Constraining light dark matter scenarios using long-lived particles

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NCBJ

23/06/2019

From 1807.00971 and 1907.xxxx

Outline

Exploring the properties of sub-GeV dark matter through an example

Signatures of light dark sector at the intensity frontier

A broader setup: light dark sector effective theory and the intensity frontier

Introduction

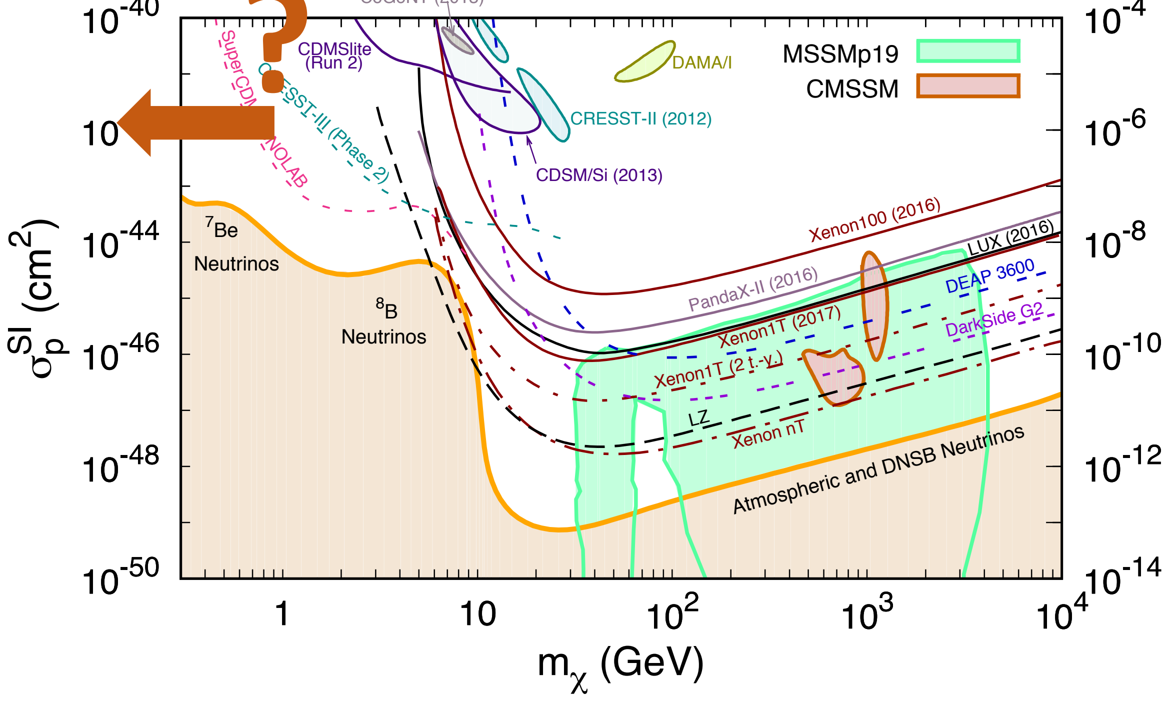
Thermal dark matter in the dark

Light dark sectors and dark matter

- WIMP Dark matter is a mature area of research

→ what about lighter (sub-GeV) DM ?

From ArXiv:1707.06277



- Intense experimental effort in the intensity frontier

  → ≳ 10 relevant experiment in next 2 years

Information | References (339) | Citations (182) | Files | Plots

US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

Marco Battaglieri (SAC co-chair) (INFN, Genoa), Alberto Belloni (Coordinator) (Maryland U.), Aaron Chou (WG2 Convener) (Fermilab), Priscilla Cushman (Coordinator) (Minnesota U.), Bertrand Echenard (WG3 Convener) (Caltech), Rouven Essig (WG1 Convener) (SUNY, Stony Brook), Juan Estrada (WG1 Convener) (Fermilab), Jonathan L. Feng (WG4 Convener) (UC, Irvine), Brenna Flaugher (Coordinator), Patrick J. Fox (WG4 Convener) (Fermilab) *et al.* Show all 251 authors

Jul 14, 2017 - 113 pages

Information | References (355) | Citations (19) | Files | Plots

Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report

J. Beacham (Ohio State U., Columbus (main)), C. Burrage (U. Nottingham), D. Curtin (Toronto U.), A. De Roeck (CERN), J. Evans (Cincinnati U.), J.L. Feng (UC, Irvine), C. Gatto (INFN, Naples & NIU, DeKalb), S. Gninenko (Moscow, INR), A. Hartin (U. Coll. London), I. Irastorza (U. Zaragoza, LFNAE) *et al.* Show all 33 authors

Jan 20, 2019 - 150 pages

- Not all DM-motivated, yet most can be used to constrained scenarios of sub-GeV, thermal DM

What is required for such a light DM?

- Many different approaches, most include additional, light dark sector
  - Literature often focuses on finding new mechanisms → with great success

Impeded DM
1609.02147,…

Co-scattering DM
1705.08450, 1705.09292,…

iDM
hep-ph/0101138, …

Selfish DM
1504.00361,…

Secluded DM
0711.4866, …

Co-decaying DM
1607.03110, …

Cannibal DM
1602.04219, …

Forbidden DM
Griest-Seckel, 1505.07107, …

Semi-annihilating DM
1003.5912, …

Boosted DM
1405.7370, 1503.02669…

<Your choice> DM
1906.xxxx

… and many other

→Seemingly only limited by our ability to invent new names …

→… and by usually a non-minimal accompanying dark sector

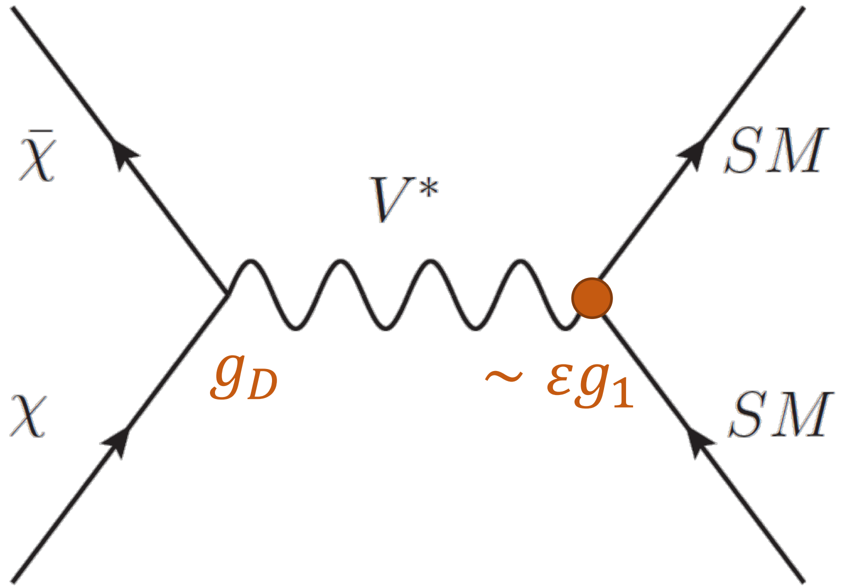
Exploring the properties of sub-GeV dark matter through an example

Model builing, Relic density, Astrophysical bounds

Building a toy-model for sub-GeV DM

- For this talk, let's try to build a simple, self-consistent dark sector model with sub-GeV dark matter → study detection prospects

- Suppose a vector mediator (dark photon), and (mostly in this talk) fermion dark matter
- Try to keep model building SM/WIMP-like then see the various possible regimes



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

Kinetic mixing and dark Higgs mechanism

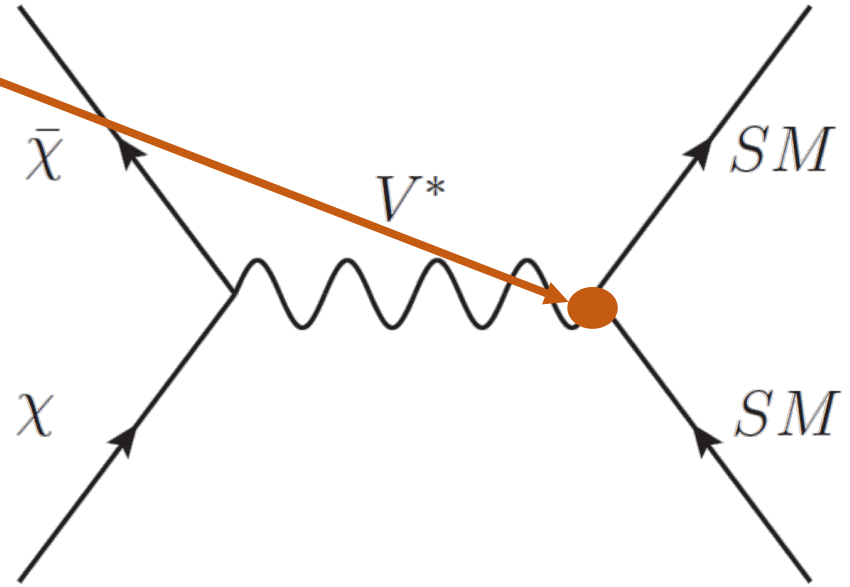
- Coupling to SM obtained through "kinetic mixing" term

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, with SSB



- Anomaly cancellation -> Introduce a Dirac fermion dark matter

$$\chi = (\chi_L, \bar{\chi}_R)$$

Fermion dark matter example

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

- Yukawa couplings to the dark Higgs S

  → Avoid Dirac DM (CMB exclusion)

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

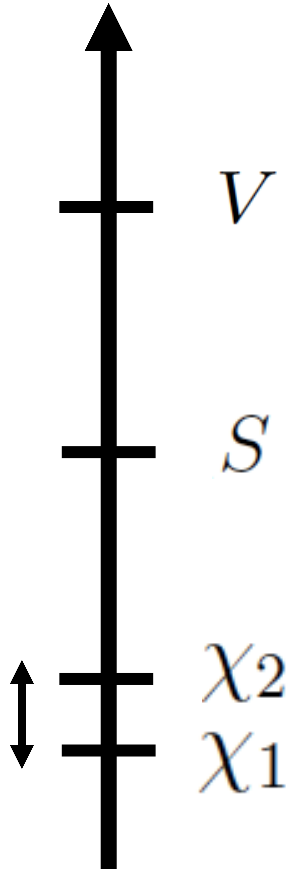
$$M_\chi = \begin{pmatrix} \sqrt{2} v_S y_{SL} & m_\chi \\ m_\chi & \sqrt{2} v_S y_{SR} \end{pmatrix}.$$

- 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

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

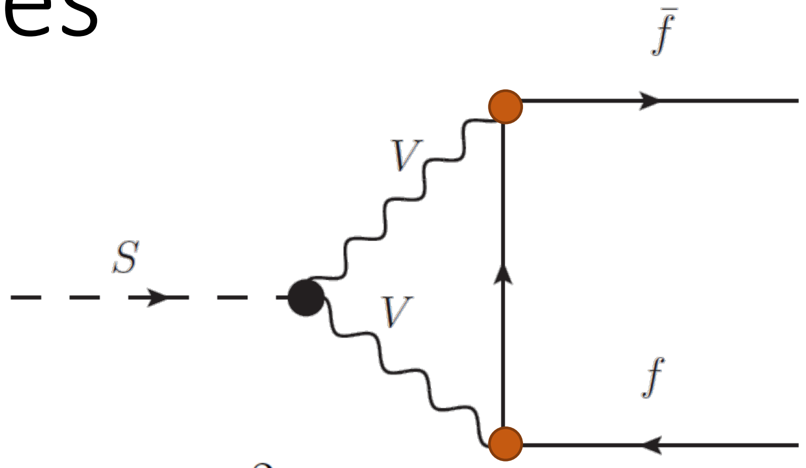
$$v_H^2 \simeq \frac{\mu_H^2}{\lambda_H}$$

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

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

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

A key aspect – Long-lived particles

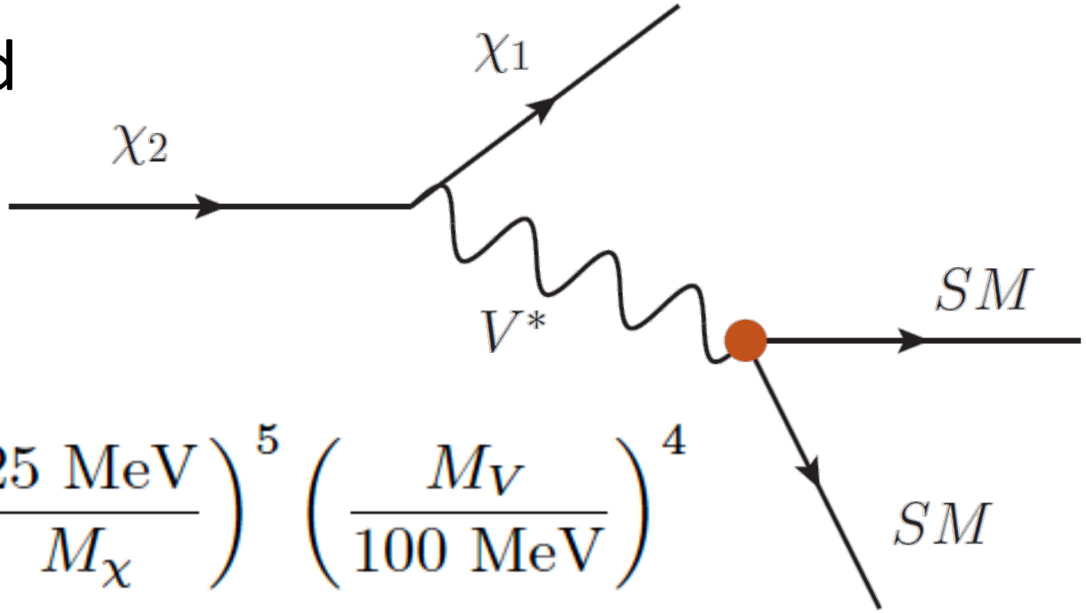


1. Decay to SM particles is the only option

   -> For instance dark Higgs boson, dark photon

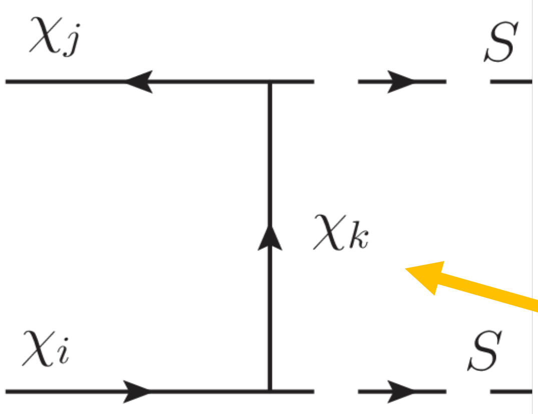
$$\tau_S \propto 1\ \mathrm{s} \times \left(\frac{\alpha'}{\alpha}\right) \times \left(\frac{10^{-3}}{\varepsilon}\right)^4 \left(\frac{100\ \mathrm{MeV}}{M_S}\right) \left(\frac{M_V}{100\ \mathrm{MeV}}\right)^2$$

