Light dark matter, dark sector EFT and long-lived states

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Based on 1807.10314 and 1912.xxxx

Outline

Introduction: sub-GeV dark matter and dark sectors

Long-lived states in and EFT description

Production of light dark sector at the intensity frontier and EFT

Signatures of light dark sectors and limits

Introduction

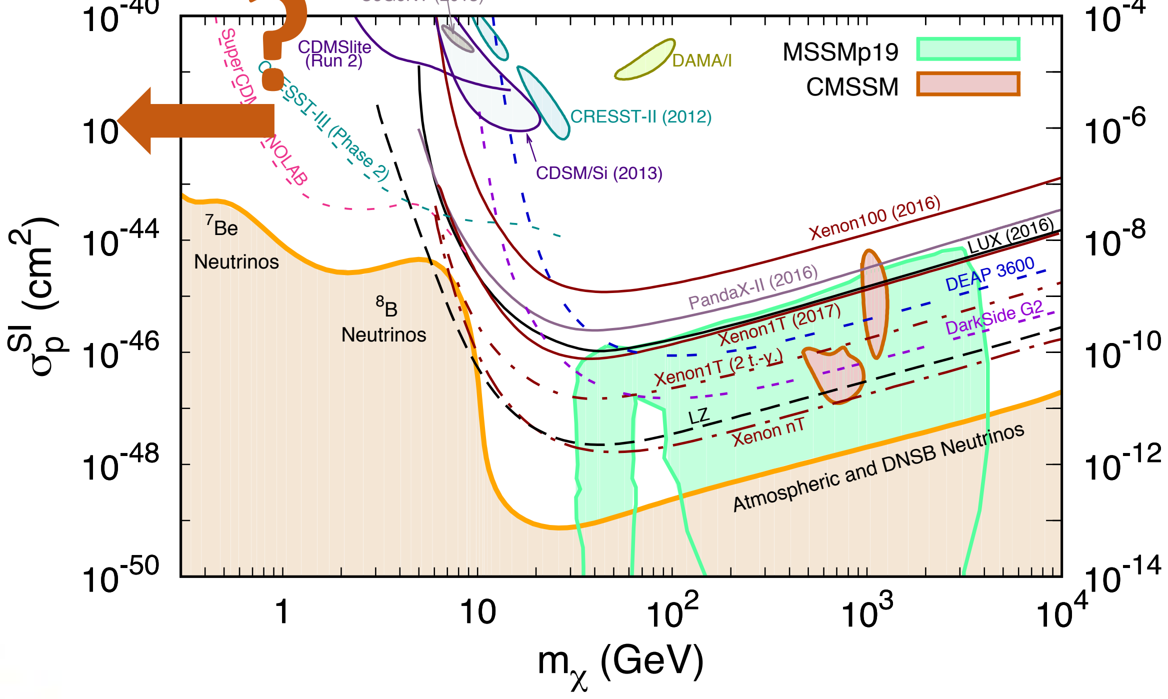
sub-GeV DM and dark sector: an example

Light dark sectors and dark matter

- WIMP Dark matter is a mature area of research

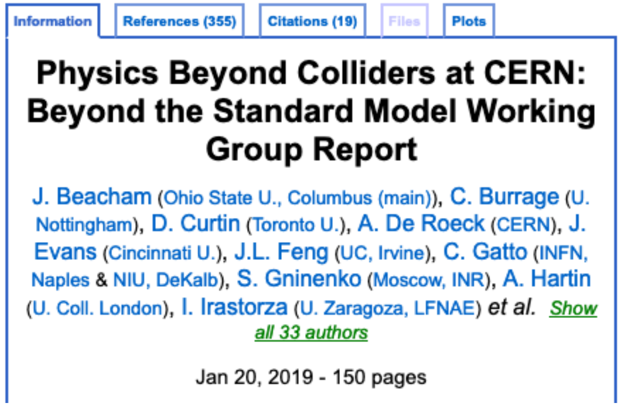
→ what about lighter (sub-GeV) DM ?

From ArXiv:1707.06277



- Strong experimental effort in the intensity frontier

→≳ 10 relevant experiment in next 2 years

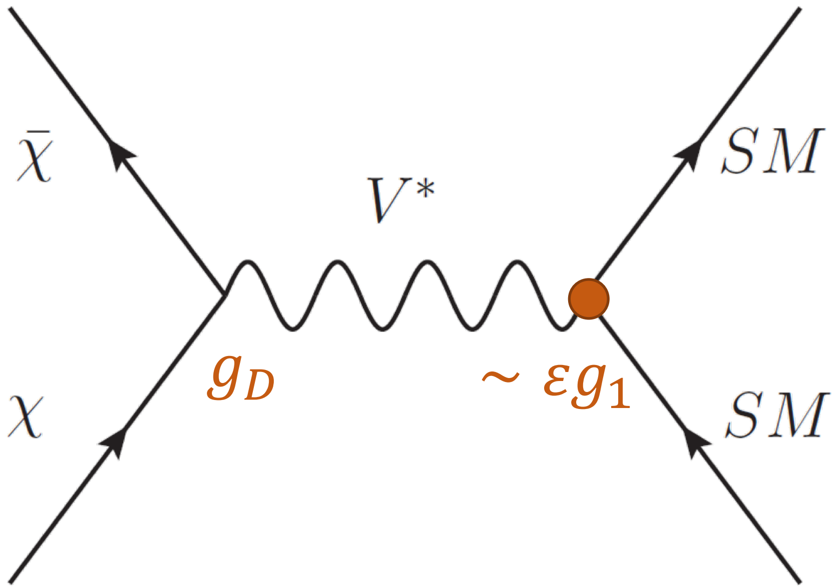


- Not all DM-motivated, yet most can be used to constrained sub-GeV thermal DM and dark sectors

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

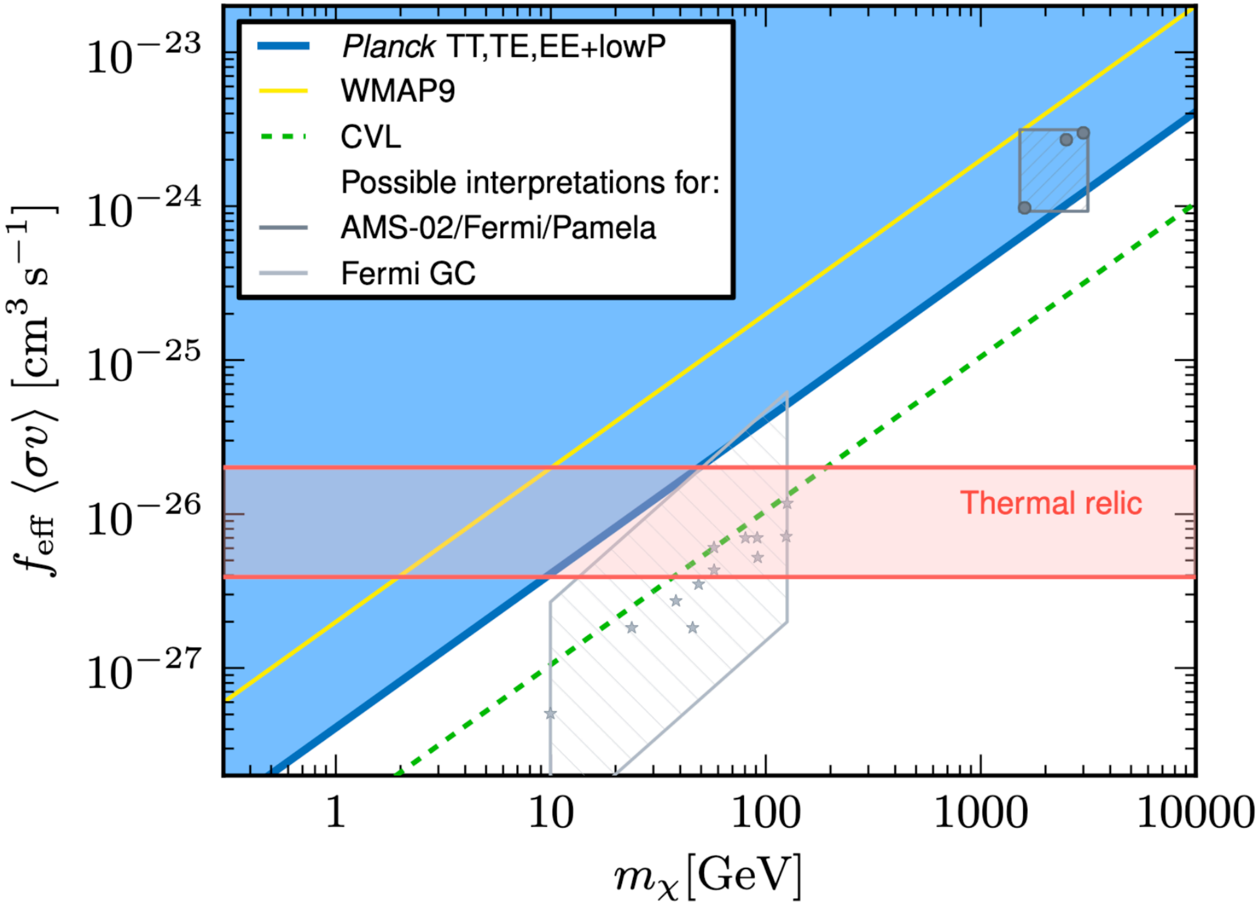
$$\Omega h^2 \sim 0.1 \times \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{0.1}{\alpha_D}\right) \times \left(\frac{25\ \mathrm{MeV}}{M_\chi}\right)^2 \left(\frac{M_V}{75\ \mathrm{MeV}}\right)^4$$

