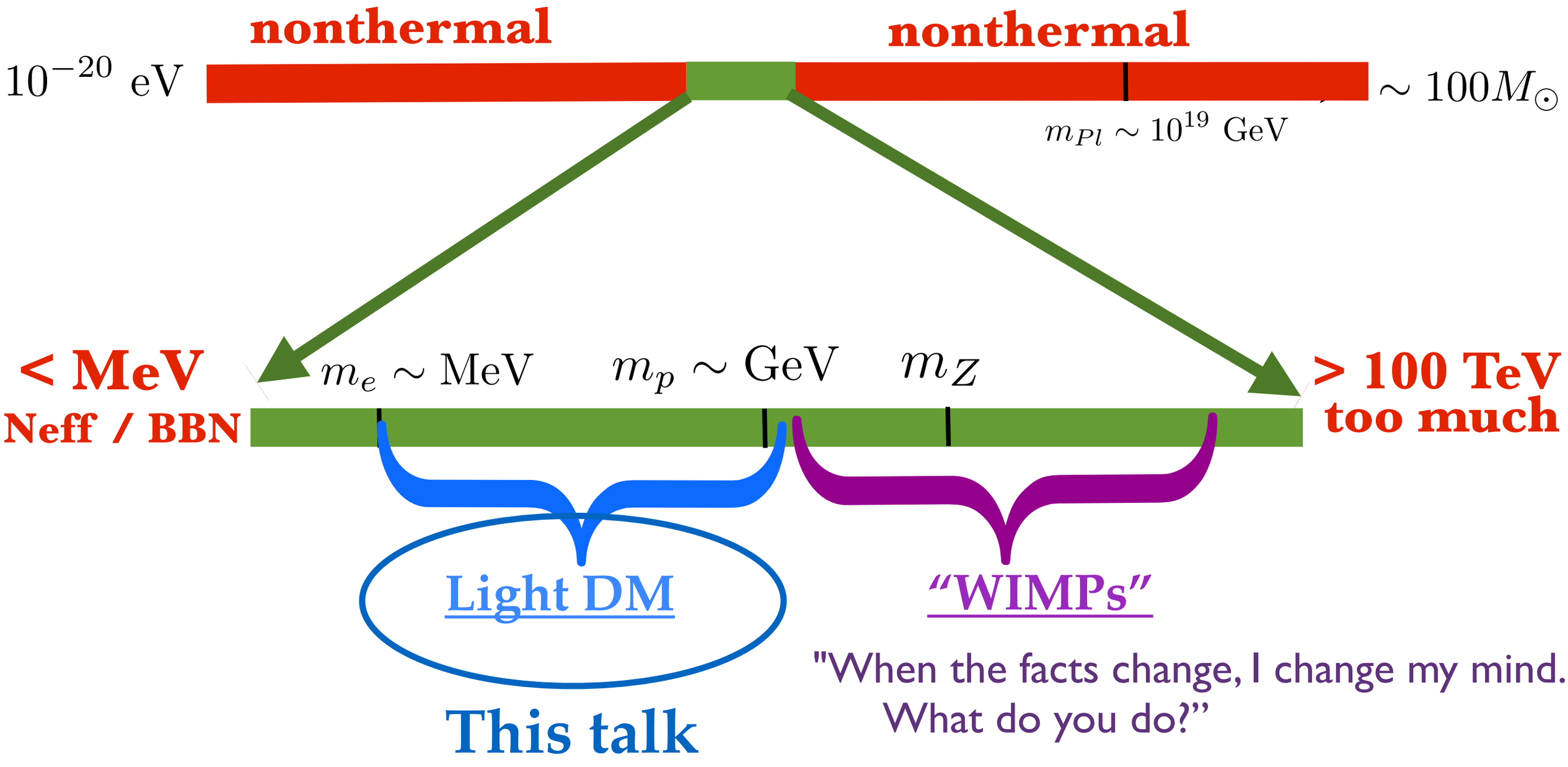
Secluded Dark Matter ($< \mathrm{GeV}$)

Gordan Krnjaic

RF6 Meeting, Dec 4, 2020

Thermal Dark Matter



"When the facts change, I change my mind.
What do you do?"

- John Maynard Keynes

Light DM vs. WIMPs

LDM must be SM neutral

Else would have been discovered

LDM needs light new force carriers

Overproduced without light, neutral "mediators"

$$\sigma v \sim G_F^2 m_\chi^2 \sim 10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Always too small if weak scale

Annihilation through *renormalizable* interactions

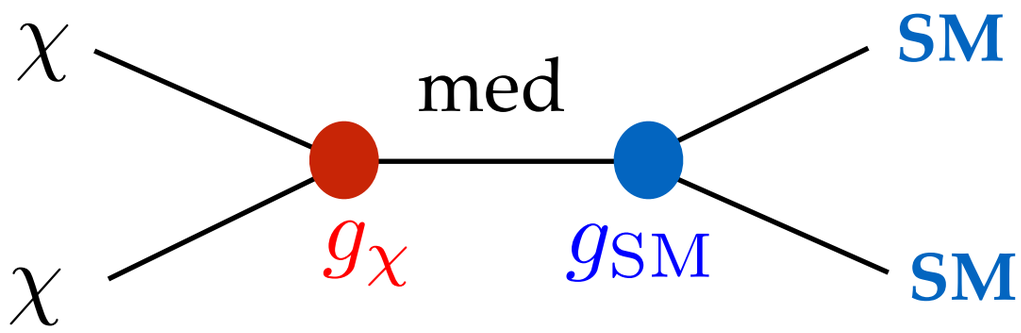
Easy to categorize options

Who's Heavier: DM or Mediator?

See Asher's talk five minutes ago

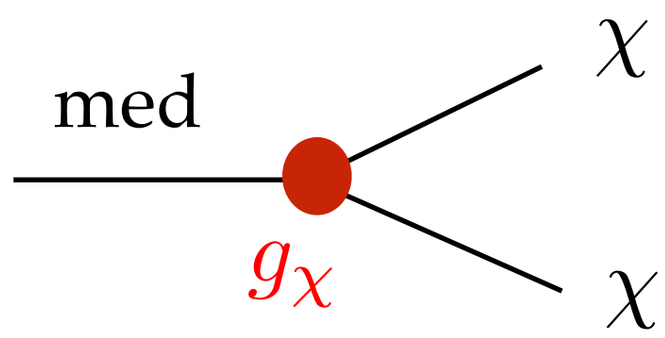
Direct Annihilation

$m_\chi < m_{\rm med}$



Predictive thermal targets

Abundance depends on $g_{\rm SM}$

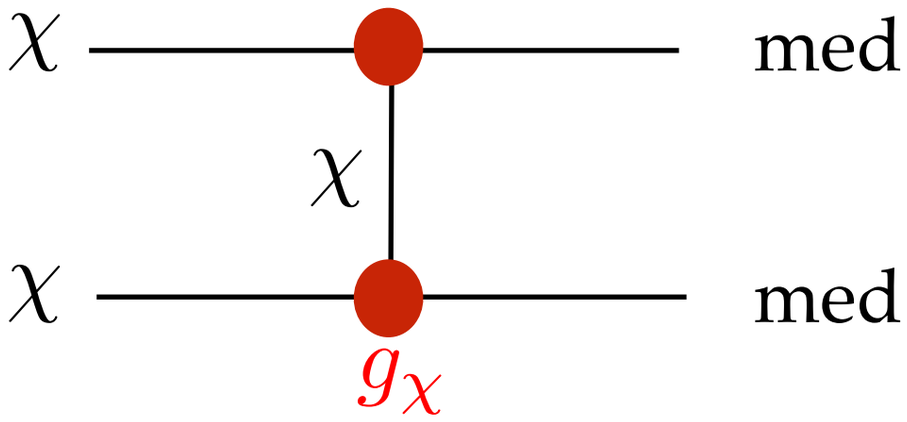


Mediator decays **to DM***

Who's Heavier: DM or Mediator?