2. Internal dark sector decays must proceed through off-shell mediator
   - For instance dark Higgs boson
   - heavy dark sector state



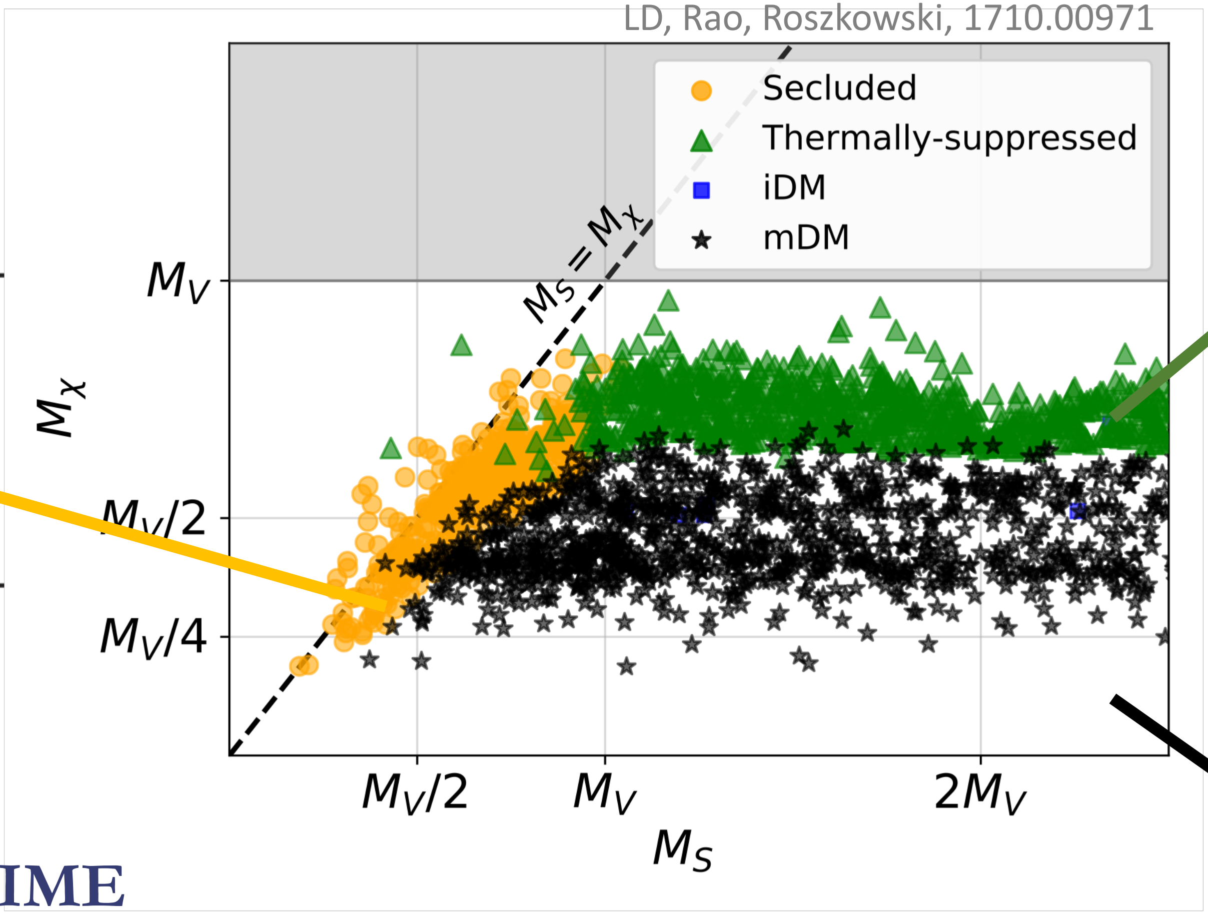
$$c\tau_{\chi_2} \propto 100\ \mathrm{m}\ \times \left(\frac{0.1}{\alpha_D}\right) \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{0.2 M_\chi}{\Delta_\chi}\right)^5 \left(\frac{25\ \mathrm{MeV}}{M_\chi}\right)^5 \left(\frac{M_V}{100\ \mathrm{MeV}}\right)^4$$

Typical regimes with correct relic density

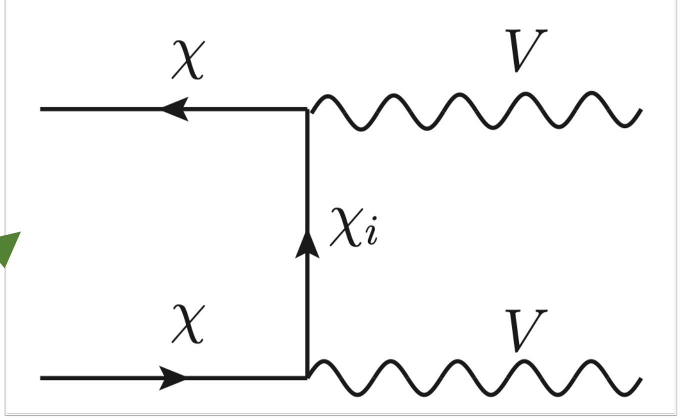


$$M_\chi \gtrsim M_S$$

SECLUDED REGIME

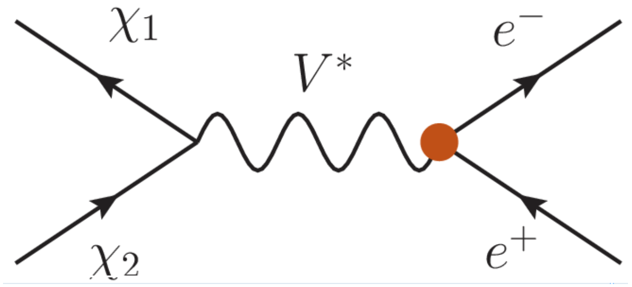


FORBIDDEN REGIME



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

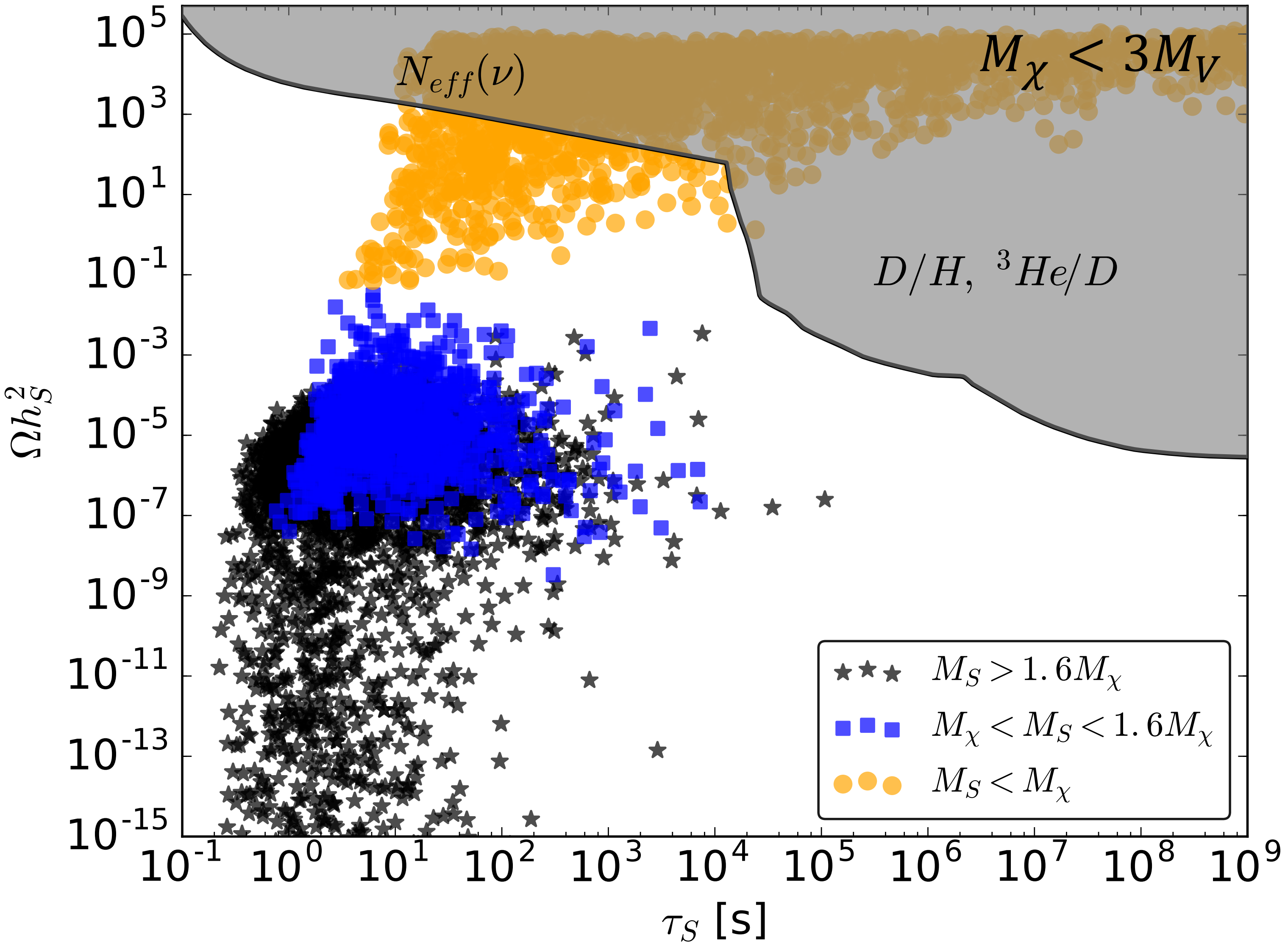
iDM/mDM REGIME



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

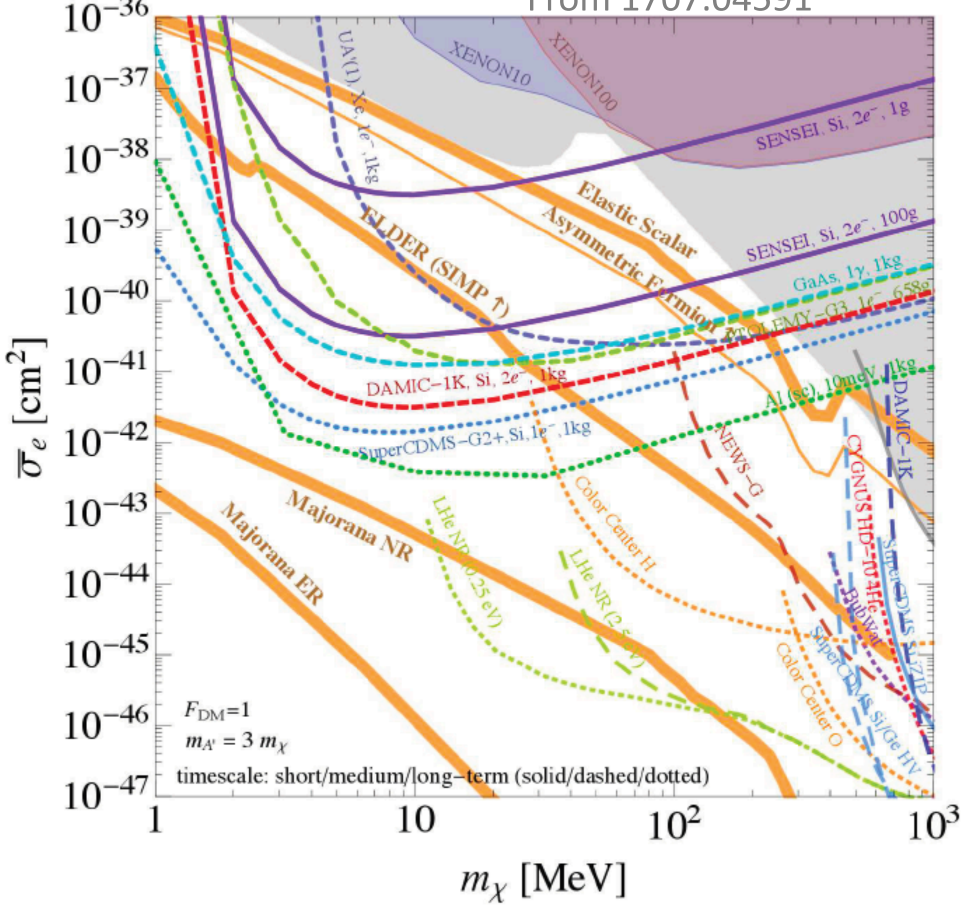
LD, Rao, Roszkowski, 1710.00971

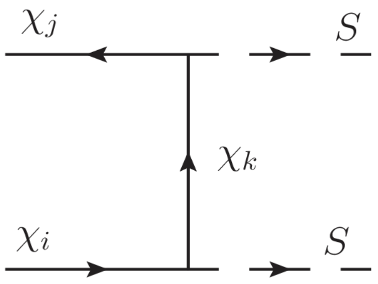


Direct and indirect detection bounds

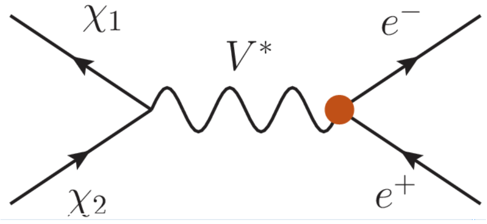
- Late-time annihilation
  - Standard CMB bound -> s-wave annihilation channel forbidden
  - → either p-wave channel or irrelevant at CMB (e.g. co-annihilation)

From 1707.04591

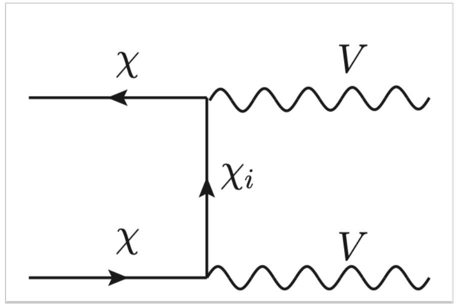




P-wave



Co-annihilation



Thermal suppression

- Direct detection, *many* upcoming experiments

  → Standard searches currently only relevant for scalar DM case (since either inelastic DM or Majorana DM)

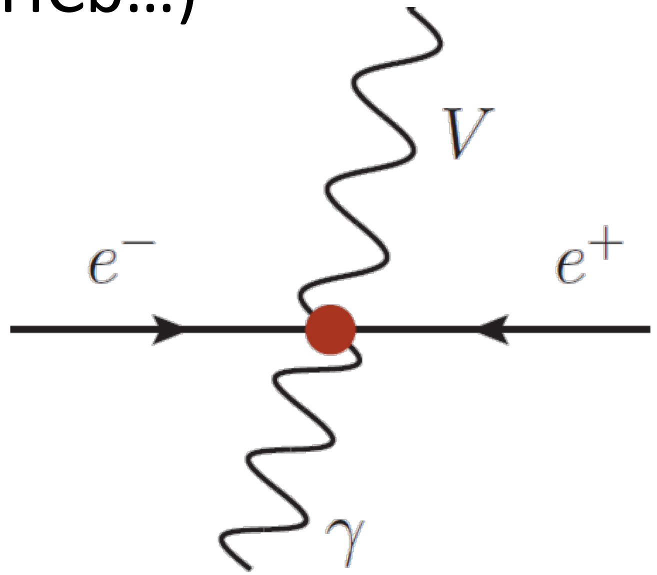
Signatures of light dark sector at the intensity frontier