- 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



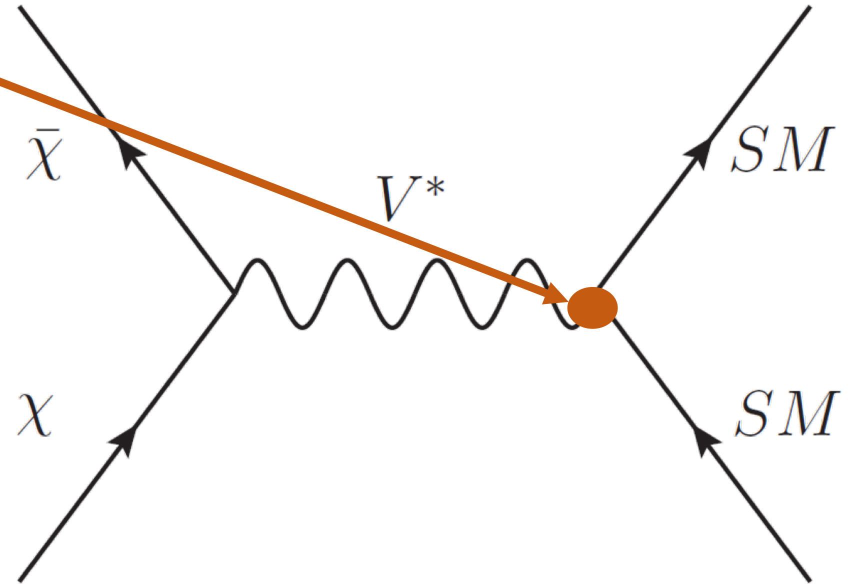
Kinetic mixing and dark Higgs mechanism

- 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

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

- Yukawa couplings to the dark Higgs S

  → Avoid Dirac DM (CMB exclusion)

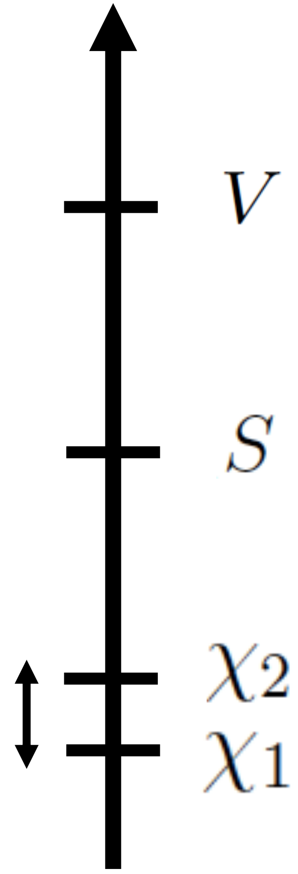
  →After $U(1)_D$ symmetry breaking, the dark matter acquires a Majorana mass

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

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

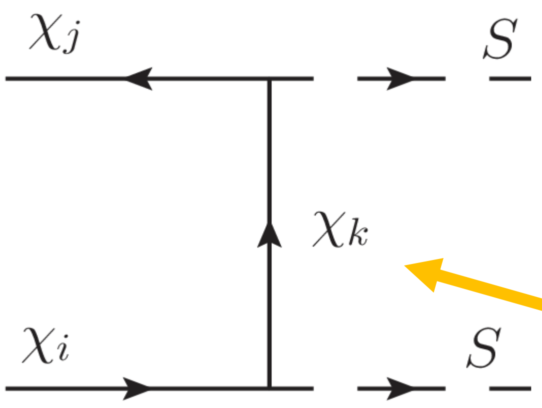
$$M_S = \sqrt{2\lambda_S} v_S$$

$$M_{\chi 2} - M_{\chi 1} = \sqrt{2} v_S (y_{SR} + y_{SL})$$



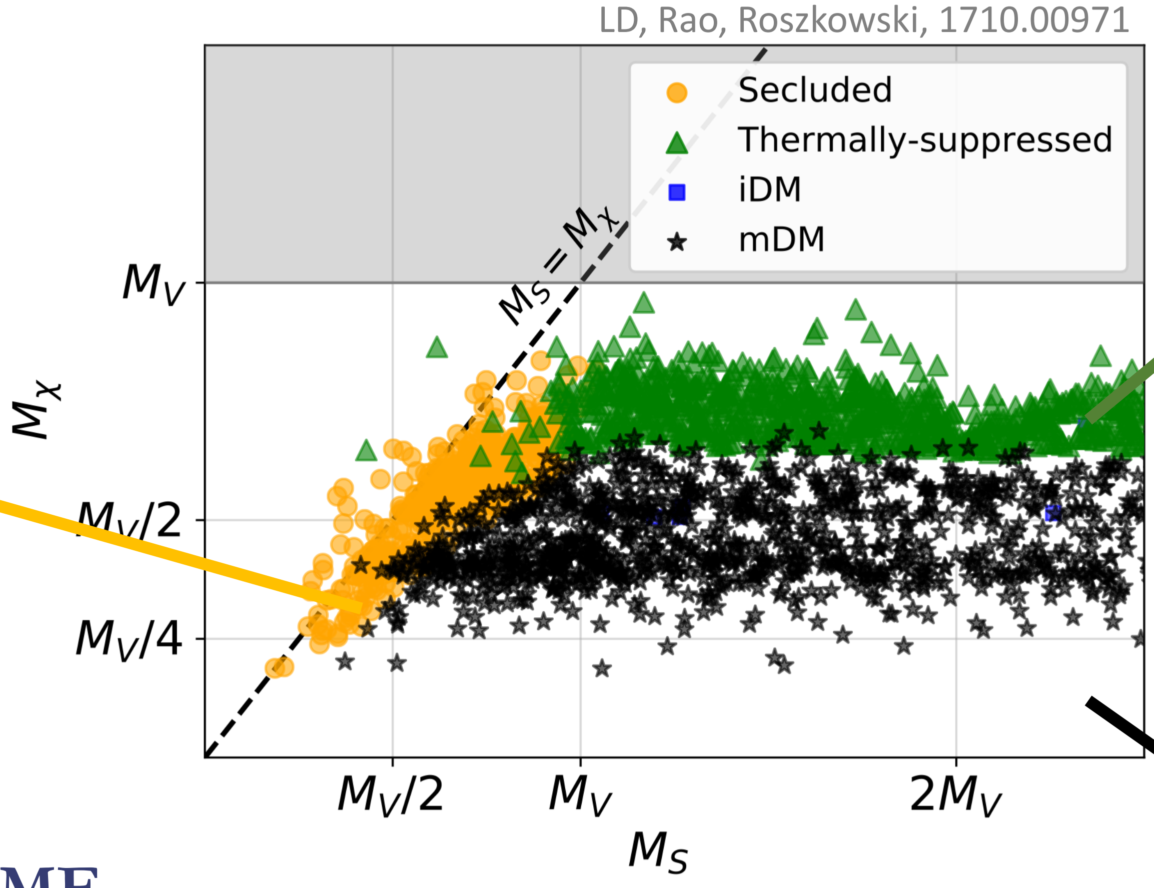
- After diagonalization → two Majorana fermions

Typical regimes with correct relic density

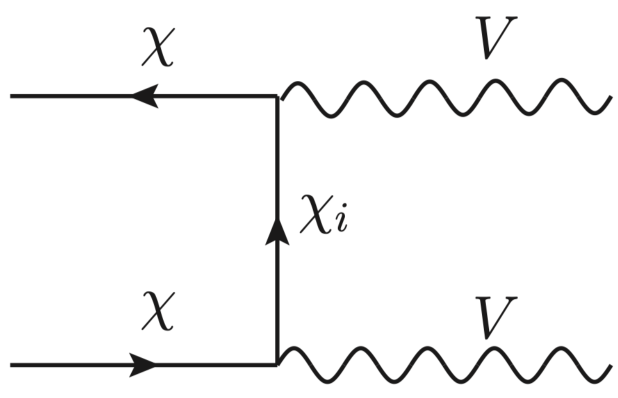


$$M_\chi \gtrsim M_S$$

SECLUDED REGIME

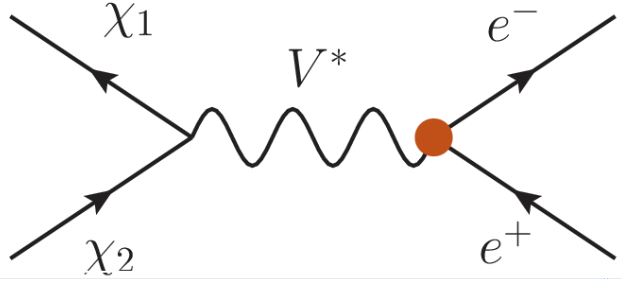


FORBIDDEN REGIME



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

iDM/mDM REGIME



Long-lived states and EFT

Dark sectors, their long-lived states and how to describe them

Complete models of light thermal DM

- Strong theoretical developments toward building models of thermal sub-GeV DM

- 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,…

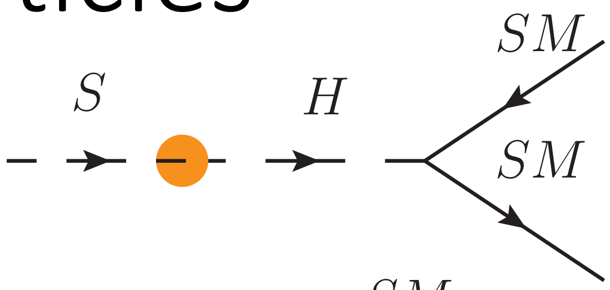
Forbidden DM
Griest-Seckel, 1505.07107, …

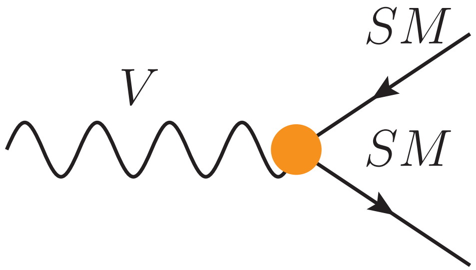
Co-decaying DM
1607.03110, …

Impeded DM
1609.02147,…

…and many more recent

A key consequence: long-lived particles

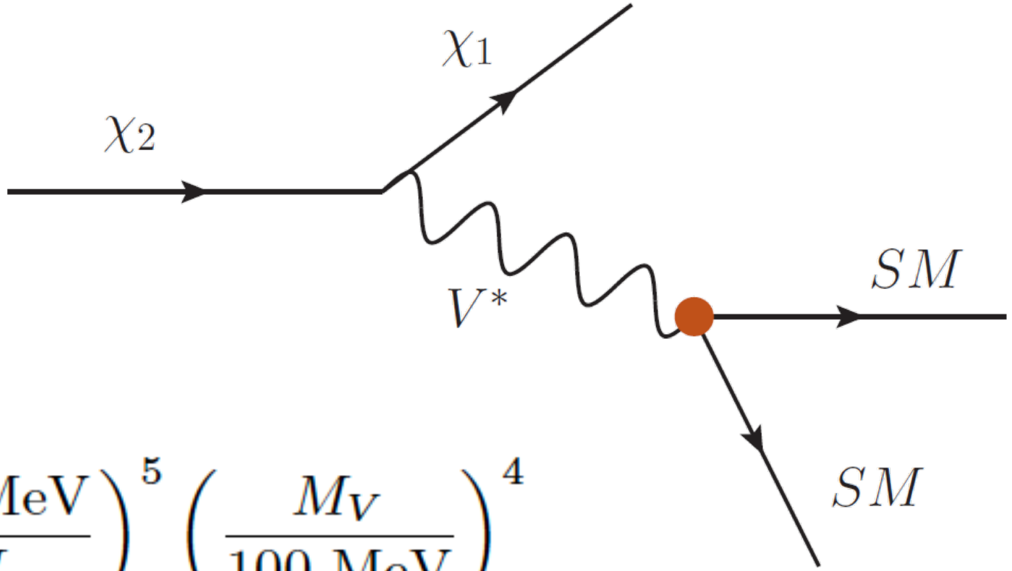




- Decays involving SM particles are often the only option for unstable dark sector states
  - Through the portal -> e.g. dark Higgs boson, dark photon

