Light dark sectors in sub-GeV dark matter scenarios

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23/05/2018

From LD, Rao, Roszkowski, 1710.00971, 1806.xxxx

Outline

Introduction: Dark matter, downhill in mass

Building a light thermal dark matter

Dark sector and cosmological bounds

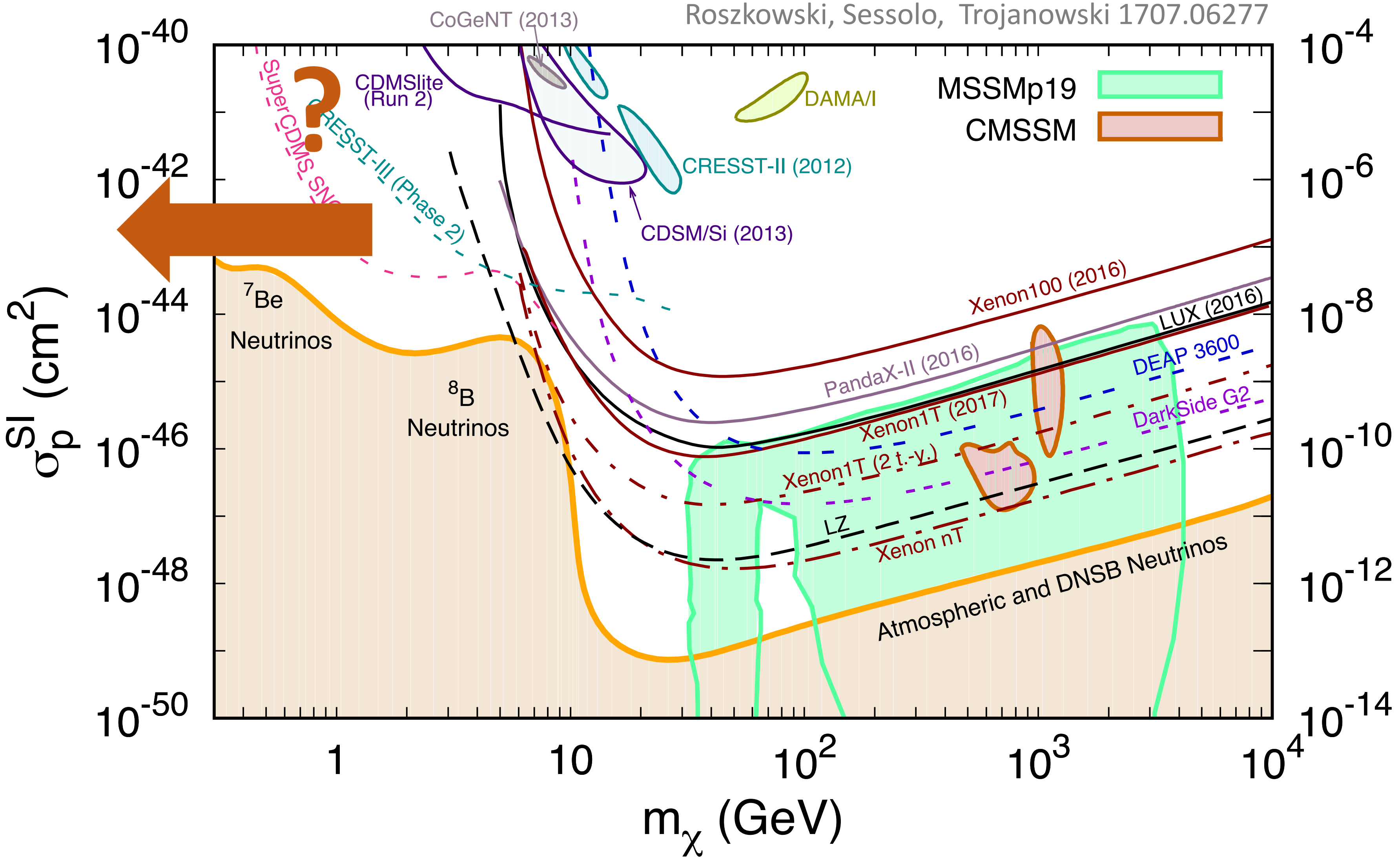
Accelerator-based signatures

Introduction

Thermal dark matter, downhill in mass

Light thermal dark matter

- Huge experimental progress
  - Simplest SUSY WIMP will soon be covered
- What about the lower mass range?
  - Thermal DM allowed, SIDM motivation
  - Cannot be s-wave annihilation $m_\chi \gtrsim$ 10 GeV bound



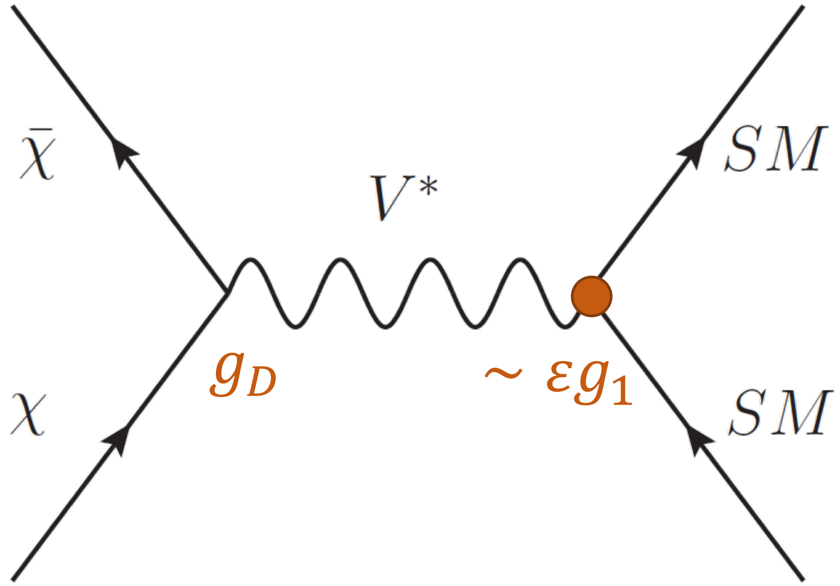
What is required for such a light DM?

- Many different approaches, (e.g asymmetric DM, SIMP, etc..)
  - Pospelov, Ritz, Voloshin, Feng, Kumar, Nussinov, Kaplan, Luty, Zurek …

- Here: keep model building simple, thermal freeze-out & SM motivated

- Obtaining the thermal relic density (from freeze-out) → effective annihilation mechanism
  - In practice, that means a new force, hence, e.g a new massive vector boson

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



Building a light thermal Dark Matter

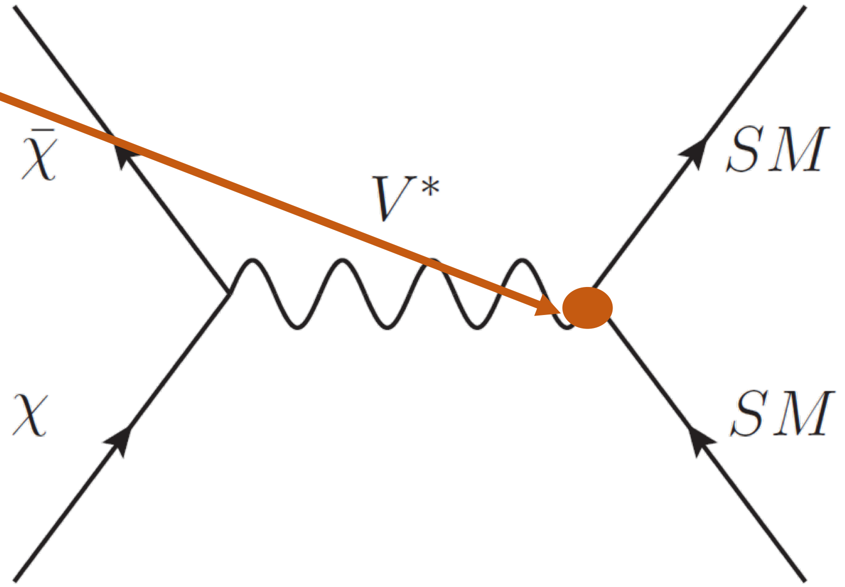
Kinetic mixing and dark Higgs mechanism

- Coupling to SM obtained through “kinetic mixing” term

Kinetic mixing term

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

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

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

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

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

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

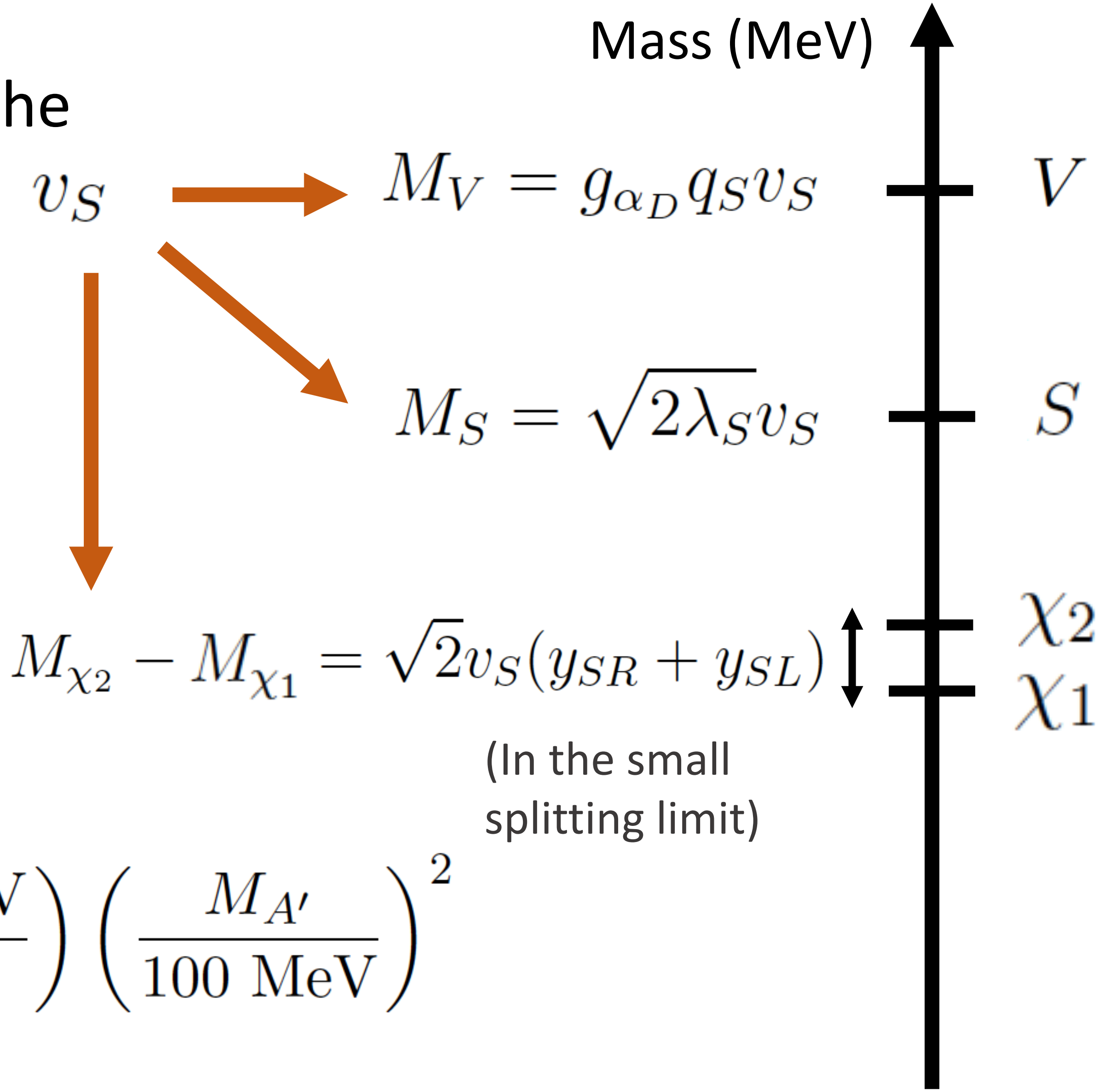
- After diagonalization → two Majorana fermions, χ_1 and χ_2 with variable mass splitting depending on the Yukawas