Production and detection at accelerator-based experiments

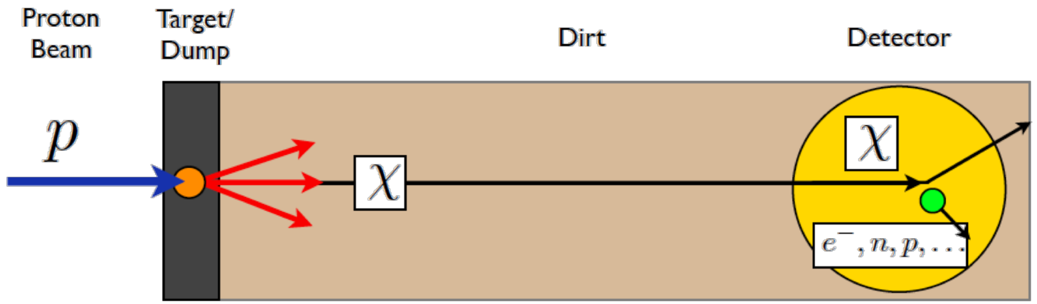
Dark Sector searches - production

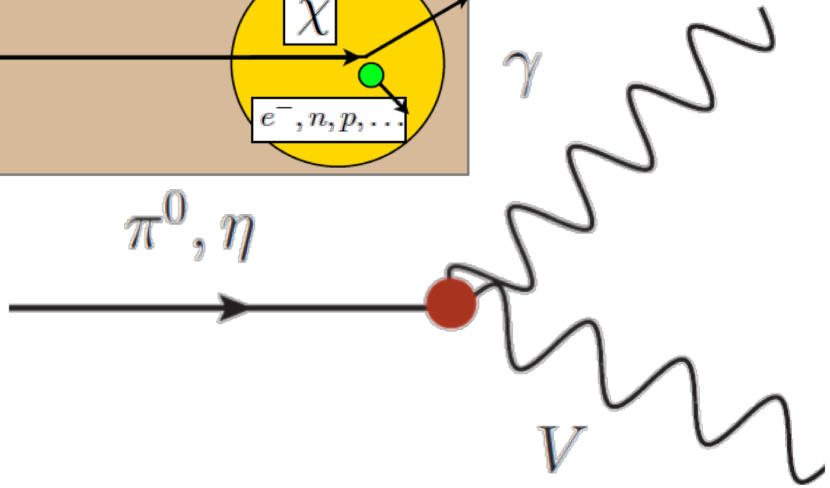
- Light dark sector particles may be accessible at the *intensity frontier*
  - « Low »-energy installations but with high intensity (e.g. LSND: $10^{22}\ \pi^0$)

Precision experiments at collider (e.g BaBaR, BELLE, LHCb…)



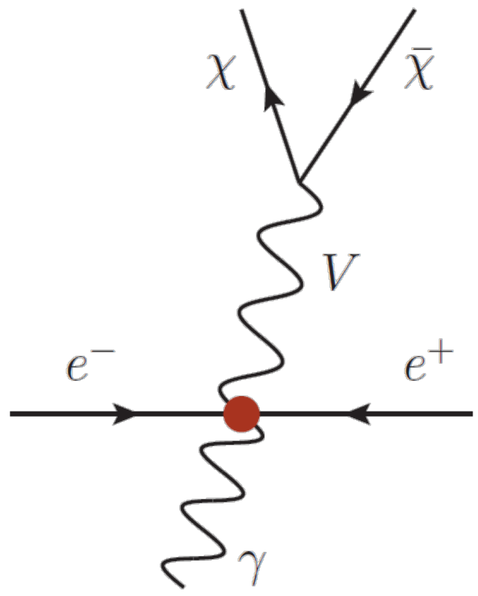
Beam-dump/fixed-target types of experiments (LSND, E137…)



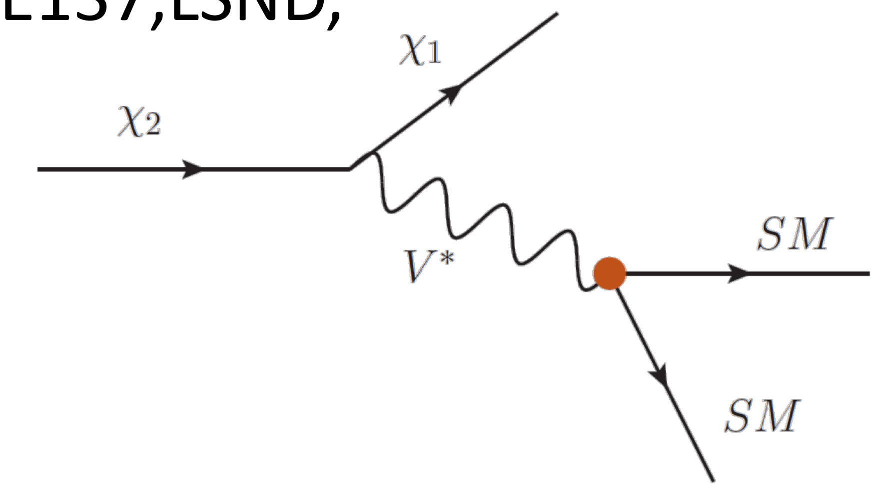


Dark Sector searches -detection

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

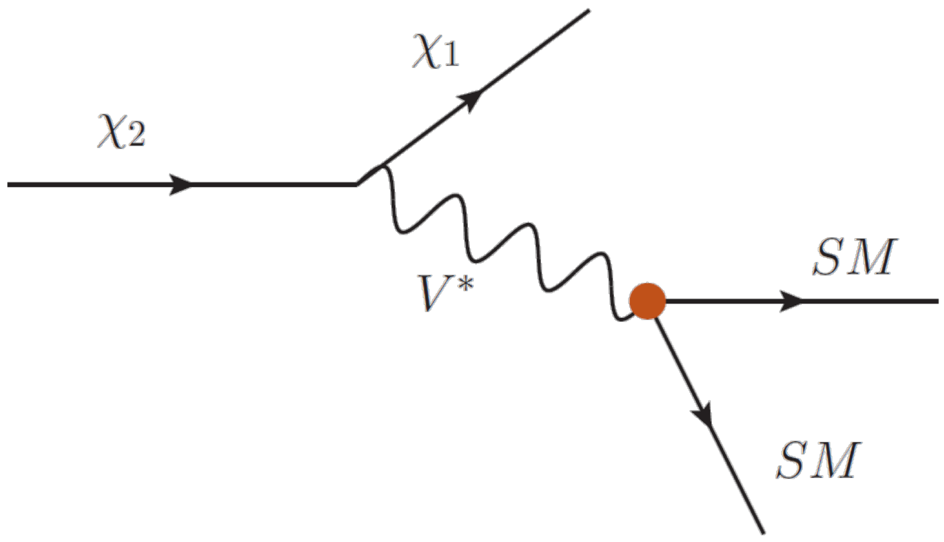


- Dark sector beam production and detection
  - Scattering: Searching for DM via scattering in fixed targed/long-baseline neutrinos experiments (E137,LSND, miniBooNE …)
  - Dark sector visible decay: Detection of an electron/positron pair in fixed target/beam dump experiments



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



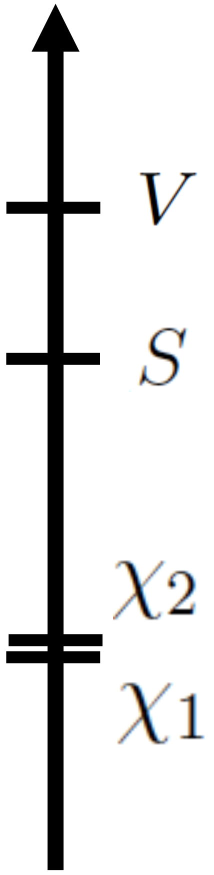
$$c\tau_{\chi_2} \propto 100 \text{ m} \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{10^{-3}}{\varepsilon}\right)^2\left(\frac{0.2}{\Delta_\chi}\right)^5\left(\frac{25 \text{ MeV}}{M_S}\right)^5\left(\frac{M_V}{100 \text{ MeV}}\right)^4$$

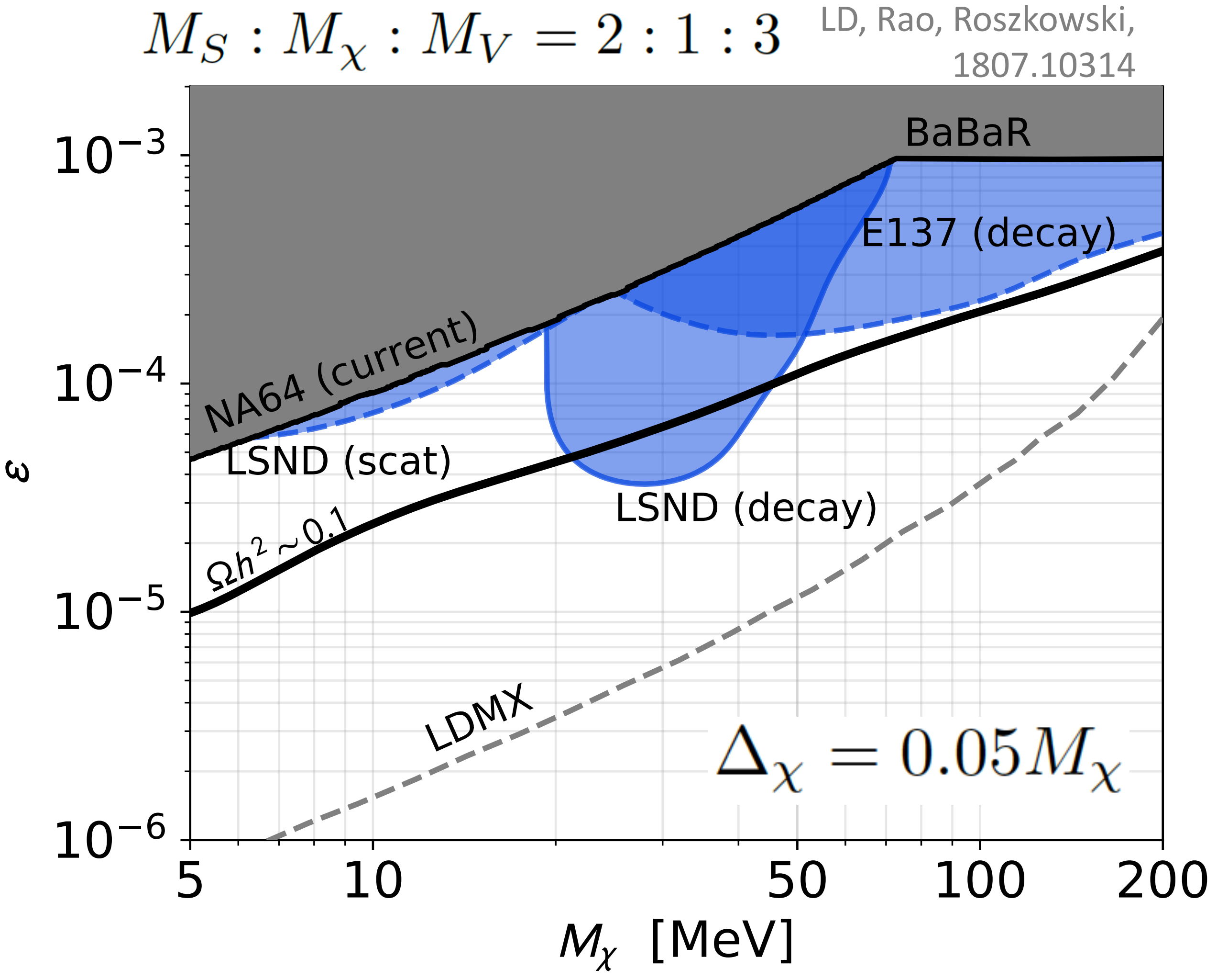
- In the optimum case $\text{NoE}_{\text{HDS}} \propto \varepsilon^2$

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

Inelastic DM regime

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

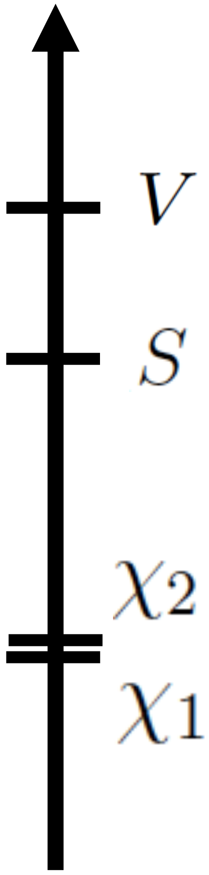


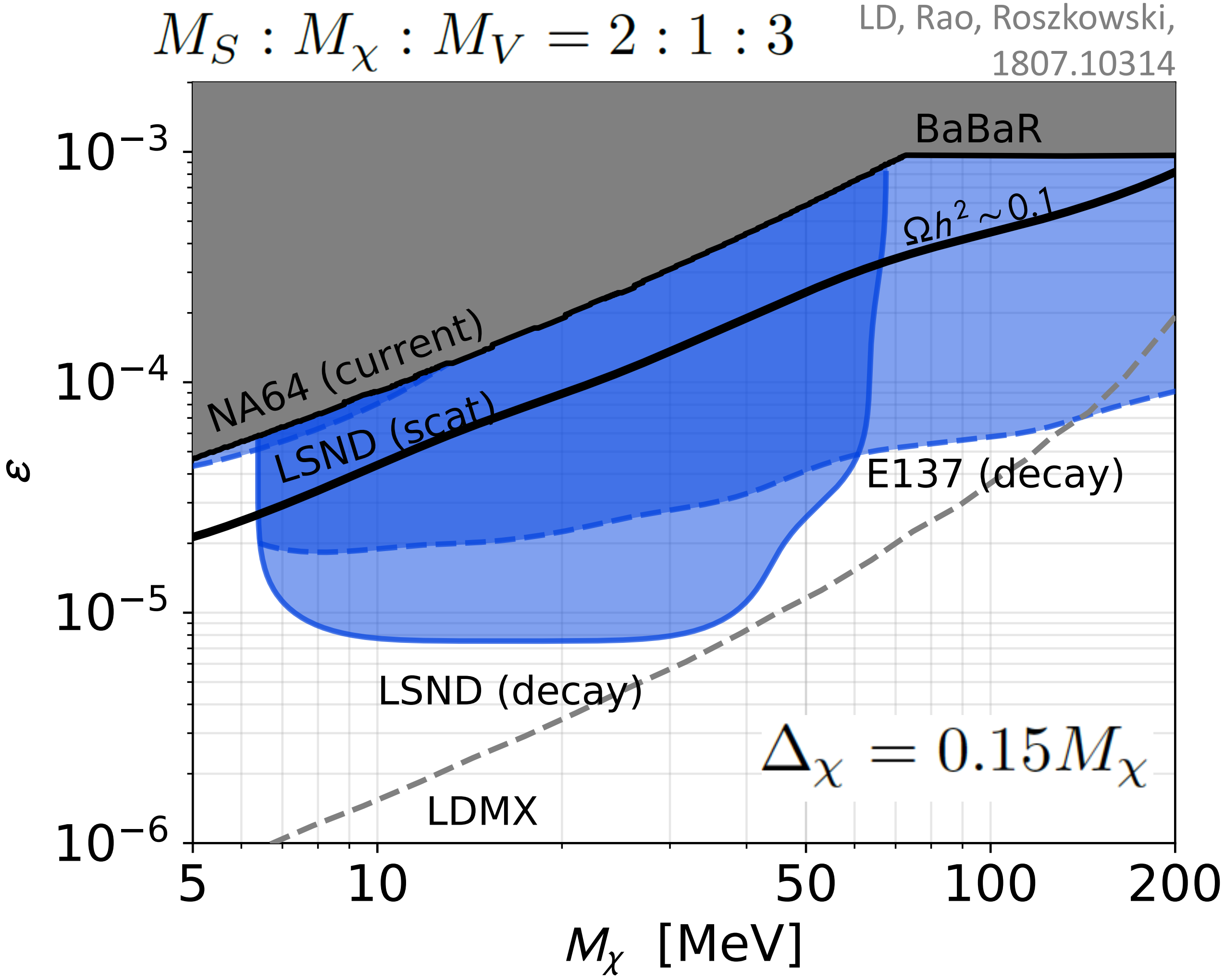


- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+ e^-$ decay
  - χ_1 scattering
- When consider dark sector decays, decades-old experiment are still strongly ahead of current mono-photon searches!

