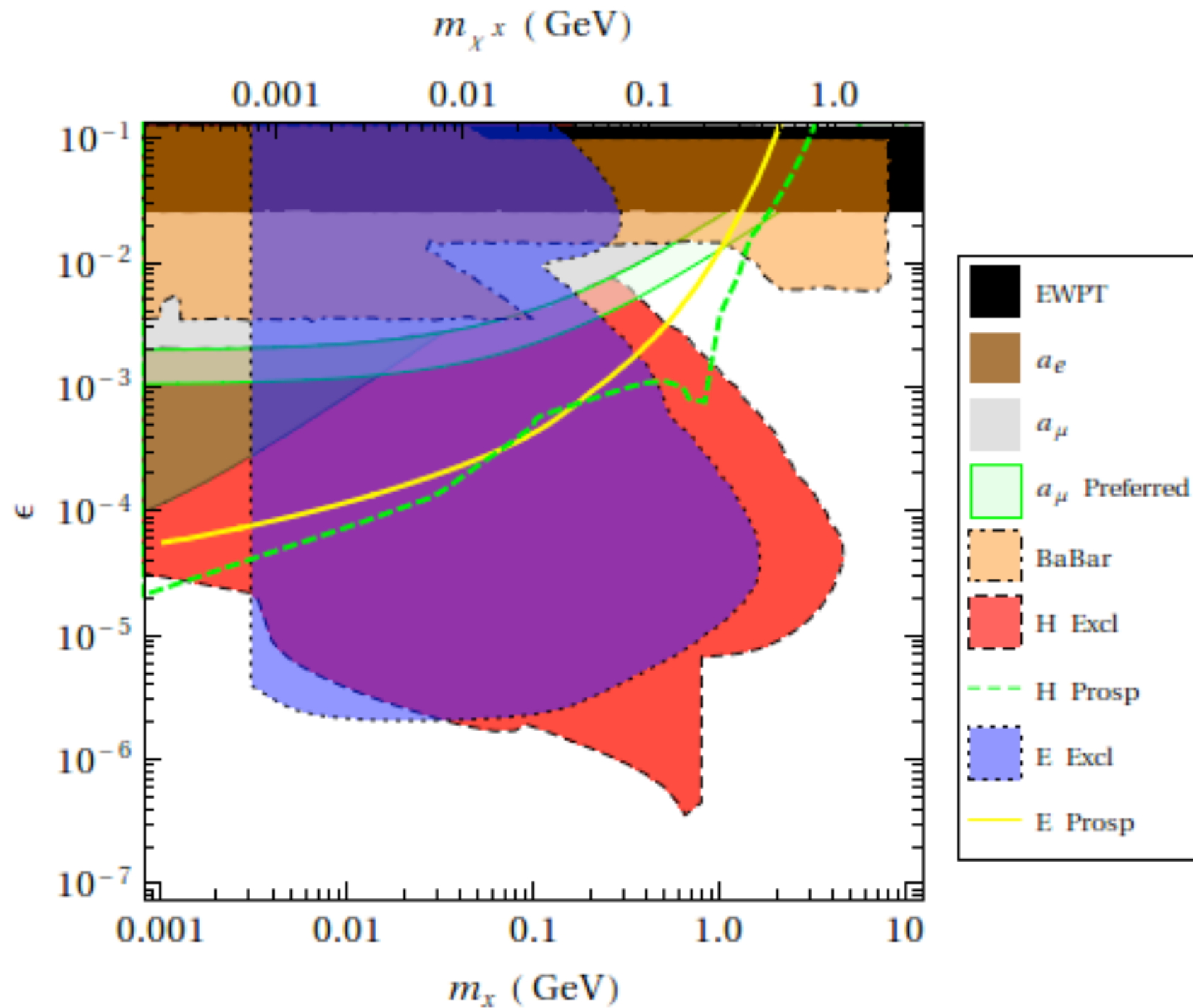


E Beam



H Beam

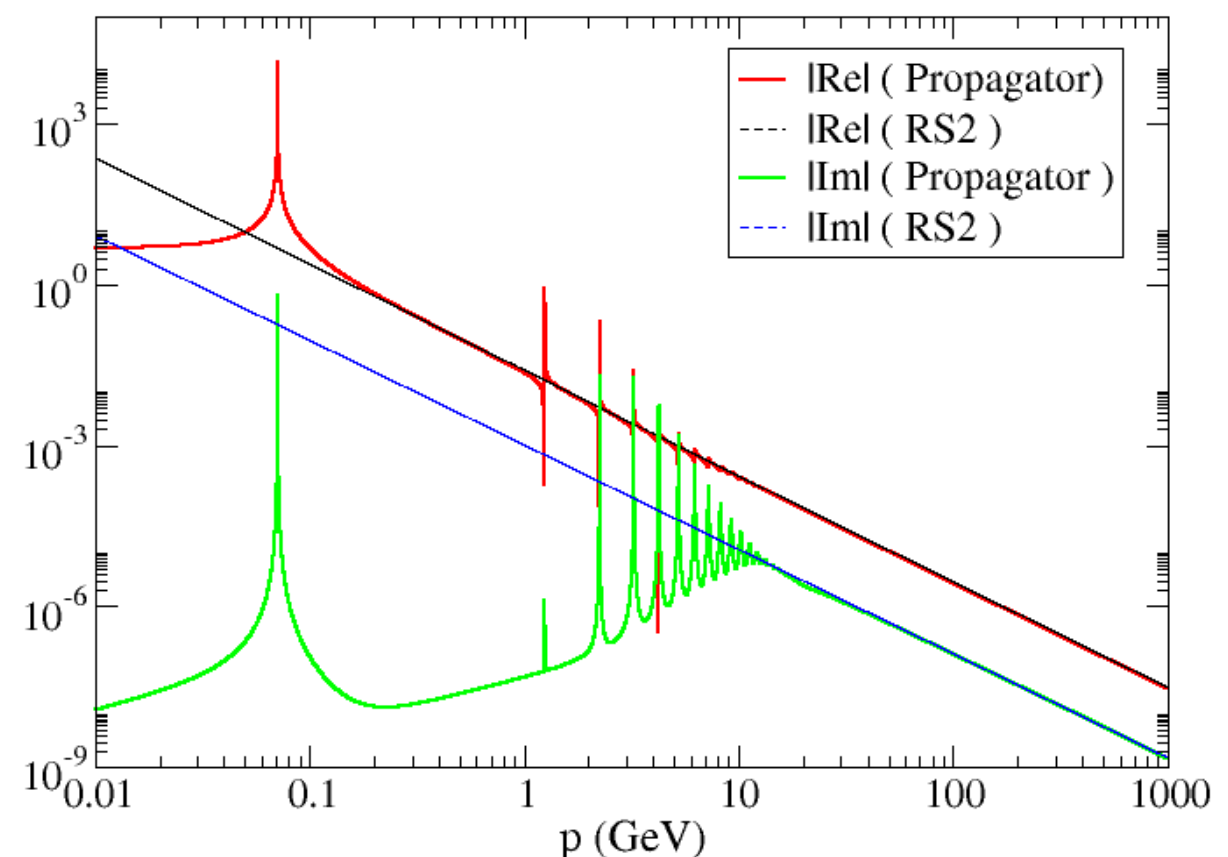
