Particle Dark Matter Below a GeV: Models and Opportunities

Natalia Toro (SLAC & Stanford)

A Rainbow of Dark Sectors
Mar 25, 2021

Outline

- ✦ Hidden sector picture for sub-GeV dark matter
  - – A bottom-up taxonomy
- ✦ Following the trail of DM abundance
  - – Thermal freeze-out
    - ‣ Powerful hints from CMB constraints
    - ‣ Predictive models as key milestones for experiment, and how to find them
    - ‣ Some more open-ended scenarios
  - – ~~Freeze-in if time permits~~ (but see K. Schutz talk)

sub-GeV DM ⇝ Hidden sector

i.e. matter neutral under SM, with new interactions

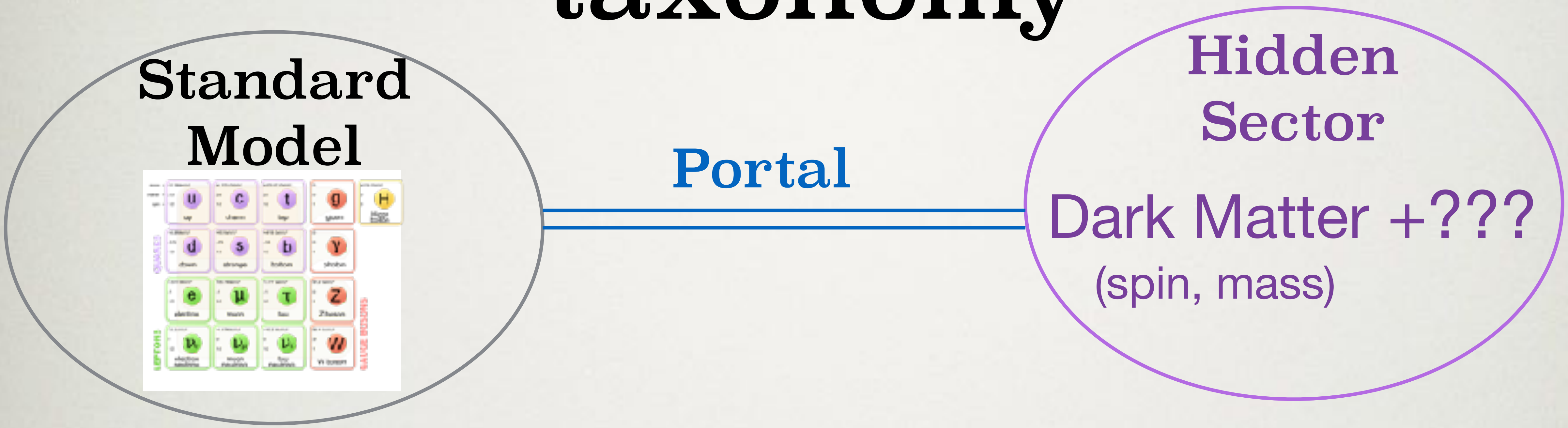
- ✦ Light SM-charged particles* excluded by collider searches → must be neutral

* Very small electric charges – which we'll come back to – are "exception that proves the rule"

- ✦ DM must have some interactions…
  - – If we want to see it
  - – Some non-gravitational interaction **typically required to explain origin of DM** [exception – see N. Bernal's talk]

Precedent in nuclear structure & hadron spectrum –
*Puzzles about structure of **matter** led to prediction of **new forces** & related symmetries up to 40 years ahead of their time*

Towards hidden sector taxonomy



The **portal** couplings connecting SM to the dark sector are strongly constrained by Lorentz invariance, SM symmetries. This makes them a useful basis for classification.

The Portals

Interactions with **dimensionless** couplings dominate at low energy

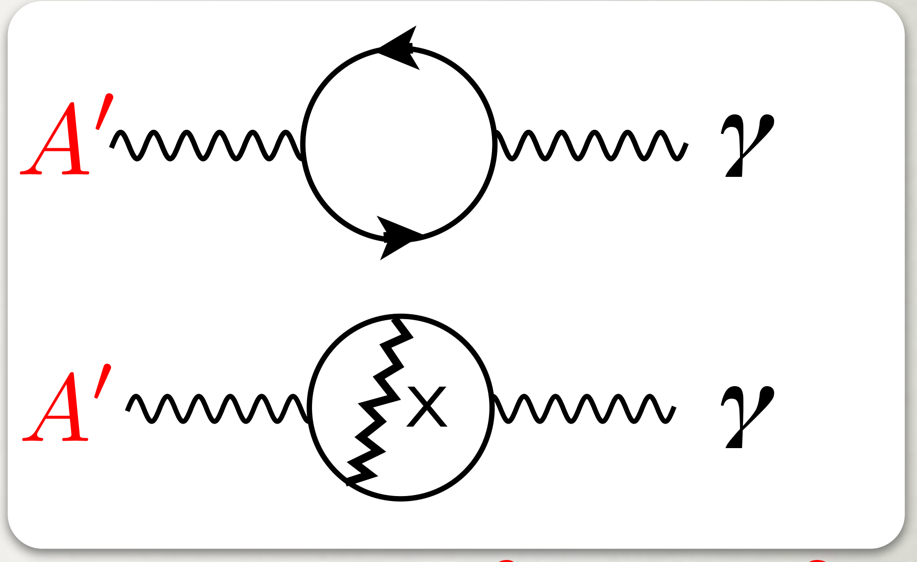
Vector Portal	$\frac{1}{2}\epsilon_Y\, F^Y_{\mu\nu} F'^{\mu\nu}$
Higgs portal[1]	$\epsilon_h\, \lvert h\rvert^2 \lvert\phi\rvert^2$
Higgs portal[singlet]	$A_h \lvert h\rvert^2 \phi$
Neutrino Portal	$\epsilon_\nu\, (hL)\psi$
Conserved currents	$\epsilon_V\, \bar{f}\gamma^\mu q_f f V_\mu$

Great working example: Compatible with cosmology in simple models, illustrative – focus here for most of my talk

How weakly Coupled?

Small couplings are **generic** if portal interactions generated radiatively

- Some portal interactions are further suppressed by small Yukawas

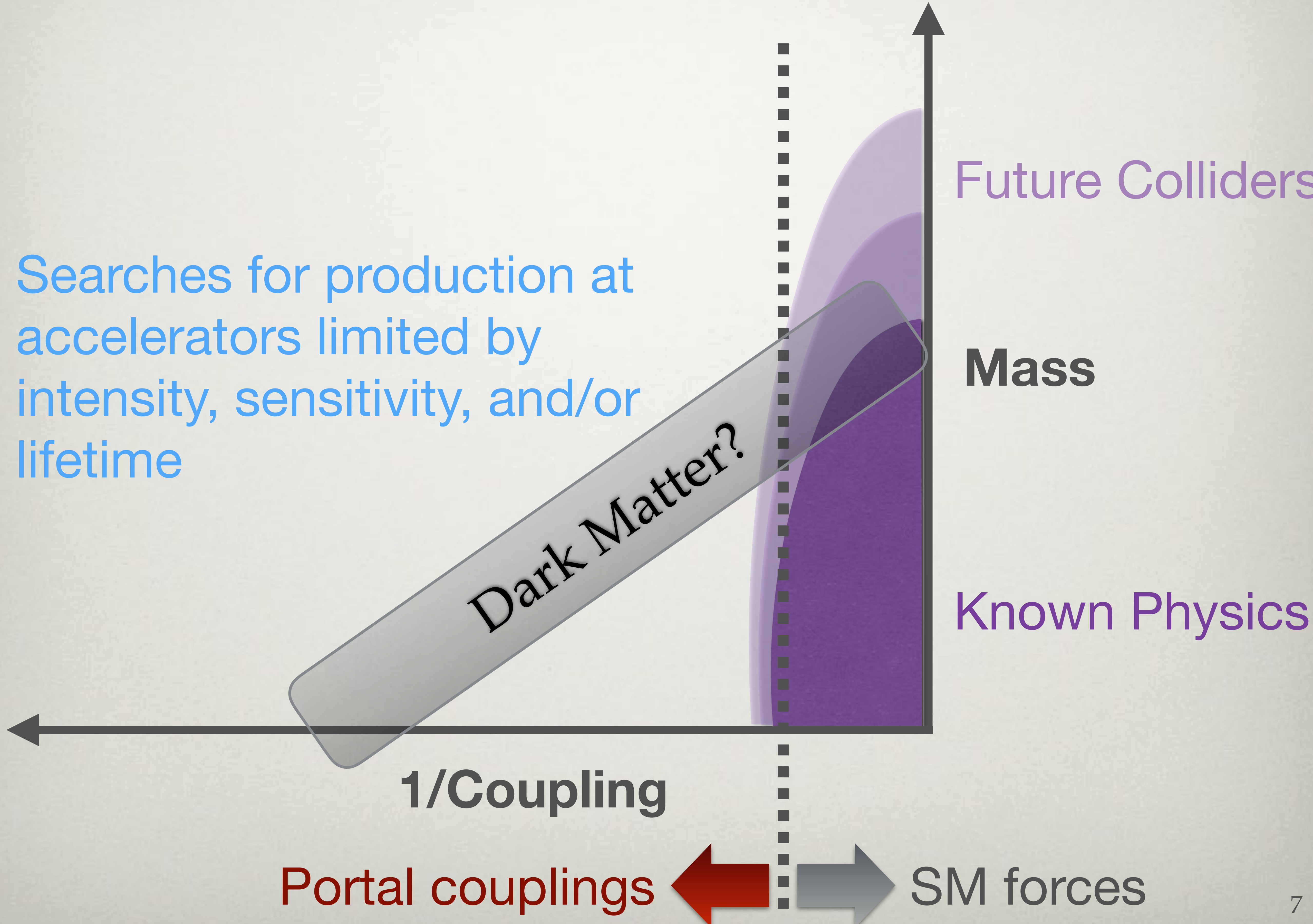


$g_{\mathrm{SM}} \sim (10^{-6} - 10^{-2})e$

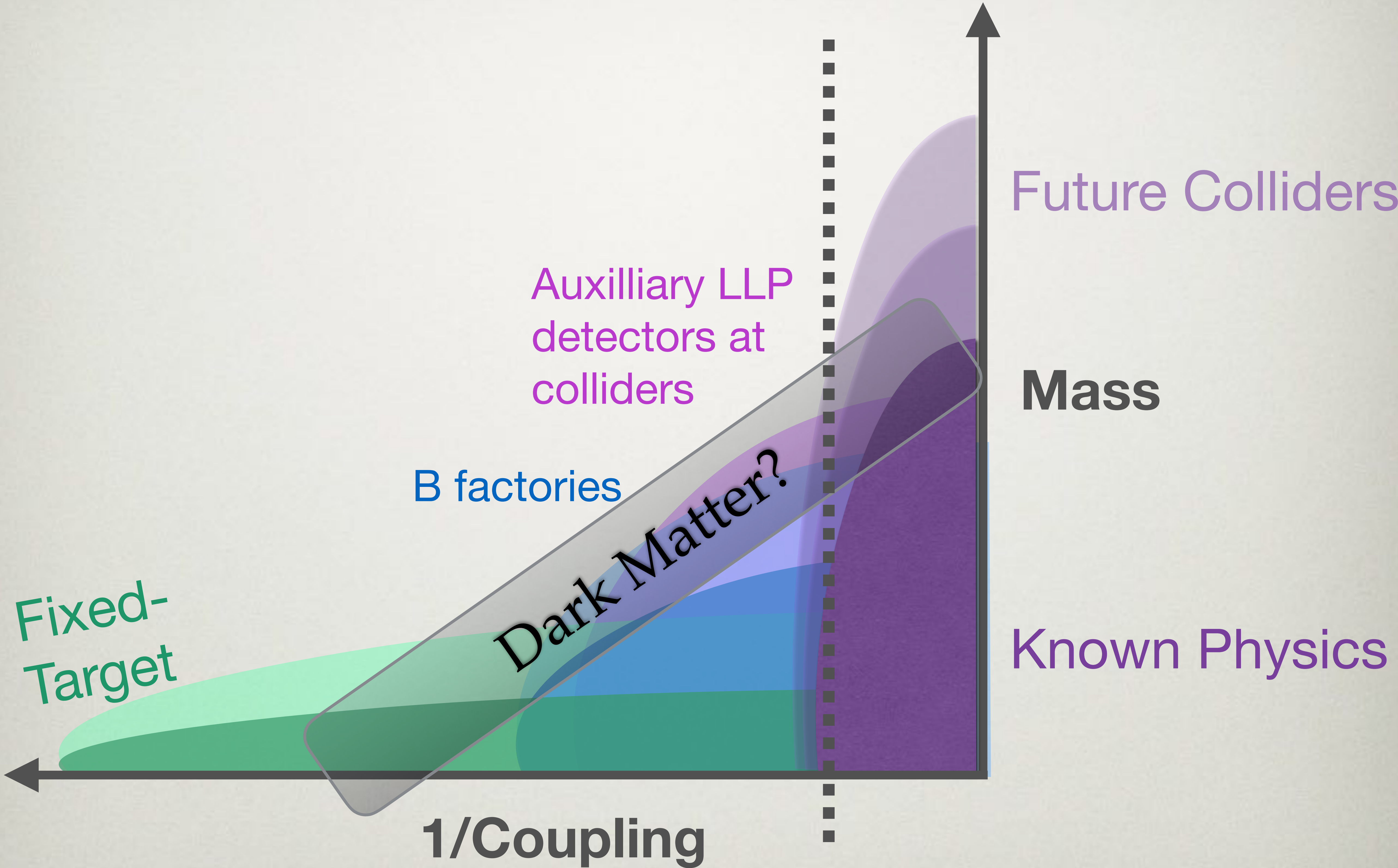
Small couplings can motivate small masses, naturally (analogous to $\mathbf{m_{proton}}$, $\mathbf{m_{electron}} \ll \mathbf{m_{Weak}}$ in Standard Model)

New Physics at Low Mass Scales?

Searches for production at accelerators limited by intensity, sensitivity, and/or lifetime



New Physics at Low Mass Scales?



Need multiple experiments to explore this landscape broadly!

A Rich Arena for Particle Physics

DM-detector interactions (Direct Detection, …)

Light DM production at accelerators

Indirect detection

Mediator production at accelerators

Cosmic Probes of annihilation, light dof, …

Self-Interaction in Cosmological Structures

Models are key for connecting these – the connections are powerful, but in many cases depend intricately on assumptions!

