Dark Matter Theory Space

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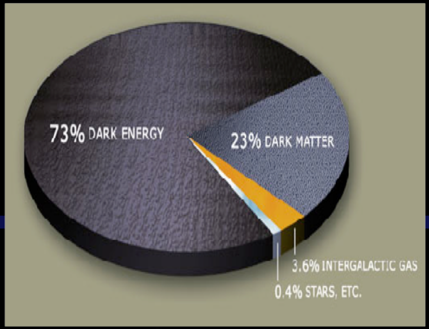
The power of the dark side

Holds the Universe together and makes *85% of all the matter in it!*



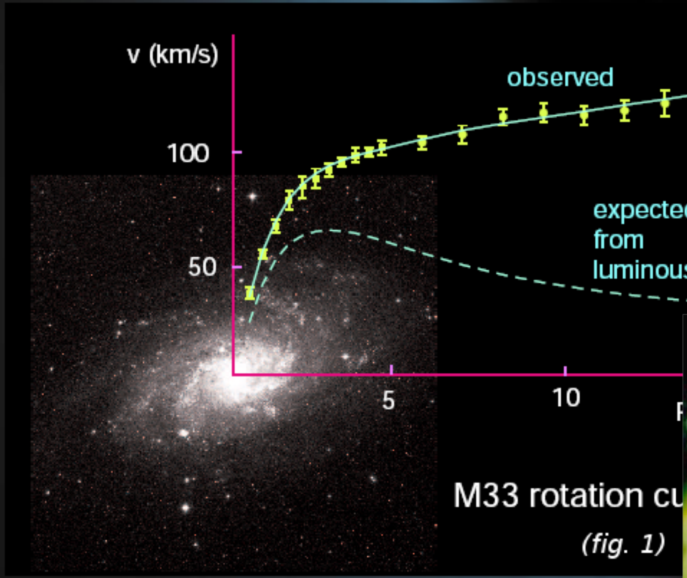
Strongest evidence for DM comes from its interactions with visible matter in the Milky Way

Standard Newtonian gravity

$$v_c(r) = \sqrt{\frac{GM}{r}}$$

But, observations show flattening of v_c , hence

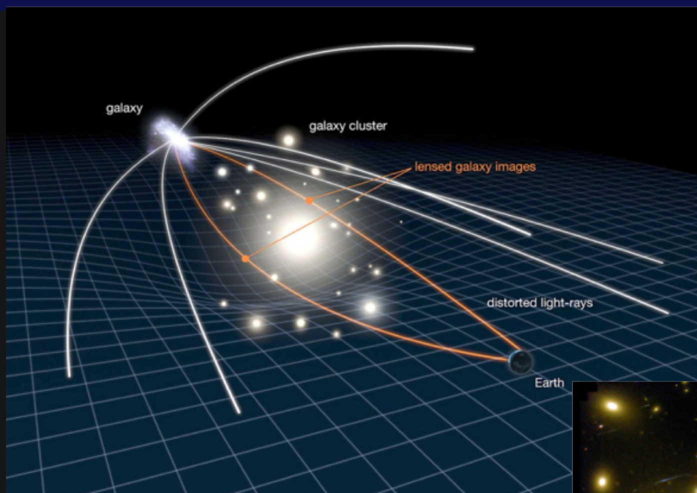
$$M(r) \propto r.$$



Something invisible is holding stars in orbit

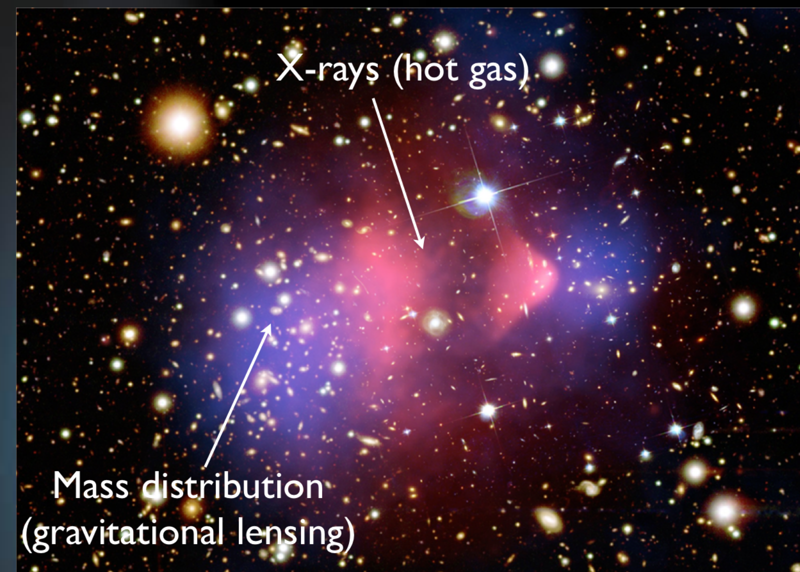
Evidence for DM on many scales at many times

Gravitational Lensing



Images of distant galaxies distorted by bending of light by strong gravitational fields

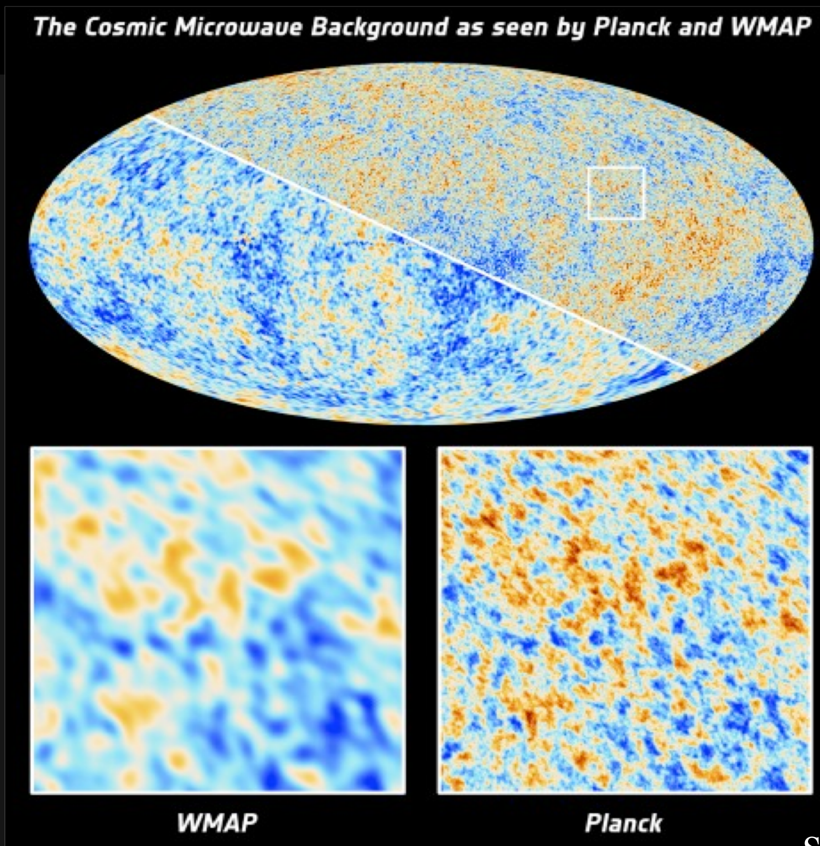
Galaxy Cluster Collisions

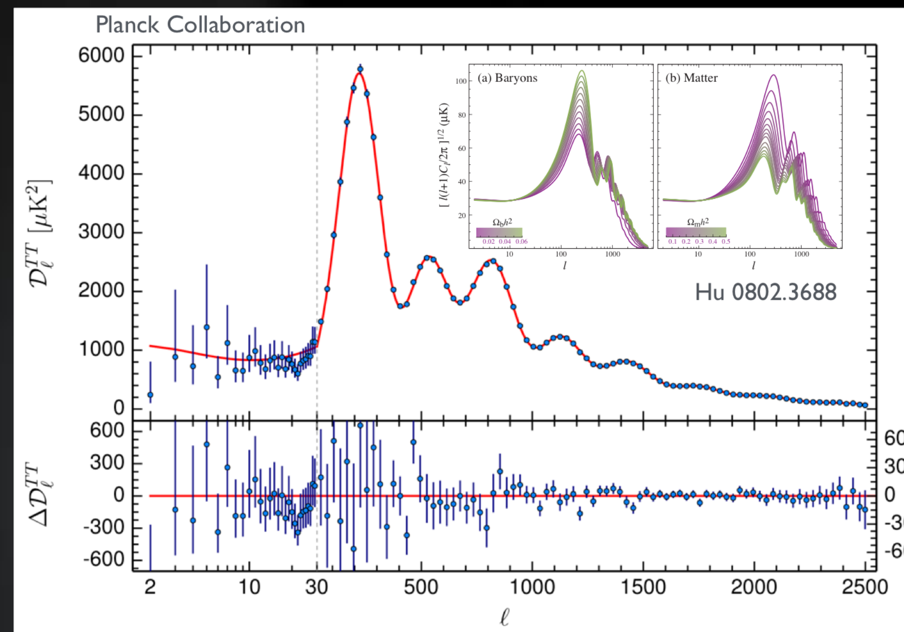


Two galaxies collided, leaving behind the interacting gas, while the DM of both galaxies passed through ➔ upper limit on the self interaction of the DM

Evidence for DM on many scales at many times

CMB Power Spectrum



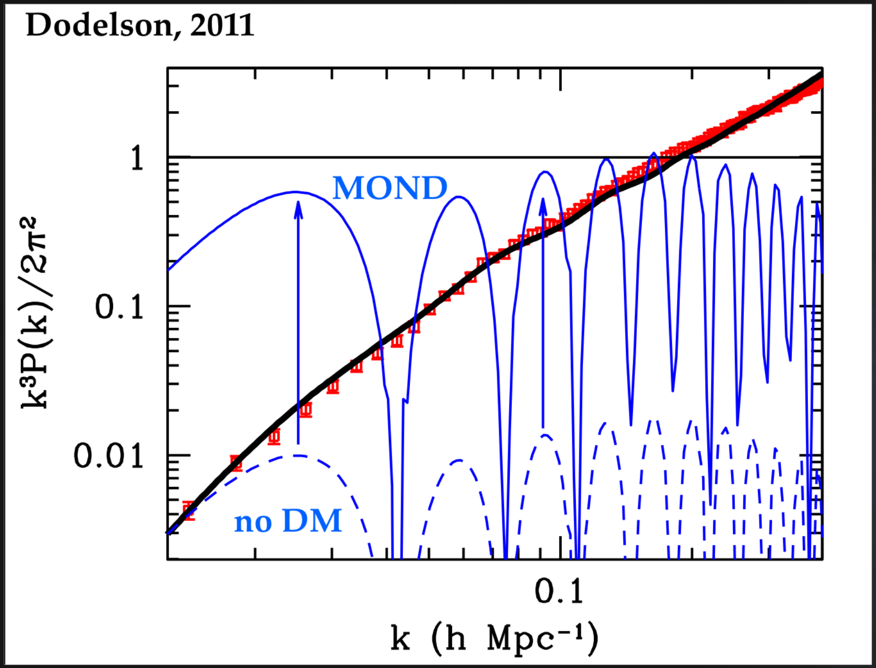


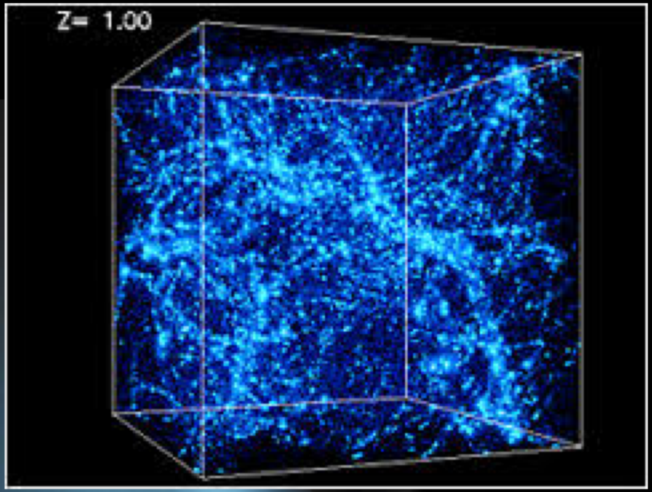
Fluctuations in the CMB temperature spectrum at different angular scales on the sky

Constraints on the third peak yield the first direct evidence for dark matter at the epoch of recombination.

