Light Thermal DM & The Higgs Portal

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1512.04119

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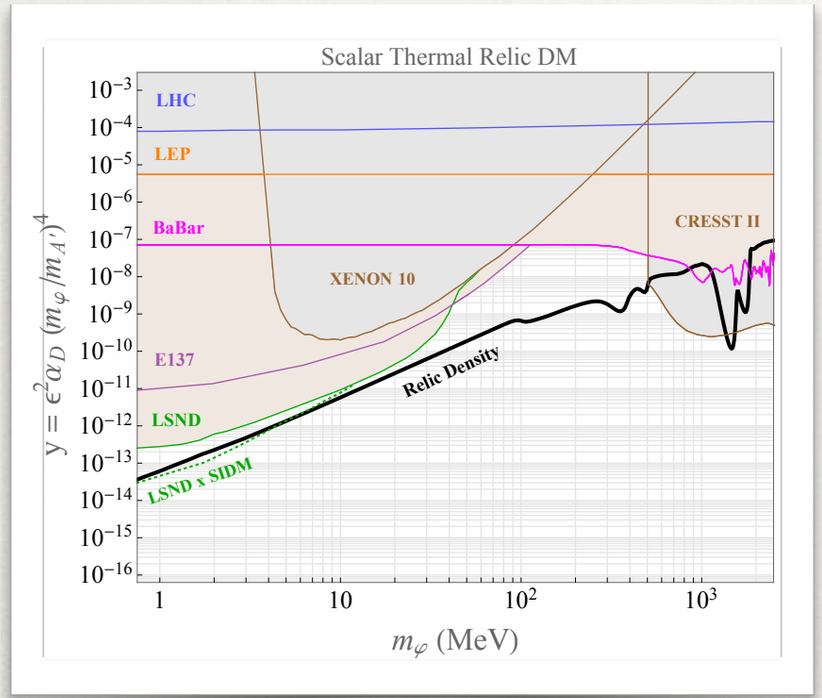
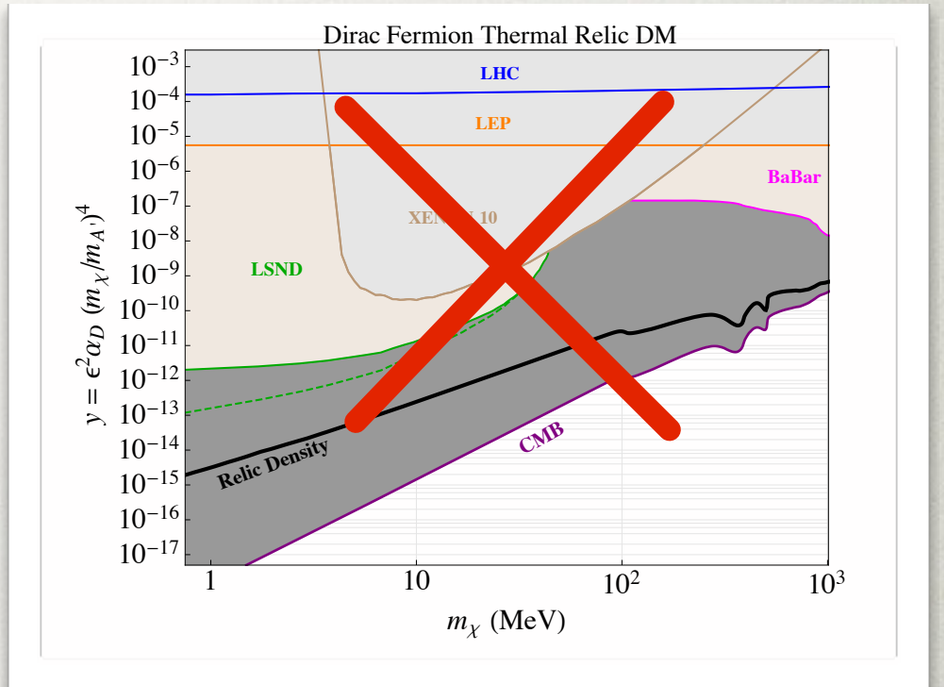
Vector Portal: Many Options

(Philip's Plenary Talk)

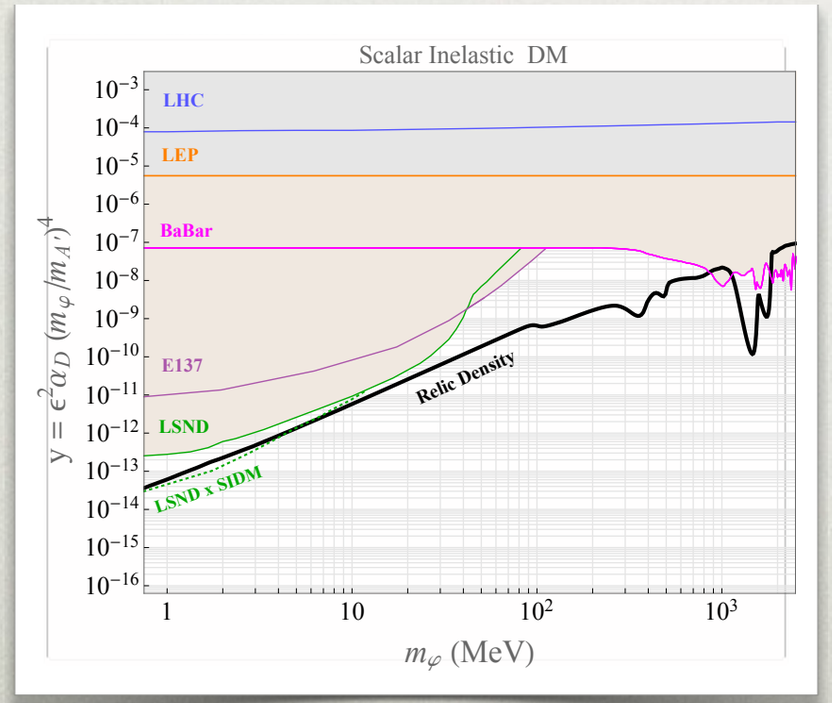
Scalar | **Fermion**

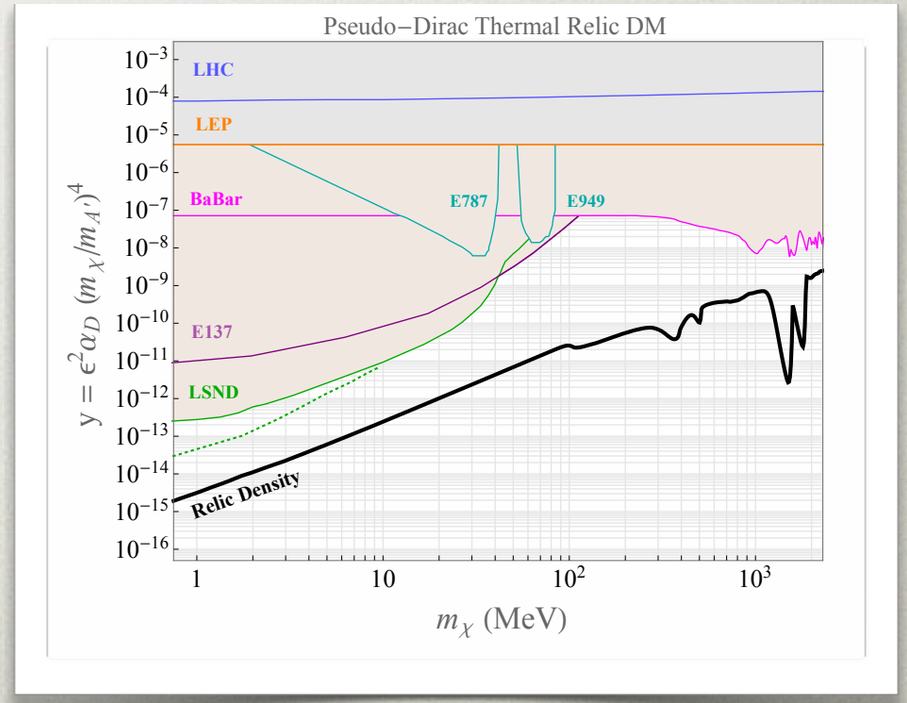
Thermal Elastic





Thermal Inelastic





Historical Analogy

Understanding the Weak Force

Discovery of radioactivity		(1890s)
Fermi Scale identified	$G_F \sim \frac{1}{(100\ \mathrm{GeV})^2}$	(1930s)
Non-Abelian Gauge Theory		(1950s)
Higgs Mechanism		(1960s)
W / Z bosons		(1970s)
Higgs discovered		(2010s)

