Searching for long-lived particles in sub-GeV dark sectors

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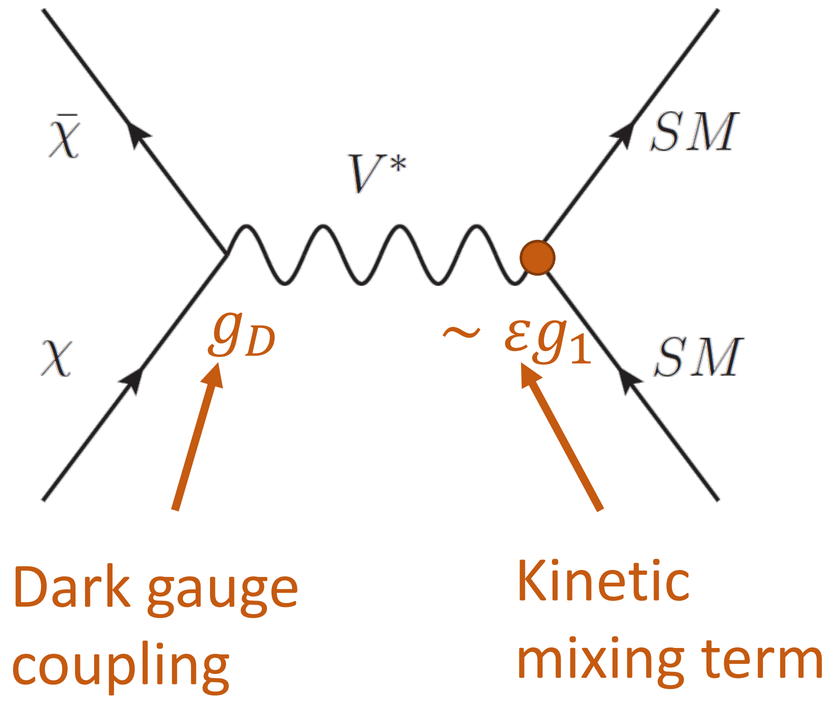
From LD, Rao, Roszkowski, 1807.00971

Thermal dark matter in the dark

Dark sector from sub-GeV dark matter

- WIMP models of Dark matter is a mature research area
  - Apply the same type of mechanisms, but lower mass range?
- Thermal sub-GeV dark matter easily achievable
  - Typically requires additional light dark sector, tasked with obtaining the proper relic density
- Let's consider a simple sub-GeV fermion DM example
  - Vector mediator -> Dark photon
  - Mass to the dark photon -> Dark Higgs
  - Dark matter -> Pseudo-Dirac fermion (i.e two Majorana fermions χ_1, χ_2 with small splitting Δ_χ)



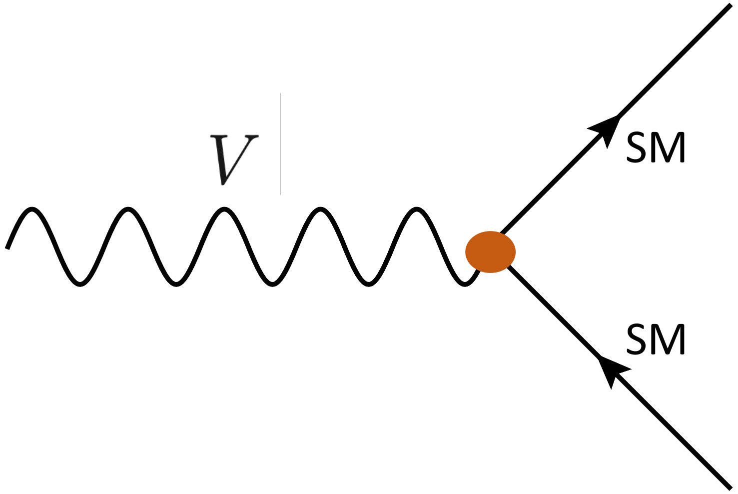
$$\Omega h^2 \sim 0.1 \times \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{0.1}{\alpha_D}\right) \left(\frac{25\ \text{MeV}}{M_\chi}\right)^2 \left(\frac{M_V}{75\ \text{MeV}}\right)^4$$

A key aspect – long-lived particles

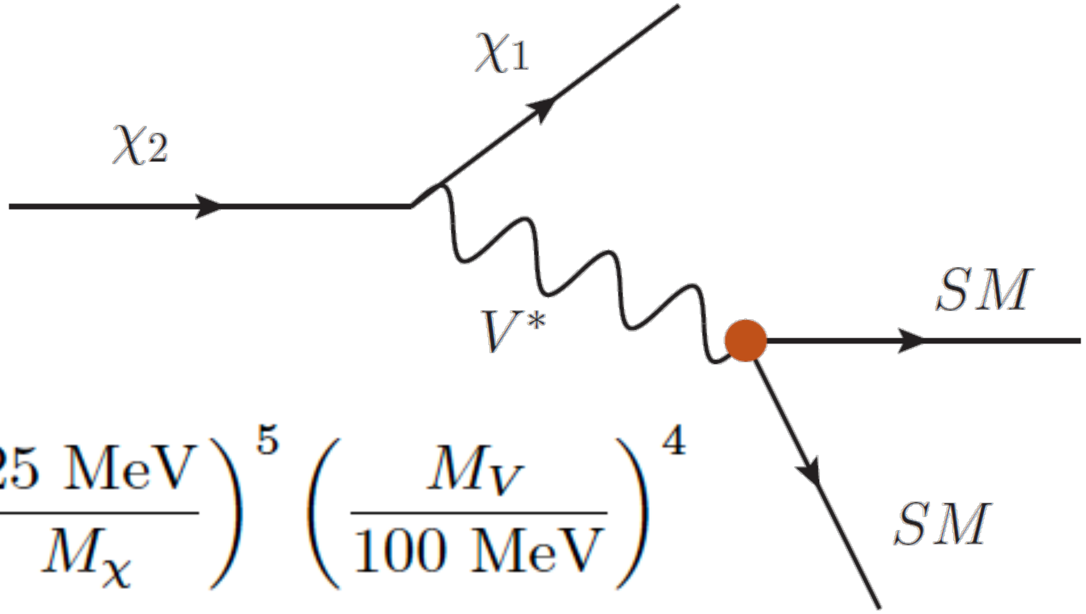
1. Decay to SM particles through the portal is the only option

   -> For instance dark photon

   -> Light dark Higgs boson (can be extremely long-lived)



2. Internal dark sector decays with mass thresholds → proceed through off-shell mediator
   - heavy dark sector state, or dark Higgs



$$c\tau_{\chi_2} \propto 100\ \mathrm{m}\ \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{10^{-3}}{\varepsilon}\right)^2\left(\frac{0.2M_\chi}{\Delta_\chi}\right)^5\left(\frac{25\ \mathrm{MeV}}{M_\chi}\right)^5\left(\frac{M_V}{100\ \mathrm{MeV}}\right)^4$$

Dark sector signatures at accelerators

Production and detection at accelerator-based experiments

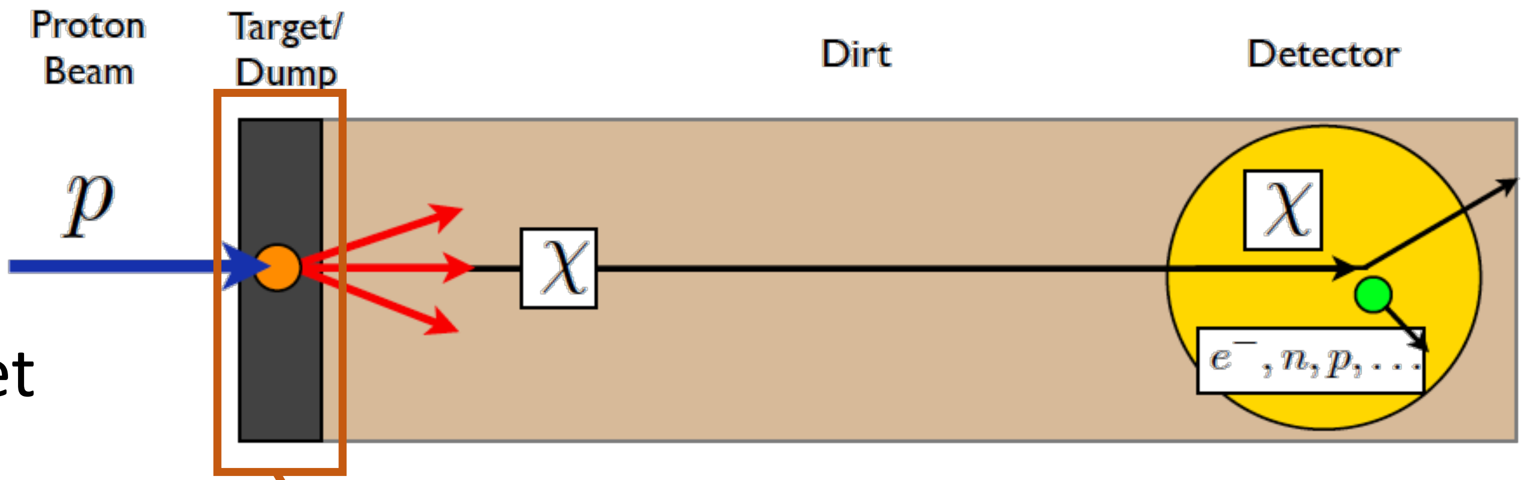
Dark Sector searches - production

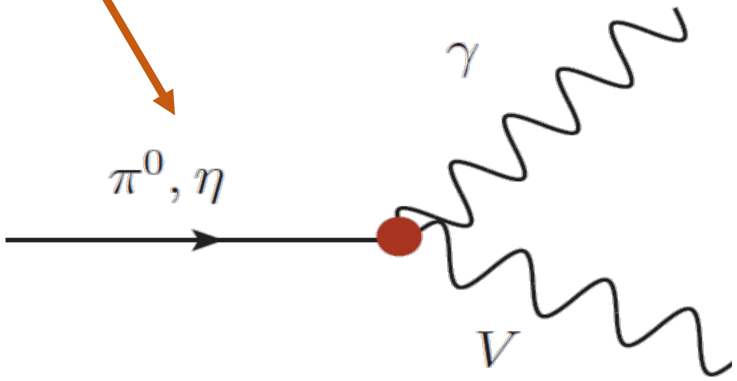
- Light dark sector particles may be accessible at the *intensity frontier*
  - « Low »-energy installations but with high intensity (LSND: $10^{22}\ \pi^0$)

- Colliders (BELLE, ...)
- Beam-dump/fixed-target types of experiments

→ Neutrinos (LSND, miniBooNE ...)

→ Rare mesons decay (NA64, ...)

