

Light Thermal DM & Higgs Portal Mediators

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CERN-EPFL-Korea Theory institute
"New Physics at the Intensity Frontier"

Zeroth Order Outstanding Problems

Matter Asymmetry
Inflation



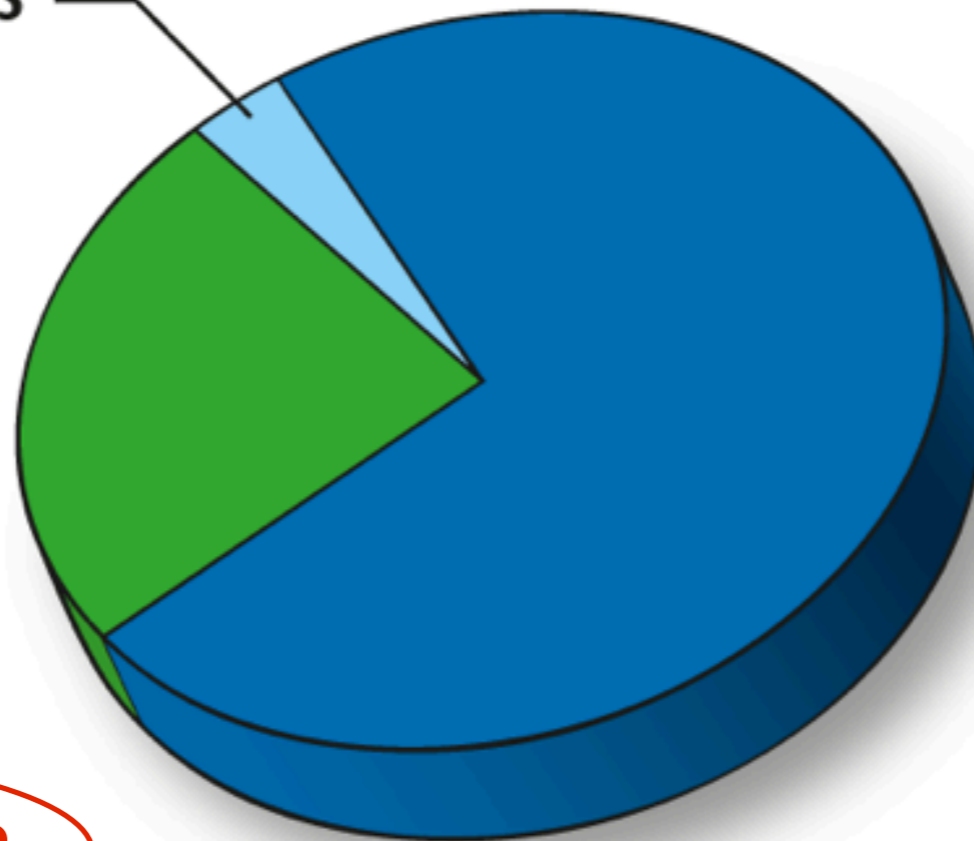
**Accelerated
Cosmic
Expansion**



Atoms
4.6%

Dark
Energy
71.4%

Dark
Matter
24%

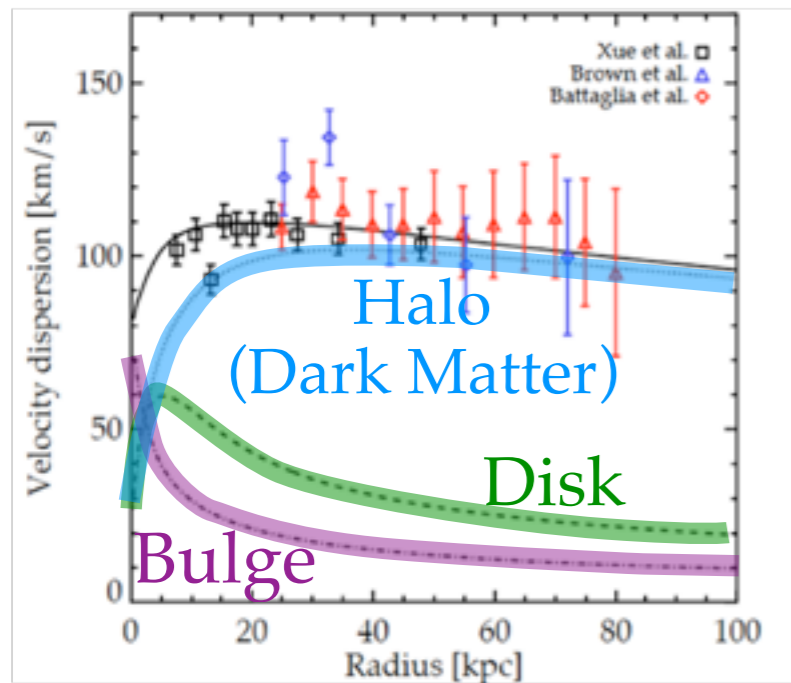


TODAY

What is this stuff?

All other problems generically require extremely high scales DM can be much lighter