Spectrum and dark Higgs boson

- The dark Higgs VEV sets most of the mass scales

- If $S \to \chi_1 \chi_1$ not available, the dark Higgs is typically very long-lived

  → Treat this setup as a two-component Dark matter scenario

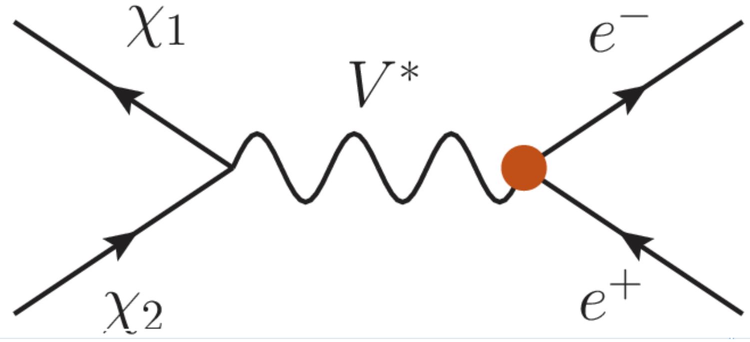


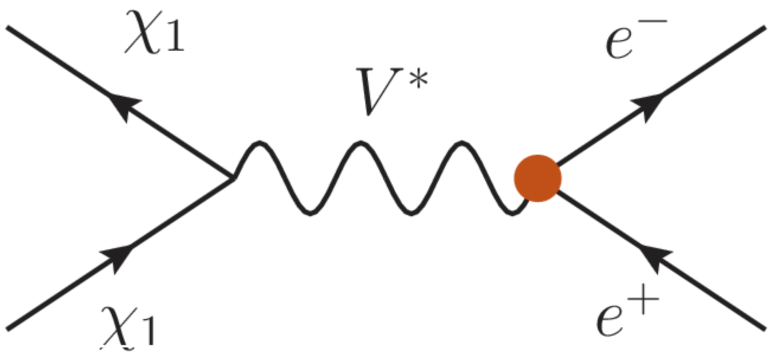
$$\tau_S \propto 1\ \mathrm{s} \times \left(\frac{\alpha'}{\alpha}\right) \times \left(\frac{10^{-3}}{\varepsilon}\right)^4 \left(\frac{100\ \mathrm{MeV}}{M_S}\right) \left(\frac{M_{A'}}{100\ \mathrm{MeV}}\right)^2$$

Dark sector and cosmological constraints

Relic density, CMB bounds, BBN bounds

Relic density (1)





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

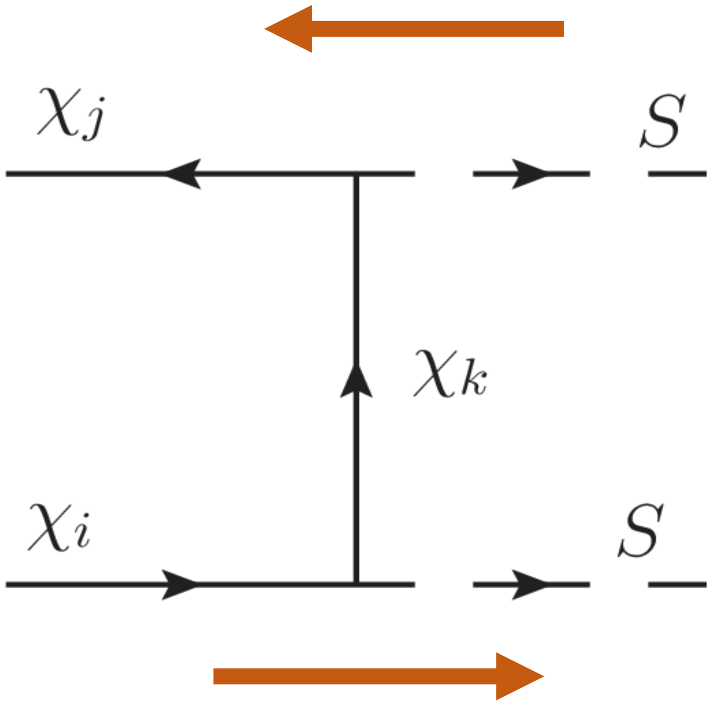
$$\sigma \propto \frac{v_S^2}{m_\chi^2} (y_{SR} - y_{SL})^2 \varepsilon^2 \alpha_D$$

- Relevant in Pseudo-Dirac limit
- Relevant in high-splitting case

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

Relic density (2)

- When the dark Higgs boson lighter than DM
  → "secluded" DM annihilation

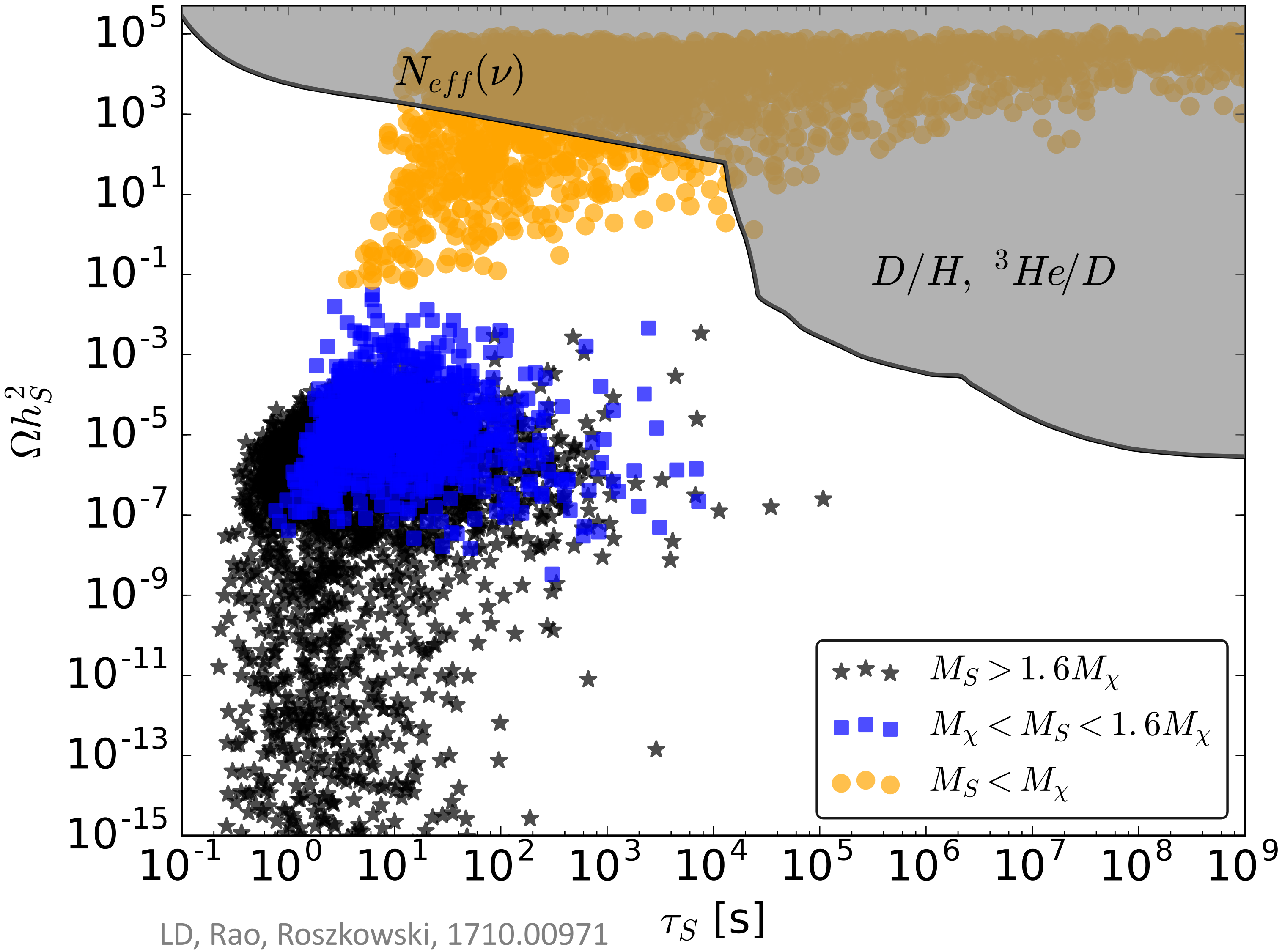


- If the dark Higgs is long-lived -> participates in freeze-out, gets a metastable density.