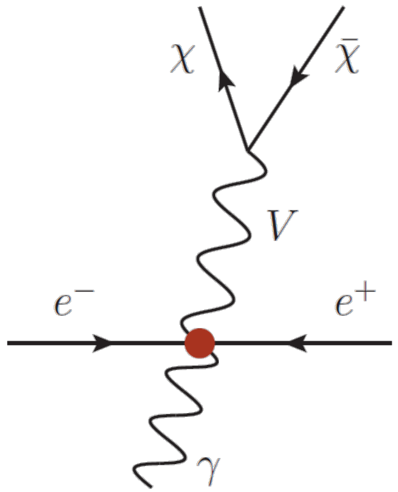




production through meson decays

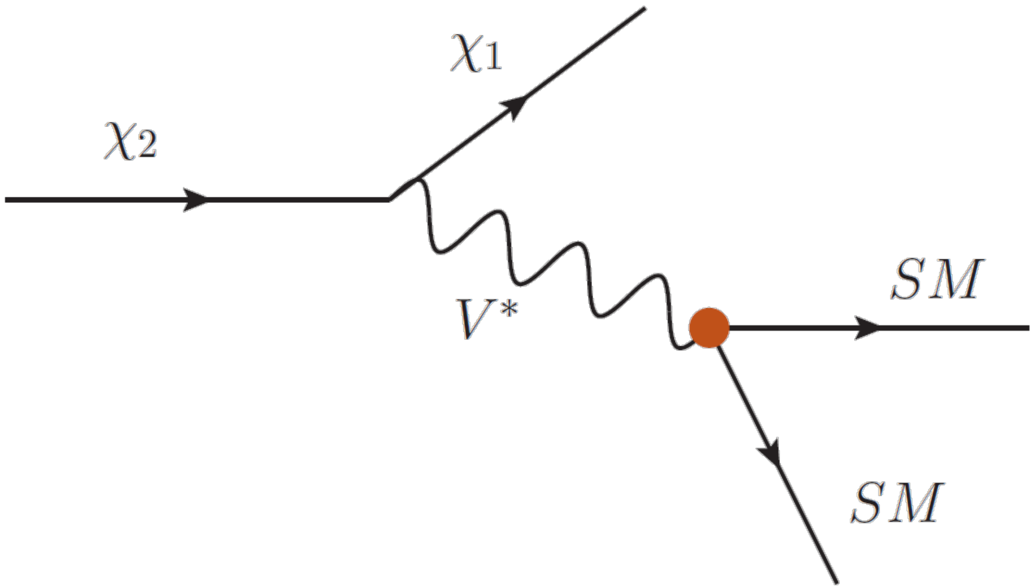
Dark Sector searches -detection

- Missing energy/ Invisible decay: Mono-photon searches missing energy signature @ BaBar, NA64.
  - Mostly model independent, $\varepsilon < 10^{-3}$



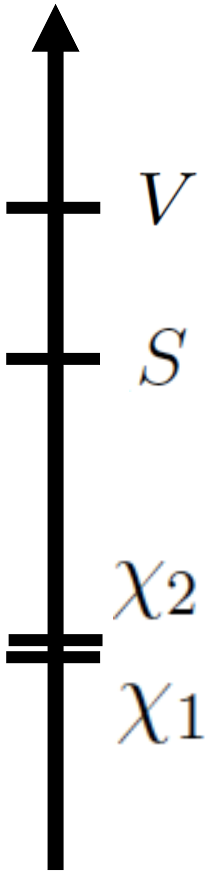
- Dark sector Scattering : Searching for DM via scattering

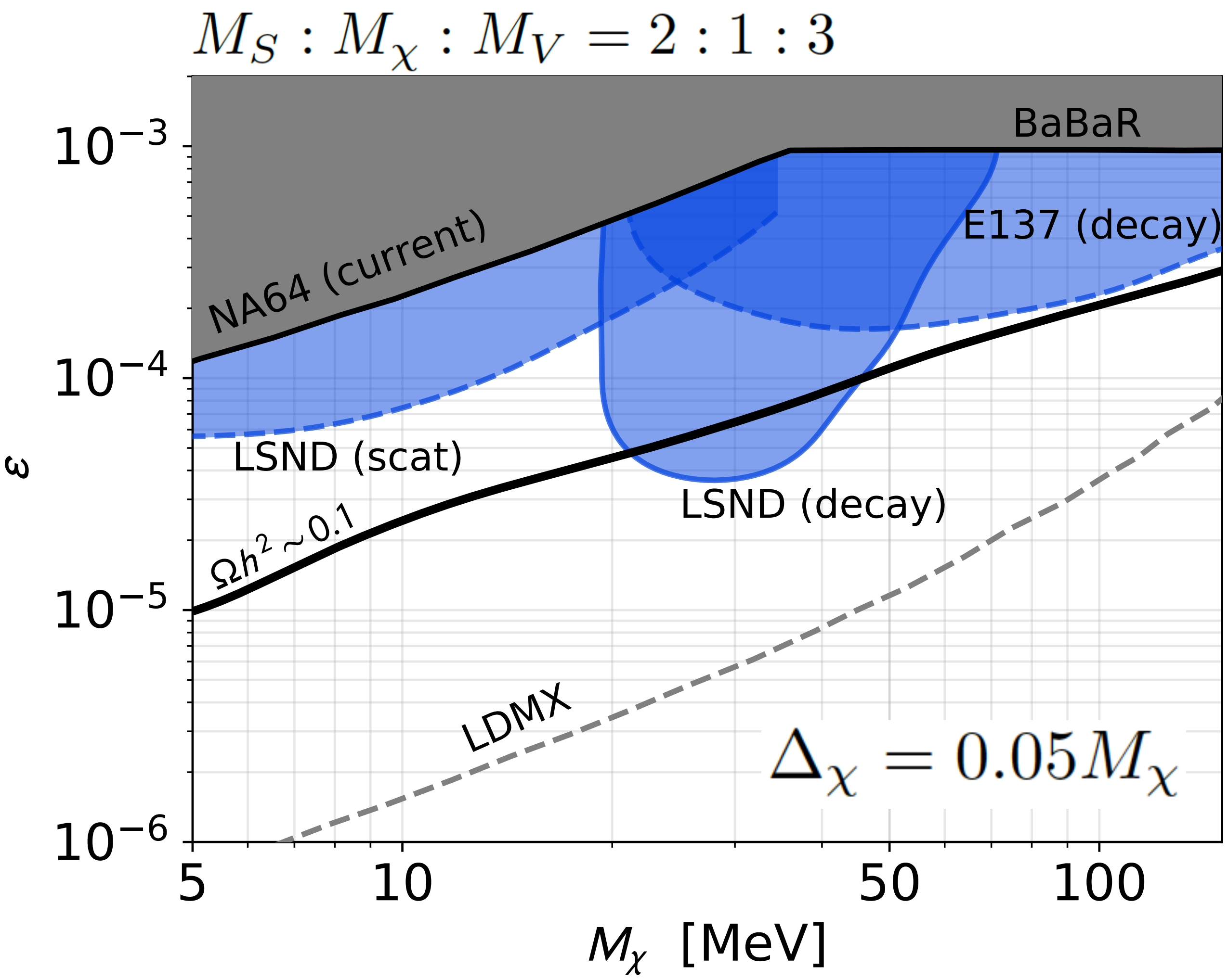
- Dark sector visible decay: Detection of an electron/positron pair in fixed target/beam dump experiments/long-baseline neutrinos experiments (E137,LSND, miniBooNE …)



Inelastic DM regime

- Relic density fixed by s-channel, co-annihilation process: $\chi_1\chi_2 \to e^+e^-$

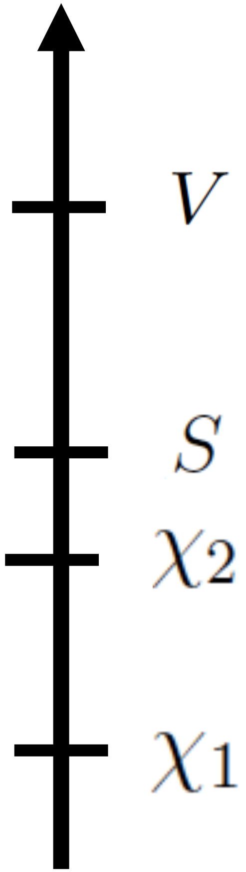


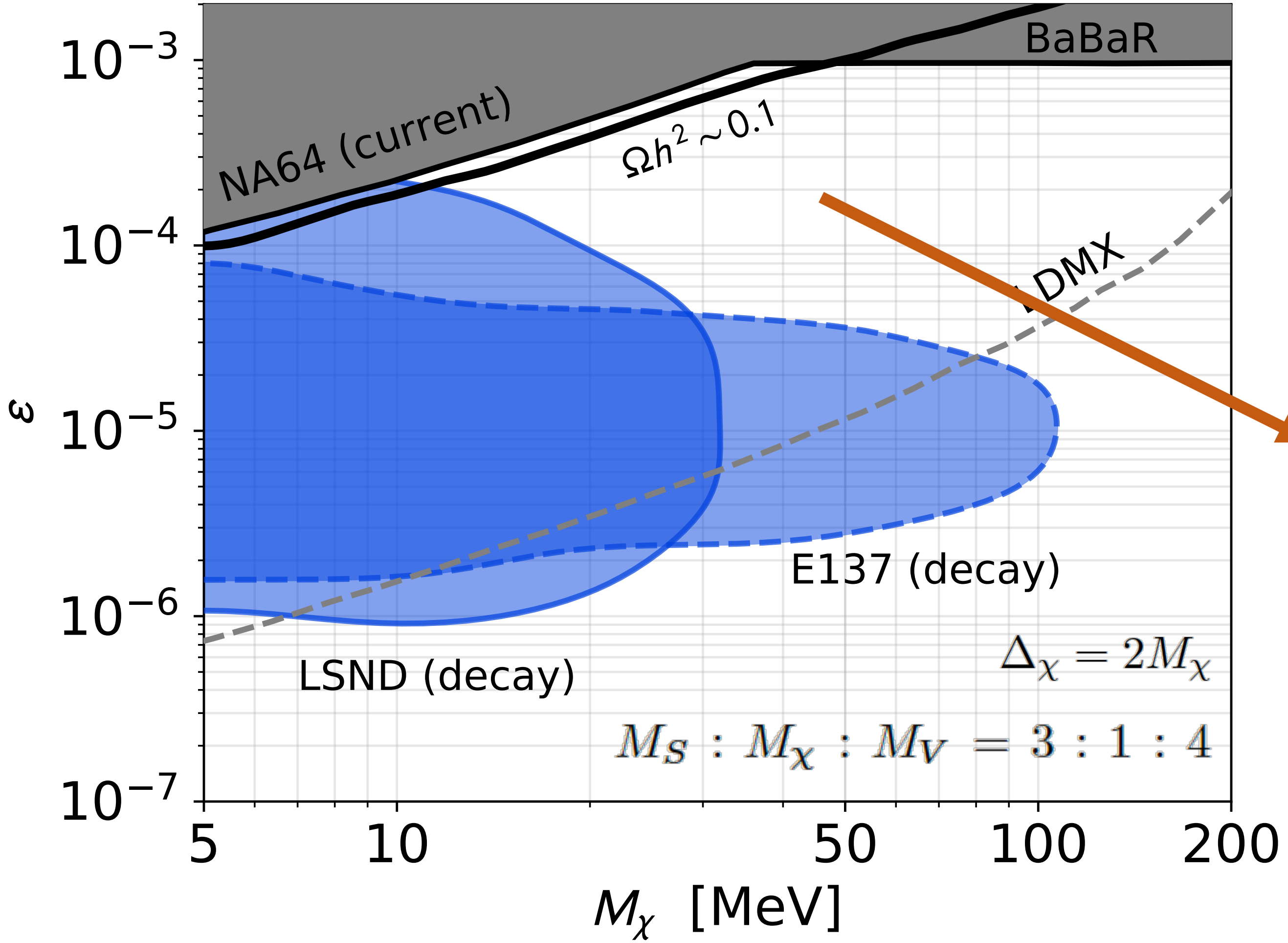


- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+e^-$ decay
  - χ_1 scattering
- When consider dark sector decays, decades-old experiment are still strongly ahead of current mono-photon searches!