Following the trail of Dark Matter Abundance

- There are only three things we know about dark matter
  - We know it doesn't interact much (<)
  - We know it doesn't decay much (<)
  - And we know how much there is (=)

Following the trail of Dark Matter Abundance

- There are only three things we know about dark matter; hidden sectors can nicely explain all of them
  - We know it doesn't interact much
    - *SM-neutral, weak coupling*
  - We know it doesn't decay much
    - *Carry conserved hidden-sector charge*
  - And we know how much there is
    - ***Makes sense to follow this hint!***
    - ***Portal interactions alter abundance at late times so we are obliged to consider them.***

Taxonomy from Dark Matter Origin

Stronger — interactions — weaker

Was DM ever in thermal equilibrium with the SM?

no

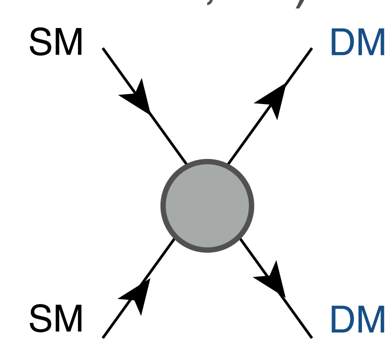
Is DM produced in thermal era?

no – before

Abundance from initial conditions, e.g. inflationary axion

yes

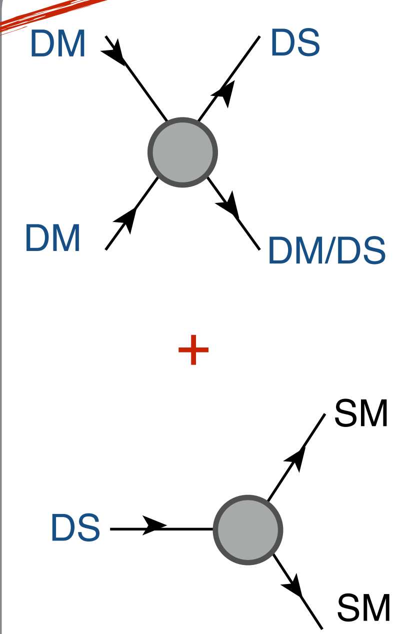
Produced by weak contact w/ thermal bath (sterile ν, freeze-in, …)



yes
(UV insensitive)

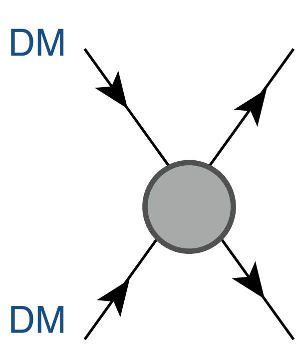
How was the DM abundance depleted?

indirectly



and variants
Secluded, SIMP, ELDER, forbidden, co-scattering

directly
*economical
*especially predictive



+ variants

WIMP, Sub-GeV Relic
+asymmetric variants

table adapted from 1807.01730

DM produced in thermal era – when we understand the Universe best

Taxonomy from Dark Matter Origin

Stronger — interactions — weaker

Was DM ever in thermal equilibrium with the SM?

no

Is DM produced in thermal era?

no – before

Abundance from initial conditions, e.g. inflationary axion

yes

Produced by weak

Produced without thermalizing

SM DM

See K. Schutz's talk

yes
(UV insensitive)

How was the DM abundance depleted?

indirectly

Thermalizes with something else that thermalizes with SM

forbidden, co-scattering

directly
*economical
*especially predictive

Thermalizes with SM

WIMP, Sub-GeV Relic
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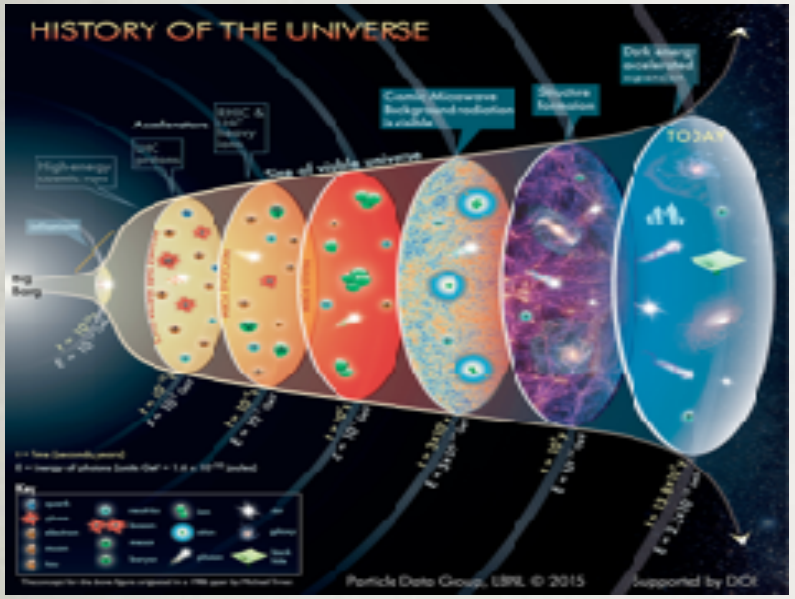
DM produced in thermal era – when we understand the Universe best

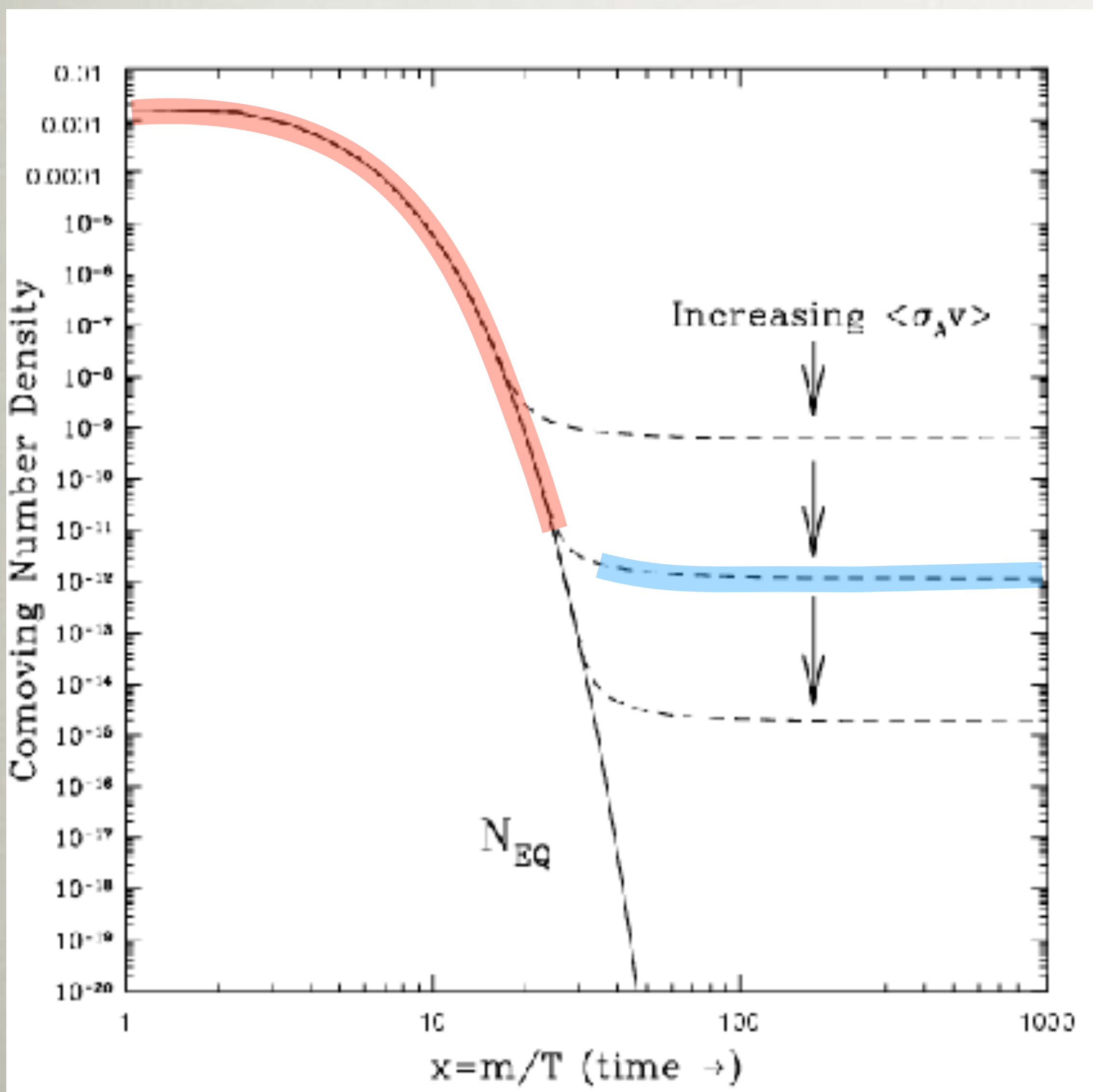
WIMPs and Thermal Freeze-Out



Simple and predictive – early abundance set by equilibration with SM particles, late abundance set by dilution in expanding Universe

$$\frac{dn}{dt} = -\langle \sigma_A v \rangle \left(n^2 - n_{\rm eq}^2\right) - 3Hn$$

$n_{\rm eq} \sim e^{-m/T}$ as Universe cools



Freeze-out transition when the scales of two terms are equal:

$$n_{\rm eq}^f \approx H^f / \langle \sigma_A v \rangle$$

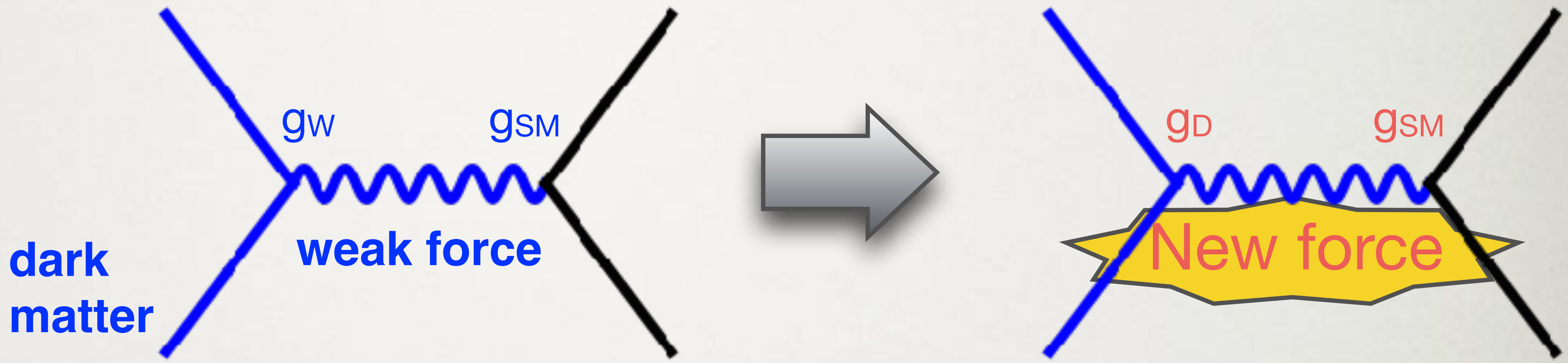
$$\Omega_X \rho_c \sim \frac{T_0^3}{T_f^3} m_X\, n_{\rm eq}^f$$

Measured abundance →

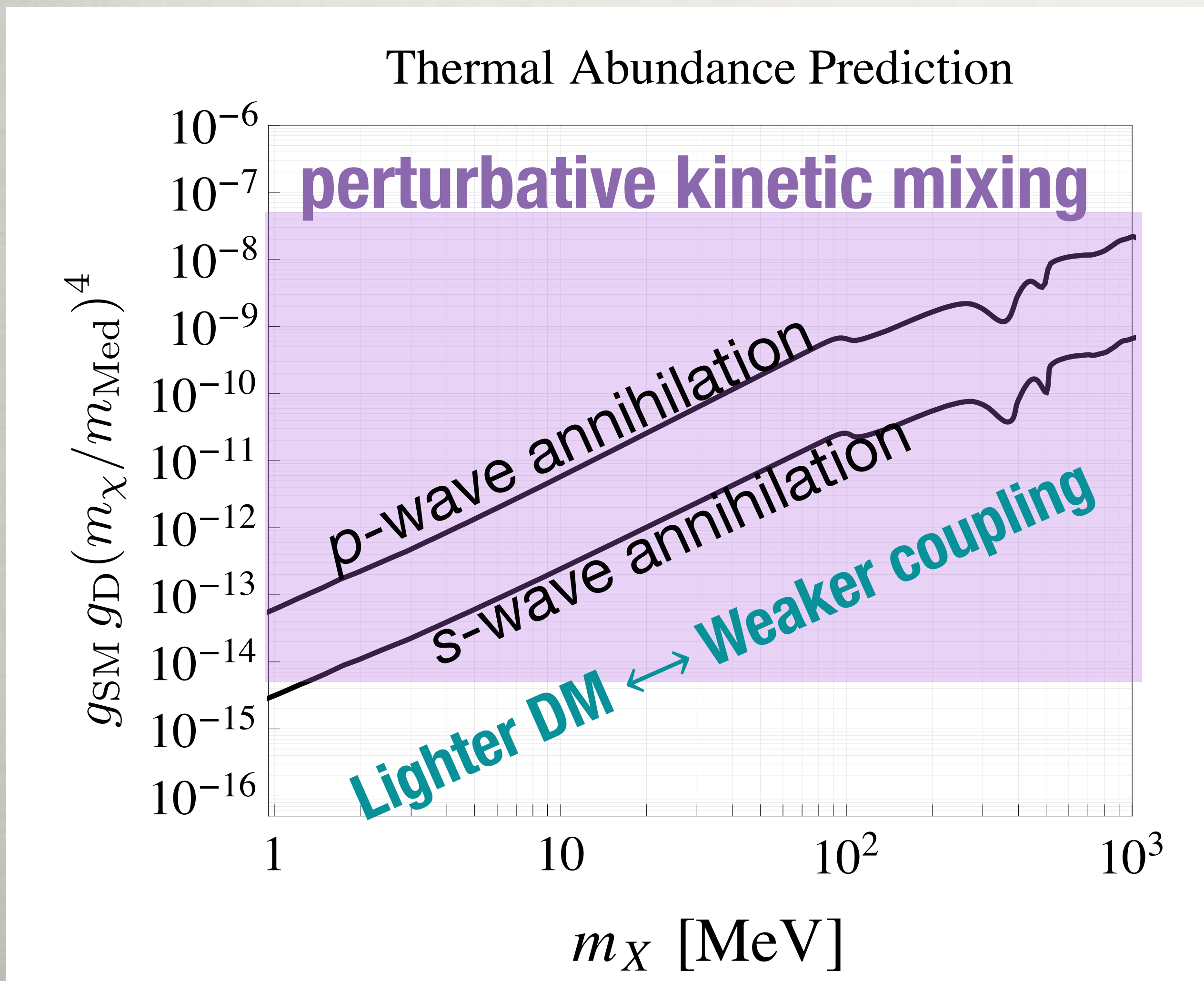
$$\boxed{\langle \sigma_A v \rangle \simeq 3 \cdot 10^{-26} {\rm cm}^3/{\rm s} \simeq \frac{1}{(20 {\rm TeV})^2}}$$