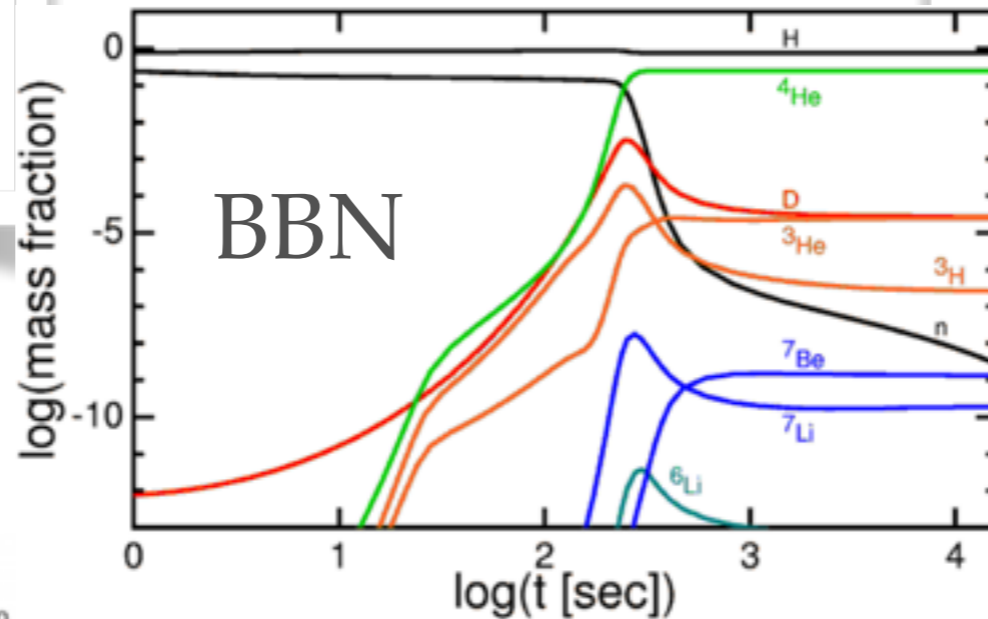
Obligatory DM Slide



Rotation
Curves

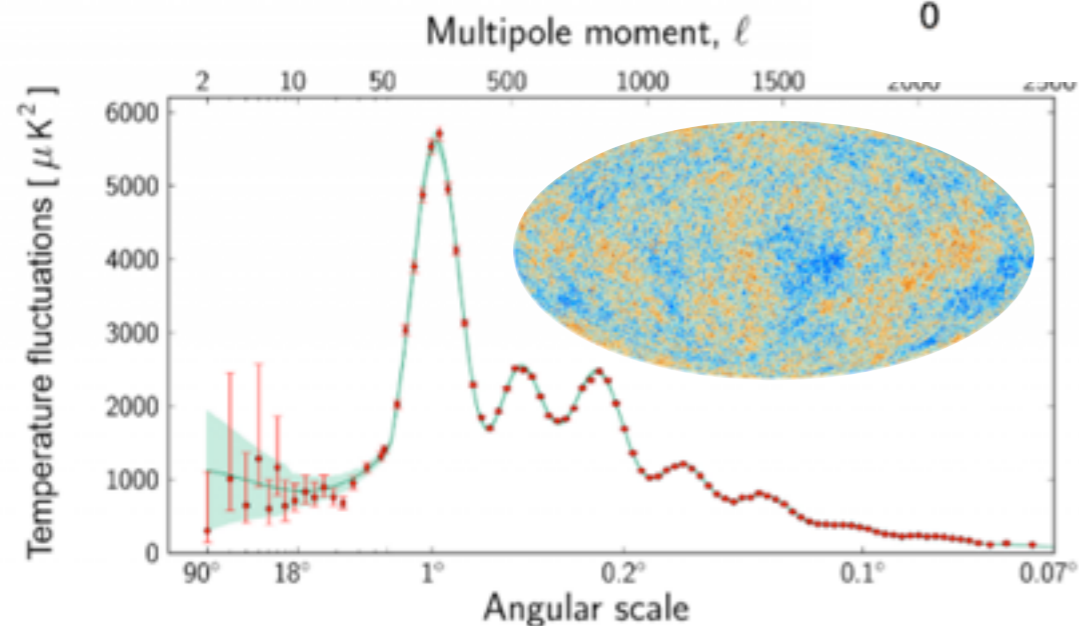


Gravitational
Lensing

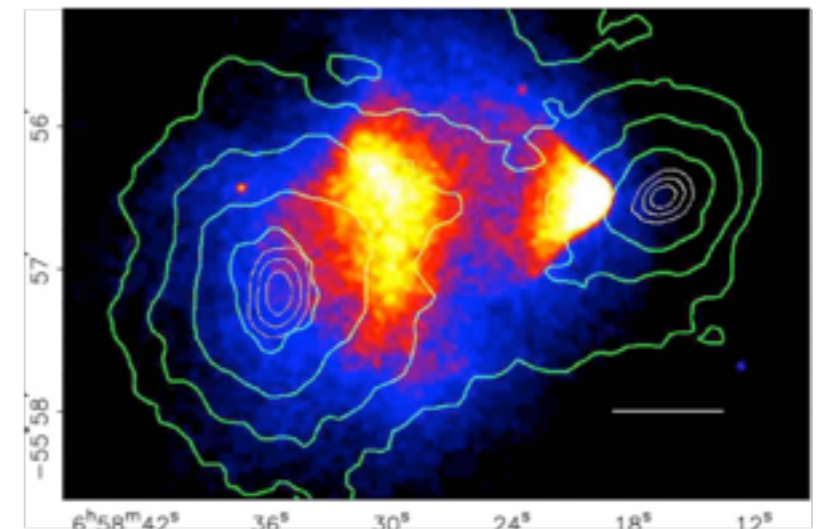


BBN

CMB



Cluster
Collisions



lots of evidence, but all gravitational...

Historical Analogy

Understanding the Weak Force

Discovery of radioactivity (1890s)

Fermi Scale identified $G_F \sim \frac{1}{(100 \text{ GeV})^2}$ (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? > 2017

Non-gravitational interactions not guaranteed

No clear target of opportunity

Discovery time frame? $t > 80$ yrs

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

If nature is unkind, we may never know the right scale



Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

Thermal Equilibrium

Advantage #1: Minimum Annihilation Rate

Equilibrium, achieved easily with a tiny DM/SM coupling

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

Generically overproduces DM

Requires *much larger* annihilation cross section to deplete

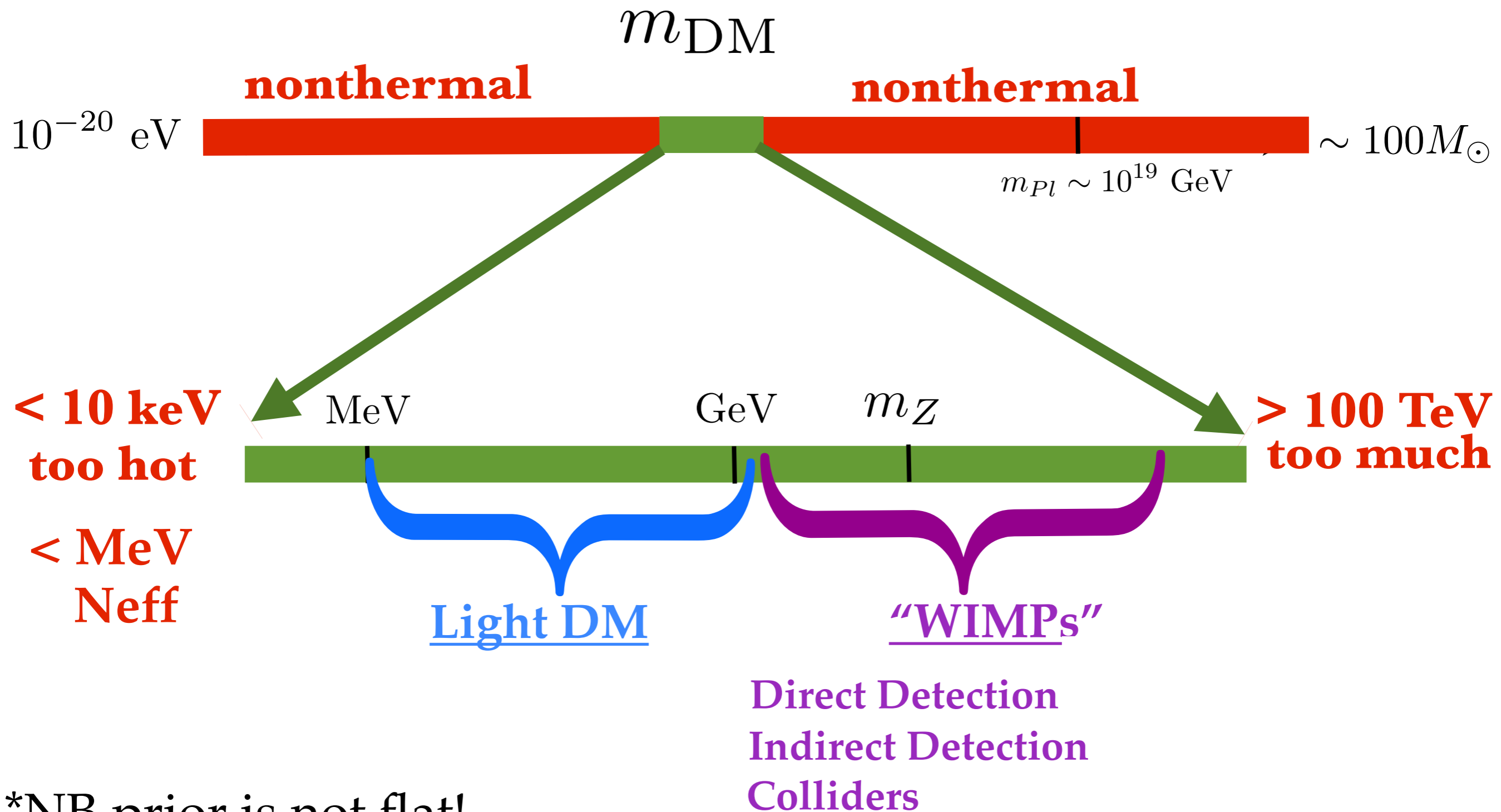
$$\sigma v \geq \sigma v_{\text{relic}} \sim 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$$

$=$ symmetric thermal DM

$>$ asymmetric DM

Thermal Equilibrium

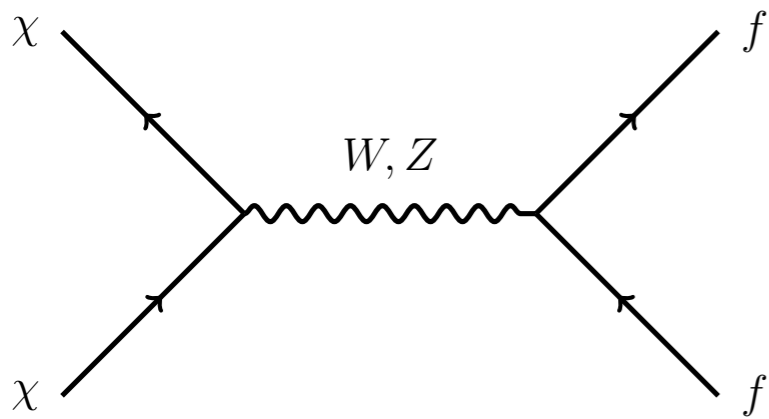
Advantage #2: Narrows Mass Range



Heavy vs. Light # 1

LDM needs new forces

Heavy DM can achieve right abundance w/ SM weak force



$$\sigma v \sim \frac{m_\chi^2}{m_Z^4} \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \left(\frac{m_\chi}{\text{TeV}} \right)^2$$

For LDM, annihilation via SM forces is too weak
so equilibrium is lost too soon

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

DM overproduced unless there are light new force carriers

Avoiding LDM Overproduction

Choose light mediator

Must be SM singlet, options limited by SM gauge invariance

Vector Portal

mix w/ photon
(or gauge B-L etc.)

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

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
(or gauge B-L etc.)

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

Lots of attention here
(wont discuss here)

Neutrino Portal
mix w/ RHN

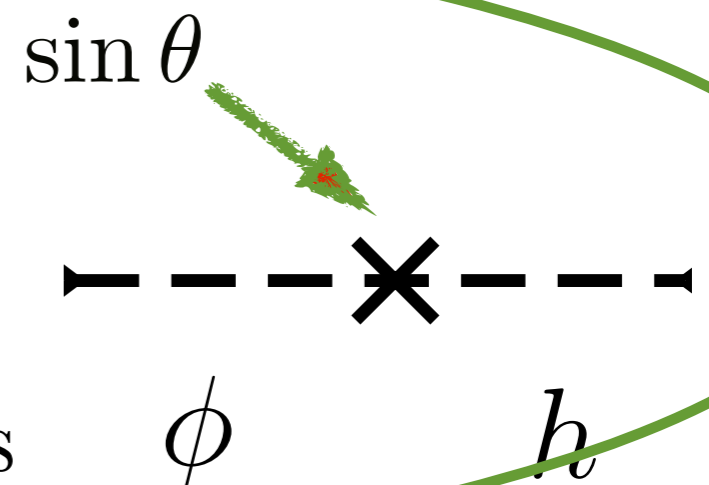
$$H^\dagger \bar{L} N$$

Hard to make thermal
(decays, ν masses etc.)