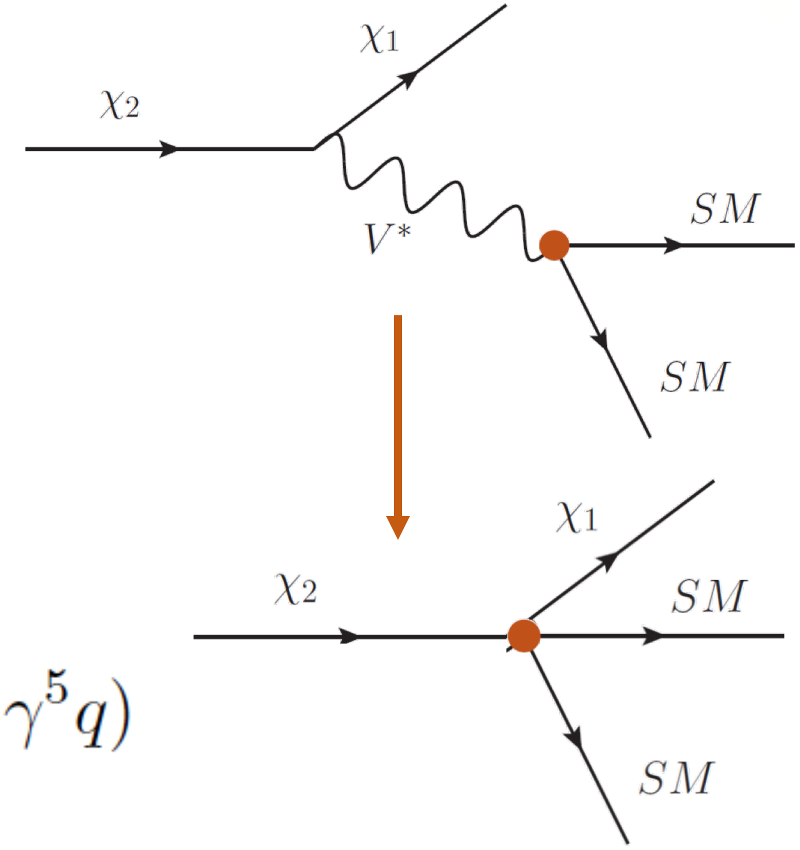
$$c\tau_{V\to e^+e^-} \sim 1\ \text{cm} \times \left(\frac{10^{-5}}{\varepsilon}\right)^2 \left(\frac{M_V}{100\ \text{MeV}}\right)$$

- 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….)



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

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

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

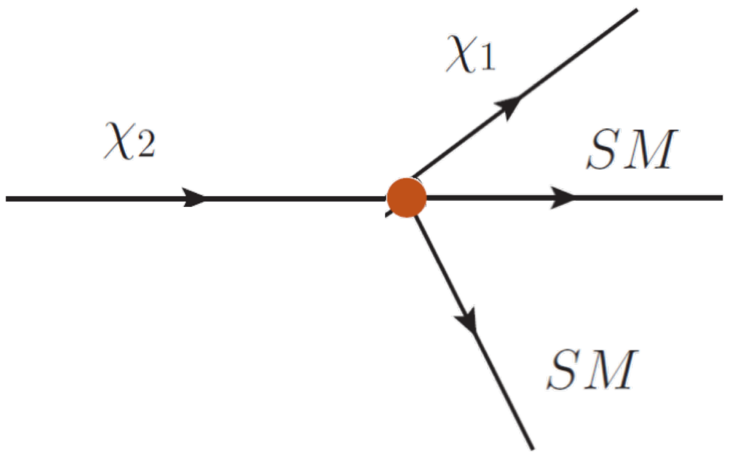
- Basic equivalence with a dark photon model with kinetic mixing ε and coupling g_D:

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

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

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



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

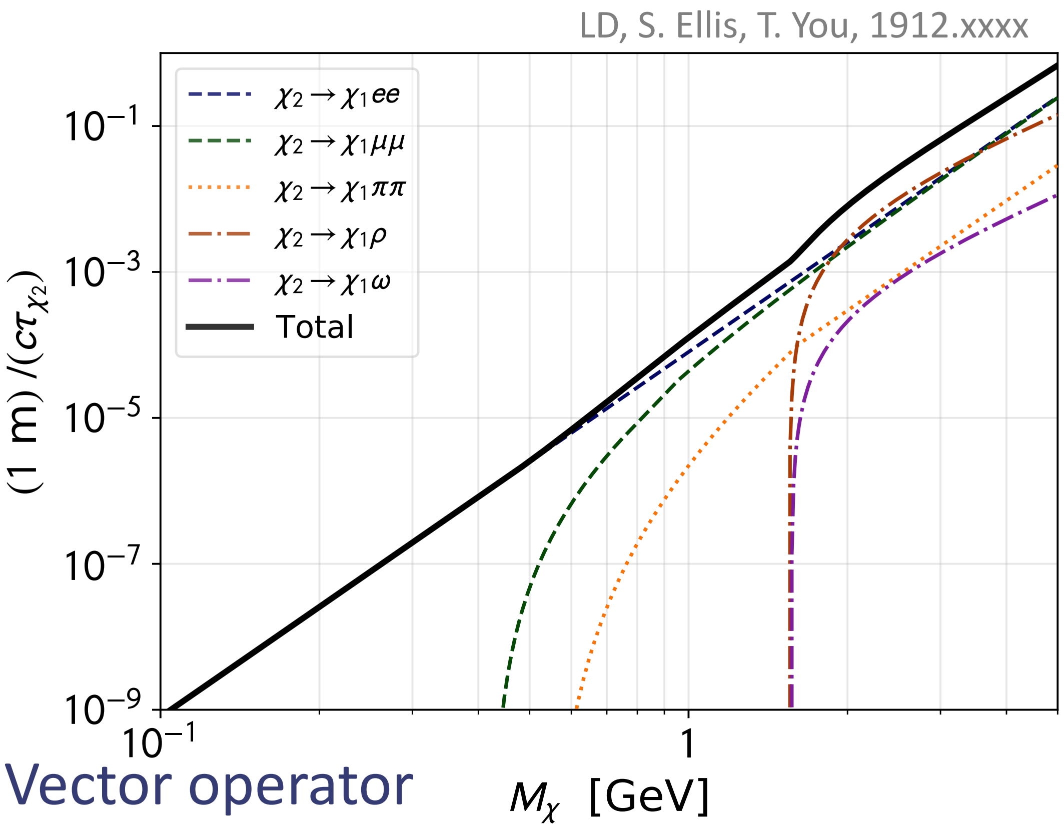
(Vector operator)

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

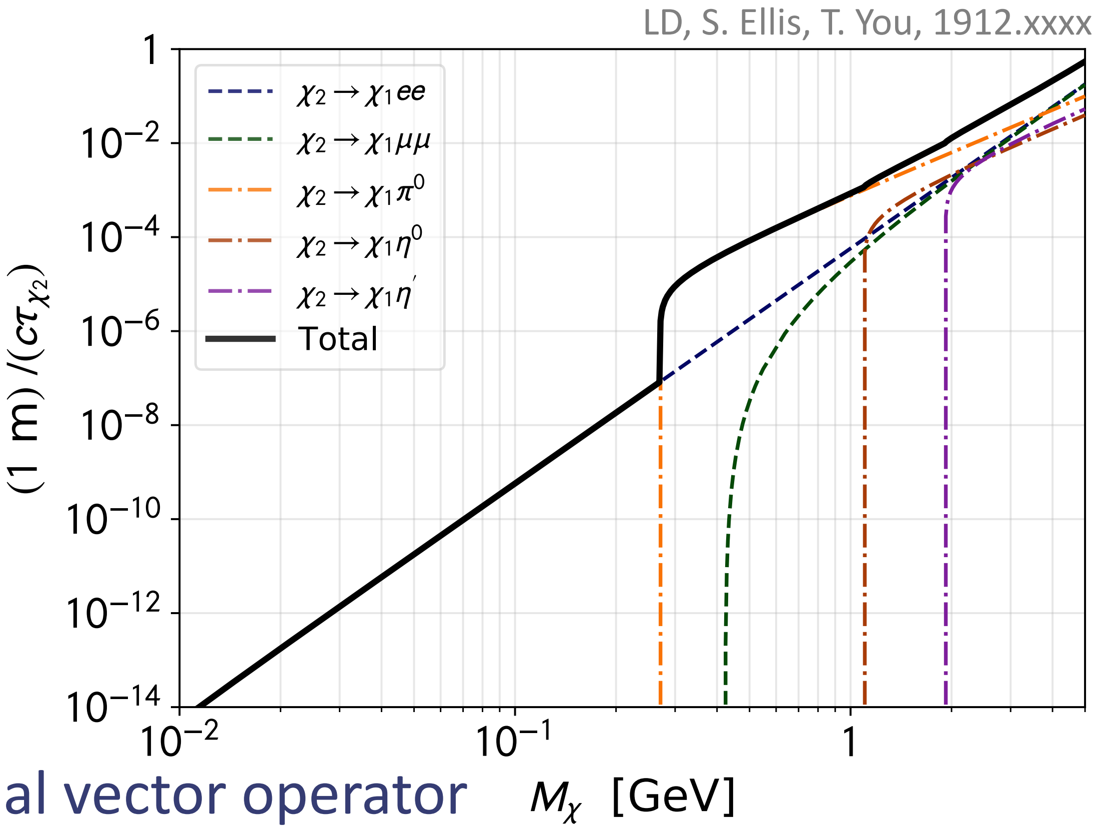
$$c\tau^{\mathrm{sat}} \sim 2\ \mathrm{m} \times \left(\frac{\Lambda/\sqrt{g}}{1\ \mathrm{TeV}}\right)^4 \left(\frac{1\ \mathrm{GeV}}{M_{\chi_2}}\right)^5$$