Evidence for DM on many scales at many times

Matter Power Spectrum

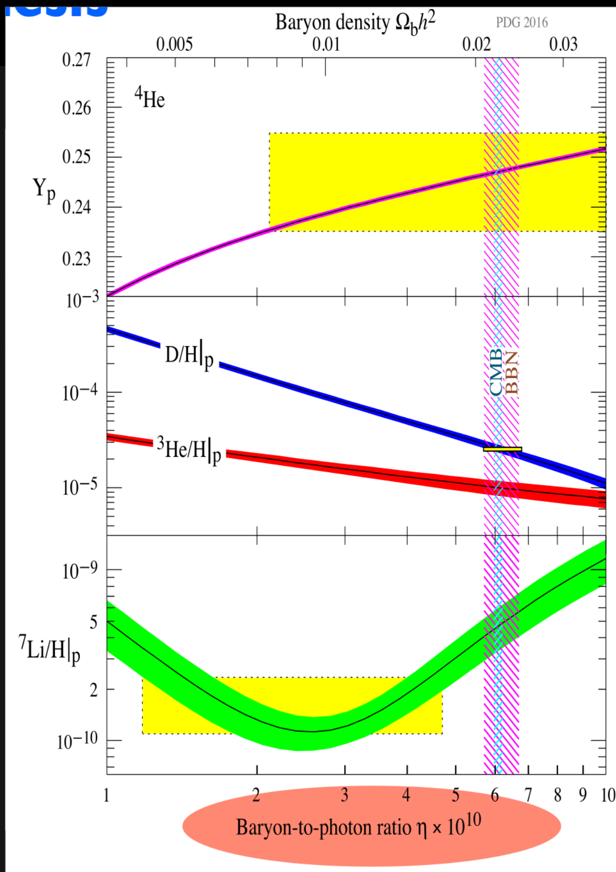




Observation & theory agree with ~ 85% pressure-less matter, 15% conventional baryonic

Evidence for DM on many scales at many times

Big Bang Nucleosynthesis



Hot soup of protons & neutrons, can predict light element abundance ~ 5% into baryons

BBN earliest epoch of which we have data, at T ~ MeV

Most DM candidates are relics from the pre-BBN era, from which we have no data

Key point: $\Omega_b = \rho_b/\rho_c$ counts everything, hence DM cannot be SM particles

What do we know about DM?

Makes up 23% of the universe

Has attractive gravitational interactions (like ordinary matter but is non-baryonic)

Is either stable or has a lifetime $\gg t_U$.

Is not observed to interact with light (weakly coupled, neutral or "milli-charged",

The bulk of the DM must be dissipationless, but part of it could be dissipative

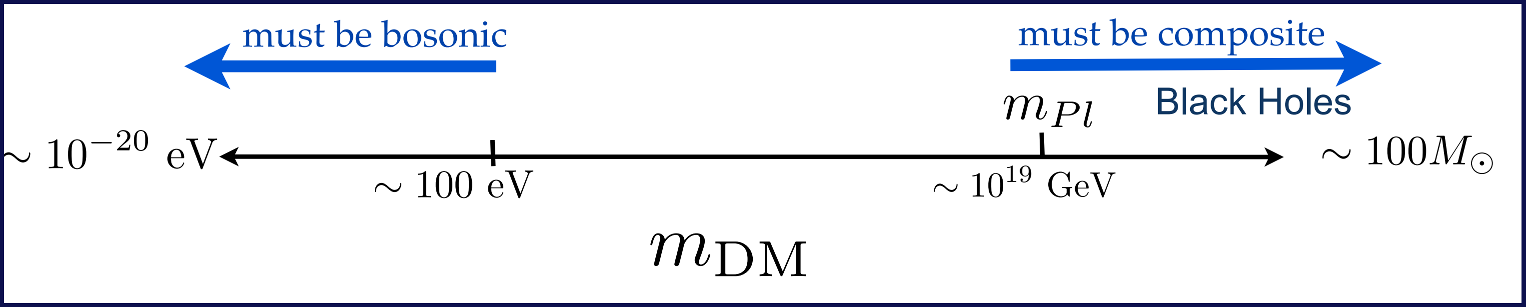
Has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is very large.

Was non-relativistic at time of CMB (Cold or Warm possible to account for all the large scale structure observations, hence New physics BSM needed)

What is it?
Which are its detailed properties?
Does it have Higgs-like interactions?
How to search for it?

Understanding the DM Sector

Particle physics properties constrains the range of possible masses



Folding in assumptions about the evolution of the DM density in the early Universe can motivate more specific mass scales

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?

Thermal Equilibrium:
Easily realized in the early Universe

If interaction rate exceeds Hubble expansion

$$\mathcal{L}_{\rm eff} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu \chi)(\bar{f}\gamma_\mu f)$$

$$H \lesssim n_\chi \sigma v \quad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \lesssim \left.\frac{g^2 T^5}{\Lambda^4}\right|_{T=m_\chi}$$

Equilibrium is easily achieved in the early universe if

$$g \gtrsim 10^{-8} \left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Applies to nearly all models with couplings large enough for detection (rare counter example: QCD axion DM, freeze in DM)

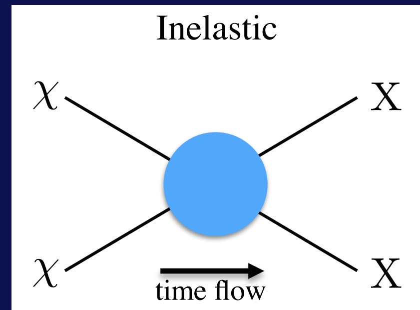
Axions may provide a solution to the strong CP problem and be a CDM candidate

Freeze in: Feebly Interacting Massive Particle (FIMP) interacting so feebly with the thermal bath that it never attains thermal equilibrium (indep. of UV conditions)

Evolution of the Dark Matter Density: Thermal DM

$$\Gamma_{\mathbf{inelastic}} = n_\chi < \sigma v >$$

chemical equilibrium



At sufficiently high Temperature, the interaction
χ χ ⟷ XX is in thermal equilibrium,
DM particles are constantly replenished

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

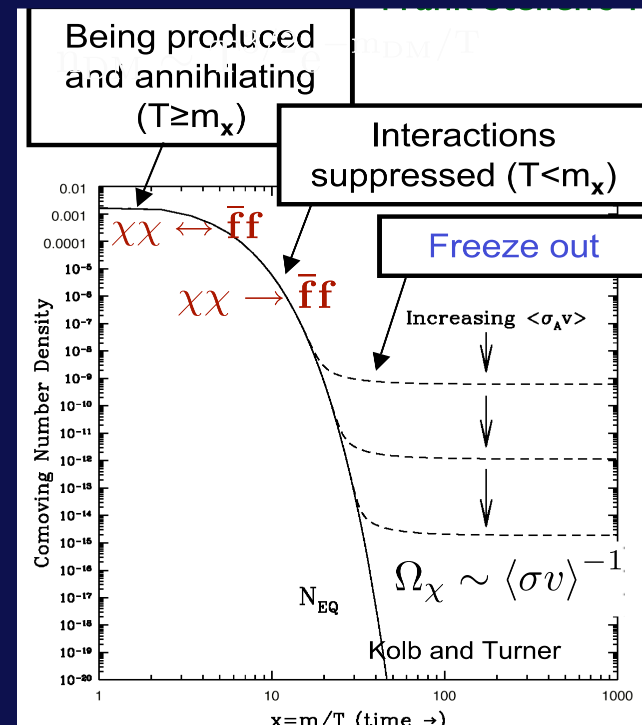
As the Universe expands & temperature decreases
number density decreases
For T< m_{DM} interactions get suppressed (Cold DM)

$$n_{DM} \sim T^{3/2} e^{-m_{DM}/T}$$

Finally forward reaction stops (too hard for DM particles to find each other to annihilate)
DM density frozen in time:

$$\Gamma_{\mathbf{inelastic}} = n_\chi < \sigma v > \sim H$$

(Cold DM)



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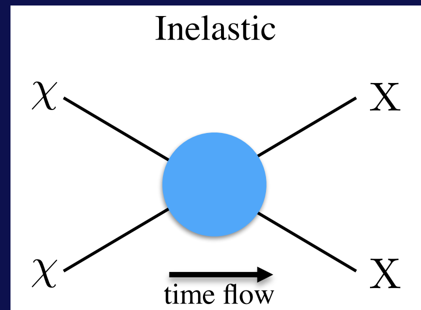
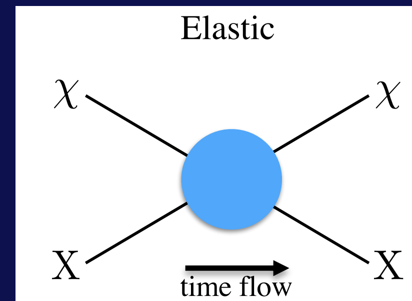




$\Gamma_{\mathbf{elastic}} = n_X < \sigma v >$

kinetic equilibrium

$n_X \sim T^3$

As X are relativistic

Cold Dark Matter is non-relativistic at Freeze out ➔ $n_{DM} \sim T^{3/2} e^{-m_{DM}/T}$

Hot Dark Matter is relativistic at Freeze out -➔ $n_{DM} \sim T^3$

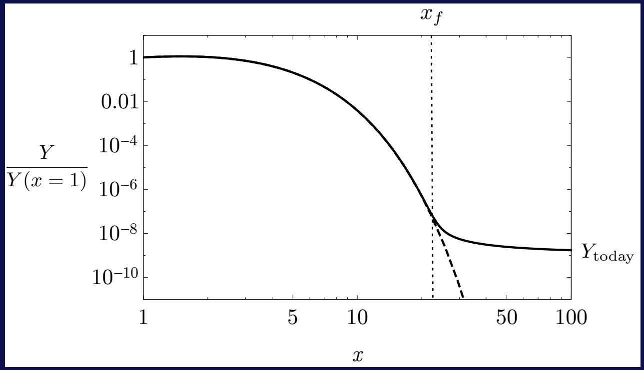
Warm dark matter is in between

After freeze out, DM is no longer in chemical eq., but it remains in thermal eq. with the surrounding plasma via elastic interactions.
After a certain point it decouples and DM is free streaming ($\Gamma_{elastic} < H$)

For Cold (Hot) Dark Matter kinetic decoupling happens only after freeze out (earlier).
Detailed studies of the DM free streaming after decoupling constrain warm DM candidates, that predict less structure on small scales than actually observed.

