Light dark sectors and the fermion portal

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Based on 2001.01490 with T. You and S. Ellis

Outline

Introduction: Dark sector and portals

Light dark sector searches through the fermion portal

Limits and UV scale

Introduction

Dark sectors and portals

Dark sectors, how to define them and make them interact with the SM

Light BSM physics and dark sectors

- Dark sector = "new neutral particles which interact with the SM via suppressed new interactions"

→ Assumed light (less than few GeV) for detection prospects

- Appear in various NP models aiming at dark matter, neutrino masses, strong CP problem, flavour etc …

- Strong experimental effort: the intensity frontier

  →$\gtrsim$ 10 relevant experiments in next 2 years

- Not all of them dark sector motivated (neutrino, flavour …)

  → Work needed to asses their potential for various dark sectors

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

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

Portals to dark sectors

- How can we "hide" new physics at light mass? → has to be SM gauge singlet
- "Dark sector" phenomenology -> relies on "portal" operators, gauge singlet of the SM
  - They can be bundled with neutral, dark particles in the Lagrangian

SM operator		Example Dark sector	
$\|H\|^2 \quad (d=2)\,,$	Scalar portal	$\|S\|^2$	Dark Higgs
$F_{\mu\nu} \quad (d=2)\,,$	Vector portal	$F'^{\mu\nu}$	Dark photon
$LH \quad (d=5/2)\,,$	Neutrino portal	N	Sterile neutrino

… next in line?

$$\frac{c_{ij}\mathcal{O}_{SM}^{(d)i}\mathcal{O}_{HS}^{(d')j}}{\Lambda_{ij}^{d+d'-4}}$$

The fermion portal

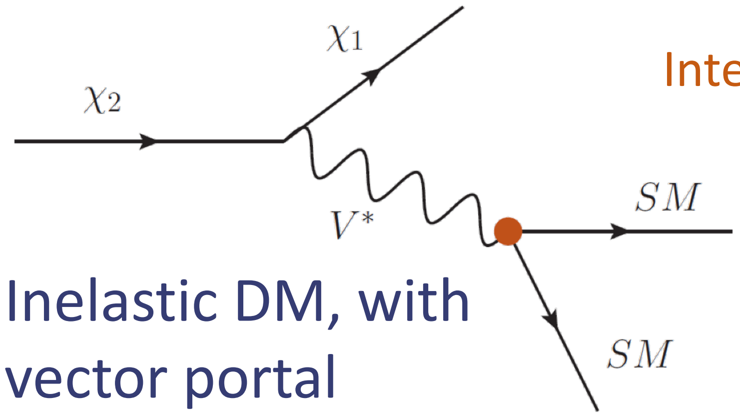
- Dimension 3 gauge singlet ? → Pair of LL or RR fermion $\bar{f}_i \, \Gamma^\mu f_j \quad (d=3)$
- The typical dark sector side can be
  - New boson, for instance $L_\mu - L_\tau$ gauge boson → Dimension 4, traditionally called vector portal
  - Derivative scalar coupling, $\partial_\mu \phi$ → Dimension 5, Axion-like portal
  - Dark fermion pair $\bar{\chi}_i \, \Gamma^\mu \chi_j$ → Dimension 6: the fermion portal

→ Vector or Axial-vector operator
→ Couplings to quarks & leptons with potential flavour-violation

$$\frac{g_q^{ij}}{\Lambda^2}\bar{\chi}_2(\gamma^5)\gamma^\nu\chi_1 \; \bar{q}_i(\gamma^5)\gamma_\nu q_j \qquad \frac{g_\ell^{ij}}{\Lambda^2}\bar{\chi}_2(\gamma^5)\gamma^\nu\chi_1 \; \bar{\ell}_i(\gamma^5)\gamma_\nu \ell_j$$

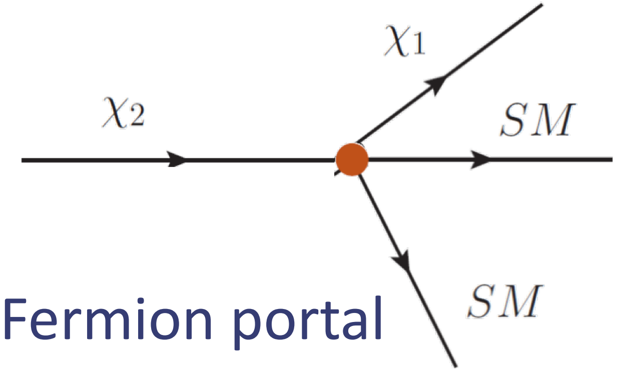
UV origin and effective description

- Since higher-dimensional, can be obtained by from another portal model after integrating out the mediator (e.g dark photon)



Inelastic DM, with vector portal

Integrate out V^*



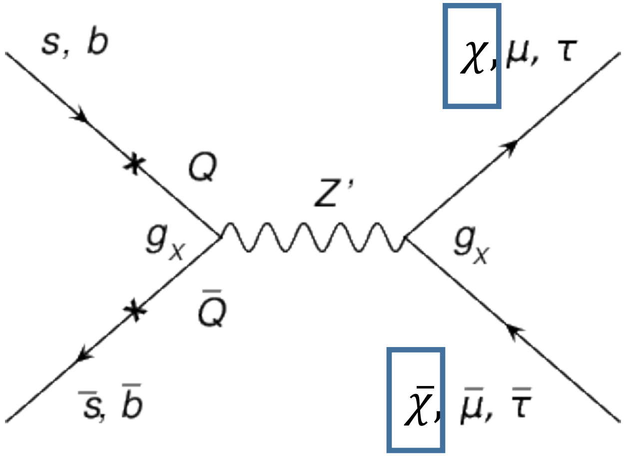
Fermion portal

- More generally, straightforwardly obtained if new UV theories with a light dark sector.
  - E.g. new vector mediator for LHCb flavour anomalies, replace the muons with a dark fermion

$O_9 \sim \bar{b}\gamma^\nu P_L s\, \bar{\mu}\, \gamma_\nu \mu$

$\bar{b}\gamma^\nu P_L s\, \bar{\chi}\, \gamma_\nu \chi$

$\bar{\chi}\gamma^\nu \chi\, \bar{\mu}\, \gamma_\nu \mu$

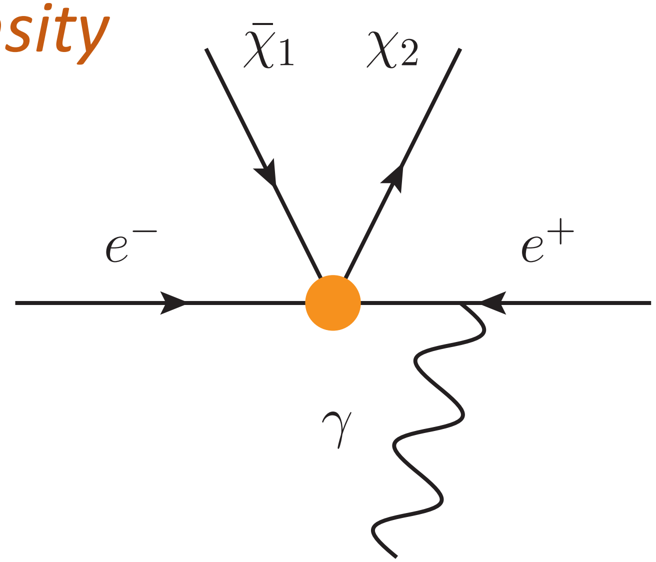


Dark sector searches and constraints

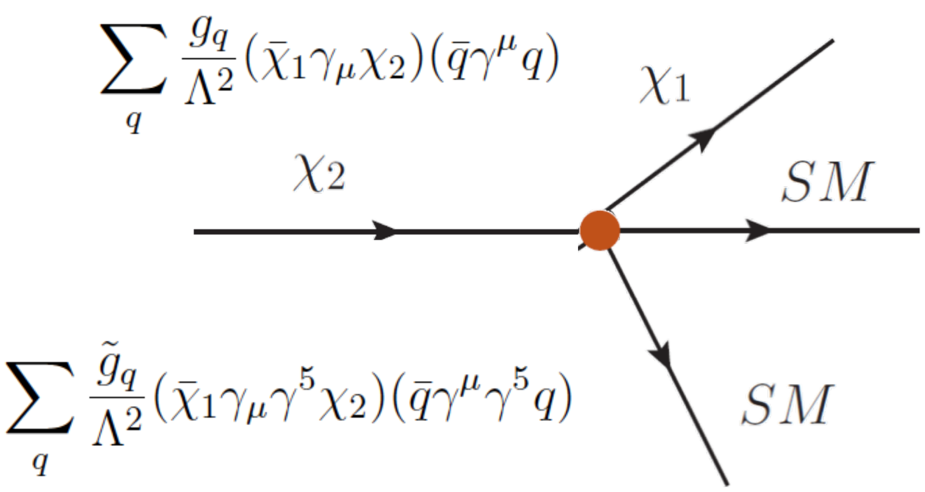
Recasting and limits using the EFT approach

Dark Sector searches in the lab

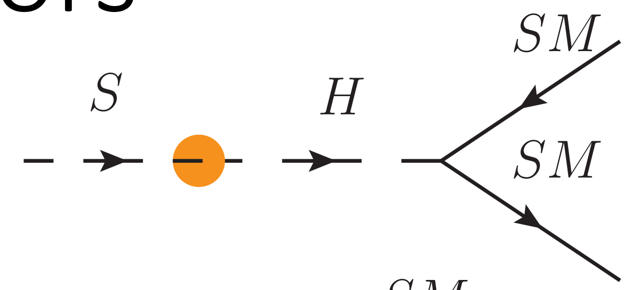
- Light dark sector particles may be accessible at *the intensity frontier* (GeV energy / large intensity / low background)

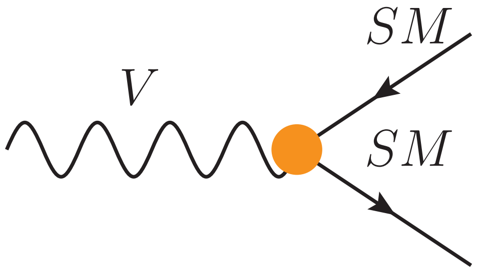


- Missing energy/ Invisible decay: Mono-photon/mono-jet searches missing energy signature @ BaBar, Belle, LEP, LHC.
- Invisible meson decay: $\pi^0 \to \bar{\chi}\chi$ (NA62), $\Upsilon \to \bar{\chi}\chi$ (BaBar) …
  - Important for flavour-violating operators, e.g. $\mathrm{B} \to K\bar{\chi}\chi$ …
- Dark sector beam production and detection
  - Scattering: Searching for DM via scattering (E137,LSND, miniBooNE …)
  - Dark sector visible decay: $\chi_2 \to \chi_1 e^+ e^-$ (LNSD, CHARM, Seaquest, FASER, etc…)



Long-lived particles and dark sectors



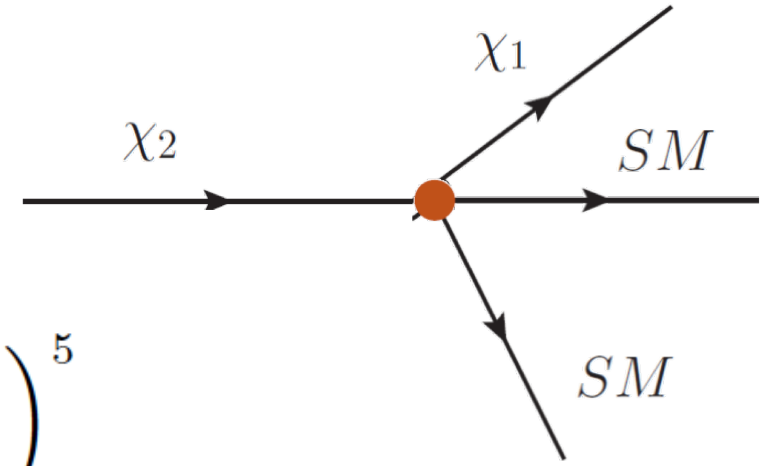


- Decays involving SM particles are often the only option for unstable dark sector states
  - Through the portal -> e.g. dark Higgs boson, dark photon

$$c\tau_{V\to e^+e^-} \sim 1 \text{ cm} \times \left(\frac{10^{-5}}{\varepsilon}\right)^2 \left(\frac{M_V}{100 \text{ MeV}}\right)$$

- Mixed visible/dark decays are also often relevant.
  - Here: dark sector decays which proceed through off-shell mediator → e.g semi-visible 3-body decays (iDM, certain sterile neutrino models, etc....)