- When the Dark Higgs is light, one in general treat this setup as being two-component Dark matter
  - The metastable Dark Higgs density will send be crucial for BBN bounds

BBN-related bounds

- Potentially large metastable density after freeze-out
- Dark Higgs decays to e^+e^-
- 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)



LD, Rao, Roszkowski, 1710.00971

Accelerator signatures

Light dark sector particles may be accessible at the *intensity frontier* and precision experiments

Dark Sector searches

Either searching for DM via scattering in fixed targed/long-baseline neutrinos experiments (LSND, miniBooNE …)

Or: we now have a light "dark sector" on top of our DM candidate,

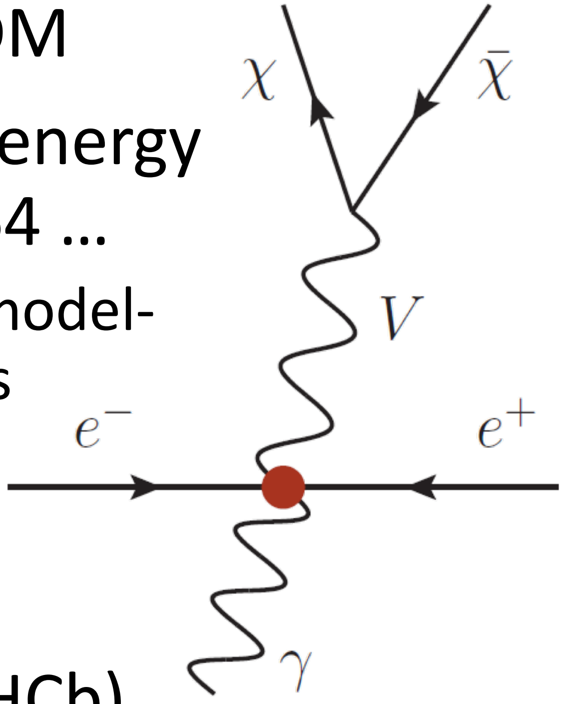
- Mediator: Dark photon V
- Dark Sector (dark Higgs S, Heavier dark sector states (e.g χ_2)

Decay to either SM and DM

→Mono-photon missing energy signature @ BaBar, NA64 …

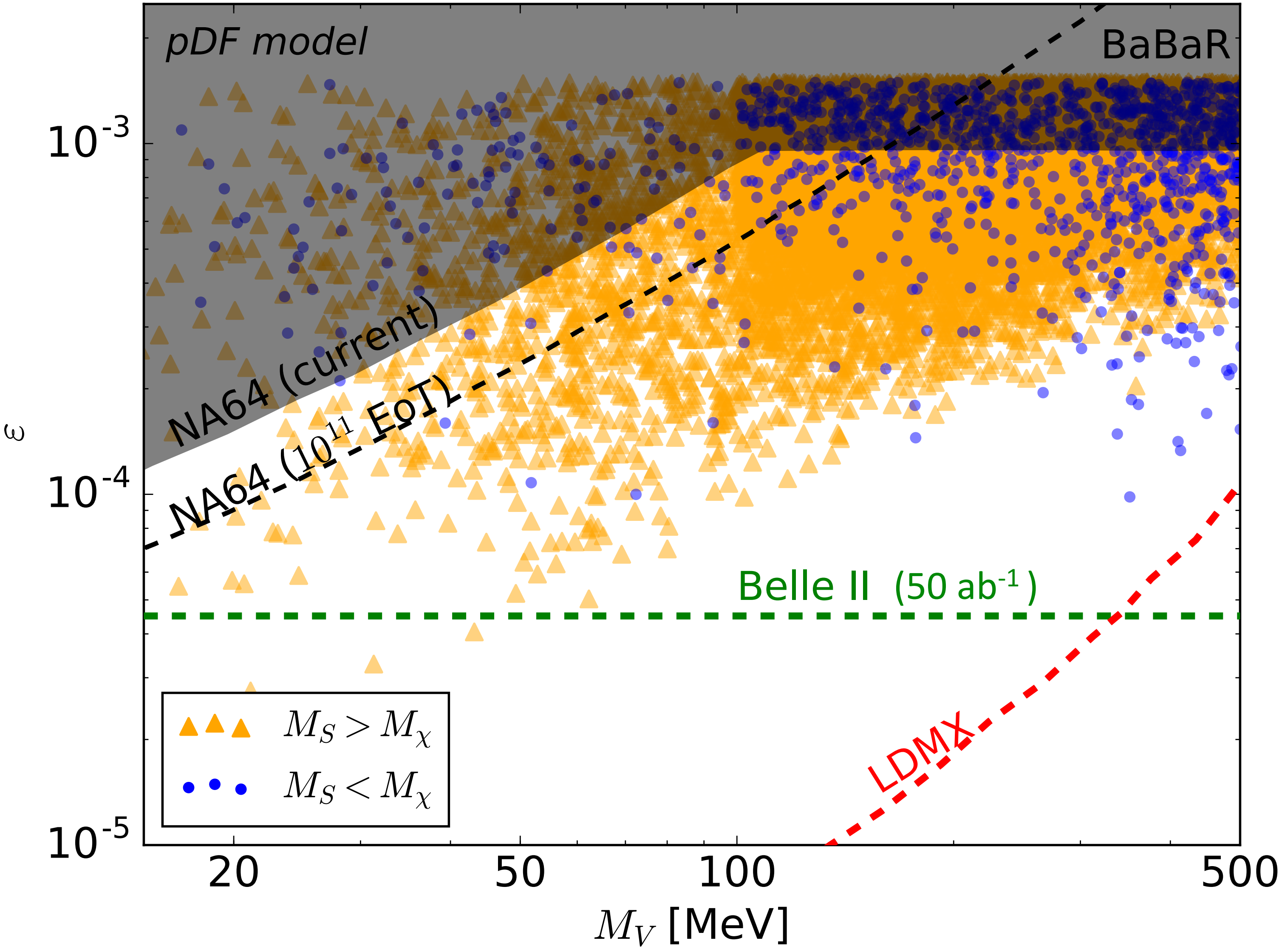
→Very strong and largly model-independent constraints on kinetic mixing $\varepsilon < 10^{-3}$

→If visible decay, slightly stronger bounds (e.g LHCb)



Example: fermion dark matter

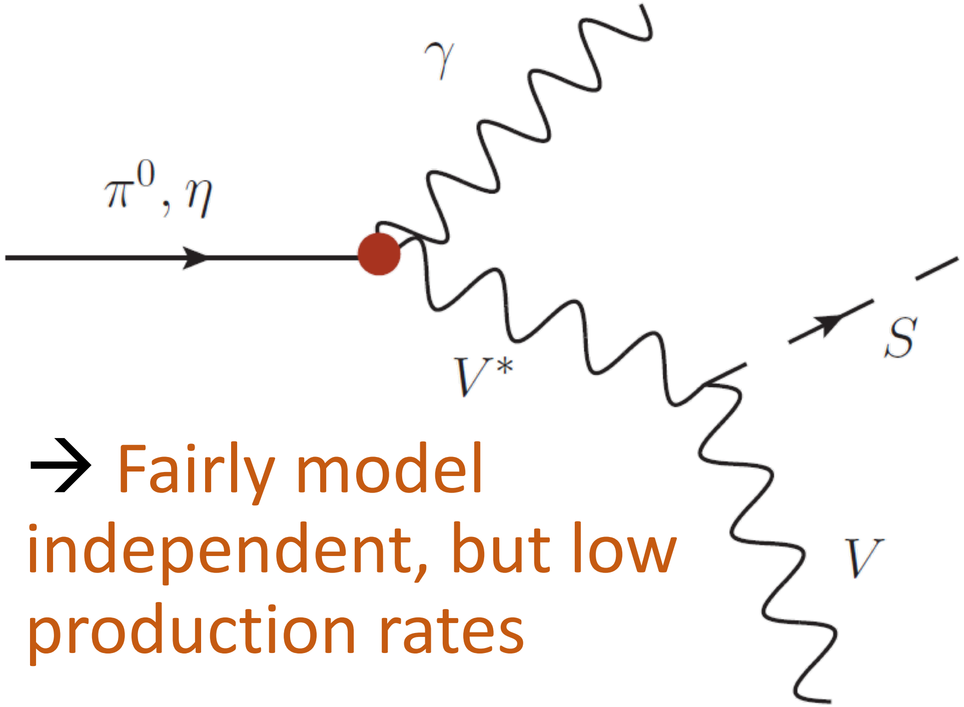
- Depends only on the kinetic mixing parameter ε and dark photon mass
- Bright prospect (e.g. Belle II, 50 ab^{-1})
- We have taken $m_{\chi_1} < m_V/3$



How do we detect it: Dark sector decay

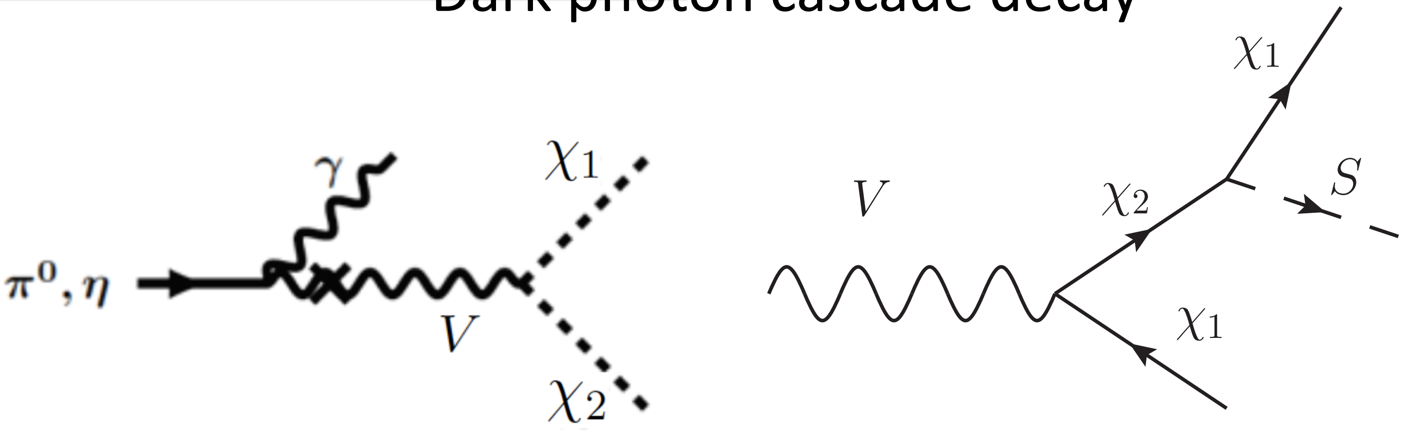
- Dark Sector contains: dark Higgs S, Heavier dark sector states (e.g χ_2)

Dark Higgstrahlung (dark Higgs)



→ Fairly model independent, but low production rates

Dark photon cascade decay



→ Strong model dependence but high production rate

- Decay : pair of e^+e^-
  → Easy to distinguish from neutrino scattering (almost zero background…)