Cold Dark Matter Preferred

The WIMP Miracle



Taking $x_f \sim 10$ and $\langle \sigma v \rangle \sim \alpha^2/m^2$, the fraction of critical density contributed by the DM today is

$$\Omega \chi h^2 \sim (10^{-26} cm^3/s)/<\sigma v> \simeq 0.1\ (0.01/\alpha)^2\ (m/100\ GeV)^2$$

➔ correct abundance today as measured by Planck and WMAP, for $\alpha \sim 0.01$ and $m \sim 100$ GeV

the "WIMP miracle"

Weak-scale DM naturally gives the correct DM density
Many well-motivated BSM models contain a parity symmetry
SM → SM BSM → - BSM

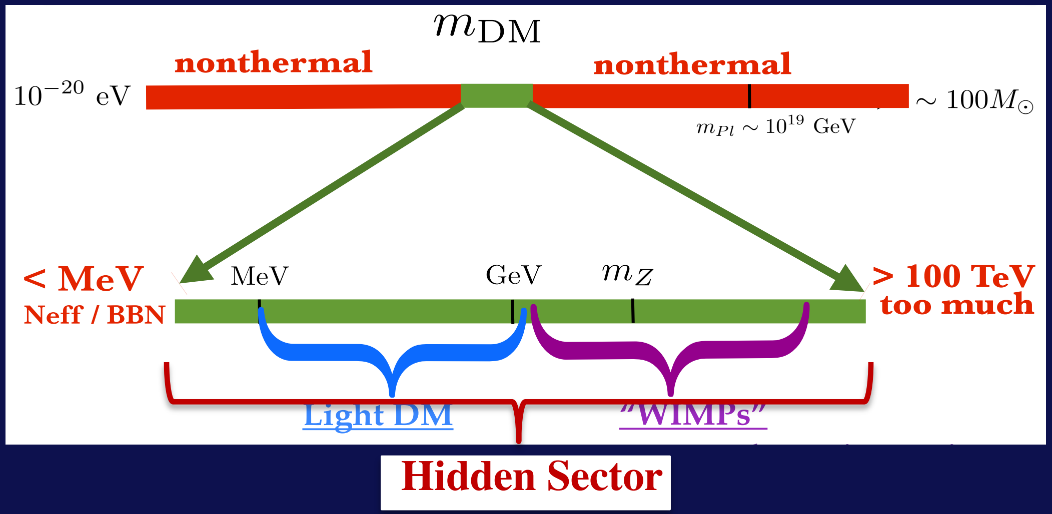
e.g. R-parity in SUSY (proton decay)
T-parity in little Higgs models (precision EW observables)
KK-parity in extra-dimensional models .....

Lightest **P**arity **O**dd **P**article is stable, may be a DM candidate
Always produced in pairs and leaves detector as MET
A wide-ranging of experimental programs targeted for WIMP searches

How much of a miracle are WIMPs?

What is really constrained is the ratio of the squared coupling to the mass.
It is possible to open up a wider band of allowed masses for thermal DM by taking $\alpha \ll 1$ while keeping α^2/m^2 fixed ($\alpha^2\, m^2/M^4$, if heavy mediators)

Thermal Equilibrium:
Narrows viable Mass range

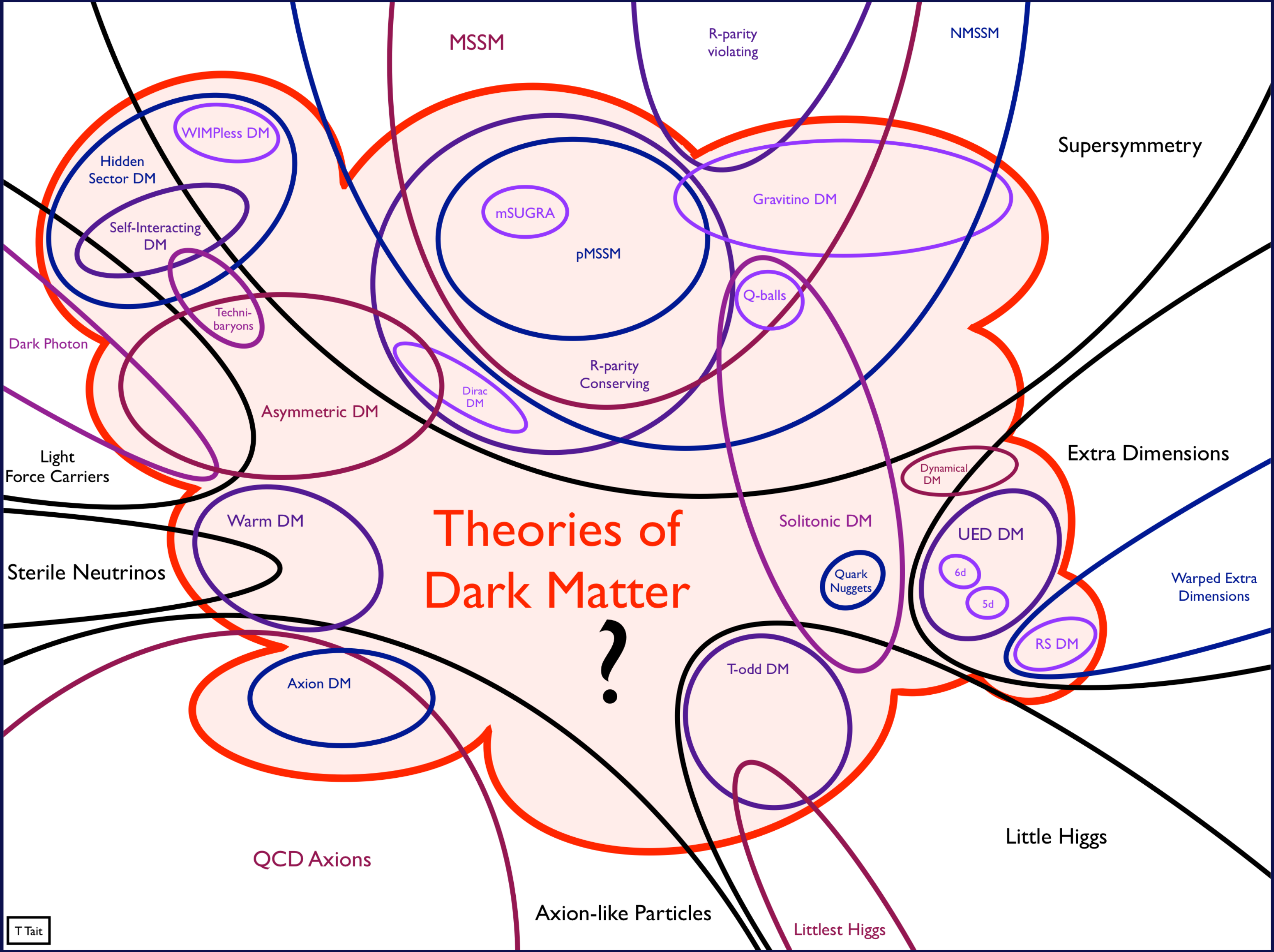


WIMPs: Interact through SM weak forces for masses below ~ 2GeV or higher than several TeV the annihilation cross section is too small, hence overabundance of thermal DM expected

Hidden Sector DM: Particles neutral under SM forces, but charged under new forces not yet discovered. Can have portal interactions with the SM & thermal freeze out or not Mass viable over a wider range than WIMPs including **Light DM down to keV range**

Low mass region Hidden Sector DM pheno is quite different from WIMP pheno

Many BSM models with DM Candidates



Minimal Annihilation Rate for symmetric and asymmetric DM

"Symmetric" DM means the DM is its own antiparticle and its relic abundance is produced by thermal freeze out

"Asymmetric" DM is realized when the DM relic abundance is created by an asymmetry between DM particles and antiparticles, in addition to the possible one induced by thermal freeze out

$$\Omega_\chi \sim \langle \sigma v \rangle^{-1}$$

Symmetric Thermal DM:
Observed density requires →

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

Asymmetric Thermal DM:
Just need to deplete antiparticles

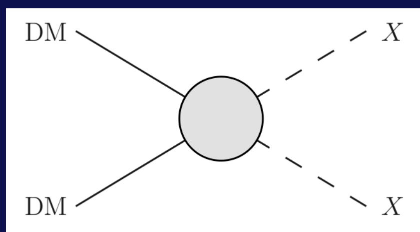
$$\sigma v_{\rm asym} > 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

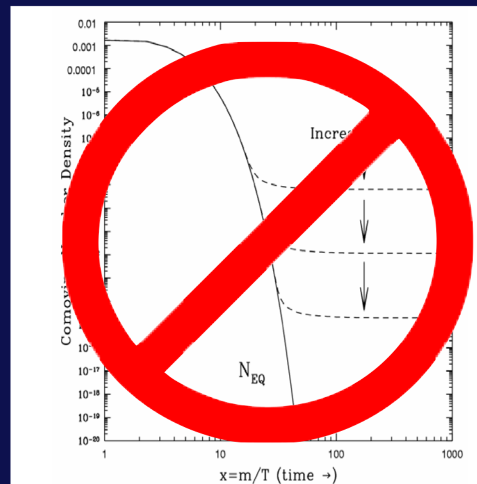
Rate can be bigger, but not smaller

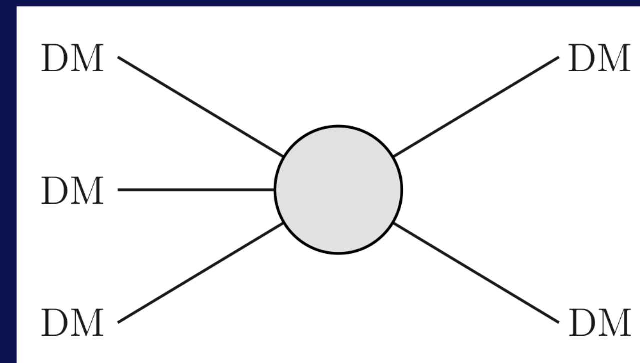
Thus many searches for Symmetric DM also Asymmetric DM scenarios