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



Decay and scattering signatures

Most existing limits are obtained for vanilla cases (e.g iDM, pure dark photon …) → need to recast these searches as function of the EFT

- Different approaches for each search strategies
  - → Meson decay: direct evalution of the BRs
  - → Adapt results from EFT-coupled dark matter candidates
  - → Full recast of existing vector portal results for searches at beam dumps
- Decay limits are particularly challenging, rescale for production rates

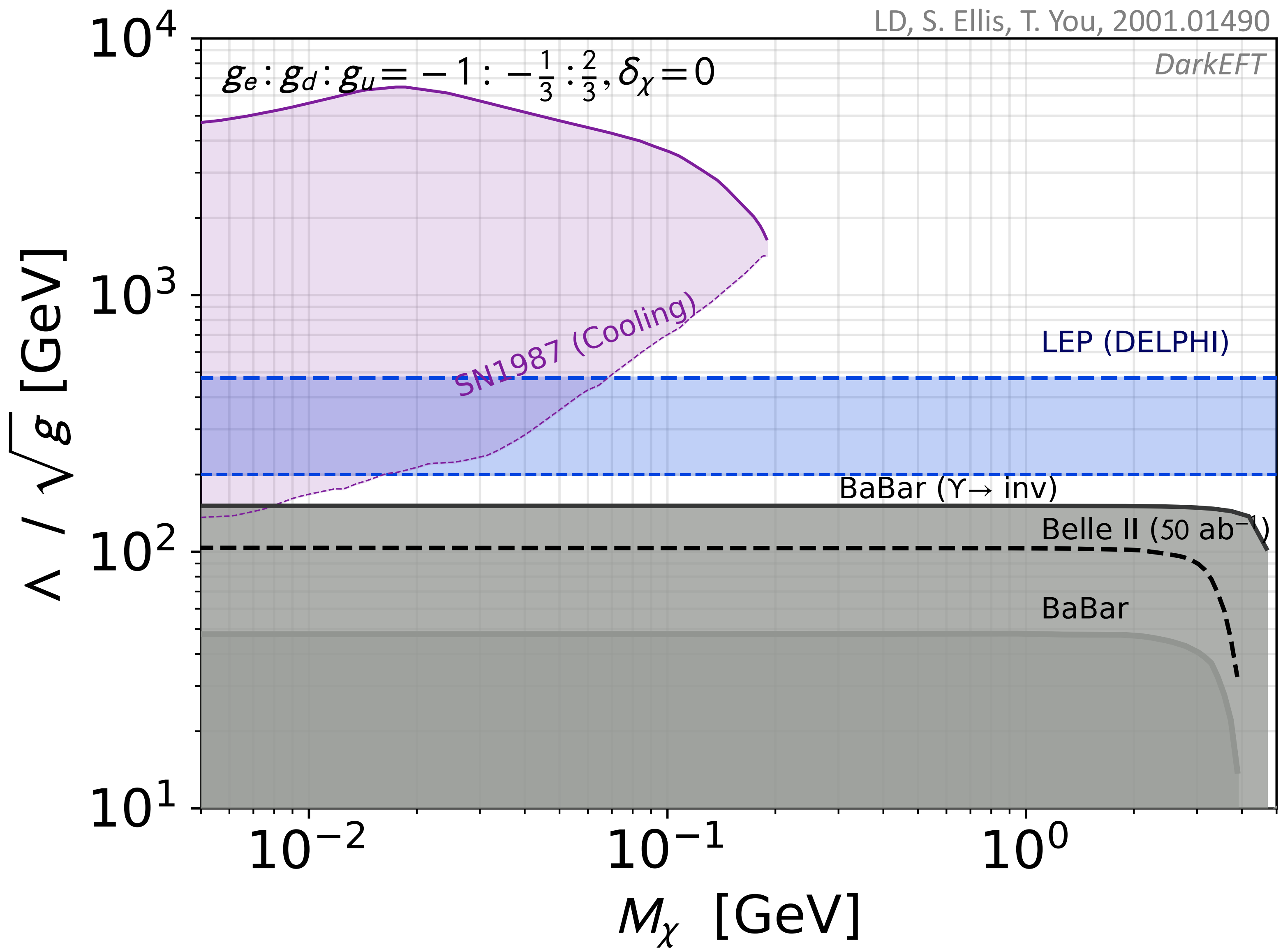
$$\Lambda_{\mathrm{lim}} = 410\ \mathrm{GeV} \times \sqrt{g_{\mathrm{eff}}} \left(\frac{0.001}{\varepsilon}\right)^{1/2} \left(\frac{\mathcal{N}^{\mathrm{eff}}_{\mathrm{prod}}}{\mathcal{N}^{\mathrm{DP}}_{\mathrm{prod}}}\right)^{1/8}$$

→For different splitting, detection probability is modified (also rescale for decay rates, keeping $M_1 + M_2$ constant)

Results and examples

Missing energy – flavor preserving

- Mono-photon not very strong (no “bump-search” in $\chi\chi$ invariant mass)
- SN1987 cooling limits
- Invisible meson decay: → strong dependence on the operator type:
  - AV : $\pi^0 \to \chi\chi$
  - V: J/Ψ , $\Upsilon \to \chi\chi$, if non-flavour diagonal, many $P' \to P\chi\chi$ limits

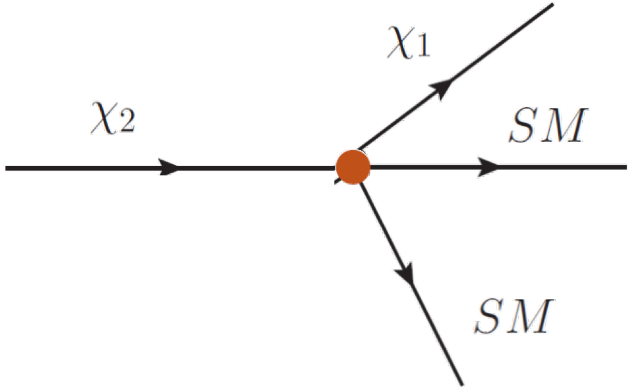


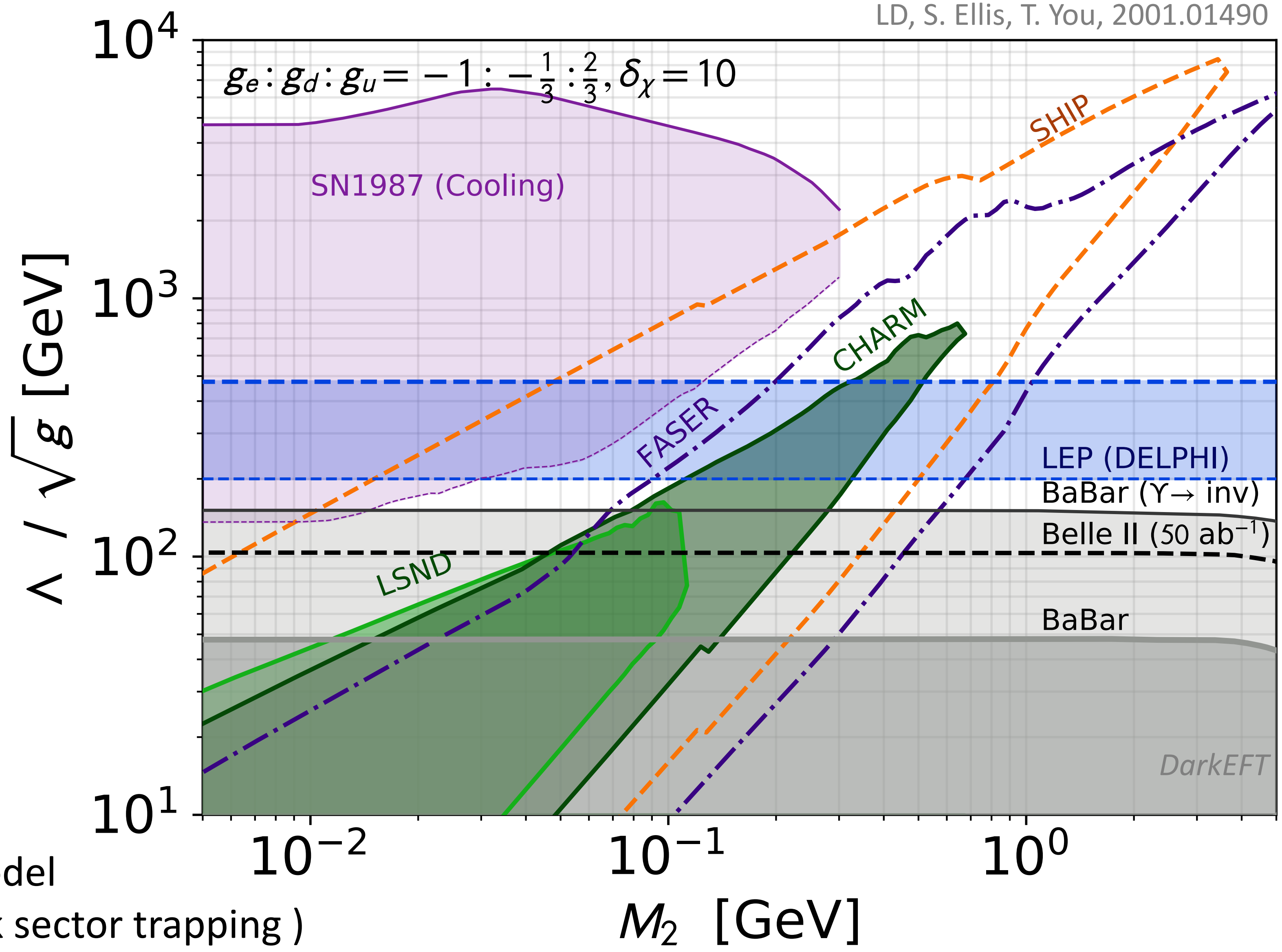
Limits in the vector case

Include limits/projections:

→Mono-photon: LEP, BaBar and Belle II

→Decay searches at saturation ($M_2 \gg M_1$) at LSND, CHARM, SeaQuest (hypothetical Phase 2 with ~ 10^{18} PoT) and SHIP