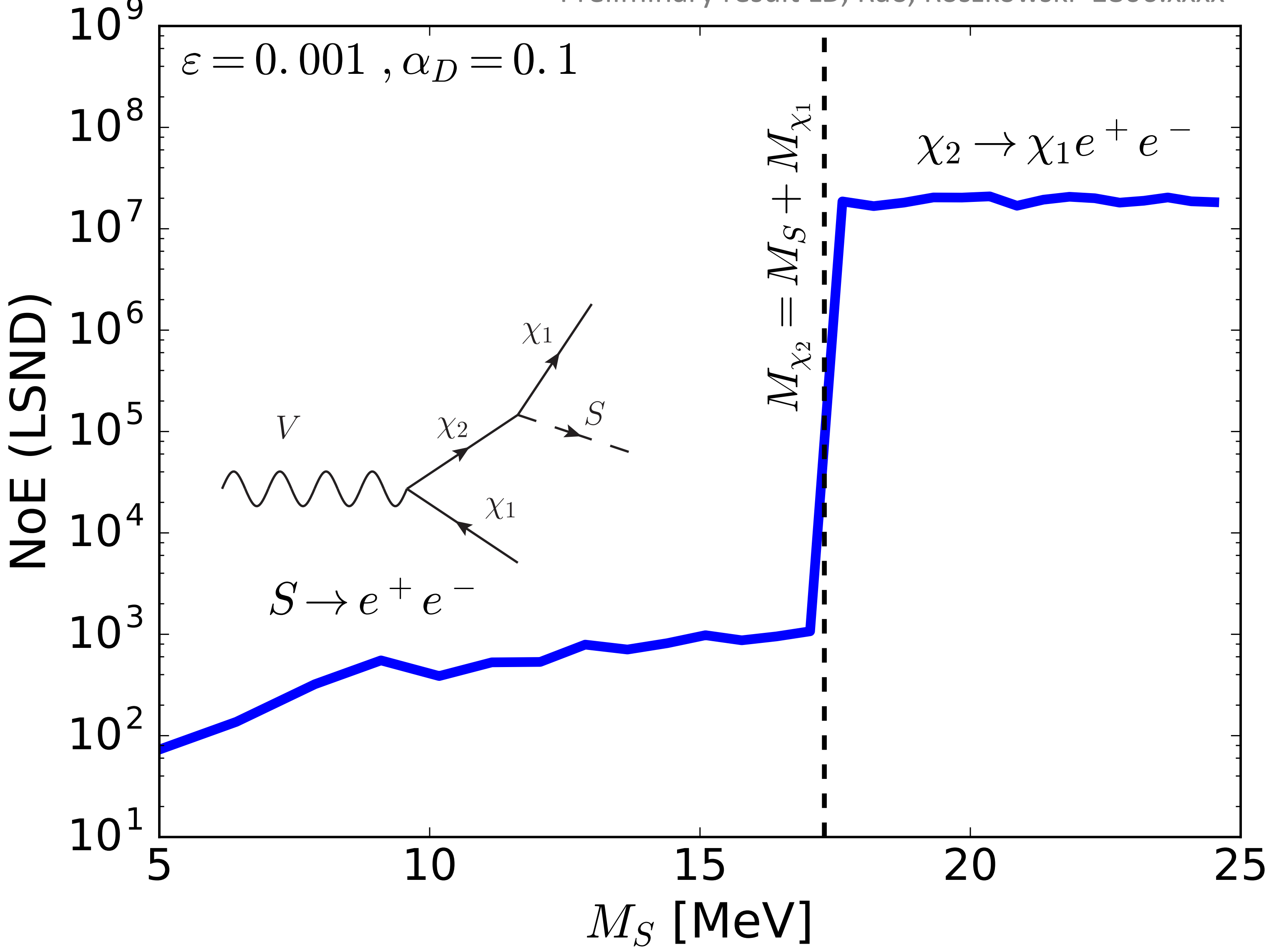
Dark sector from cascade decays

- Heavy state decay $\chi_2 \to V^*\chi_1 \to \chi_1 e^+e^-$, strongest bounds reach down to $\varepsilon \sim O(10^{-6})$
- Strong model dependence

→The presence of the dark Higgs leads to "blind spots" if $\chi_2 \to S\chi_1$ allowed

→ Typically same reach as DM scattering

Preliminary result LD, Rao, Roszkowski 1806.xxxx



Conclusion

Conclusion

- Light thermal dark matter candidates typically carry with them a small dark sector
  - Accelerator searches for this dark sector fields complementary with DM searches
  - The accompanying dark sector offers both fascinating detection prospects and very strong cosmological bounds (BBN …)
- A simple light thermal fermion DM presented, contains most used simplified models (iDM, Majorana DM)
  - Typically richer phenomenology
  - The influence of the dark Higgs has been in particular often neglected

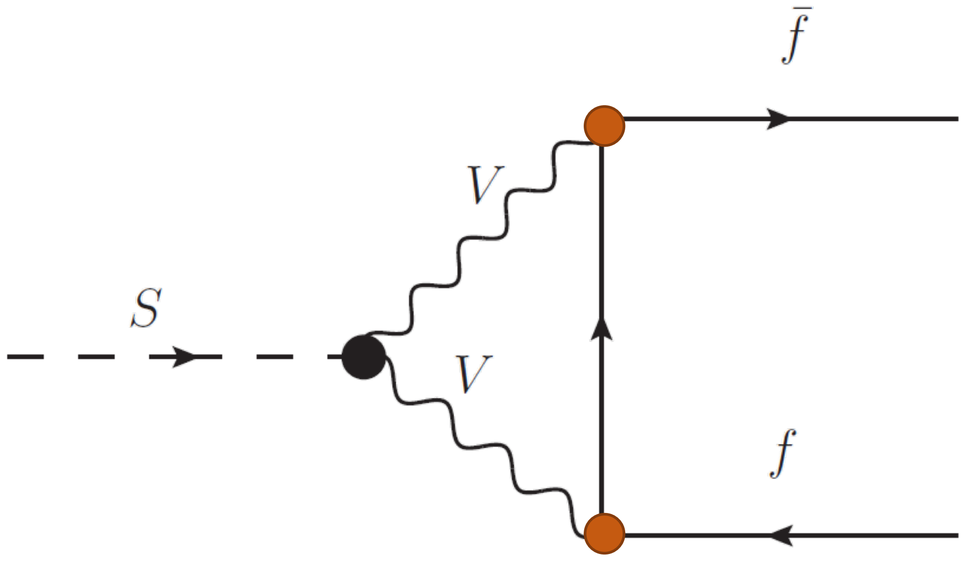
→ strong effect on relic density, BBN bounds

→ “Blind” spots from heavy dark sector states searches at accelerator

Backup slides

A key aspect - Dark Higgs life-time

- Extremely long-lived
  - Two kinetic mixing insertion needed
  - Loop-factor
- Shorter life-time above di-muon threshold
- Hadronic uncertainties after di-pion threshold



$$\tau_S \propto 1\ \mathrm{s} \times \left(\frac{\alpha'}{\alpha}\right) \times \left(\frac{10^{-3}}{\varepsilon}\right)^4 \left(\frac{100\ \mathrm{MeV}}{M_S}\right) \left(\frac{M_{A'}}{100\ \mathrm{MeV}}\right)^2$$

- If kinematically available, it can decay instantaneously to DM or dark photon

The case for small Higgs/Dark Higgs mixing

- Both the SM and dark Higgs potential must be diagonalised 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

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

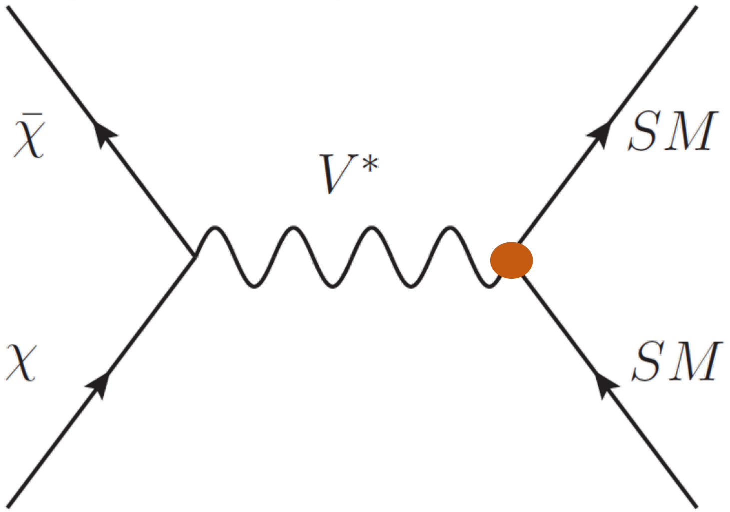
$$\tau_{S,H\text{mix}} \propto 1 \cdot 10^6 \text{ s} \times \left(\frac{100 \text{ MeV}}{M_S}\right)\left(\frac{100 \text{ MeV}}{M_V}\right)^2\left(\frac{10^{-6}}{\lambda_{SH}}\right)^2\left(\frac{q_S^2\alpha_D}{\alpha_{\text{em}}}\right)$$

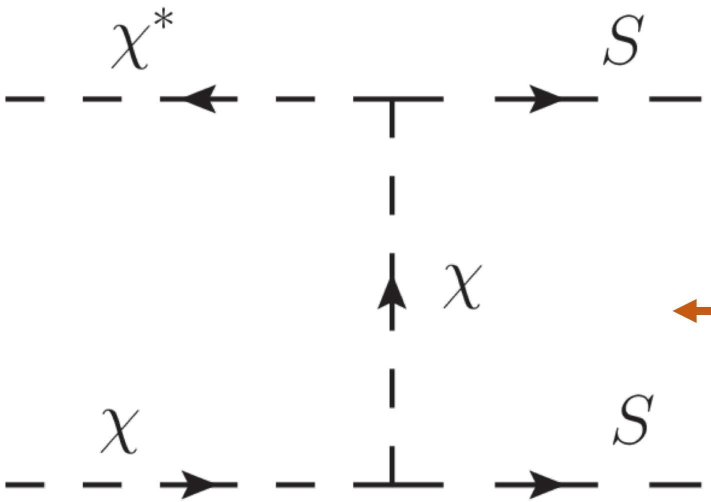
A simple scalar case

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

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

- Relic density from s-channel annihilation





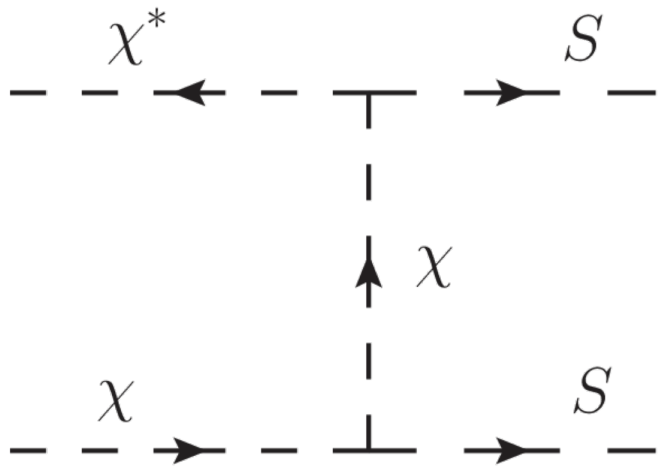
Care must be taken from indirect CMB bounds