Hidden Sector DM with other Thermal Histories

Normal CDM



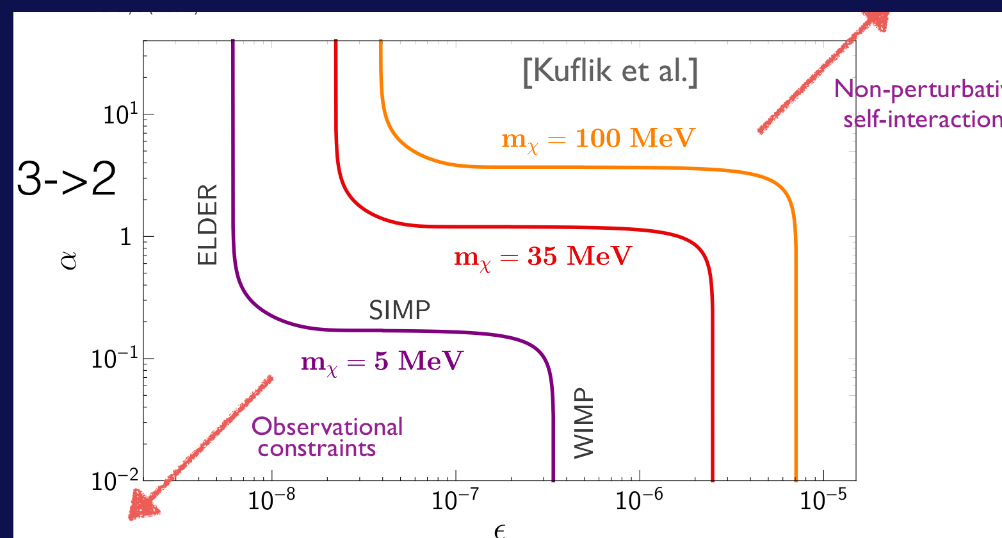




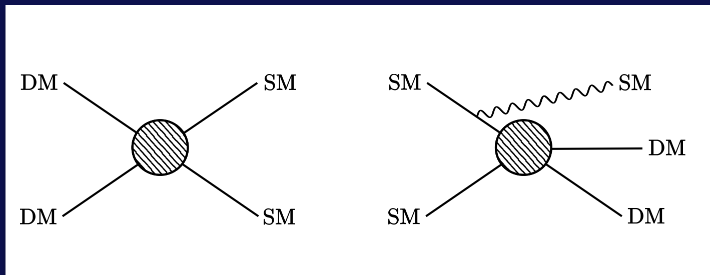
cannibalization

WIMPless-miracle
SIMP-miracle
ELDER, etc
Smoothly connected in parameter space

Relevant role of elastic DM-SM scatter



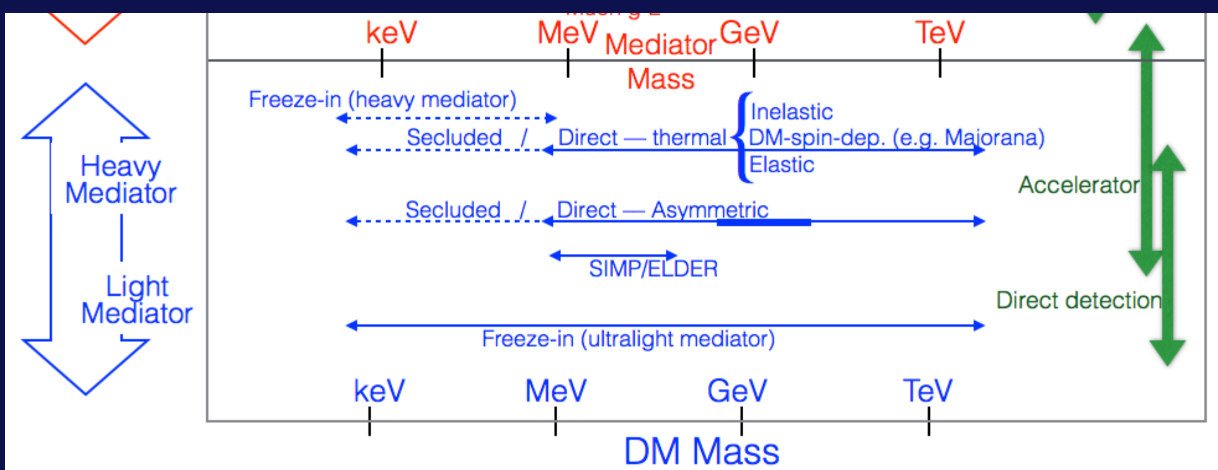
Accelerator Searches Vs Direct Detection



Strong connection between Thermal Freeze out and DM searches at collider/accelerators

Accelerator searches explore the **relativistic** production and/or interactions of DM candidates
Direct detection experiments search for the scattering of DM in the Milky Way halo off matter, with relative velocity ~ $10^{-3}c$

Such big kinematic difference may make DM scenarios accessible to one technique and not at the other techniques.

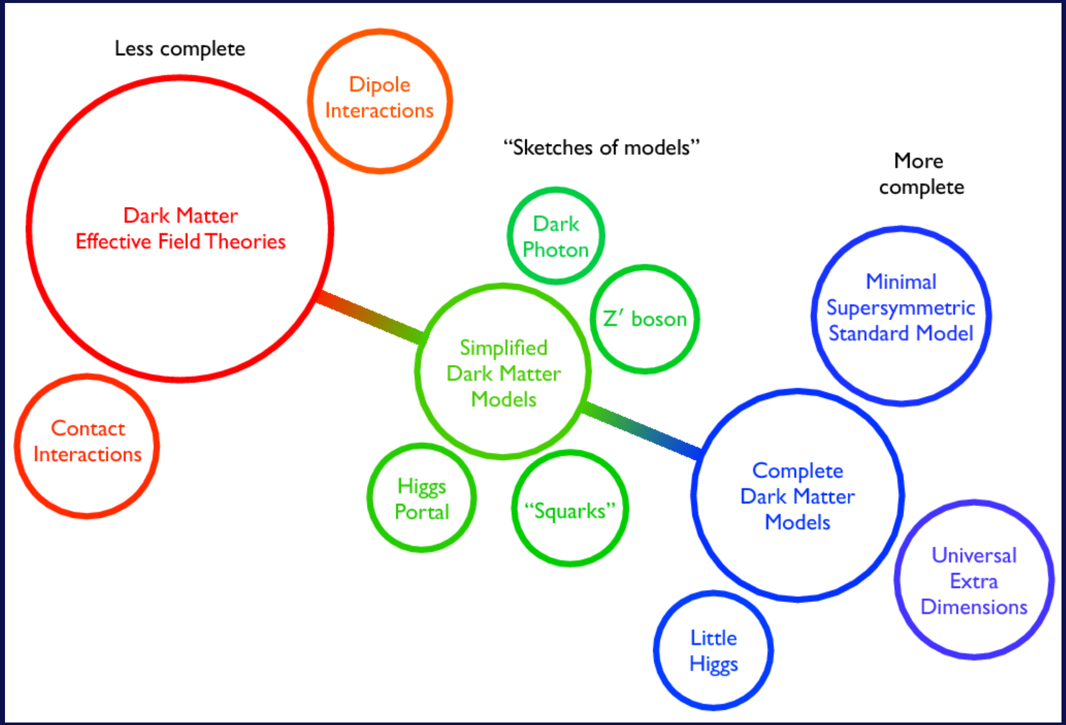


Detection Strategies

Production Mechanisms

DM Theory Space

Needed to relate information
from direct and indirect
detection experiments
with accelerator bounds/searches



- Non–renormalizable interactions → Effective Field Theory (EFT) approach

Each possible interaction characterized by
the DM candidate mass & the operator suppression scale

- Simplified models

(e.g. SM +DM + (a) mediator/s from extended SM or Dark Sector)
More parameters but describe correctly the full kinematics of DM production

- Specific more complete models

Even larger set of parameters, but allows for correlations between observables,

Simplified Models

- Should be simple enough to form a credible unit within a more complicated model
- Should be complete enough to describe accurately the relevant physics phenomena at LHC energies

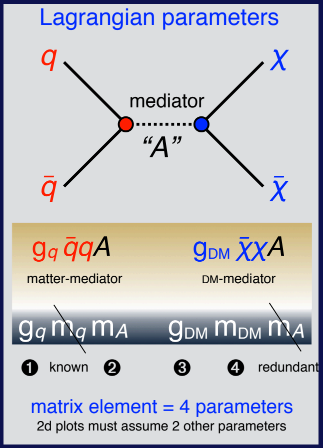
Unlike the DM–EFTs, this describes correctly the full kinematics of DM production at LHC, because they resolve the EFT contact interactions into single-particle s(t)-channel exchanges.

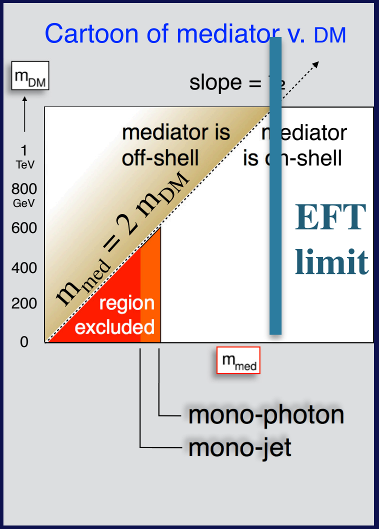
Consider only renormalizable interactions
that should not violate the exact and approximate accidental global symmetries of the SM

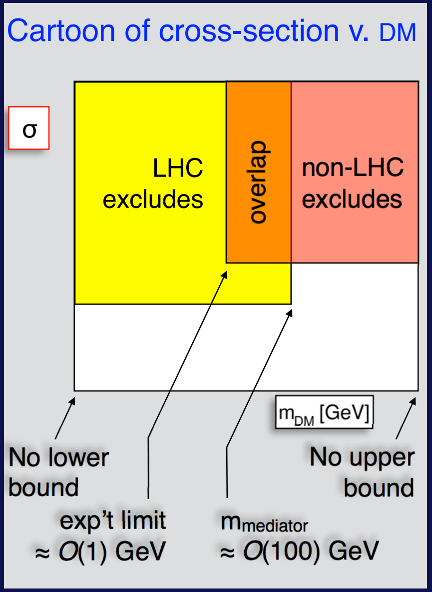
Models designed to involve few new particles & interactions.

Understood as the limit of more general scenarios, with all but the lightest dark-sector states integrated out.

Physics characterized by a small number of parameters (particle masses & couplings)







Model Building: s- Channel Mediators

❖ **Scalar mediators:** Add a scalar gauge singlet with interactions with singlet DM : Dirac or Majorana fermion or a scalar.

$$\mathcal{L}_{\text{fermion},\phi} \supset -g_\chi \phi \bar{\chi} \chi - \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right),$$

$$\mathcal{L}_{\text{fermion},a} \supset -i g_\chi a \bar{\chi} \gamma_5 \chi - \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right).$$

Scalar couples directly to SM fermions or there will be a scalar potential coupling it to the Higgs.