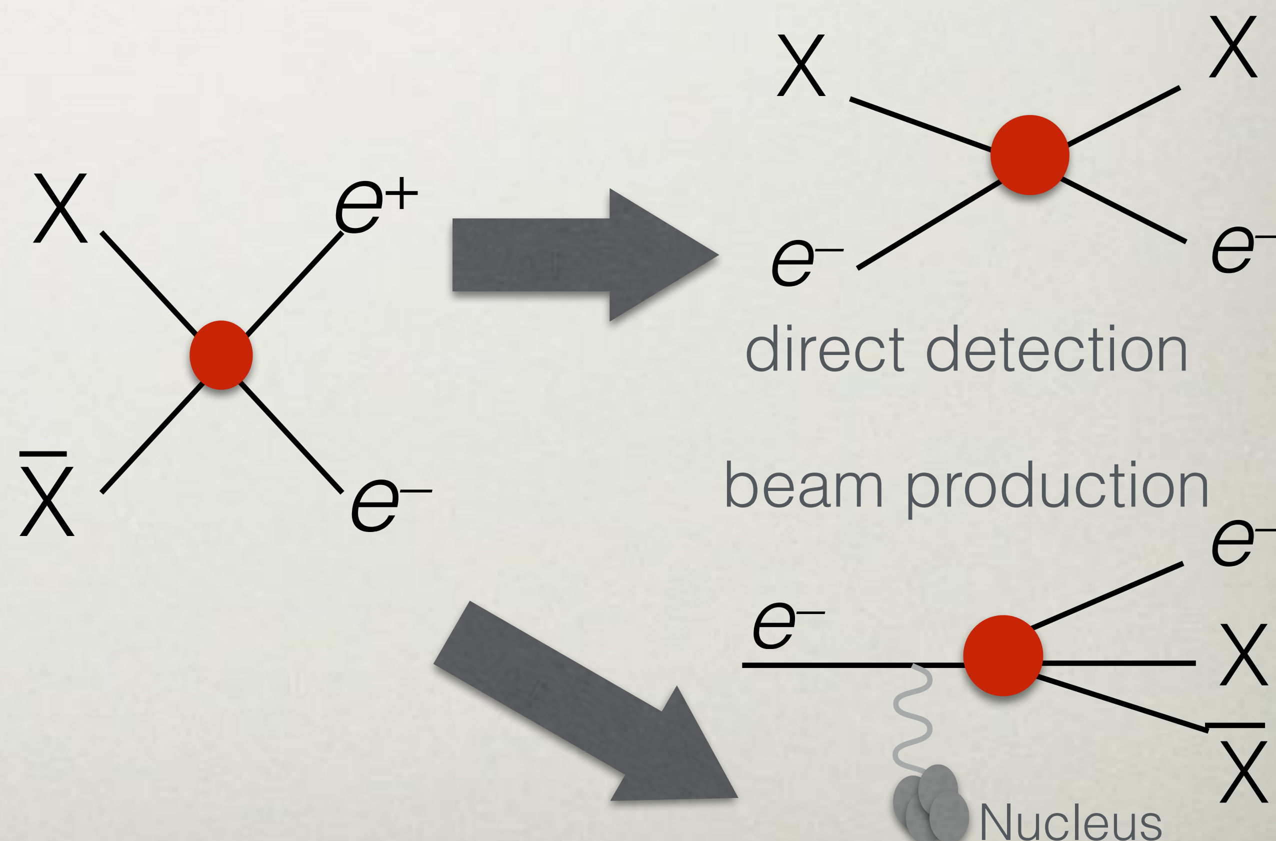
The WIMP-iest Hidden Sector DM

Same story, new force



DM abundance ⇒ predicted strength of interaction

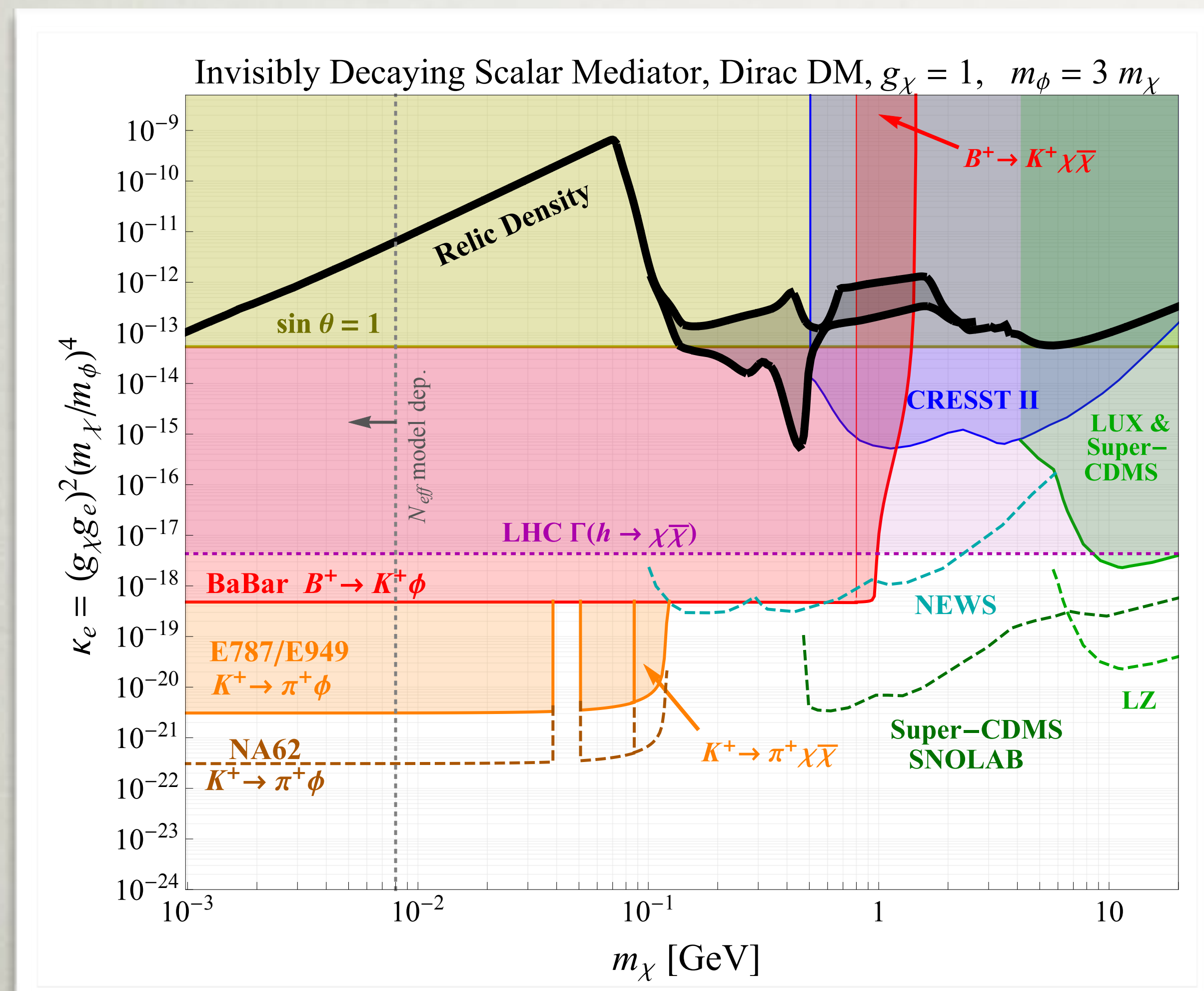




⇒ Predicted rates for observables today

Constraints from Mediator Production

- Scalar portal: mediator production & direct detection exclude all parameter space.
- Vector portal: broad regions of viable parameter space; aligned with idea of 1,2-loop generated portal coupling



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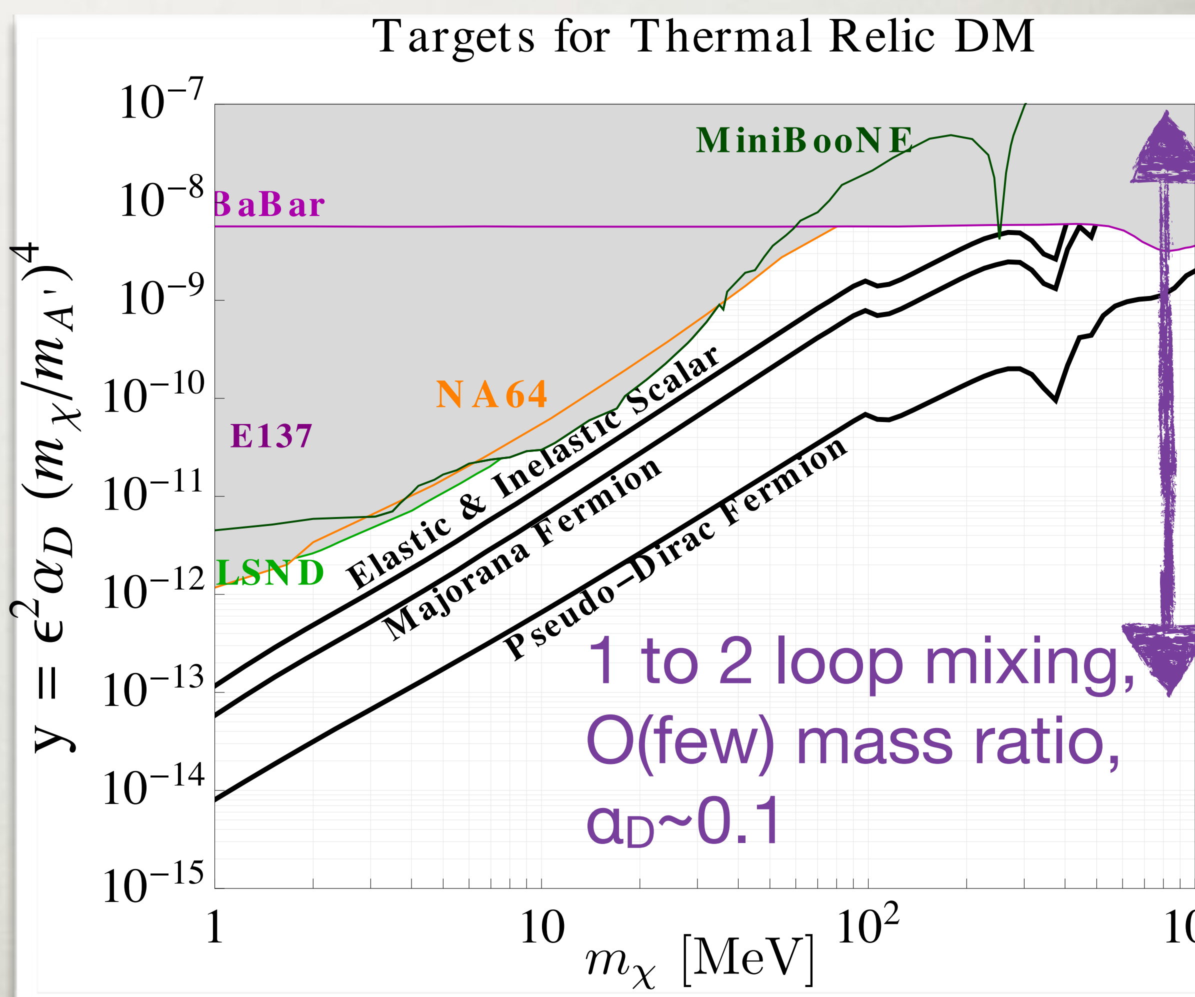
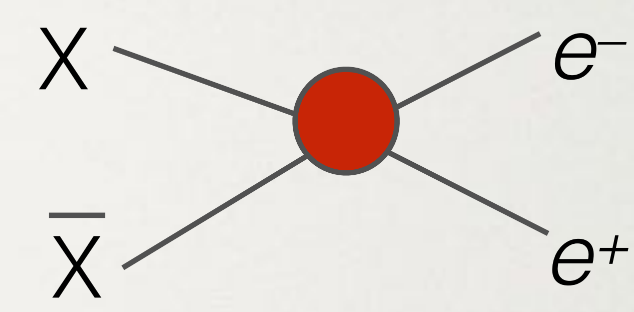
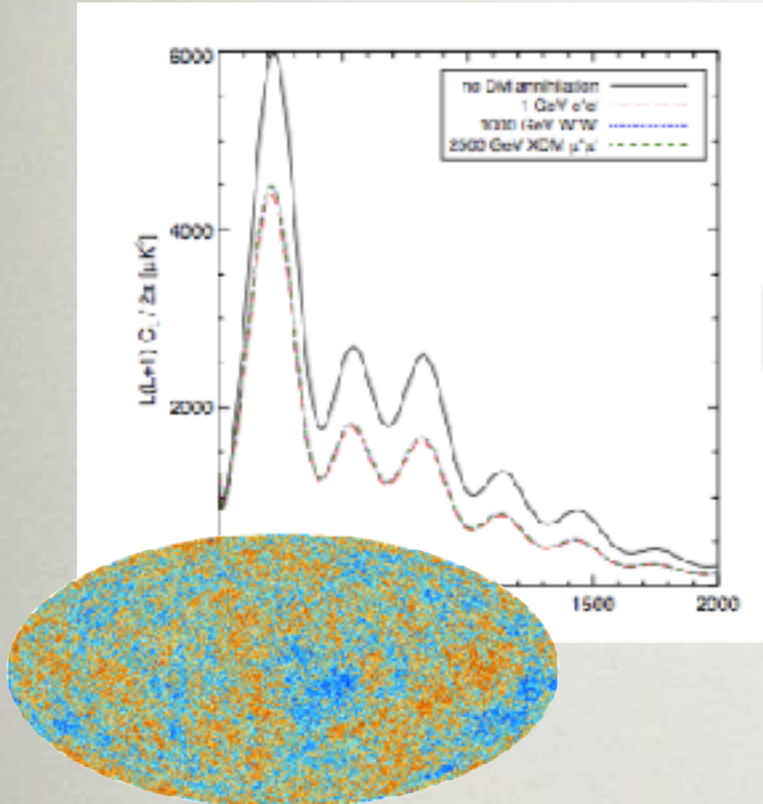
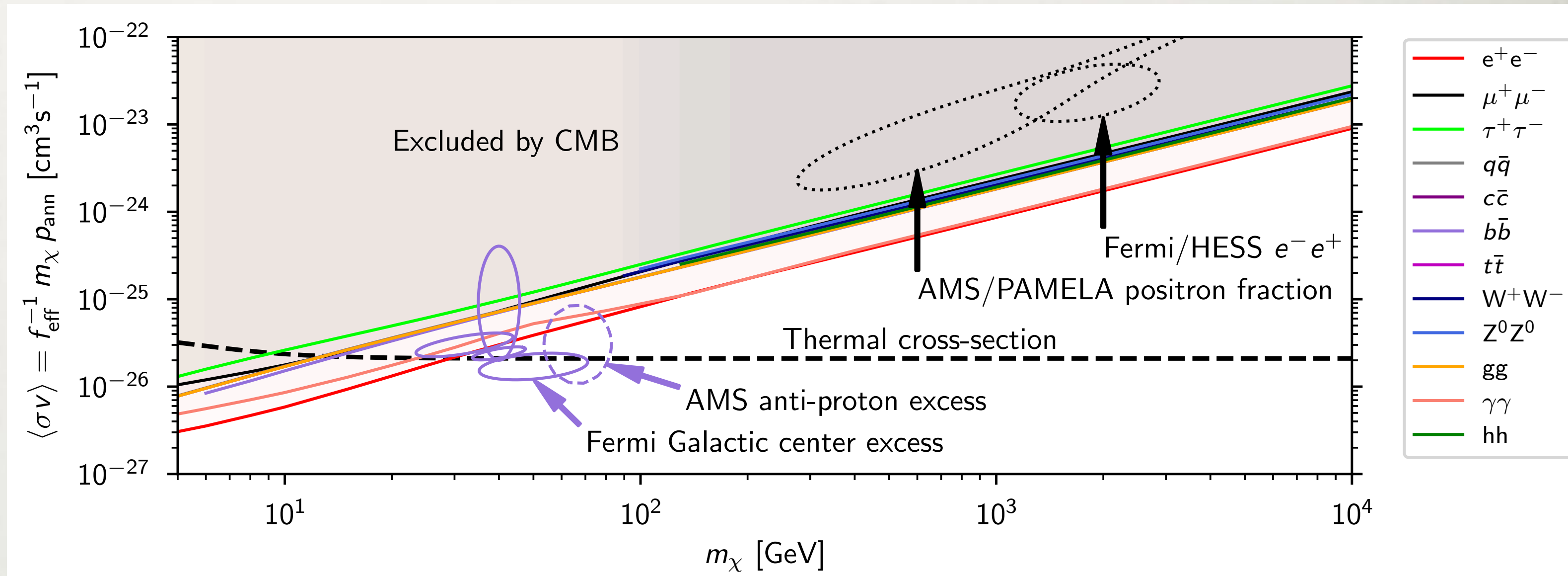


Annihilation Constraints

Planck power spectrum strongly constrains primordial annihilation of light DM







Planck 2018 VI

Excludes $\langle\sigma_A v\rangle_{\rm CMB} \approx \langle\sigma_A v\rangle_{\rm FO} \approx 3\cdot 10^{-26}{\rm cm}^3/{\rm s}$ for ≲20 GeV DM.

but CMB probes ~eV temperatures ≪ freeze-out temp

Sharpens focus to models where annihilation rates decrease at low temperatures [or dominated by neutrinos]