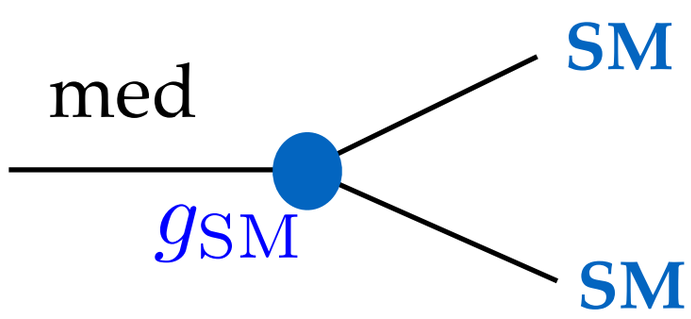
Secluded Annihilation

$m_\chi > m_{\rm med}$



No clear experimental target

Abundance set by g_χ



Mediator decays **to SM**

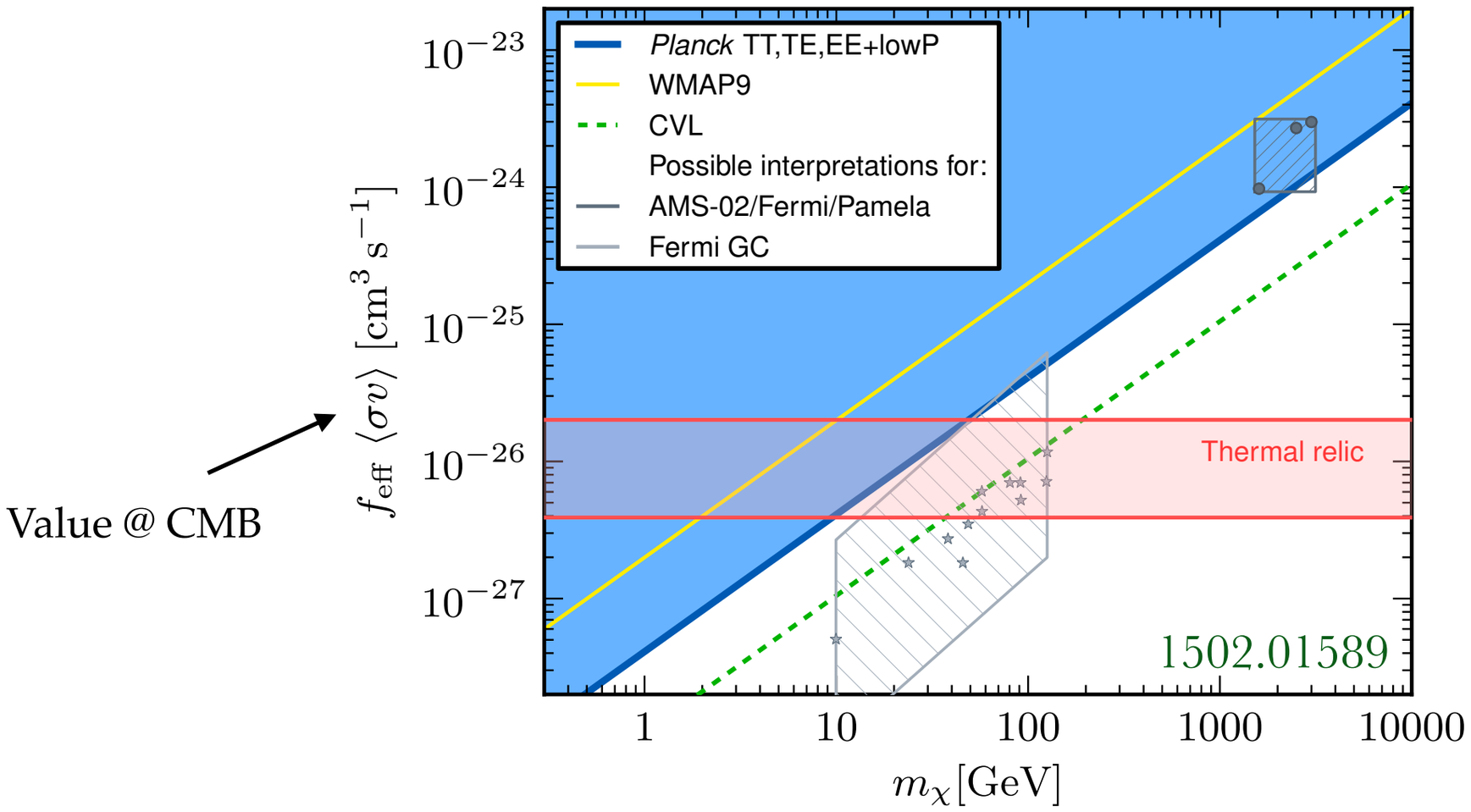
This talk

Early universe: DM+SM in equilibrium due to $g_{\rm SM}$

Freeze-out: independent of SM coupling

Secluded U(1) below the weak scale
Pospelov 0811.1030

CMB excludes many < GeV thermal DM Models



Value @ CMB

Out-of-equilibrium annihilation injects energy during CMB era

Options for safe models:

1) P-Wave Annihilation

2) Annihilation Stops pre-CMB

3) Mediator Decays to Neutrinos

Overview

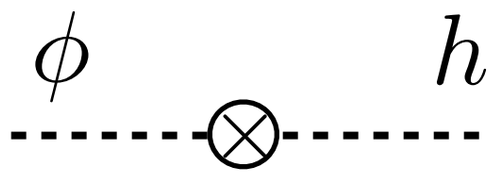
1) P-Wave Annihilation

2) Annihilation Stops pre-CMB

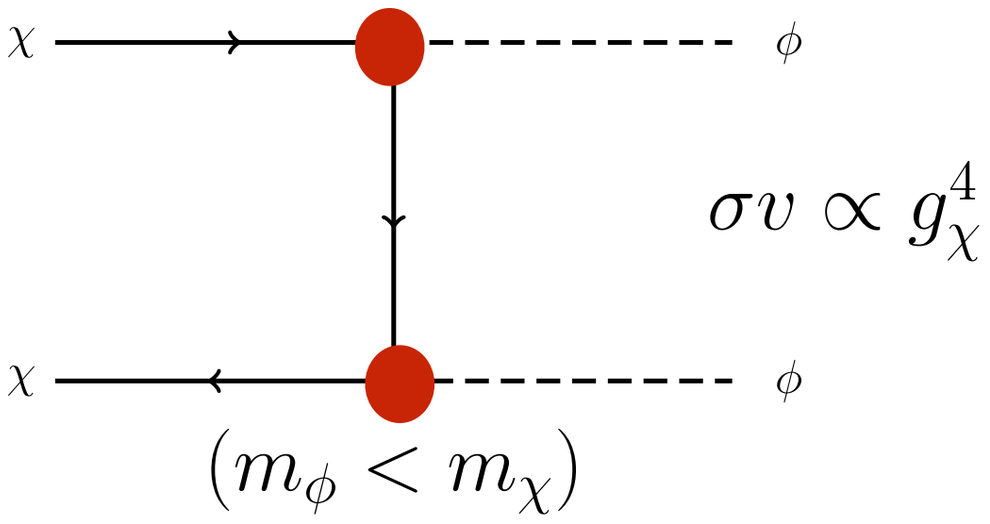
3) Mediator Decays to Neutrinos

Higgs Portal Scalar Mediator

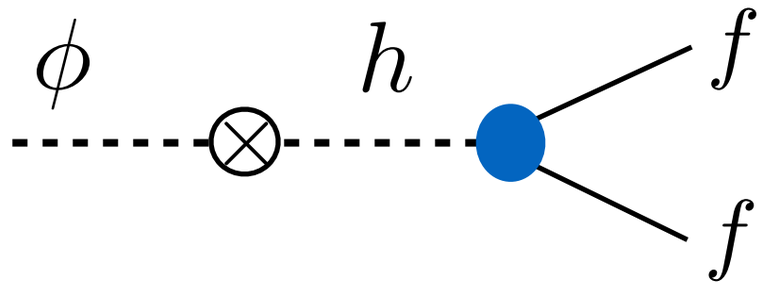
Scalar/Higgs mixing $\phi H^\dagger H \to \phi h$



Coupled to DM/SM $\mathcal{L} \supset g_\chi \phi \bar{\chi}\chi + \phi \sin\theta \sum \frac{m_f}{v} \bar{f} f$