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

Light dark sector EFT and the intensity frontier

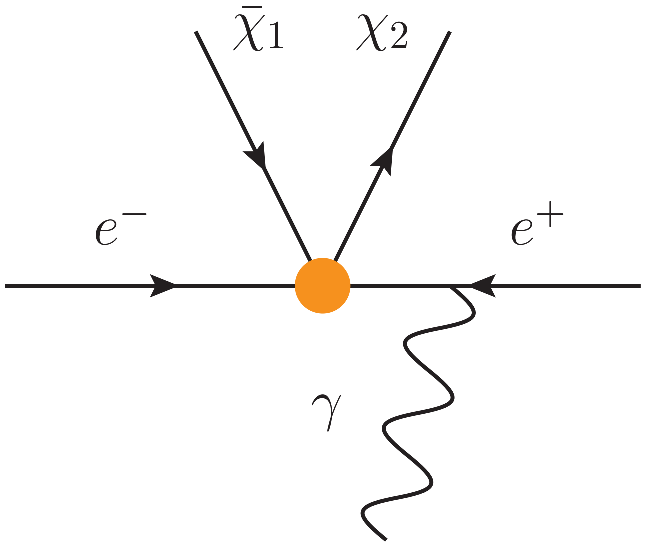
Production at accelerator-based experiments

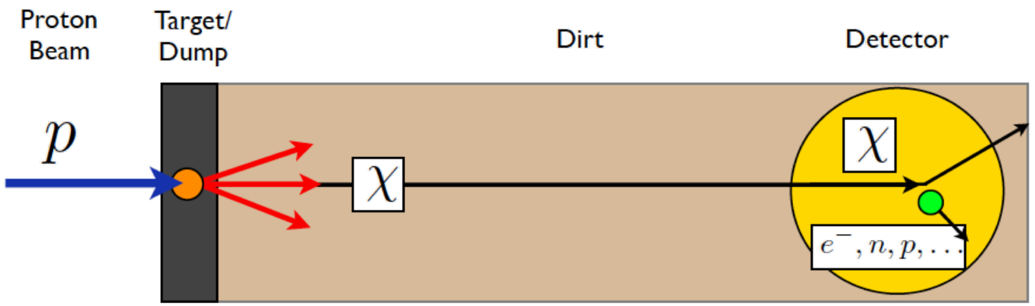
Dark Sector searches - production

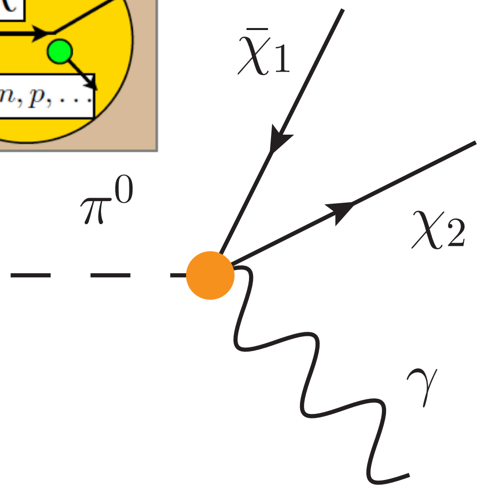
- Light dark sector particles may be accessible at the *intensity frontier* (GeV energy / large intensity / good background rejection)
  - Since typically $\Lambda > E_{cm}$, EFT description of off-shell production well-defined

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

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







Production in the light dark sector EFT

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

- Off-shell nature of the process -> Strong suppression of low energy production mechanism.

  → For meson decay, BR typically suppressed $\propto \frac{M_m^4}{\Lambda^4}$

- On-shell mediator bremsstrahlung $e^- N \to e^- N\, V$ or $p\, N \to p\, N\, V$ not available

  → 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:

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

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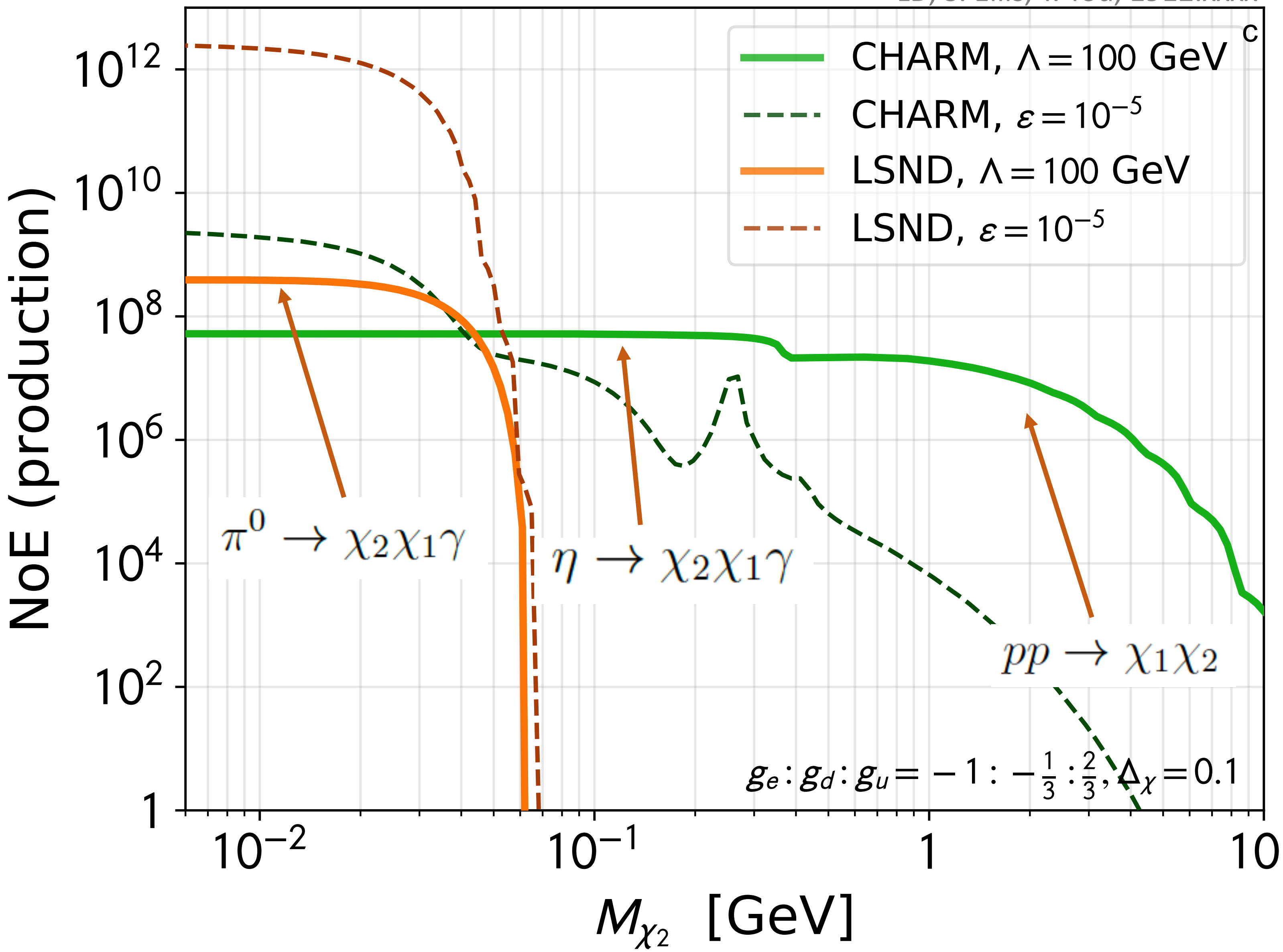

Full production – axial vector

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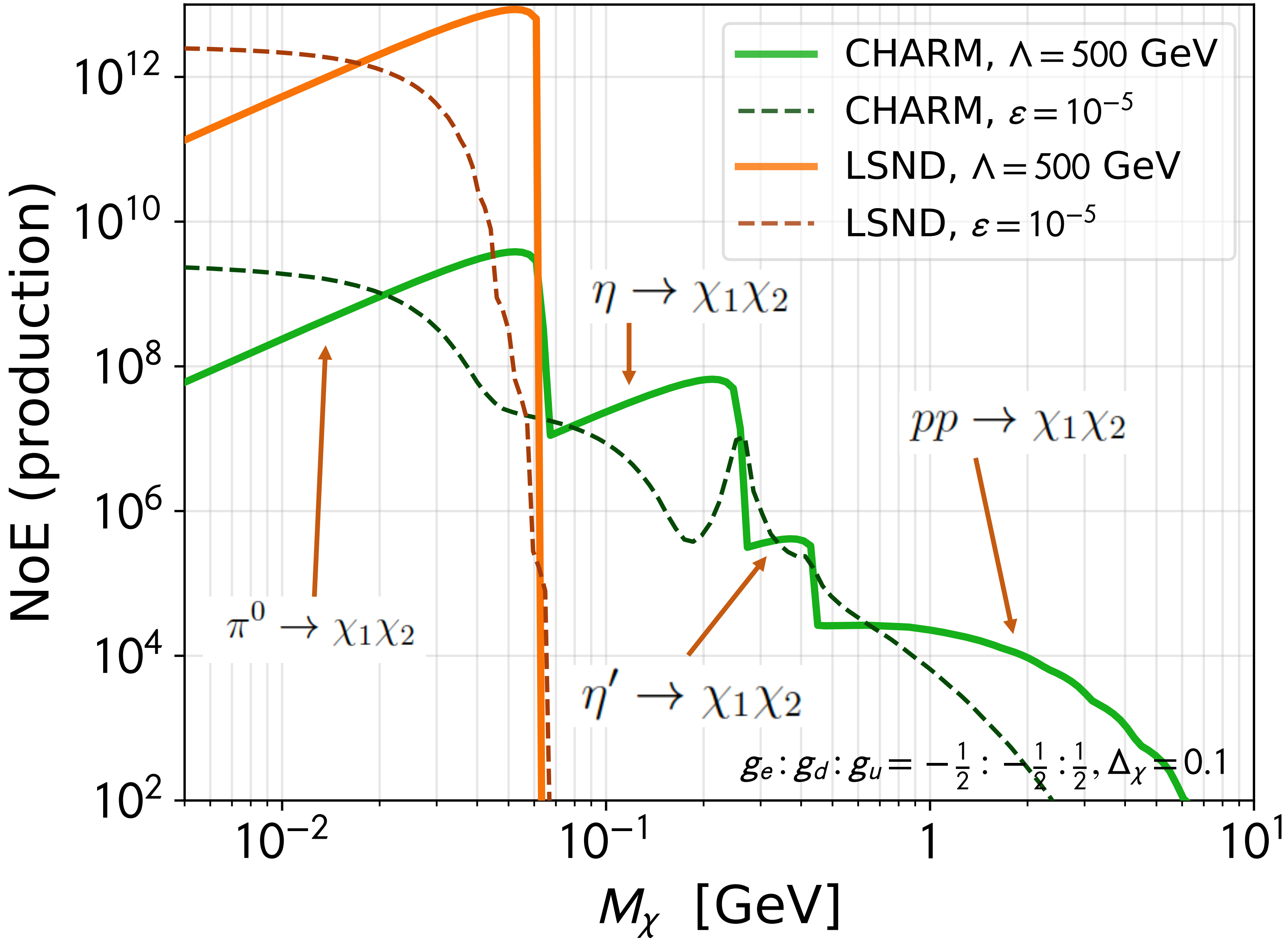
- Meson production strongly enhanced
  - 2-body decays dominant