Heavy dark sector decay in mDM

- Relic density fixed by s-channel, p-wave process: $\chi\chi \to e^+e^-$



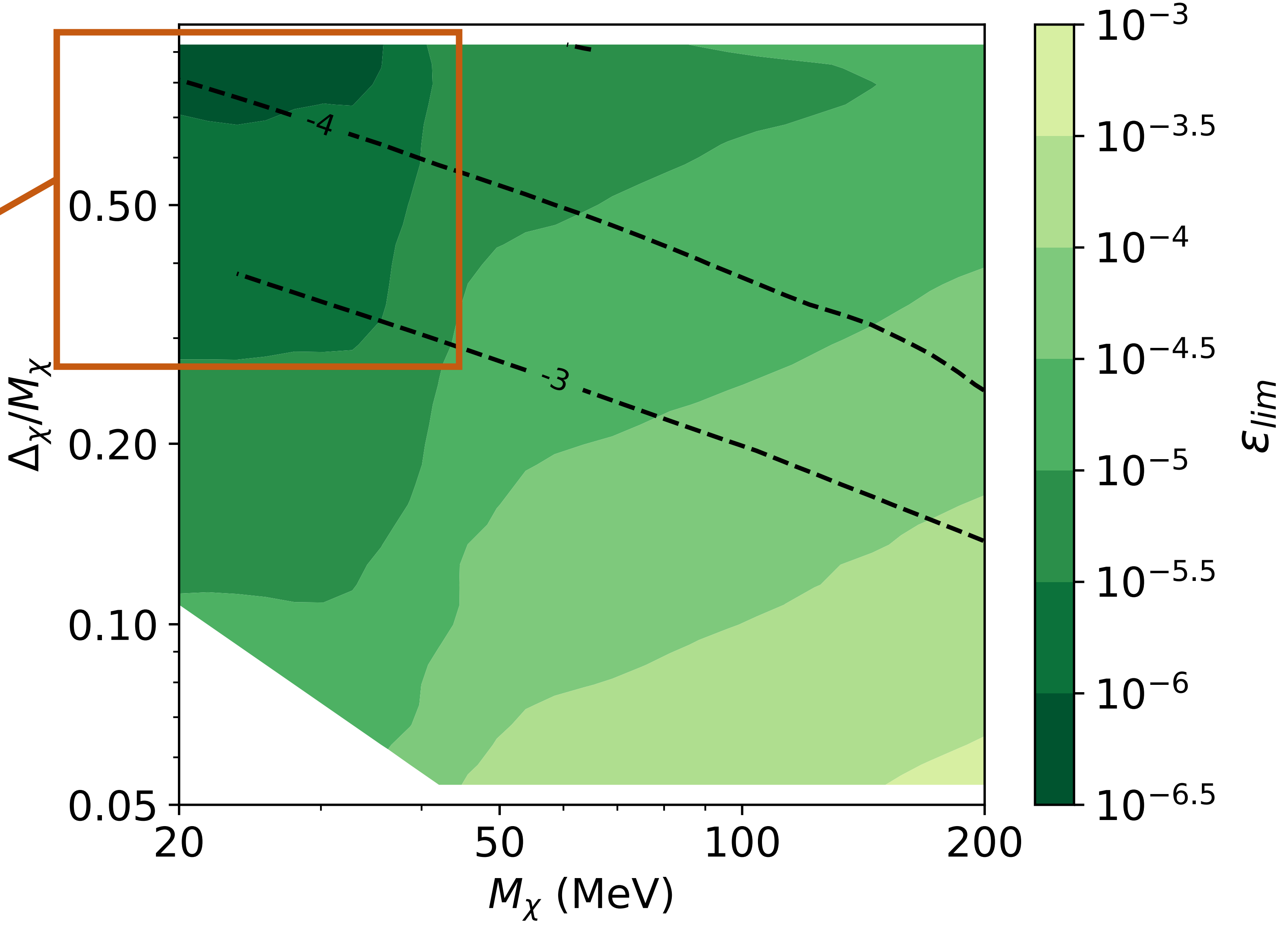


- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+e^-$ decay
- For large splitting, lifetime of order meter, $c\tau_\chi < 1\,m$
  - long baseline experiments like E137 miss critical part of the parameter space
  - Opportunity for others, MAGIX, SeaQuest, …

Mass splitting and life-time

- Model dependence but extremely strong bounds

- Formation of a detection gap (decay before the detector)



Conclusion

Conclusion

- Light thermal dark matter candidates typically carry with them a dark sector with long-lived particles
- The dark sector allows more freedom in realizing the correct relic density.
- Lead to rich phenomenology in intensity frontier experiments
  - Accelerator searches, neutrino/dark sector/flavor experiments means bright prospects for dark sector searches
  - The accompanying dark sector offers both fascinating detection prospects and very strong astrophysical bounds (BBN …)
- Dedicated analysis in such experiments have typically a strong discovery potential

Backup slides

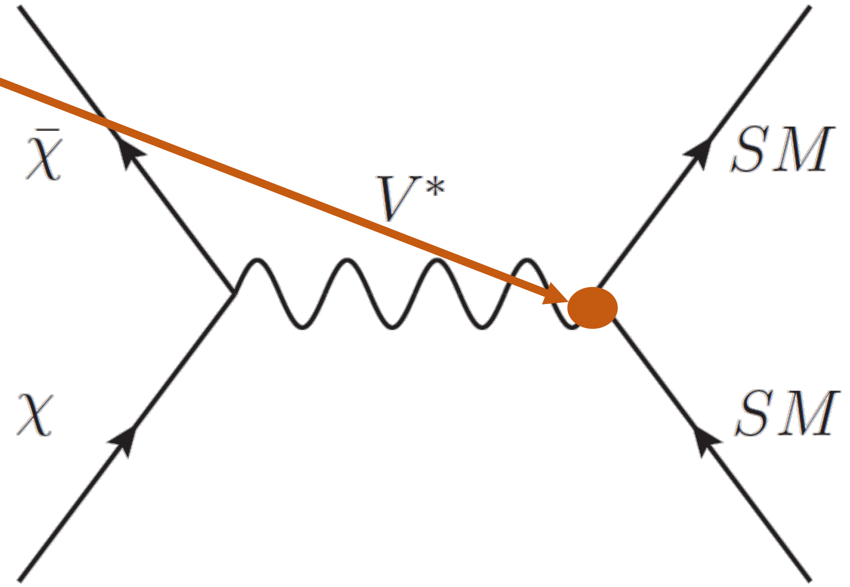
Example dark sector

- Coupling to SM obtained through "kinetic mixing" term

Kinetic mixing term

$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \boxed{\frac{1}{2}\frac{\varepsilon}{\cos\theta_w}B_{\mu\nu}F'^{\mu\nu}}$$
$$\boxed{+ (D^\mu S)^*(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4}$$

Dark Higgs potential



- After "dark" U(1) symmetry is broken, a massive light dark photon and a correspondingly light dark Higgs S.

Fermion dark matter example

$$\mathcal{L}_{pDF}^{\mathrm{DM}} = \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + y_{SL} S \bar{\chi}^c P_L \chi + y_{SR} S \bar{\chi}^c P_R \chi \; + \; \mathrm{h.c.}$$

- Anomaly cancellation -> Introduce a Dirac fermion dark matter $\chi = (\chi_L, \bar{\chi}_R)$ with Yukawa couplings to the dark Higgs S

- After $U(1)_D$ symmetry breaking, the dark matter acquires a Majorana mass

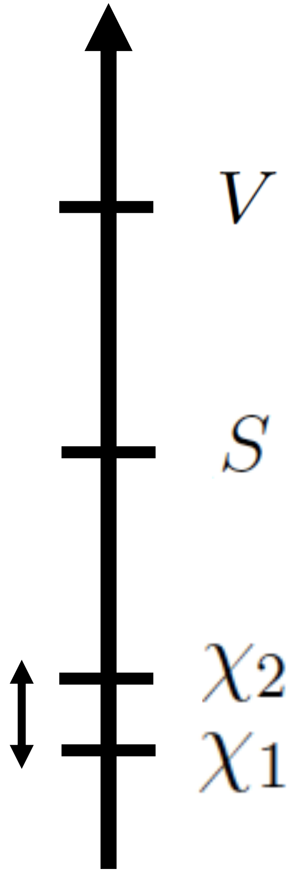
$$M_\chi = \begin{pmatrix} \sqrt{2} v_S y_{SL} & m_\chi \\ m_\chi & \sqrt{2} v_S y_{SR} \end{pmatrix}.$$

- After diagonalization → two Majorana fermions

$$M_V = g_{\alpha_D} q_S v_S$$

$$M_S = \sqrt{2\lambda_S} v_S$$

$$M_{\chi_2} - M_{\chi_1} = \sqrt{2} v_S (y_{SR} + y_{SL})$$



The case for small Higgs/Dark Higgs mixing

- Both the SM and dark Higgs potential must be minimised simultaneously

$$\mathcal{L} \supset \frac{\lambda_{SH}}{2}|S|^2|H|^2 \longrightarrow \begin{aligned} v_S^2 &= \frac{1}{\lambda_S}\left(\mu_S^2 - \boxed{\frac{\lambda_{SH}}{2\lambda_H}\mu_H^2}\right) \\ v_H^2 &\simeq \frac{\mu_H^2}{\lambda_H} \end{aligned}$$