Minimal case, with MFV and gu = gd = gl, is only a 4 param. model **mχ, mϕ/a, gχ, gu,**

❖ **Higgs portals to DM**

1) ***Direct Higgs portal:*** *DM scalar singlet* under the SM couples through a quartic interaction with the Higgs

$$\mathcal{L}_{\text{scalar},H} \supset -\lambda_\chi \chi^4 - \lambda_p \chi^2 |H|^2$$

2) ***Higgs portal through S:*** *DM fermion singlet* under the SM couples to a scalar boson which itself mixes with the Higgs

$$\mathcal{L}_{\text{fermion},H} \supset -\mu_s s^3 - \lambda_s s^4 - y_\chi \bar{\chi} \chi s - \mu_p s |H|^2 - \lambda_p s^2 |H|^2,$$

3) ***Singlet-doublet DM*** couples to Higgs doublets and singlets (as in the MSSM where it is a bino/higgsino mixture or in the NMSSM where it can be bino-higgsino or singlino-higgsino)

Model Building: s- Channel Mediators

❖ Vector s-channel mediators (spin-1 mediators)

Add new mediator to SM, by extending its gauge symmetry by a new U(1)′ spontaneously broken such that the mediator gets a mass M_V

$$\mathcal{L}_{\text{fermion},V} \supset V_\mu \, \bar{\chi}\gamma^\mu (g_\chi^V - g_\chi^A \gamma_5)\chi + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu (g_f^V - g_f^A \gamma_5) f \,,$$

$$\mathcal{L}_{\text{scalar},V} \supset i g_\varphi V_\mu (\varphi^* \partial^\mu \varphi - \varphi \partial^\mu \varphi^*) + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu (g_f^V - g_f^A \gamma_5) f \,,$$

[For Majorana DM, the vector coupling g_χ^V vanishes, while a real scalar cannot have any CP-conserving interactions with V]

Simplified models either purely vector or axial vector mediators: $m_\chi, M_V, g_\chi, gu^{V/A}, gd^{V/A}, gl^{V/A}$

Details of the new U(1)'

Dark Higgs sector: additional Higgs field Φ with non-zero vev gives mass to mediator mixes with SM Higgs; mass of Dark Higgs close to MV (LHC pheno)

Mediator Mixing with SM gauge bosons

Loops of Fermions (charged under the SM and new U(1)′ ➔ $\mathcal{L}_{\text{kinetic}} \supset \frac{\epsilon}{2} F'^{\mu\nu} B_{\mu\nu}$

Mediators decay back in SM particles and could show up in di-jets and di-lepton searches, unless quark-mediator couplings were too small. Di-leptons are tightly constrained by LHC.

Model Building: T- Channel Flavored Mediators

- For fermionic DM, the mediator can be a colored scalar or a vector particle Φ.
  scalar case = squarks in SUSY (easy UV completion)

Given the interaction: Φχq, either Φ or χ need to carry color charge to be in a MFV case

$$\mathcal{L}_{\text{fermion},\tilde{u}} \supset \sum_{i=1,2,3} g\phi_i^* \bar{\chi} P_R u_i + \text{h.c.}$$

$$\phi_i = \{\tilde{u}, \tilde{c}, \tilde{t}\}$$

MFV requires both equal masses $M_{1,2,3}$ of the mediators, and universal couplings $g=g_{1,2,3}$ between the mediators and their corresponding quarks u_i= {u,c,t}.
T
his universality can be broken by allowing for corrections that split the mass of the third mediator (govern by the large top Yukawa coupling) from the other.

The generic parameter space is $m_\chi, M_{1,2}, M_3, g_{1,2}, g_3$

These simplified models are very similar to SUSY and studies consider independently cases with light squarks or stops/sbottoms (3 param, space)

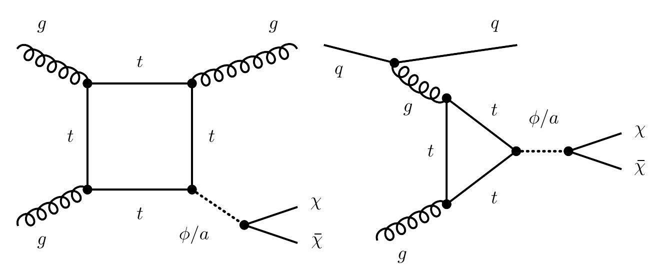
Mono-object searches for DM

The targeted interaction is pp→ χχ+X,

- **Scalar and Pseudoscalar mediator, s-channel**

Monojet search

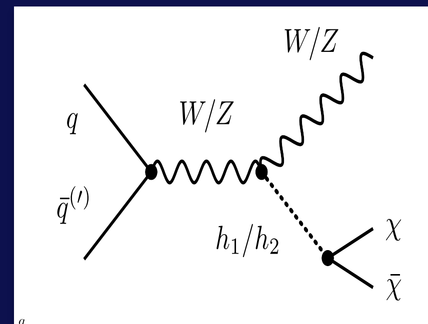
mχ,mϕ/a, gχ, gu,



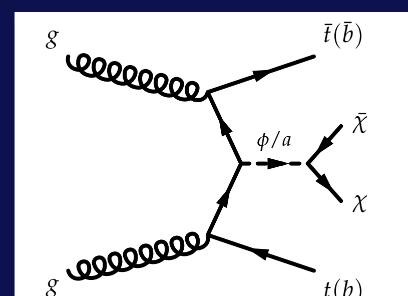
$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}}\sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i\right) .$$

$$\mathcal{L}_a = i g_\chi a \bar{\chi}\gamma_5\chi + \frac{ia}{\sqrt{2}}\sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i\right) .$$

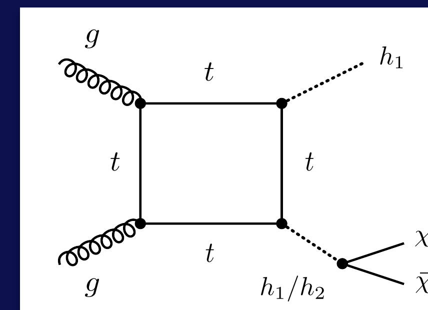
Mono-V search

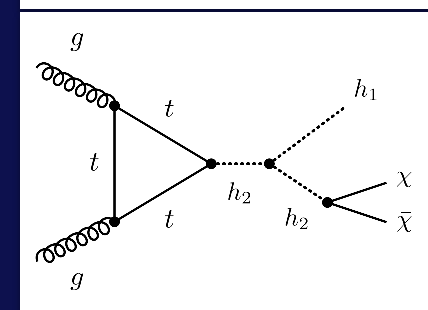


Top (bottom) pair search



Mono-Higgs search





Sensitivity of mono-boson searches (W,Z,H) to this model is low, UNLESS we consider the effects of the Higgs portal (upper middle diagram or right diagrams).

With the MFV assumption, however, the top and bottom quarks can play an important role in the phenomenology.

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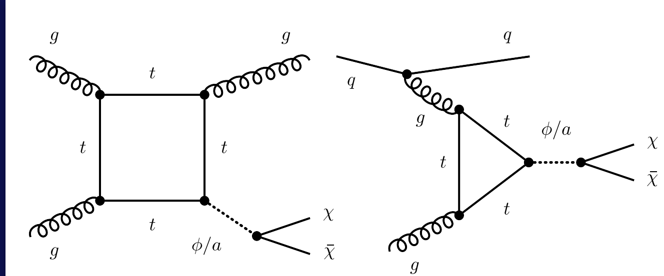
Monojet search

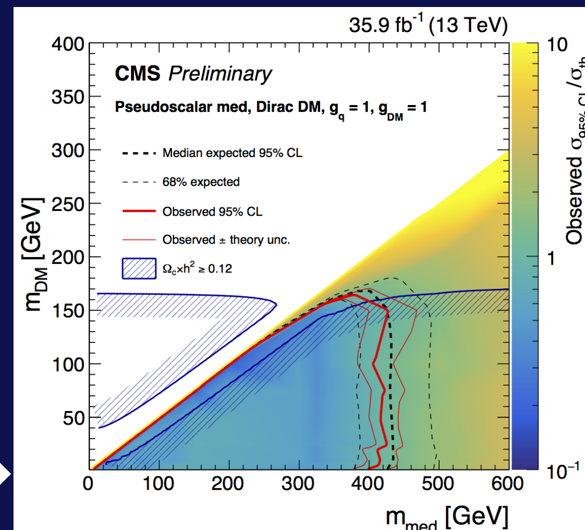
mχ,mϕ/a, gχ, gu,



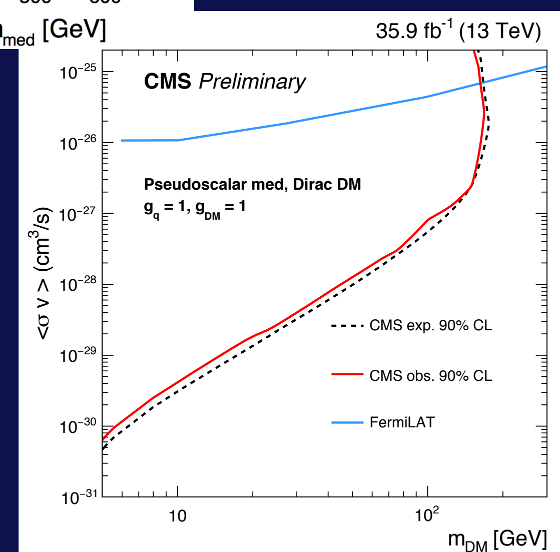
$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) .$$

$$\mathcal{L}_a = i g_\chi a \bar{\chi} \gamma_5 \chi + \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right) .$$

→



Mono-jet/s Searches at the LHC



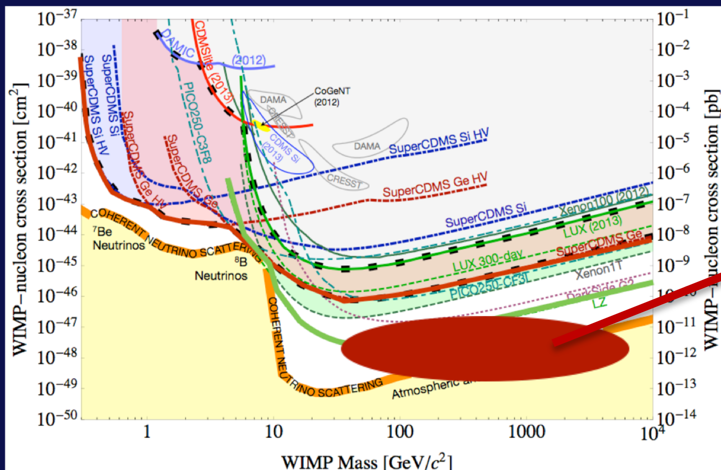
Also interesting mono-jet/s searches for vector and axial- vector mediator, s-channel, and colored scalar mediator in t-channel (SUSY-like models)

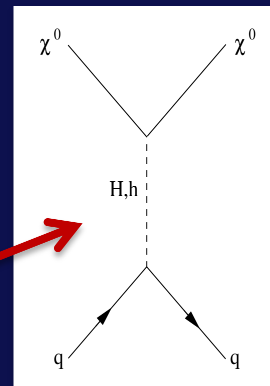
As well as other mono-objects DM searches