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

  - Pion decay contribute significantly

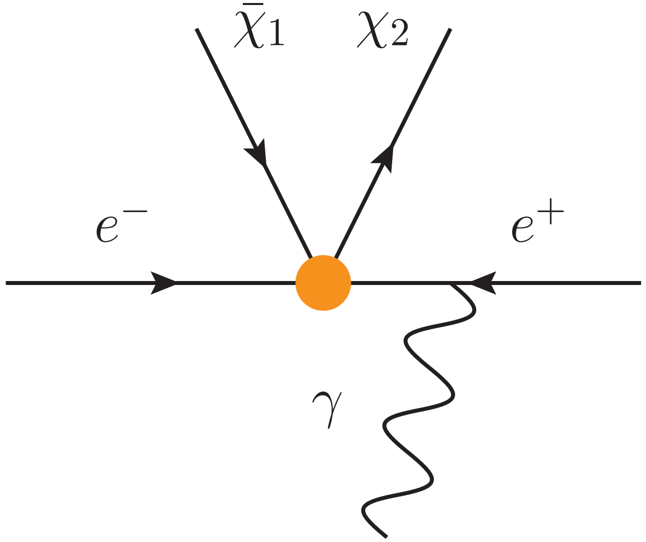


Dark sector searches and constraints

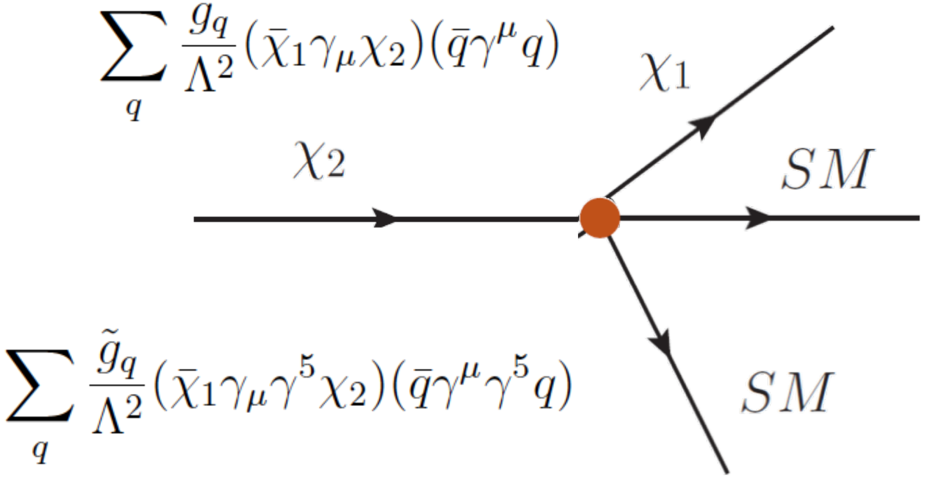
Recasting and limits using the EFT approach

Dark Sector searches in the lab

- Missing energy/ Invisible decay: Mono-photon/mono-jet searches missing energy signature @ BaBar, Belle, NA64, LEP, LHC.
- Invisible meson decay: for instance $\pi^0 \to \bar{\chi}\chi$ (NA62)
    - Important for flavour-violating operators



- Dark sector beam production and detection
    - Scattering: Searching for DM via scattering (E137,LSND, miniBooNE …)
    - Dark sector visible decay: (LNSD, CHARM, Seaquest, FASER, etc…)



Recasting in the light EFT approach

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

- Mono—photon searches are also weakened since no "bump-search" can be performed in $\chi\chi$ invariant mass
- Different approaches for each search strategies → Decay limits are particularly challenging

→ need to rescale for production rates

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

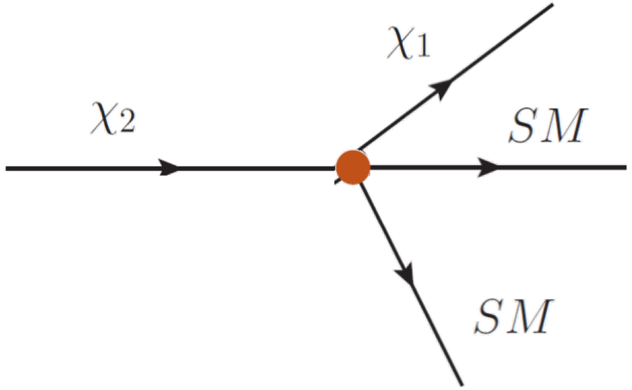
→For different splitting, detection probability is modified (also rescale for decay rates)

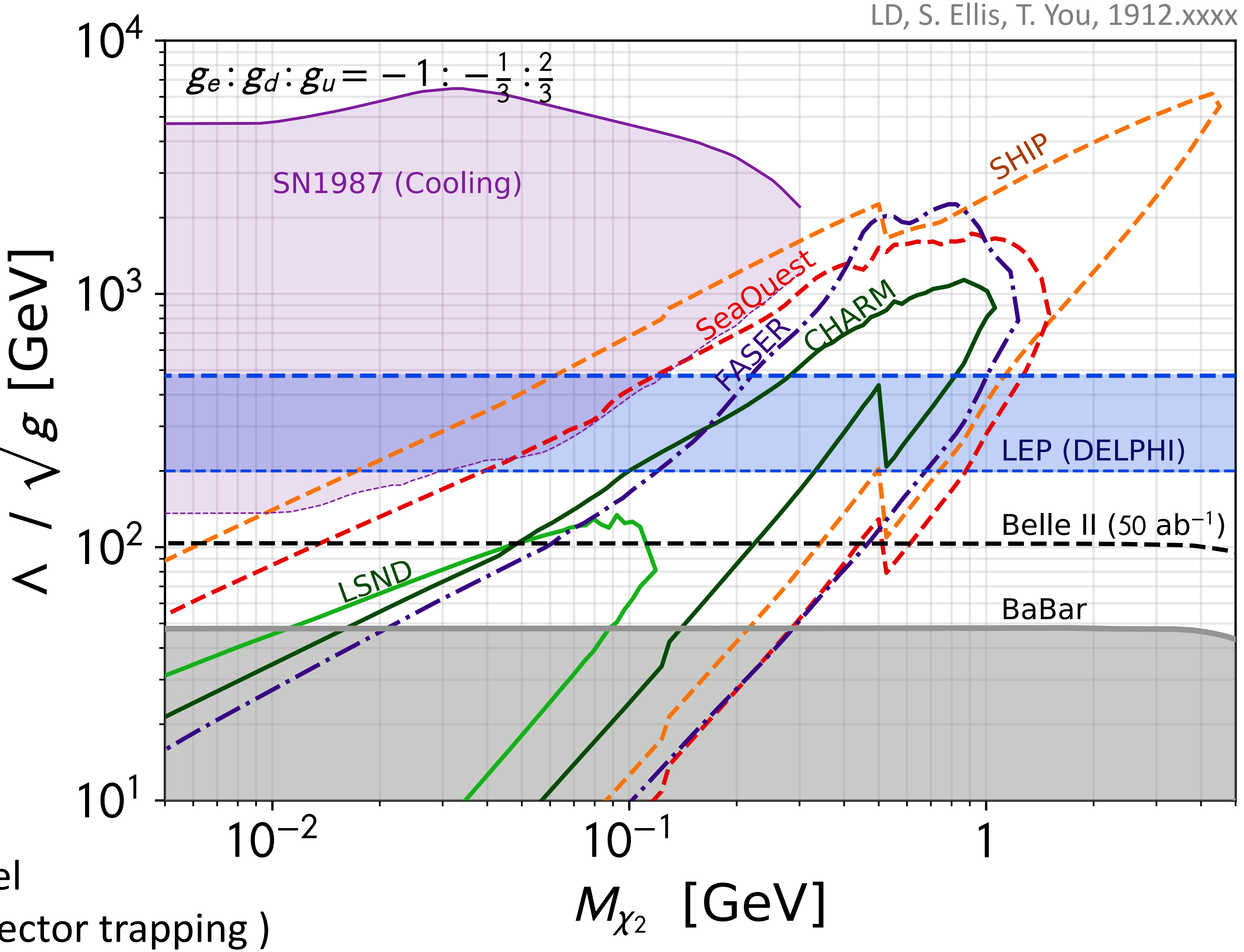
Limits in the vector case

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 $\sim 10^{18}$ 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