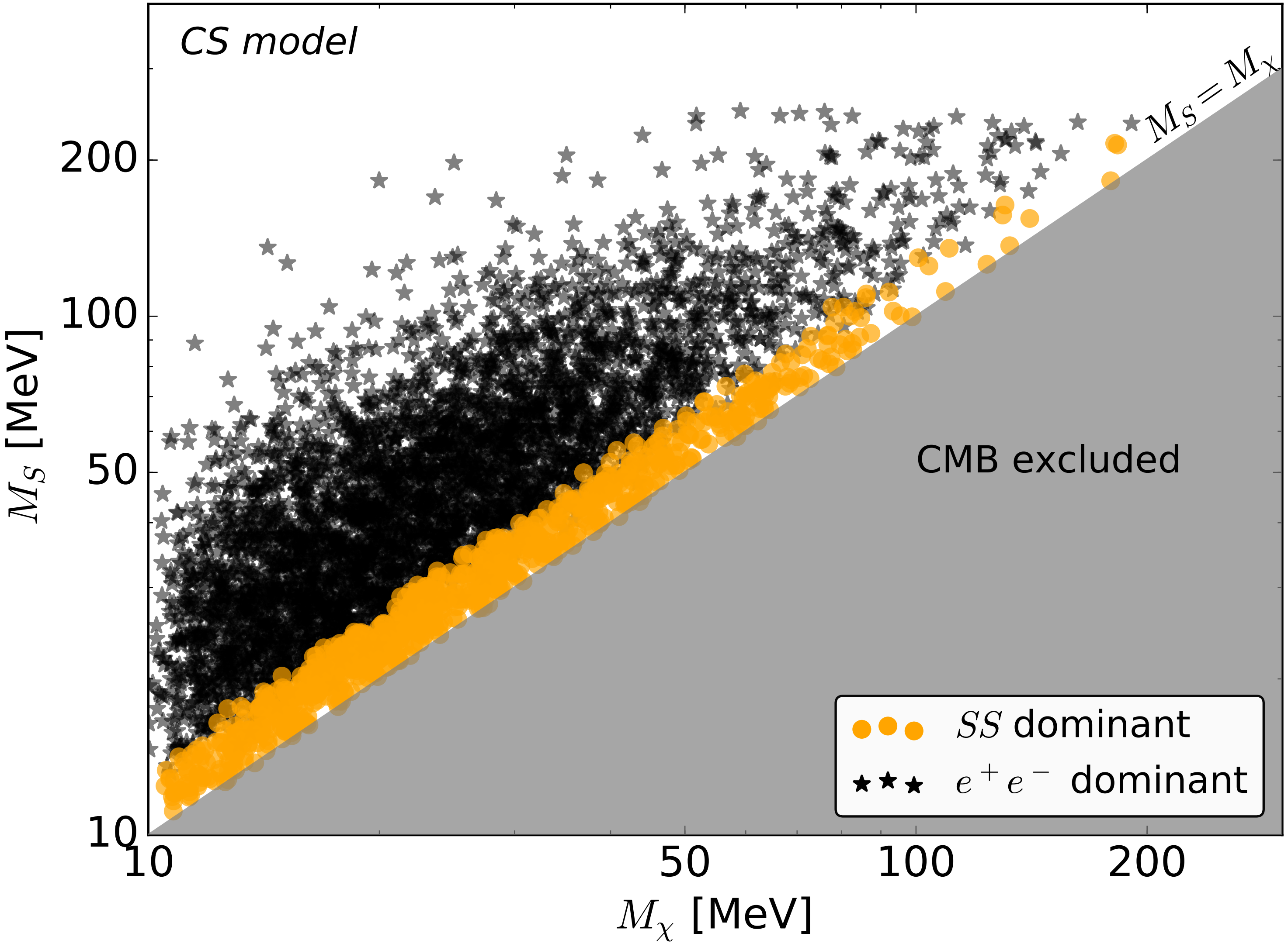
The process $\chi^*\chi \to S\,S$ is s-wave

CMB bounds -- the scalar case

- The only s-wave channel

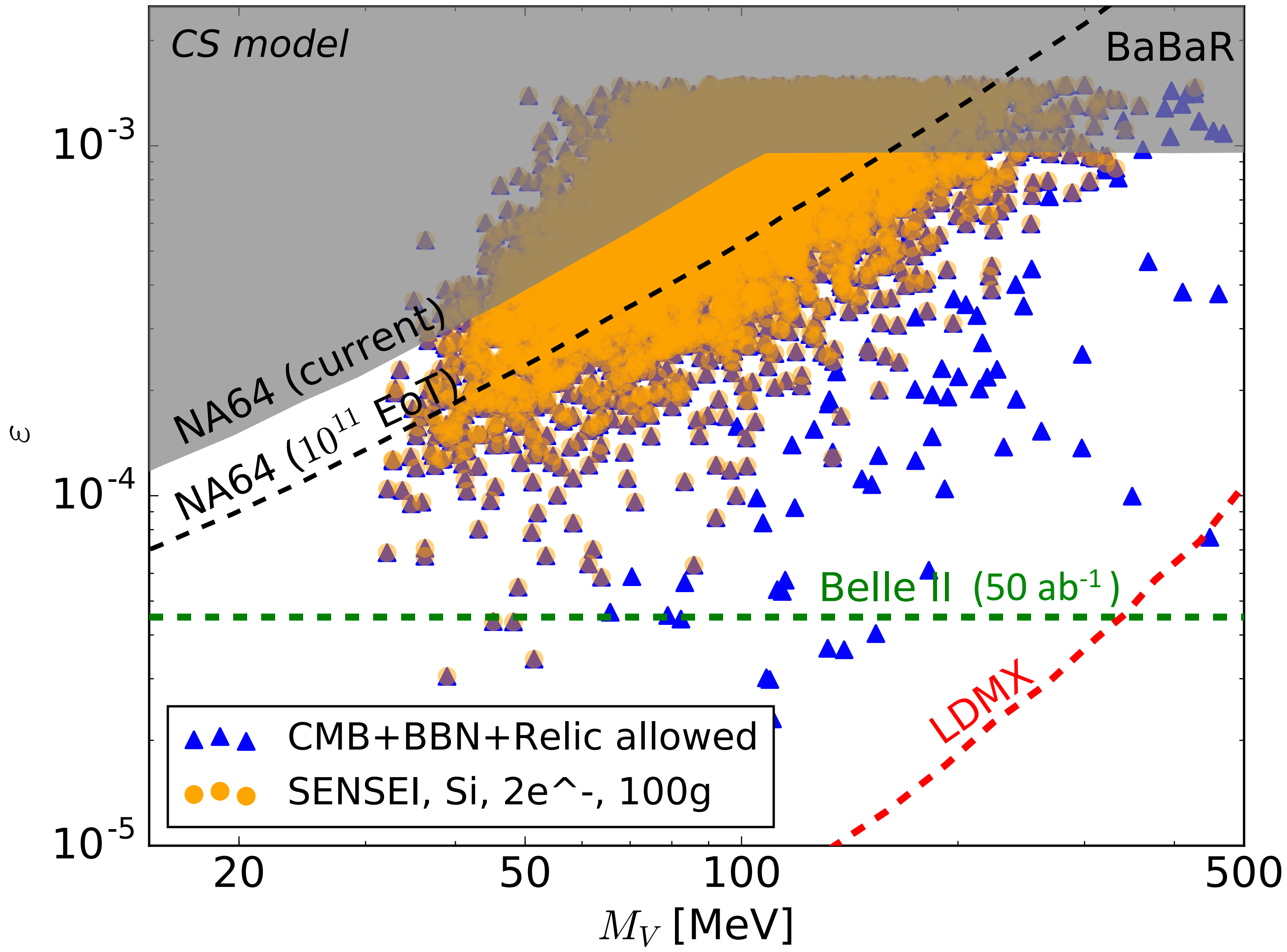
When $M_\chi > M_S$, t-channel annihilation into dark Higgs



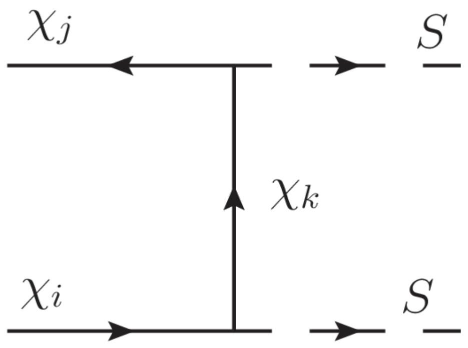


Direct detection strategy-- the scalar case

- Upcoming bounds from, e.g SENSEI will cover most of the parameter space
- Missing energy searches are already competitive!