AND direct Searches for the DM Mediators

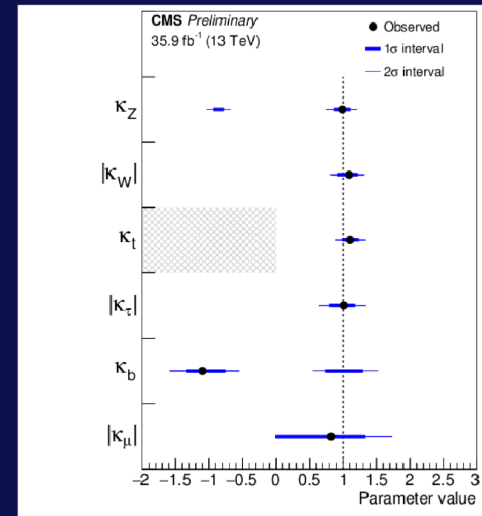
Dark Matter Direct Detection

Starting to probe the Higgs portal





LHC Run 2 Results



Data on SM-like Higgs signals ➔Alignment

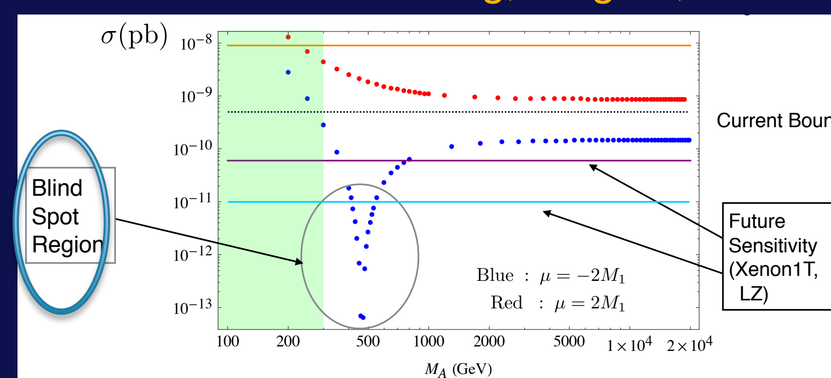
Close to Alignment (MSSM)

$$\sigma_p^{SI} \sim \left[(F_d^{(p)} + F_u^{(p)})(m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta(-F_d^{(p)} + F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2} \right]^2$$

$$2\,(m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} \simeq -\,\mu \tan\beta \frac{1}{m_H^2}$$

Destructive interference between h and H contributions for negative values of μ (cos2β negative)

Huang, Wagner, '15



Still room for a SUSY WIMP miracle

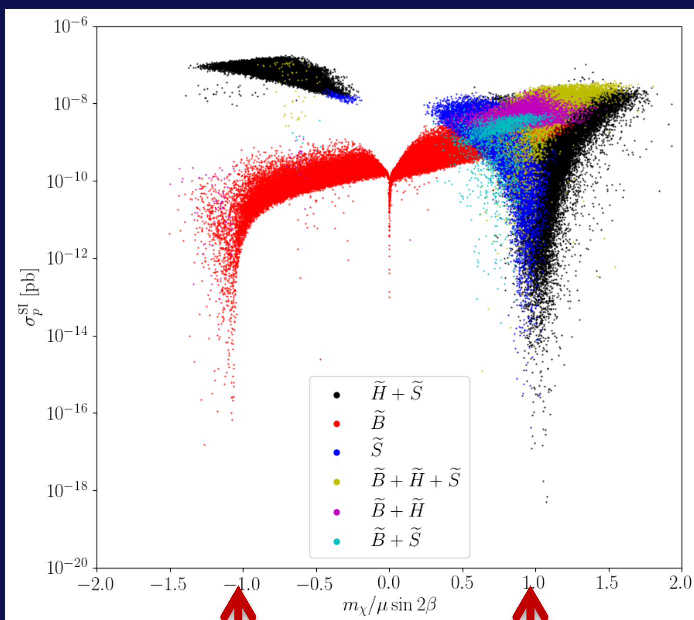
Blind Spots in Direct DM detection in the NMSSM

Possible to have a three way cancellation between the hs, h and H contributions

$$\sigma_{SI} \propto \left\{ \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) \frac{2\,t_\beta}{m_h^2} + \frac{t_\beta}{m_H^2} + \frac{1}{m_{h_S}^2} \left(2\,S_{h,s} + \frac{\lambda\, v}{\mu} \right) \left[\frac{\lambda\, v}{\mu^2}\, m_\chi + S_{h,s} \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) + \frac{\kappa\, \mu}{\lambda^2\, v} \right] \right\}^2 .$$

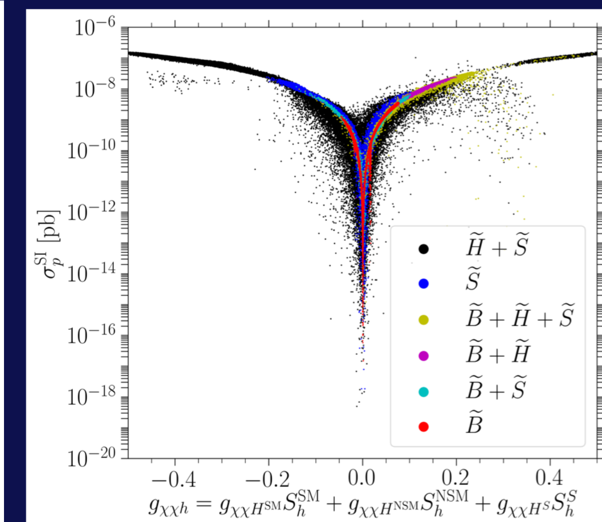
$$S_{h,s} \approx \frac{-2\lambda v \mu \epsilon}{(m_h^2 - m_{h_S}^2)}$$

Cheung, Papucci, Sanford, Shah, Zurek '14



μ < 0

μ > 0



Higgs Mixing Effects:
Couplings to the 125 GeV Higgs tend to be suppressed close to the blind spots. However, they remain relevant in the singlino region, denoting the presence of relevant interferences

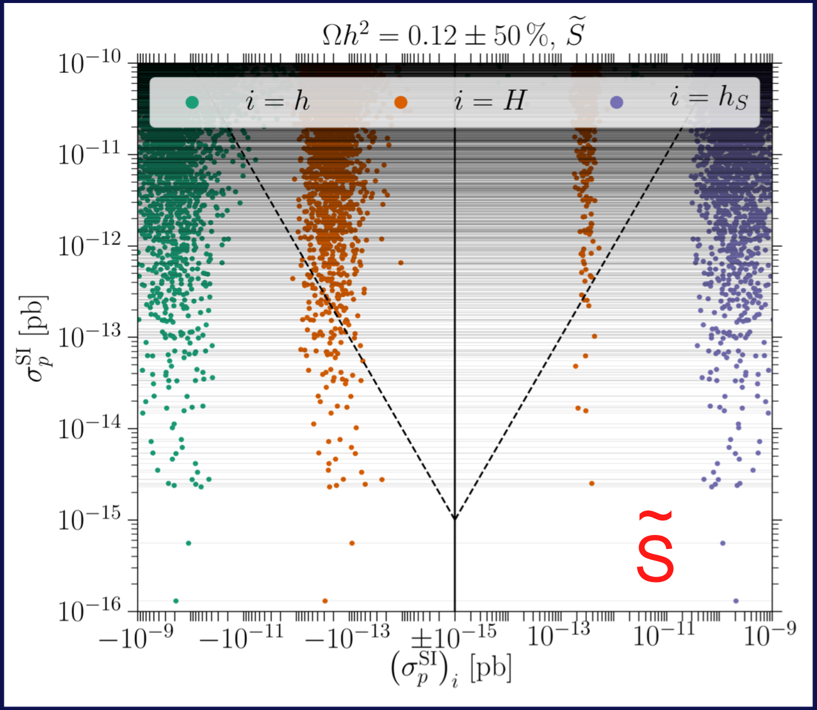
A SM-like Higgs would have couplings that vanish when $m_\chi = \pm\mu \sin(2\beta)$. The plus and minus signs correspond to the cases in which the neutralino is Bino-Higgsino or Singlino-Higgsino admixtures.

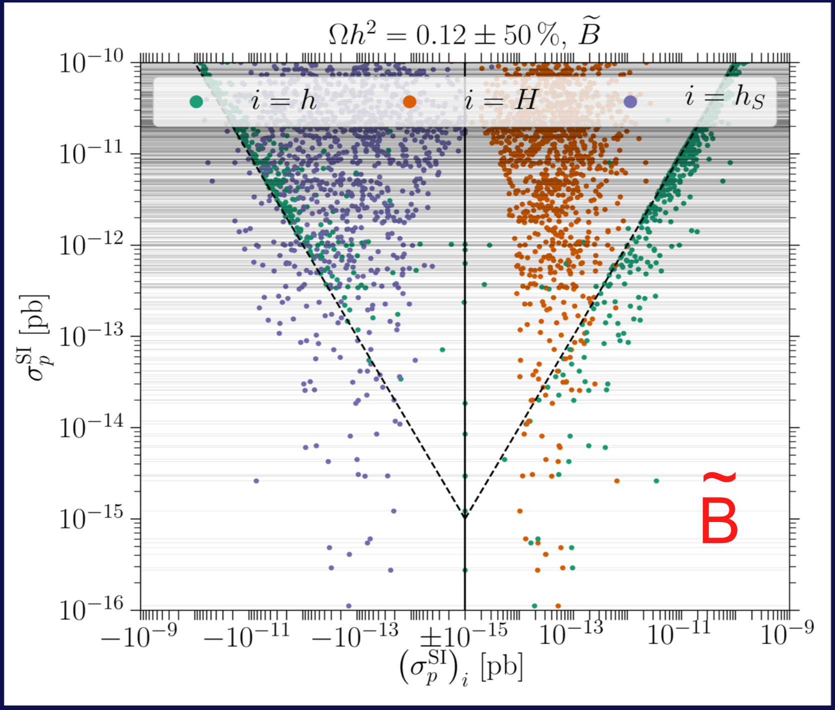
Baum, M.C. Shah, Wagner '18

NMSSM opens up new possibilities

Contributions to SI XS of the different (scalar) Higgs bosons

and sign of the different scalar contributions to the SI cross section.





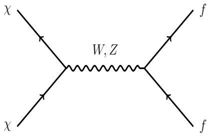
Mostly singlinos: coupling to Higgs larger than for Bino ➔ SM-like Higgs coupling close to blind spot and destructive interference with singlet and non-SM CP even doublet needed
Thermal Relic can be obtained via Z (G) annih.

Mostly Binos: SM-like Higgs provides the dominant contribution.
NEW Bino well-tempered region, with small couplings to Higgs and proximity to blind spot
Thermal Relic density via resonant Z, Higgs annih, or co-annihilation of bino with singlino

Light Dark Matter *< GeV model Building*

DM must be a SM singlet
(else would have been discovered (LEP...)

Freeze out needs new forces
DM overproduced if no light new "mediators"



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

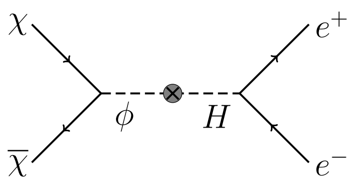
Lee/Weinberg '79

observables signatures of Hidden Sector Light DM will depend on the type of force between DM & SM matter, and the nature of the DM coupling to that force

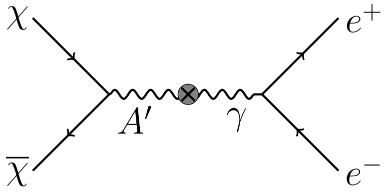
Unique renormalizable int. of an SM-neutral boson compatible with all SM symmetries

$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu}F'^{\mu\nu} & \text{vector portal} \quad \Rightarrow \quad g_f^V \approx \epsilon e q_f \\ (\mu\phi + \lambda\phi^2)H^\dagger H & \text{Higgs portal} \quad \Rightarrow \quad g_f^S = \mu m_f/m_h^2 \end{cases}$$

ε small enough to have escaped detection, still right relic DM density



$\epsilon\,\phi H^\dagger H$



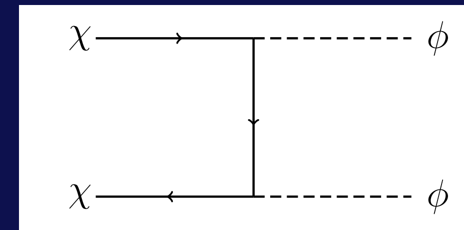
$\epsilon F'_{\mu\nu}F^{\mu\nu}$

New scalar mediator mixing w/ Higgs

New vector mediator A'mixing w/ photon

Who's Heavier? The DM or the Mediator?