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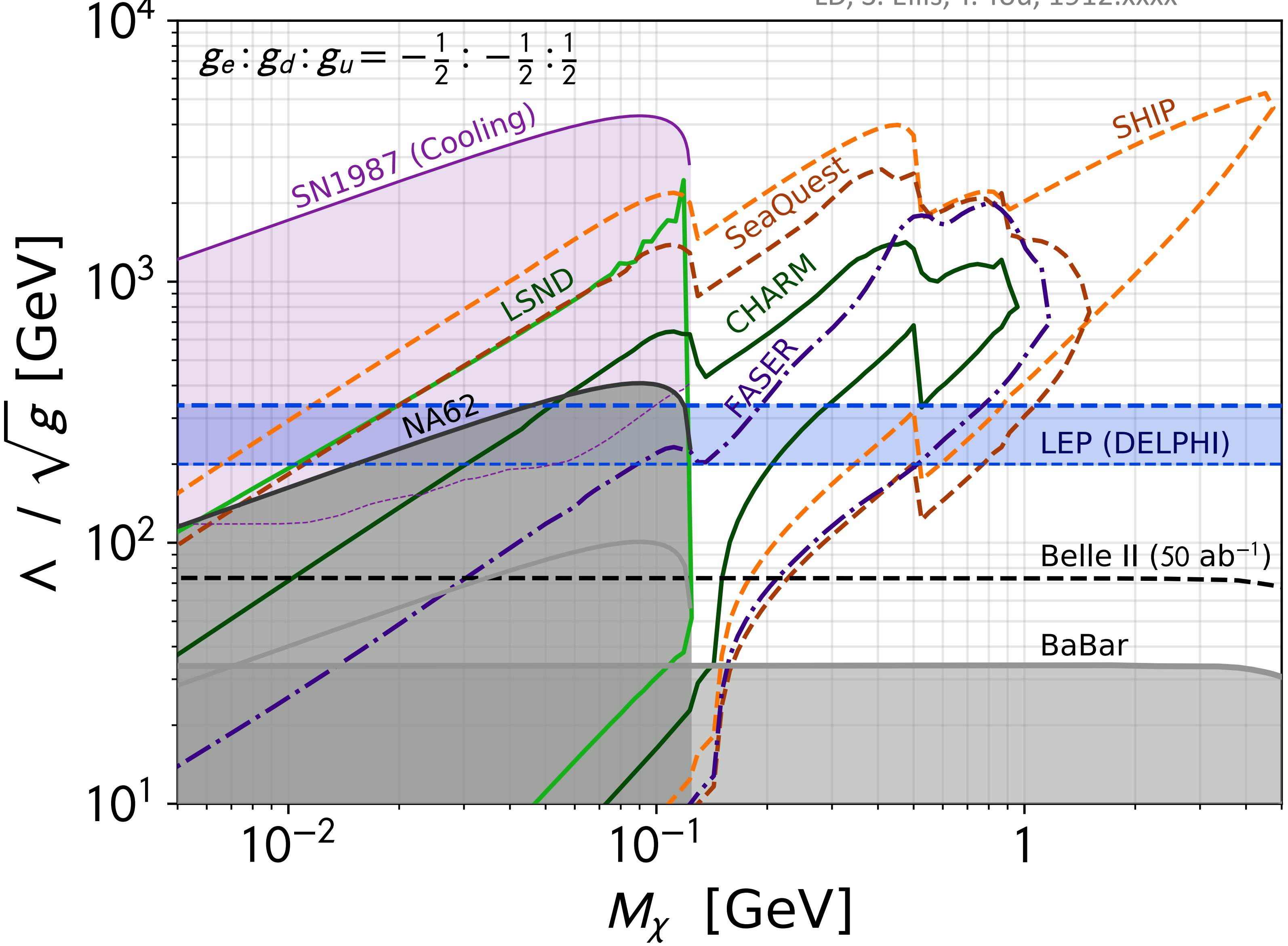

Varying the splitting

- 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

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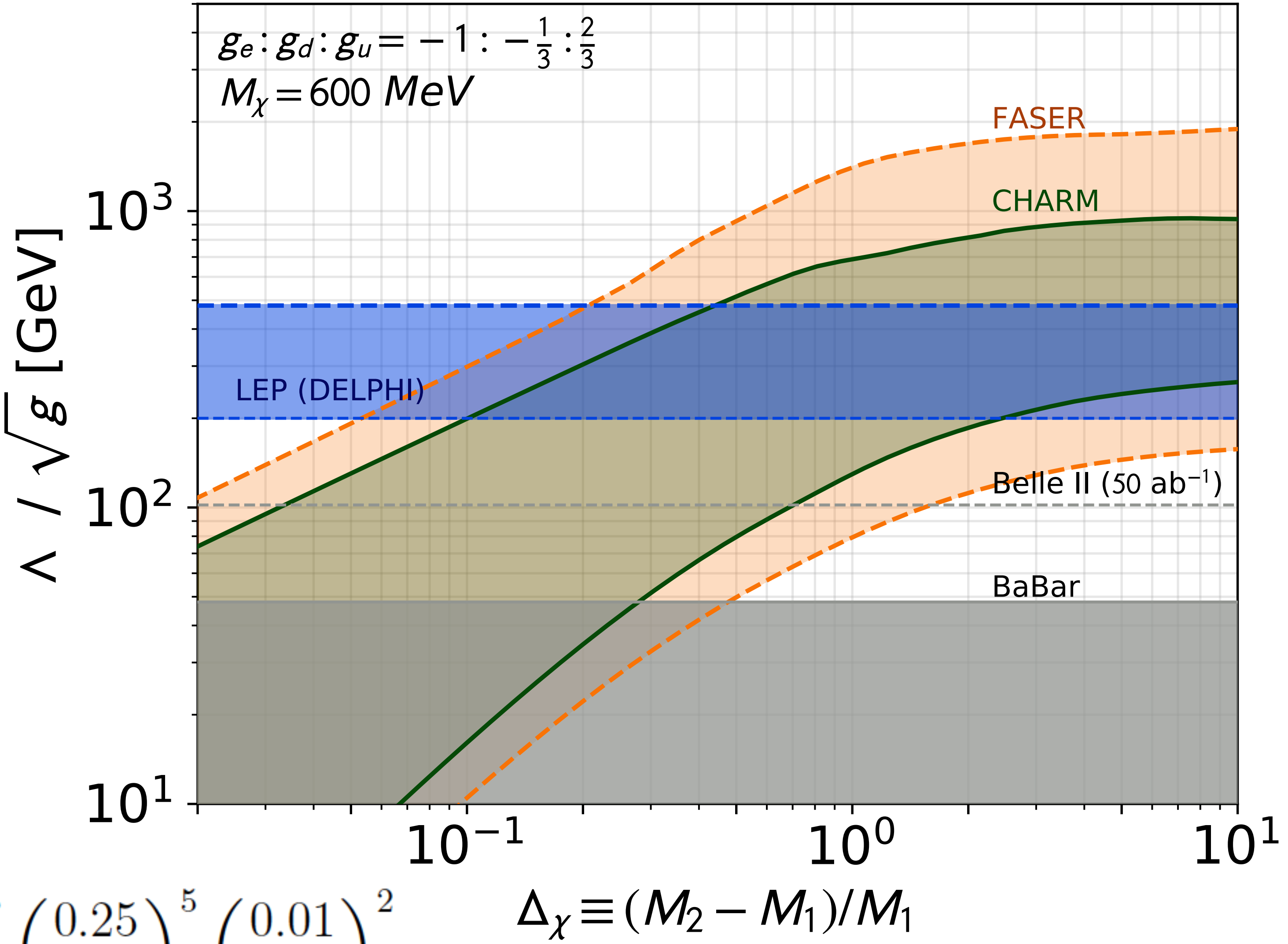

$$c\tau^{\mathrm{pD}} \sim 375\ \mathrm{m} \times \left(\frac{100\ \mathrm{GeV}}{\Lambda}\right)^4 \left(\frac{1\ \mathrm{GeV}}{M_{\chi 1}}\right)^5 \left(\frac{0.25}{\Delta_\chi}\right)^5 \left(\frac{0.01}{g}\right)^2$$

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)

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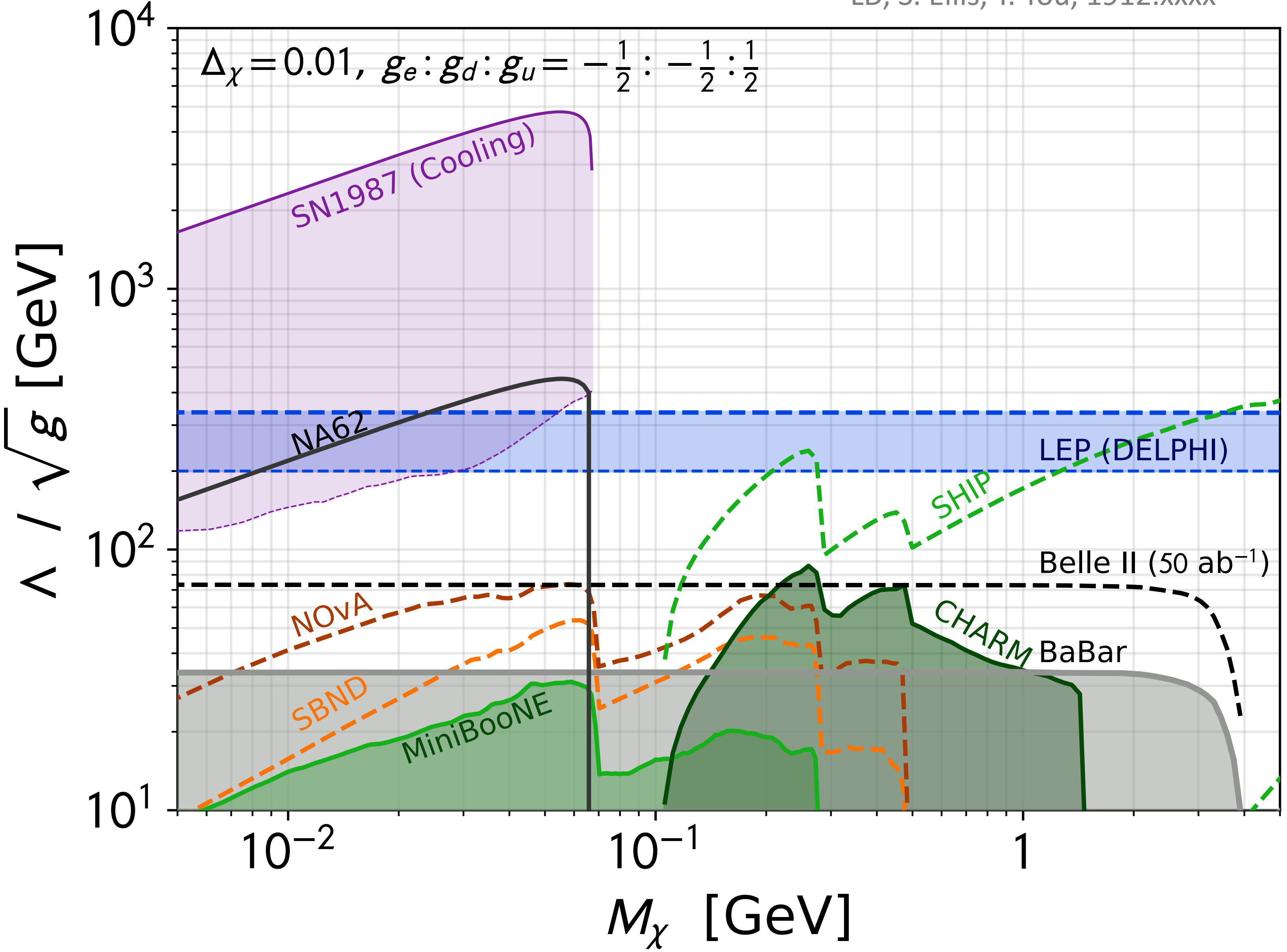