Higgs Portal
mix w/ SM Higgs

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

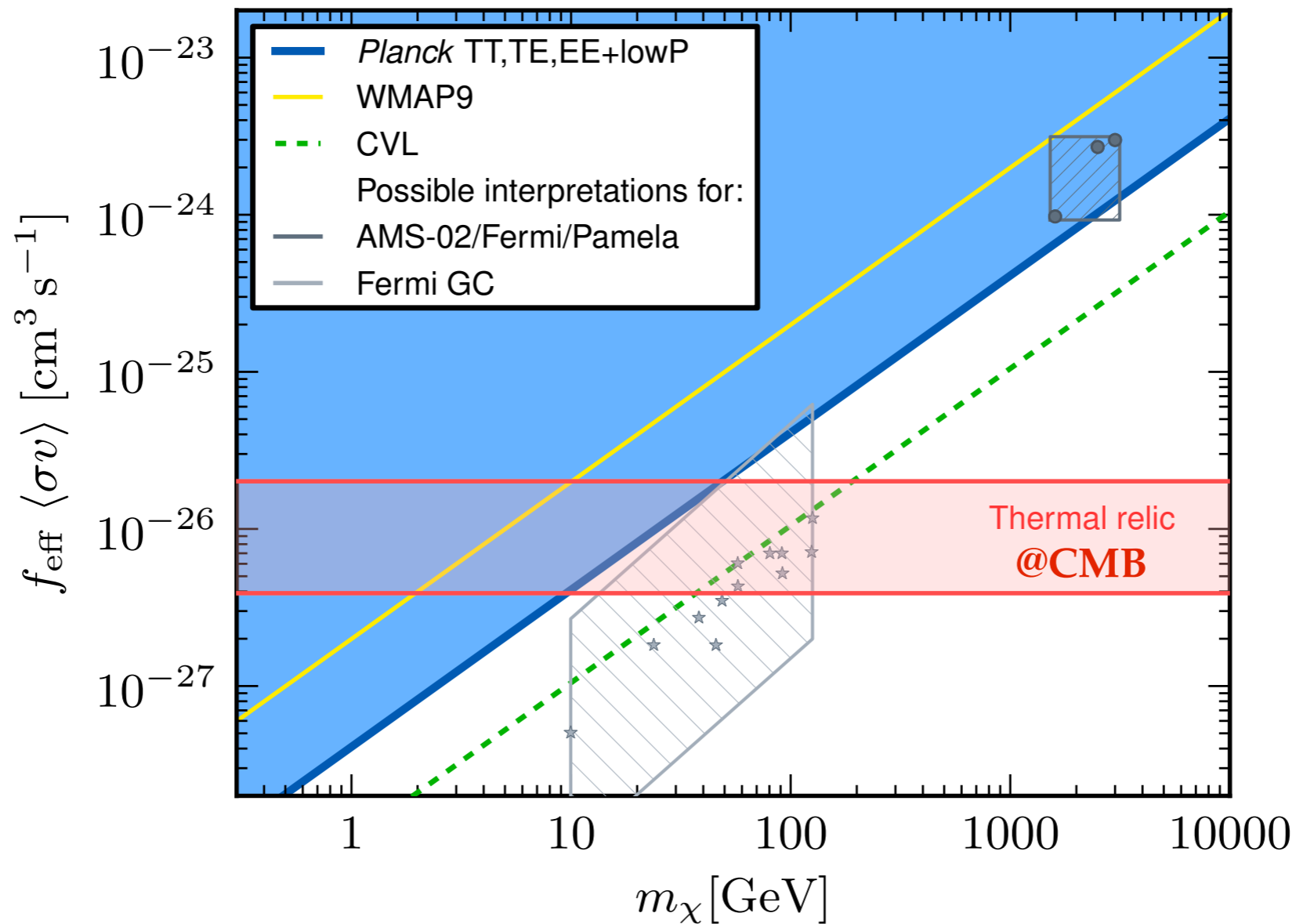
SM coupling \propto fermion mass



Heavy vs. Light # 2

CMB rules out LDM < 10 GeV?

Planck
1303.5076



Safe models: cross section is smaller @ CMB
or annihilation stops @ CMB

Option 1: Smaller Cross Section

Velocity / Temperature Dependence

$$\sigma v \propto v^2$$

Rate large at freeze-out w/ $v \sim 0.1 c$

$$\langle \sigma v \rangle \big|_{T=m_\chi} = 3 \times 10^{-26} \text{ cm}^3/\text{s} \implies \Omega_\chi = \Omega_{\text{DM}}$$

Velocity redshifted at late times

$$\langle \sigma v \rangle \big|_{T=\text{eV}} \ll 3 \times 10^{-26} \text{ cm}^3/\text{s} \implies \text{CMB safe}$$

Choose DM/mediator combination to get v -dependence

Option 2: Annihilation Stops Later

Case Study: **Asymmetric DM**

Annihilation @ $T \sim m$ reduces antiparticle fraction

$$n_\chi \neq n_{\bar{\chi}} \propto \exp(-\langle\sigma v\rangle)$$

Counterintuitive: larger cross section is safer!

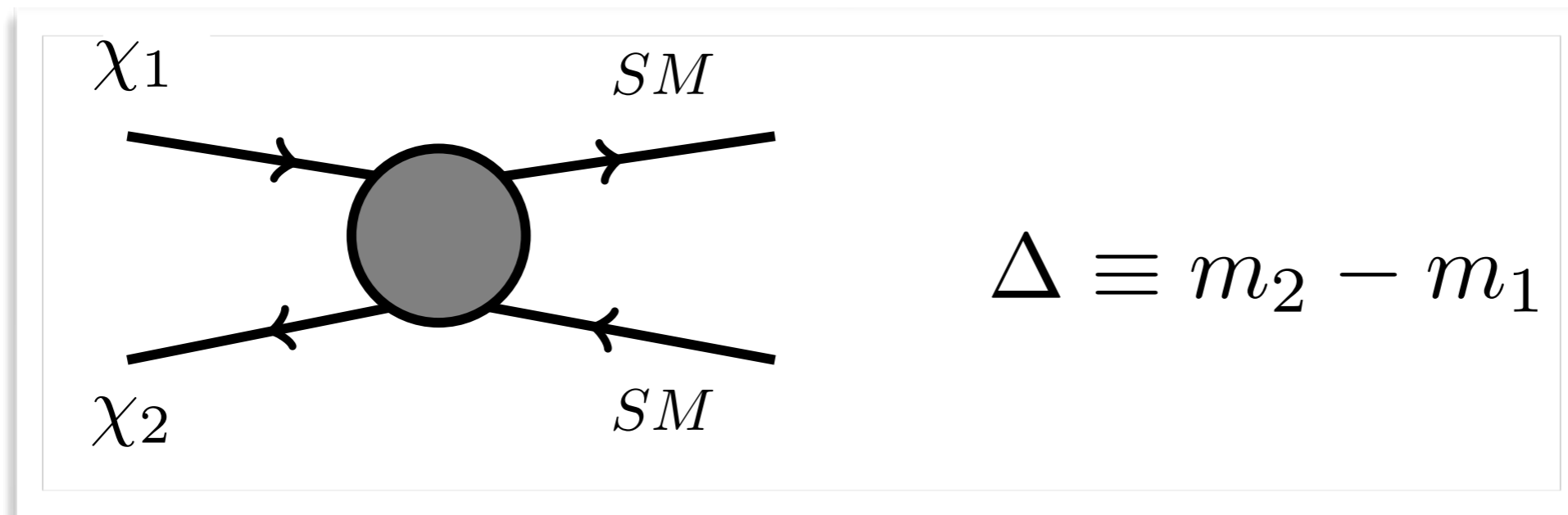
$$\frac{f_{\text{eff.}} \langle\sigma v\rangle e^{-\langle\sigma v\rangle}}{m_\chi} \ll 2 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-1}$$

Easily satisfies CMB bound with $\langle\sigma v\rangle > 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$
as required for asymmetric DM