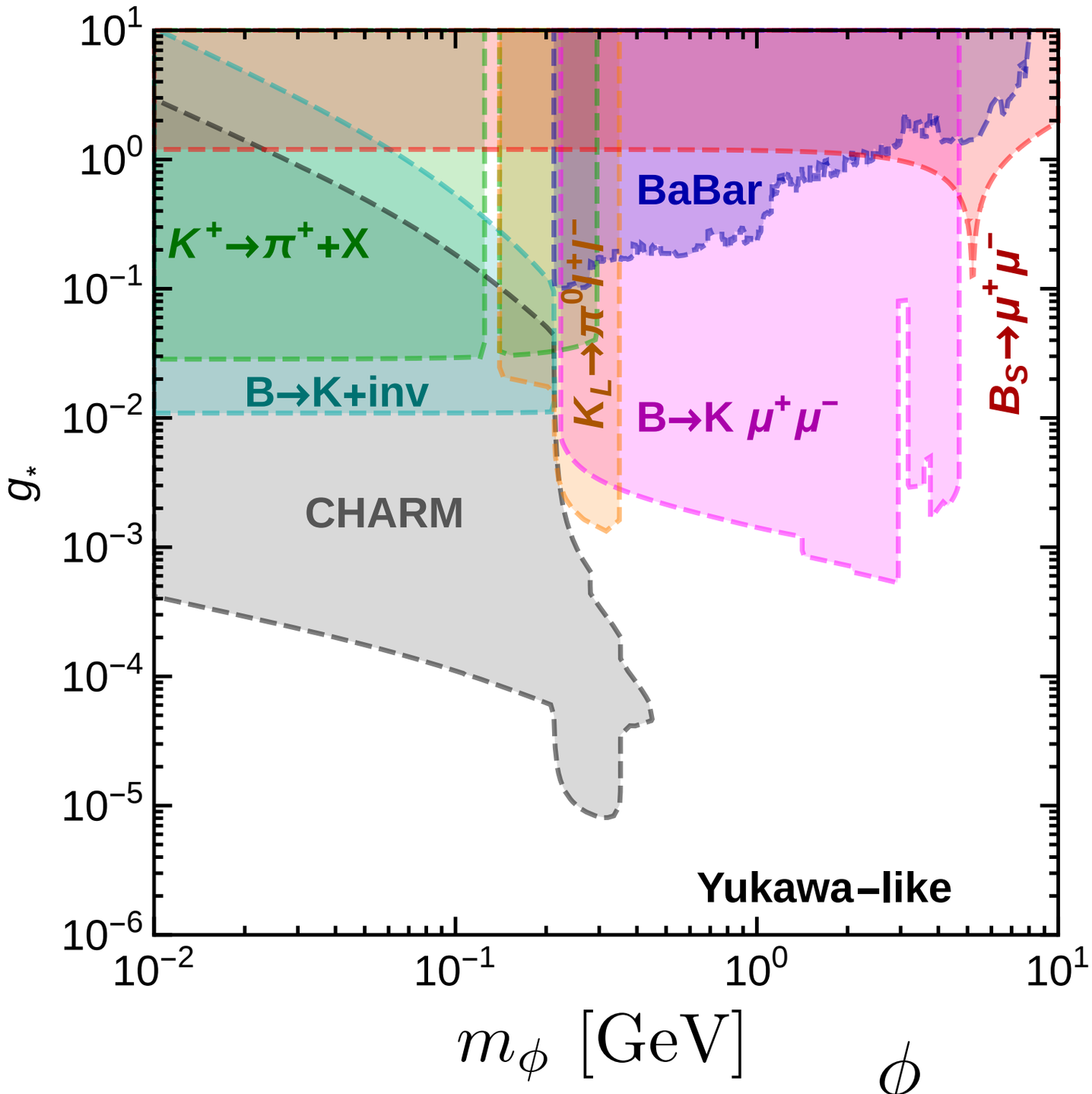


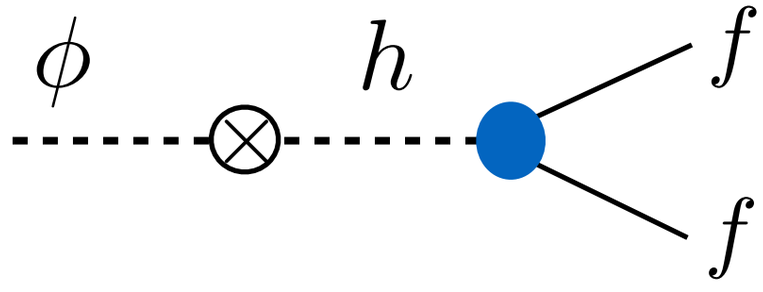
Decays like a light Higgs



Requires fermion DM for p-wave annihilation $\sigma v \propto v^2$

Higgs Portal Scalar Mediator





Alekhin et. al. 1504.04855

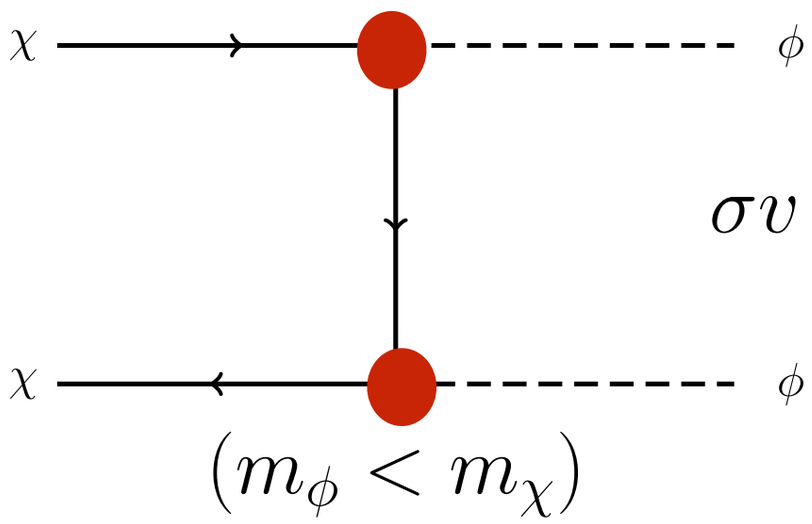
GK 1512.04119

Flavored Scalar Mediator

UV Theory gives flavor specific operator Batell, Freitas, Ismail, McKeen 1712.10022

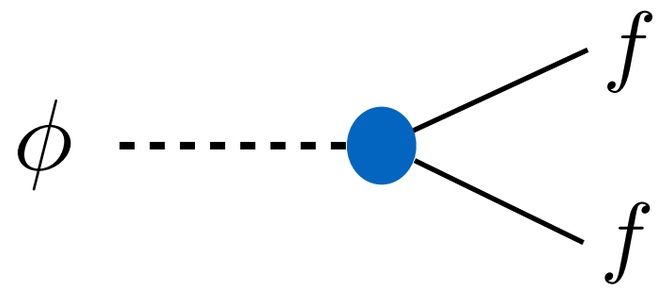
$$\mathcal{L}_{\text{eff}} = \frac{c_f}{\Lambda}\phi H \bar{f} f \to \frac{c_f v}{\Lambda}\phi \bar{f} f$$

Coupled to DM/SM $\mathcal{L} \supset g_\chi \phi \bar{\chi}\chi + g_f \phi \bar{f} f$