→SN1987 cooling limits, but strong model dependence in the lower bounds (dark sector trapping)

Limits in the axial-vector case

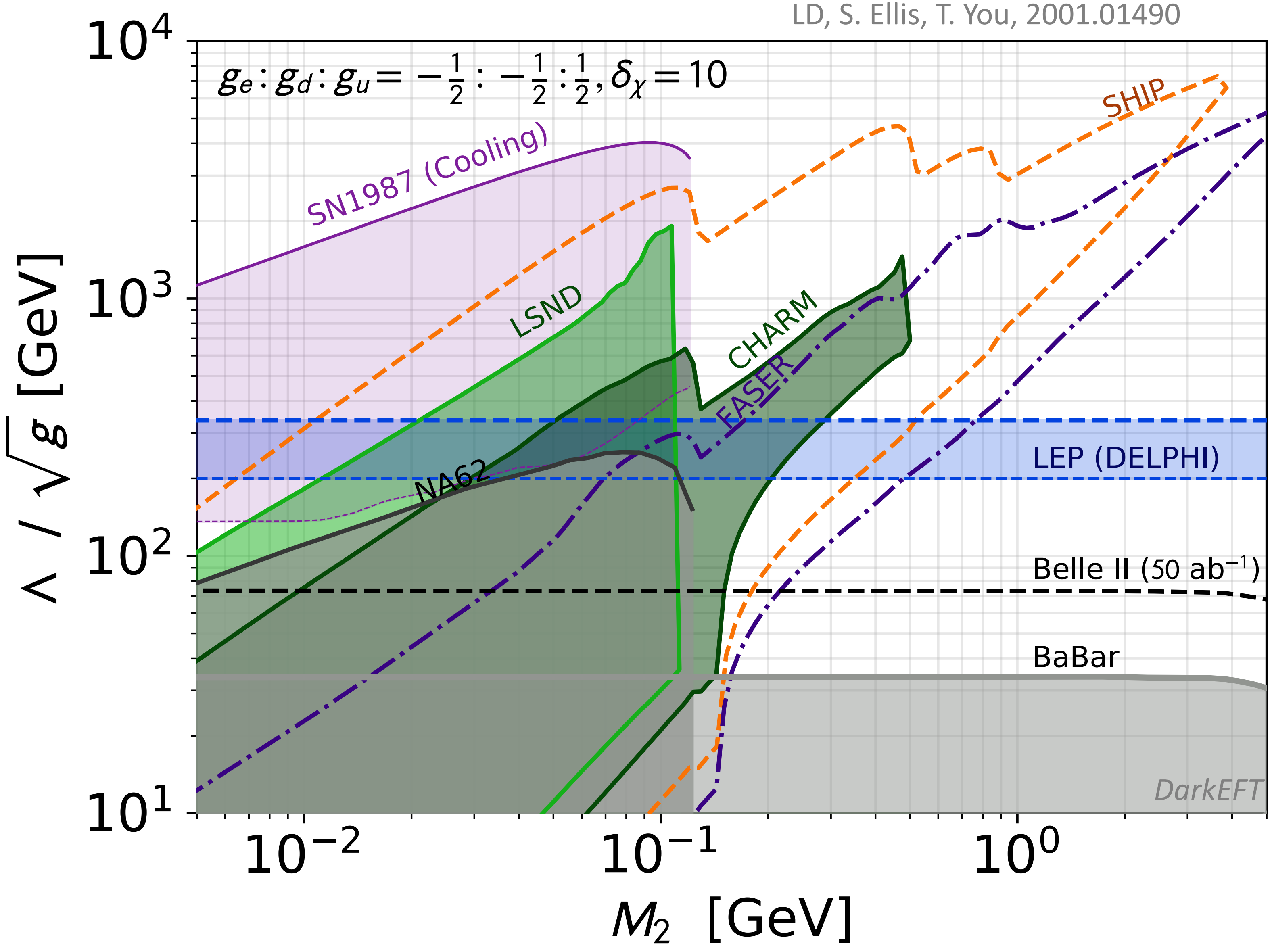
- Mesons production strongly enhanced

→Better low-mass limits

  - LSND (0.8 GeV beam) probes up to 1 TeV

- SN1987 based on invisible π^0 decay
- All limits based only on first generation couplings

LD, S. Ellis, T. You, 2001.01490

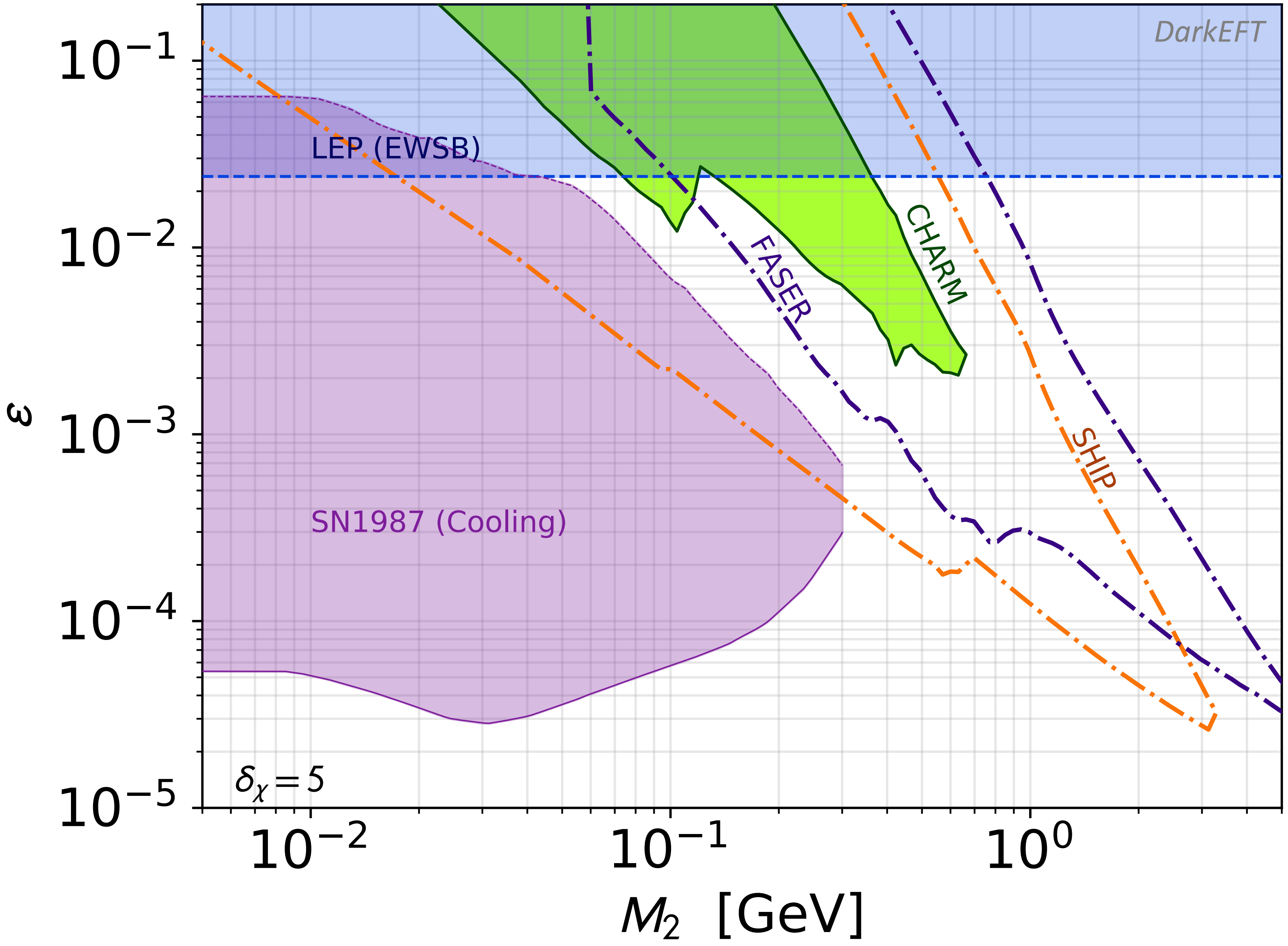


Practical example: off-shell dark photon

LD, S. Ellis, T. You, 2001.01490

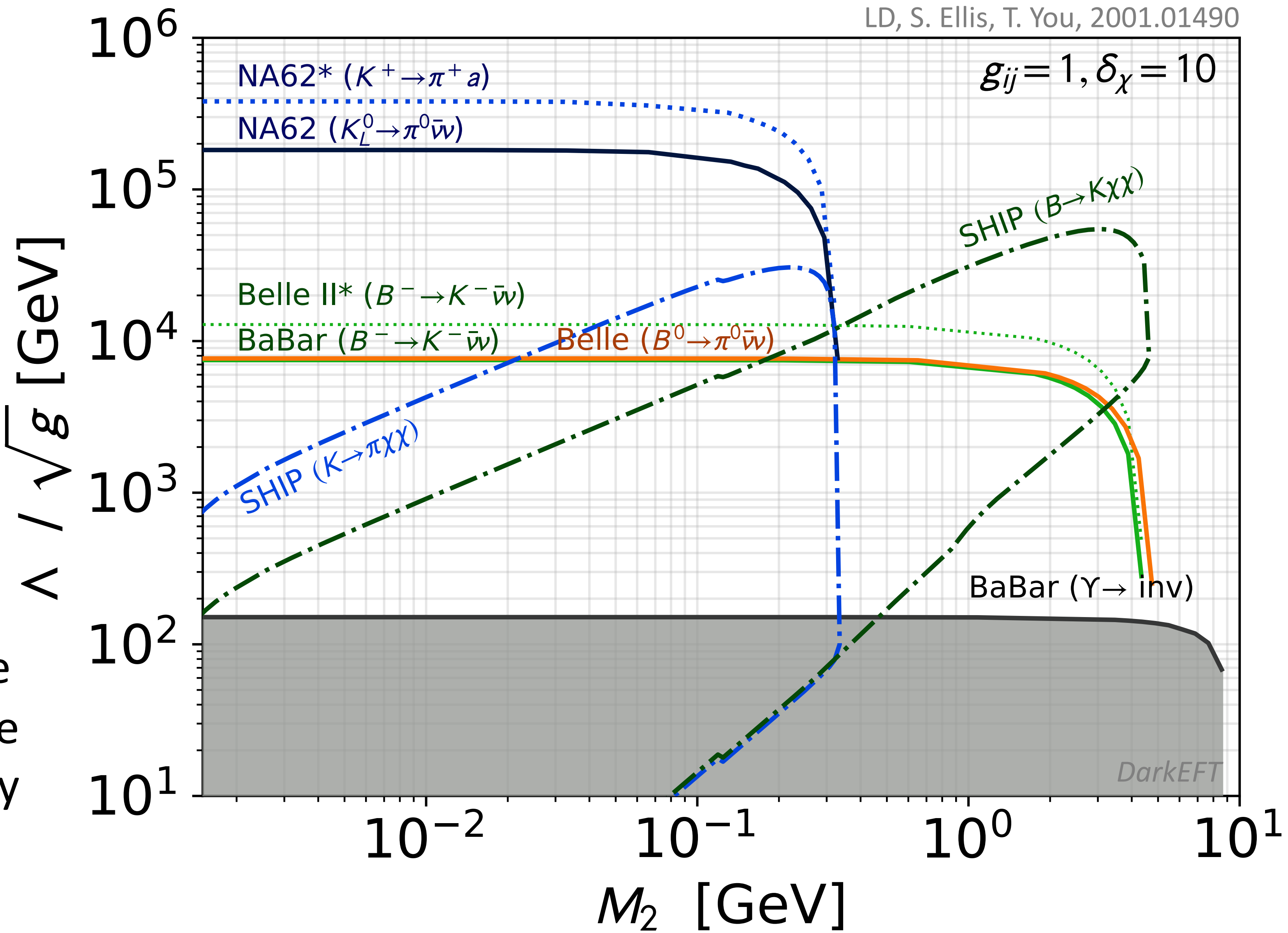
- Standard iDM scenario with a heavy dark photon ($M_V \sim 20$ GeV, with $M_V \gg M_\chi$)