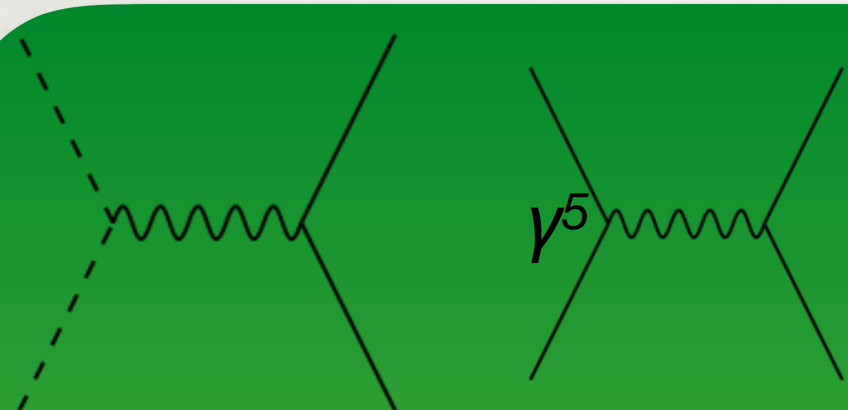
Light Thermal Dark Matter Confronts the CMB

Both scalar and fermion DM models survive CMB constraint

~~Dirac Fermion~~

p-wave annihilation

$\sigma_{\text{ann}} \sim v^2 \sim T/m_{\text{DM}}$

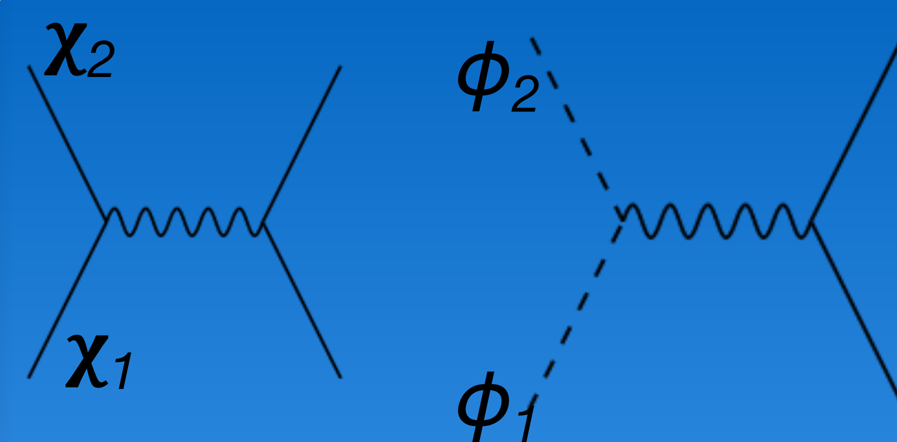


Scalar

Majorana

inelastic (co)annihilation

$\Gamma_{\text{ann}} \sim n_1 n_2 \sigma_{\text{ann}}$

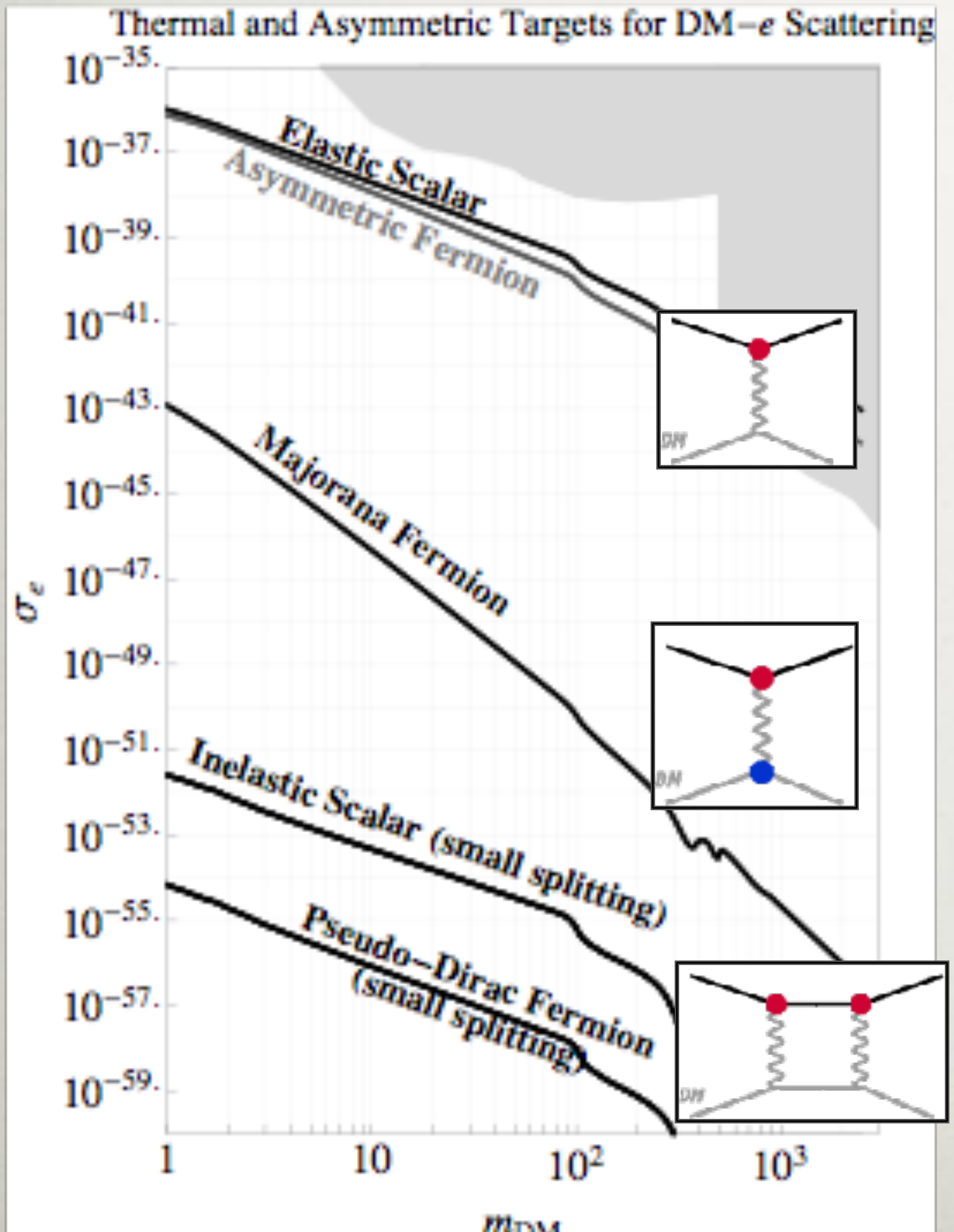


Pseudo-Dirac

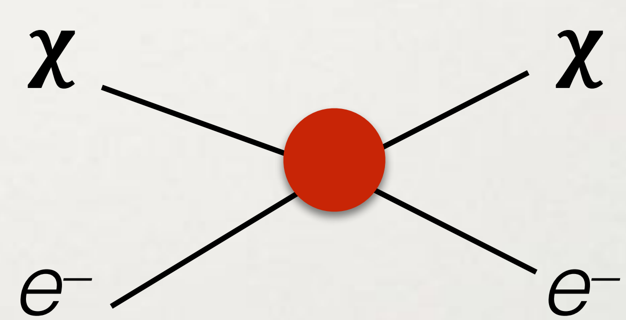
Inelastic Scalar

generic if DM has U(1)-breaking mass term

Velocity-Dependence and Direct Detection: Good News and Bad News



Some effects that suppress non-relativistic annihilation **also suppress non-relativistic scattering**

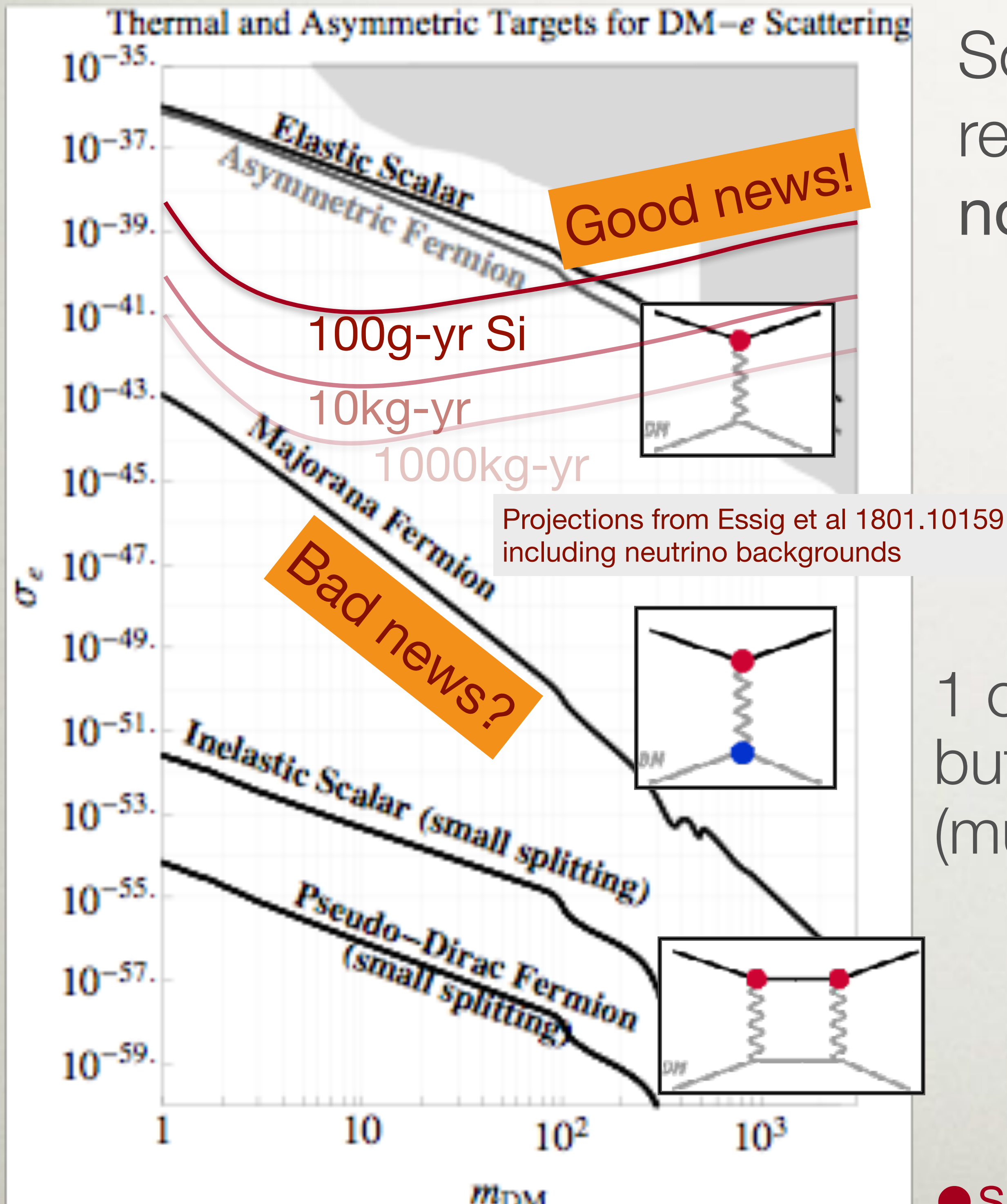


$v_{DM} \sim 10^{-3}\, c$

1 order of magnitude spread in coupling, but tens of decades in spread for $\sigma_{\chi e}$ (much like for WIMPs!)

● Small DM-SM coupling
● Velocity-suppression

Velocity-Dependence and Direct Detection: Good News and Bad News



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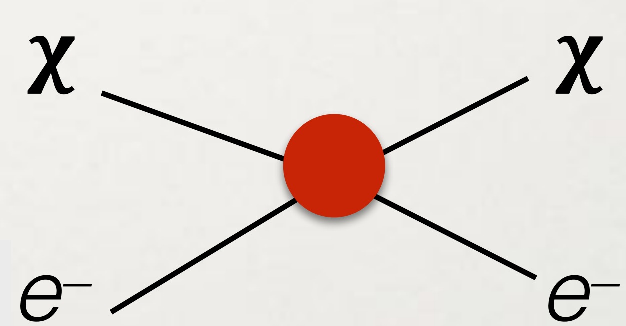

v_{DM}~10^{-3} c

1 order of magnitude spread in coupling, but tens of decades in spread for $\sigma_{\chi e}$ (much like for WIMPs!)

● Small DM-SM coupling
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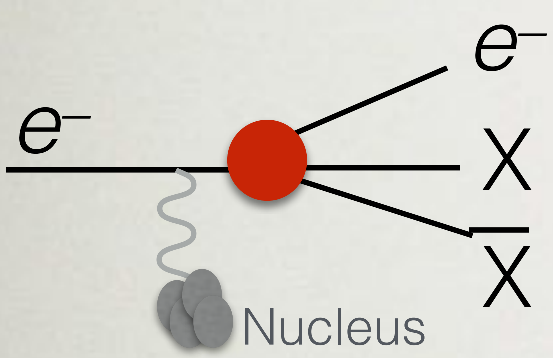
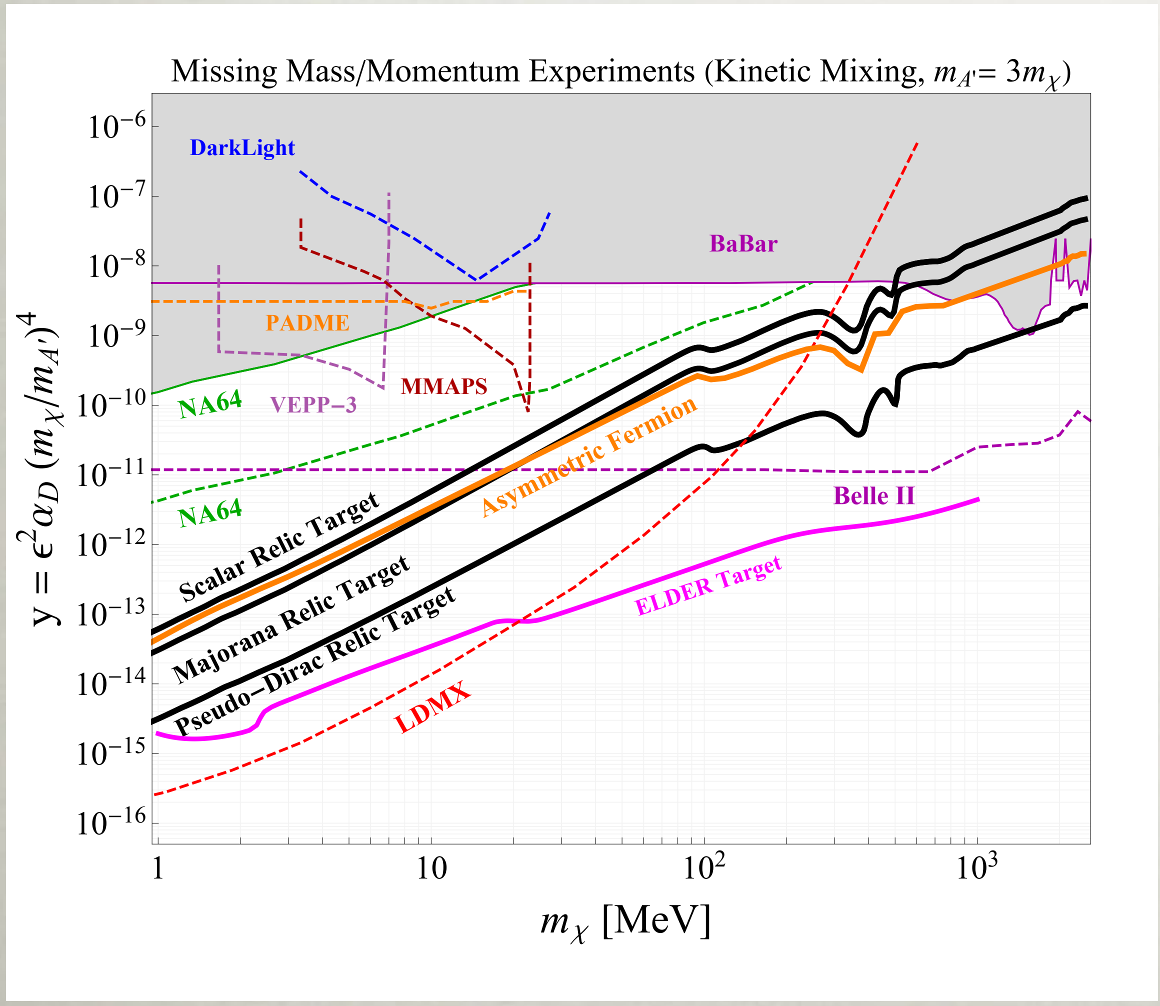
Good news for challenging cases I



Accelerator searches for dark matter probe semi-relativistic kinematics – similar to Big Bang production of DM, so different DM spins look similar.