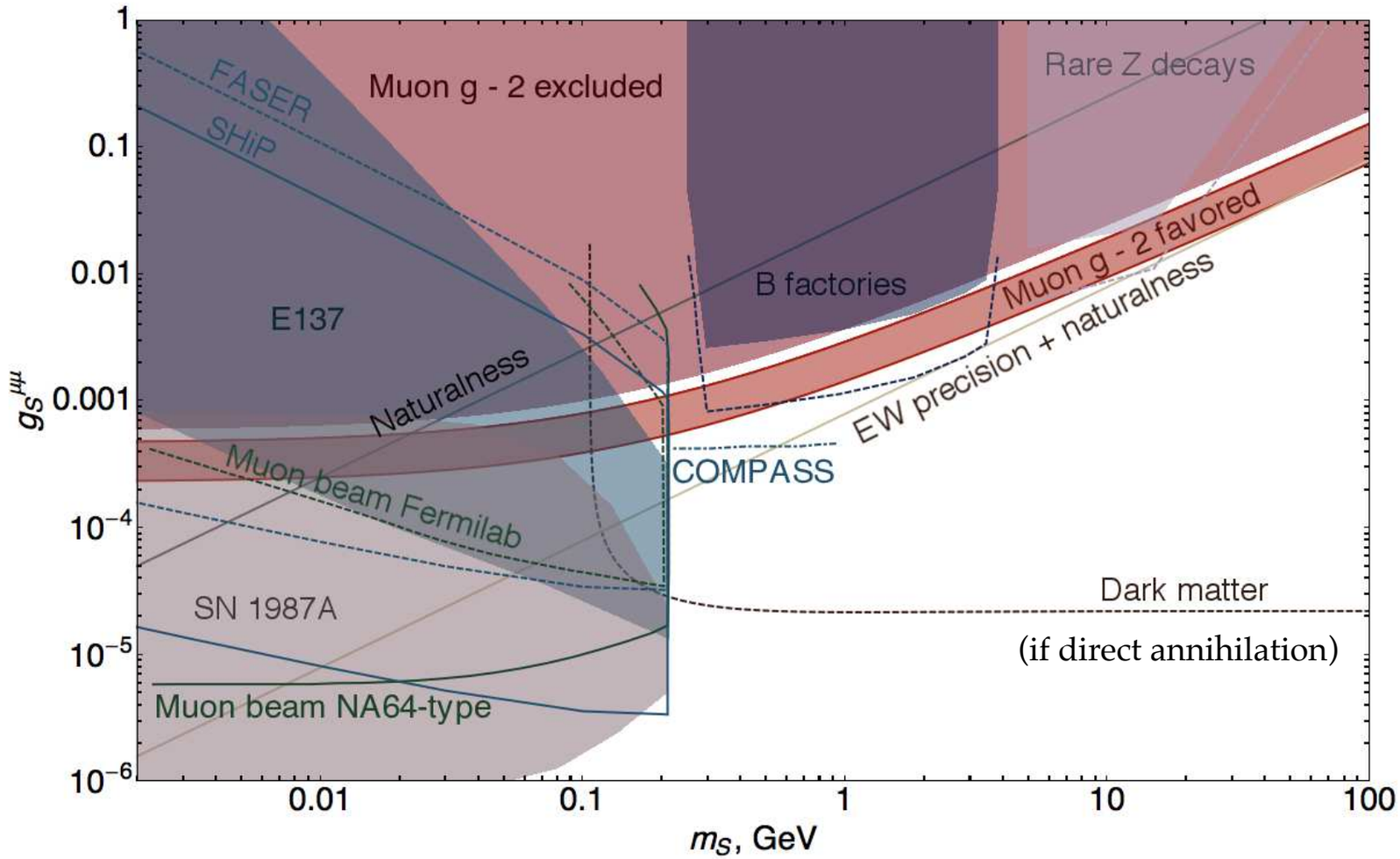
$\sigma v \propto g_\chi^4$

Decays to its favorite flavors



Requires fermion DM for p-wave $\sigma v \propto v^2$

Flavored Scalar Mediator



Heavy vectolrike leptons mix with muon, to generate mediator coupling

Mediator enables DM > muon annihilation

Batell, Freitas, Ismail, McKeen 1712.10022

"Axion Portal" Pseudoscalar Mediator

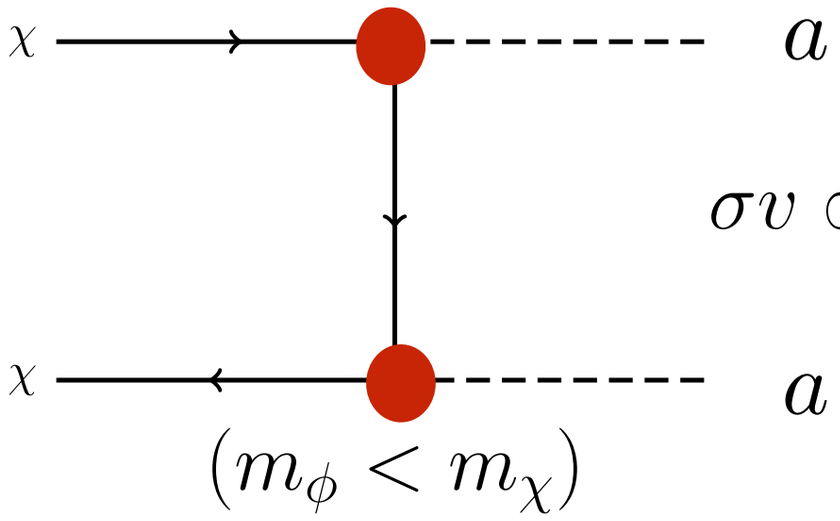
Axion like mediator

$$\mathcal{L}_{\text{eff}} \supset \frac{c_\gamma}{4\Lambda} a F^{\mu\nu}\tilde{F}_{\mu\nu} - \frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