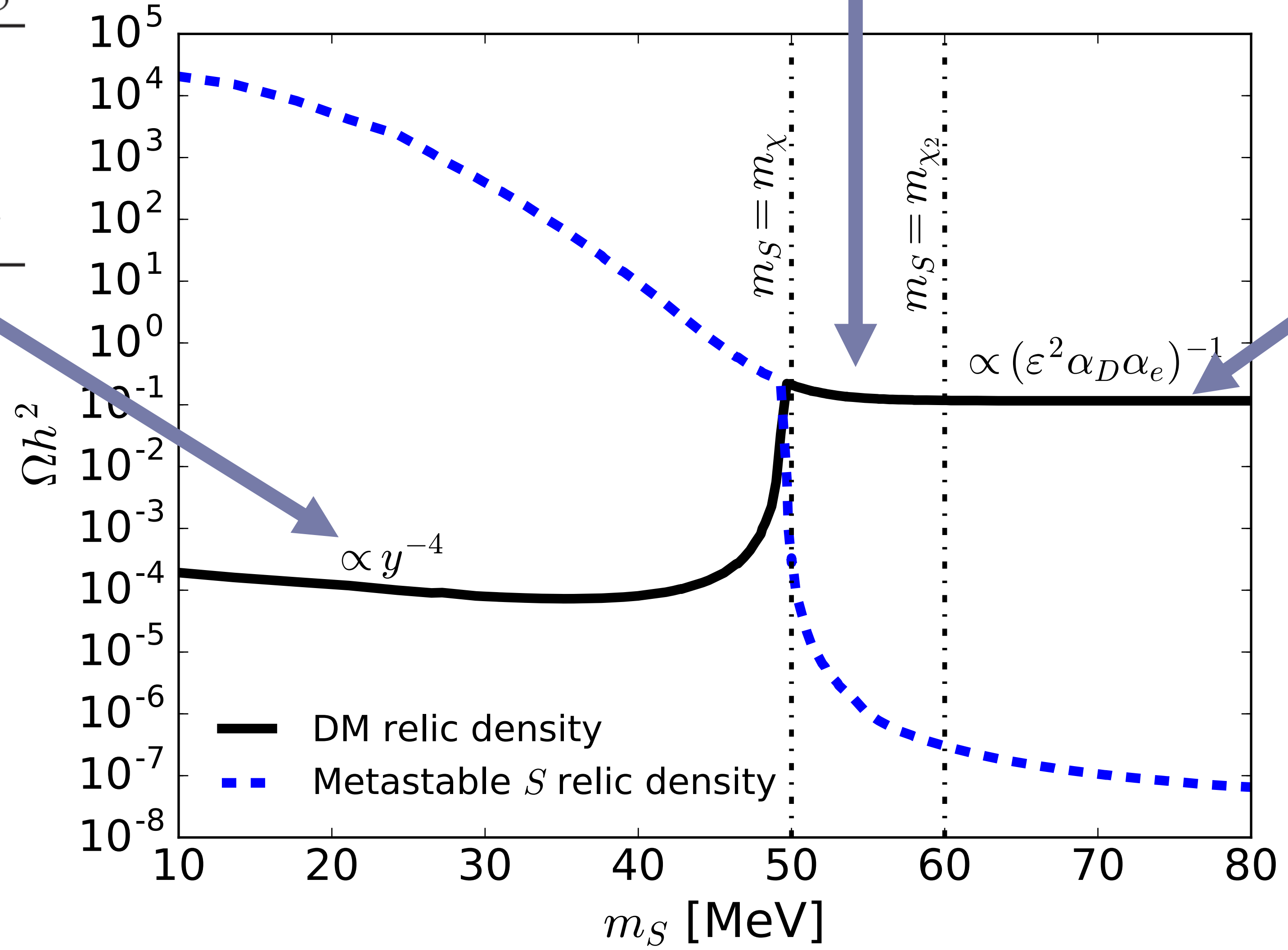
Fermionic DM – Dark Higgs impact



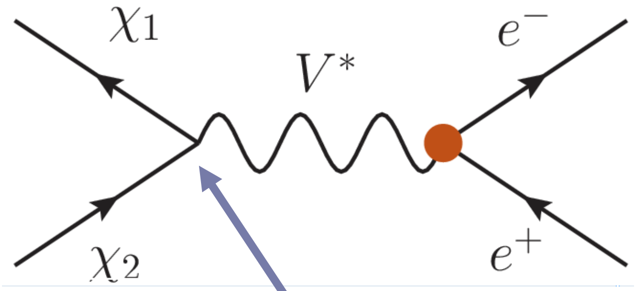
Secluded regime

→ Large Dark Higgs metastable density

Dark Higgs depletes χ_2 population



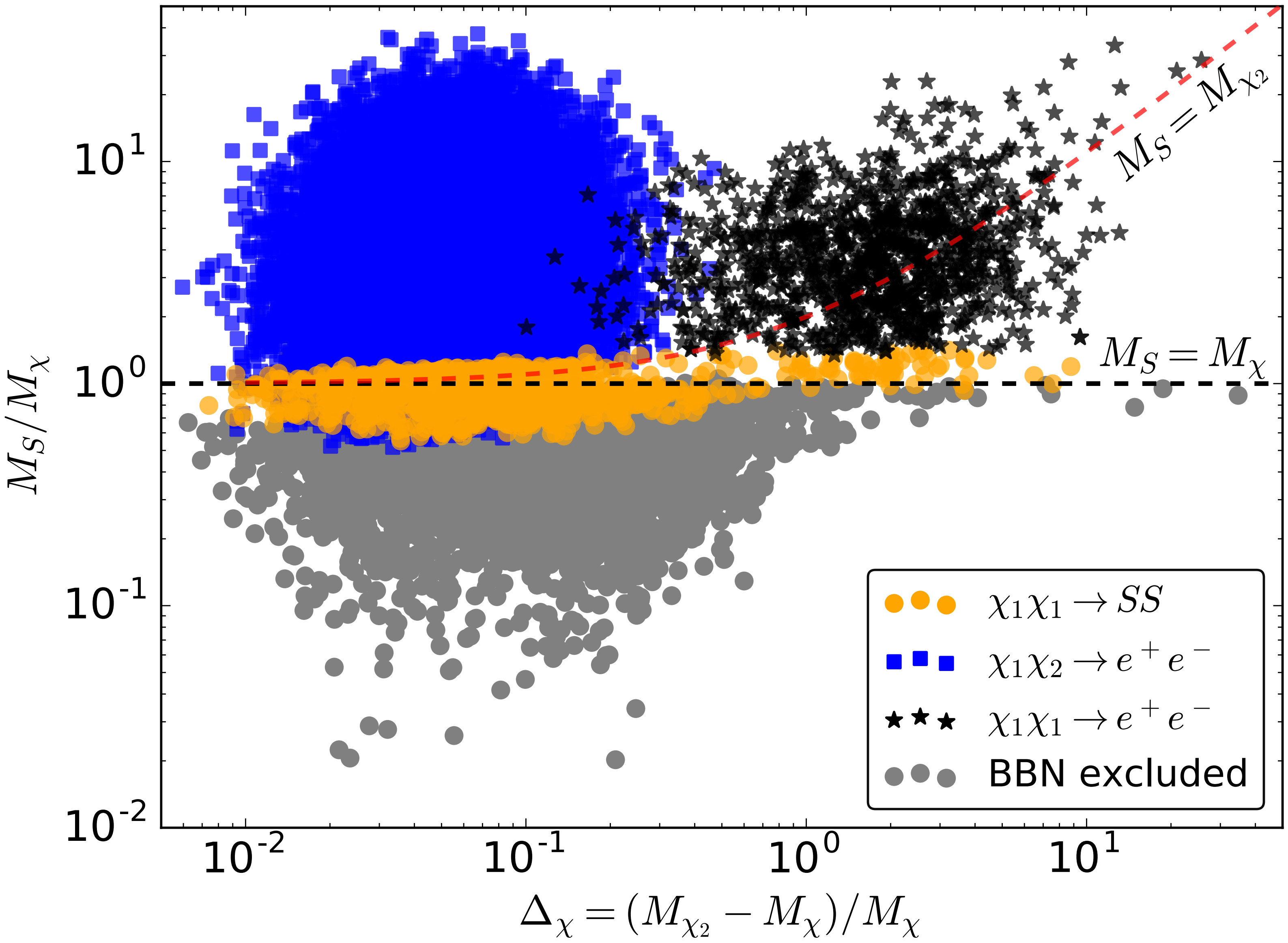
Pseudo-Dirac: Co-annihilation region



Dominant vertex for almost Dirac DM

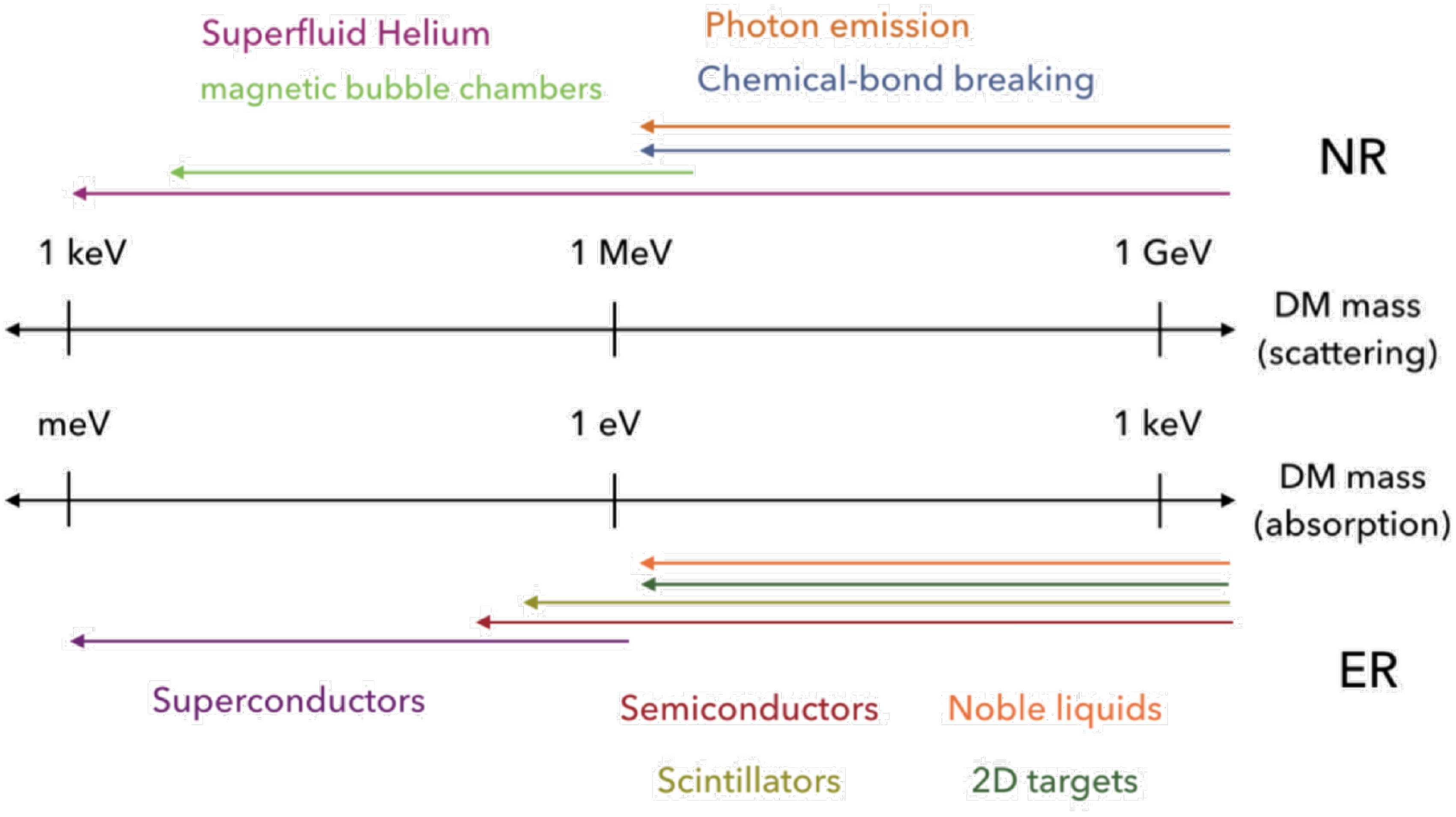
Fermionic DM – Summary

- Three interesting regimes with starkly different phenomenology:
  - The pseudo-Dirac case $m_{\chi_1} \sim m_{\chi_2}$
  - The Majorana DM case $m_{\chi_2} \gg m_{\chi_1}$
  - Secluded regime $m_S < m_{\chi_1}$



Detection strategies, sub-GeV DM

- Need for low-threshold experiments
  - DM-electron scattering
  - DM- low-Z elastic nucleus interactions
  - Bremsstrahlung in inelastic DM-nucleus scattering
- DAMIC, SENSEI, UA',NICE, SuperCDMS,NEWS