Each step required revolutionary theoretical/experimental leaps

$$t \sim 100 \text{ years}$$

How long will we wait for DM?

Discovery of missing mass	(1930s)
Rotation curves	(1970s)
CMB power spectrum	(1990s)
Relevant scale?	**> 2016**

Non-gravitational interactions not guaranteed
No clear target of opportunity

Discovery time frame? $t > 80$ yrs

What's so great about "Thermal"?

Advantage #1: Minimum Annihilation Rate

Equilibrium, achieved easily with a tiny DM/SM coupling

$$n_{\rm DM} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$

Generically overproduces DM

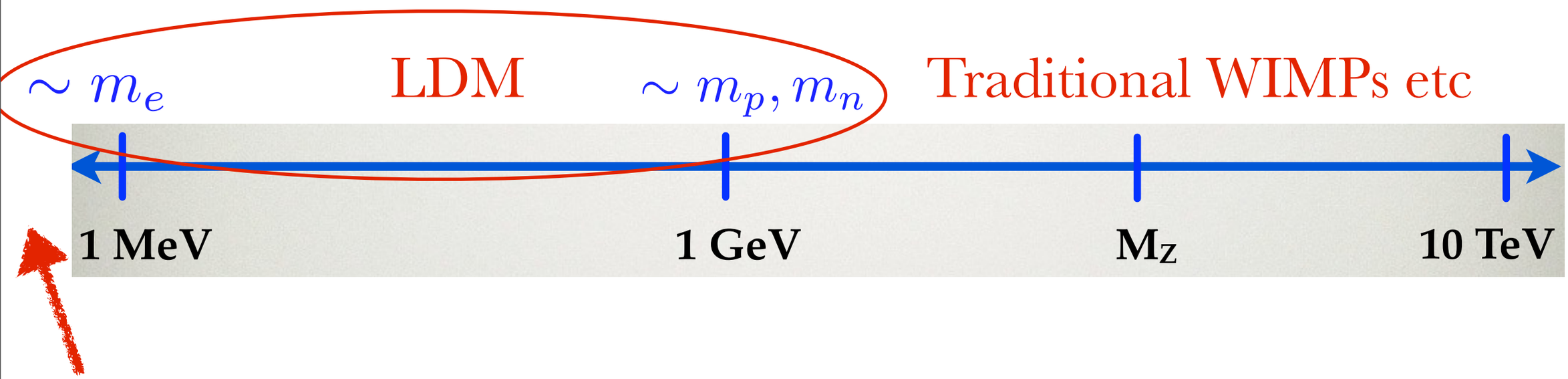
Requires *much larger* annihilation cross section to deplete

$$\sigma v \geq \sigma v_{\rm relic} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

$=$ symmetric thermal DM **$>$ asymmetric DM**

What's so great about "Thermal"?

Advantage #2: Narrow(er) Mass Range



< 10 keV DM too hot
spoils structure formation

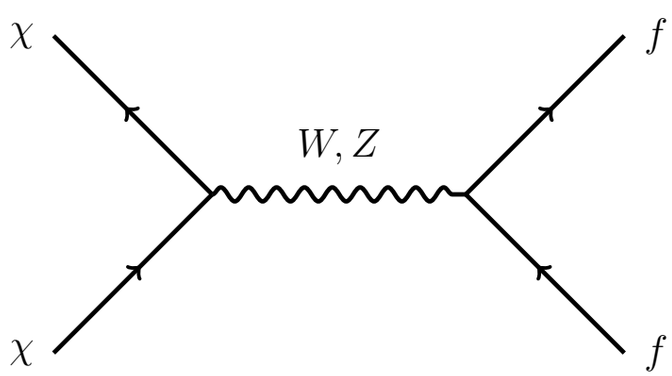
> 100 TeV DM
overproduced

LDM region is conceptually different

Heavy vs. Light # 1

LDM needs new forces

Heavy DM can avoid overproduction w/ SM gauge bosons



$$\sigma v \sim \frac{\alpha_W^2 m_\chi^2}{m_Z^4} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

for $m_\chi \sim$ TeV

For LDM, annihilation via SM forces is too weak

$$m_\chi \sim \text{ MeV } \implies \sigma v \ll 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

LDM overproduced unless there are light, new "mediators"