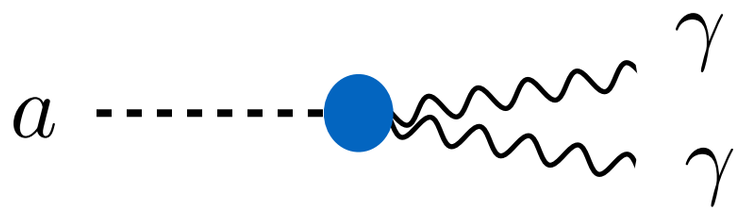
Add coupling to DM

Nomura, Thaler 0810.5397

$$\mathcal{L} \supset i g_\chi a \bar{\chi}\gamma^5\chi$$



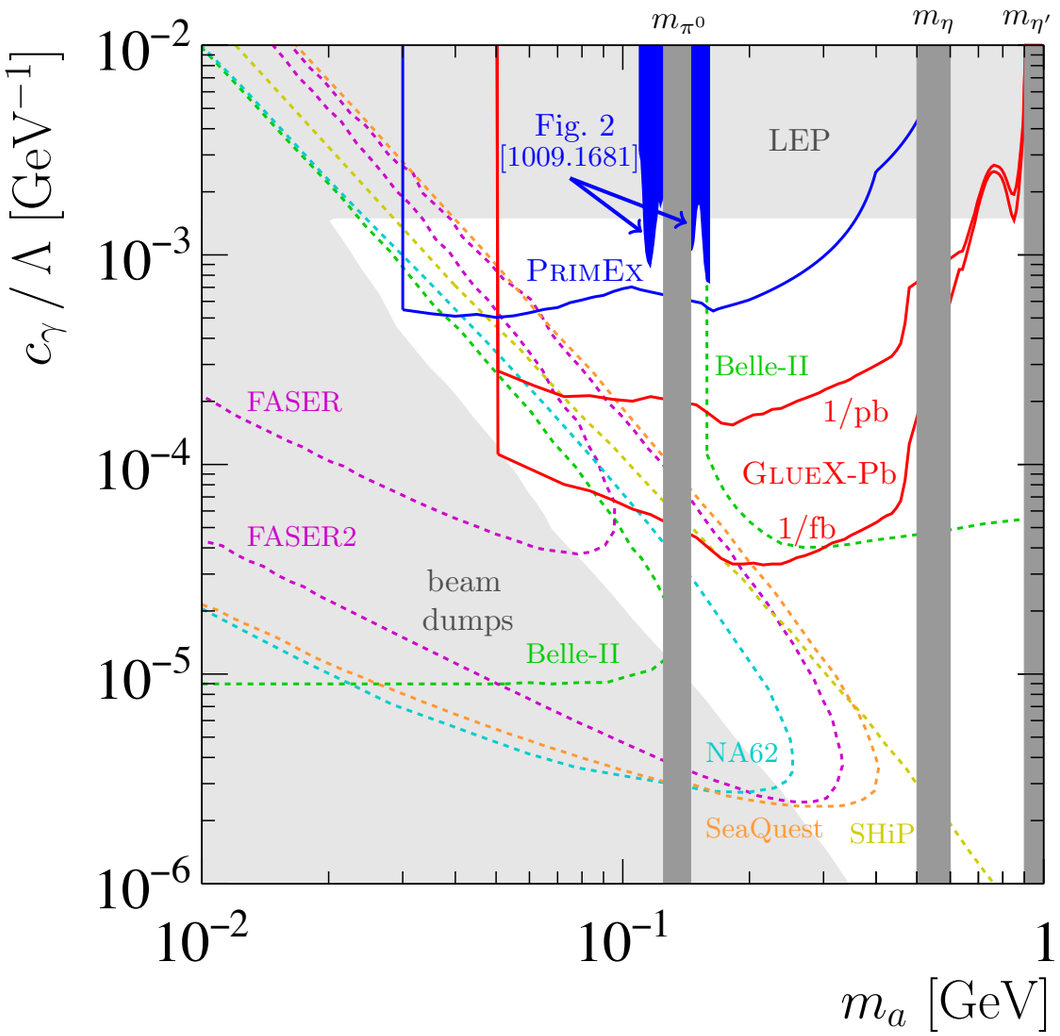
$$\sigma v \propto g_\chi^4$$

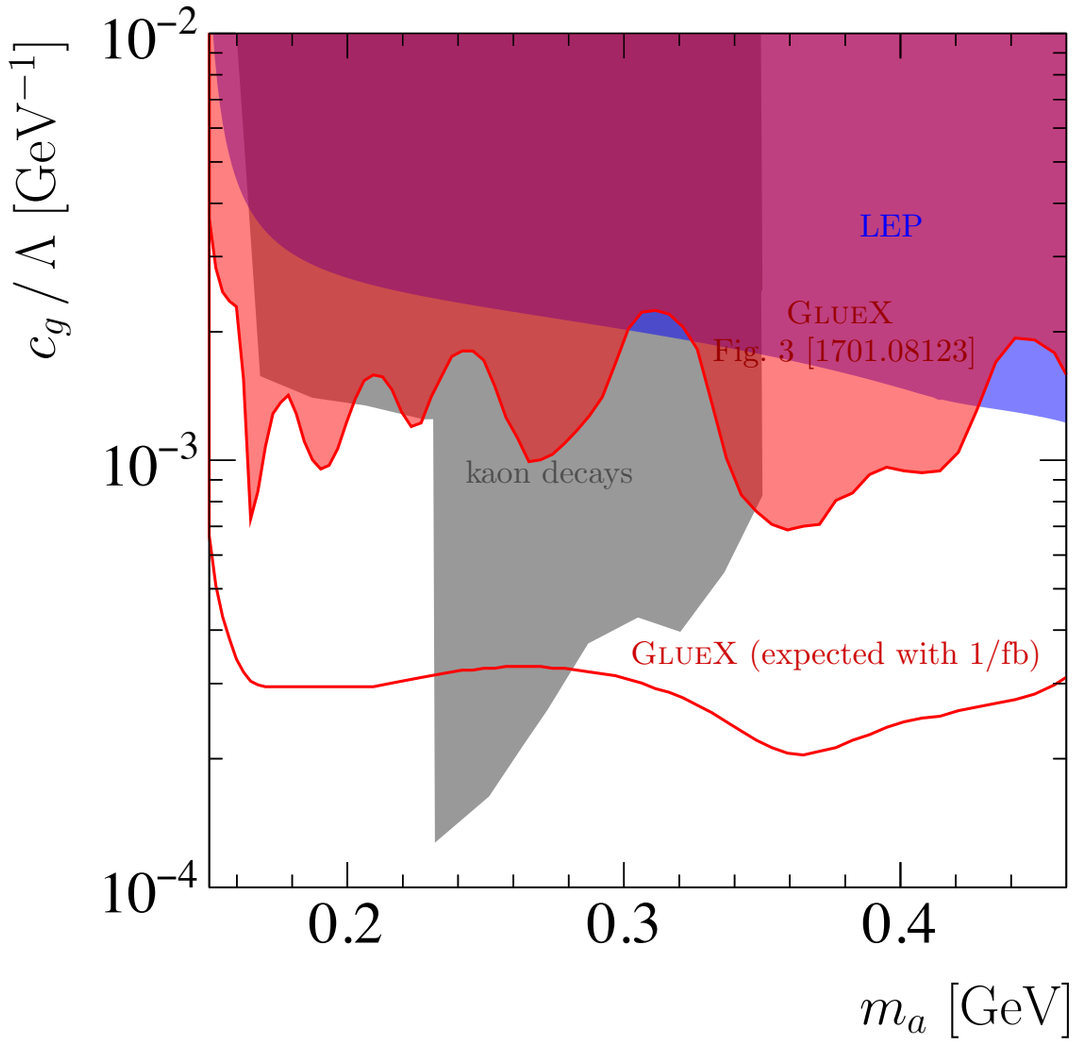


Requires fermion DM for p-wave $\sigma v \propto v^2$

Mixed annihilation bad $\chi\chi \to \phi\,(\text{scalar}) + a(\text{pseudo})$ is s-wave

"Axion Portal" Pseudoscalar Mediator





Aloni Fanelli Soreq Williams 1903.03586

Overview

1) P-Wave Annihilation

2) Annihilation Stops pre-CMB

3) Mediator Decays to Neutrinos

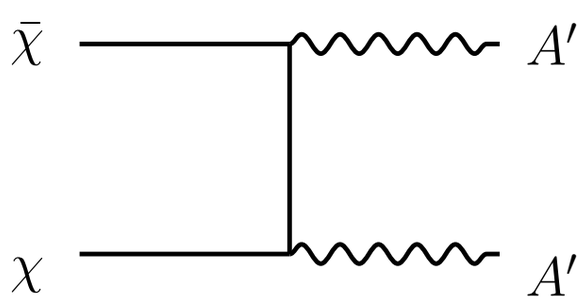
Asymmetric Dark Matter

Large particle/antiparticle asymmetry is safe from CMB

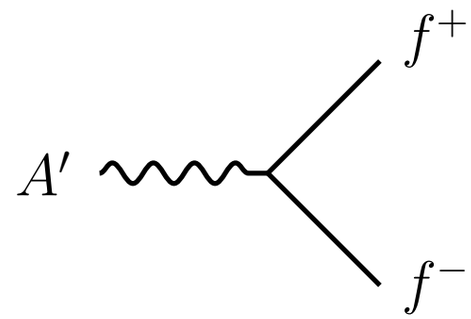
Lin, Yu, Zurek 1111.0293

$$n_{\overline{\chi}} \propto e^{-\sigma v}$$

Familiar vector mediators can now work for < GeV asymmetric DM



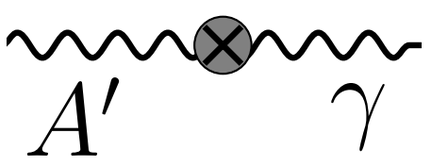
$$\sigma v \propto v^0 = \text{const.}$$



Works for kinetic mixing (dark photon A') or new gauged 5th force (V)