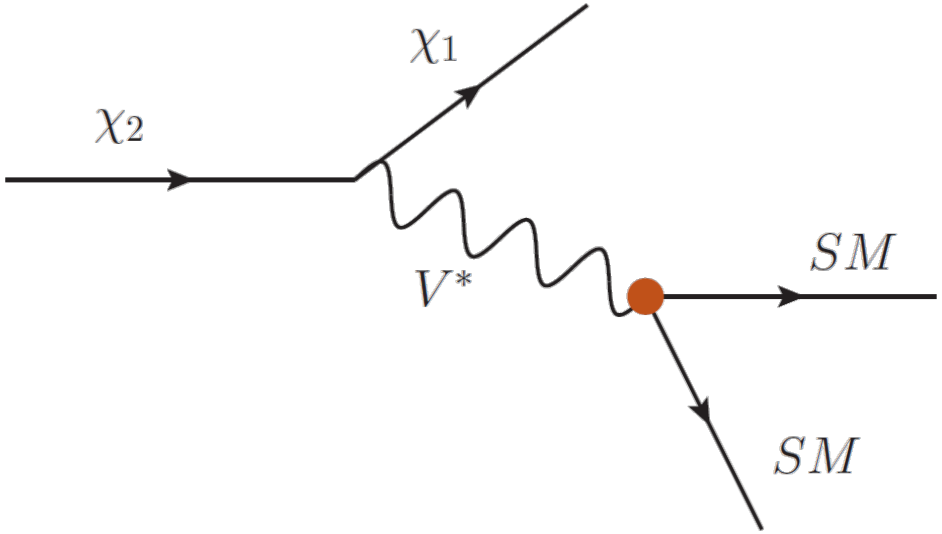
- In order to avoid tuning the bare mass μ_S against the SM Higgs contribution, this implies

$$\longrightarrow \lambda_{SH} \sim \frac{M_S^2}{v_H^2} \sim 10^{-8} \text{ - } 10^{-6}$$

$$\tau_{S,H\text{mix}} \propto 1 \cdot 10^6 \text{ s} \times \left(\frac{100 \text{ MeV}}{M_S}\right)\left(\frac{100 \text{ MeV}}{M_V}\right)^2\left(\frac{10^{-6}}{\lambda_{SH}}\right)^2\left(\frac{q_S^2\alpha_D}{\alpha_{\text{em}}}\right)$$

Heavy dark sector decays

- Dark sector decays through off-shell mediator -> typical decay length of order meter
  - →Decay into pair of electrons (no background)
  - →In optimum region, large portion of the heavy dark states decay in the detector



$$c\tau_{\chi_2} \propto 100\ \mathrm{m}\ \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{10^{-3}}{\varepsilon}\right)^2\left(\frac{0.2}{\Delta_\chi}\right)^5\left(\frac{25\ \mathrm{MeV}}{M_S}\right)^5\left(\frac{M_V}{100\ \mathrm{MeV}}\right)^4$$

- In the optimum case $\mathrm{NoE}_{\mathrm{HDS}} \propto \varepsilon^2$

- Dark Higgs boson can belong to this category with $S \rightarrow Ve^+e^-$ is opened

Looking forward …

- Many upcoming relevant experiments: both neutrino , dark sector-oriented/Rare mesons decay ones

Running: Belle II, BDX@JLab, SBN, SeaQuest, NA62, KOTO

2020: LHCb Run 3, FASER, NA62+

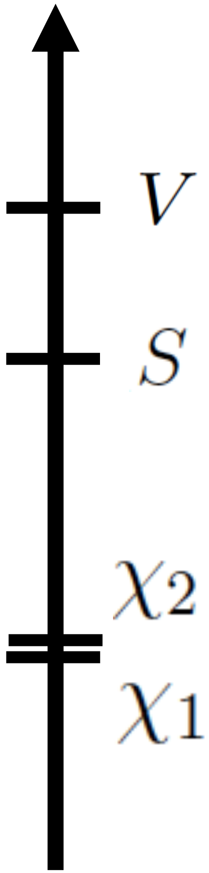
2021: MAGIX, BDX @MESA

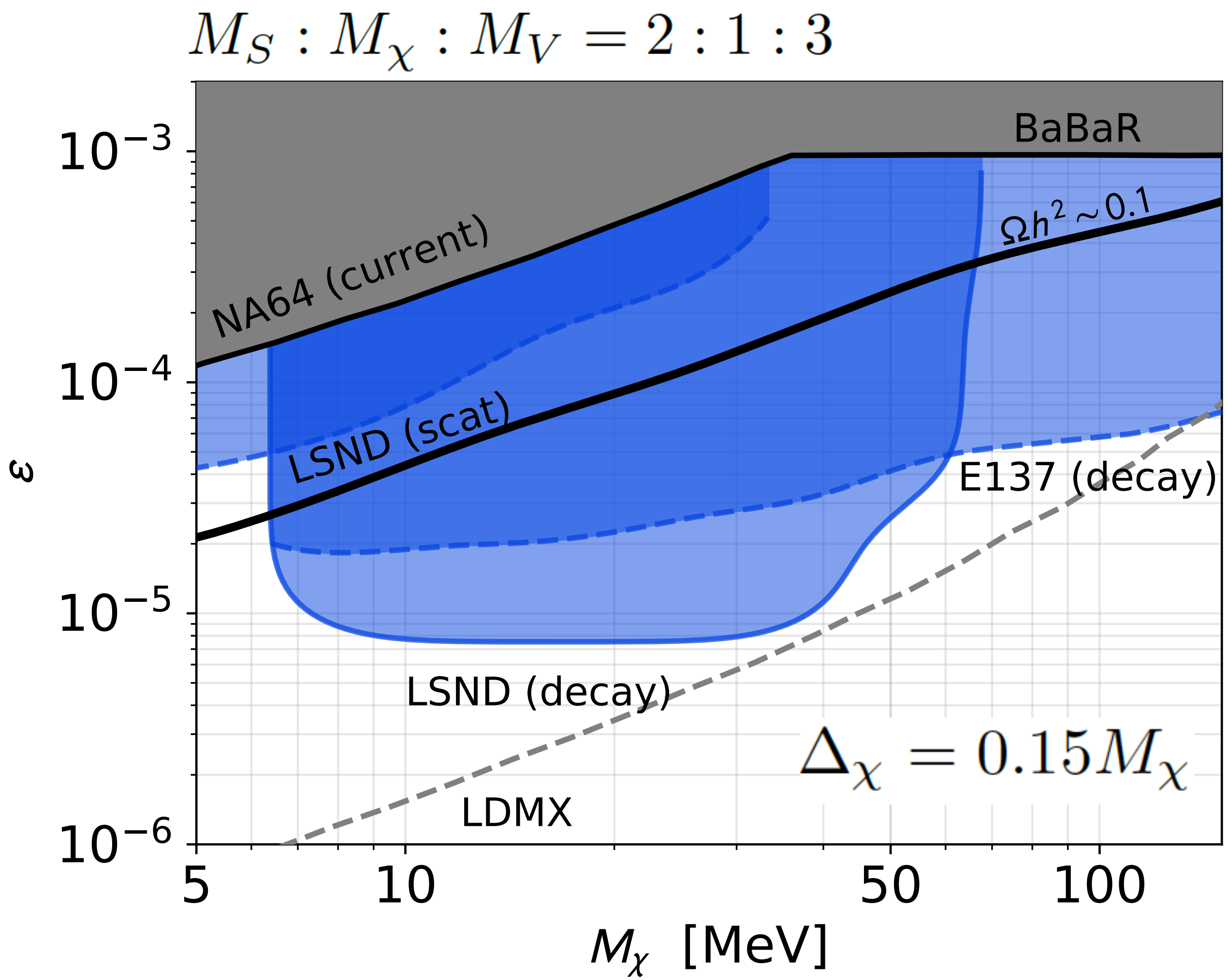
Around HL-LHC: MATHUSLA, SHIP, CODEX-b, KLEVER, LBNF/DUNE

(Many missing, not all of them are funded yet…)

Inelastic DM regime

- Relic density fixed by s-channel, co-annihilation process: $\chi_1\chi_2 \to e^+e^-$

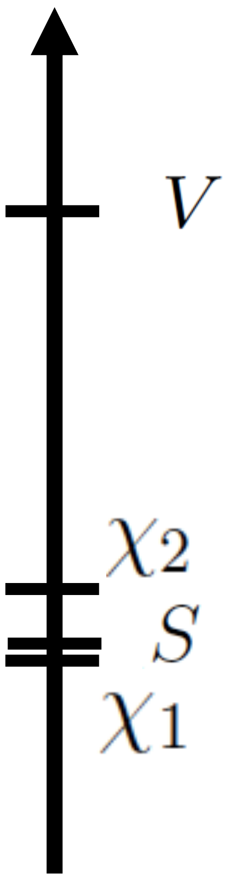


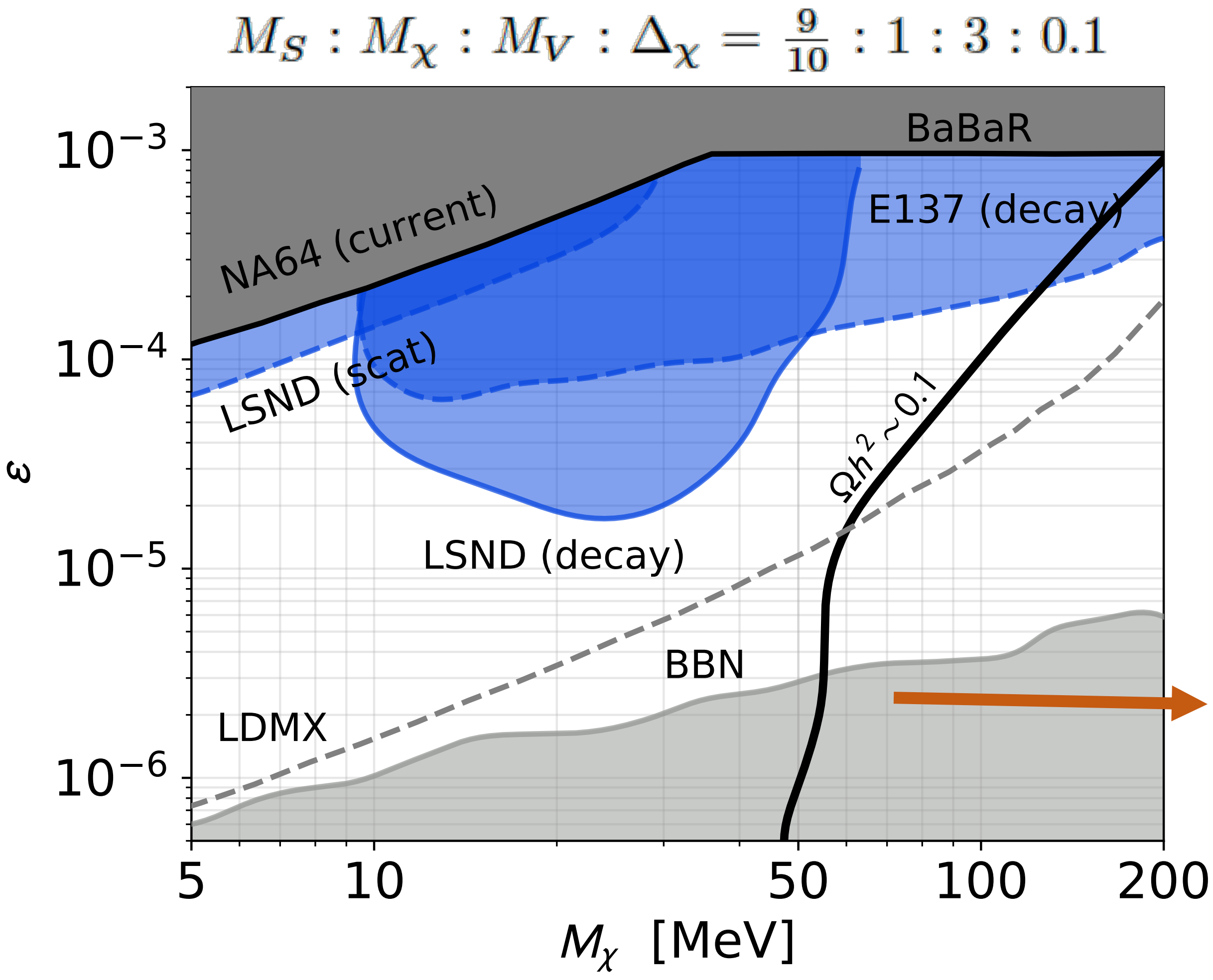


- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+e^-$decay
  - $\chi_1$scattering
- When consider dark sector decays, decades-old experiment are still strongly ahead of current mono-photon searches!