Inelastic DM regime

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

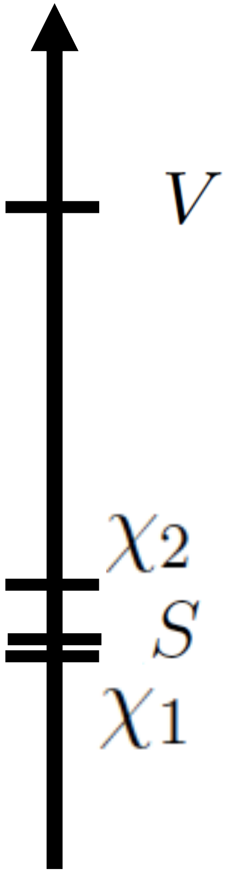


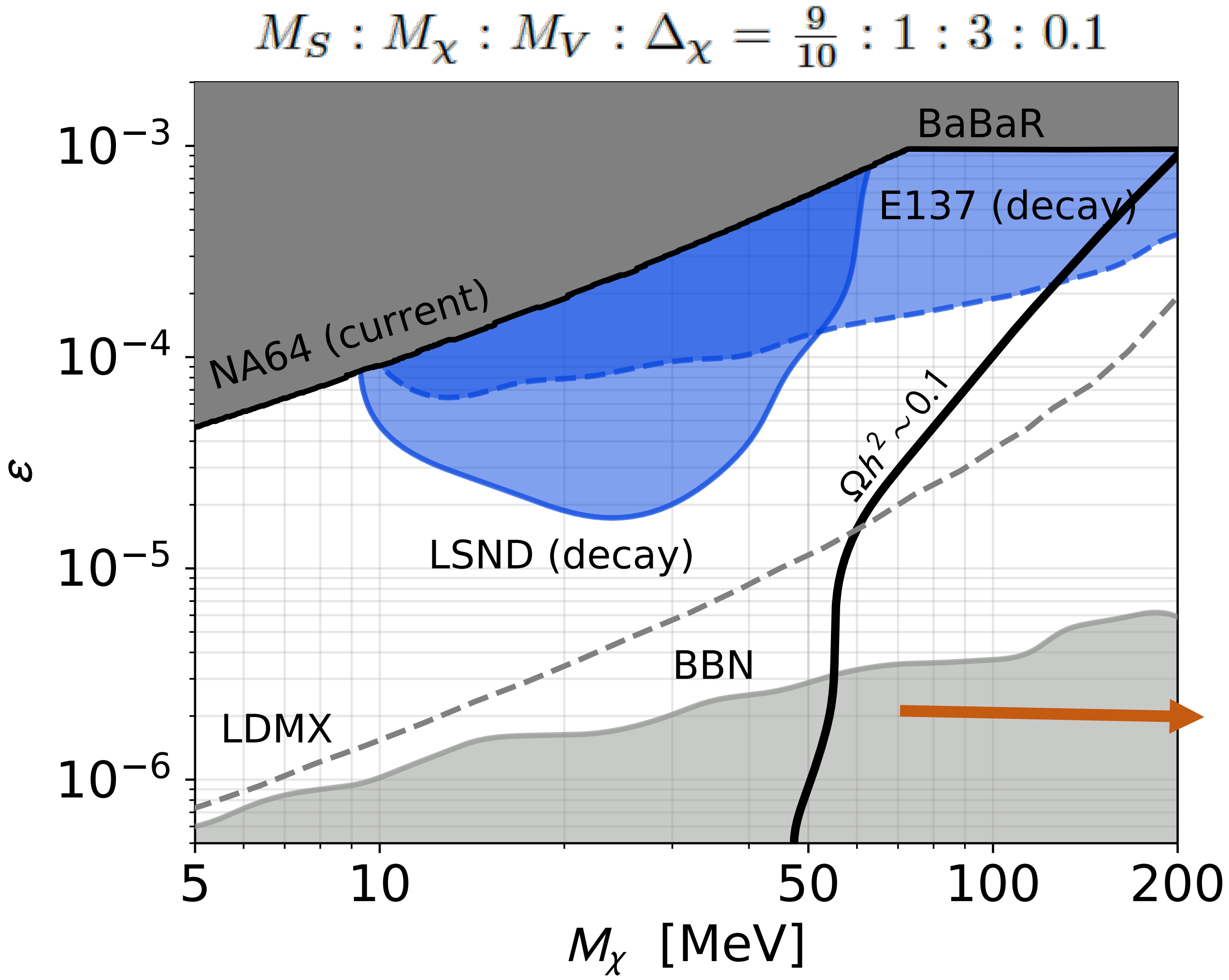


- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+ e^-$ decay
  - χ_1 scattering
- When consider dark sector decays, decades-old experiment are still strongly ahead of current mono-photon searches!

Secluded DM regime

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





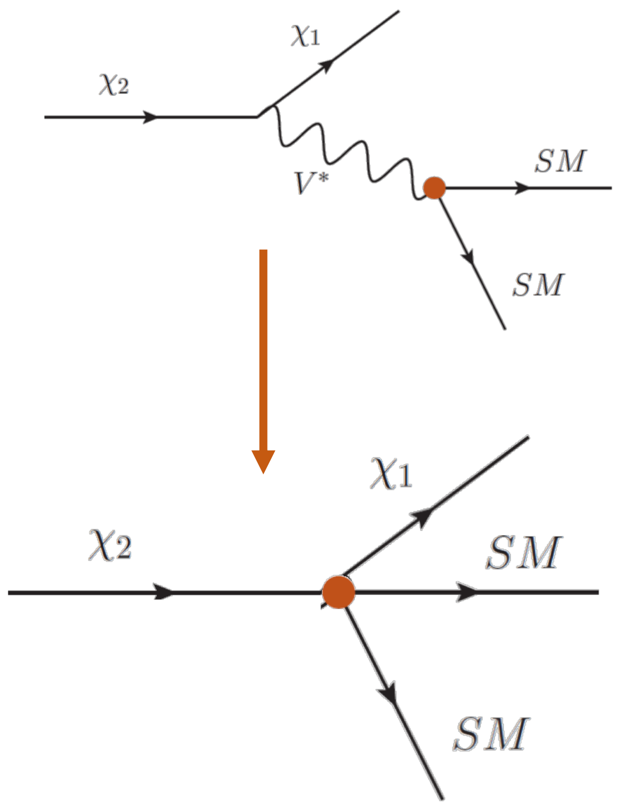
- Main signatures:
  - Missing energy searches
  - $\chi_2 \rightarrow \chi_1 e^+ e^-$ decay
  - χ_1 scattering

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

Light dark sector effective theory and the intensity frontier:
the fermion portal

The off-shell effective approach

- Supposed a large mass splitting between dark matter and mediator scale
  - →Effective theory description relevant (same for leptons)



Vector operator

$$\sum_q \frac{g_q}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\chi_2)(\bar{q}\gamma^\mu q)$$

Axial vector operator

$$\sum_q \frac{\tilde{g}_q}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\gamma^5\chi_2)(\bar{q}\gamma^\mu\gamma^5 q)$$

- Based on the above diagram, basic equivalence

$$\frac{\Lambda}{\sqrt{g}} \sim \frac{M_V}{\sqrt{\varepsilon g_D e}}$$

→ Could probe scale 2 to 3 orders of magnitudes larger than χ

The off-shell effective approach (2)

- For off-shell mediator, long-lifetime comes from mass suppression
  - Typically need to go to the saturation limit $M_1 \ll M_2$

$$c\tau^{\rm sat} \sim 2\ {\rm m} \times \left(\frac{\Lambda/\sqrt{g}}{1\ {\rm TeV}}\right)^4 \left(\frac{1\ {\rm GeV}}{M_{\chi_2}}\right)^5$$

- One can also search for “grey sector” with mixed coupling/heavy scale suppression

$$c\tau^{\rm pD} \sim 375\ {\rm m} \times \left(\frac{100\ {\rm GeV}}{\Lambda}\right)^4 \left(\frac{1\ {\rm GeV}}{M_{\chi_1}}\right)^5 \left(\frac{0.25}{\Delta_\chi}\right)^5 \left(\frac{0.01}{g}\right)^2$$

- Production is completely modified vs. the on-shell dark photon mediator
  - Strong suppression of lower energy processes → typical suppression $\propto \frac{M_m^4}{\Lambda^4}$
  - No CS from dark photon bremsstrahlung → Electron beam-dump hardly relevant

Meson decays in the fermion portal

- Depending on the nature of the operators, different production channels

Vector operator

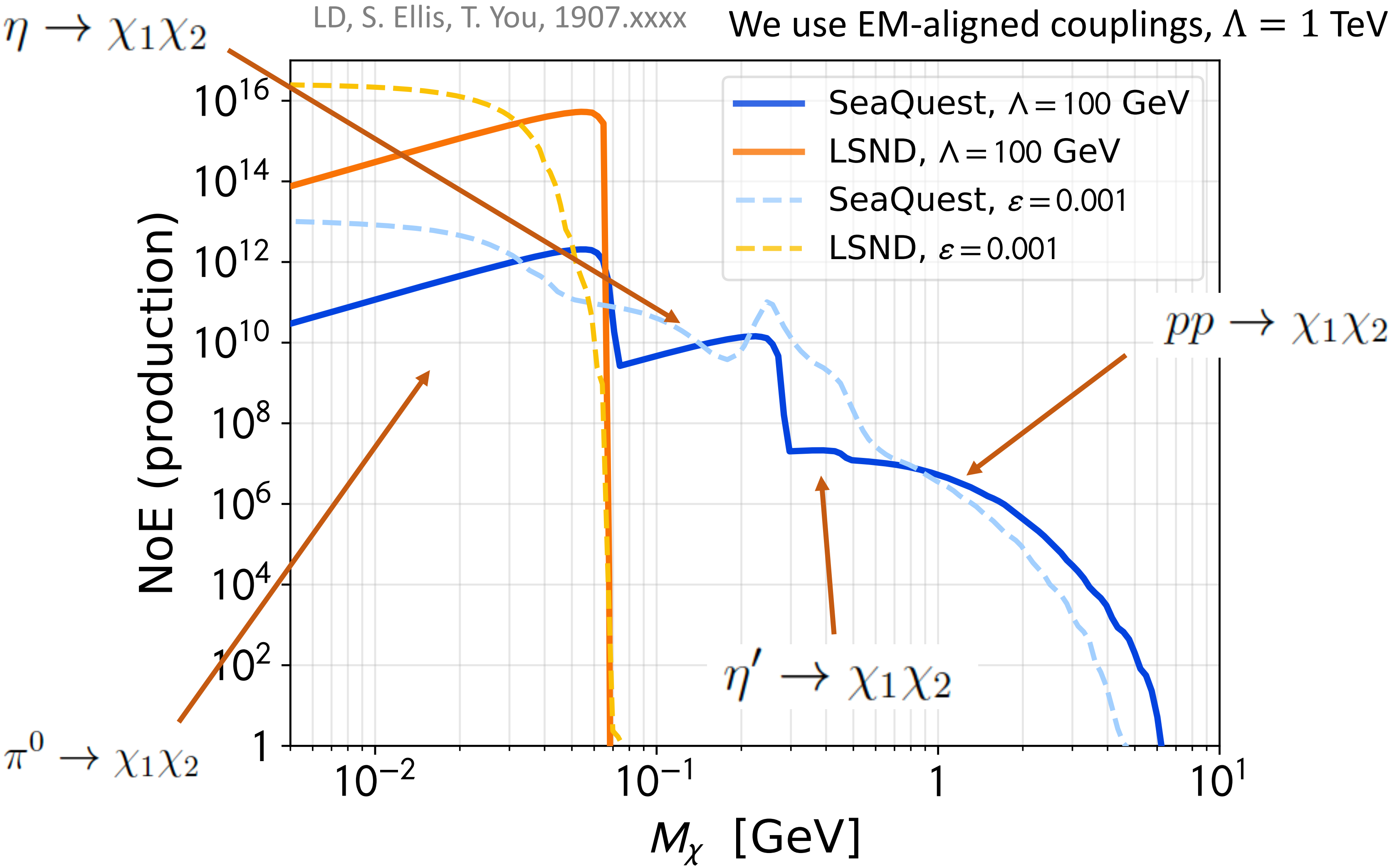
$$\pi^0, \eta, \eta' \to \gamma\chi\chi$$
$$\rho, \omega \to \chi\chi$$