Avoiding LDM Overproduction

Choose light mediator

Must be SM singlet, options limited by SM gauge invariance

Vector Portal
mix w/ photon

$$\epsilon F_{\mu\nu} F'_{\mu\nu}$$

Neutrino Portal
mix w/ RHN

$$H^\dagger L N$$

Higgs Portal
mix w/ SM Higgs

$$(H^\dagger H)\phi$$

Avoiding LDM Overproduction

Choose light mediator

Must be SM singlet, options limited by SM gauge invariance

Vector Portal
mix w/ photon

$$\cancel{\epsilon F_{\mu\nu} F'_{\mu\nu}}$$

Lots of attention here

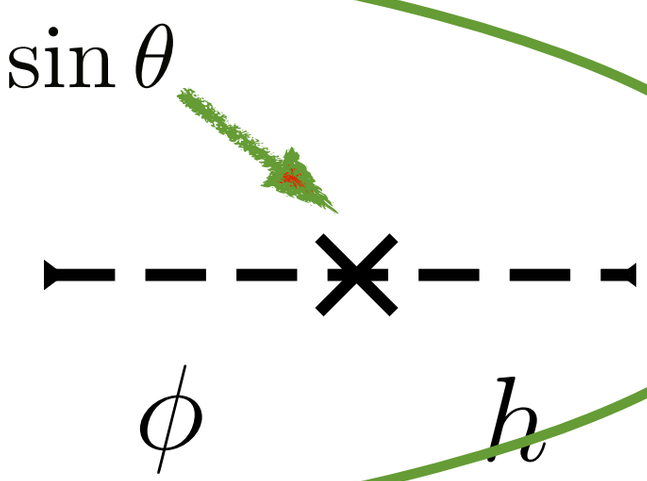
Neutrino Portal
mix w/ RHN

$$\cancel{H^\dagger L N}$$

See Alex Friedland's Talk

Higgs Portal
mix w/ SM Higgs

$$(H^\dagger H)\phi$$

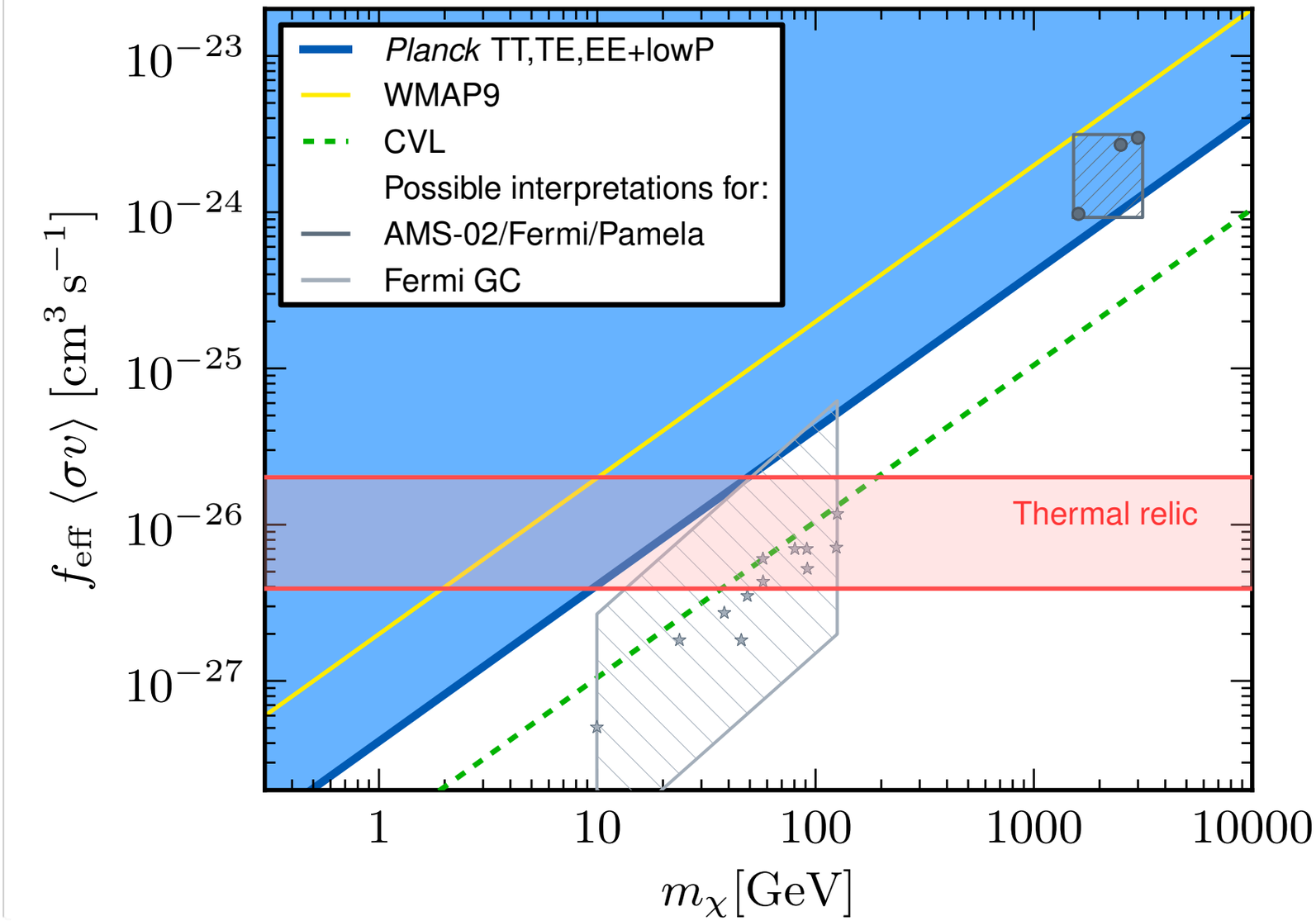


SM coupling $\propto$ fermion mass

Heavy vs. Light # 2

CMB rules out LDM < 10 GeV?

Planck 1303.5076



Cross section is smaller @ CMB $\sigma v \propto v^2$

OR

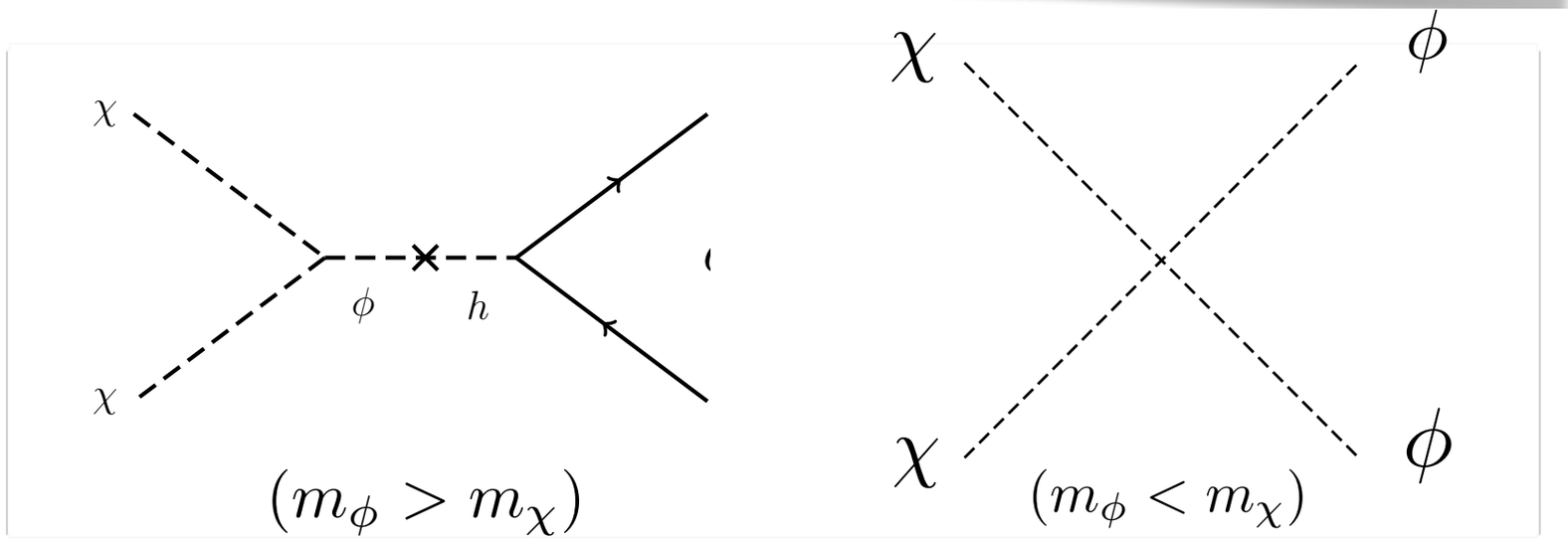
Annihilation shuts off @ CMB e.g. $n_\chi \neq n_{\bar{\chi}}$

How to survive CMB for scalar mediator?

Choose LDM candidate & coupling

Scalar DM

both s-wave!