Option 2: Annihilation Stops Later

Case Study: **Inelastic couplings**

Two-level co-annihilating system



As universe cools, heavier state is Boltzmann suppressed

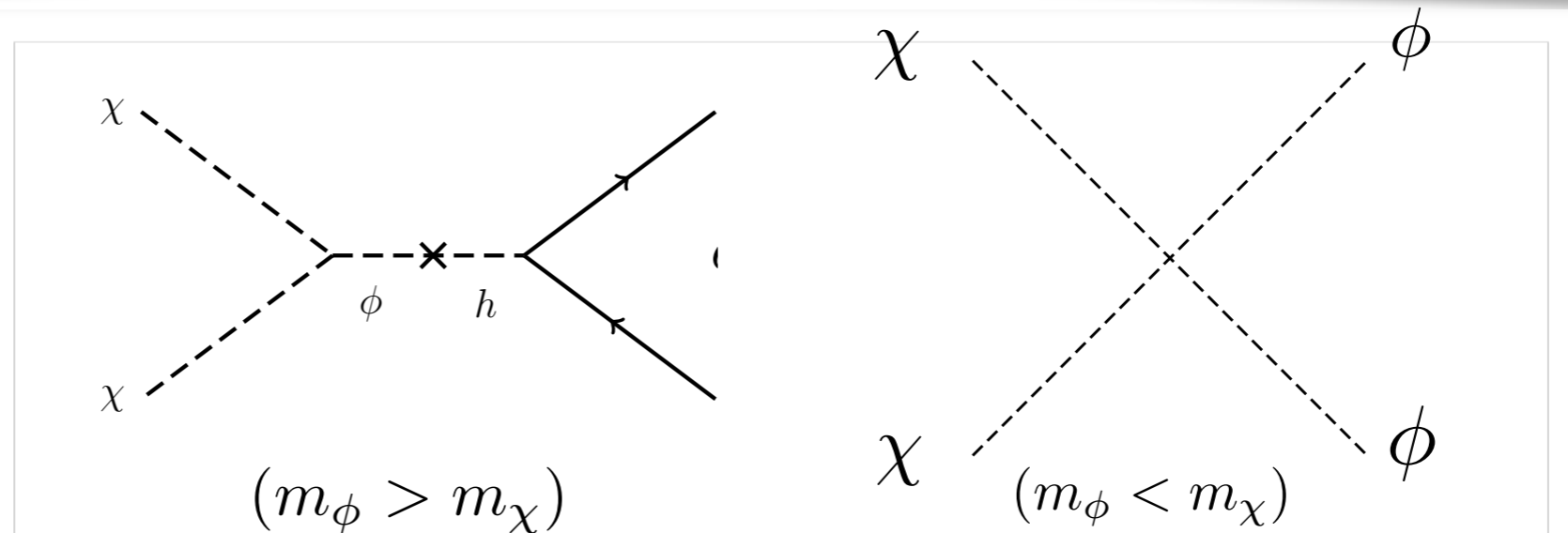
$$n_{\chi_2} \propto e^{-\Delta/T}$$

annihilation shuts off at late times

Generic (e.g if dark there are dark Dirac & Majorana masses)

Choose CMB safe DM for scalar mediator

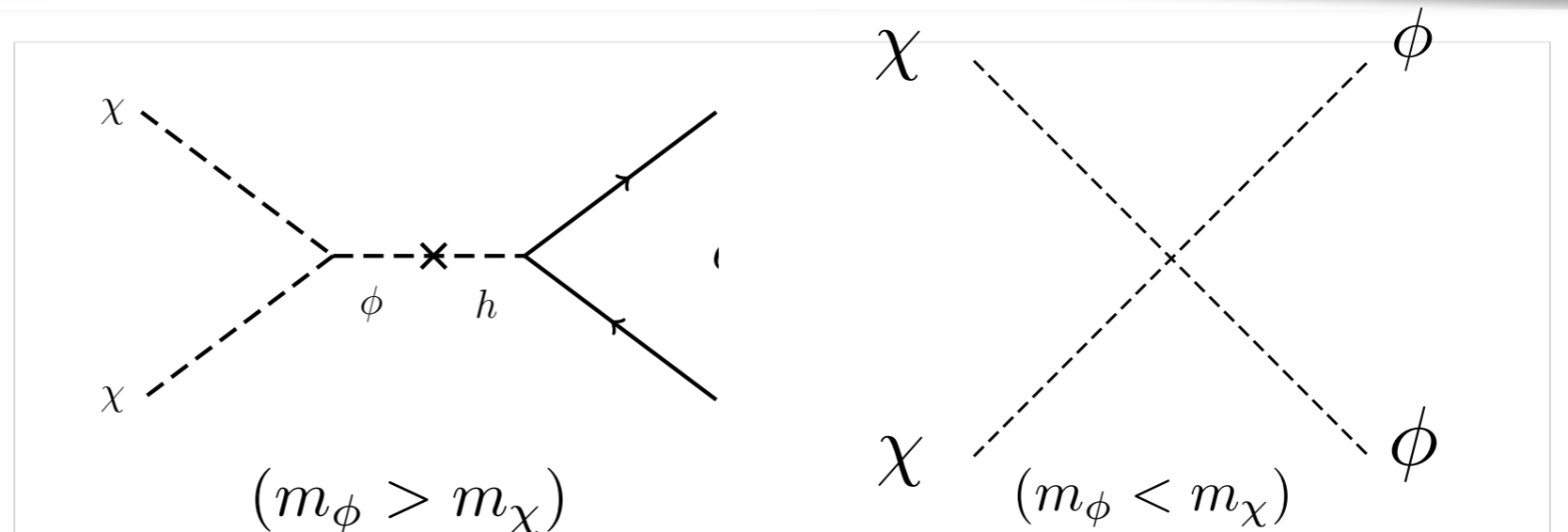
Scalar DM
s-wave
annihilation



Need particle asymmetry and/or inelasticity for CMB safety

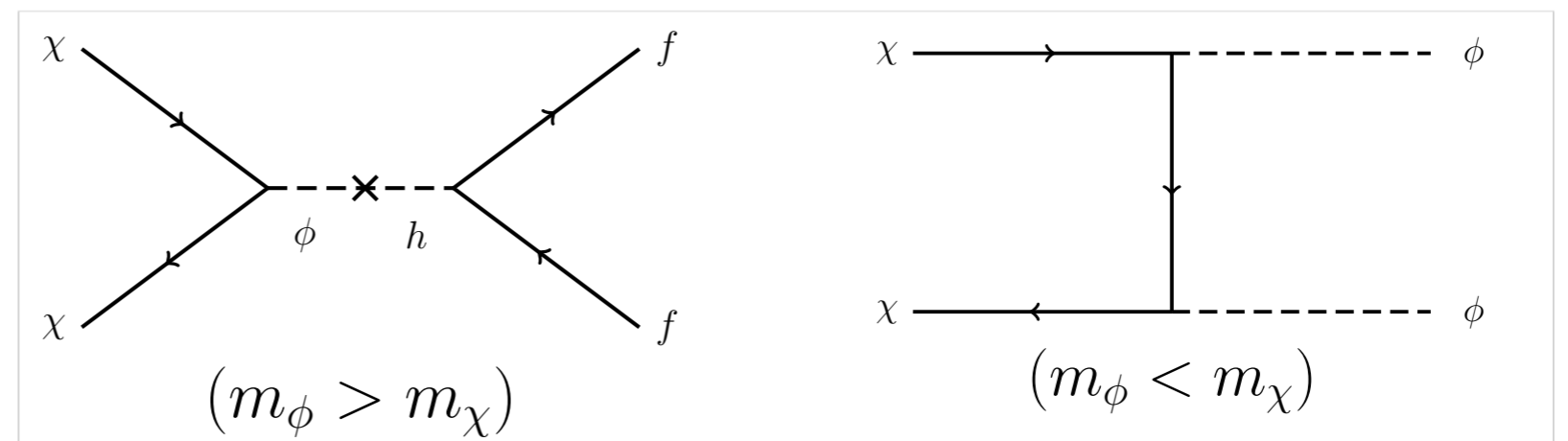
Choose CMB safe DM for scalar mediator

Scalar DM
s-wave
annihilation



Need particle asymmetry and/or inelasticity for CMB safety

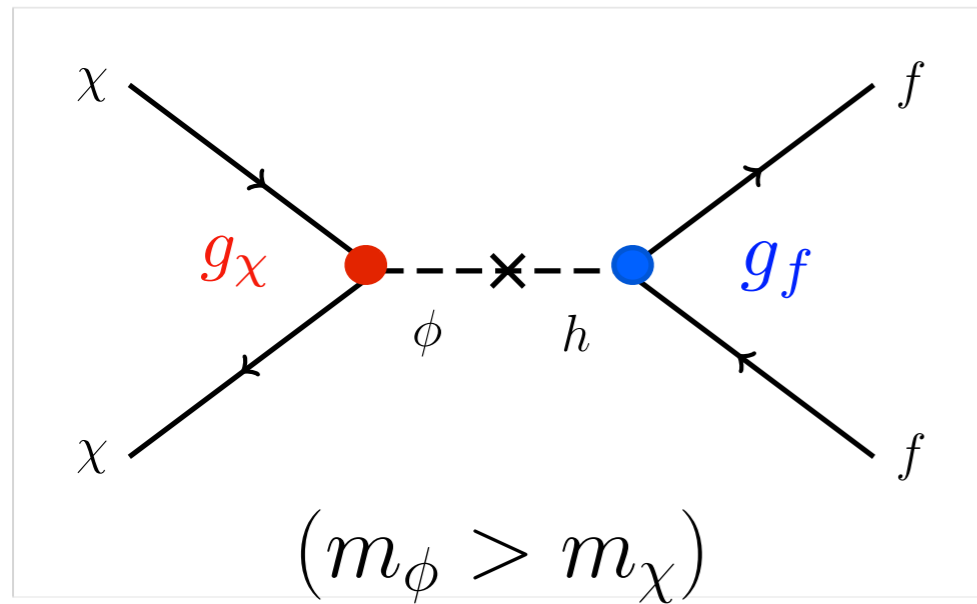
Fermion DM
p-wave annihilation
 $g_\chi \phi \bar{\chi} \chi$