Secluded DM regime

- Relic density mainly fixed by t-channel process, $\chi\,\chi \to S\,S$



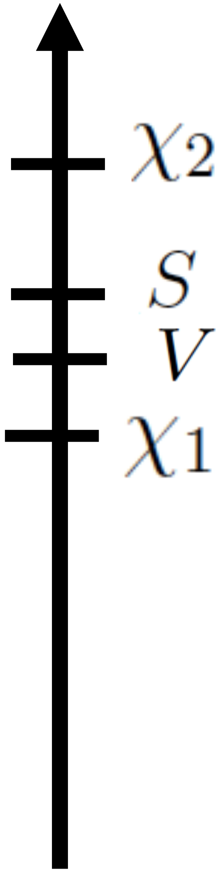


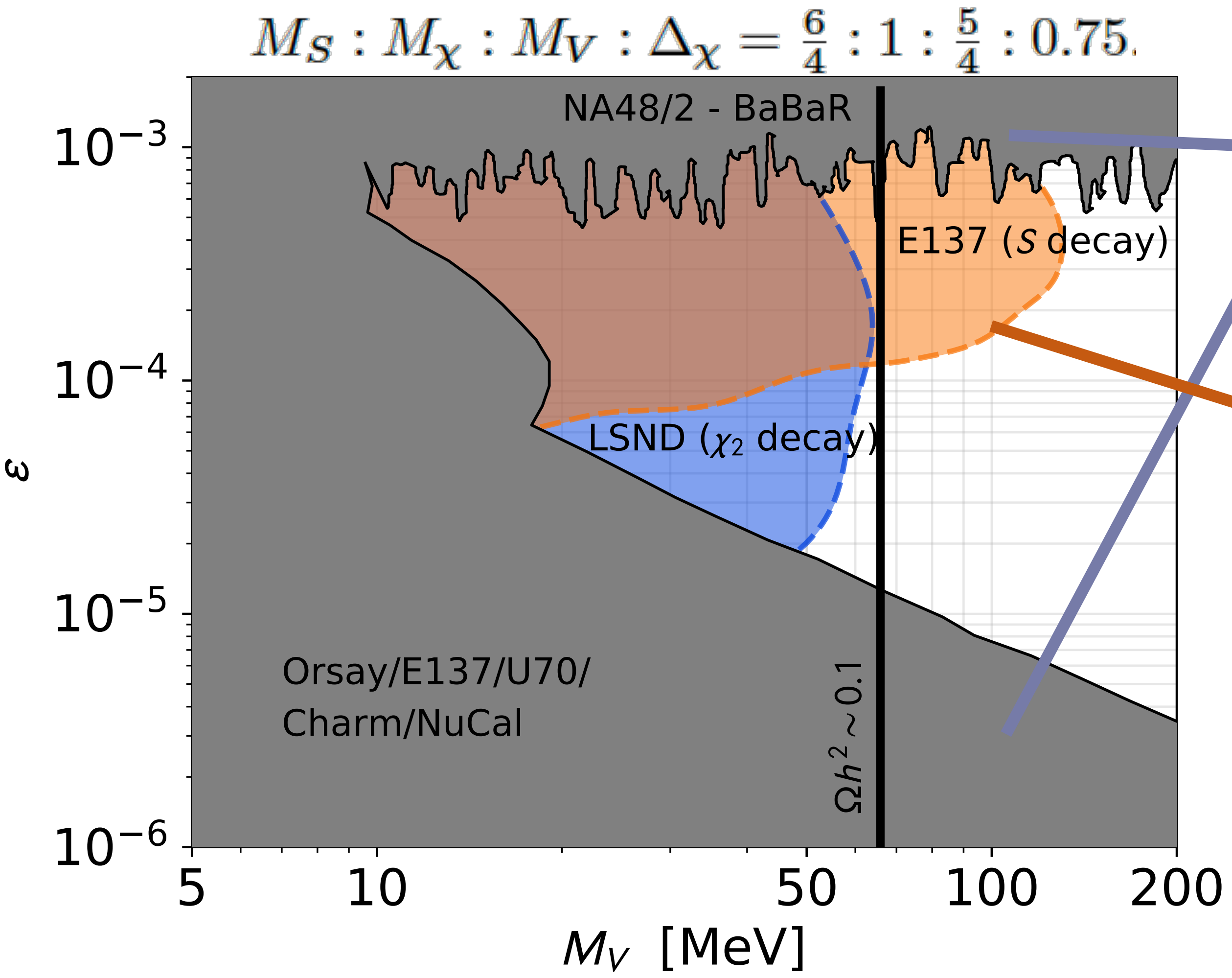
- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+ e^-$ decay
  - χ_1 scattering

- Dark Higgs boson is both very long-lived and abundantly produced
  → BBN bound

Forbidden DM regime

- Relic density fixed by thermally suppressed t-channel process, $\chi\,\chi \to V\,V$

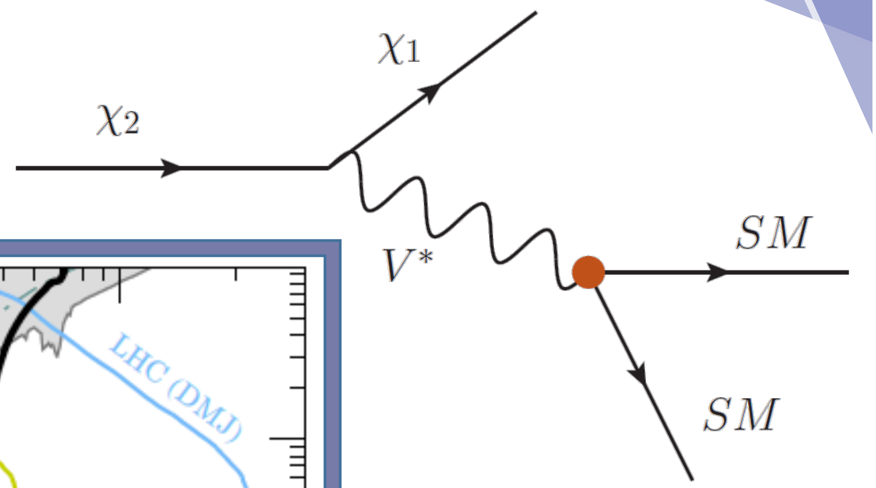




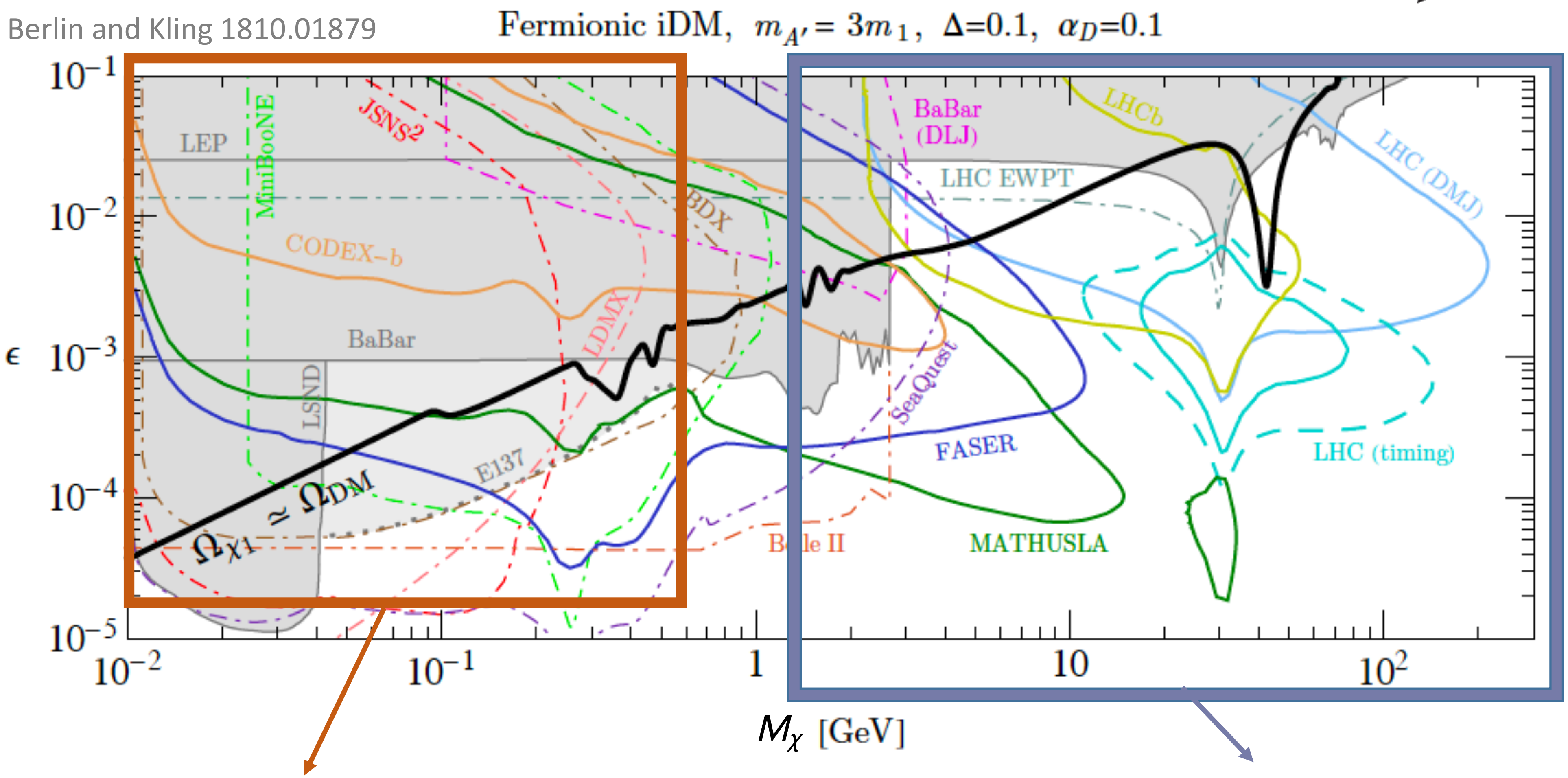
- $M_V \sim M_\chi \rightarrow$ Dark photon decays visibly
- $S \to V\, e^+ e^-$ kinematically open, dark Higgs lifetime shorter