From arXiv:1707.04591

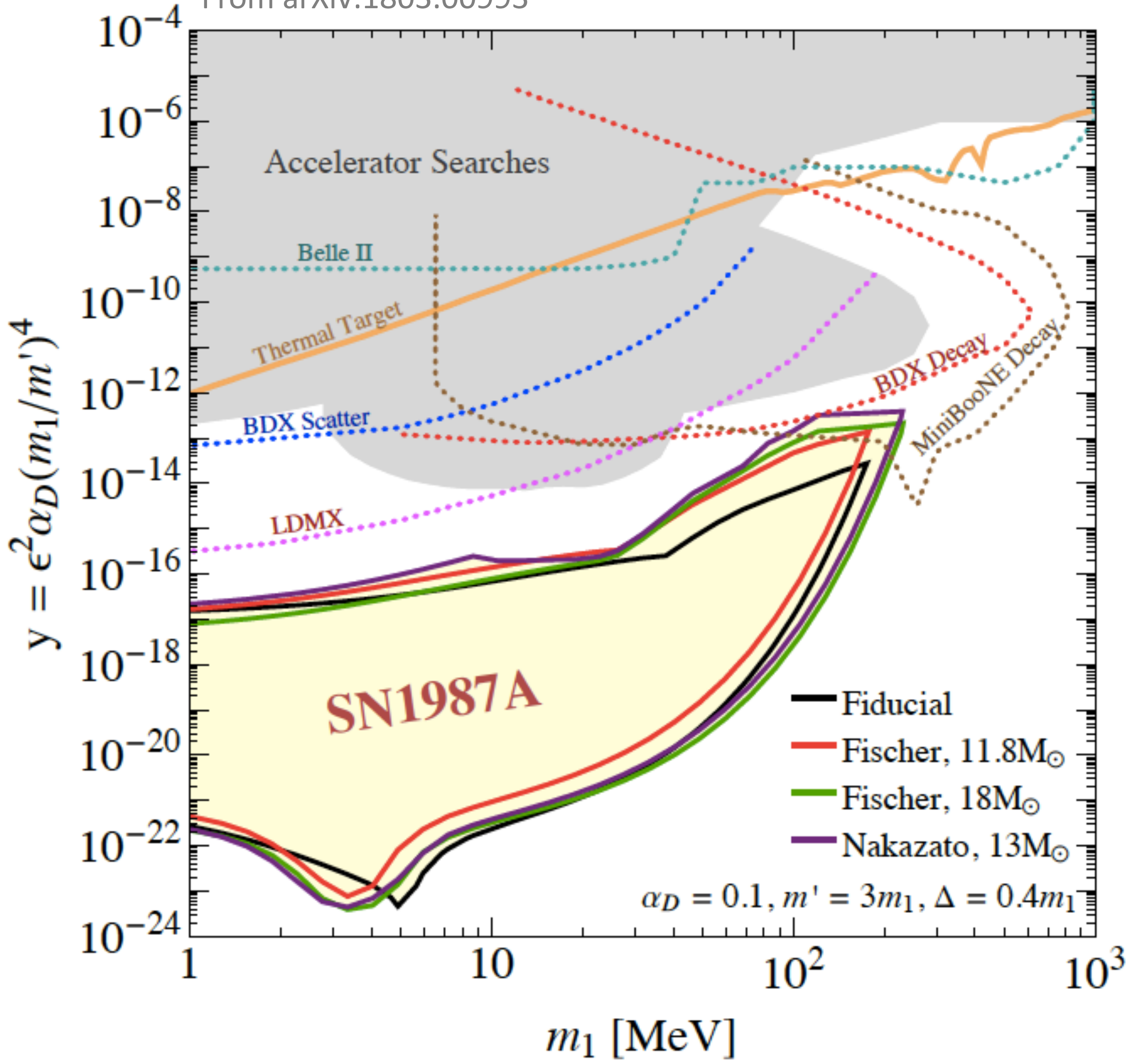
SN 1987A bounds

- Typical bounds arise when DM do not scatter enough and escape the SN core

$$\alpha_D \epsilon^2 < O(\text{few}) \times 10^{-14}$$

- Not relevant for pseudo-Dirac case/Majorana case at the thermal target
- Dark Higgs bounds may be relevant at $m_S < M_{\chi_1}$ or $m_S < M_{\chi_2} - M_{\chi_1}$
  → Under investigation

From arXiv:1803.00993



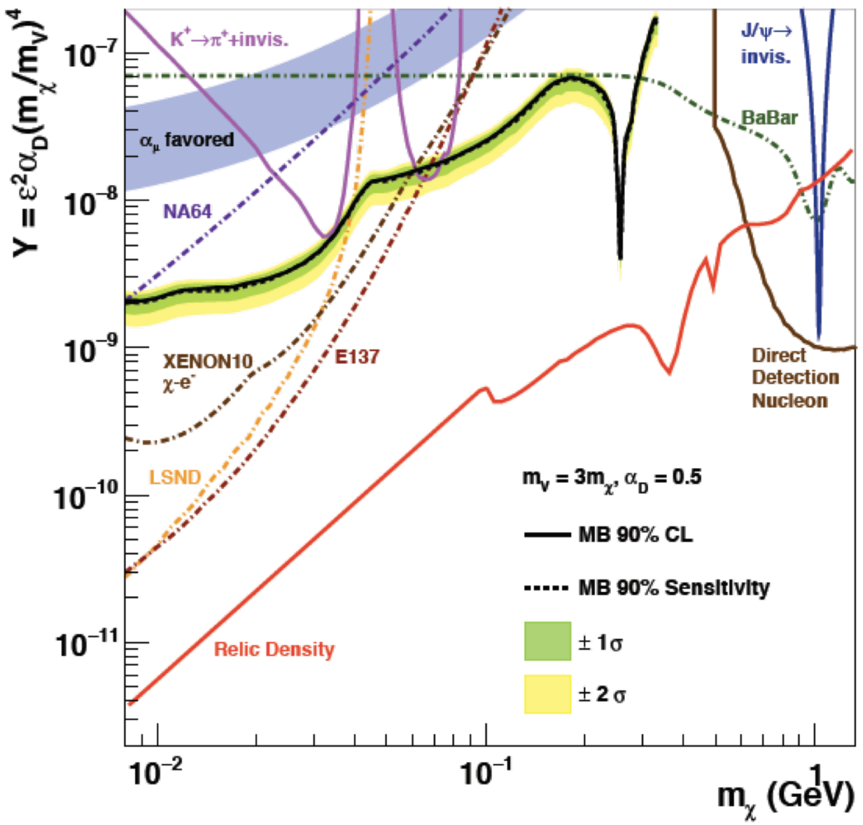
Already rich literature…

- Typical current bounds are competitive w.r.t missing energy searches

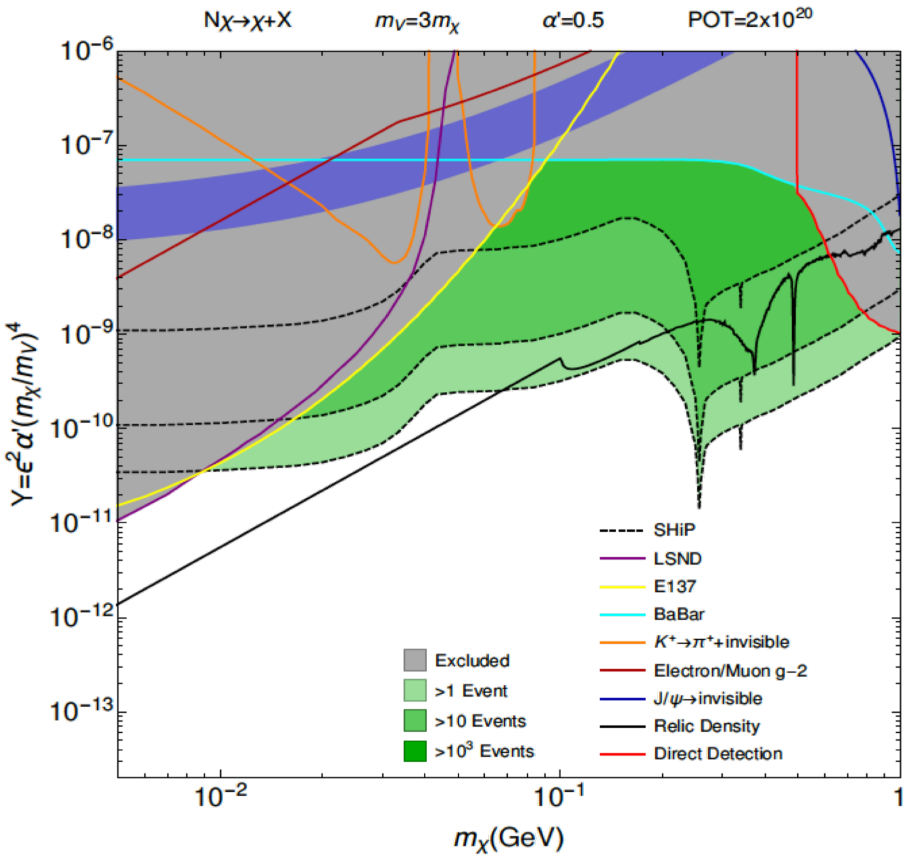
- Compensate reduced yields with high statistics