- Very weak limits from Babar (no resonance search available)
- Relic density through e.g. $\chi_1\bar{\chi}_1 \to SS$ dark Higgs boson



Flavour violating limits

- Focus on flavor violation in the quarks sector: $b \to s\,, b \to d, s \to d$
- Flavour-violating decays may be used as a production mechanism!
  - The plot assumes the same coupling for the production and decay $\chi_2 \to \chi_1 e^+ e^-$



Conclusion

Conclusion

- Dark sector with long-lived particles -> Important search targets for intensity frontier experiments
- When the mediator is too heavy to be produced directly, describe the phenomenology as an “off-shell” -> fermion portal
  - Typical of new UV theories with new, light sectors
- Lead to rich phenomenology in intensity frontier experiments, with different prospects than standard “on-shell” portals

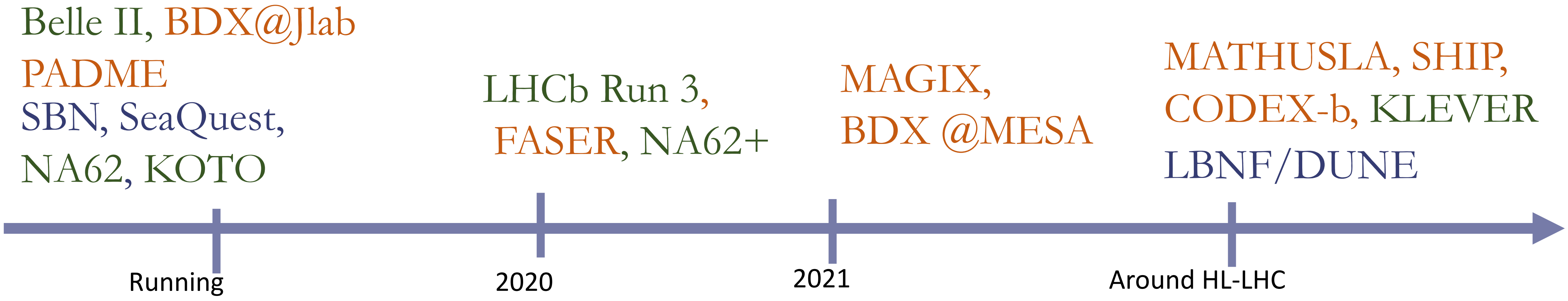
→ Release a python package, *DarkEFT*, to provide recasted limits for any effective coupling.

(at github.com/Luc-Darme/DarkEFT)

Backup slides

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…



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

Production in the fermion portal

Production is strongly modified w.r.t the on-shell portals

- Off-shell nature of the process -> Strong suppression of low energy production mechanism.
  - → For meson decay, BR typically suppressed $\propto \frac{M_m^4}{\Lambda^4}$
- Mediator bremsstrahlung $e^- N \to e^- N\, V$ or $p\, N \to p\, N\, V$ also suppressed
  - → Electron beam-dump production suppressed
- When available, direct production more relevant since higher c.o.m energy compared to Λ

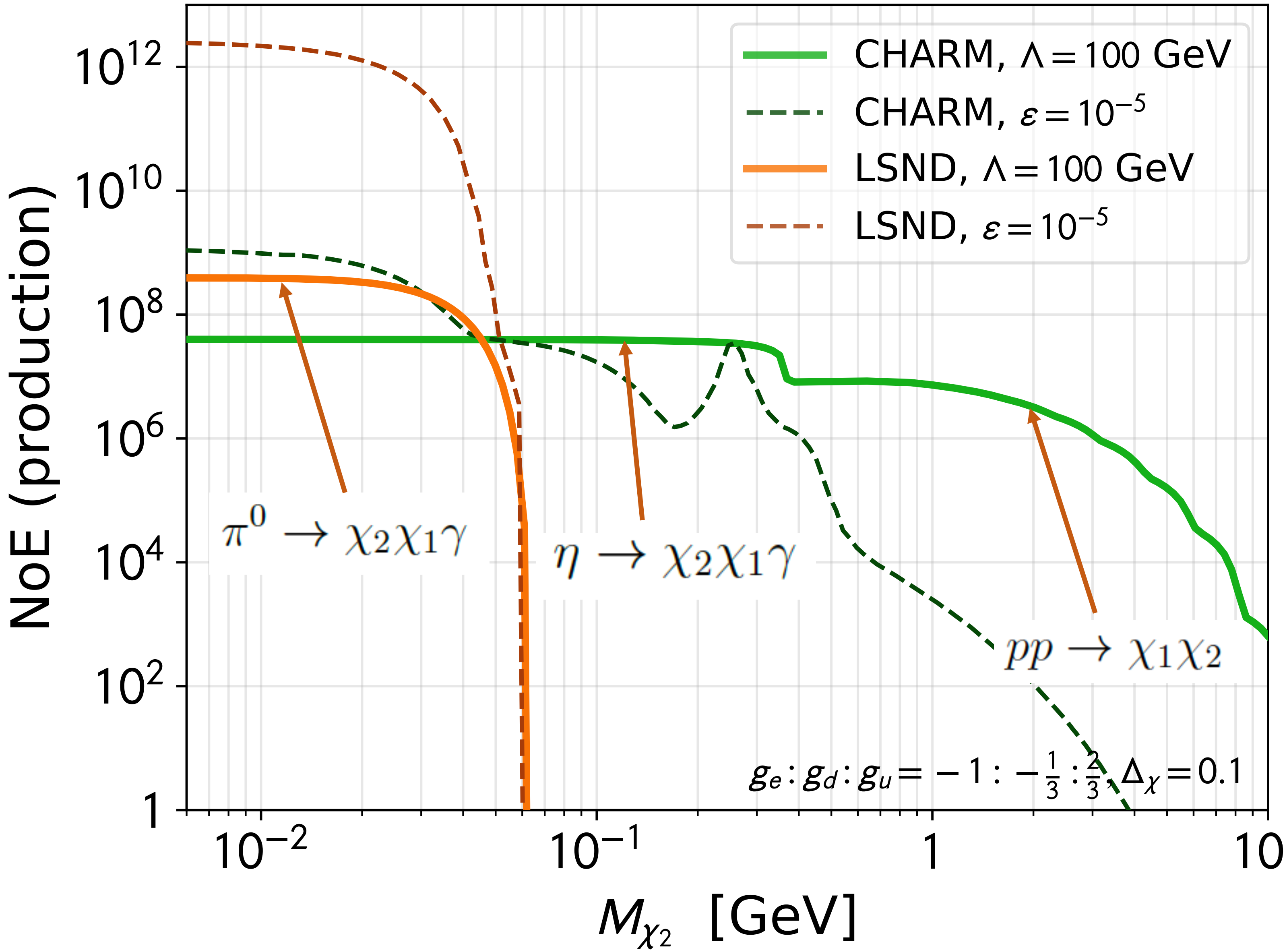
Depending on the nature of the operators, different production channels from meson decay

Full production – vector coupling

- Main exp. properties
  - LSND: $\sim 10^{23}$ PoT and 0.8 GeV beam
  - CHARM: $\sim 10^{18}$ PoT and 400 GeV beam
- Strong differences with dark photon case
- Meson decay allowed for VV operator:

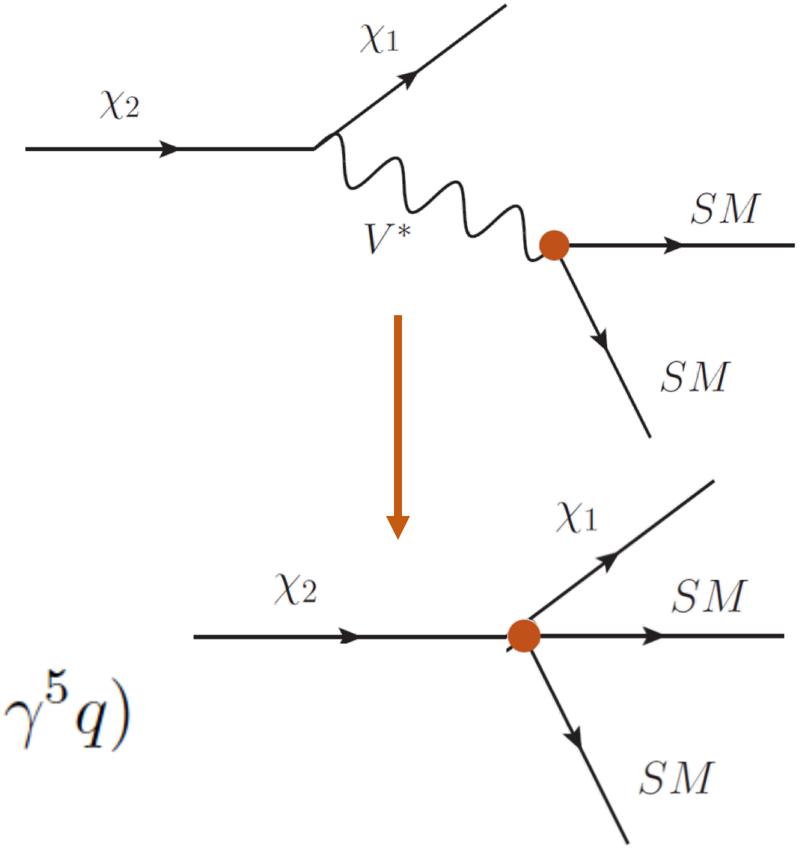
$$\pi^0, \eta, \eta' \to \gamma\chi\chi$$
$$\rho, \omega \to \chi\chi$$

LD, S. Ellis, T. You, 2001.01490



The off-shell effective approach

- Relevant for decay mediated by an "off-shell" mediator
  → Effective theory description (cf Fermi theory)
  can be seen as a "fermion portal"



Vector operator

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

Axial vector operator

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

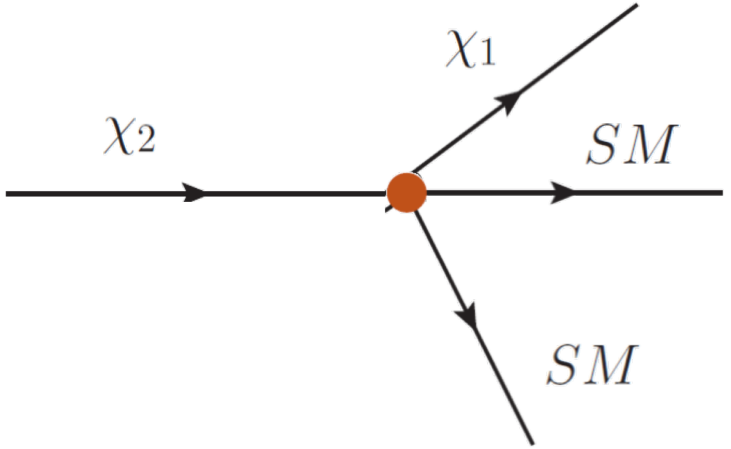
- Basic equivalence with a dark photon model with kinetic mixing ε and coupling g_D:

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

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

Signatures and decay

- Typical decay length of order meter
  →Decay into pair of electrons (no background from neutrino scattering)
  →In optimum region, large portion of the heavy dark states decay in the detector



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

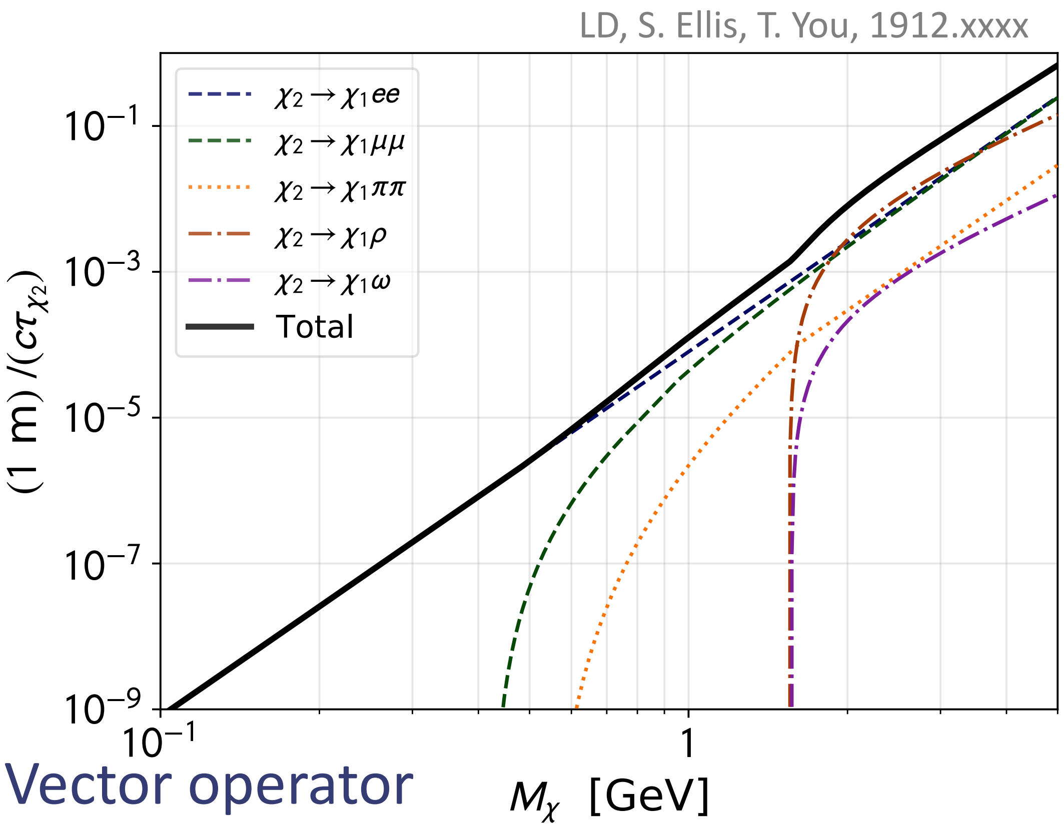
(Vector operator)

- Leptonic channel almost always dominant/significant BR (exception AV case)
- Reach also for $M_2 \gg M_1$

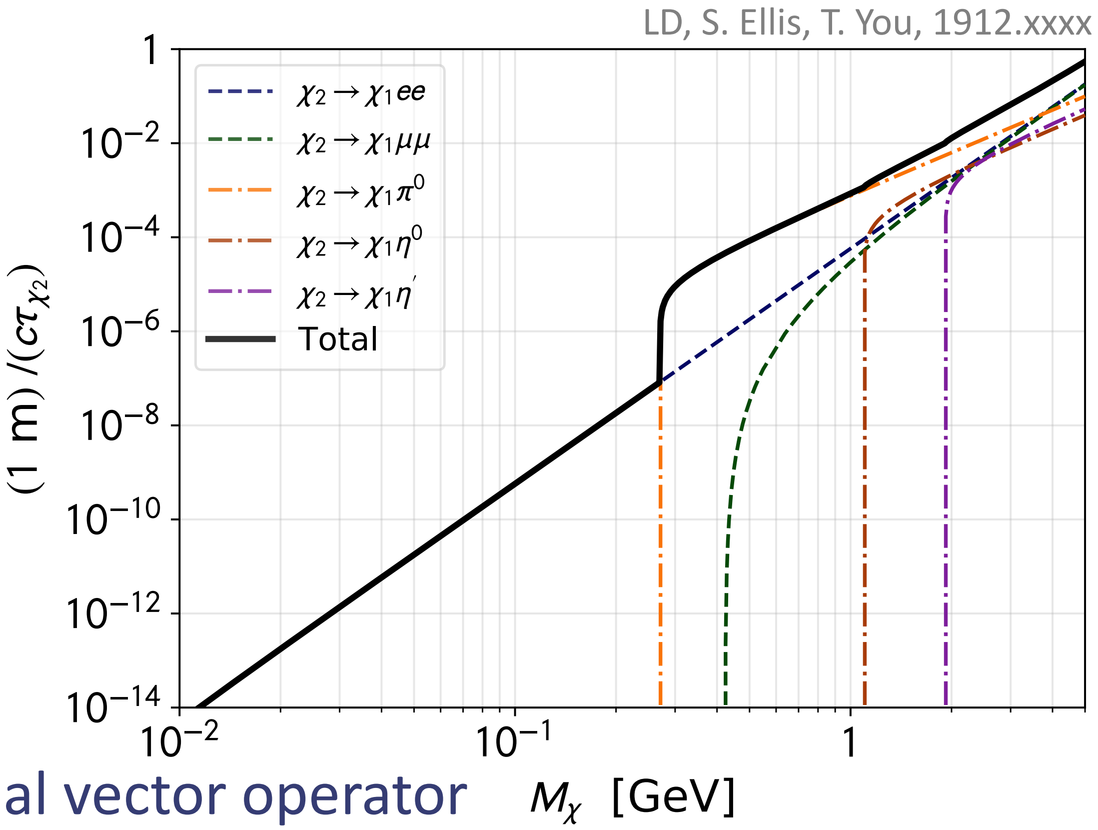
$$c\tau^{\rm sat} \sim 2 \text{ m} \times \left(\frac{\Lambda/\sqrt{g}}{1 \text{ TeV}}\right)^4 \left(\frac{1 \text{ GeV}}{M_{\chi_2}}\right)^5$$

Decay rate of heavy state

- The decay rate depends on the possible decay channel → depends on the operator type ($M_2 \gg M_1$ and $\Lambda = 5$ TeV)



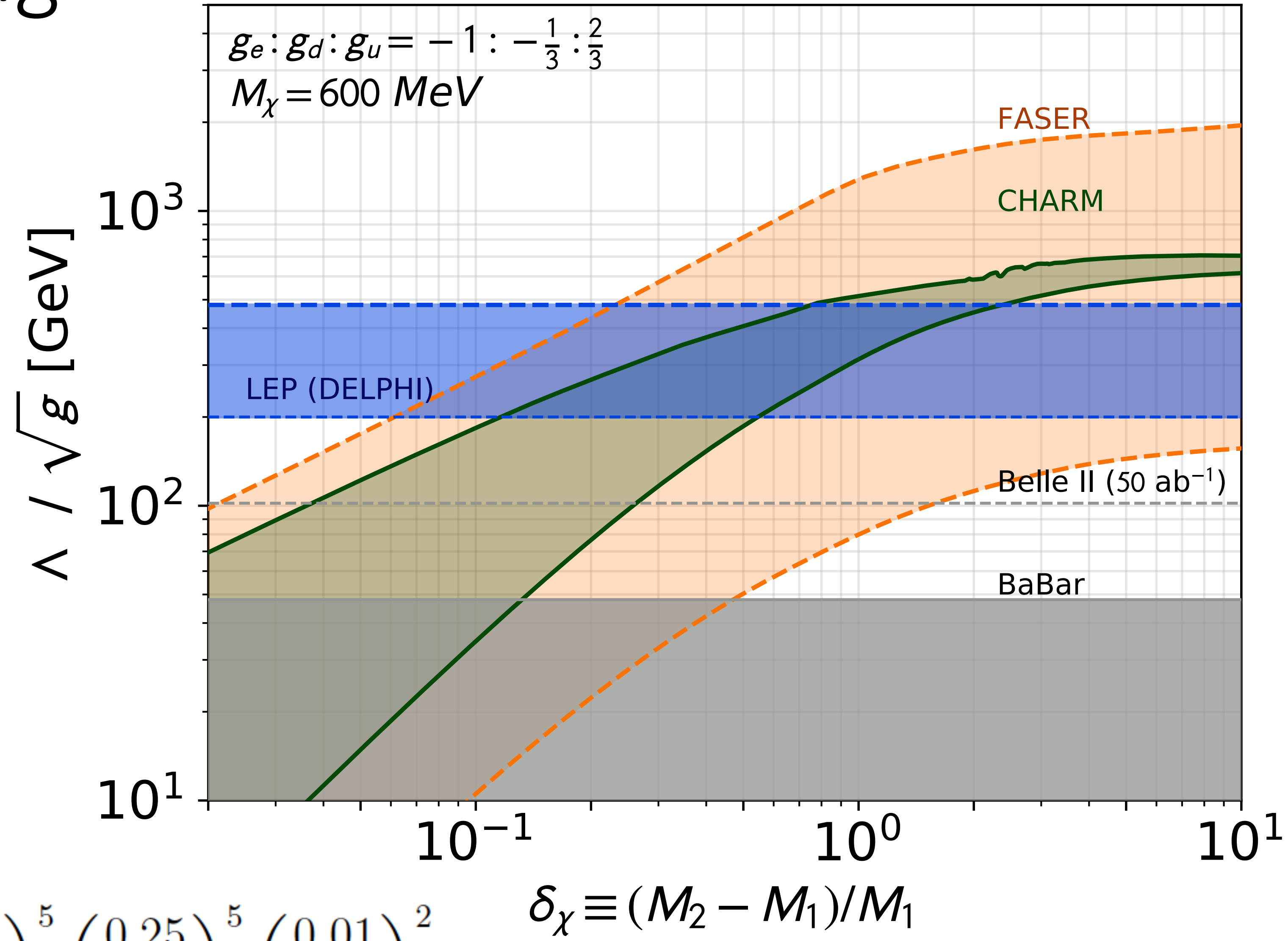
Vector operator



Axial vector operator

Varying the splitting

- Decay signatures depends strongly on splitting $M_2 - M_1$
  - Lifetime scales as $(M_2 - M_1)^{-5}$
  - Then reach saturation for $M_2 \gg M_1$
- Both upper limits and lower limits are modified
  - Long-lived limit -> linear suppression
  - Short-lived limit ->exponential dependence