Practical example: off-shell dark photon

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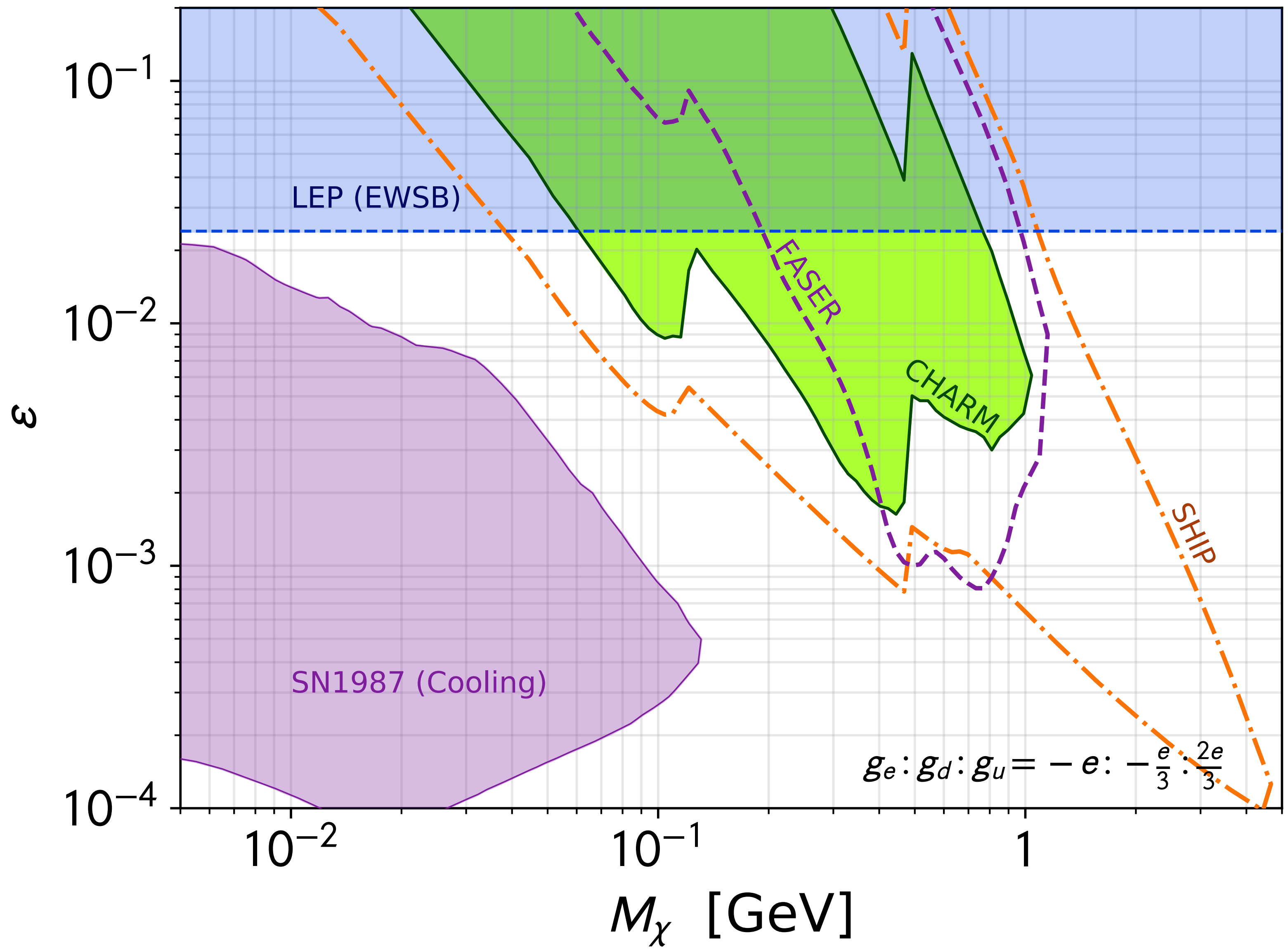
- Standard iDM scenario with a heavy dark photon ($M_V \sim 30$ GeV, with $M_V \gg M_\chi$)

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



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

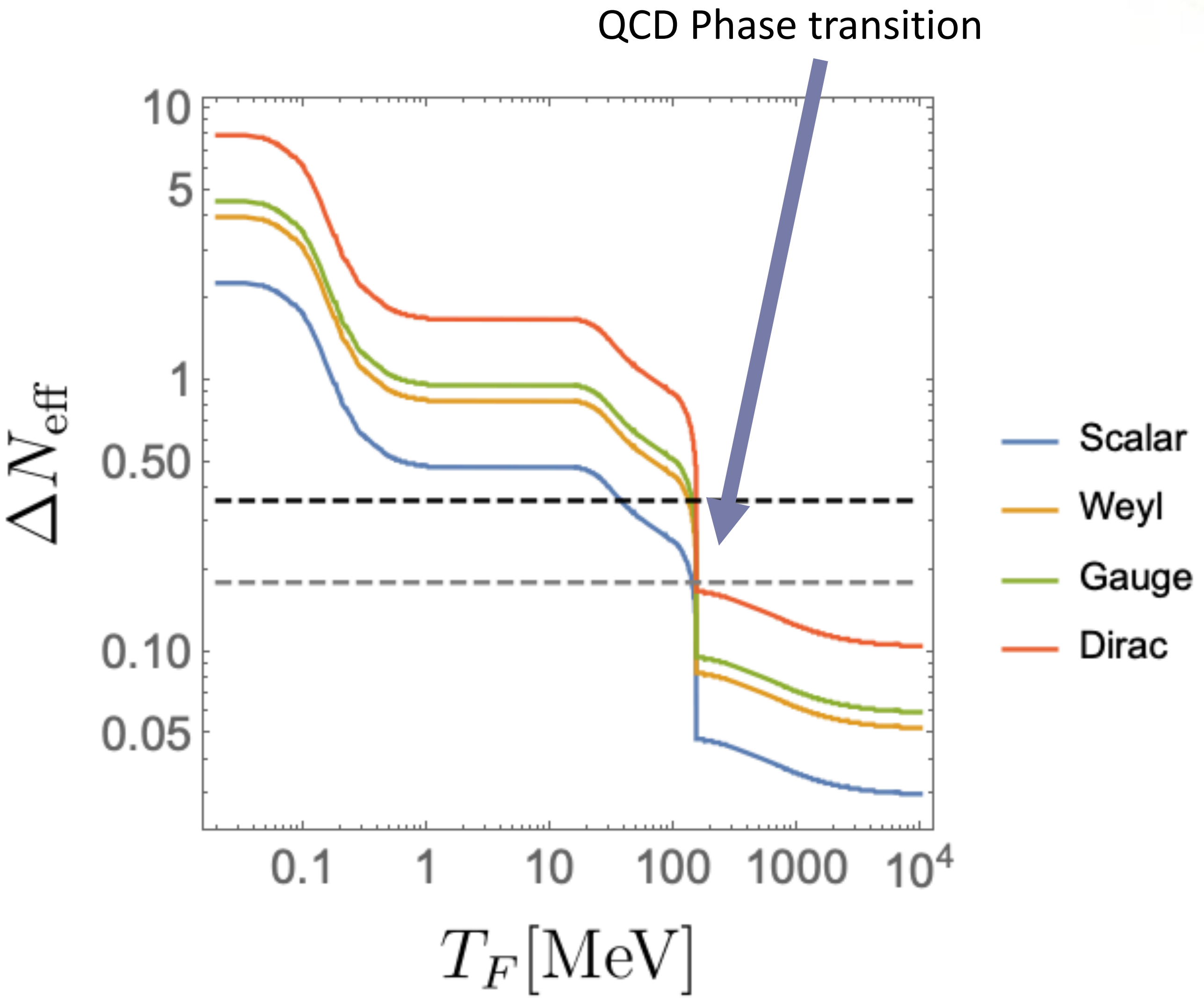
- Light thermal dark matter models typically include a dark sector with long-lived particles -> Important search targets for intensity frontier experiments
- When the mediator is too heavy to be produced directly, describe the phenomenology as an “off-shell” fermion portal -> EFT description
- Lead to rich phenomenology in intensity frontier experiments, with different prospects than standard “on-shell” portals

→ Will be release in a python package, to provide recasted limits for any effective coupling