Axial vector operator

$$\pi^0, \eta, \eta' \to \chi\chi$$

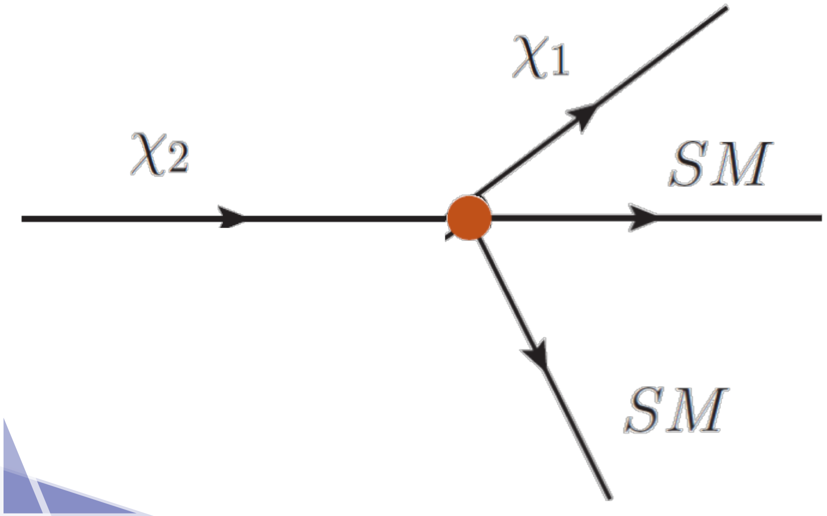
LD, S. Ellis, T. You, 1907.xxxx

We use EM-aligned couplings, $\Lambda = 1$ TeV



Limits in the vector case

- We consider the saturation limit $M_2 \gg M_1$
- Beam-dump experiment probing significantly above their energy



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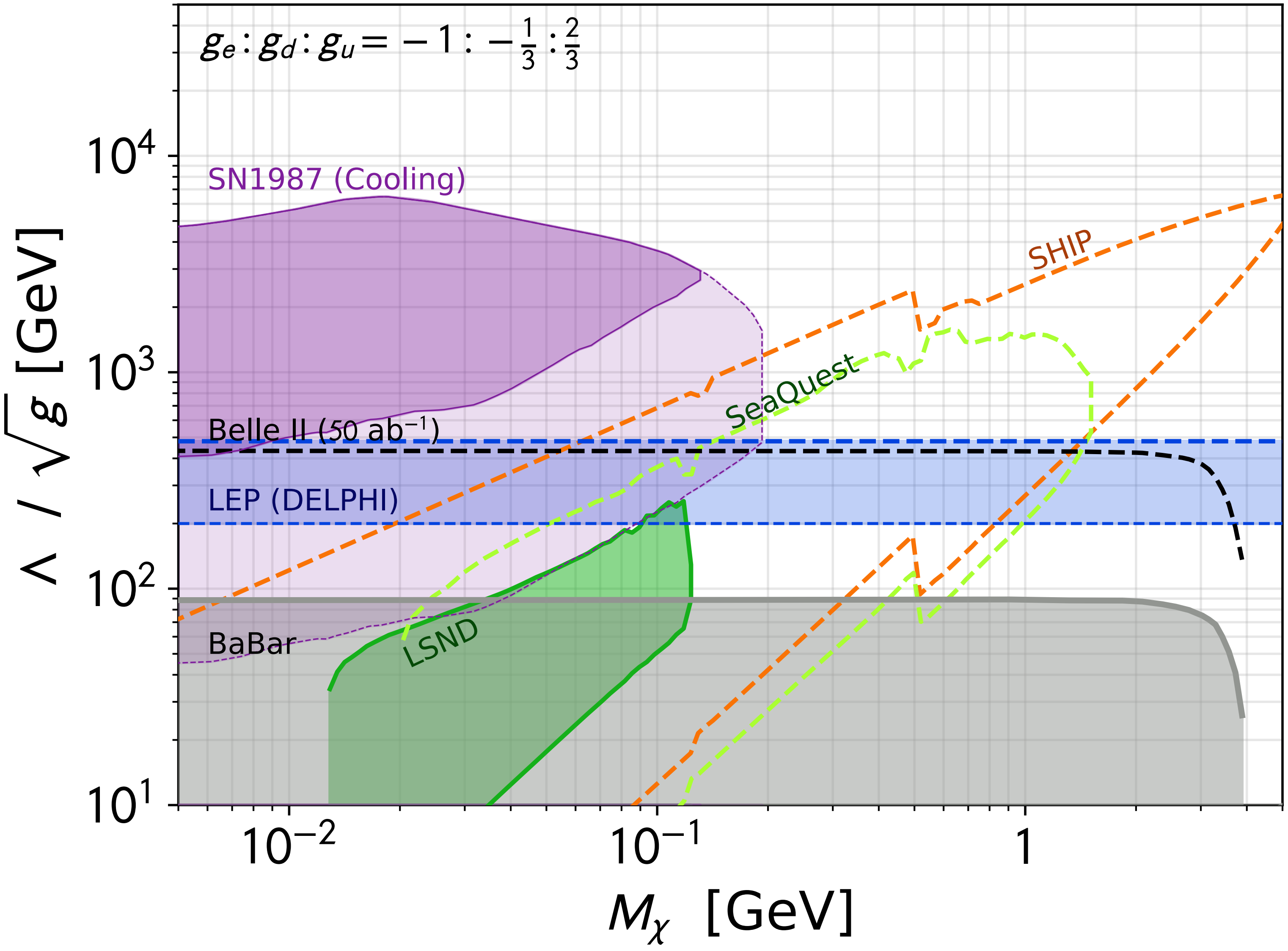

Varying the couplings and splitting

- Reach of decay signatures depends strongly on Δ_χ, reach of collider mono-X on g_{eff}

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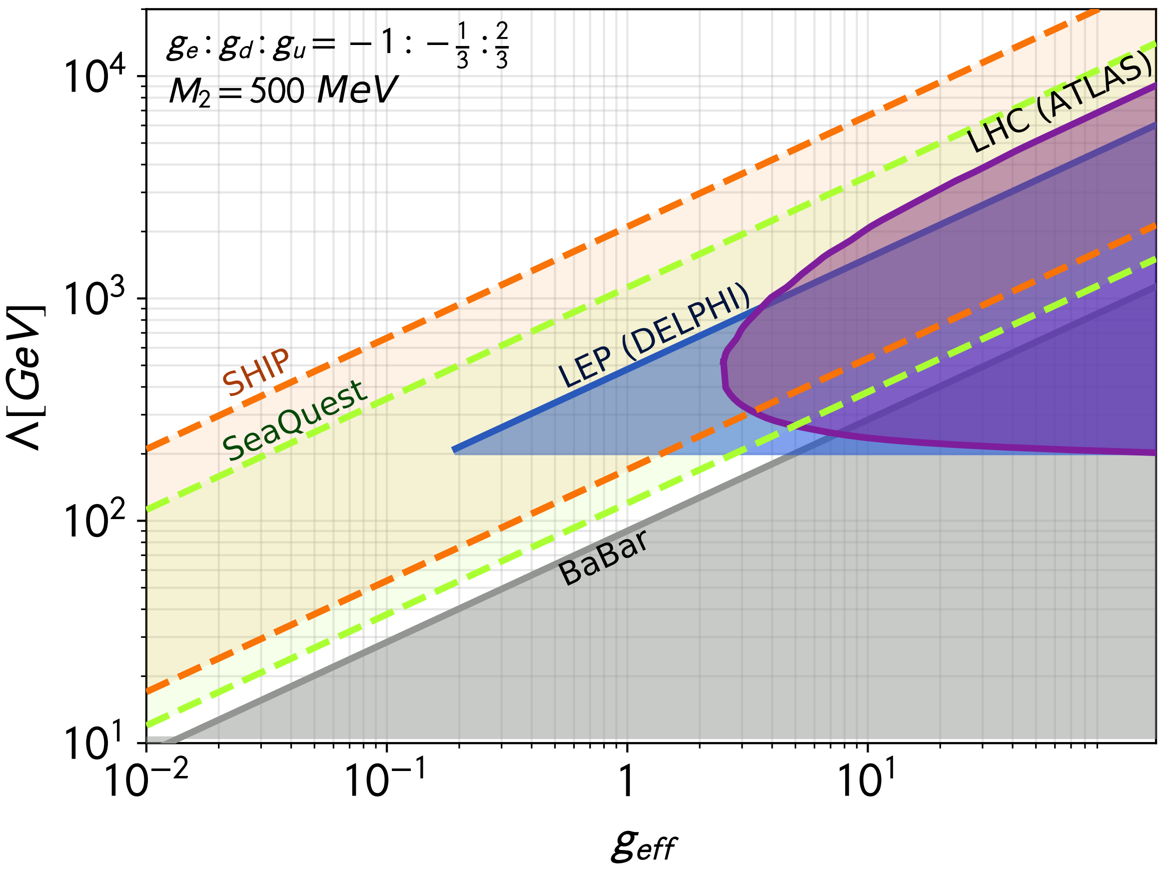

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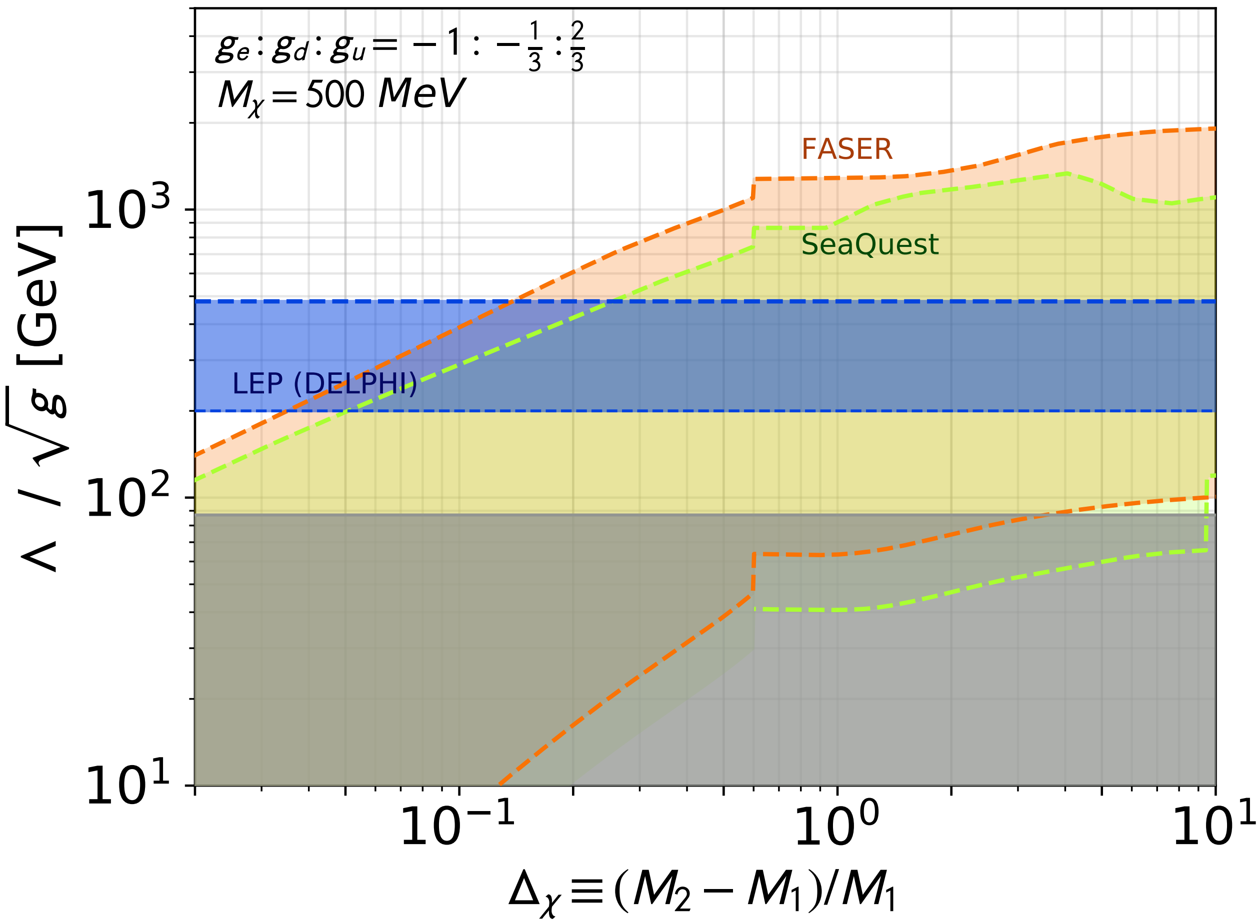

Limits in the axial-vector case

- Mesons production strongly enhanced

→ Better low-mass limits

- SN1987 based on π^0 decay
  - -> Very uncertain lower limit (also splitting-dependent)
- Notice the low limit for SHIP/SeaQuest

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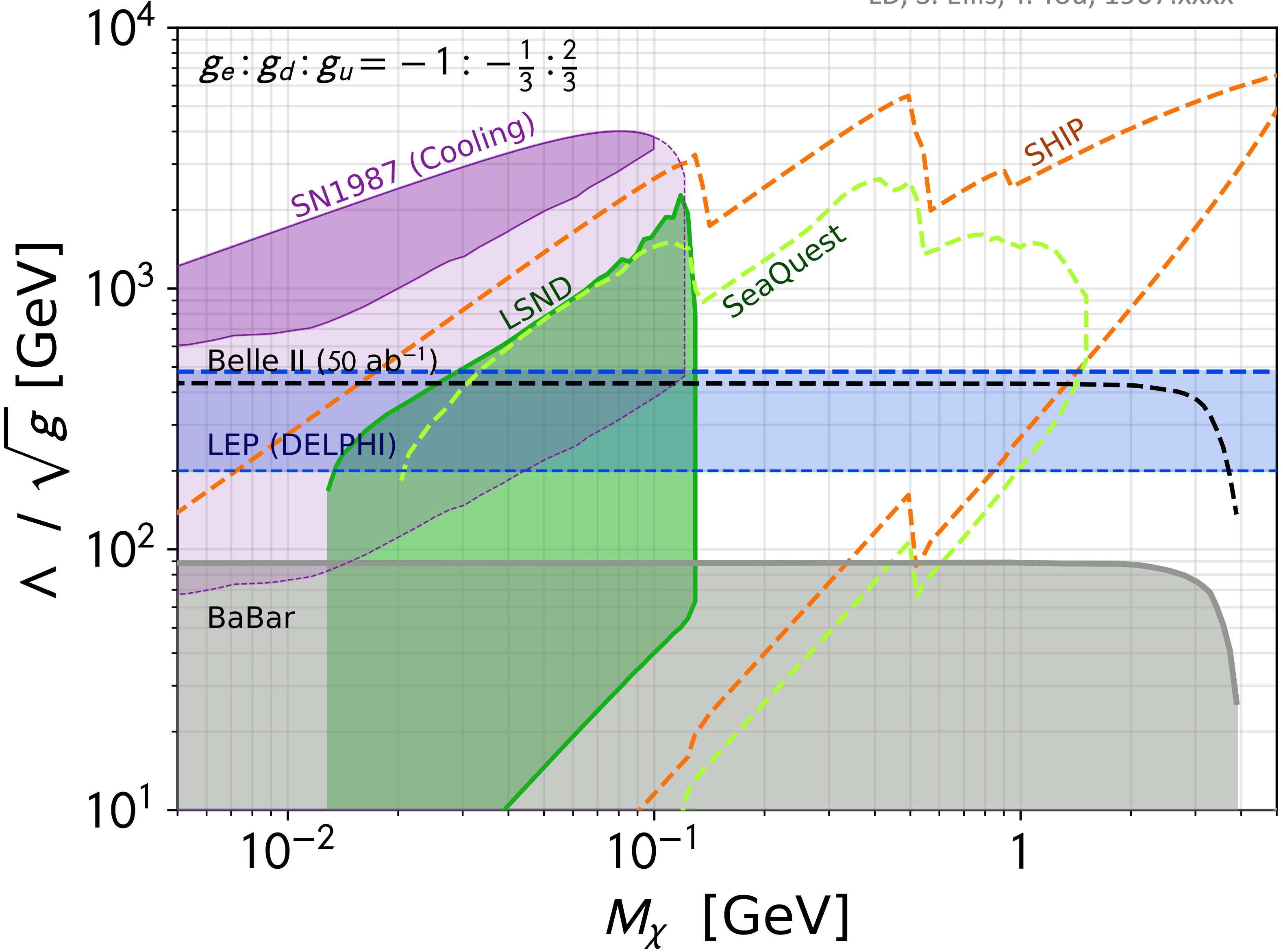