Need particle asymmetry or inelasticity for CMB safety

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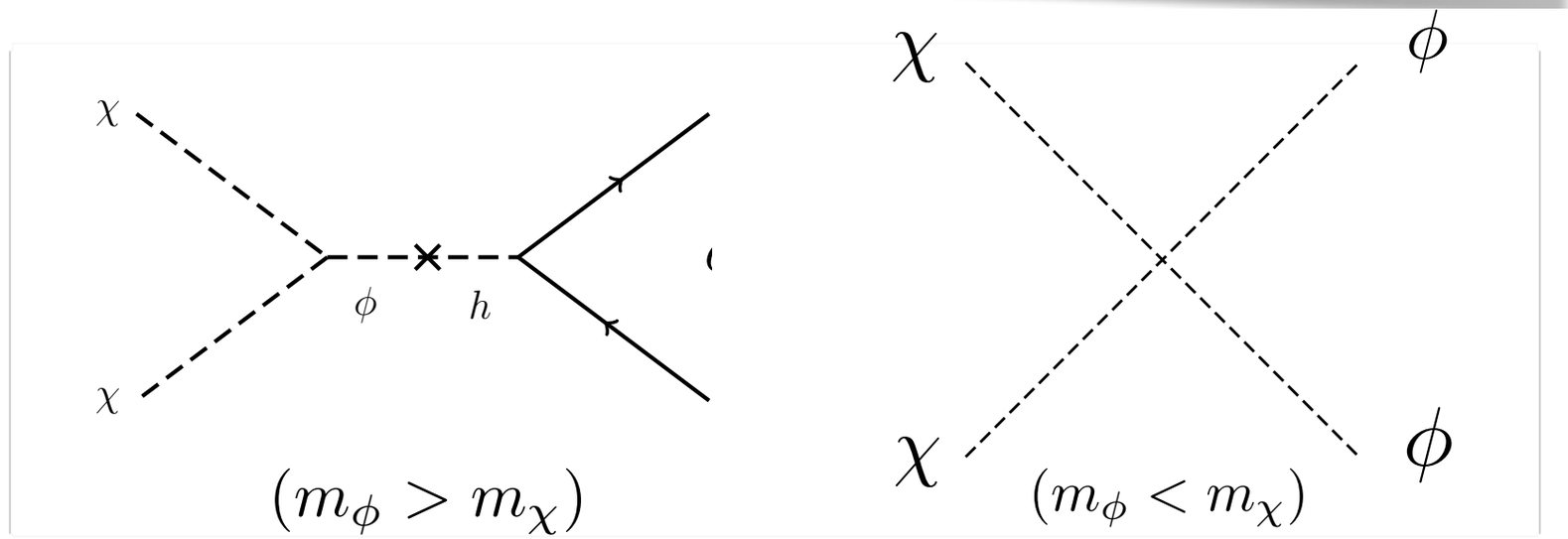
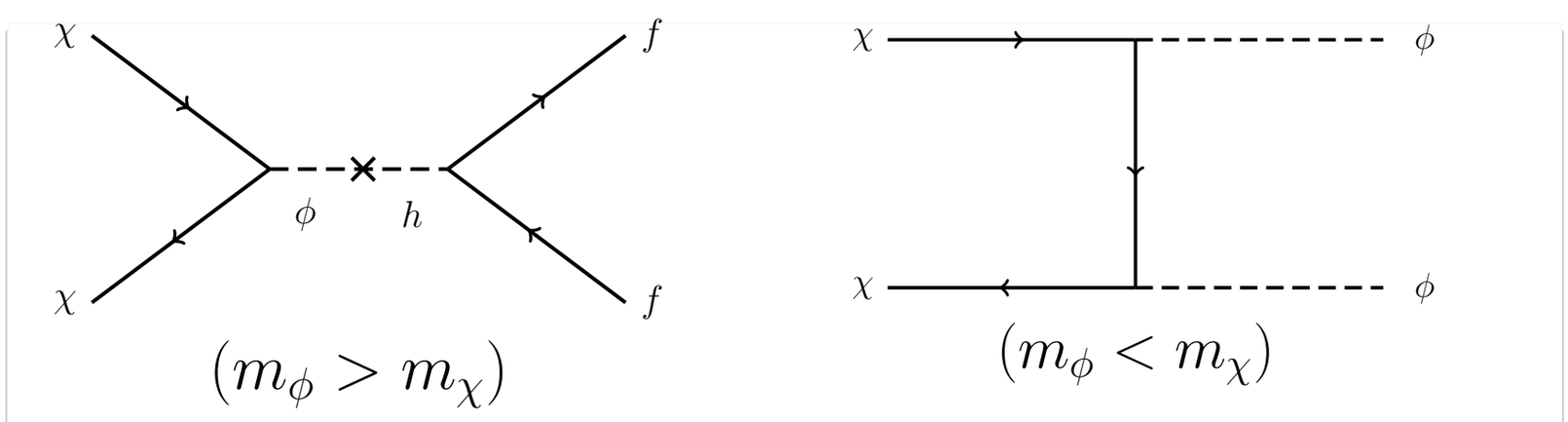


Need particle asymmetry or inelasticity for CMB safety

Fermion DM

$g_\chi \phi \bar{\chi} \chi$



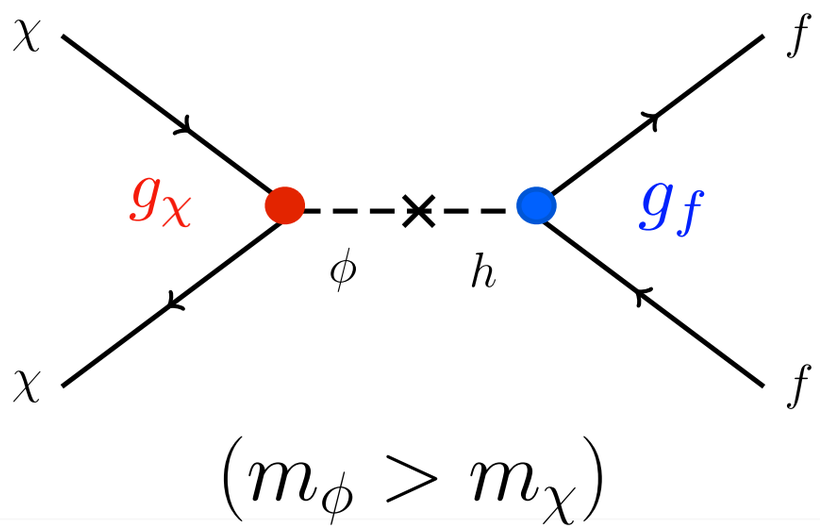
Can also include $\phi \bar{\chi} \gamma^5 \chi$

must be tiny (adds s-wave piece)

Both CMB ok!

$\sigma v \propto v^2$

Thermal Target: Direct Annihilation to SM



$$g_f = g_e \left(\frac{m_f}{m_e} \right)$$

Coupling scales with SM fermion mass

$$\sigma v = \sum_f (\sigma v)_f \propto \underbrace{g_\chi^2 g_e^2 \left(\frac{m_\chi}{m_\phi} \right)^4}_{} \frac{1}{m_\chi^2}$$