See talks by
L. Tompkins,
L. Molino

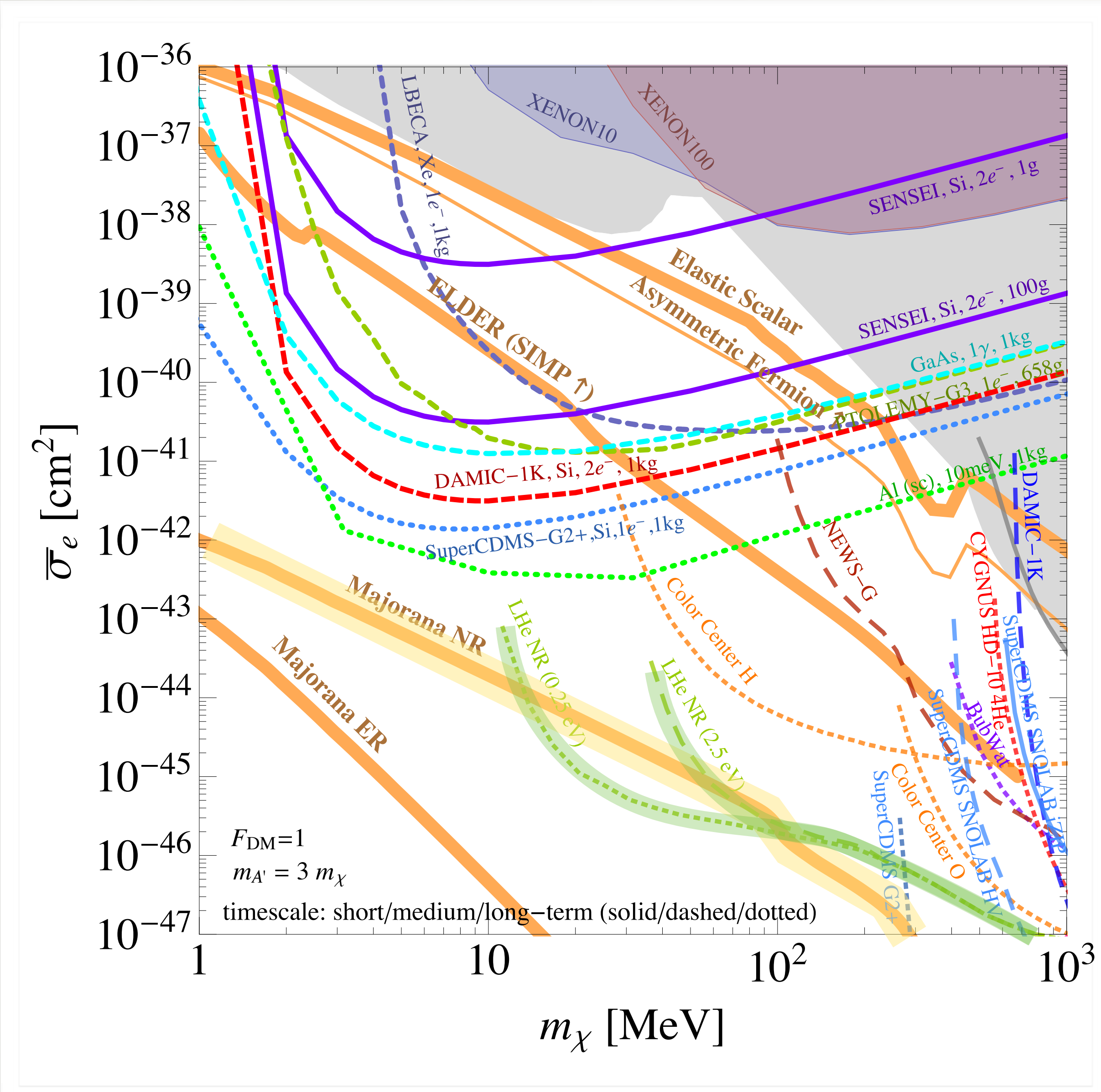


Cosmic Visions DM 2017

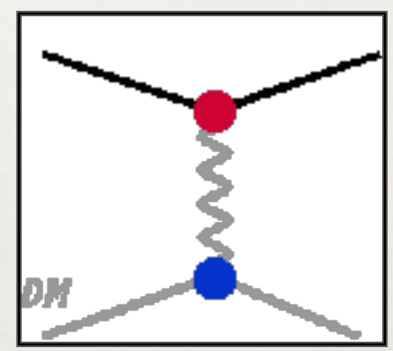
Most searches probe ***both*** portal mediator decays to DM and non-resonant DM production

Complementary constraints on SM decays of portal mediator see B. Shuve, J. Strube, H. Otono talks

Good news for challenging cases II



Majorana thermal DM more accessible with NR than ER searches

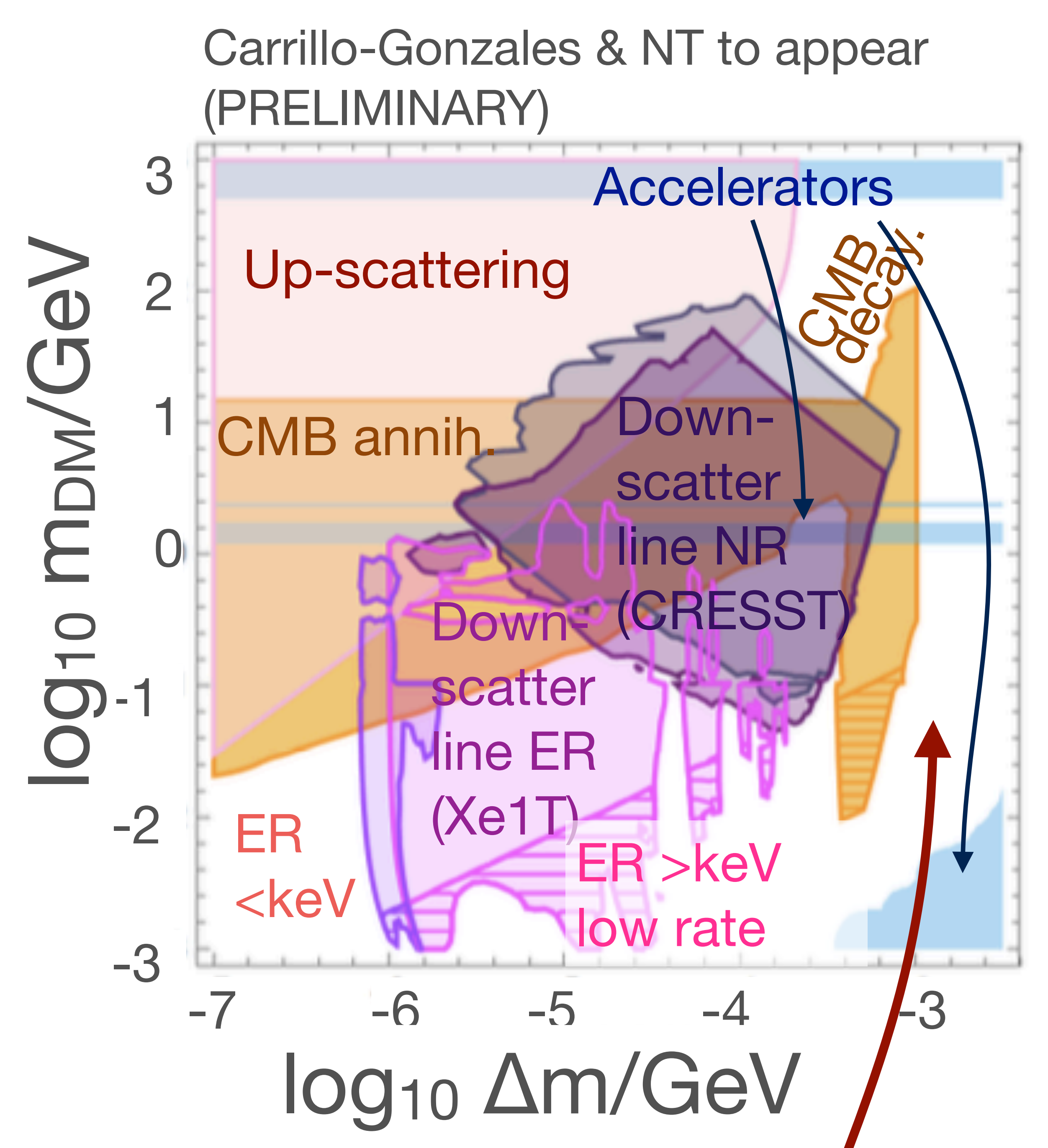


Majorana coupling suppressed by $\Delta p/m_{DM}$;

$m_{Nuc}>m_{DM}>m_e$ implies larger Δp in nuclear recoils

Low-threshold LHe detectors may get there!

Good news for challenging cases III



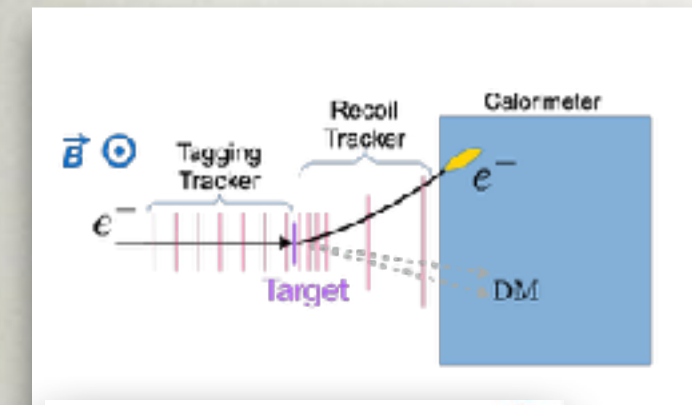
Inelastic models feature DM "excited states" that **may be cosmologically stable**

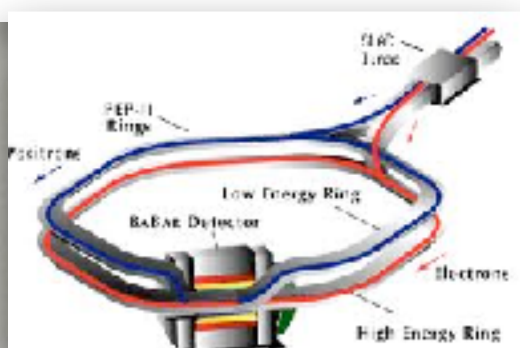
- small (calculable) abundance
- observable down-scattering ***lines*** in nuclear and electron recoil
  (see also 2006.13918 Baryakhtar, Berlin, Liu, Weiner)

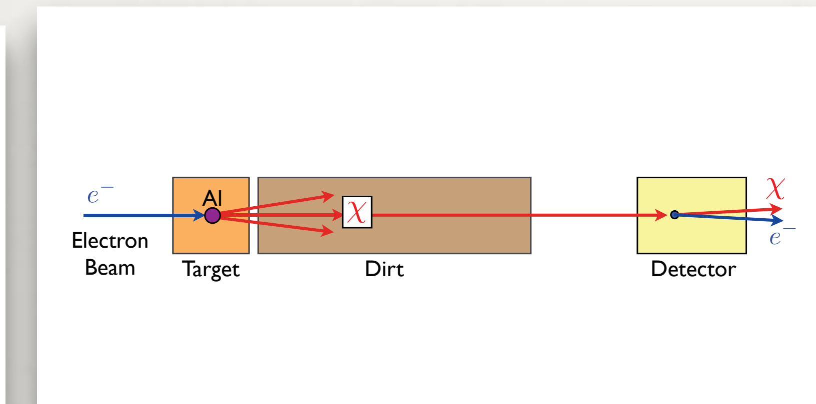
(Short-lived excited state – Can **boosted DM**-like signals give hints of this DM's presence in the Milky Way halo?)

Towards a Dark Standard Model?

Not just great discovery/exclusion potential – but real possibility to explore the physics of the dark sector ***in detail*** with multi-experiment program.

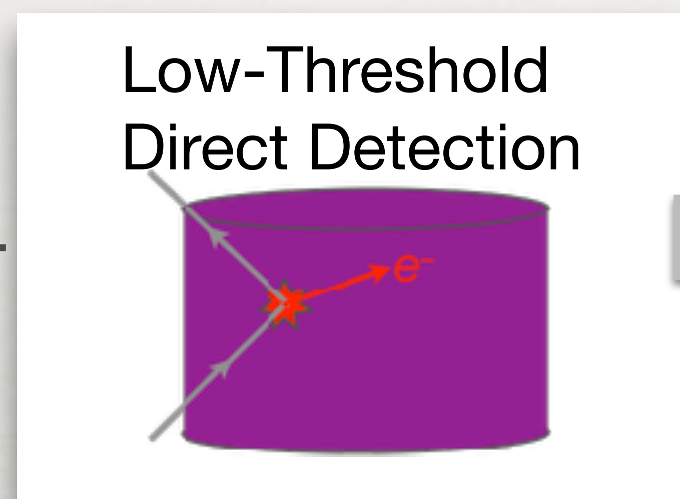






- Dark Matter and force-carrier mass
- Effective charges of Dark Matter and ordinary matter

\+



- Abundance
- Cosmological lifetime
- Spin

Identifying a candidate as "the dark matter" might be harder than finding it. But multiple paths to discovery → ability to learn a lot about DM properties.

Another direction of challenge

Dark sector ⇒ other light states. Multiple coupled Boltzmann equations can be relevant. e.g.