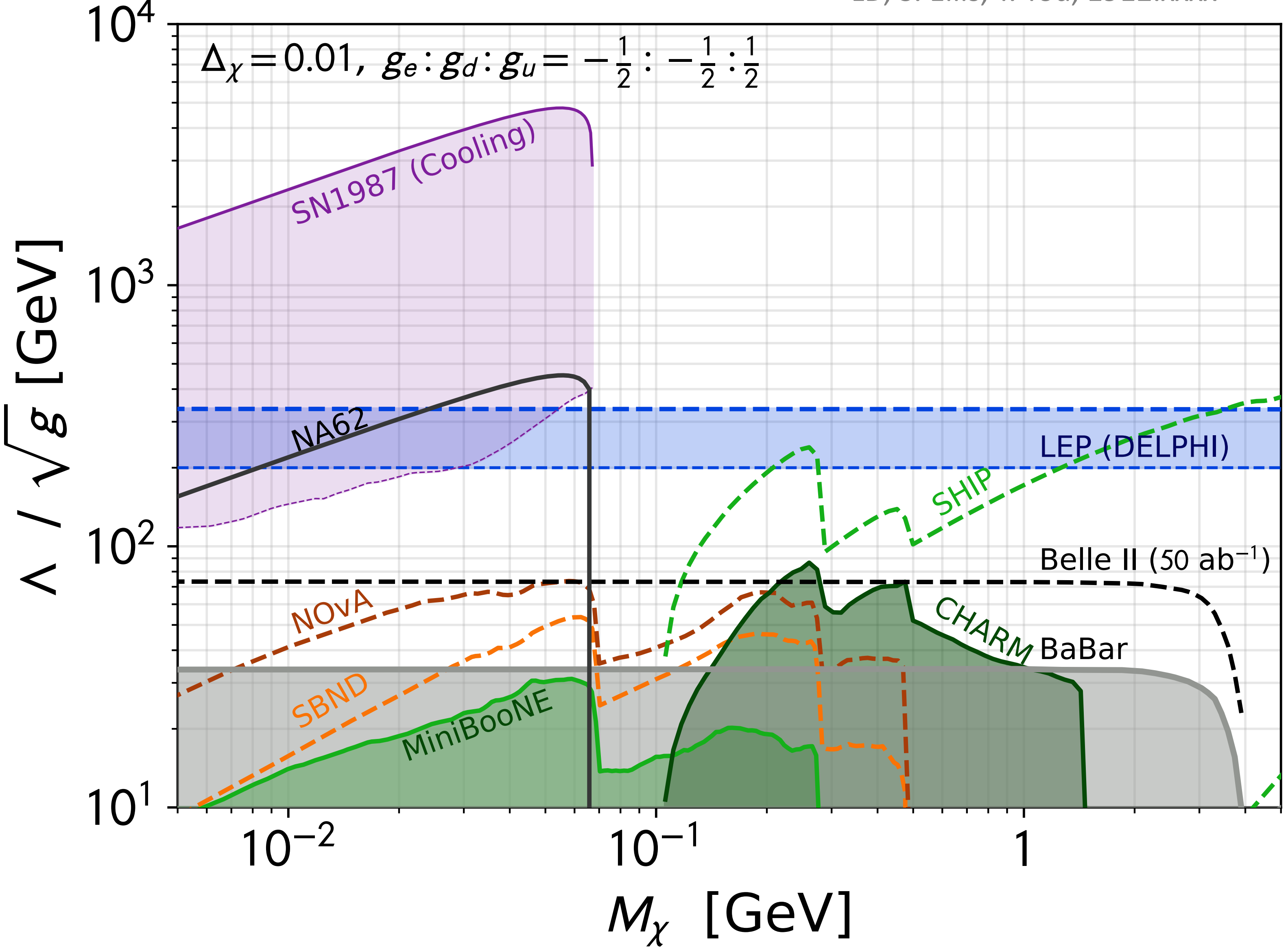


$$c\tau^{\rm pD} \sim 375 \text{ m} \times \left(\frac{100 \text{ GeV}}{\Lambda}\right)^4 \left(\frac{1 \text{ GeV}}{M_{\chi 1}}\right)^5 \left(\frac{0.25}{\Delta_\chi}\right)^5 \left(\frac{0.01}{g}\right)^2$$

Small-splitting limits

- Invisible meson decay
  - Recent NA62 on $\pi^0 \to inv$
- Scattering limits in future neutrinos experiment can play a role
- Decay limits shifted to higher mass ($2m_e$ threshold)

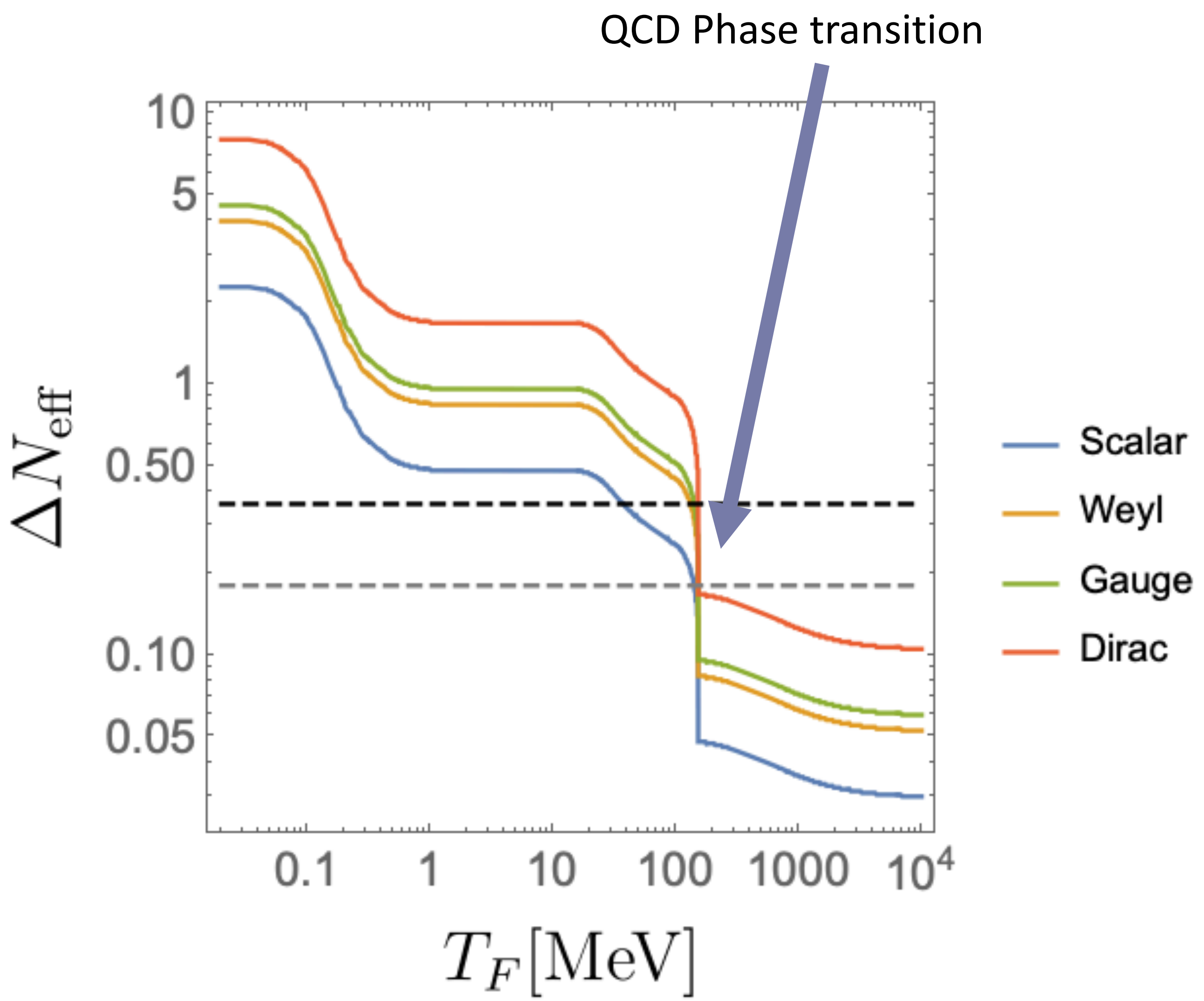
LD, S. Ellis, T. You, 1912.xxxx



Astrophysical limits

- For $M_2 \gg M_1$, the lightest dark sector can be relativistic relic
- One can still obtain dark matter candidate for iDM setup for masses around the GeV

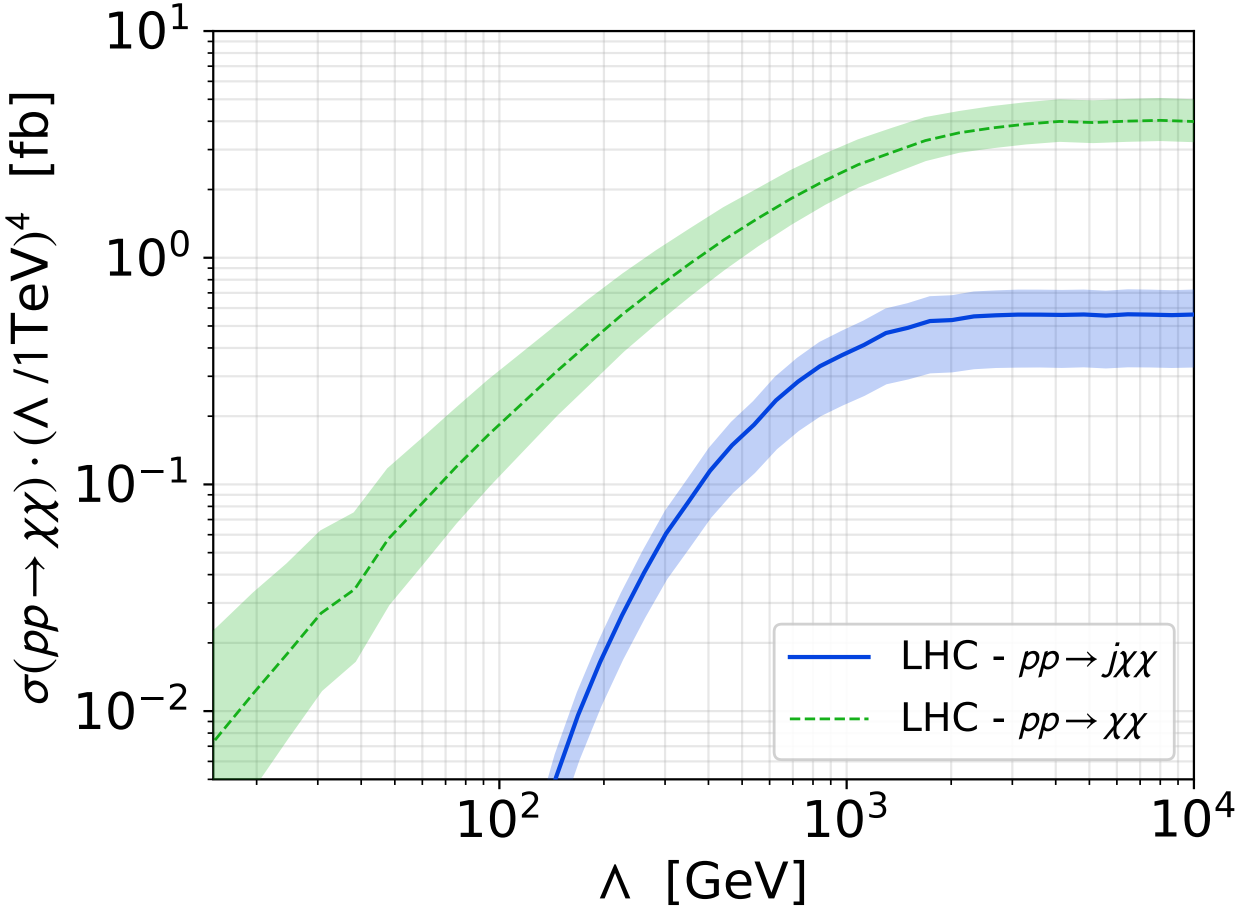
$$\Omega h^2 \sim 0.3 \times \left(\frac{2\ \mathrm{GeV}}{M_\chi}\right)^2 \left(\frac{\Lambda/\sqrt{g}}{500\ \mathrm{GeV}}\right)^4$$