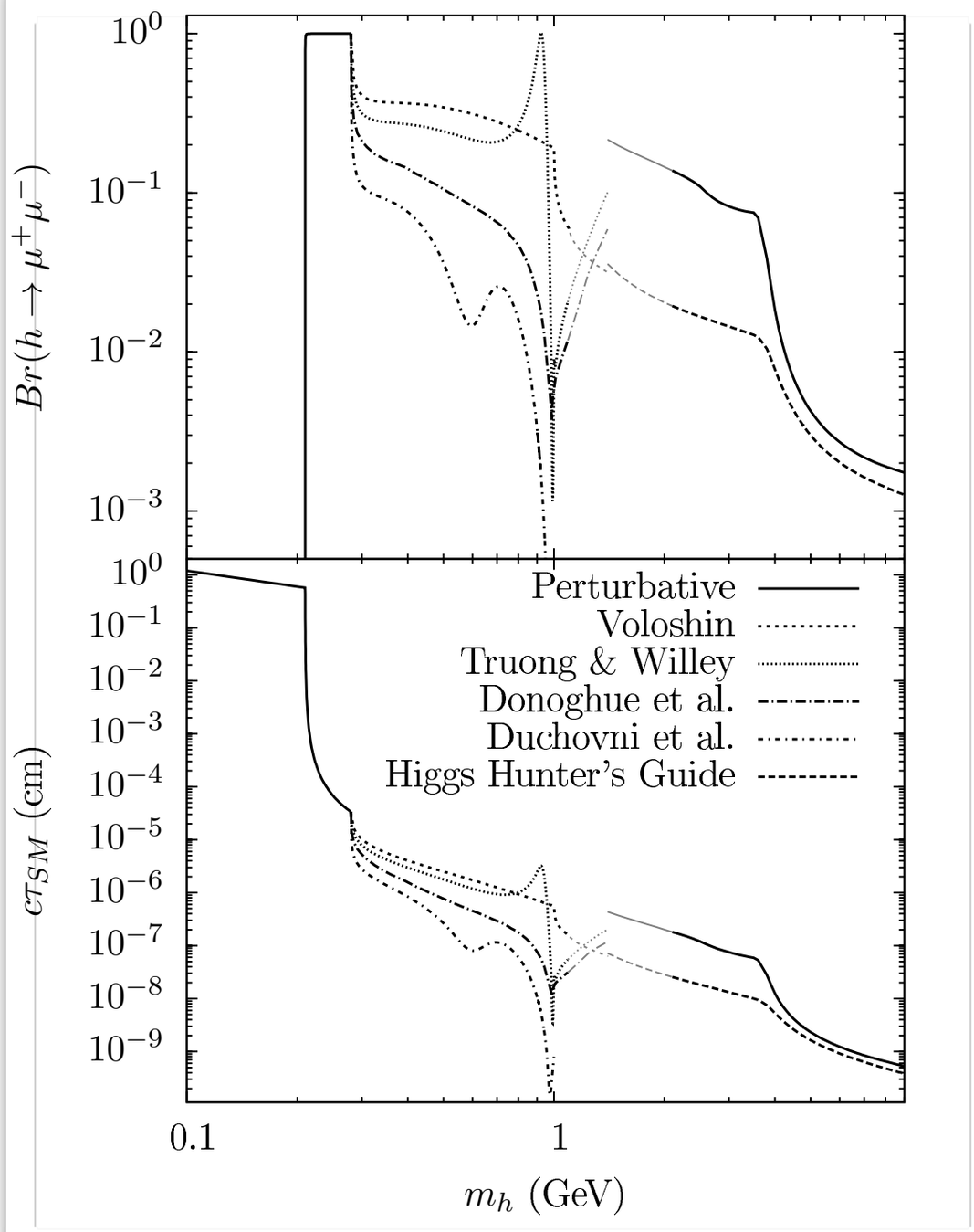
In analogy with
dark photon target

$$y \equiv g_\chi^2 g_e^2 \left(\frac{m_\chi}{m_\phi} \right)^4$$

Normalized to electron coupling because it's relevant for every mass point

Thermal Target: Direct Annihilation to SM

Large theory uncertainty in SM coupling near QCD scale

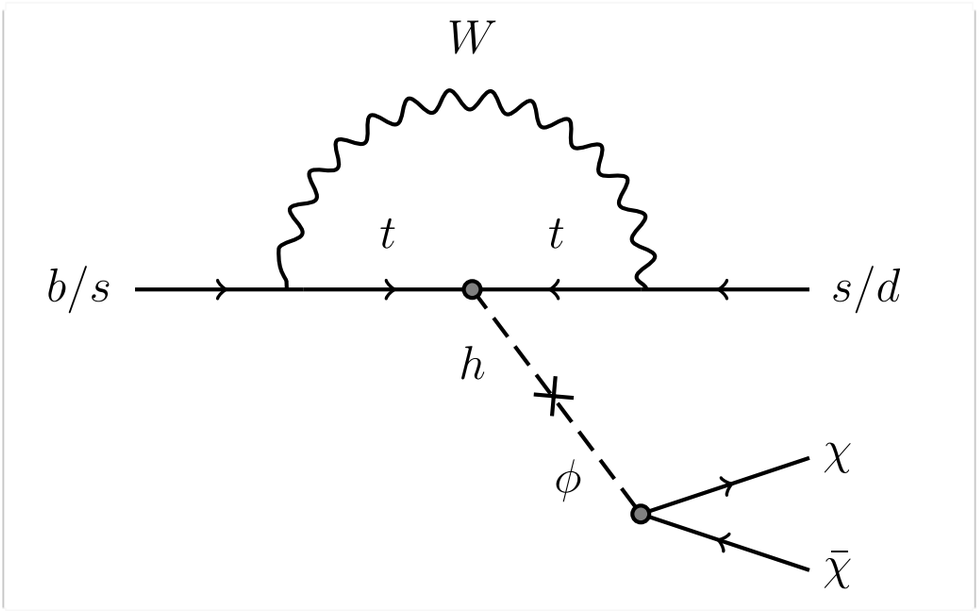


Estimate from different numerical extractions from light Higgs literature

$$g_f(s) \simeq \sin\theta \sqrt{\frac{8\pi}{m_h}\Gamma(h \to \mathrm{SM})}\,\Big|_{m_h=\sqrt{s}}$$

Clarke, Foot, Volkas 1310.8042

Thermal Target: Rare B/K Decays



2/3 body decays to LDM/mediator

$$B^+ \to K^+\phi,\ K^+\chi\chi$$

$$K^+ \to \pi^+\phi,\ \pi^+\chi\chi$$

constrained by

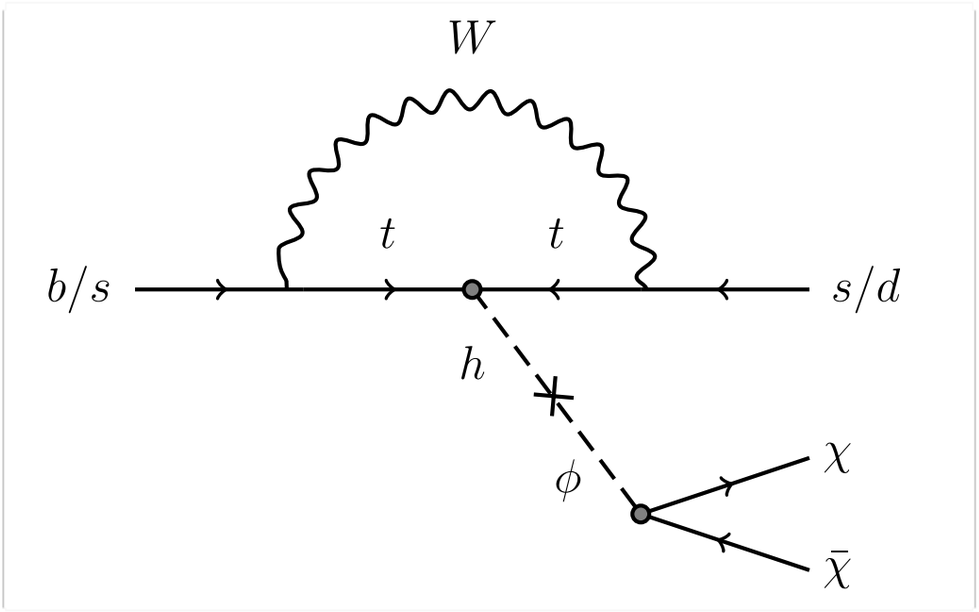
$$B^+ \to K^+\nu\bar{\nu} \qquad K^+ \to \pi^+\nu\bar{\nu}$$

Annihilation rate set by *small* yukawas

FCNC constraints set by *top* yukawa

Bird, Jackson, Kowalewski, Pospelov
arXiv: 0401195

How to compare meson decays w/target?