"Secluded" Annihilation: $m_\chi > m_\varphi$



No info on mediator-SM coupling
➔No target@Accelerators
Mediator decays to SM, not to DM

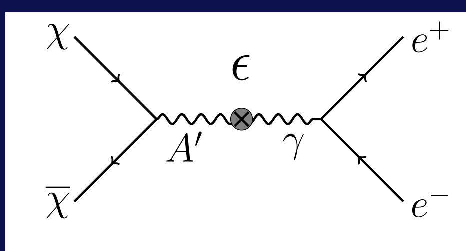
$\langle\sigma v\rangle \propto g_{DM}^4 / m_\chi^2$

- Scalar Mediator → annihilation rate v^2 suppressed, ok if g_{DM} right relic
- Vector Mediator → annihilation rate unsuppressed : excluded by CMB power spectrum

$p_{ann} = f_{\text{eff}} \langle\sigma v\rangle_{T\sim \text{eV}} / m_{DM} < 3.5 \times 10^{-11}\,\text{GeV}^{-3}$ ➔ $\langle\sigma v\rangle_{cmb}/m_\chi <\sim 3\times10^{-28}\,\text{cm}^3\text{s}^{-1}\text{GeV}^{-1}$

Direct Annihilation: $m_\chi < m_\varphi$

$\langle\sigma v\rangle \propto g_{DM}^2\, g_{SM}^2\, m_\chi^2/m_{MED}^4$



- **Planck CMB power spectrum ➔** ok for DM scalar or Majorana fermion via a vector mediator

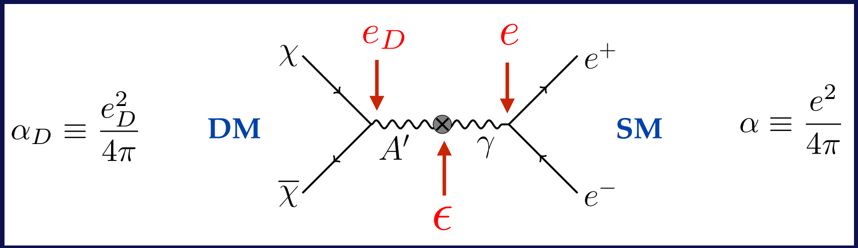
(scalar mediator excluded by meson decay constraints)

S-channel annihilation into SM particles ➔ Minimum SM coupling

g_{DM} & $m_\chi/m_{A'}$ at most O(1) ➔ min g_{SM} compatible with Ω_χ

Predictive, falsifiable target@ accelerators

Representative Model: Dark QED

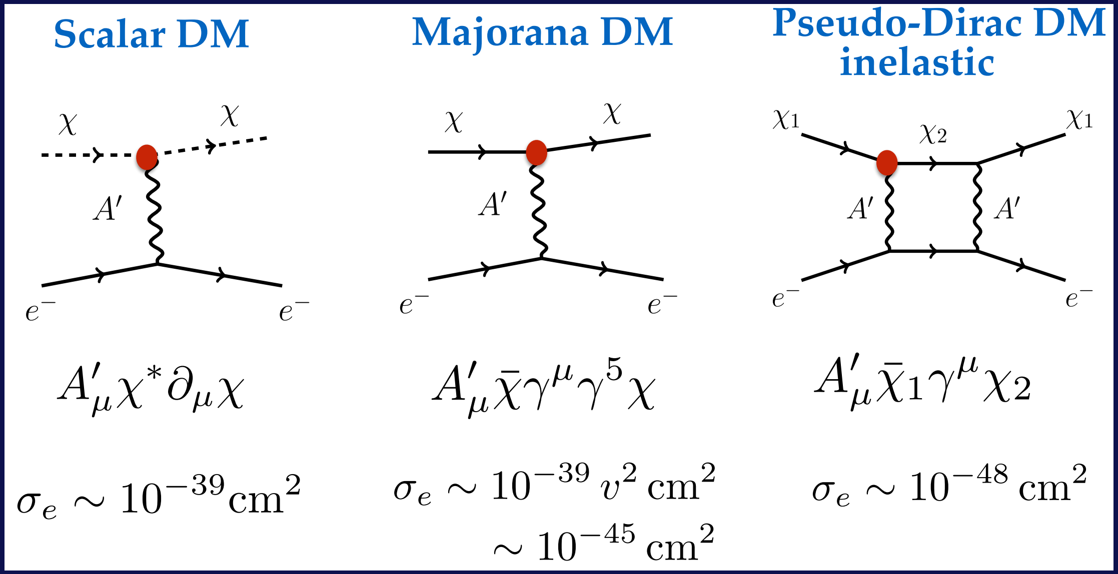


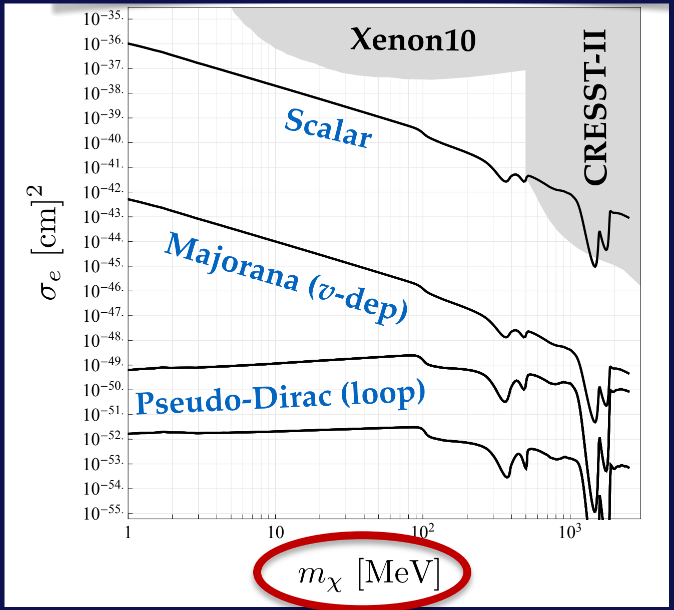
DM charged under new force: $e_D \sim e$

Allowed small A'-photon mixing: $\varepsilon \ll 1$

SM acquires small charge under A' : $e\varepsilon$

Viable models by Direct Detection Scattering





Each ● interaction can realize thermal annihilation at T ~ M

Light Dark Matter Searches at Accelerators

Accelerators offer key advantages in the search of MeV-GeV thermal DM

Overcome kinetic thresholds, search for mediators, …

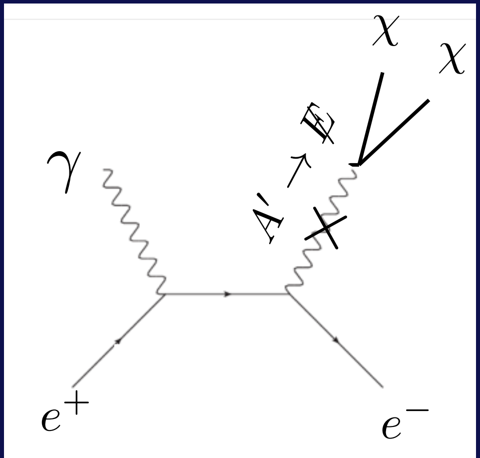
- Mono-photon + MET at Lepton colliders analogous to LHC searches
- Electron and Proton Beam Dump Experiments
- Missing Energy/momentum at fixed target experiments

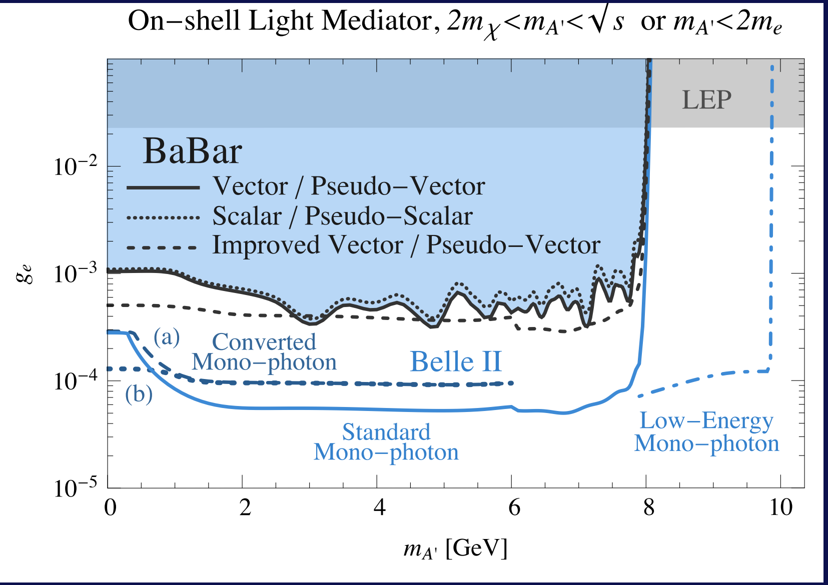
Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam
Future US initiatives							
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$	
Future international initiatives							
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020
Current and completed initiatives							
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done

Signatures @ B-Factories

mono photon + missing energy

e+e- → γ (A'→χχ)



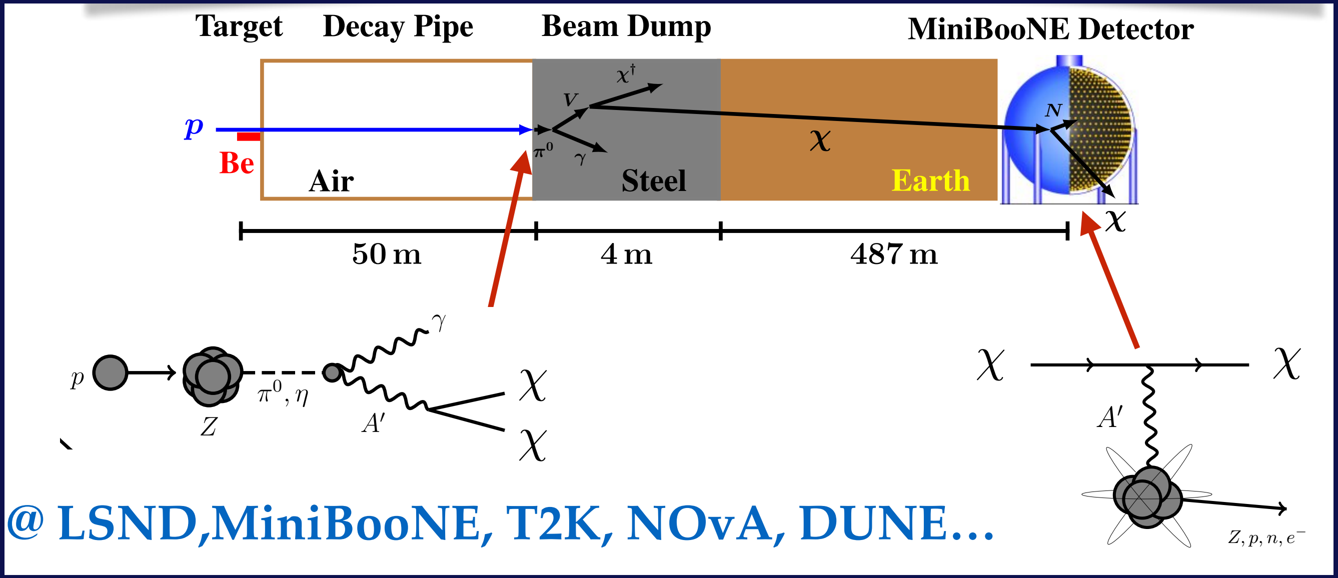


- Identified as a narrow resonance over a smooth background.
- Requires a well-known initial state & reconstruction of all particles besides the DM.
- A large background usually arises from reactions in which particle(s) escape undetected → detectors with good hermeticity required.