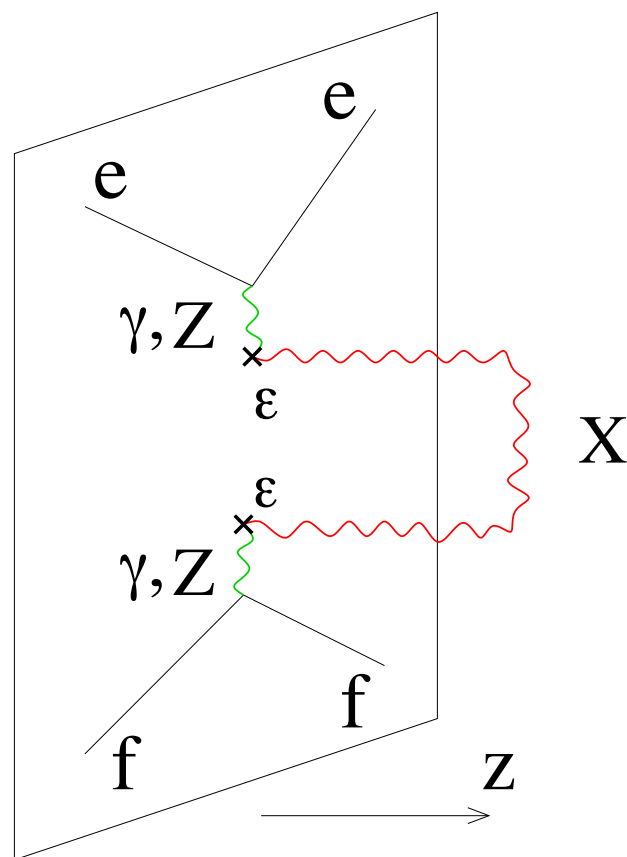
Case D - Summary