Can also include $\phi \bar{\chi} \gamma^5 \chi$
must be small (adds s-wave terms)

Both CMB safe $\sigma v \propto v^2$

Thermal Target: Direct Annihilation to SM



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

Coupling scales with SM fermion mass

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

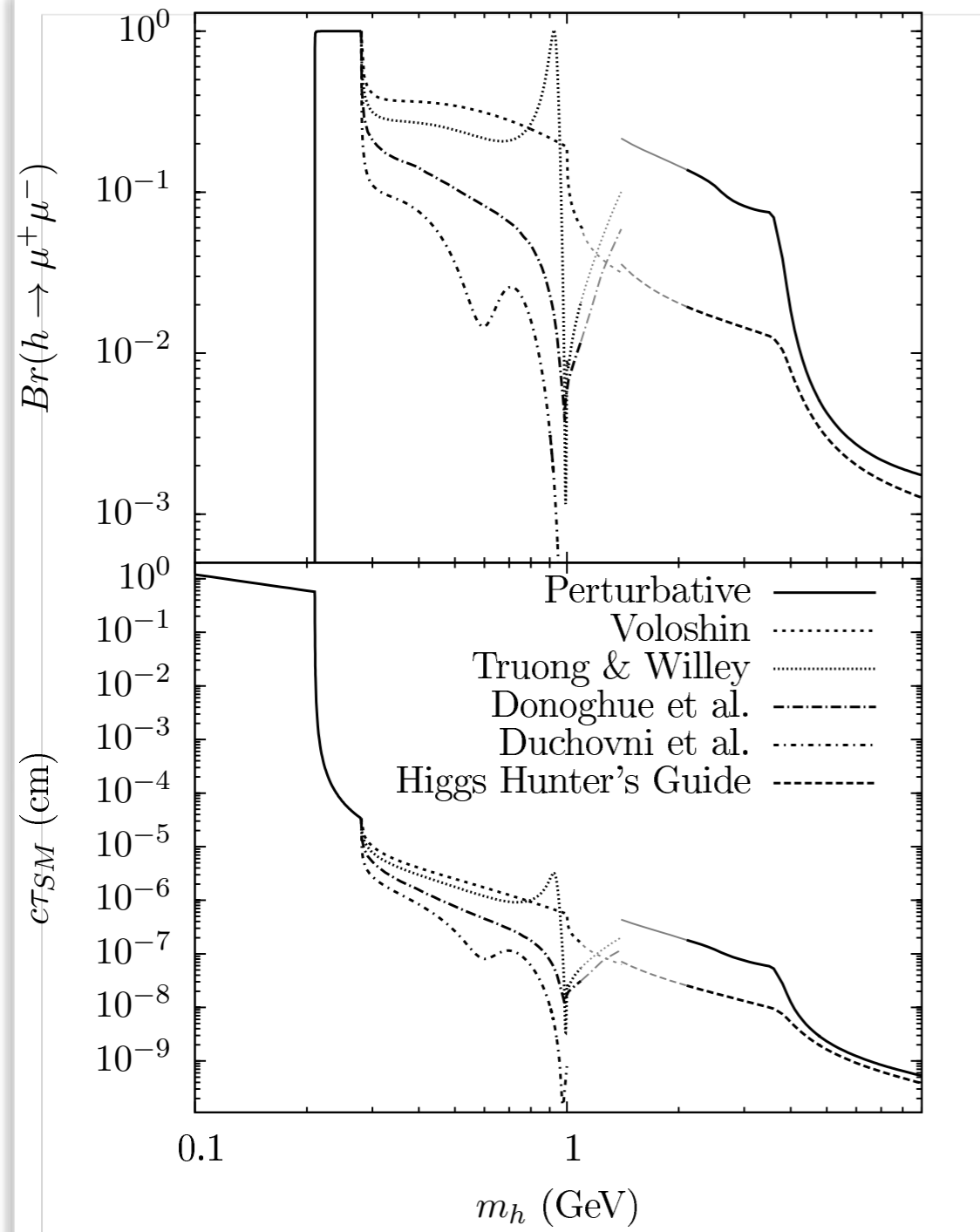
Define dimensionless target

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

Normalized to electron coupling because rate exists for every mass point

Thermal Target: Direct Annihilation to SM

Large theory uncertainty in SM coupling near QCD scale

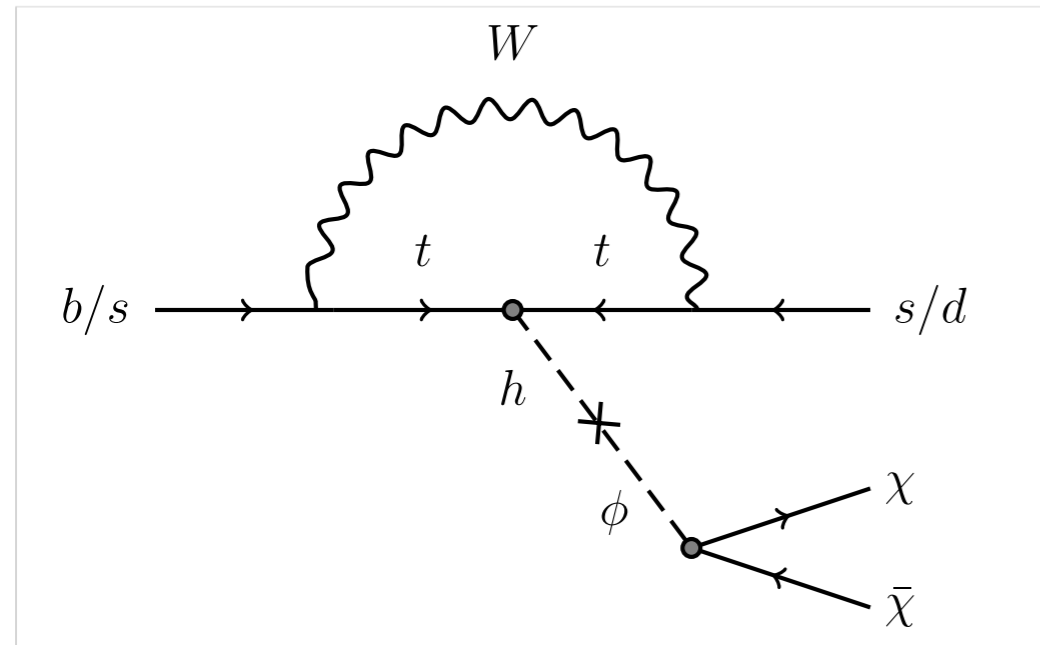


Estimate from different
numerical extractions
from light Higgs literature

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

Thermal Target: Rare B/K Decays

2 / 3 body decays to LDM / mediator



$$B^+ \rightarrow K^+ \phi, \quad K^+ \chi \chi$$

$$K^+ \rightarrow \pi^+ \phi, \quad \pi^+ \chi \chi$$

constrained by

$$B^+ \rightarrow K^+ \nu \bar{\nu} \quad K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