$$\epsilon e A'_\mu J^\mu_{\rm EM}$$

$$g V_\mu J^\mu_{\rm SM}$$

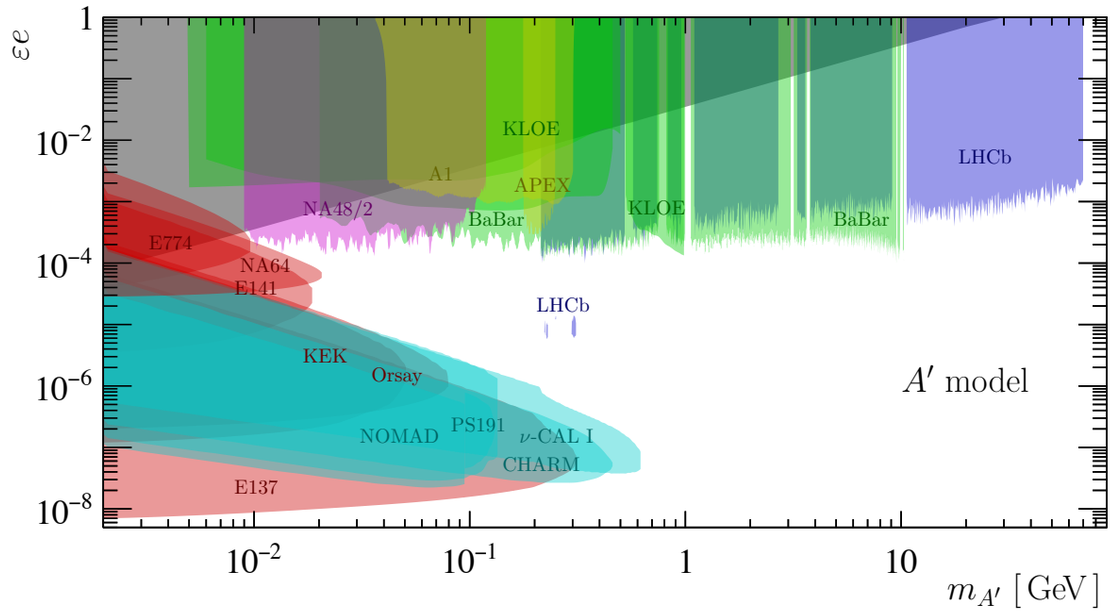


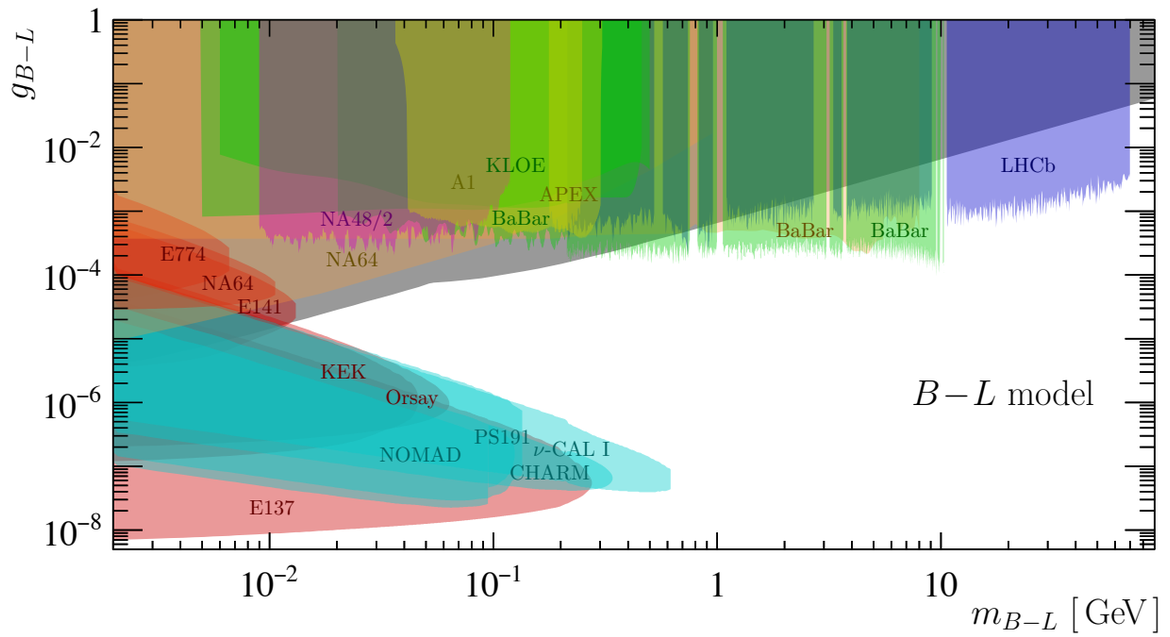
Anomaly free 5th force options

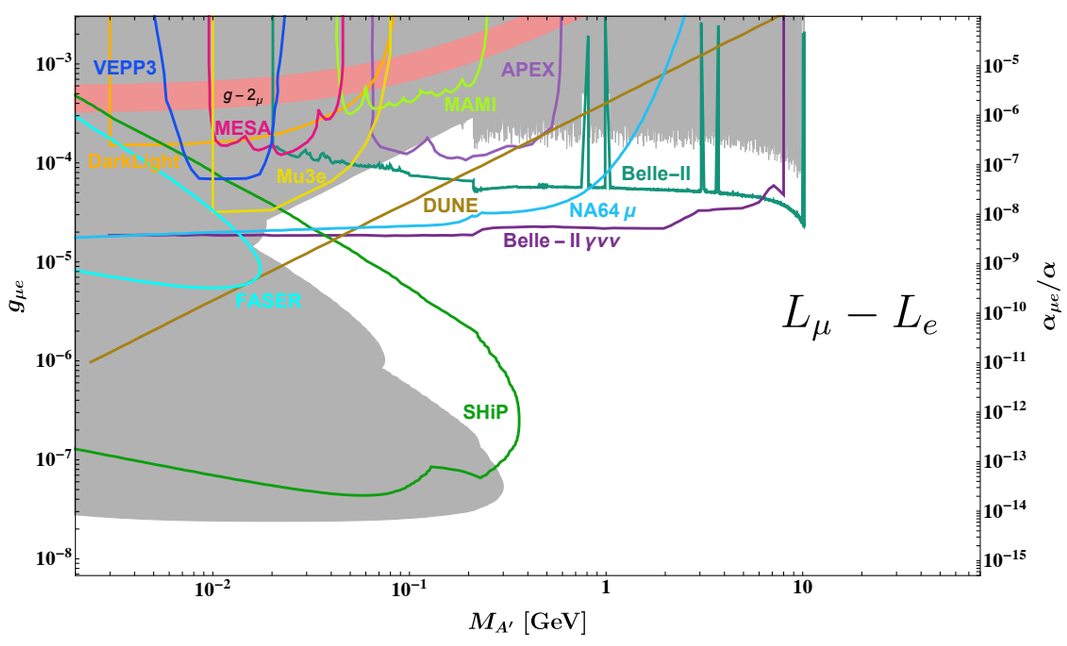
$$B-L, \quad L_i - L_j, \quad B - 3L_i$$

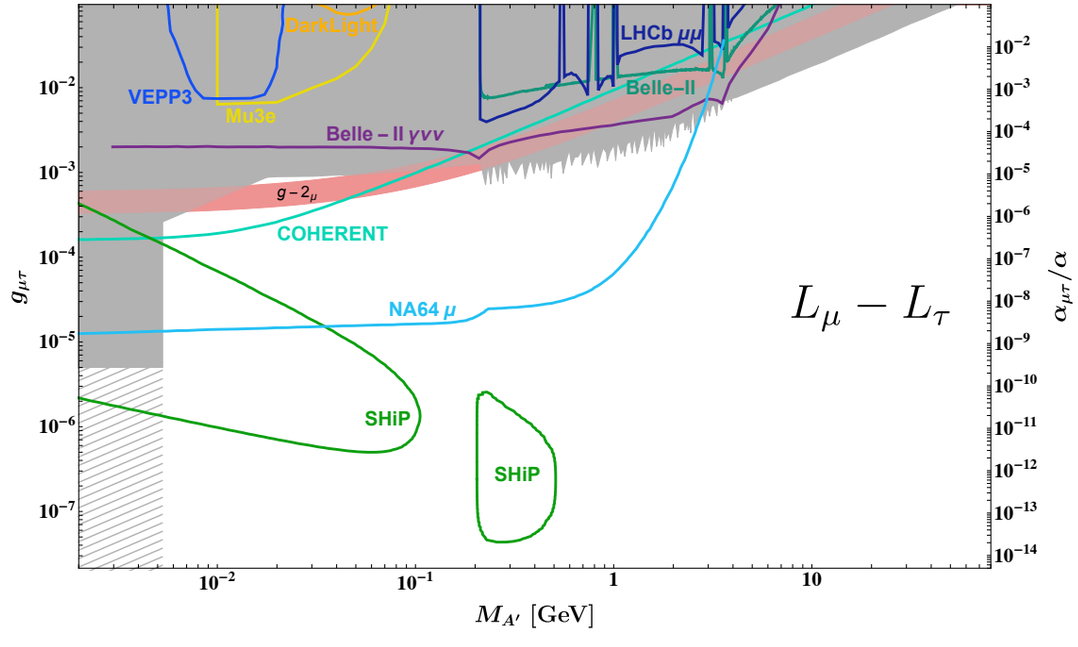
Asymmetric Dark Matter

Iten Soreq Williams Xue 1801.04847





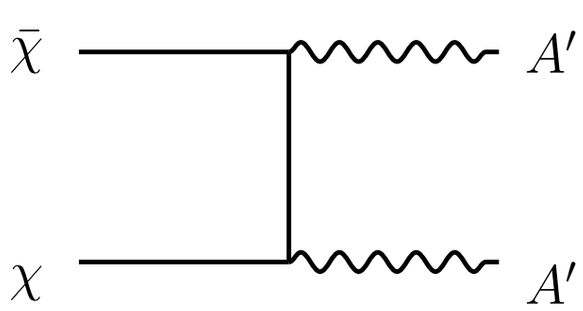




Bauer, Foldenauer, Jaeckel, 1803.05466

Forbidden Dark Matter

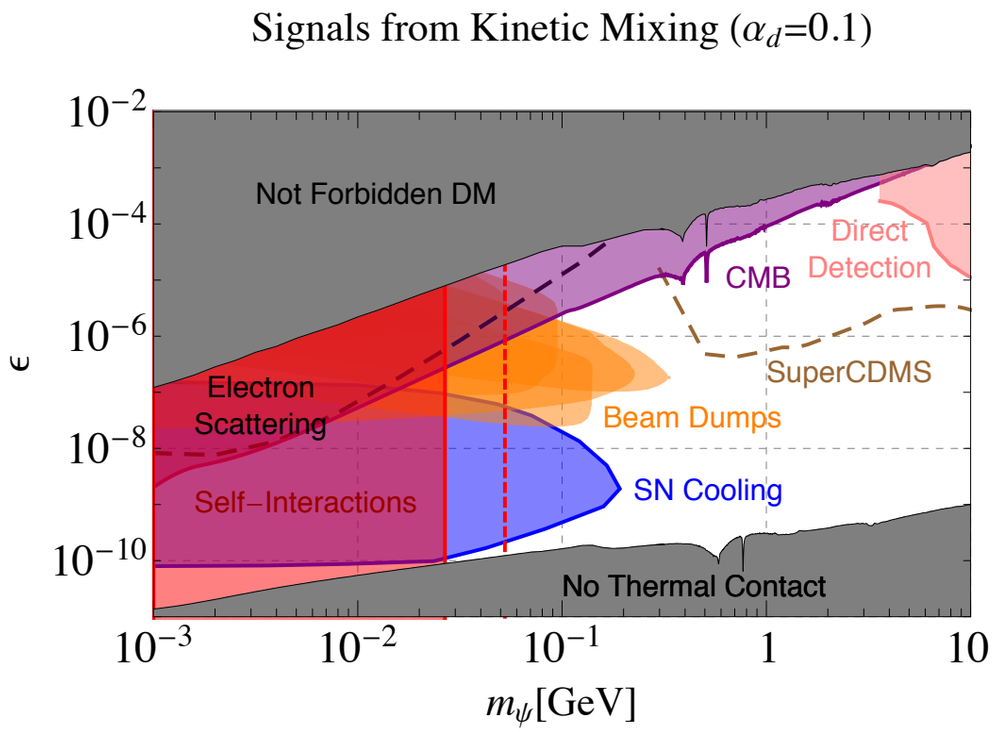
Mediator is *mildly heavier* than DM, but SM coupling is tiny

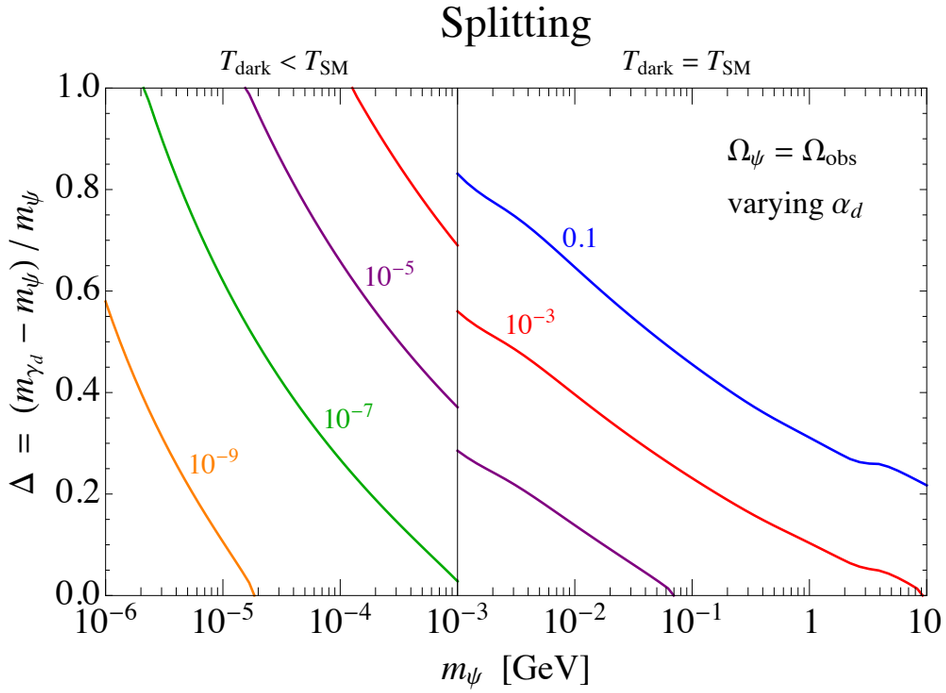


$$2m_\chi > m_{A'} > m_\chi$$ A' decays to SM

$$g_\chi \gg \epsilon$$ Suppress direct annihilation

Early universe DM has velocity tail, can annihilate to heavier A'