Extra Slides: Warped

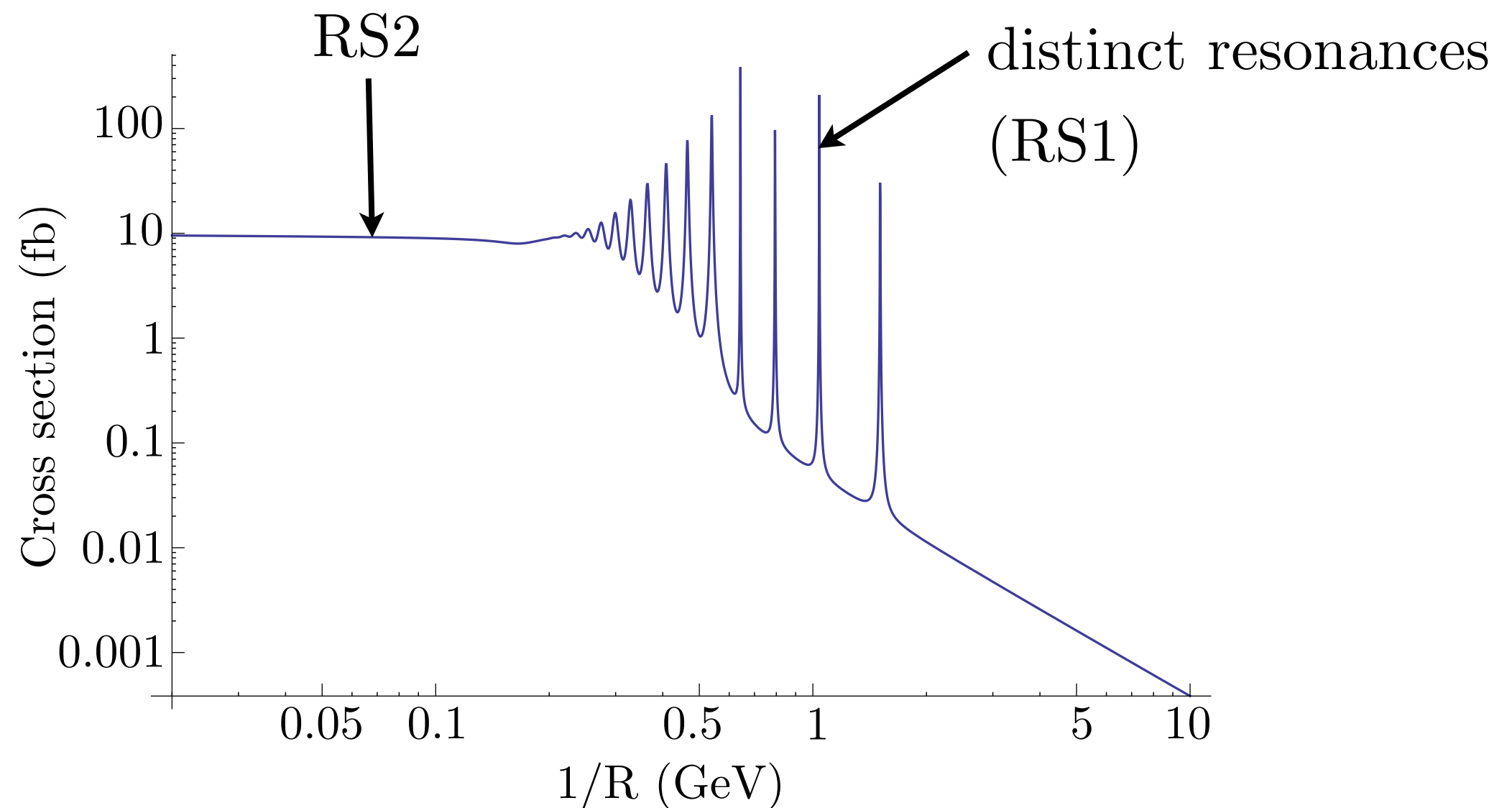
Hidden Warped Sector: Signals

- Visible signals typically involve UV to UV propagators.
- These should be under control for $\sqrt{s} \ll 1/R_1$, even if $\sqrt{s} \gg 1/R_2$, where the KK description fails.
- Idea: match to RS2 and use unitarity for inclusive rates.



Hidden Warped Sector: Inclusive Production

- Inclusive hidden production at BaBar: $\sqrt{s} = 10.58 \text{ GeV}$



Extra Slides: Dark Glue

Dark Glueballs in the Early Universe

- Assume thermal decoupling of dark and SM sectors.
⇒ independent temperatures and entropies

- Adiabatic: $R \equiv \frac{s_x}{s} = \text{constant}$

- Glueballs form in a confining transition at:

$$T_x \simeq 1.25 \Lambda_x \simeq m_{0^{++}}/5 \quad [\text{Lucini, Teper, Wenger 2005}]$$

Weakly first-order for $N = 3$, stronger for larger N .

- Relic dark glueballs can contribute to the DM density!