Conclusion

Looking forward …

- Many upcoming relevant experiments:
  - Neutrino experiments -> the near detectors can search for dark sector particles
  - Dark sector-oriented -> looking for decays/ missing energy
  - Flavour/ Rare mesons decay -> Missing energy searches, invisible meson decay, etc…

Running: Belle II, BDX@Jlab, PADME, 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…)

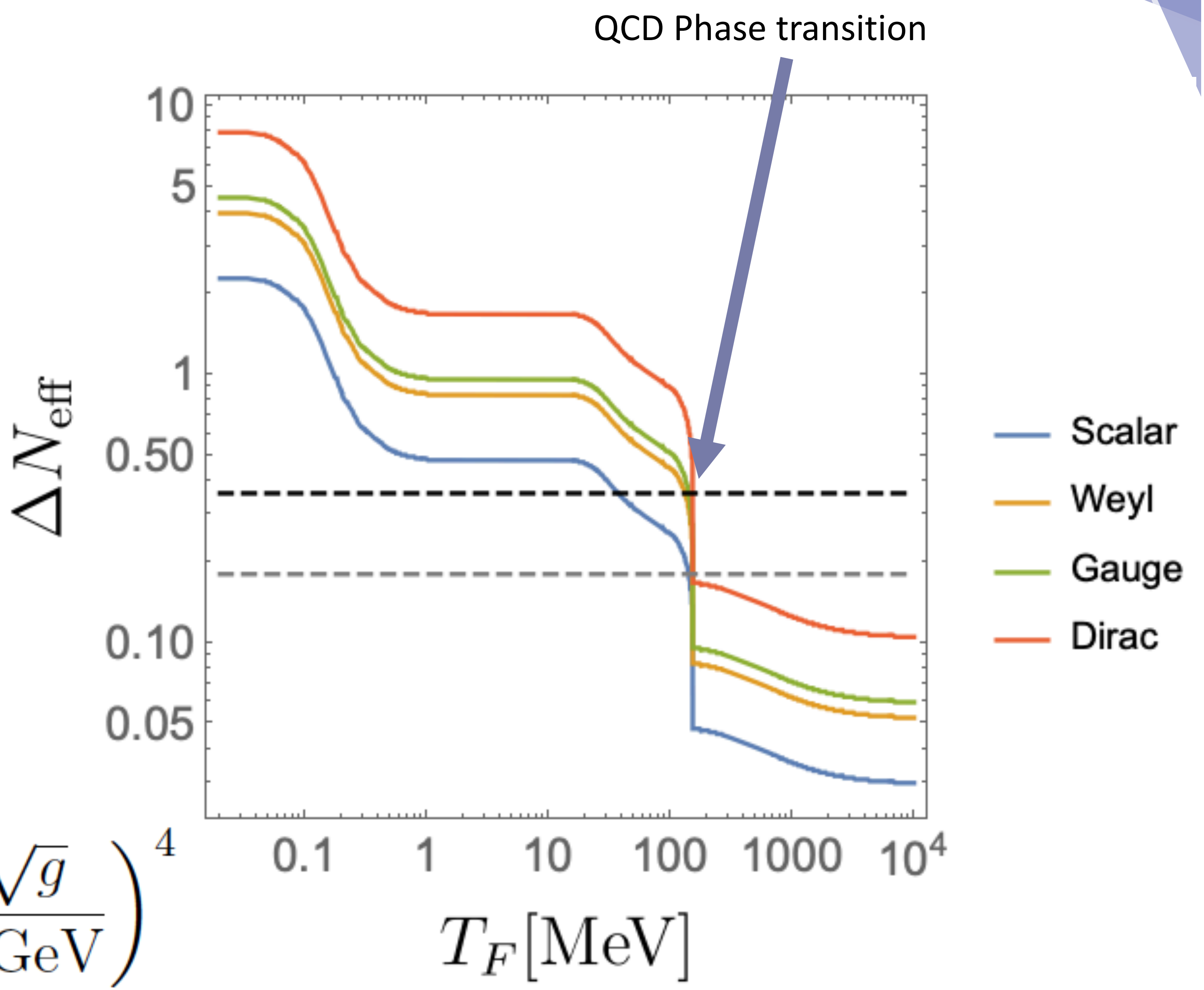
Conclusion

- 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

Astrophysical limits

- For $M_2 \gg M_1$, the lightest dark sector can be relativistic relic
- More generally, one can still obtain dark matter candidate for iDM setup, e.g. for charm annihilation



$$\Omega h^2 \sim 0.3 \times \left(\frac{2\ \text{GeV}}{M_\chi}\right)^2 \left(\frac{\Lambda/\sqrt{g}}{500\ \text{GeV}}\right)^4$$

Meson decays in the fermion portal

- Depending on the nature of the operators, different production channels

Vector operator → $\pi^0, \eta, \eta' \to \gamma \chi \chi$
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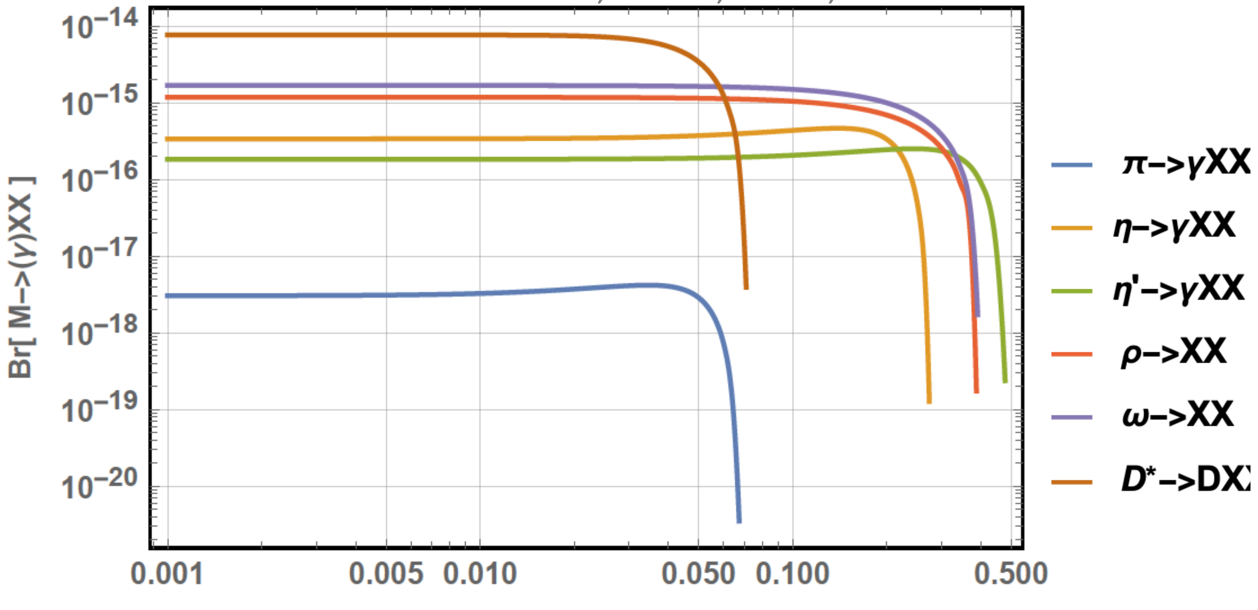
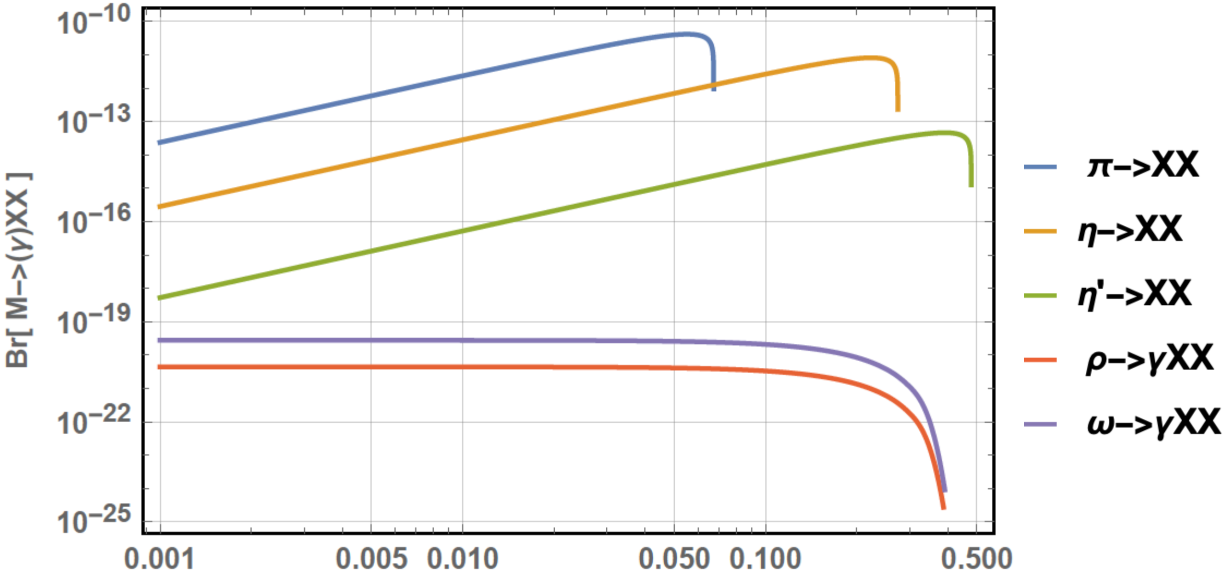
Axial vector operator → $\pi^0, \eta, \eta' \to \chi \chi$

LD, S. Ellis, T. You, 1907.xxxx



LD, S. Ellis, T. You, 1907.xxxx

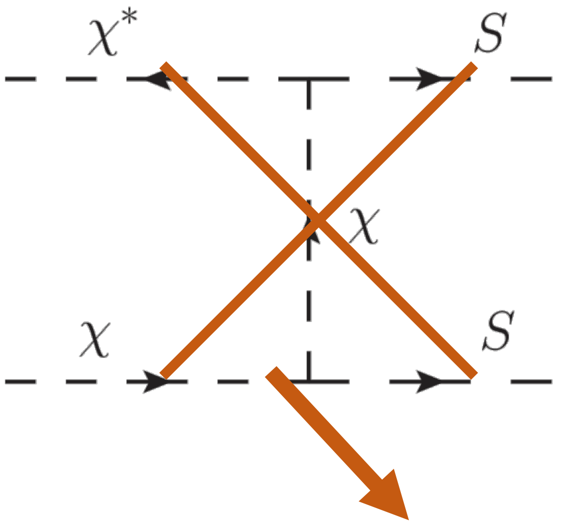


We use EM-aligned couplings, $\Lambda = 1$ TeV

- Invisible meson decay limits relevant mostly for AV case, for $\Lambda \sim 100$ GeV