Secluded DM

Annihilation DM⟷ϕ

Decay ϕ⟷SM

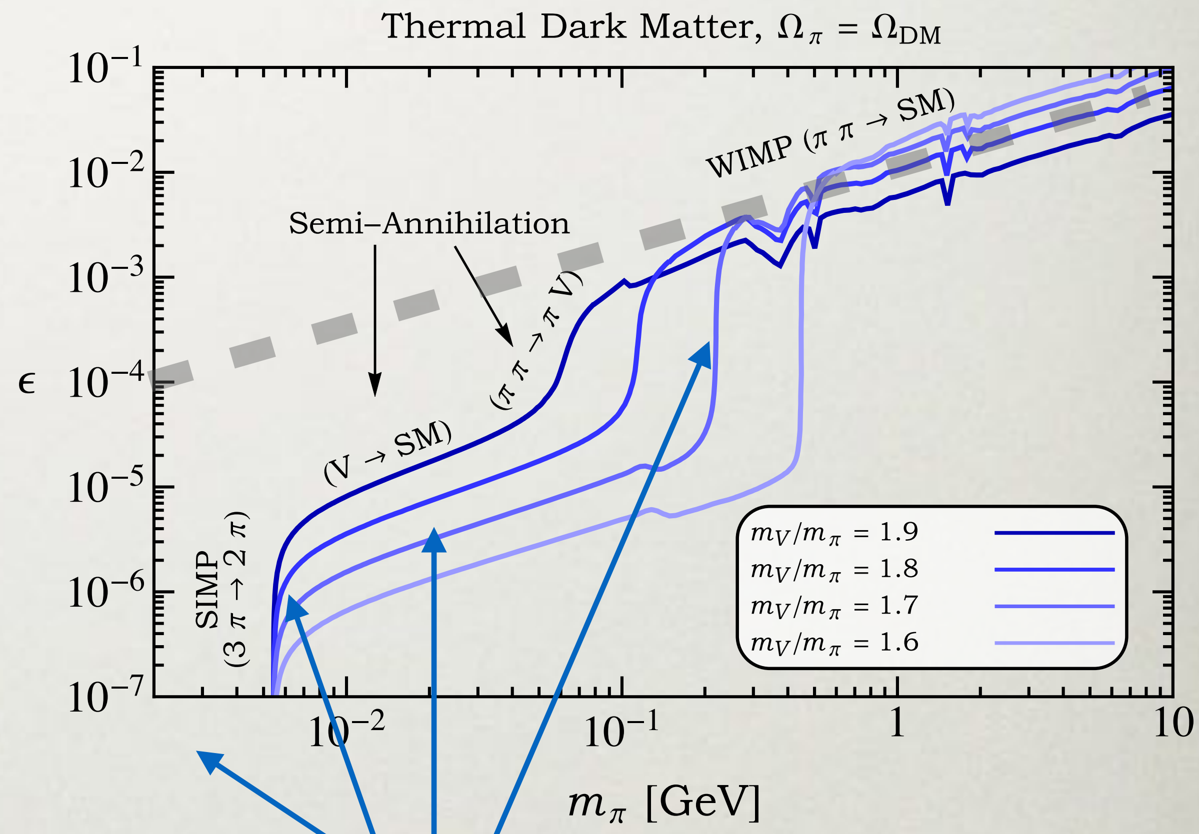
If annihilation freezes out first then still need

$$\langle \sigma_A v \rangle_{\mathrm{FO}} \approx 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

…but lose connection between abundance & portal coupling.

Strongly Interacting DM

DM="pion" of confined dark sector.



4 new domains where different reactions control abundance [ELDER not shown in plot]

+forbidden, not-forbidden, co-scattering, and many more

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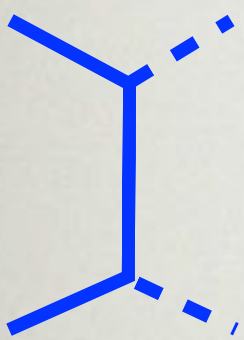
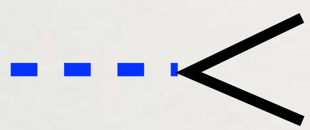
Secluded DM



Annihilation
DM⟷ϕ



Decay
ϕ⟷SM

Strongly Interacting DM

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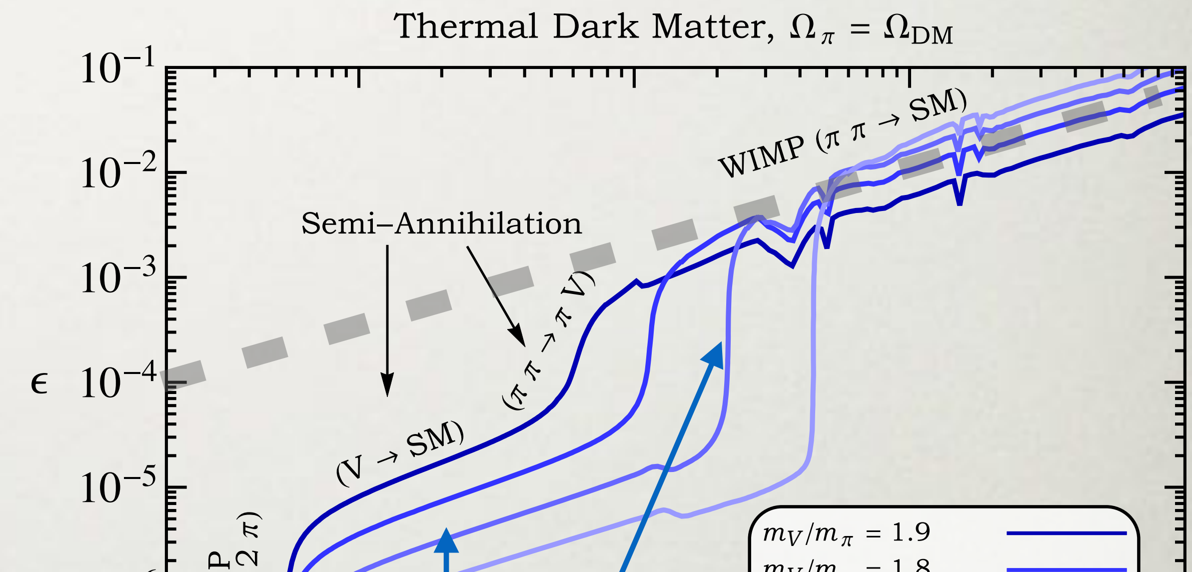

If
fi
⟨
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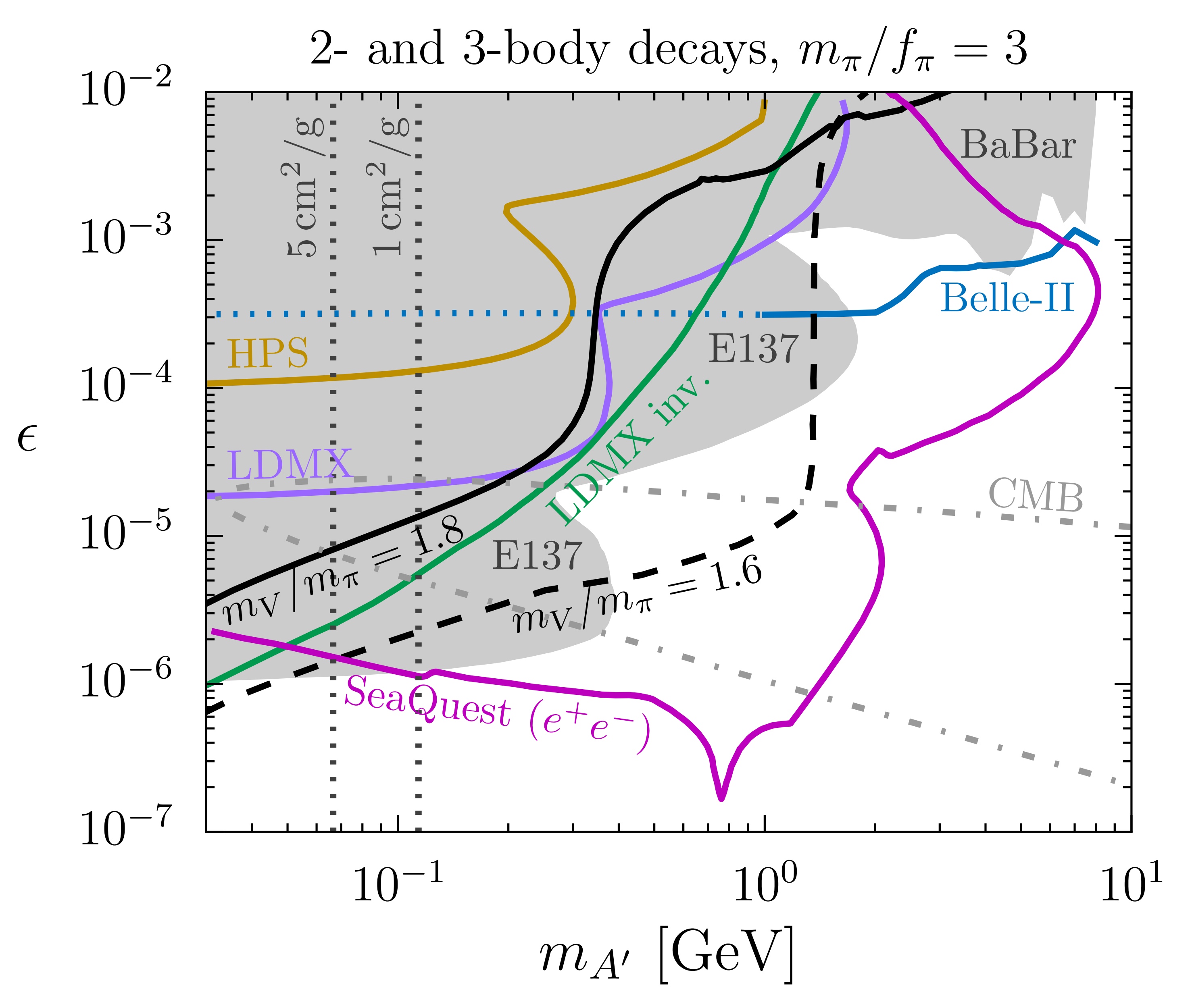
ELDER

These cases motivate a broader **range of couplings** than the "minimal" DM⟷SM thermal models. They imply tractable ***but harder*** "region-like" targets for observation.

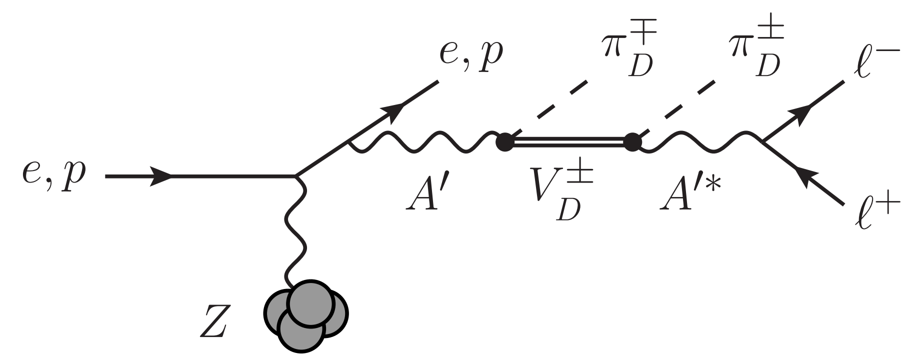
+forbidden, not-forbidden, co-scattering, and many more

Common Theme

These models often rely on **mediator** or **DS-exotic** decay to SM for chemical or kinetic equilibration. ***Discovering these at accelerators offers key handle on these models.***



Example: DM from confined dark sector



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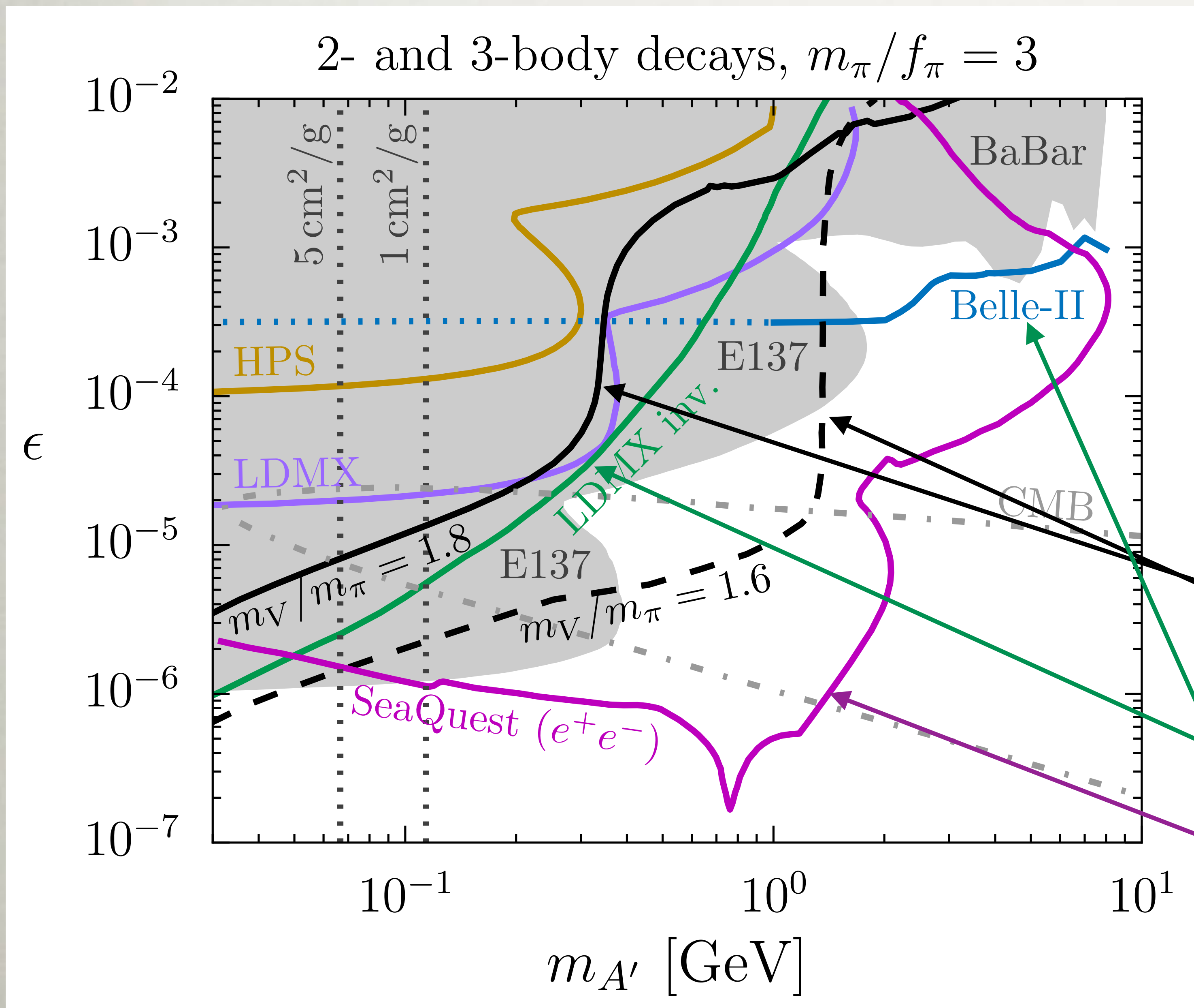
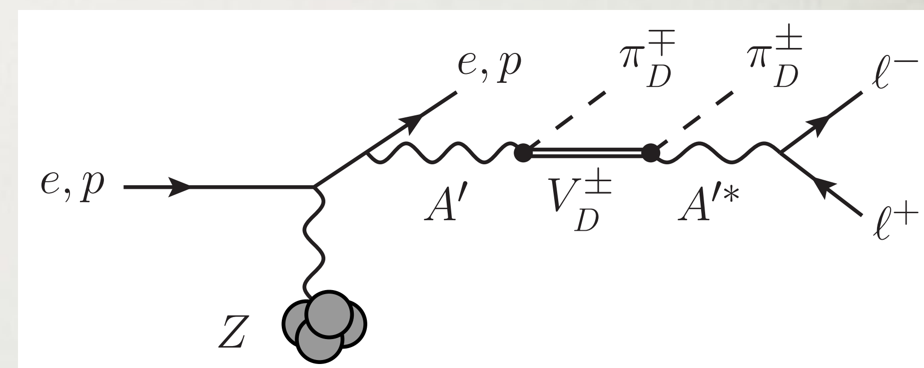