  $c\,\tau_S \sim 1 - 100\, m$
- Thermal target independent of kinetic mixing

Heavy dark sector decays (2)

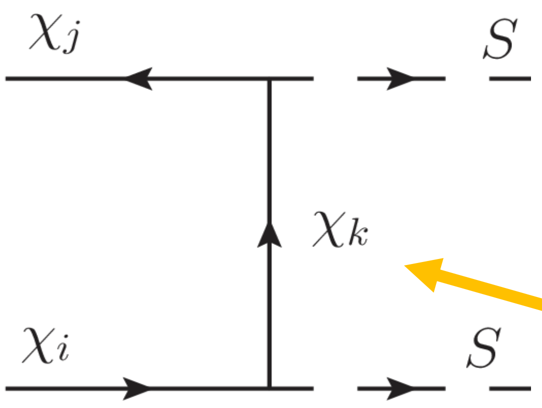


From Berlin and Kling 1810.01879

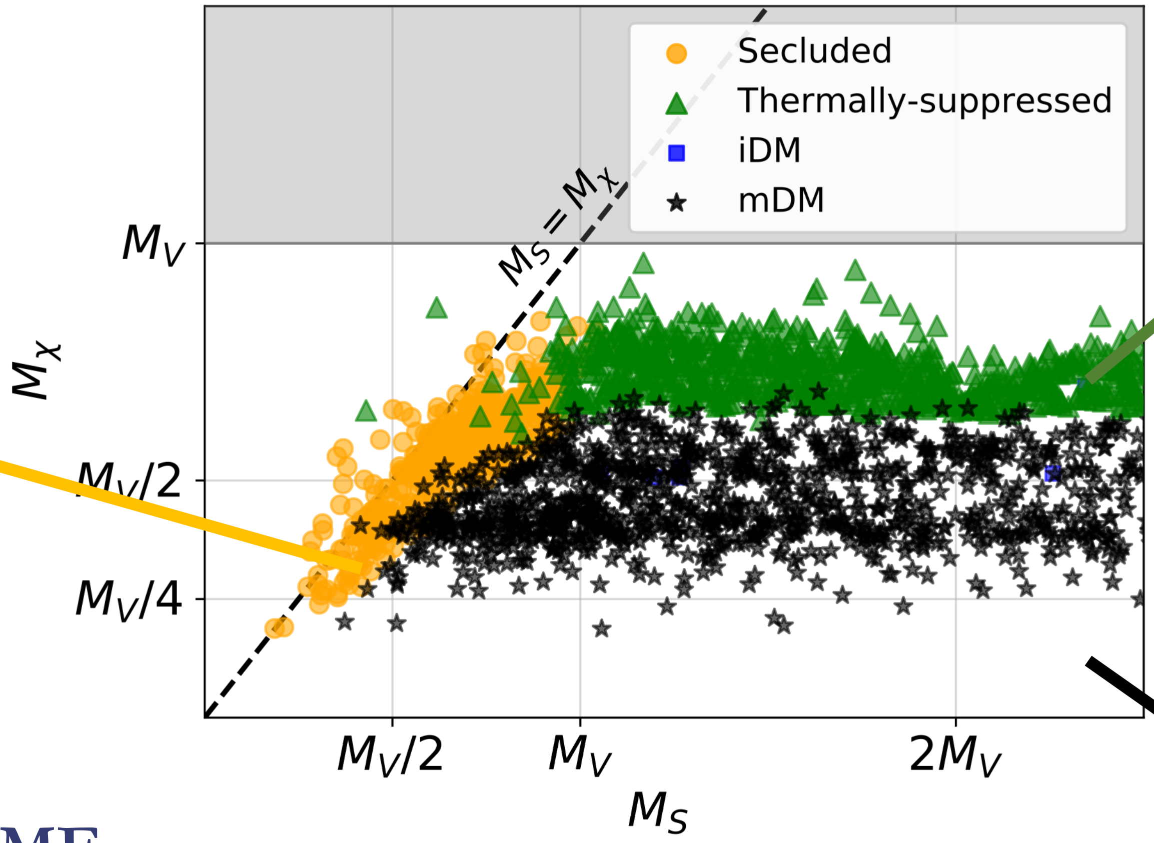


- High-intensity frontier: basically electrons physics
- LHC-related: Displaced muon jets, LLP…

Typical regimes with correct relic density

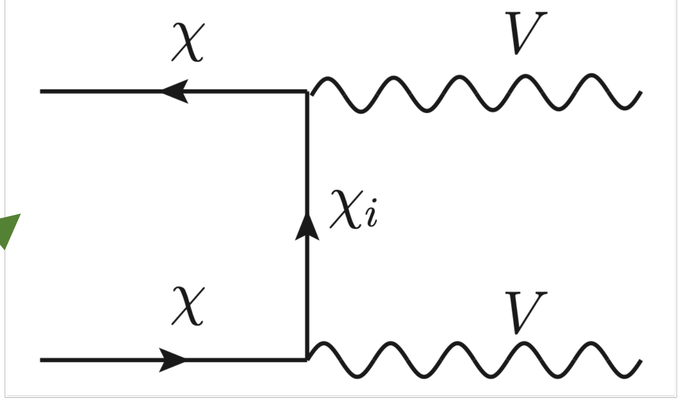


$$M_\chi \gtrsim M_S$$



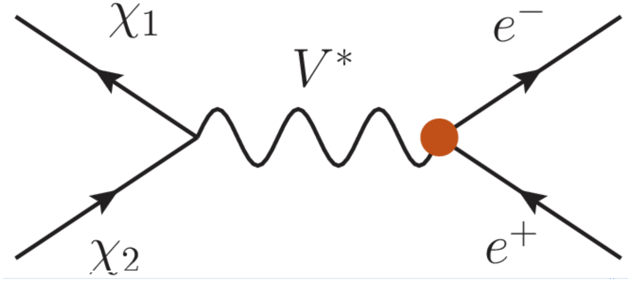
SECLUDED REGIME

FORBIDDEN REGIME

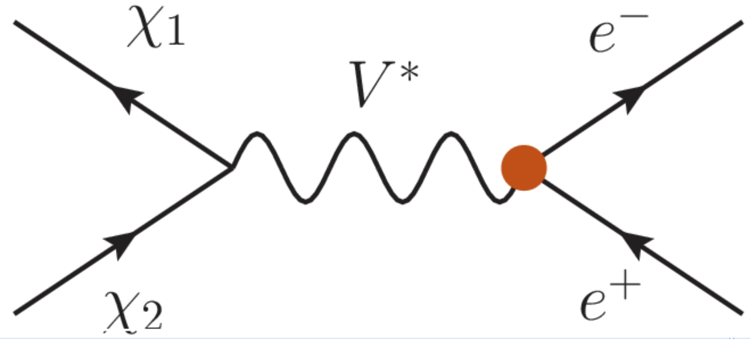


$$M_\chi \lesssim M_V \lesssim M_S$$

iDM/mDM REGIME



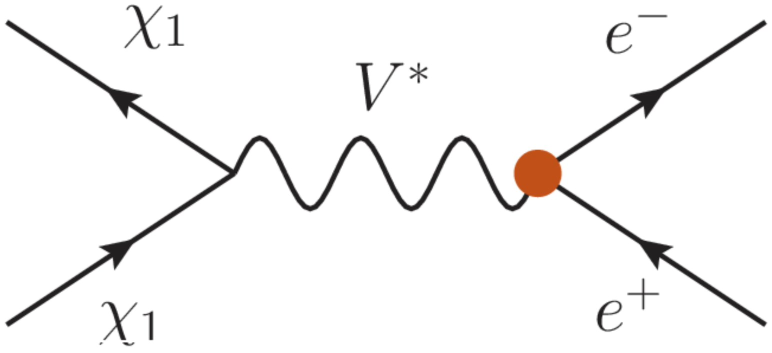
Fermion DM: Relic density (1)



$$\sigma \propto \varepsilon^2 \alpha_D$$

- Relevant in Pseudo-Dirac limit

Co-annihilation process



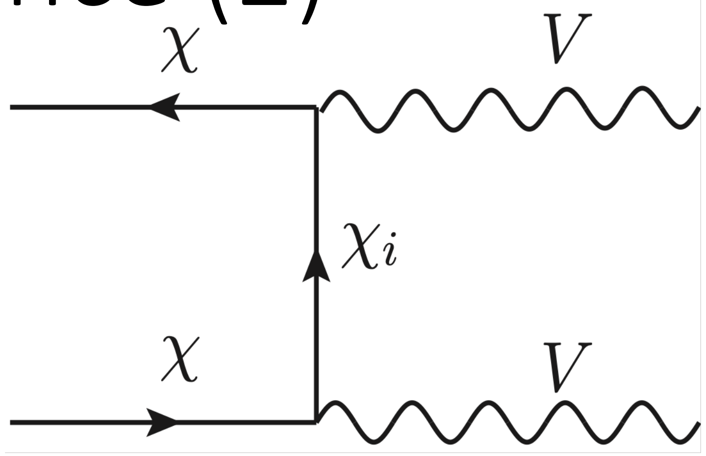
$$\sigma \propto \frac{v_S^2}{m_\chi^2} (y_{SR} - y_{SL})^2 \varepsilon^2 \alpha_D$$

- Relevant in high-splitting case

p-wave process

$$\begin{pmatrix} \boxed{\sqrt{2} v_S y_{SL}} & \boxed{m_\chi} \\ \boxed{m_\chi} & \boxed{\sqrt{2} v_S y_{SR}} \end{pmatrix}$$

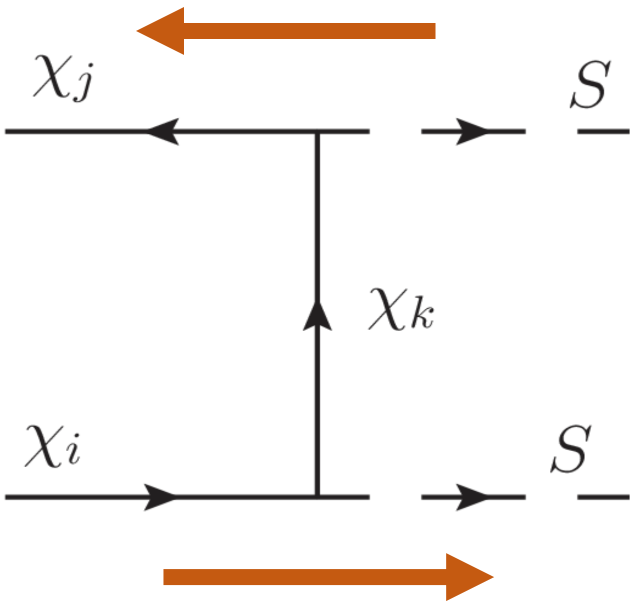
Relic density – Dark sector influence (2)



- Forbidden DM: annihilation into dark photon also possible, Thermal suppression due to mass

$$M_\chi \lesssim M_V \lesssim M_S$$

→ Exponentially suppressed at CMB temperature



- Typically allows for a "secluded" DM annihilation
  - The dark Higgs is long-lived -> participates in freeze-out, gets a metastable density.