Annihilation rate set by *small* yukawas

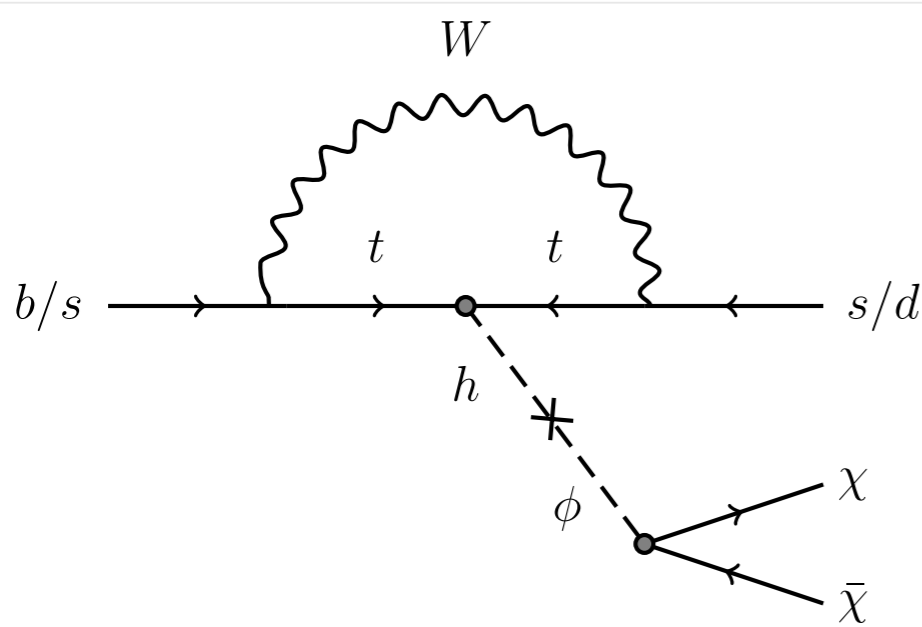
FCNC constraints set by *top* yukawa

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

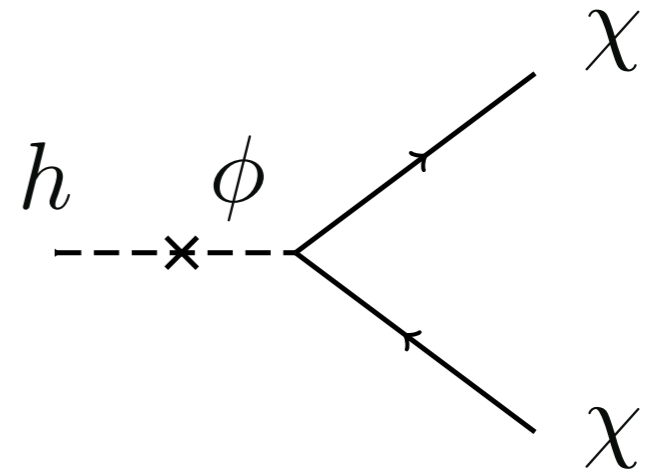
$$\Delta\text{Br}(B^+ \rightarrow K^+ \cancel{E}) \propto g_f^2 = y \times \underbrace{\frac{1}{g_\chi^2} \left(\frac{m_\phi}{m_\chi} \right)^4}_{\text{DM mass/coupling}}$$

Conservative worst-case “y” reach g_χ , $m_\phi/m_\chi \rightarrow \mathcal{O}(1)$
(choose smallest mass ratio still consistent with direct annihilation)