On shell decays to mediator independent of DM

Need to assume DM mass/coupling for thermal comparison

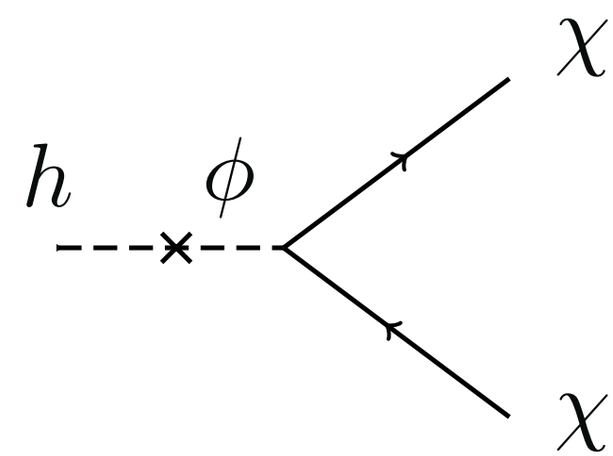
$$\Delta\mathrm{Br}(B^+ \to K^+ \not{E}) \propto g_f^2 = y \times \underbrace{\frac{1}{g_\chi^2}\left(\frac{m_\phi}{m_\chi}\right)^4}$$

Conservative worst-case "y" reach $g_\chi \ , \ m_\phi/m_\chi \to \mathcal{O}(1)$

Thermal Target: Other Constraints

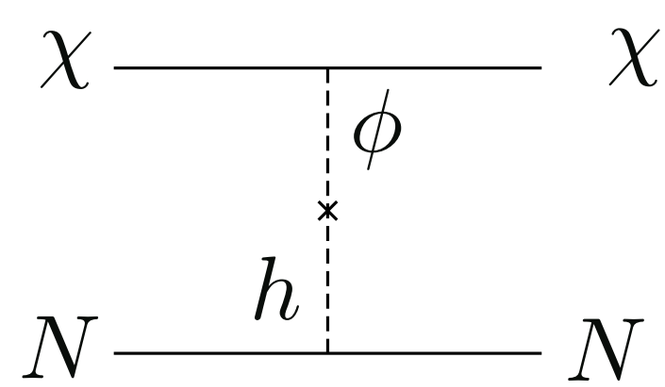
Higgs Invisible Width

Possibly compensate with additional h production, but can't avoid interference with $4l$ final state