Backup slides

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

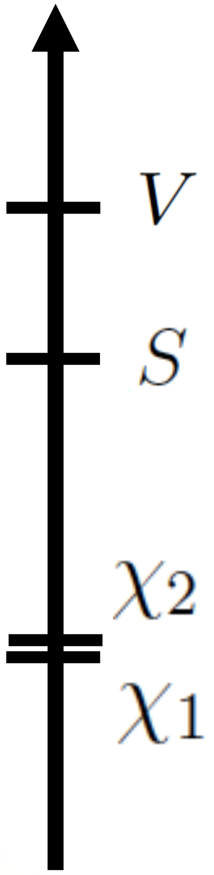


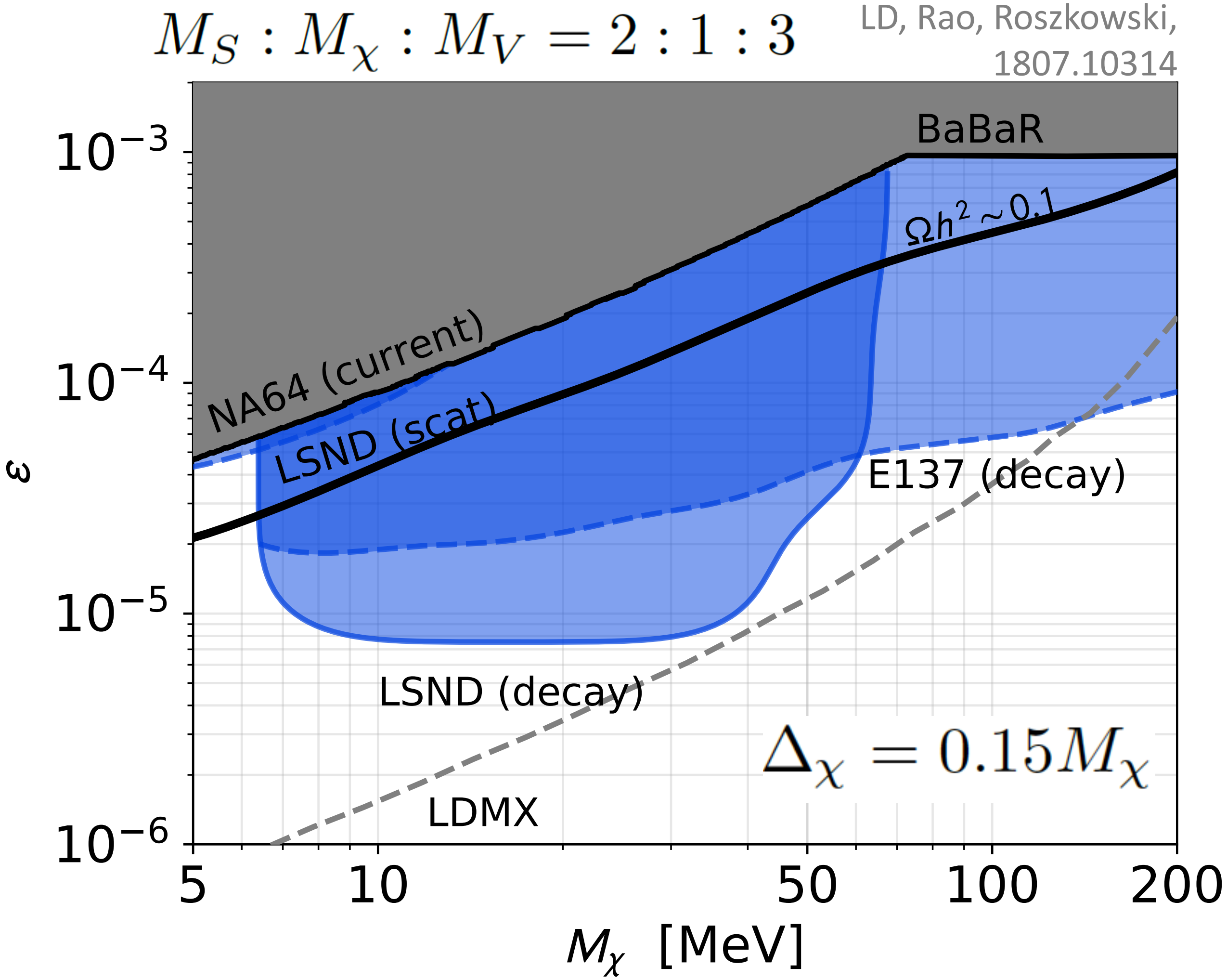
$$\Omega h^2 \sim 0.3 \times \left(\frac{2\ \mathrm{GeV}}{M_\chi}\right)^2 \left(\frac{\Lambda/\sqrt{g}}{500\ \mathrm{GeV}}\right)^4$$

- 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

Inelastic DM regime

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

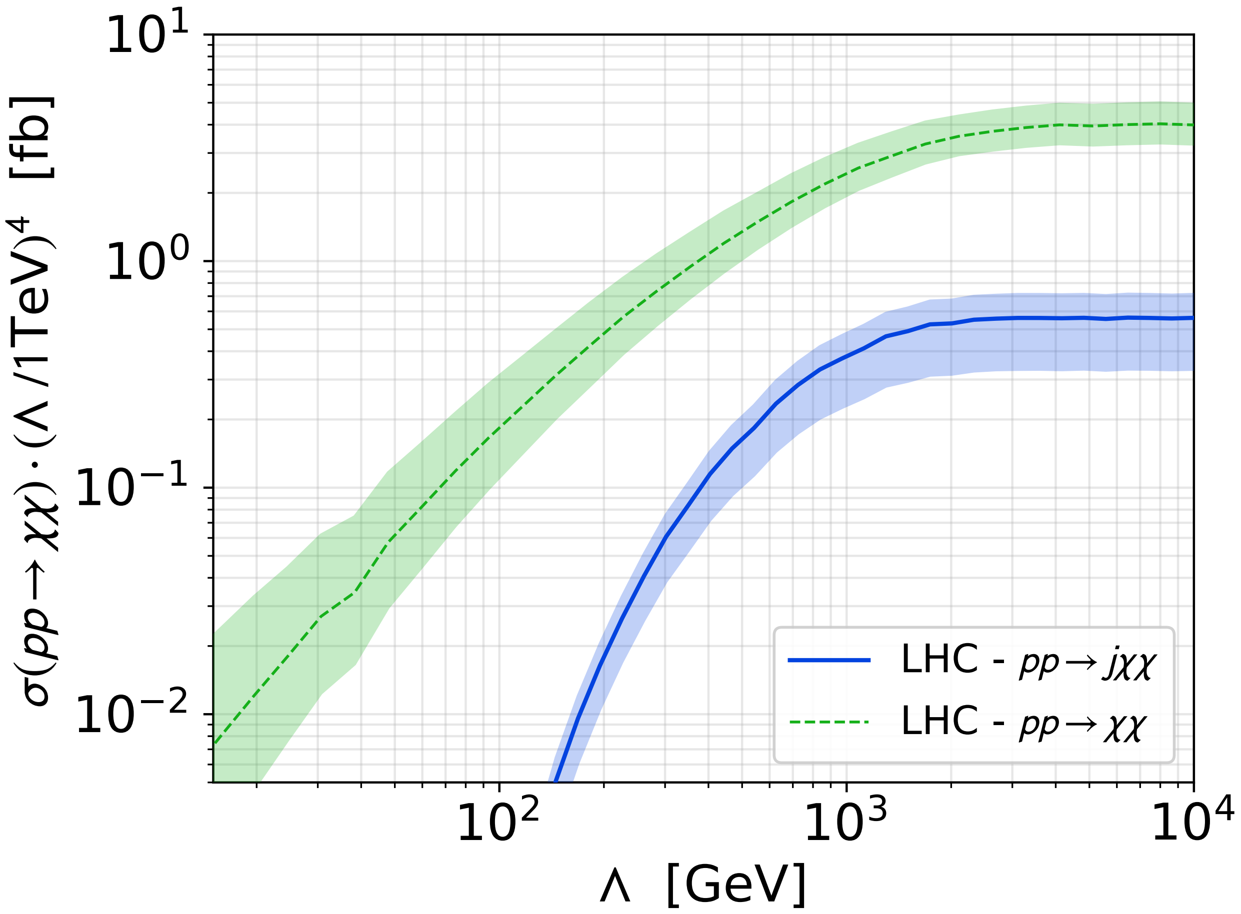




- Main signatures:
  - Missing energy searches
  - $\chi_2 \to \chi_1 e^+ e^-$ decay
  - χ_1 scattering
- When consider dark sector decays, decades-old experiment are still strongly ahead of current mono-photon searches!

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



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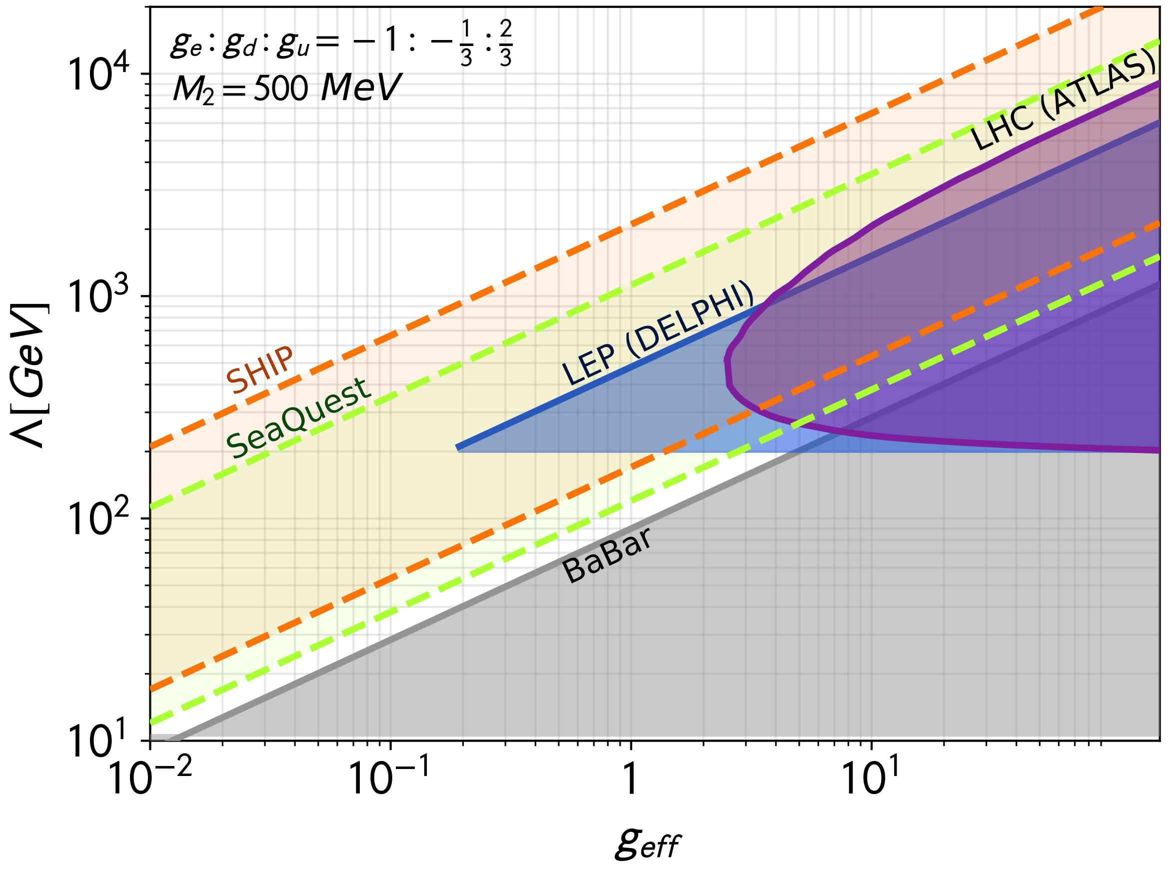

SN 1987A bounds

- 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