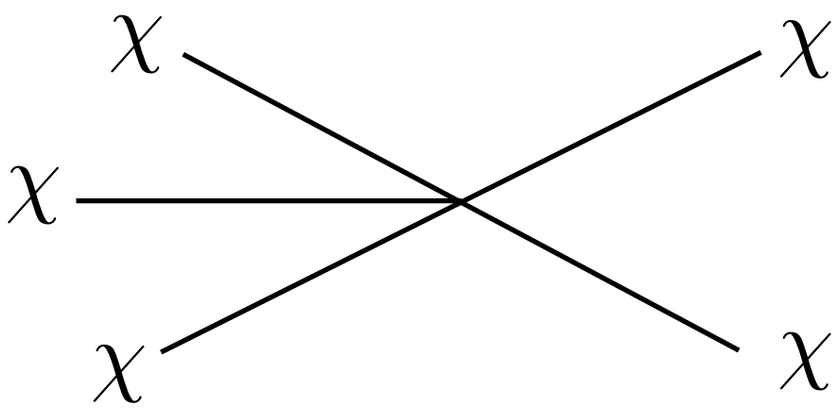


Carlson, Machacek, Hall '92

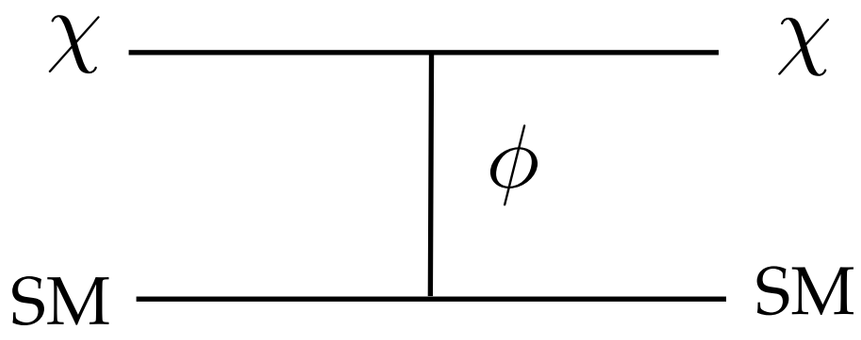
D'Agnolo, Ruderman 1505.07107

SIMPs and 3-2 Annihilation

Annihilation



Cooling w/ mediator



Cannibalization: 3-2 annihilation only (DM hot, ruled out)