Example: DM from confined dark sector

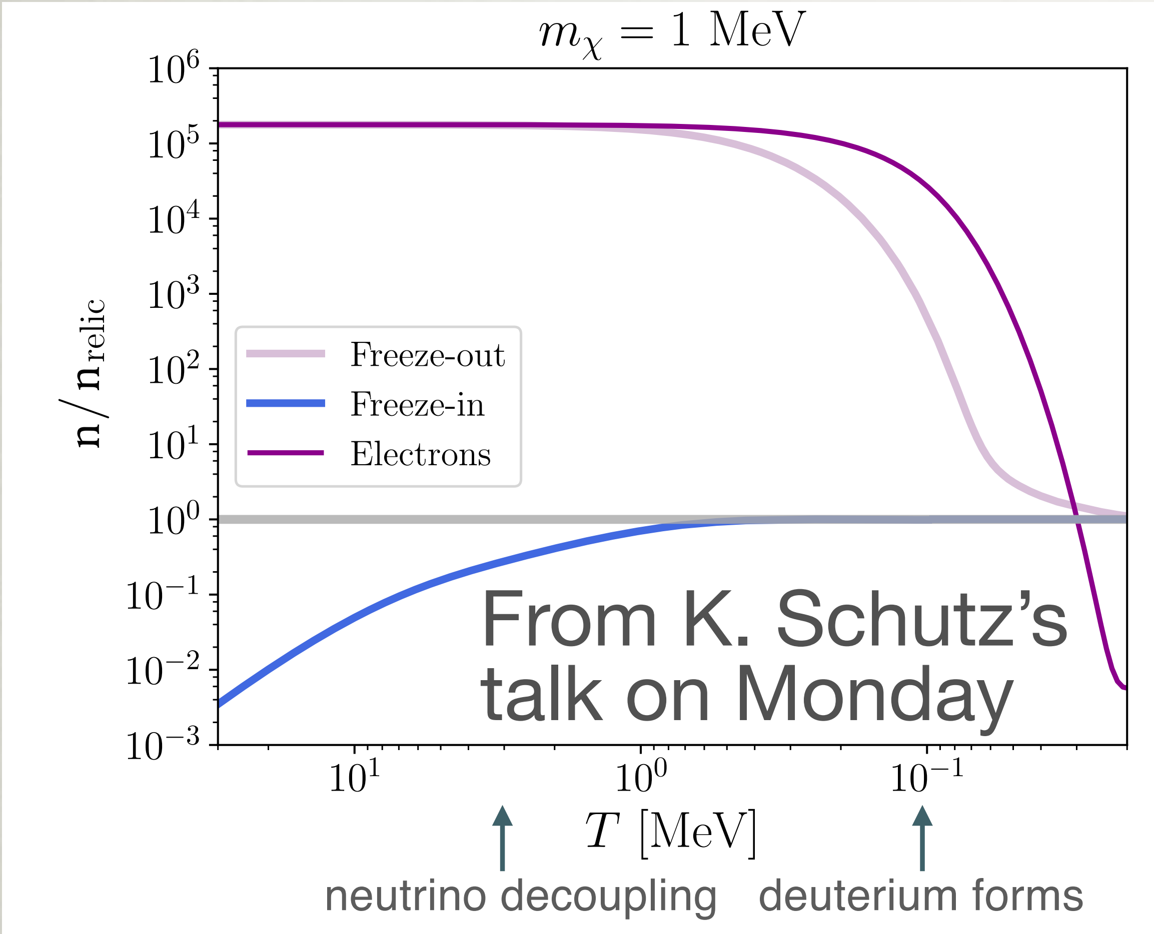


Expected signal (range of parameters)

DM production sensitivity

exotic production sensitivity

Dark Matter Freeze-In



One of the few simple possibilities for sub-MeV DM produced in thermal era

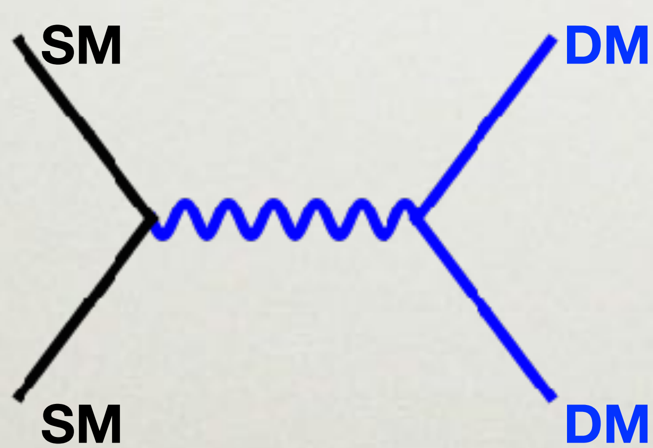
Freeze-in requires $\alpha_{DM} \times \alpha_{SM} \sim 10^{-26}$

⇒ naively undetectable

…but for sub-MeV DM, independent bounds on α_{DM} and α_{SM} imply **very** light mediator, $\lesssim 10^{-10}$ eV

→ Weak but *long-range, EM-like* coupling

If DM initial abundance vanishes, feeble DM-SM interactions produce DM in early Universe, but never enough to thermalize



(also possible –but not required – for heavier DM)

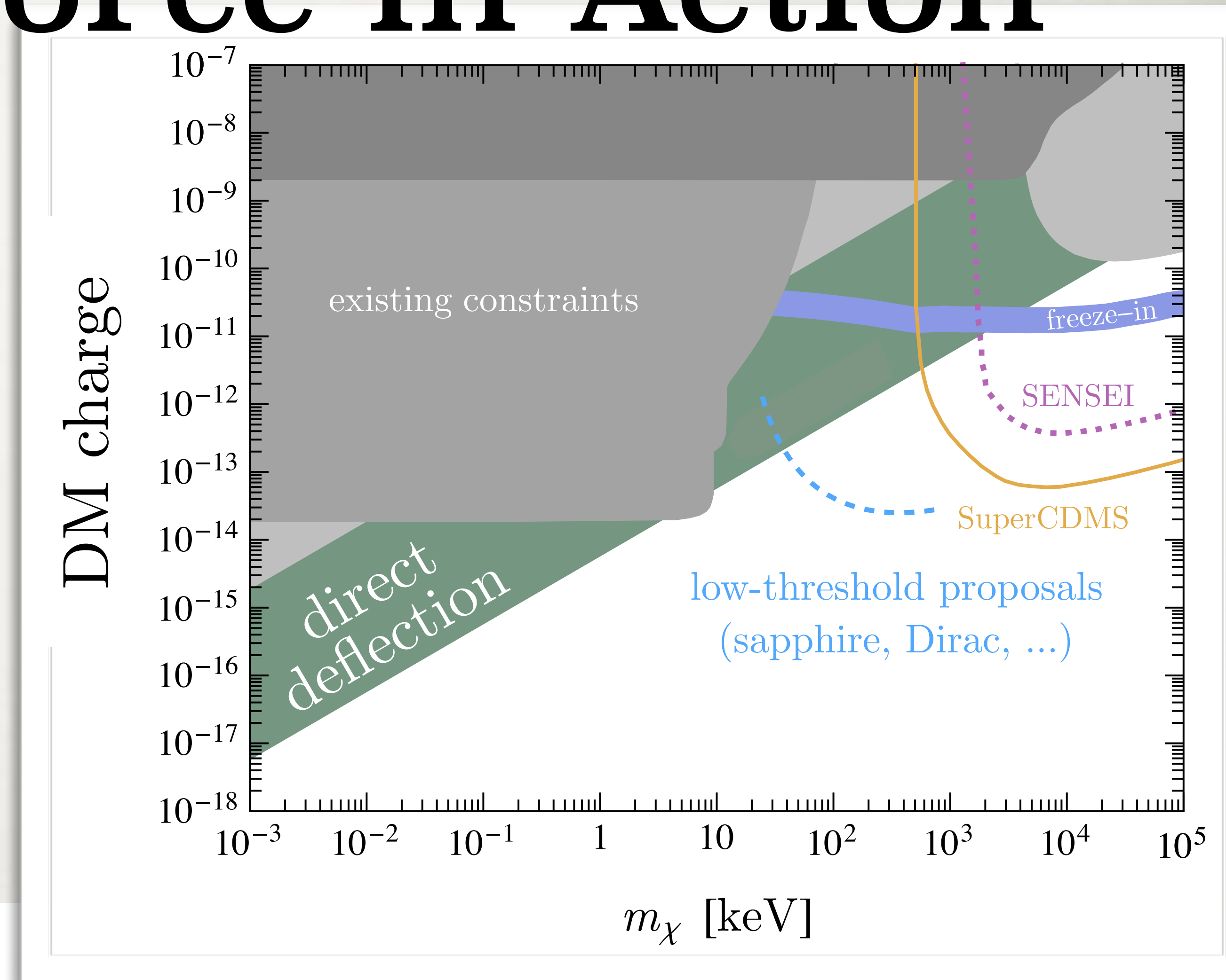
Finding Freeze-In: Long-Range Force in Action

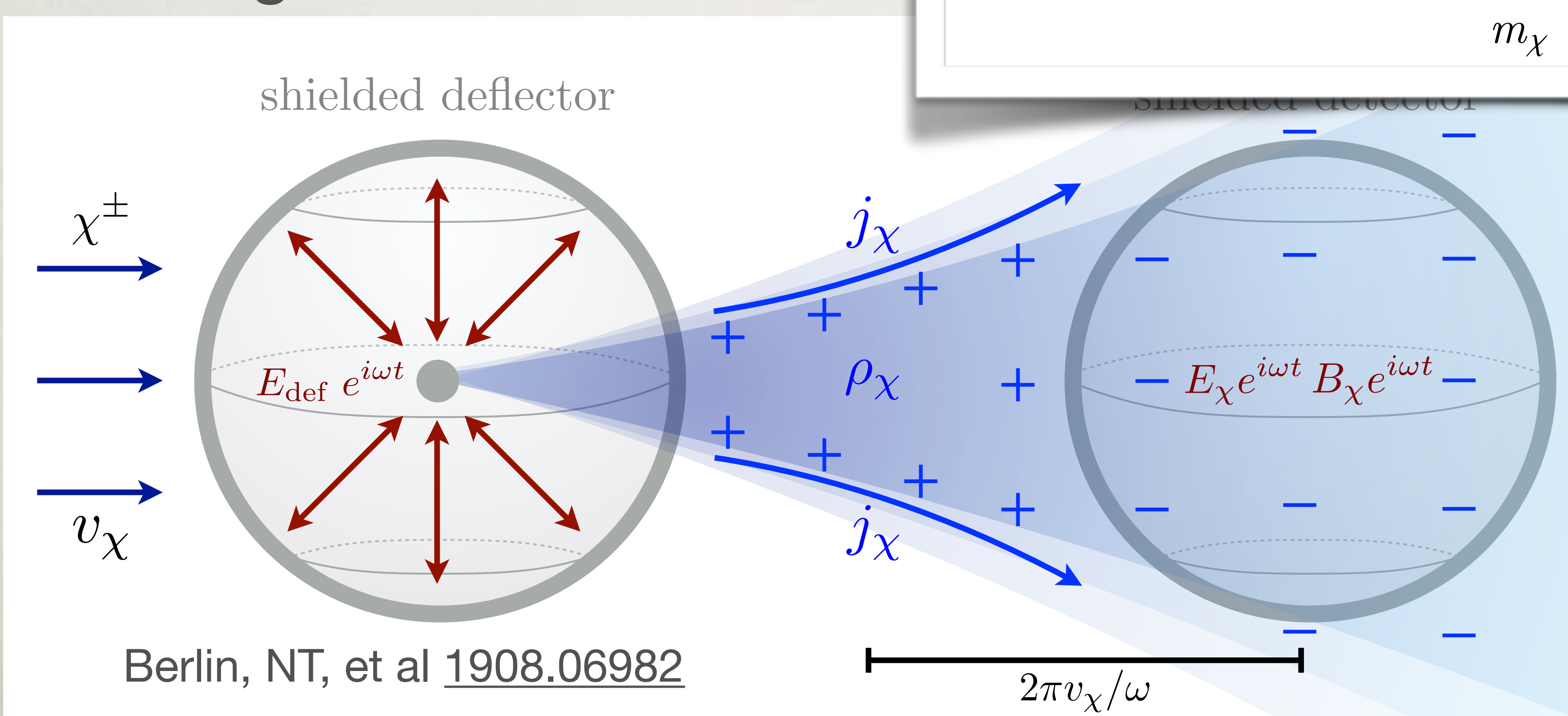
Direct Detection:

Light mediator & ≲keV momentum transfer → **enhanced (hence detectable) cross-section**

Direct *Deflection*:

Applied EM field induces ***classical*** deflection of DM charges – measure resulting fields in resonant detector





Berlin, NT, et al 1908.06982

Complementary scaling with DM mass!

Great probe of halo velocity profile b/c signal is $O(v)$

Conclusions

- ✦ Sub-GeV DM → Hidden Sector
  - Bottom-up “portal” organization
  - New forces → new particles beyond DM
  - Abundance is a strong hint → **follow it!**
- ✦ Landscape of models & experimental opportunities
  - Minimal freeze-out models can be found/excluded at accelerators – need **tapestry of experiments** to find the DM in our halo, measure its properties.
    - ‣ Freeze-in (especially sub-MeV) calls for more variety
  - Less simple freeze-out mechanisms allow weaker couplings, but have additional observational handles
- ✦ *The story is intricate, but exciting and worth telling.*
- ✦ **Challenge: how to organize these possibilities and take stock of what the experiments teach us?**

Thank you all for listening,

and to the organizers for an fantastic virtual conference!