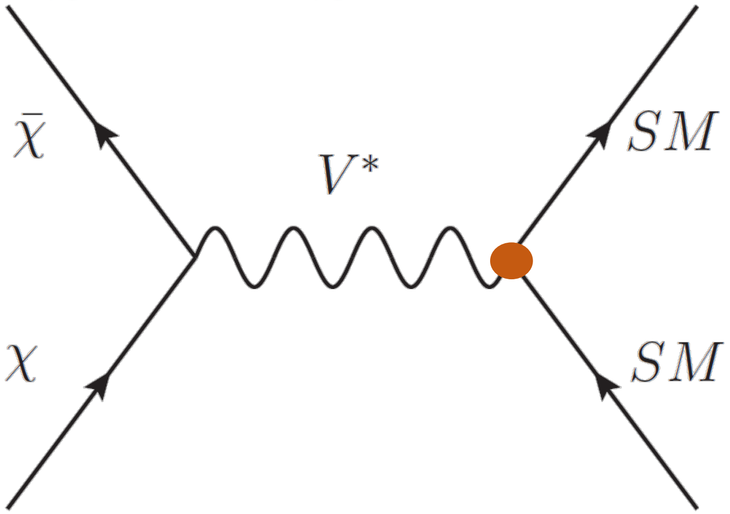
p-wave process - >Velocity suppressed

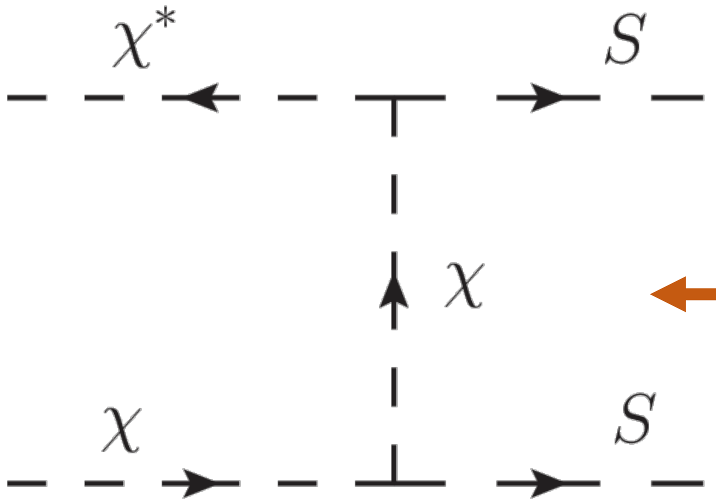
Aside: simple scalar case

- We introduce a complex scalar DM χ charged under $U(1)_D$

$$\mathcal{L}_{CS}^{\rm DM} = (D^\mu \chi)^*(D_\mu \chi) - m_\chi |\chi|^2 + \lambda_\chi |\chi|^4 + \lambda_{\chi S} |\chi|^2 |S|^2$$

- Relic density from s-channel annihilation



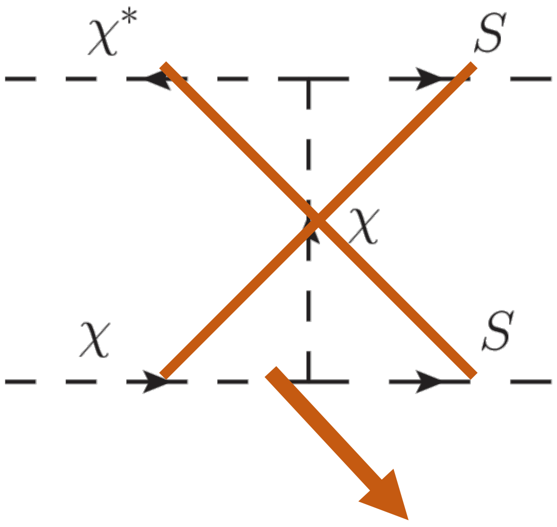


Or through t-channel $\chi^*\chi \to S\,S$ is s-wave

CMB bounds -- the scalar case

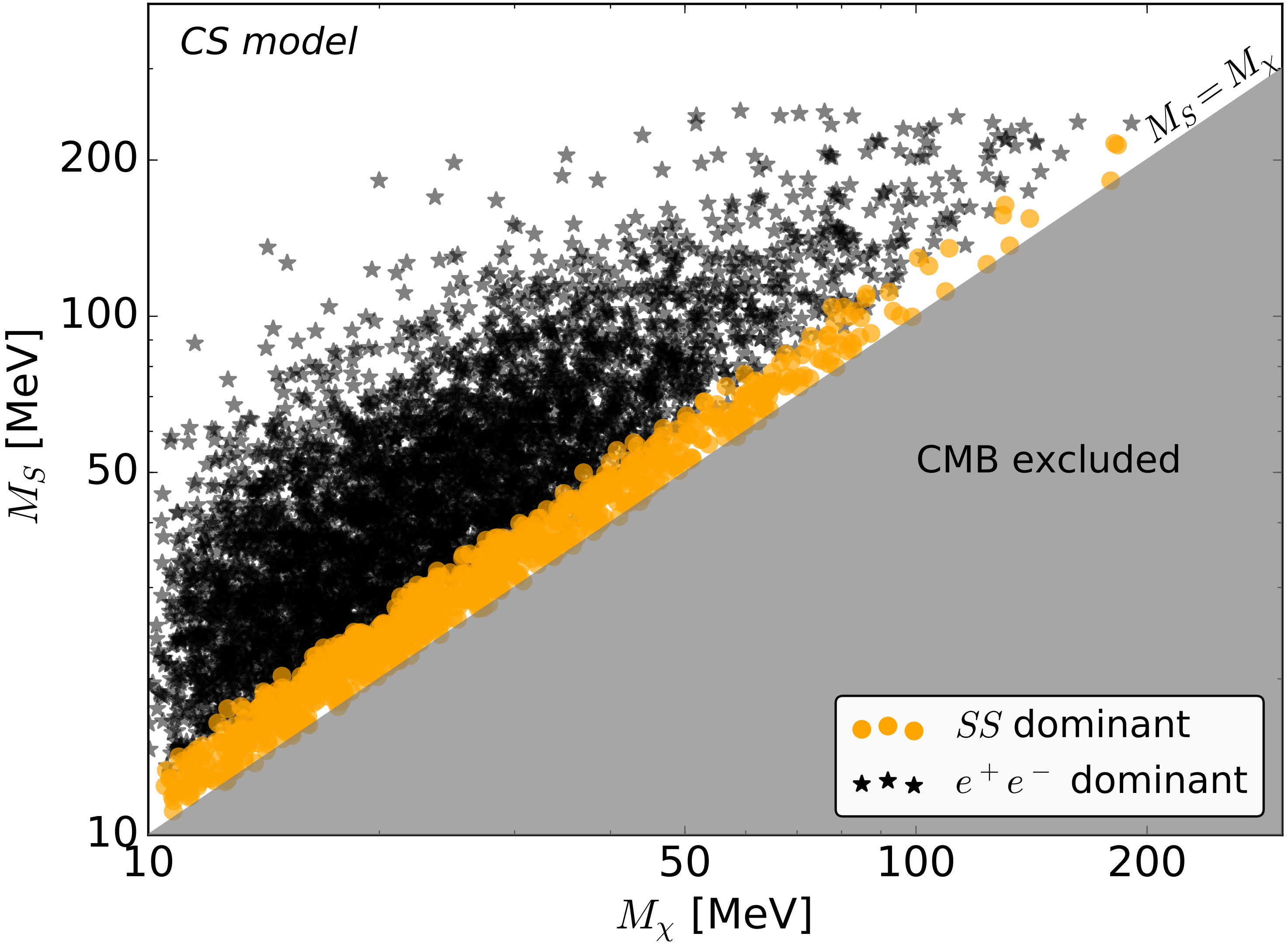
- Planck measurements,

  → forbids dark matter with s-wave annihilation and mass below the tens of GeV (1604.02457)