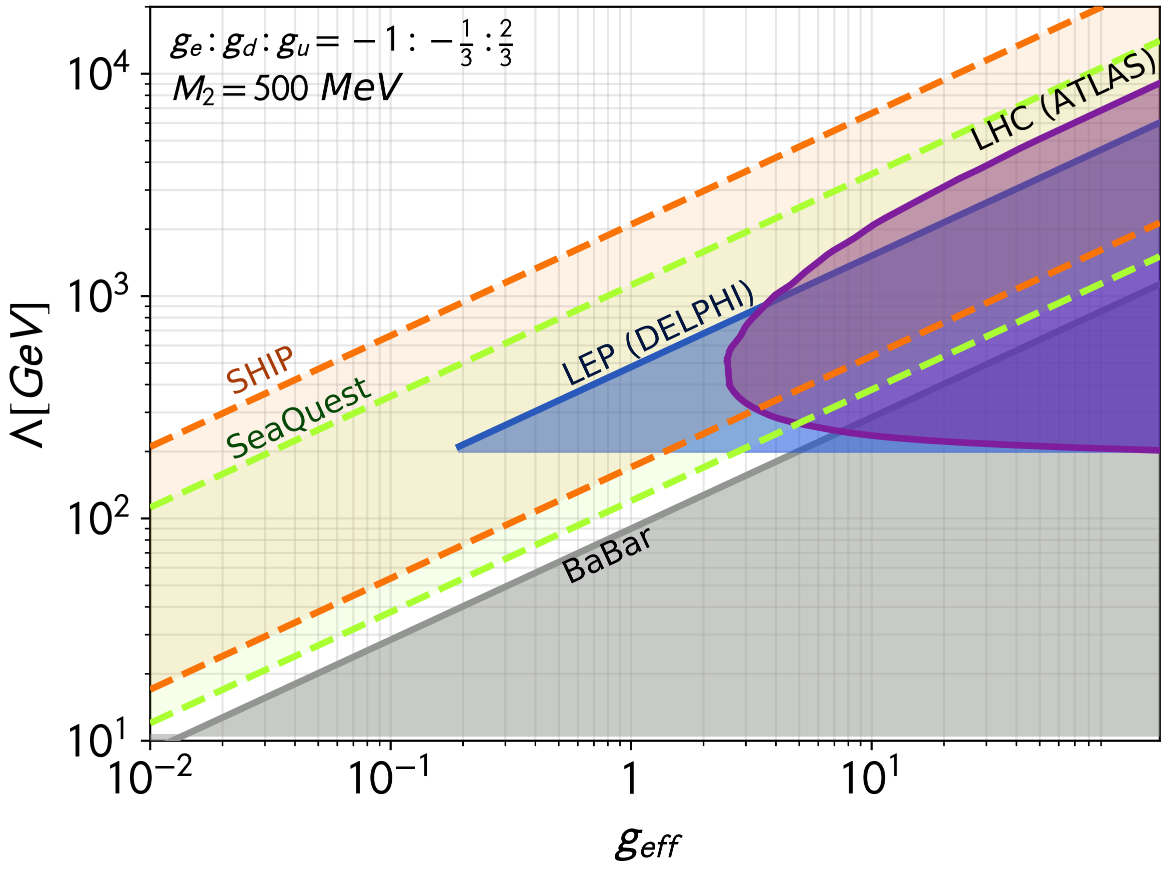
- Additional dynamics in the hidden sector may fix the relic density, e.g. $\chi_1\bar{\chi}_1 \to SS$ of iDM with a dark Higgs boson

EFT limitation at LEP and LHC

- EFT not applicable if roughly the c.o.m energy of the process higher than the scale → significantly discussed for dark matter at LHC



LD, S. Ellis, T. You, 1912.xxxx



An early motivation: models of sub-GeV DM

- Interest in dark sectors also driven from strong theoretical developments toward building models of thermal sub-GeV DM
- Found that dark matter is bundled with a dark sector
  with potentially many particles in it
  - Required to obtain the proper relic density (while avoiding CMB limits)
  - Implied from top-down approach (e.g anomaly cancellations, Higgs mechanism for dark photon mass, etc…)

iDM
hep-ph/0101138, …

Secluded DM
0711.4866, …

Semi-annihilating DM
1003.5912, …

Boosted DM
1405.7370, 1503.02669…

Selfish DM
1504.00361,…

Forbidden DM
Griest-Seckel, 1505.07107, …

Co-decaying DM
1607.03110, …

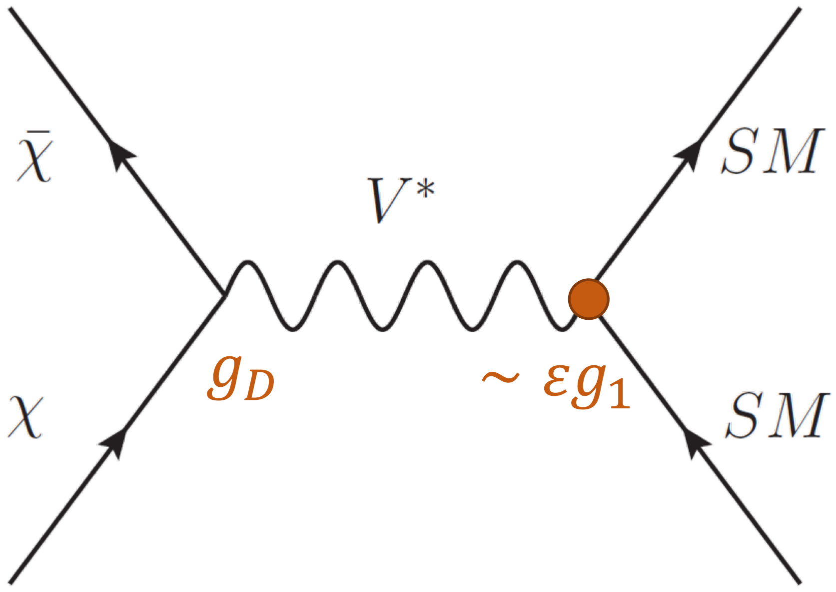
Impeded DM
1609.02147,…

…and many more recent

Sub-GeV DM, a step-by-step example

- Sub-GeV DM typically require an additional "dark sector"
- Let's try to build a simple, self-consistent dark sector model with sub-GeV dark matter → presence of long-lived state

- Suppose a vector mediator (dark photon), and (mostly in this talk) fermion dark matter
- Try to keep model building SM/WIMP-like and maintain top-down consistency



Astrophysics of sub-GeV DM

- Relic density -> sub-GeV particles, $\varepsilon \sim 10^{-3}$ suppression

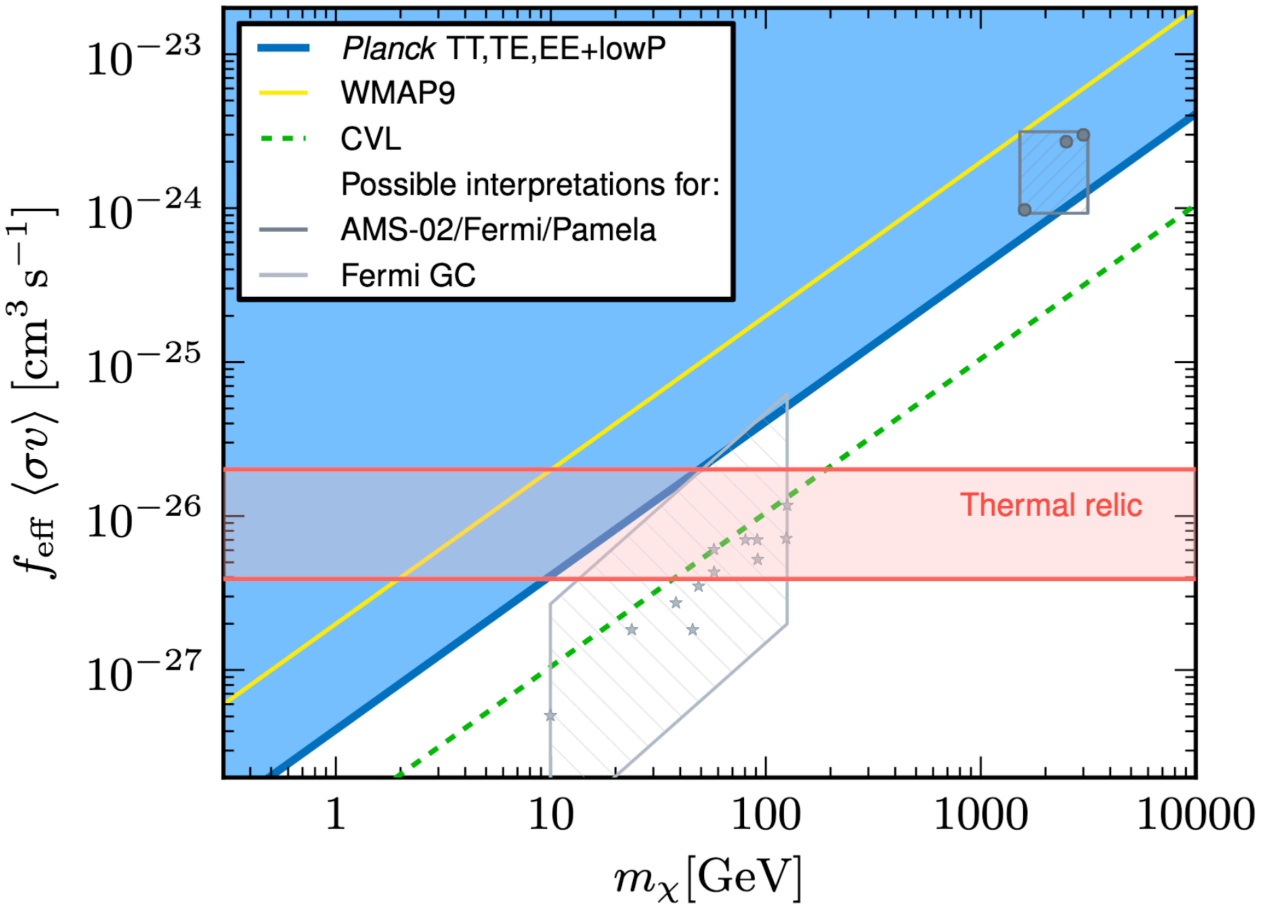
$$\Omega h^2 \sim 0.1 \times \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{0.1}{\alpha_D}\right) \times \left(\frac{25\ \text{MeV}}{M_\chi}\right)^2 \left(\frac{M_V}{75\ \text{MeV}}\right)^4$$

- CMB limits

  →No active annihilation process by the time of CMB

  → Exclude s-wave annihilation, requires additional mechanism (p-wave, co-annihilation …)