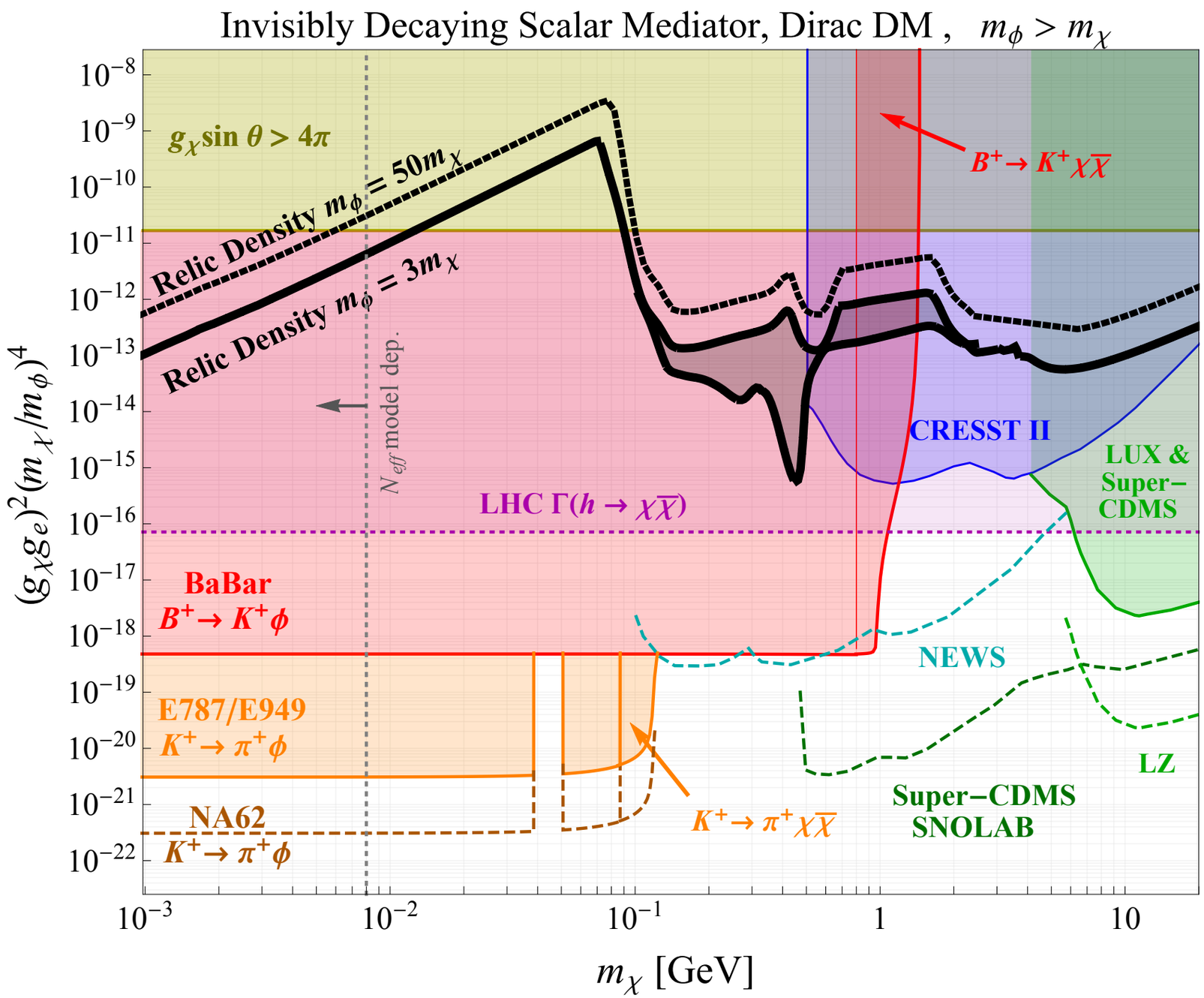


Low Mass Direct Detection

assuming elastic scattering

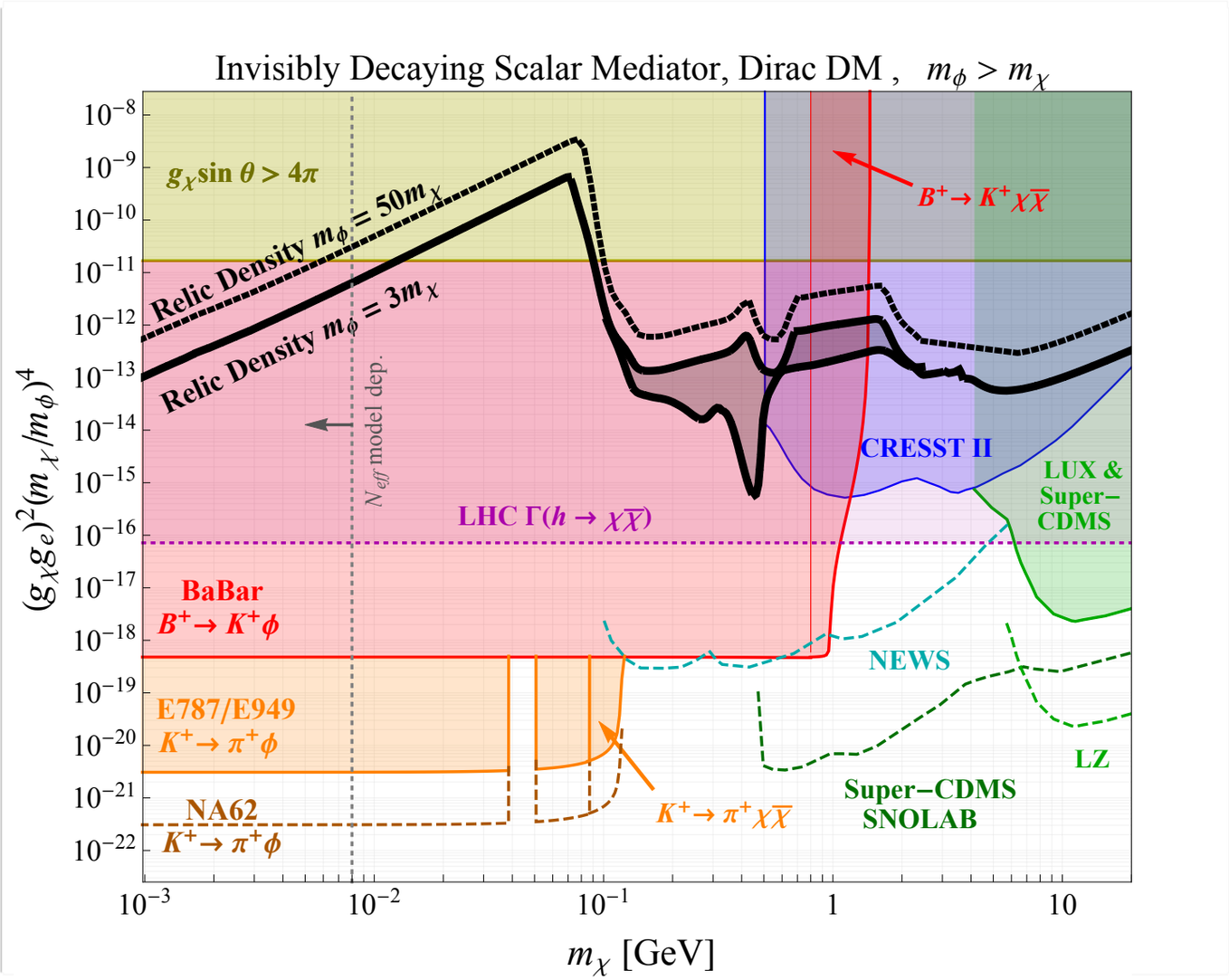


Direct Annihilation: Ruled Out



Collider and meson constraints use conservative $m_\phi = 3m_\chi$ $g_\chi = 1$

DM Model Variations?
(still assuming direct annihilation)



Asymmetric DM?

No, annihilation rate bigger

Scalar symmetric DM?

No, death by CMB

Inelasticity?

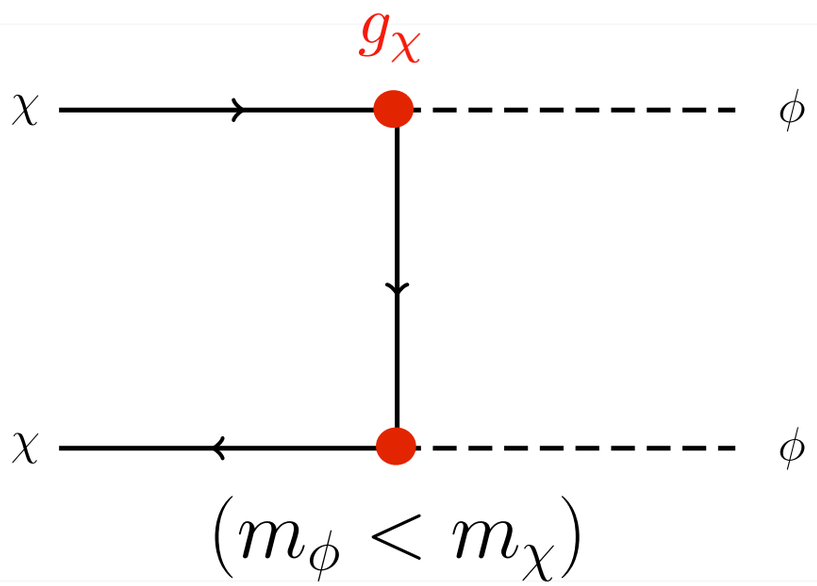
No, colliders / mesons dont care

Collider and meson constraints use conservative

$$m_\phi = 3 m_\chi \qquad g_\chi = 1$$

Additional motivation for dark photon DM program

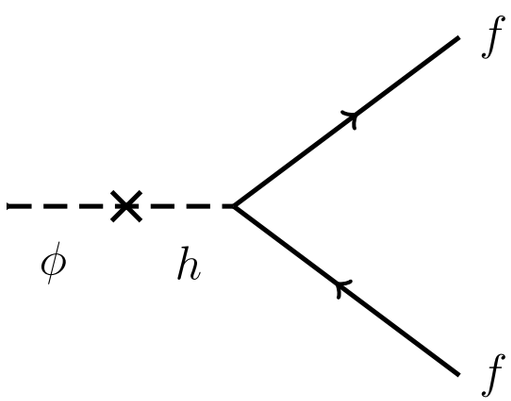
Annihilation to Mediators: Thermal Target?