- Low kinetic mixing region hard to probe due to ε^4 dependence

arXiv: 1702.02688



arXiv:1609.01770

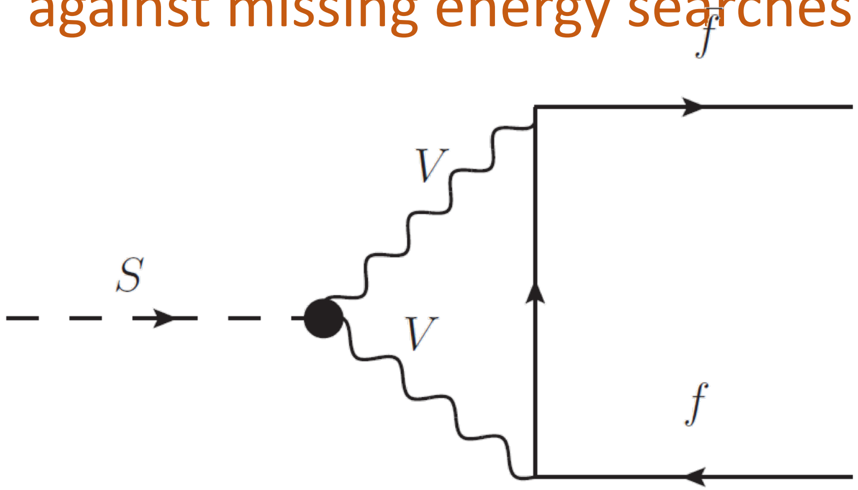


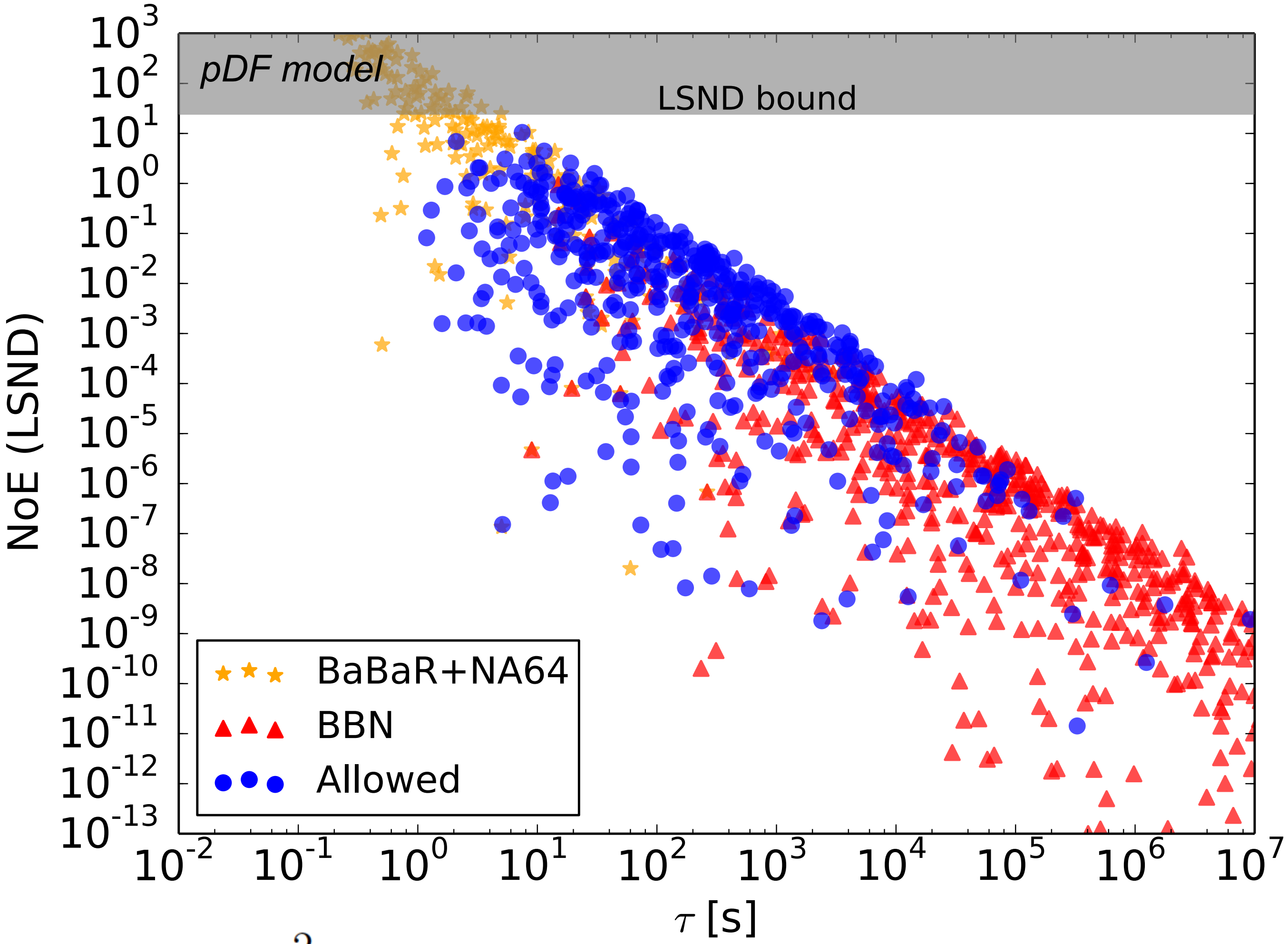
MiniBooNE: $2 \cdot 10^{20}$ proton on target, LSND: 10^{22} π^0 mesons produced…

Dark Higgs from Higgstrahlung

From LD, Rao, Roszkowski 1710.00971

- Dark Higgs boson extremely long-lived
- Number of events scale as $\alpha_D^2 \varepsilon^6$
  - Once cosmology constraints included, usually not competitive against missing energy searches

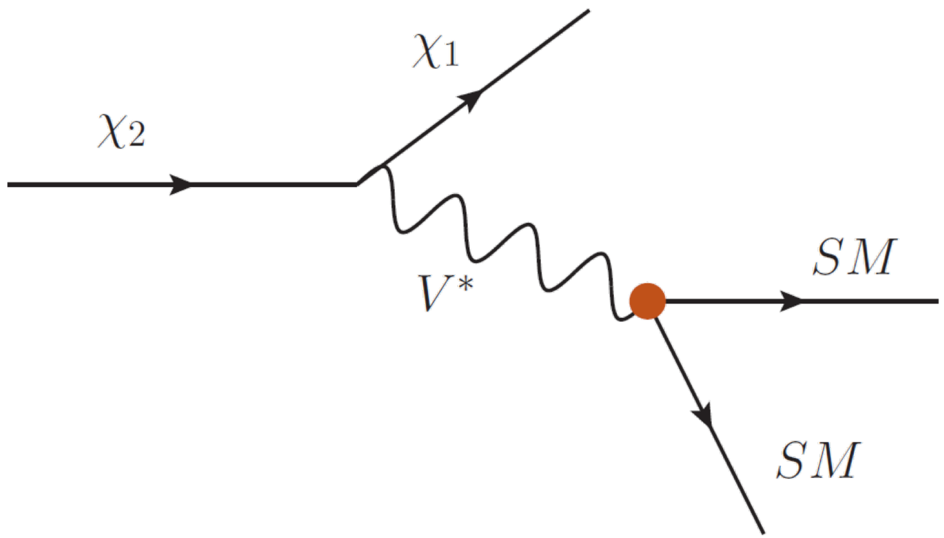




$$\tau_S \propto 1\ \mathrm{s} \times \left(\frac{\alpha'}{\alpha}\right) \times \left(\frac{10^{-3}}{\varepsilon}\right)^4 \left(\frac{100\ \mathrm{MeV}}{M_S}\right) \left(\frac{M_{A'}}{100\ \mathrm{MeV}}\right)^2$$

Heavy dark sector decay

- Key point -> The heaviest eigenstate as 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

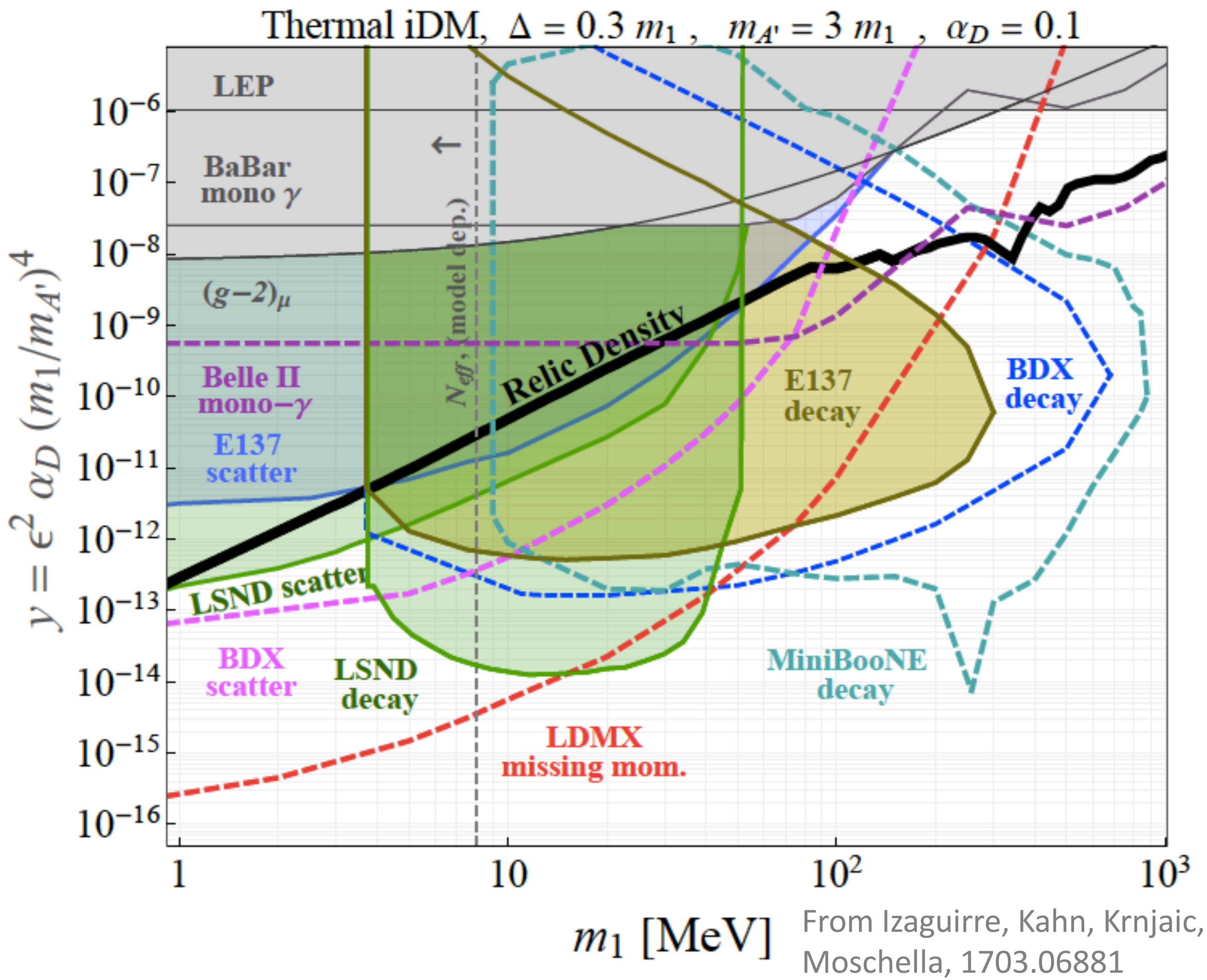


$$c\tau_{\chi_2} \propto 100 \text{ m } \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{10^{-3}}{\varepsilon}\right)^2\left(\frac{0.2}{\Delta_\chi}\right)^5\left(\frac{25 \text{ MeV}}{M_S}\right)^5\left(\frac{M_V}{100 \text{ MeV}}\right)^4$$

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

Heavy dark sector decay (2)

- Signature : pair of e^+e^-
  → Easy to distinguish from neutrino scattering (almost zero background…)
- Can reach down to $\varepsilon \sim O(10^{-6})$
- Bounds from proton beam dump experiment (LSND, miniBooNE) and electron BD (E137)
  - Old experiment giving very strong limit!



From Izaguirre, Kahn, Krnjaic, Moschella, 1703.06881