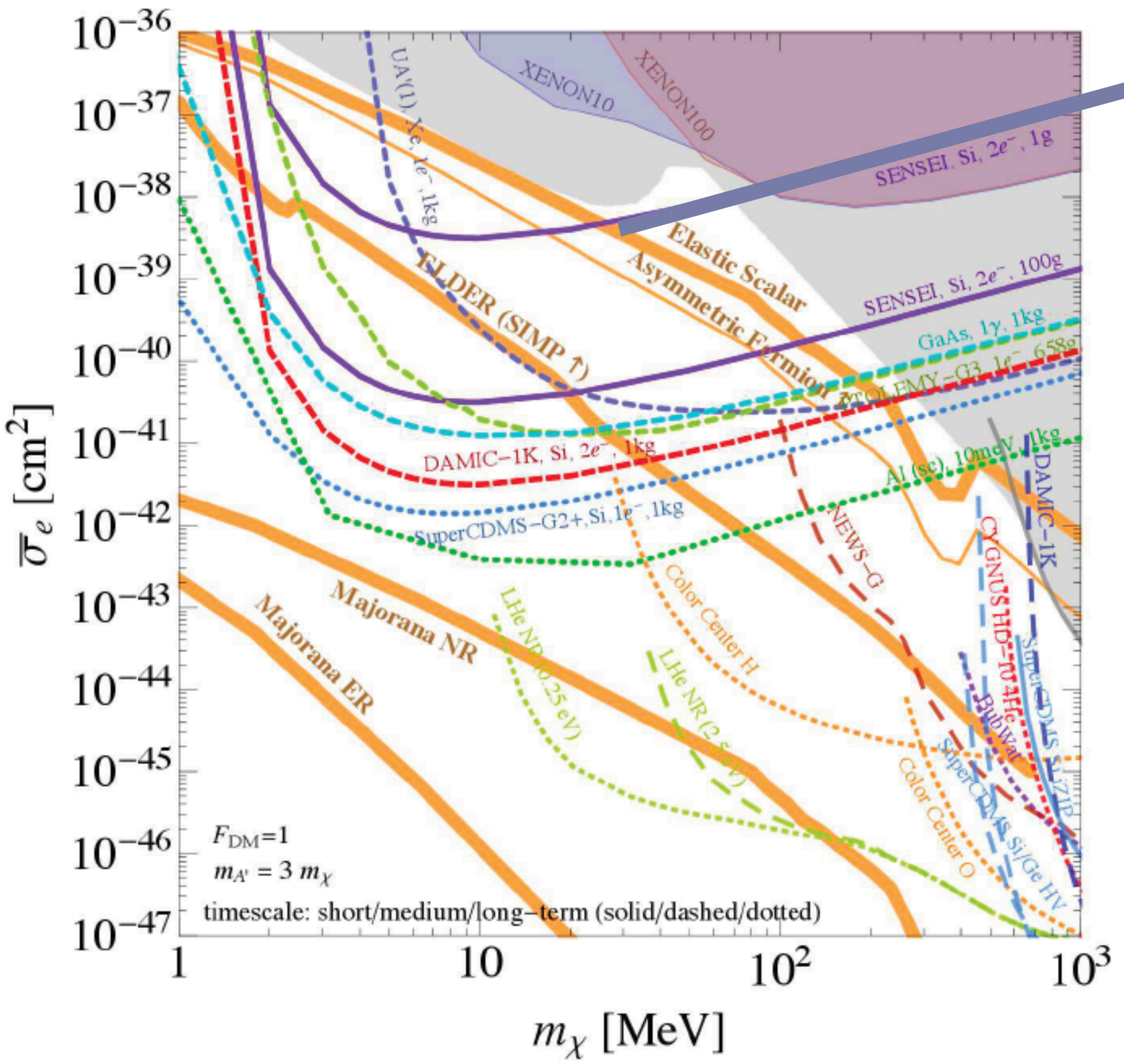
$M_\chi < M_S$

LD, Rao, Roszkowski, 1710.00971



Direct Detection

From 1707.04591



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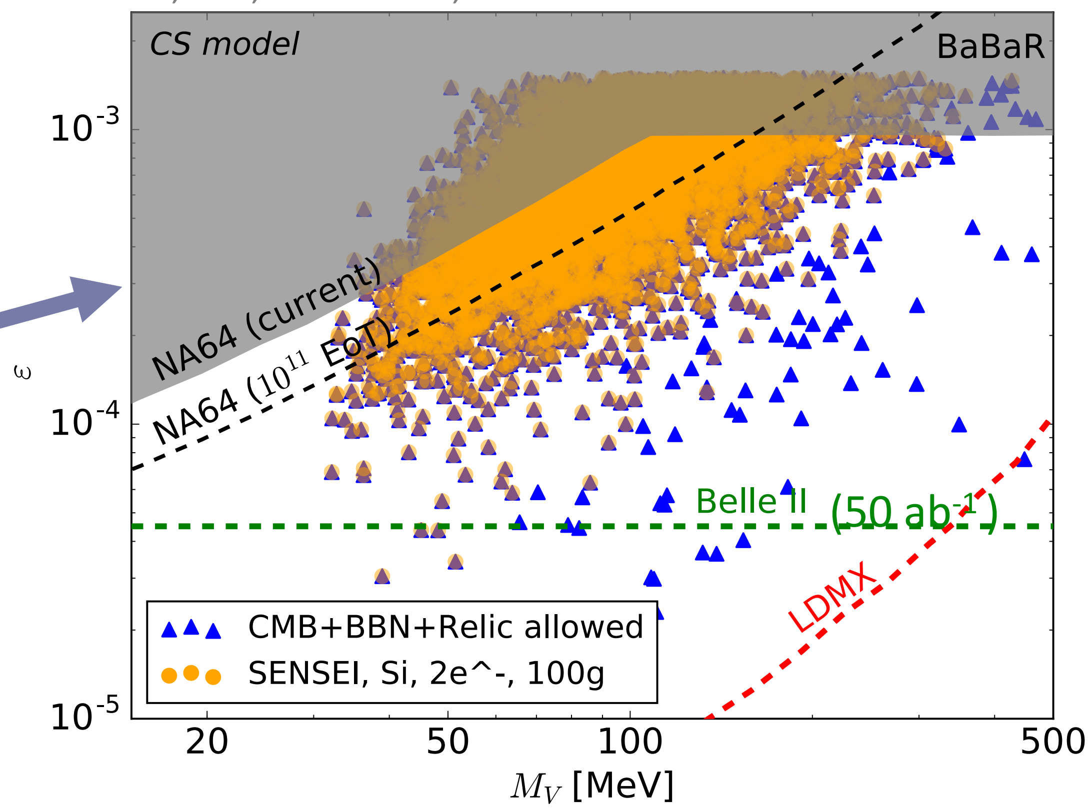
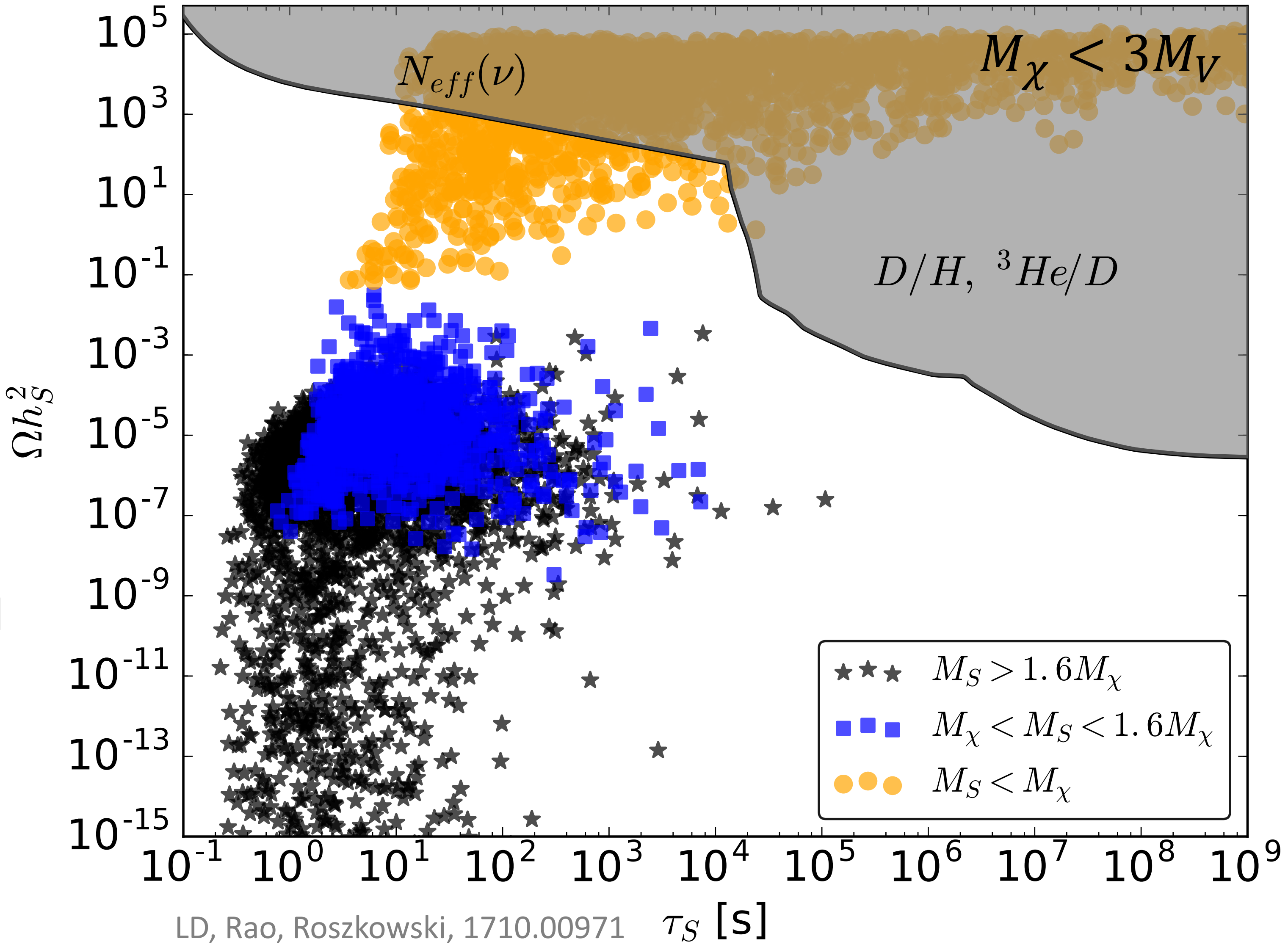


- Interesting new development: boosted. secondary DM flux (1810.10543, 1811.00520)
  - Collision with cosmic rays created boosted secondary flux
  - Allows better nucleon/electron recoil even for sub-GeV DM

→ Very interesting prospects for iDM case, only partially explored though

BBN constraints

- Potentially large S metastable density after freeze-out
- Two relevant bounds
  - N_{eff} neutrino from late time energy injection ($\tau > 0.1$s)
  - Light element aboundances, e.g D/H ($\tau > 10^4$s)
  - CMB bounds on decaying DM
- Light dark Higgs only decay electromagnetically (electron-positron pairs) → (relatively) weak bounds



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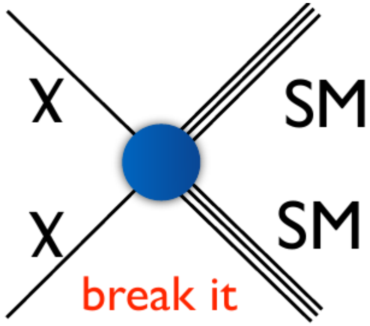
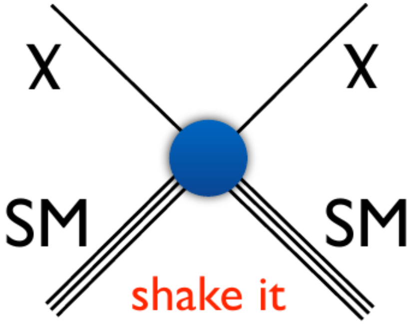
Direct and indirect detection bounds



- Late-time annihilation
  - Standard CMB bound -> s-wave annihilation channel forbidden

  --> either p-wave channel or other way of evading this bounds (e.g. co-annihilation or thermally-suppressed)



- Direct detection, *many* upcoming experiments
  - semiconductor detector (e.g superCDMS)
  - or dedicated searches for electron scattering
- Standard searches currently only relevant for scalar DM case (since either inelastic DM or Majorana DM)

Ranges for the bulk scan

Parameter	Range	Prior
M_S	5 MeV - 1 GeV	Log
g_V	0.01 - 2.5	Log
M_V	10 MeV- 500 MeV	Log
ε	0.5×10^{-6} - 0.001	Log
M_χ	-250 MeV - 150 MeV	Linear
Δ_χ	$0.01\lvert M_\chi\rvert$ - $10\lvert M_\chi\rvert$	Log
y_{DM}	-2 - 2	Linear

Table 2. Input parameters for the scans presented in Figure 2.