Annihilation rate independent of SM

$$\sigma v(\chi\chi \to \phi\phi) = \frac{3 g_\chi^4 v^2}{128\pi m_\chi^2}$$

Mediator decays visibly to SM final states



Can still produce/observe mediator, but no direct target

So long as annihilation is p-wave
DM doesn't matter for bounds

Next best thing?
Minimum mixing for thermal production

Assuming Higgs-mediator mixing *alone* produces thermal DM

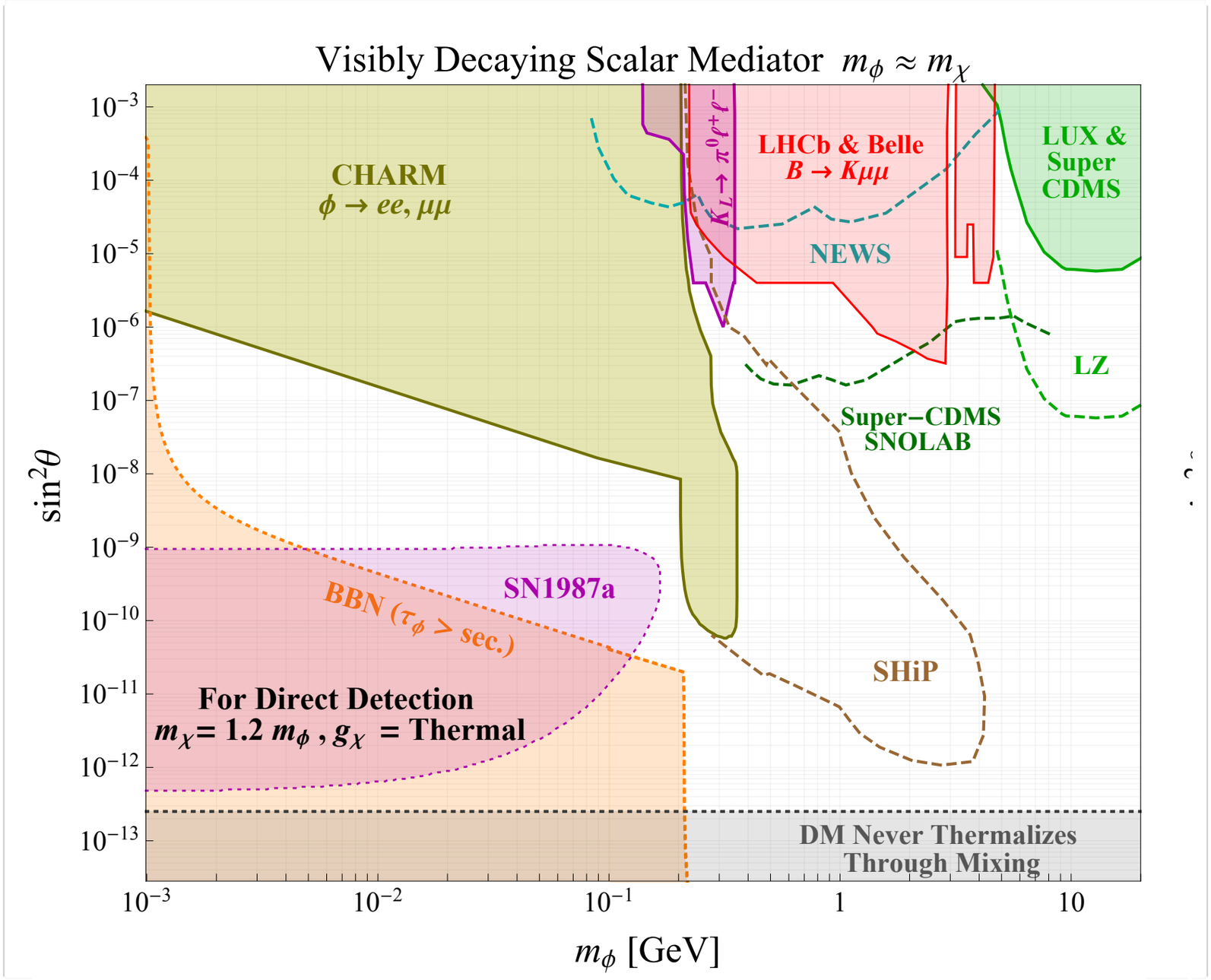
$$\Gamma_{\mathrm{SM}\to\chi\bar{\chi}} = \sum_f n_f(T)\langle\sigma|v|\rangle_{f\bar{f}\to\chi\bar{\chi}}$$

Requiring DM production > Hubble at *some point* in early universe

$$\sin^2\theta \gtrsim \frac{53\pi^3\sqrt{g_*(m_t)}\,m_t}{g_\chi^2\zeta(3)\,m_{Pl}} \approx 2\times 10^{-13}\ ,$$

Reaching this sensitivity for $g_\chi \sim \mathcal{O}(1)$
would rule out thermal DM for the visibly decaying scenario

Mediator mixing bounds (comparable DM mass)

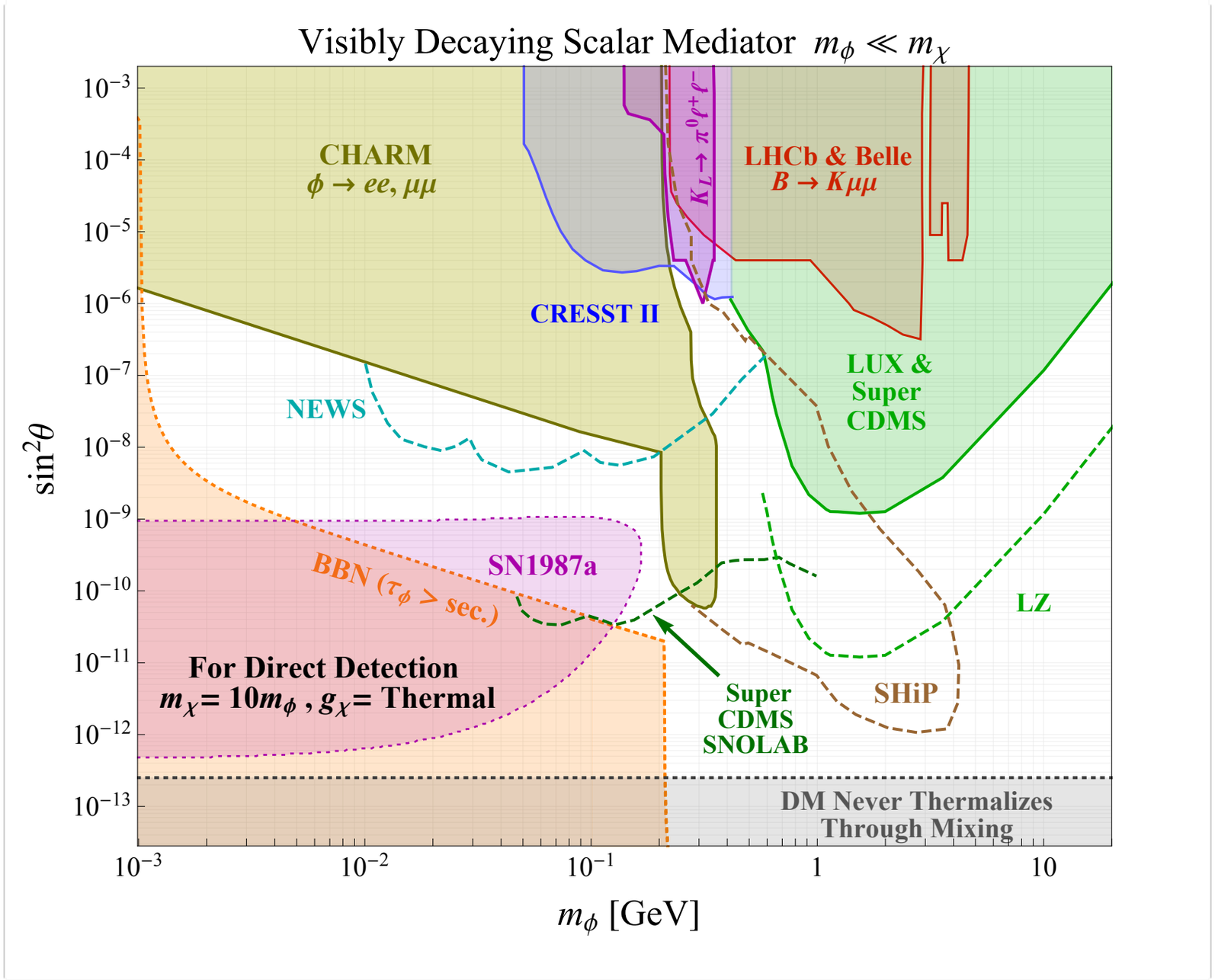


beam dump and meson bounds

Clarke, Foot, Volkas 1310.8042

Thermal DM can live anywhere unshaded

Mediator mixing bounds (hierarchical DM mass)



Larger hierarchy no longer LDM < GeV

Conclusions

Higgs portal thermal target already covered for minimal case

Direct annihilation scenario ruled out by rare meson and Higgs bounds

Insensitive to DM model variations

"Secluded" annihilation to mediators still viable

Much of remaining territory (but not all!) to be covered with next generation DD and beam dump searches (SHiP)

SHiP and other dark photon searches may be comparable

Where else should we be looking for remaining real estate?

Options at low mass are limited, leave no stone unturned