Can explore/test Scalar, Majorana, & pseudo-Dirac DM

Signatures @ Proton Beam Dumps

DM is produced pZ → pZ(A' → χχ) or, if kinematically allowed in $\pi^0/\eta' \to \gamma(A' \to \chi\chi)$



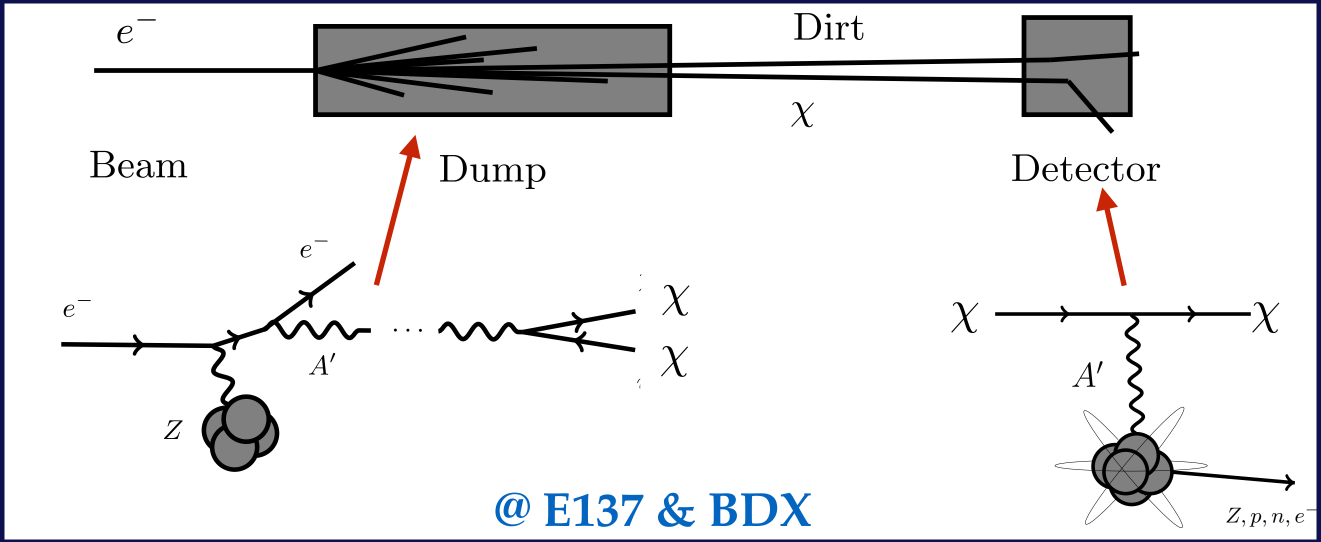
Typically detected via eχ→eχ or Nχ → Nχ scattering in a downstream detector.

- Advantage: probes DM interaction twice, providing sensitivity to DM-mediator coupling
- Requires a large proton flux to compensate for the reduced yields.
- Signature similar to that of neutrino interactions → limiting factor on sensitivity.

Can explore/test Scalar, Majorana DM

Signatures @ Electron Beam Dumps

DM is produced $e^- \mathbf{Z} \rightarrow e^- \mathbf{Z}(A' \rightarrow \chi\chi)$



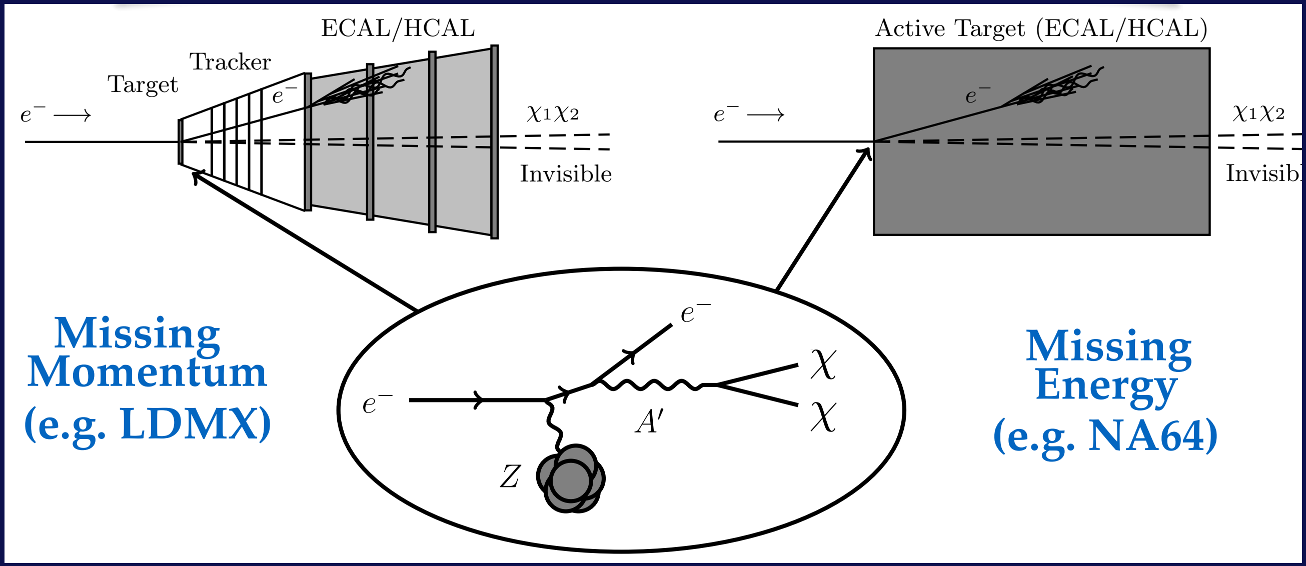
Typically detected via $e\chi \rightarrow e\chi$ or $N\chi \rightarrow N\chi$ scattering in a downstream detector.

- Advantage: probes DM interaction twice, providing sensitivity to DM-mediator coupling
- Requires a large proton flux to compensate for the reduced yields.
- Signature similar to that of neutrino interactions ➔ limiting factor on sensitivity.

Can explore/test Scalar, Majorana DM

Signatures @ Fixed Target Experiments

Missing Energy and Missing Momentum



Observe recoiling electron and compared it to the energy of the beam

If $E_R << E_B$ ➔ missing energy/momentum carried away by the escaping particles

- Critical relevance of the detector hermeticity to achieve excellent background rejection . May be important to measure the incoming electrons individually.
- Better signal yield than beam dump experiments for similar luminosity, as the DM particles are not required to scatter in the detector.

Comparing Experiments

- Define new variable to optimize thermal targets

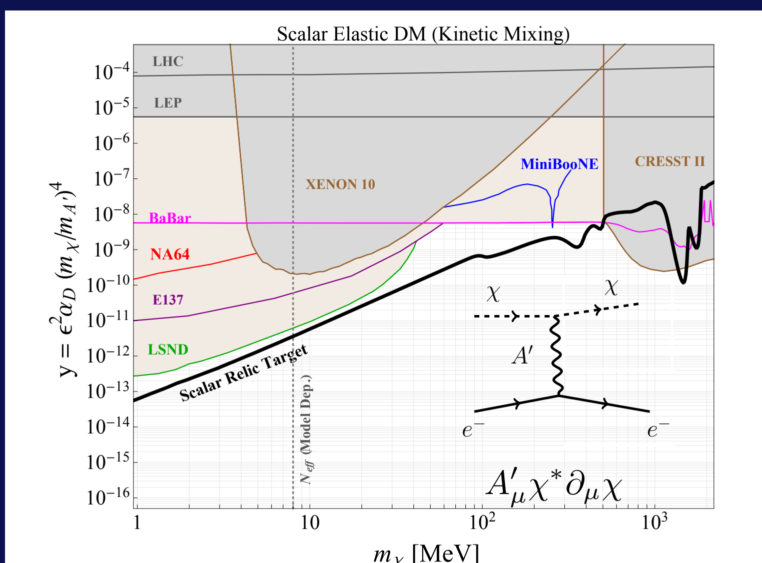
$$\sigma v \propto \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} = \left[\alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4\right] \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

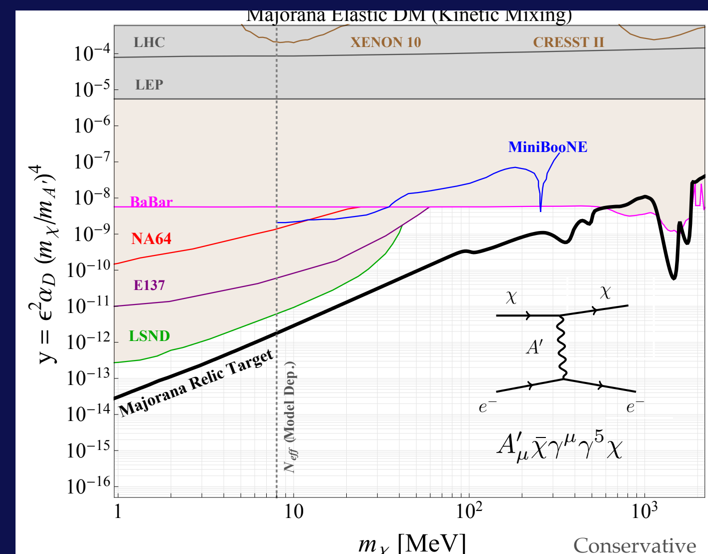
Insensitive to ratios of inputs, unique "y" for given mass (up to subleading corrections)

- Direct detection Experiment

$$\sigma^{dd}_{DM-p} \propto \left(g_q \, g_{DM} \frac{m_{DM-p}}{m^2_{med}}\right)^2$$

→ $\sigma^{dd} \propto y / m_\chi^4$





Conservative

$$\alpha_D = 0.5 \; , \; m_{A'} = 3 m_\chi$$

Next gen DD & accelerator exp. will crush this

Conclusions

Dark Matter exists but we have no clue what it is made off

Lack of Particle Physics evidence yielded to vast development in model building in the past decade, beyond WIMPs (still alive) and Axions.

Idea of existence of whole new Dark Sectors, with little or no connection to ours is in fashion

Numerous innovative experiments, pushing technology, are being developed

Possible connection of Dark Matter with the Higgs boson/s is intriguing and under scrutiny at experiments