Thermal Target: Other Constraints

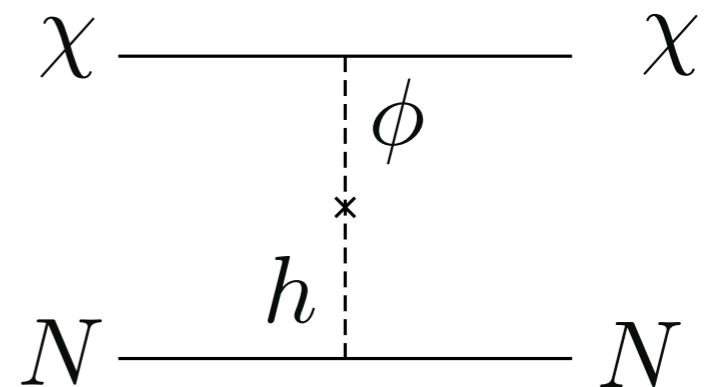
Higgs Invisible Width

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

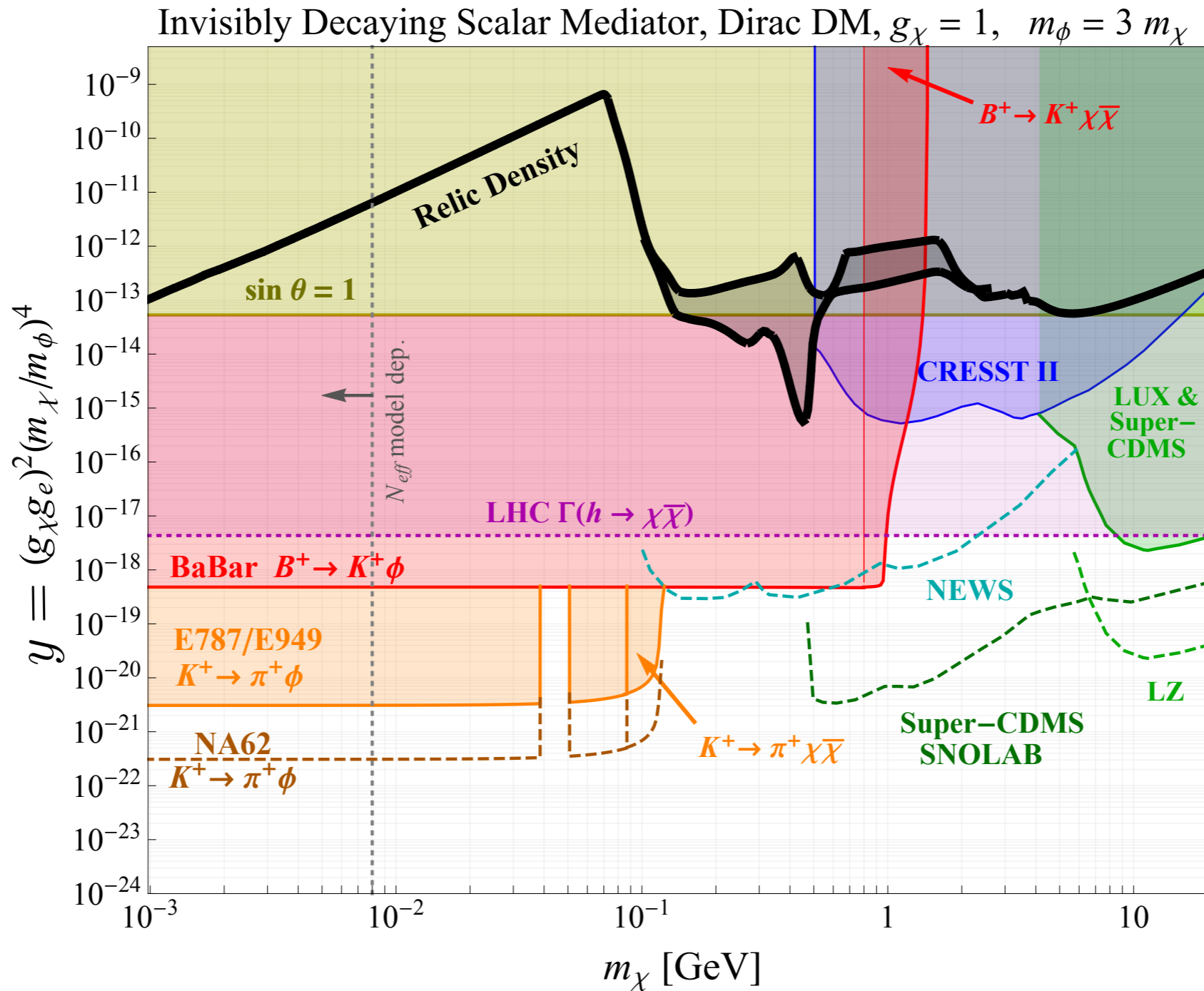


Low Mass Direct Detection \sim GeV

Assuming elastic scattering invariant comparison with thermal target

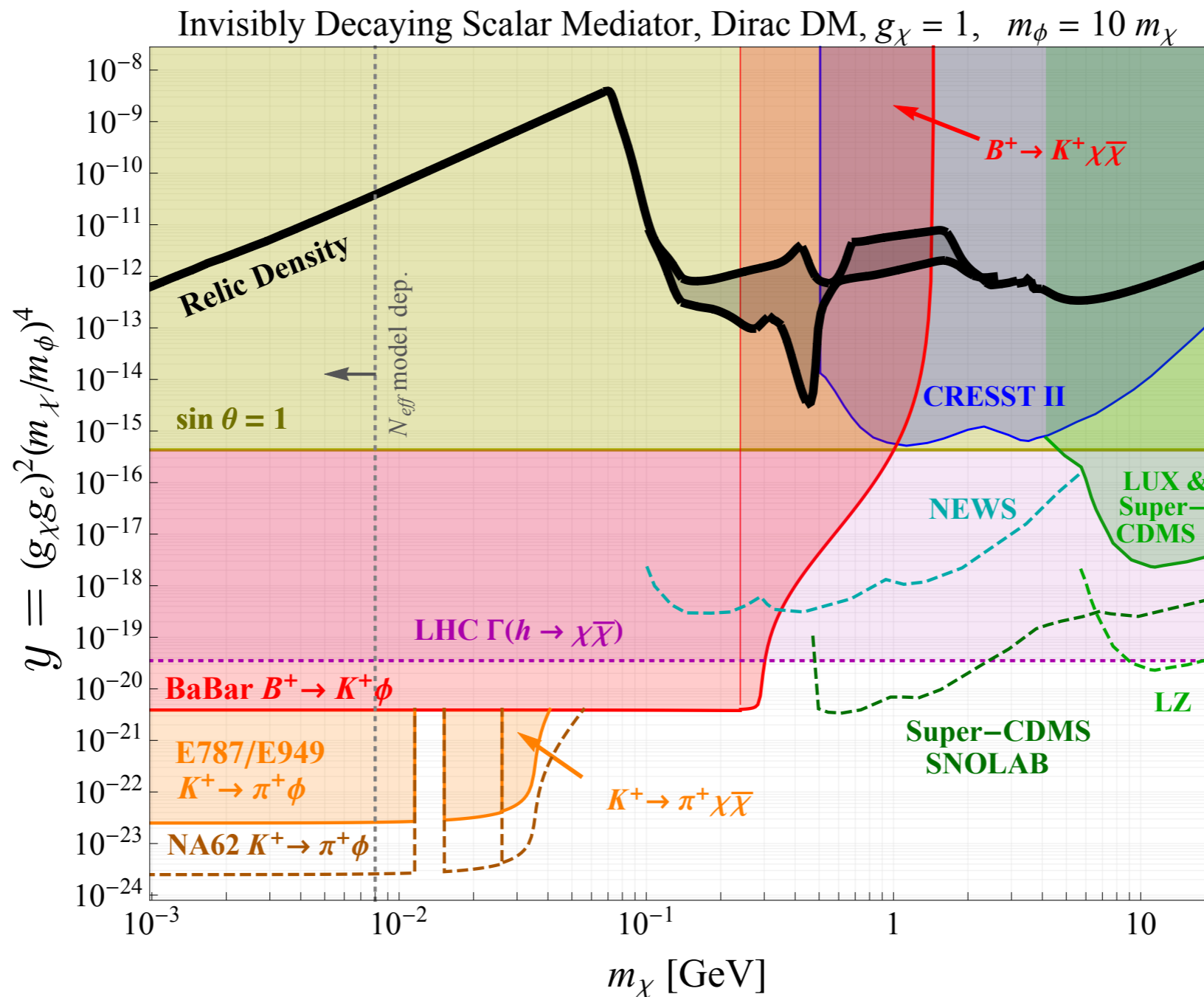


Direct Annihilation: Ruled Out



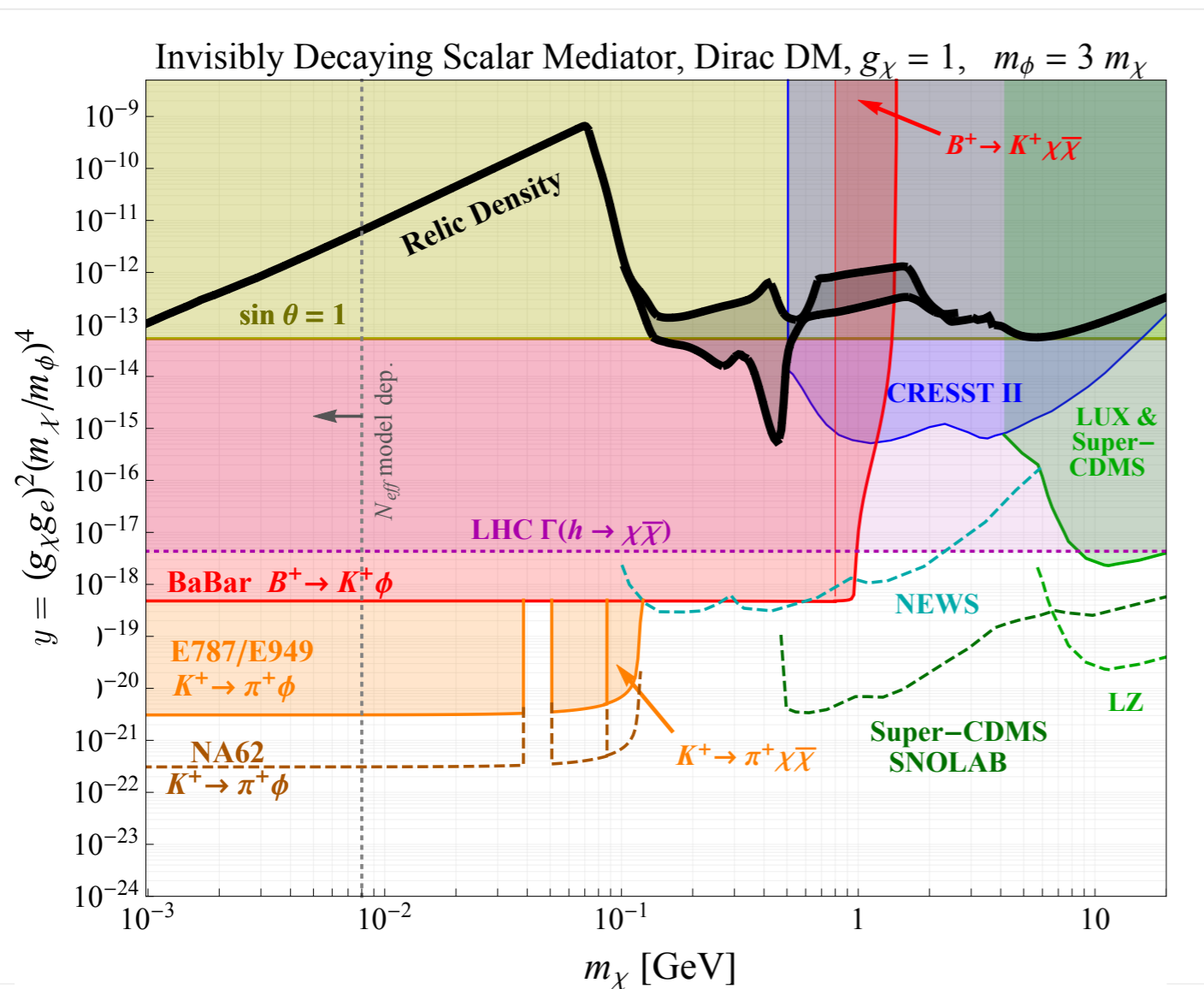
This is the most conservative prescription for all experimental bounds

Direct Annihilation: Ruled Out



Much heavier mediator is easier to rule out (need larger Higgs mixing angle)

DM Candidate Variations? (for direct annihilation)



Asymmetric DM?

No, annihilation rate bigger

Scalar symmetric DM?

No, death by CMB

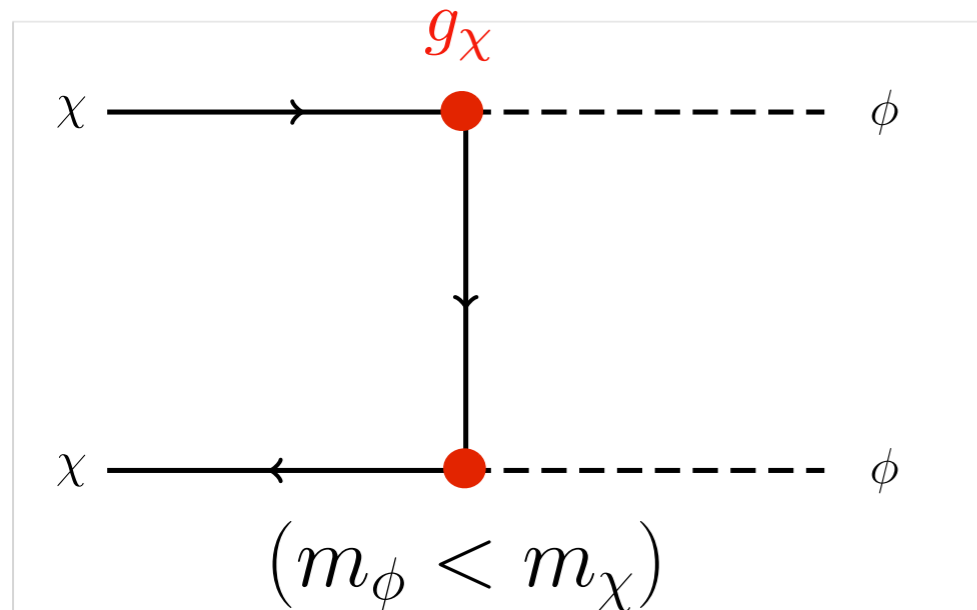
Inelastic couplings?

No, colliders / mesons don't care

**Motivates vector mediators
for direct annihilation**

Izaguirre, GK, Schuster, Toro
PRL 115 (2015) 1505.00011

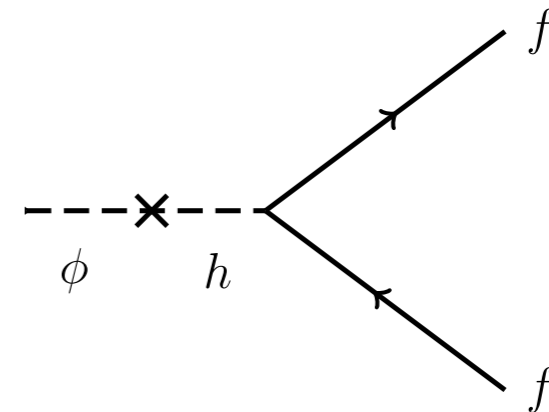
Secluded Annihilation to Mediators: Thermal Target?