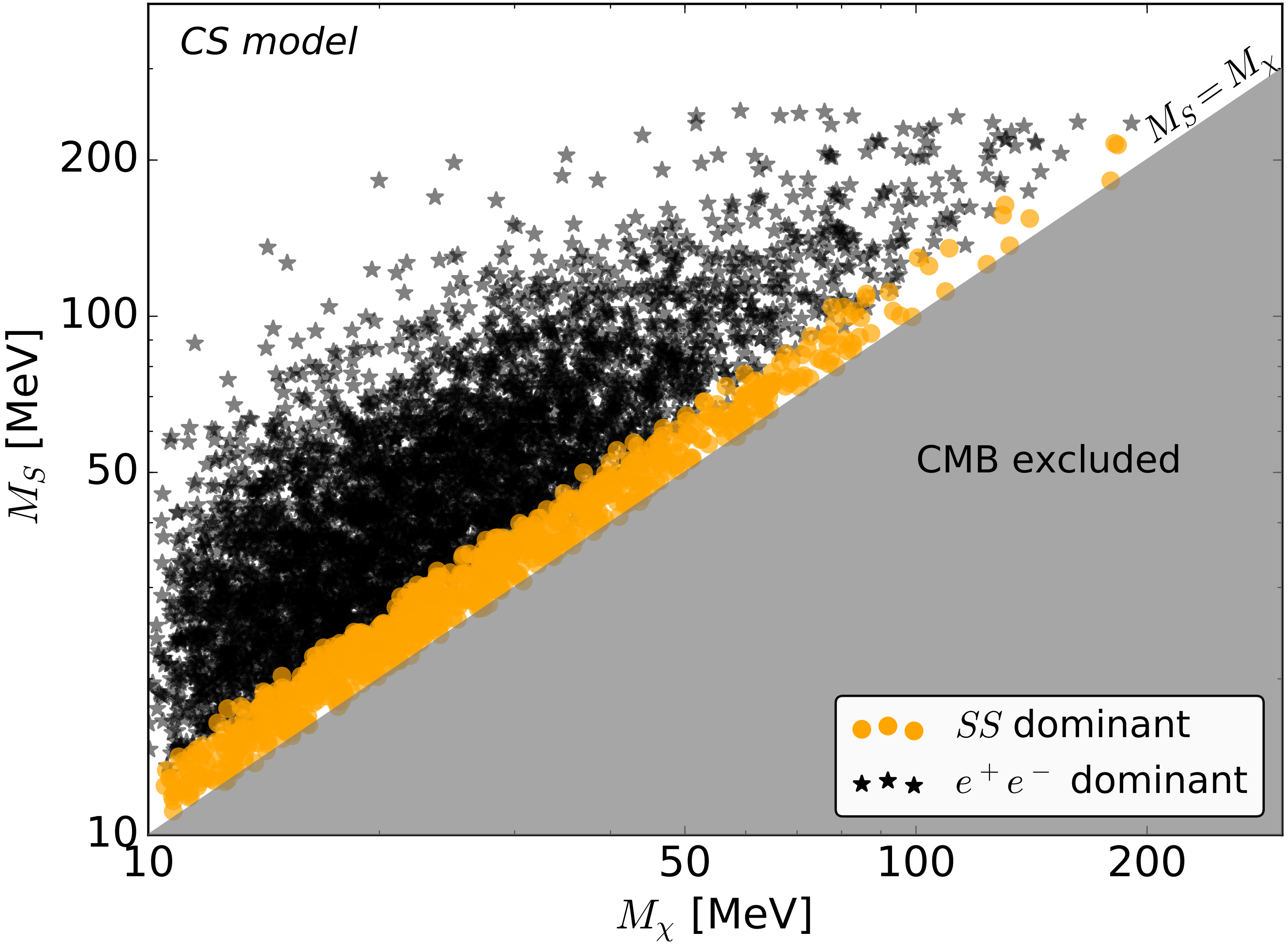
CMB bounds -- the scalar case

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



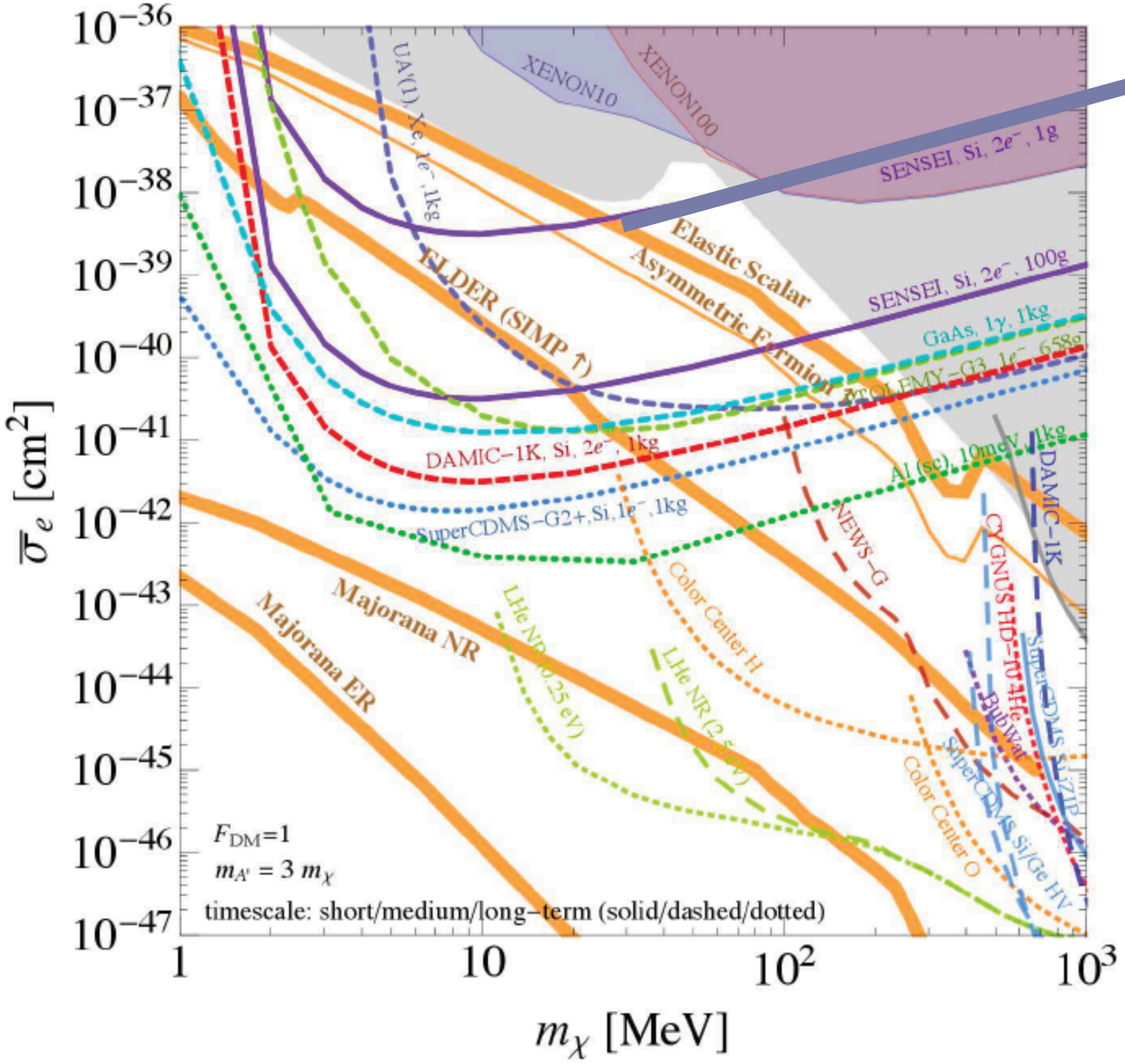
$M_\chi < M_S$

LD, Rao, Roszkowski, 1710.00971

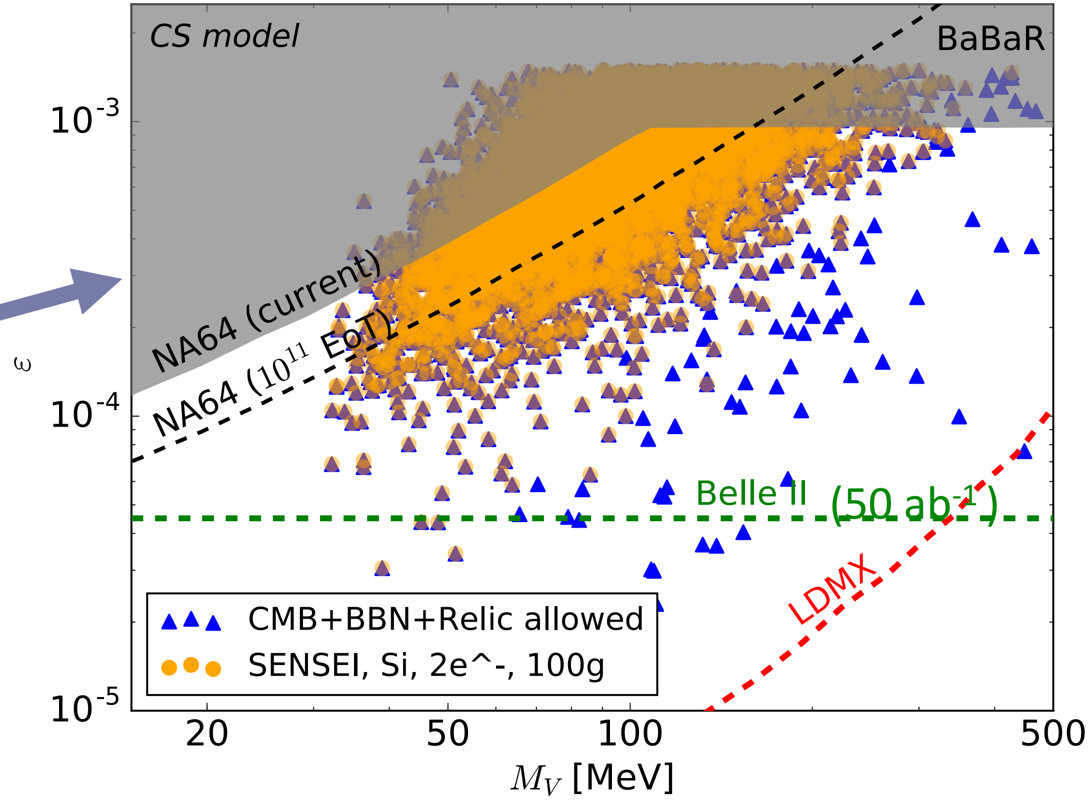


Direct Detection

From 1707.04591



LD, Rao, Roszkowski, 1710.00971



- 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

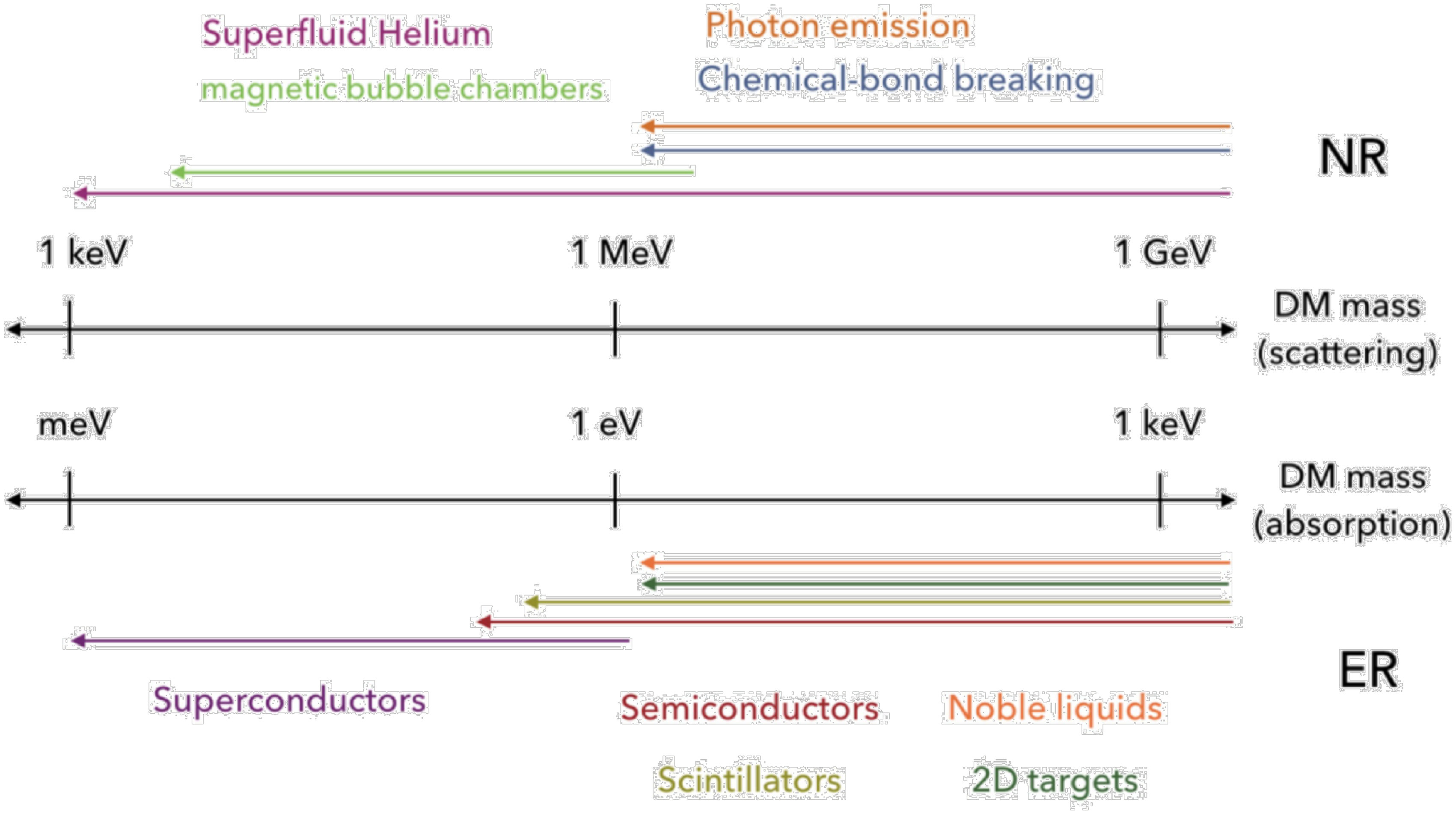
Ranges for the bulk scan

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	$0.01\|M_\chi\|$ - $10\|M_\chi\|$	Log
y_{DM}	-2 - 2	Linear

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

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

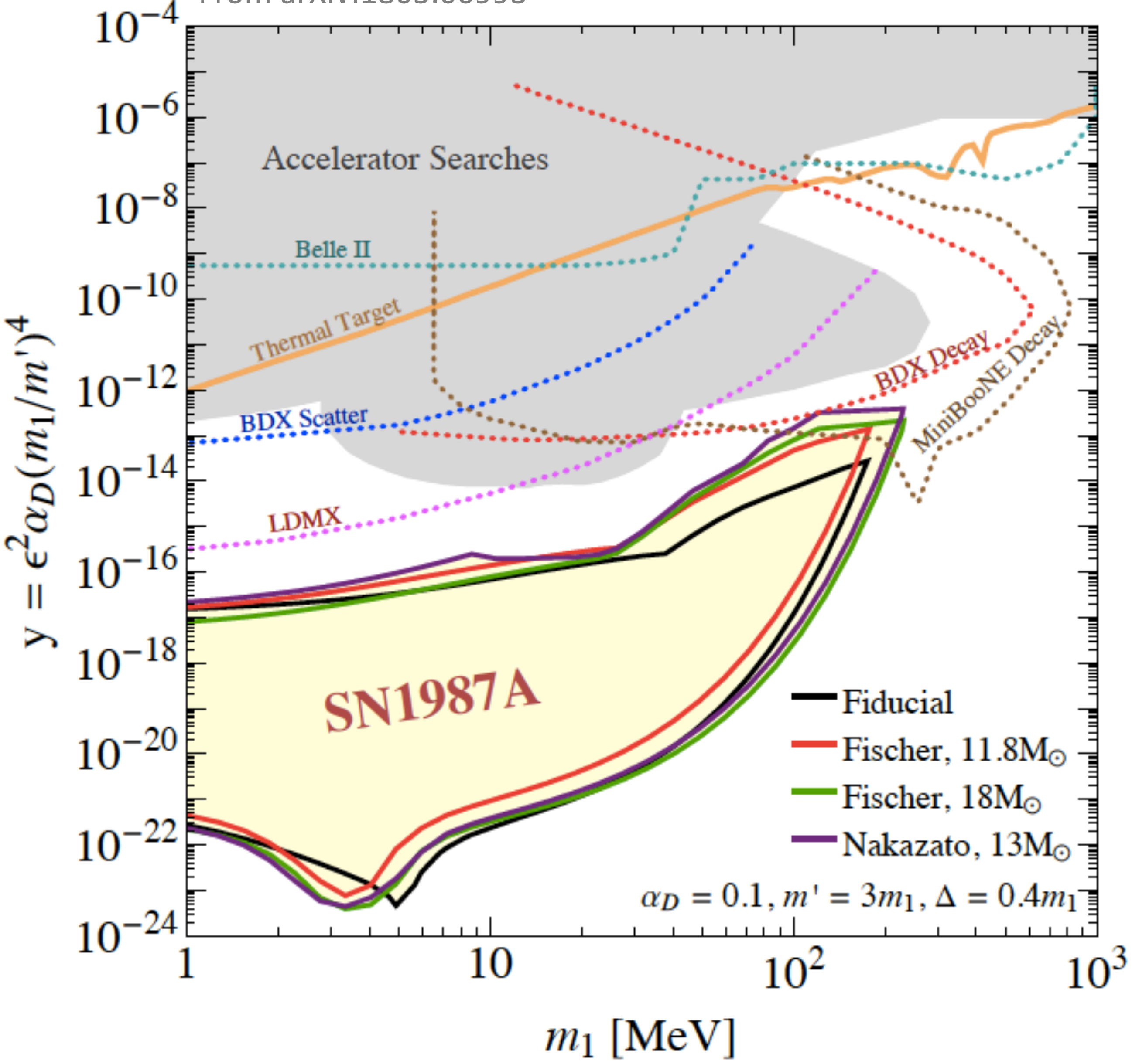
- Typical bounds arise when DM do not scatter enough and escape the SN core