Backup Slides

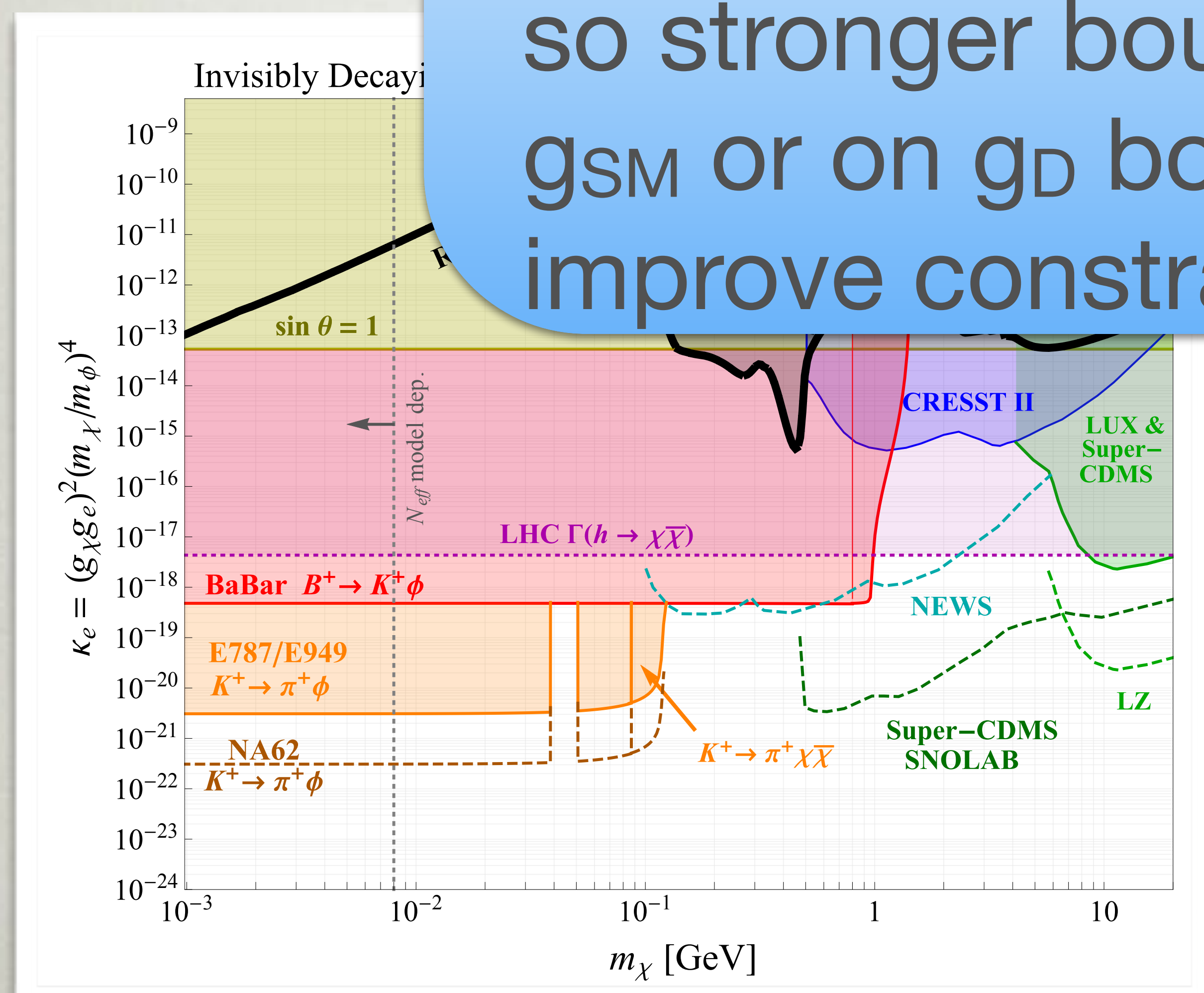
Constraints from Mediator Production

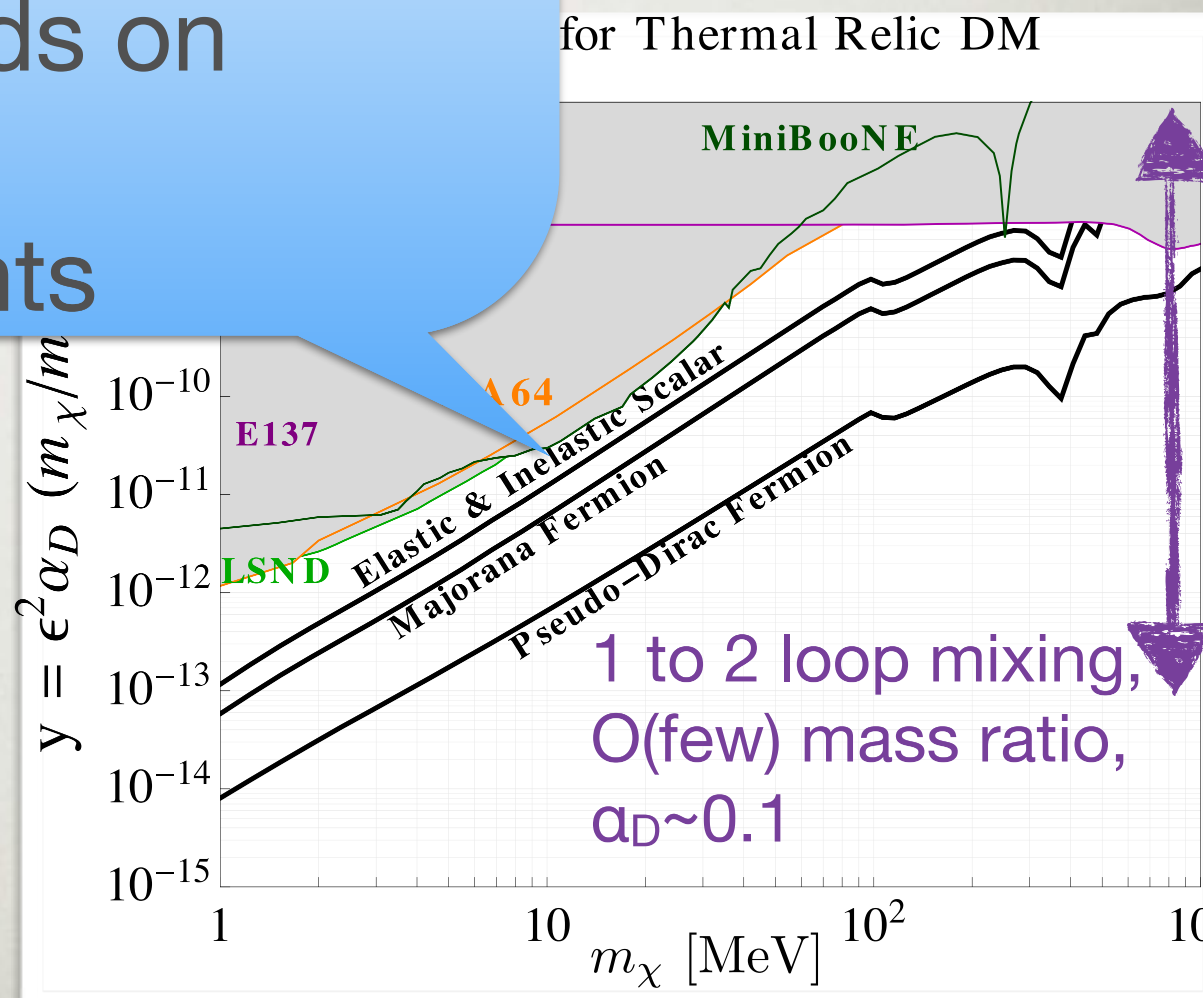
- Scalar p... l: broad regions producti... ameter space; exclude ... idea of 1,2-loop ...ortal coupling

Strictly speaking, these are

$\left(\begin{array}{l}\text{lab bound}\\ \text{on } g_{SM}\end{array}\right) \times \left(\begin{array}{l}\text{perturbativity}\\ \text{bound on } g_D\end{array}\right)$

so stronger bounds on g_{SM} or on g_D both improve constraints





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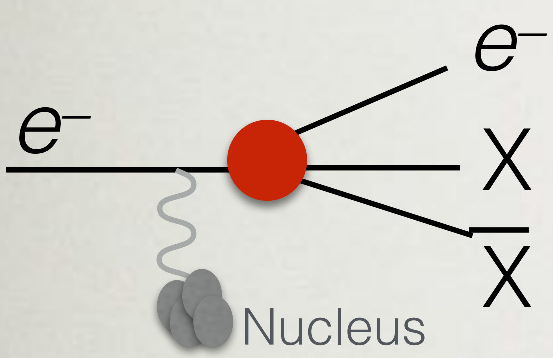
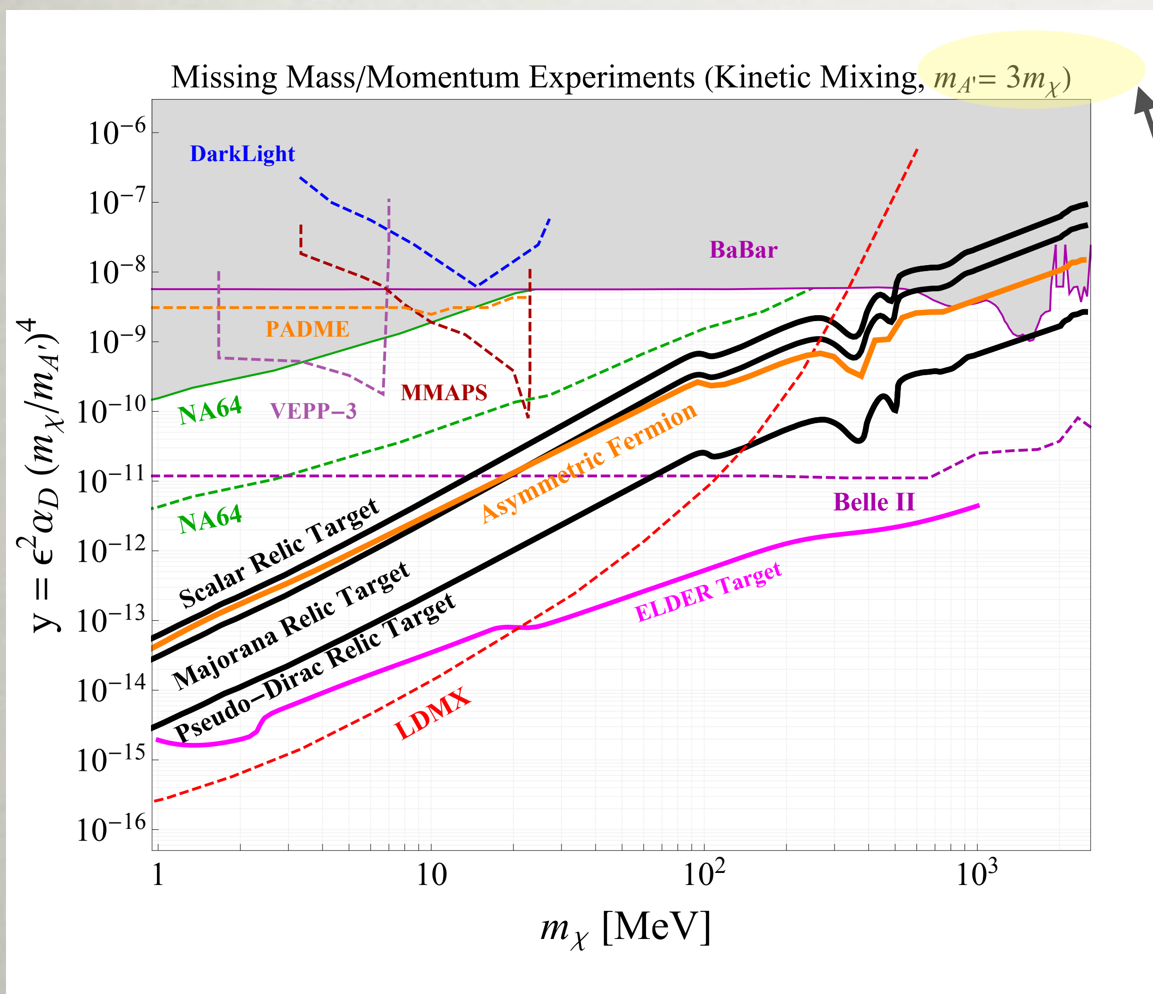
Good news for challenging cases I



Accelerator searches for dark matter probe semi-relativistic kinematics – similar to Big Bang production of DM, so different DM spins look similar.

See talks by
L. Tompkins,
L. Molino



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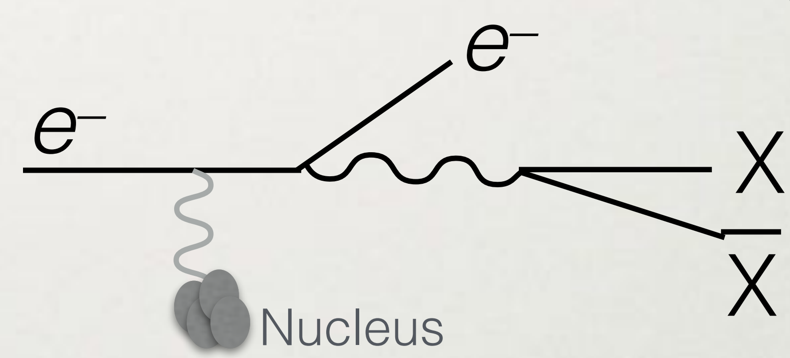
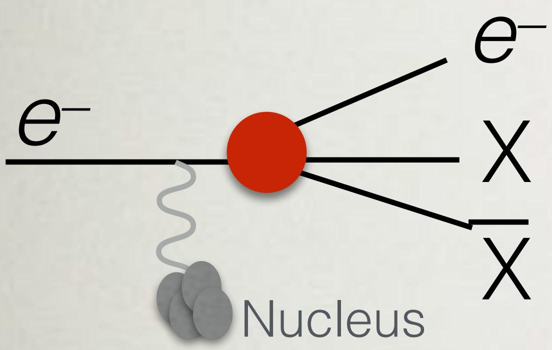


Yield often enhanced by on-shell mediator – pick parameters to keep this enhancement modest (i.e. conservative exlusions/ sensitivity)

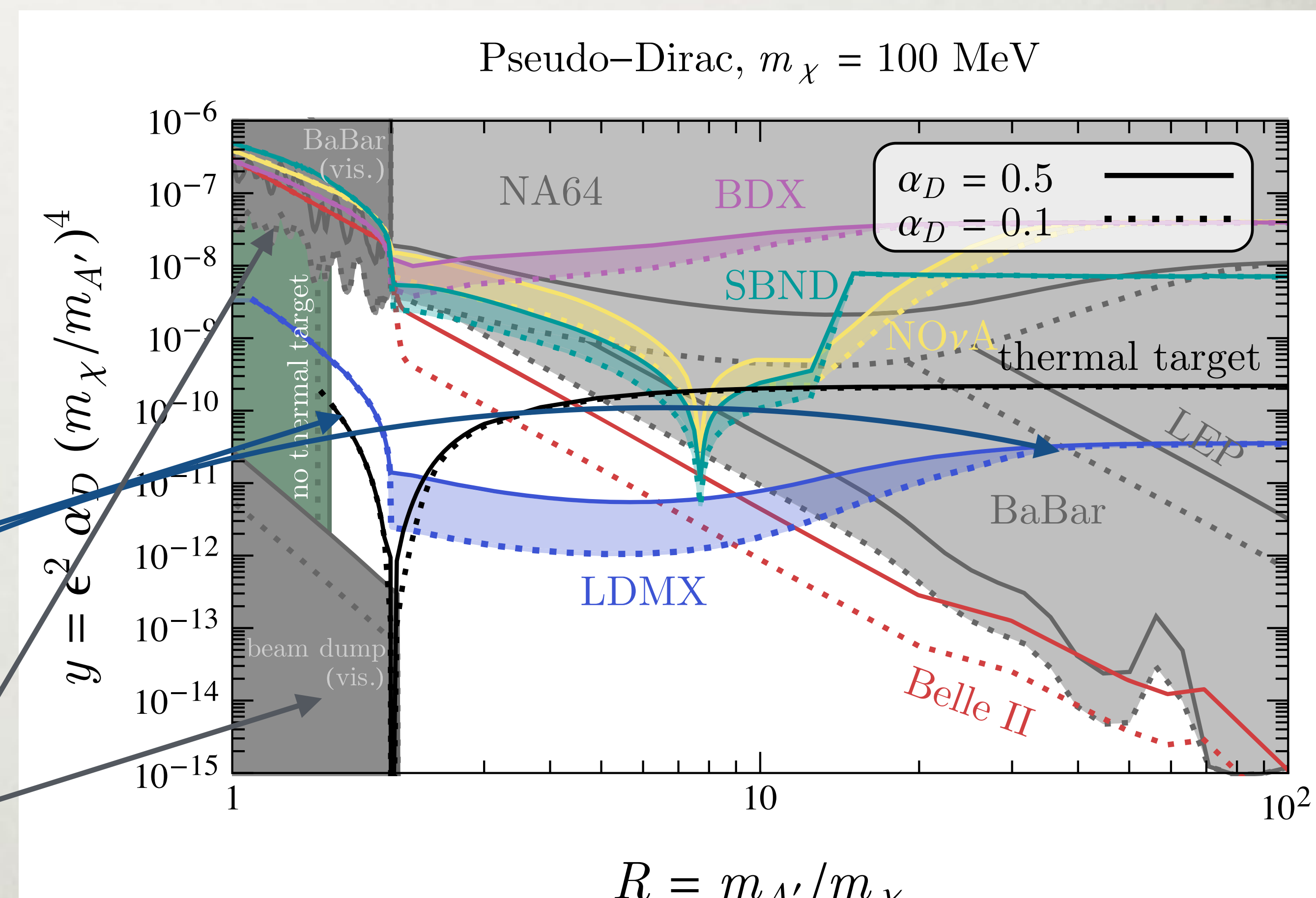
Good news for challenging cases I



Accelerator searches for dark matter probe semi-relativistic kinematics – similar to Big Bang production of DM, so different DM spins look similar.

Another parameter-space slice, highlighting

* DM search sensitivity when on-shell mediator not relevant (R<2 or »1)
* Complementarity of mediator searches (see B. Shuve, H. Otono talks)



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