Annihilation rate independent of SM

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

Mediator decays visibly to SM final states
through Higgs portal mixing



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

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

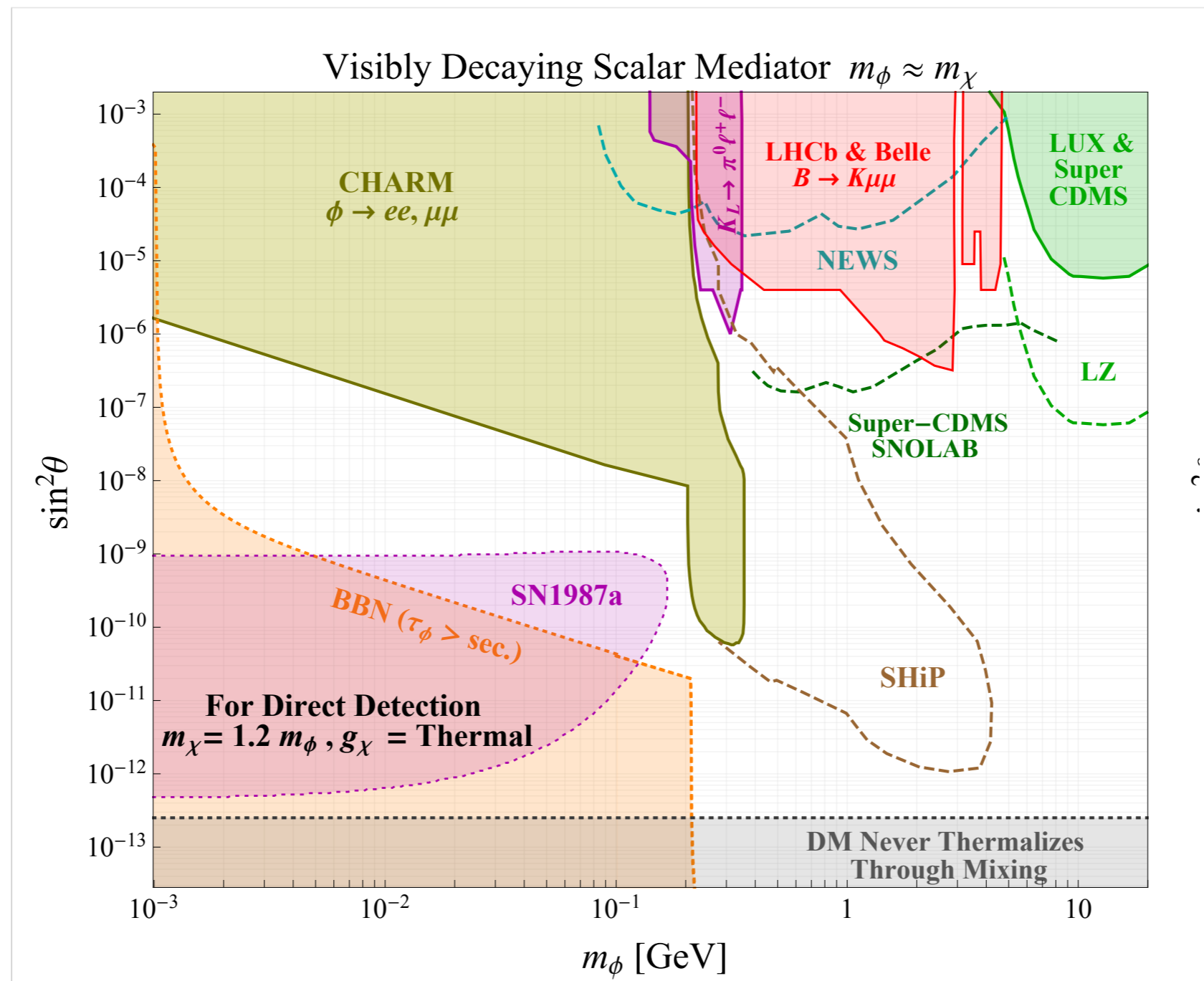
Requiring DM production rate > Hubble in early universe

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

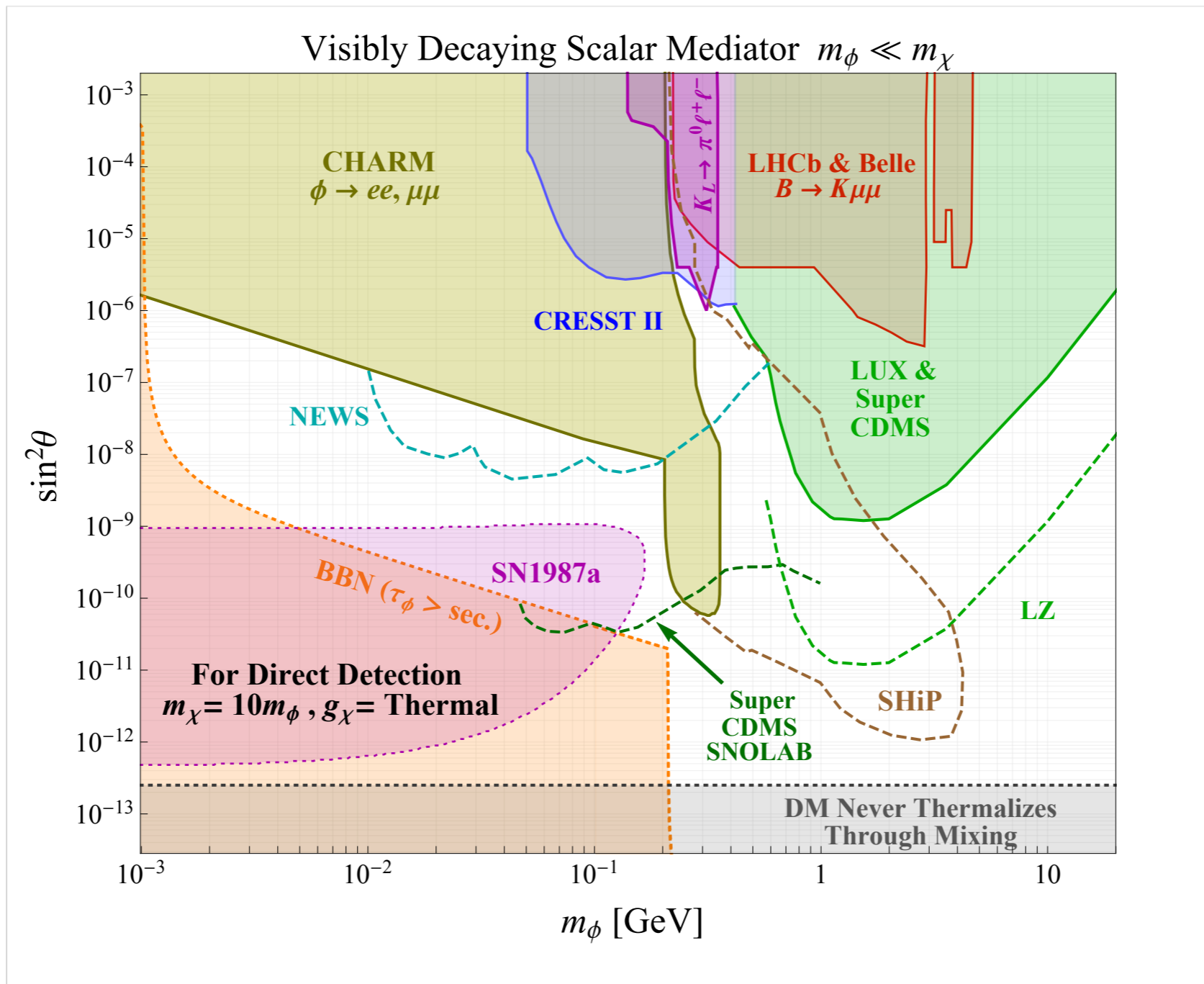
Reaching this sensitivity for $g_\chi \sim \mathcal{O}(1)$

would rule out thermal DM for the secluded annihilation scenario

Mediator mixing bounds (Comparable DM/mediator mass)



Mediator mixing bounds (hierarchical DM/mediator mass)



Larger hierarchy is no longer Light DM (more WIMP-like)

Conclusions

Thermal DM important organizing principle for discovery effort

Viable over MeV-TeV range, need new BSM forces for MeV-GeV

Finite, comprehensive list of mediator options for light new forces

Higgs portal thermal target already covered for direct annihilation

Direct annihilation scenario ruled out by rare meson and Higgs bounds

Independent of DM candidate variations (fermion / scalar / asymmetric / inelastic)

“Secluded” thermal annihilation to mediators still viable/testable

Future direct detection (LZ, NEWS, Super-CDMS SNOLAB, Xenon1T...)

Current / proposed hadronic production searches (SHiP, NA62...)

Would be interesting to see if other experiments are also sensitive

SeaQuest, DUNE, MiniBooNE, future colliders (FCC, ILC...)?