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

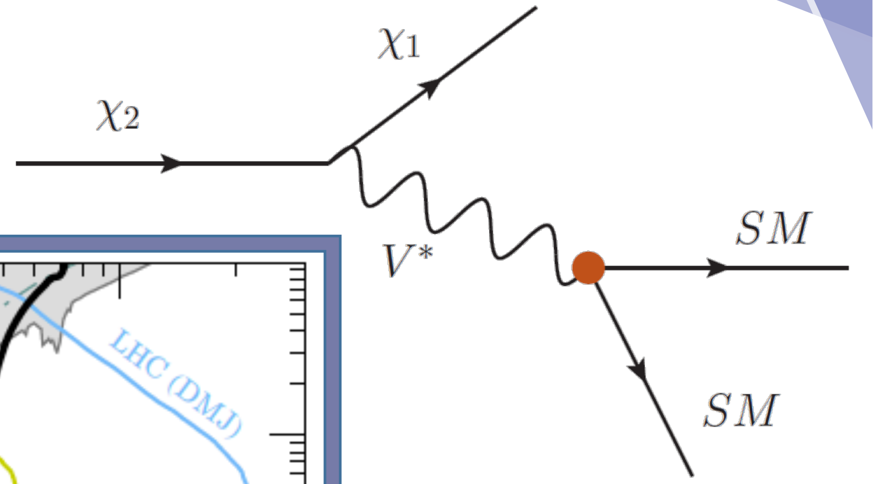
- Not relevant for pseudo-Dirac case/Majorana case at the thermal target
- Dark Higgs bounds may be relevant at $m_S < M_{\chi_1}$ or $m_S < M_{\chi_2} - M_{\chi_1}$

  → But scattering with DM halo inside the SN should be enough to trap it

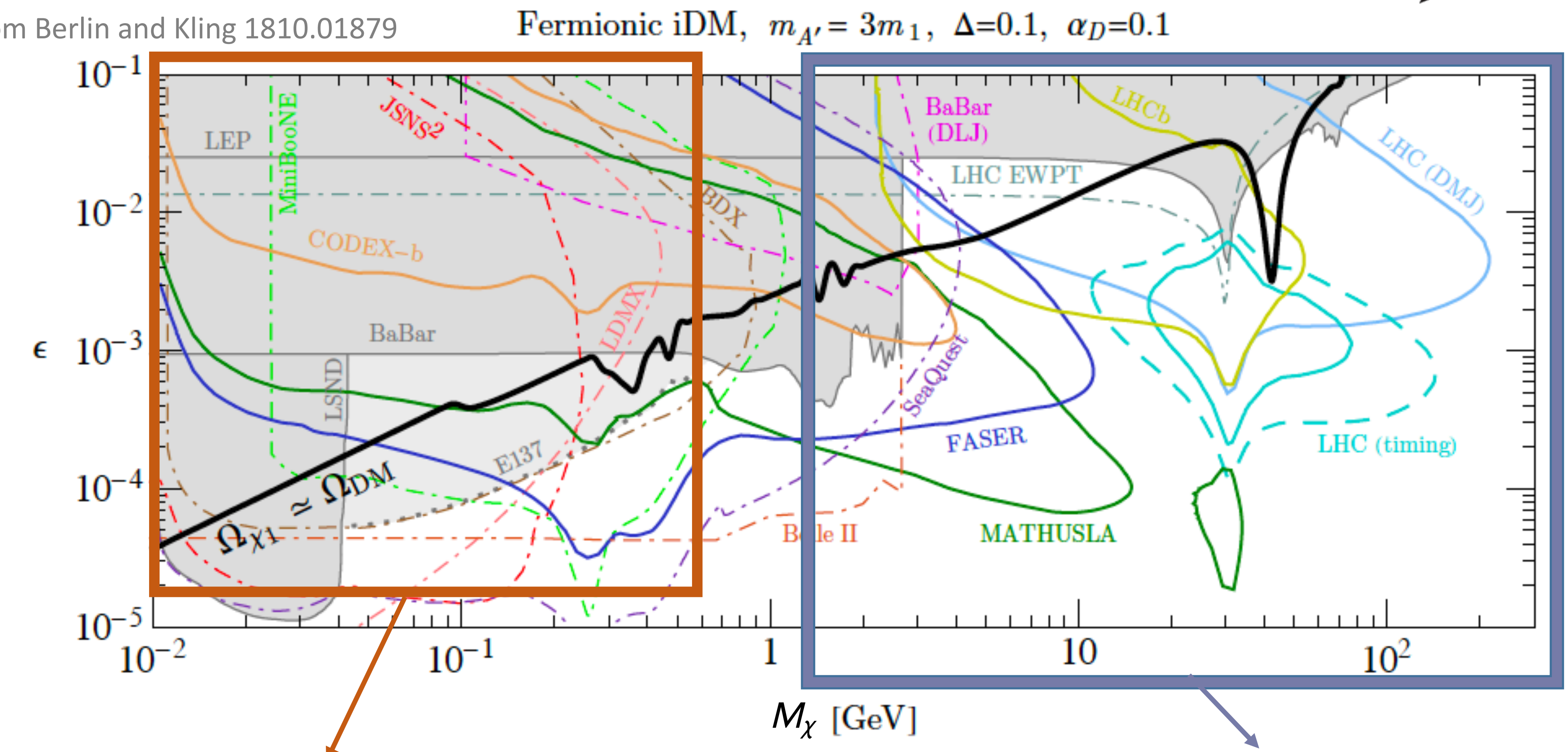
From arXiv:1803.00993



Heavy dark sector decays (2)



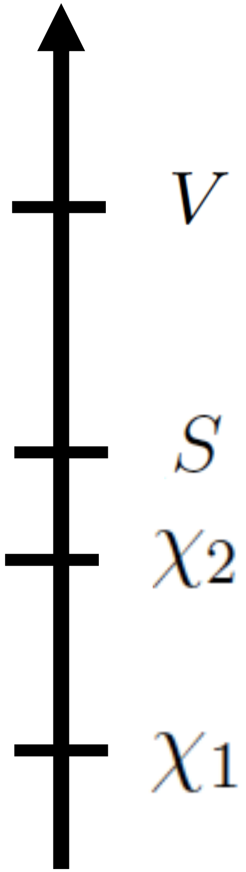
From Berlin and Kling 1810.01879

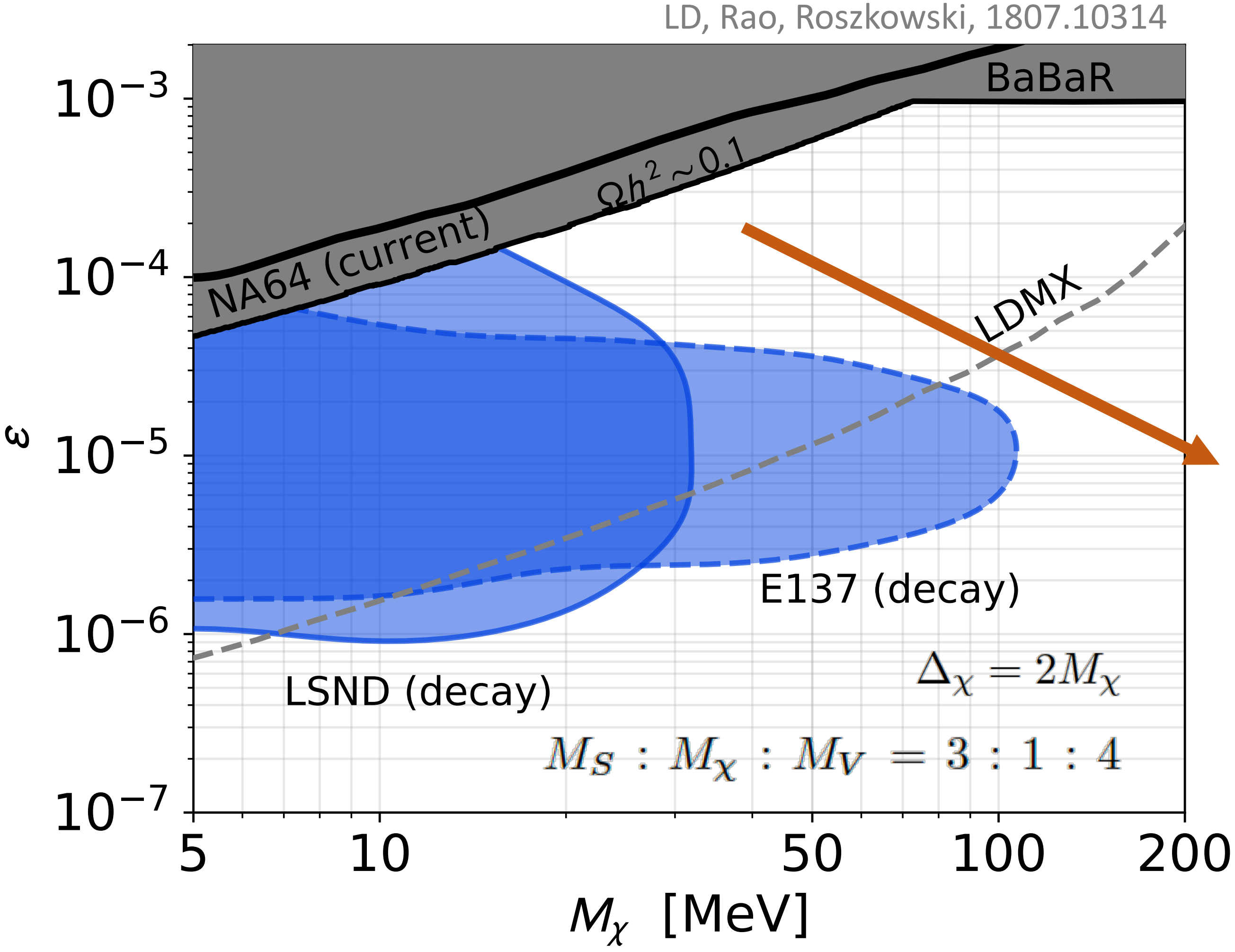


- High-intensity frontier: basically electrons physics
- "Grey sector", LHC-related: Displaced muon jets, LLP…

Heavy dark sector decay in mDM

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

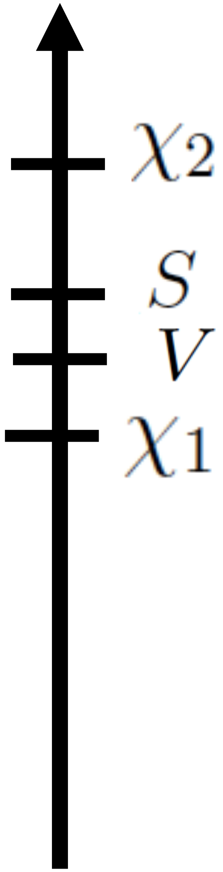


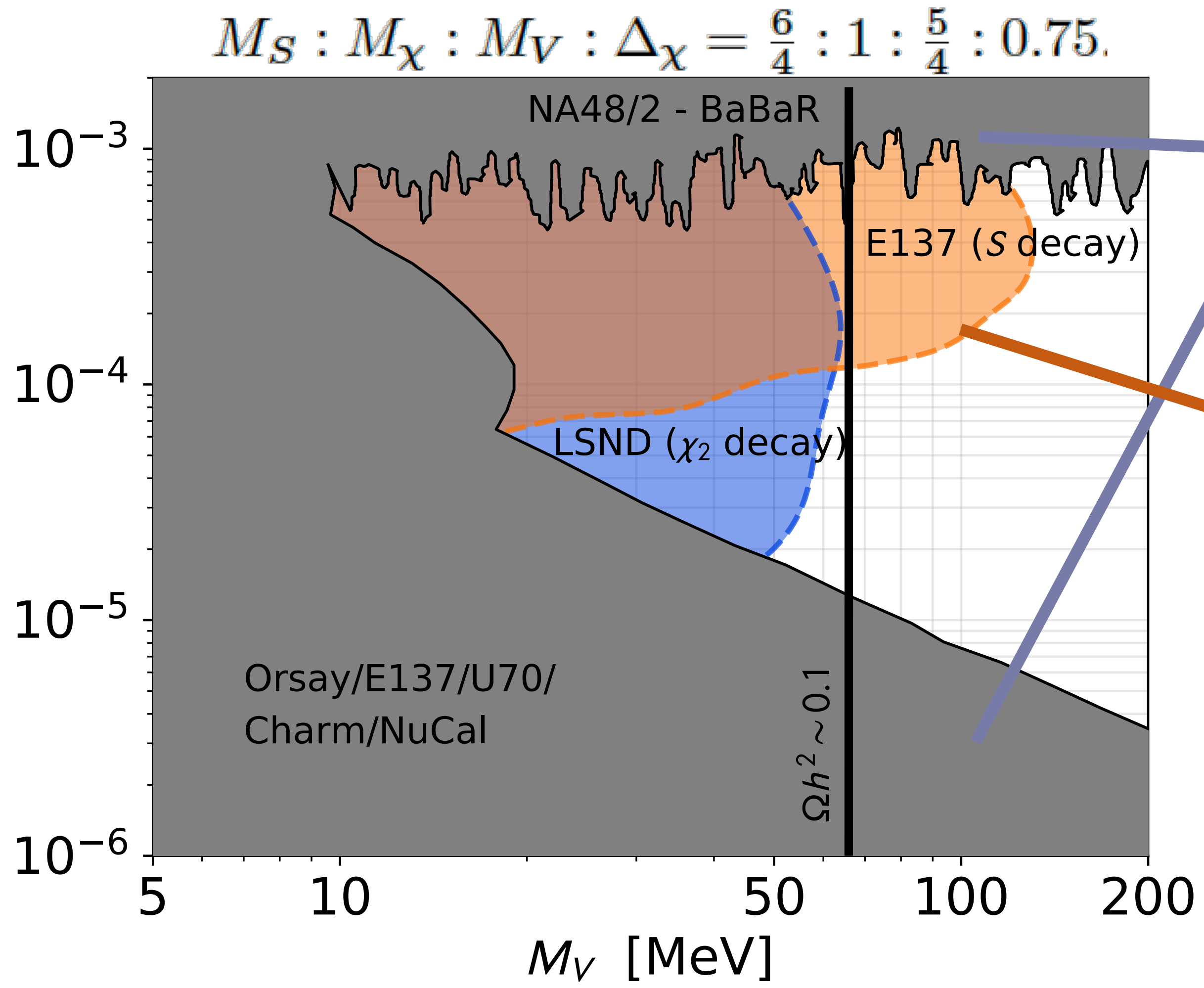


- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+e^-$ decay
- For large splitting, lifetime of order meter, $c\tau_\chi < 1\, m$
  - long baseline experiments like E137 miss critical part of the parameter space
  - Opportunity for others, MAGIX, SeaQuest, LHCb …

Forbidden DM regime

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





- $M_V \sim M_\chi$ → 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