Carlson, Machacek, Hall '92

SIMP: 3-2 freeze out, then SM scattering cools DM

Hochberg Kuflik Volansky Wacker 1402.5143

ELDER: SM-DM scattering decouples first, 3-2 freeze out later

Kuflik Prelstein Rey-Le Lorier, Tsai 1512.04545

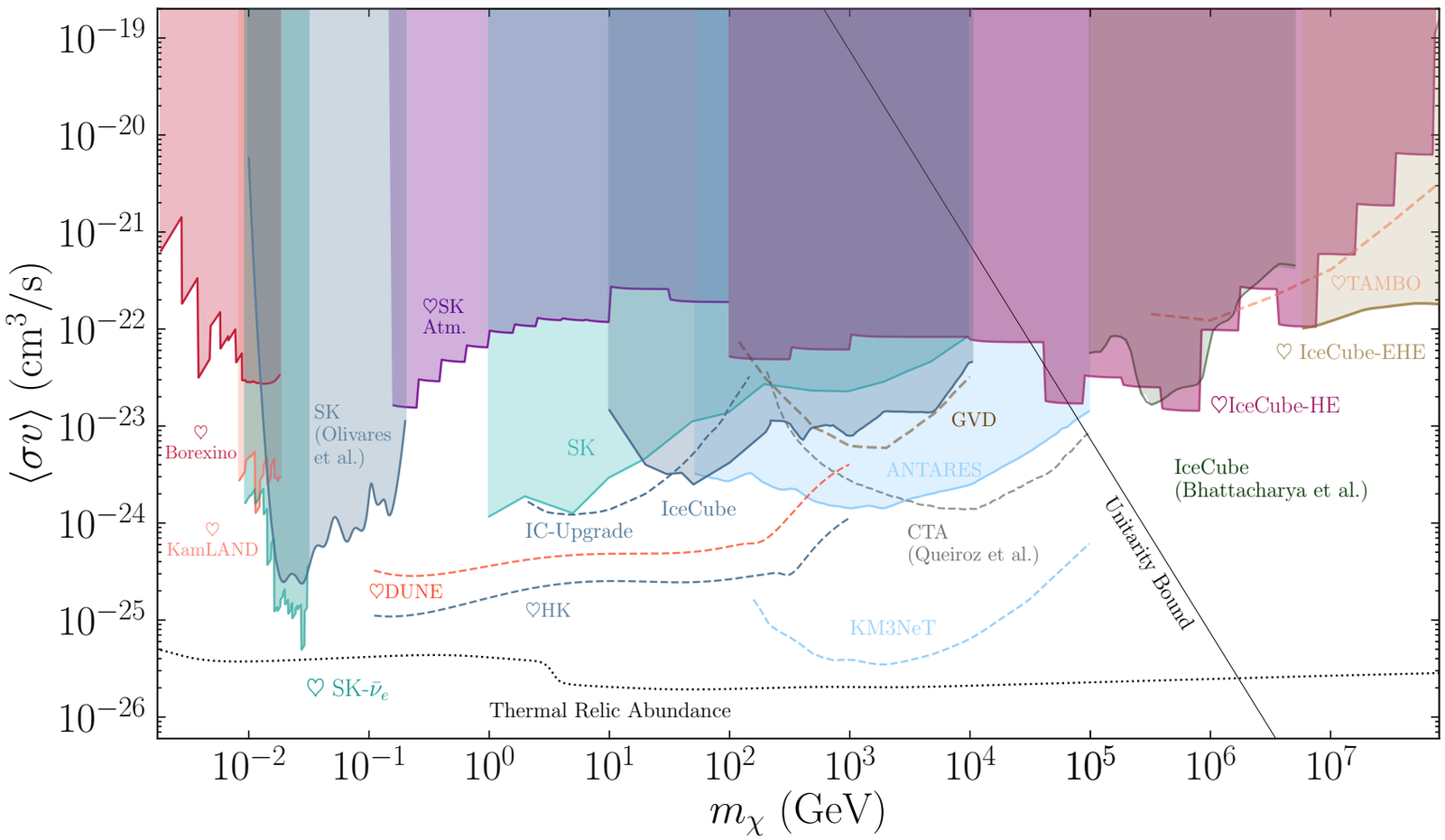
Overview

1) P-Wave Annihilation

2) Annihilation Stops pre-CMB

3) Mediator Decays to Neutrinos

Agnostic Parameter Space

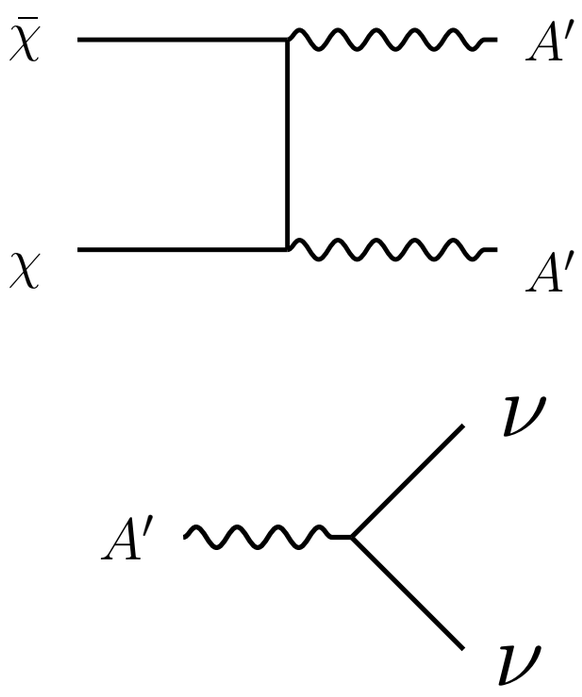


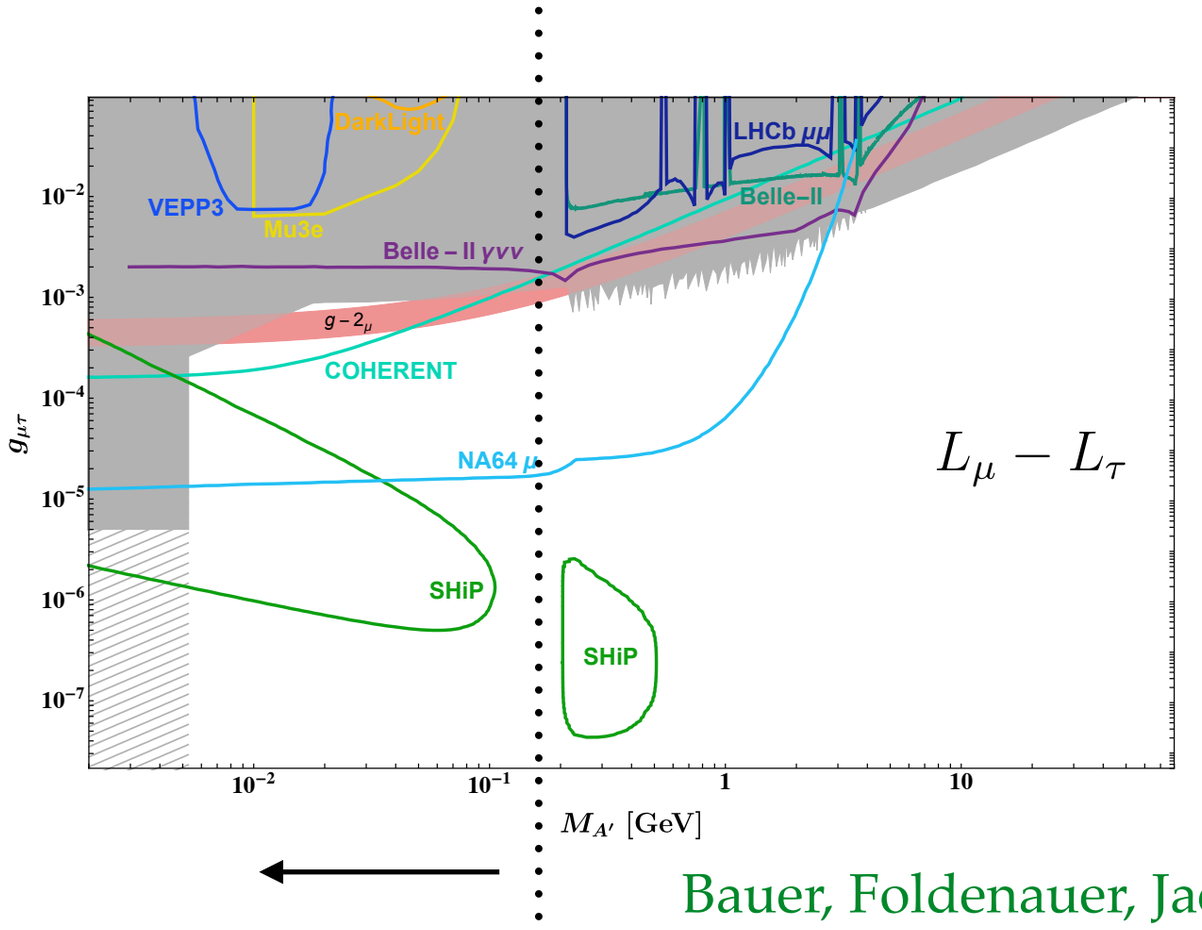
Bounds apply to direct and secluded
Easy to engineer scalar/pseudoscalar mediator

Arguelles, Diaz, Kheirandis, Olivares-Del-Campo, Safa, Vincent 1912.09486

Vector Mediator

Leptophilic gauge boson mediator couples mainly 2nd & 3rd gen





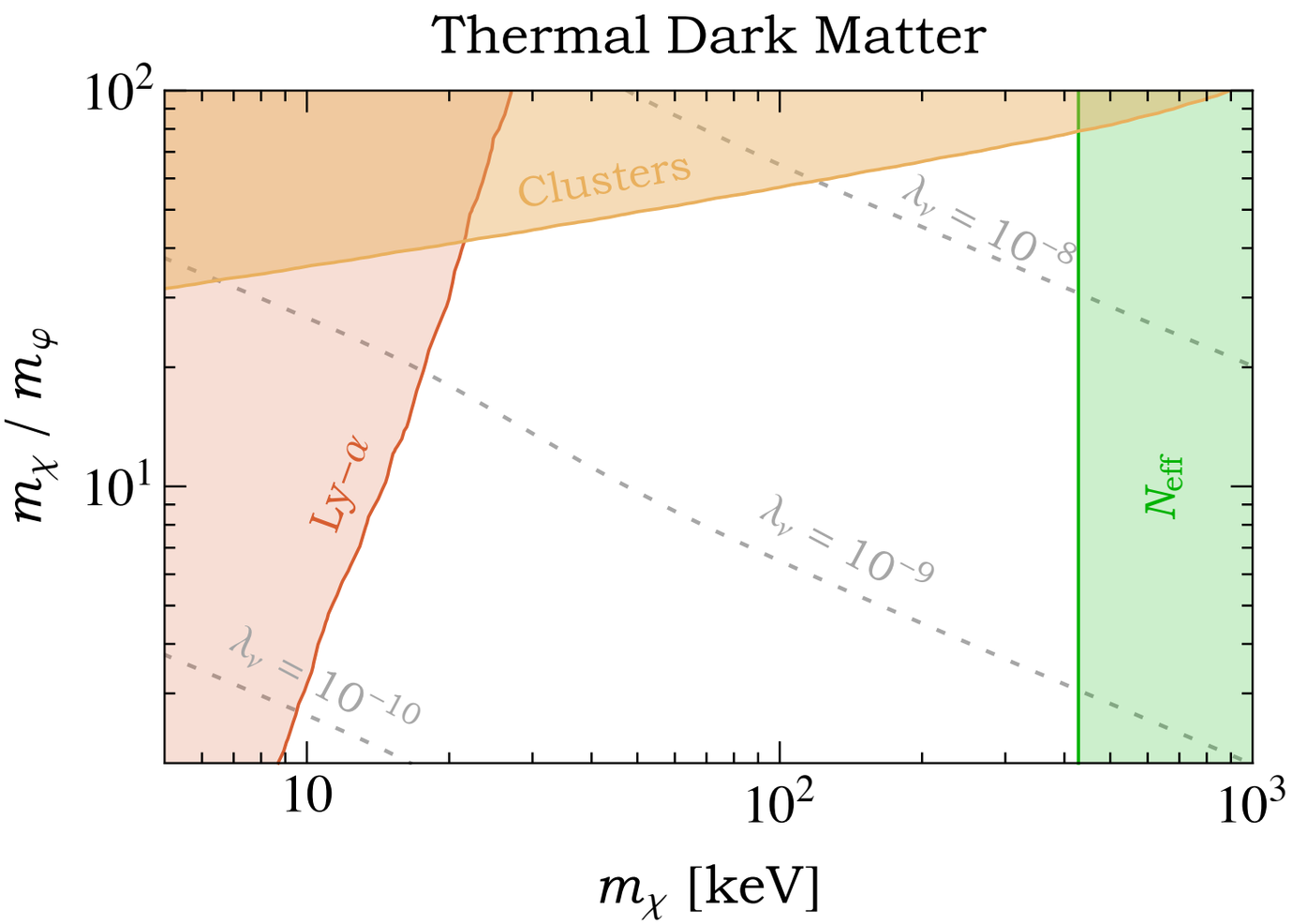
Bauer, Foldenauer, Jaeckel
1803.05466

Below muon mass, must decay to neutrinos $U(1)_{L_\mu - L_\tau}$

Only anomaly free vector option; others decay A' to electrons

Late Time Thermalization

Early times DM is not present, but produced when production rate exceeds Hubble after neutrinos decouple from photons



Light mediator m << T

$$\Gamma \sim n\sigma v \; g_\chi^4 T$$

$$H \sim T^2/M_{\rm Pl}$$

Equilibrate and freeze-out below T < MeV

$$\chi\chi \to \varphi\varphi \to 4\nu$$

Lightest possible thermal DM ~ 10 keV

Berlin, Blinov 1706.07046

Chacko, Hall, Oliver, Perelstein 0405067

Concluding Remarks

Secluded Dark Matter

Equilibrium with SM but abundance independent of SM coupling

Need light new mediator that decays to SM particles

CMB Safety Organizes Options

1) P-Wave Annihilation

Motivates (pseudo)scalar mediators

DM annihilation to vectors almost always s-wave

2) Annihilation Stops pre-CMB

Asymmetric DM, SIMPs/EDLERs, forbidden etc.

3) Mediator Decays to Neutrinos

Neutrino-philic mediators (majorons mu-tau gauge bosons)

Late time thermalization (~ 10 keV scale thermal DM)