From Klasen, Pohl and Sigl 1507.03800



Fermion dark matter example

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

- Yukawa couplings to the dark Higgs S

  → Avoid Dirac DM (CMB exclusion)

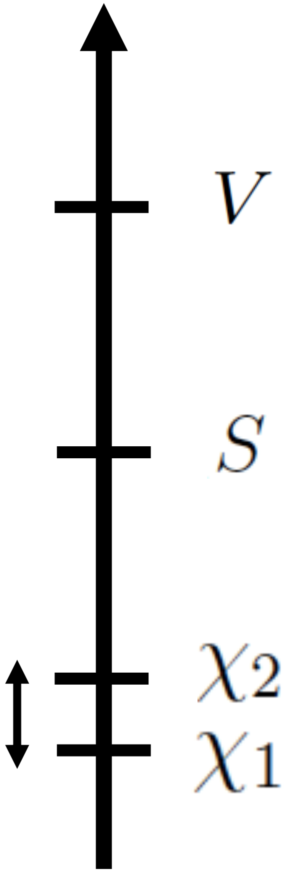
  →After $U(1)_D$ symmetry breaking, the dark matter acquires a Majorana mass

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

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

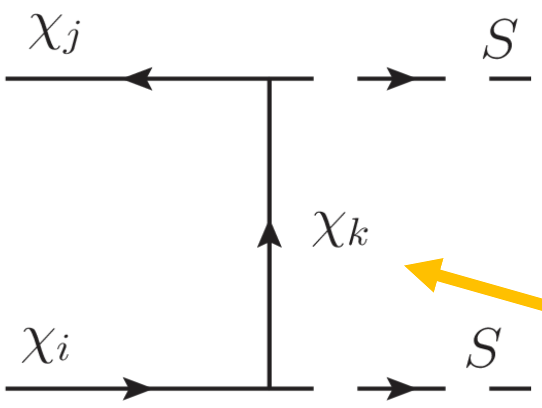
$$M_S = \sqrt{2\lambda_S} v_S$$

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



- After diagonalization → two Majorana fermions

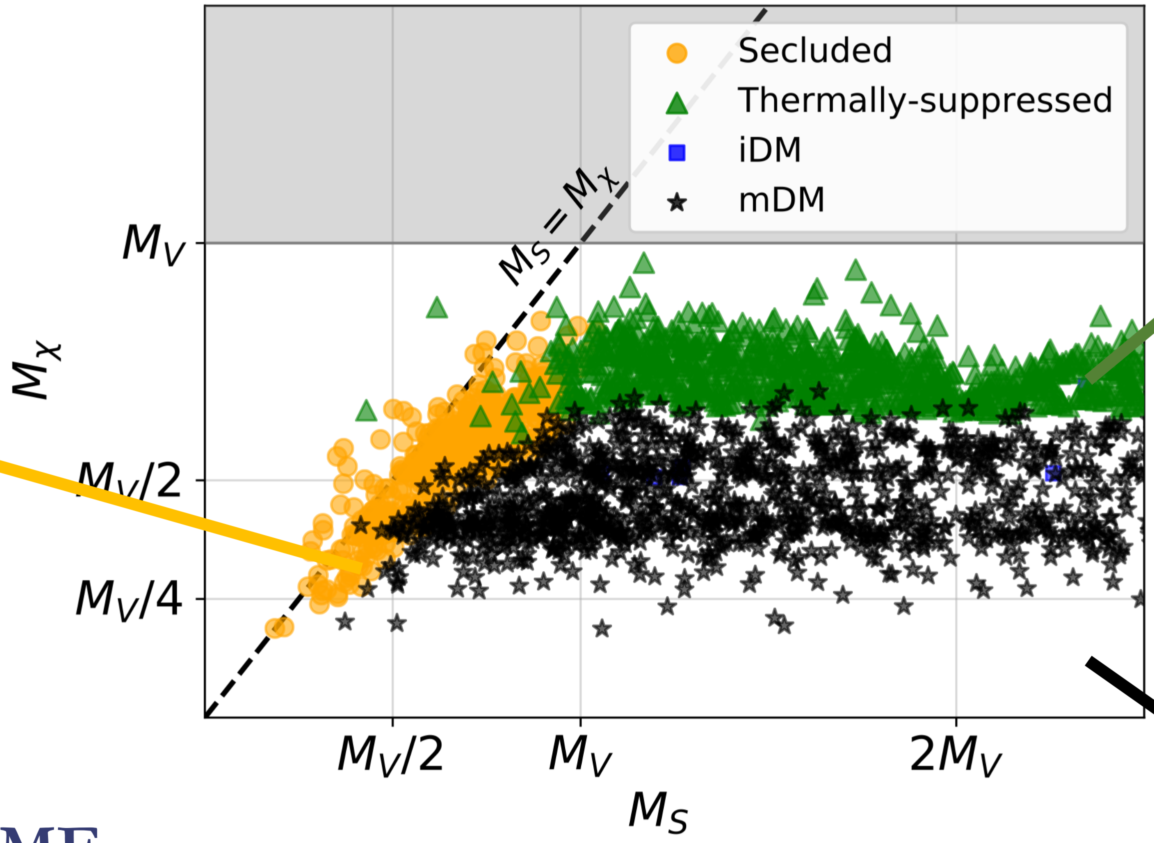
Typical regimes with correct relic density



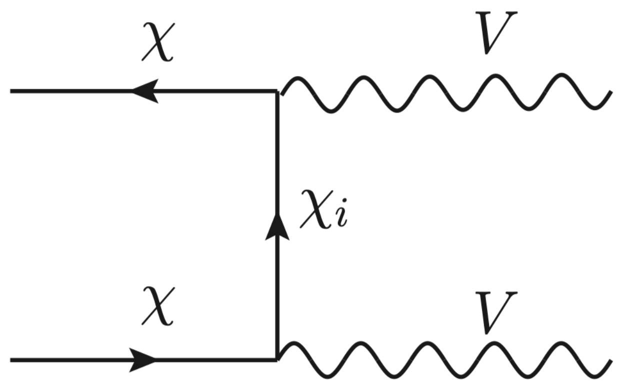
$$M_\chi \gtrsim M_S$$

SECLUDED REGIME

LD, Rao, Roszkowski, 1710.00971

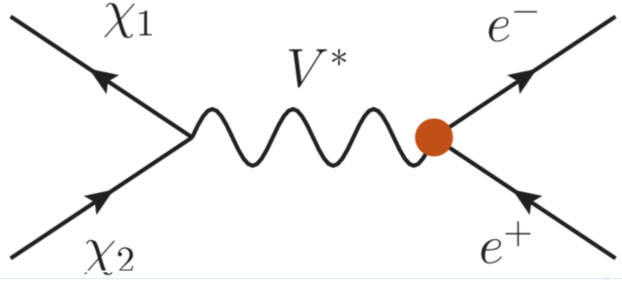


FORBIDDEN REGIME



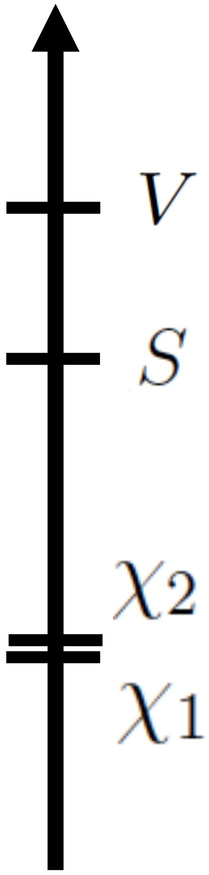
$$M_\chi \lesssim M_V \lesssim M_S$$

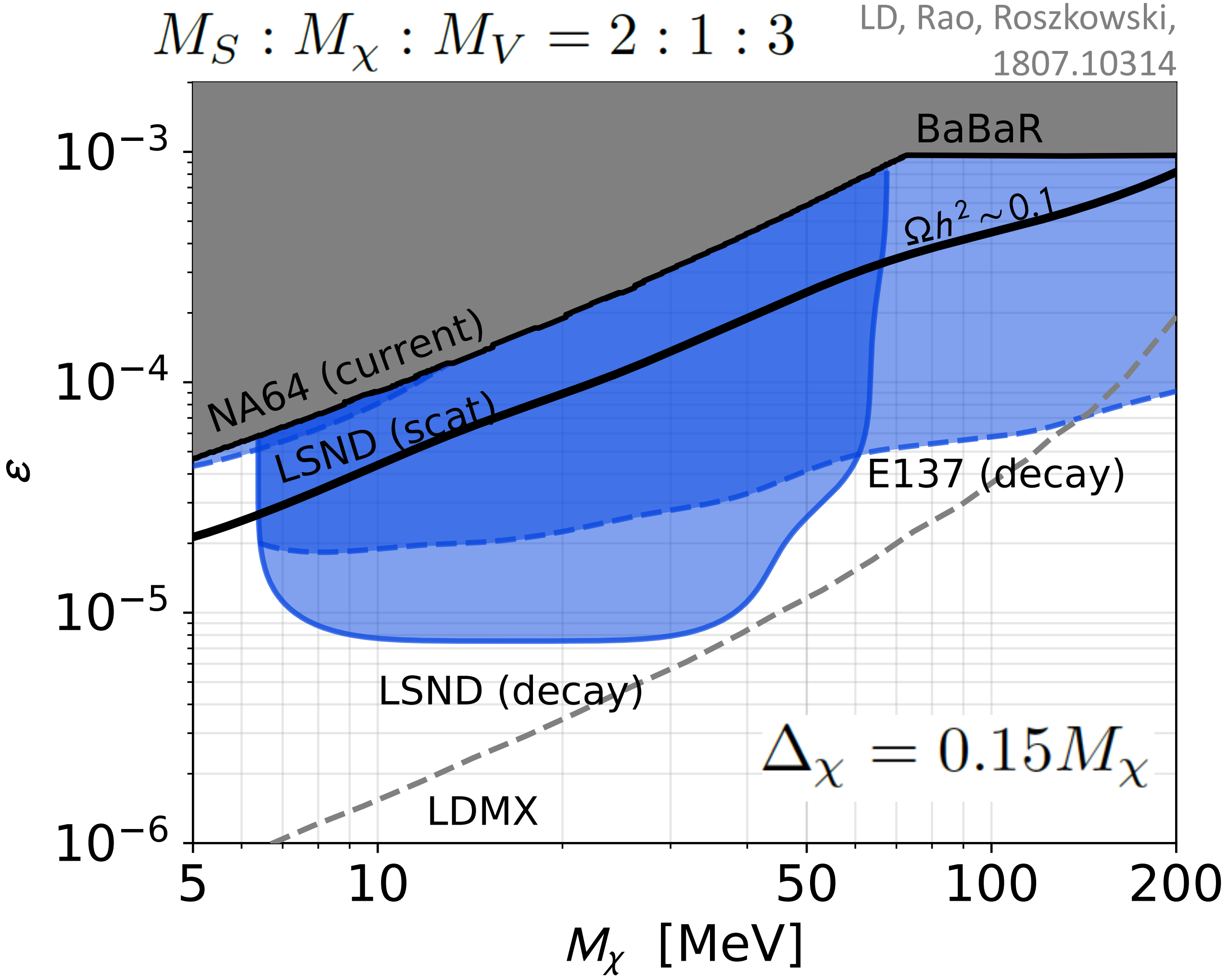
iDM/mDM REGIME



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!