Long-lived particles and co-annihilating dark matter with tau-lepton

Kazuki Sakurai

(University of Warsaw)

In collaboration with:

Valentin Khoze (Durham U.) and **Alexis Plascencia** (Case Western Reserve U.)

[arxiv:1702.00750] [JHEP 06(2017)041]

21.11.2019 @ Edinburgh

Dark Matter

- All evidence for the existence of Dark Matter is purely gravitational.

- The particle physics nature of DM is unknown.
- — is our main ‘new physics’ challenge.

- The energy density of the DM is precisely measured:

$$\Omega_{\mathrm{DM}} h^2 \simeq 0.12$$

- The thermal freeze-out is attractive scenario for particle dark matter.

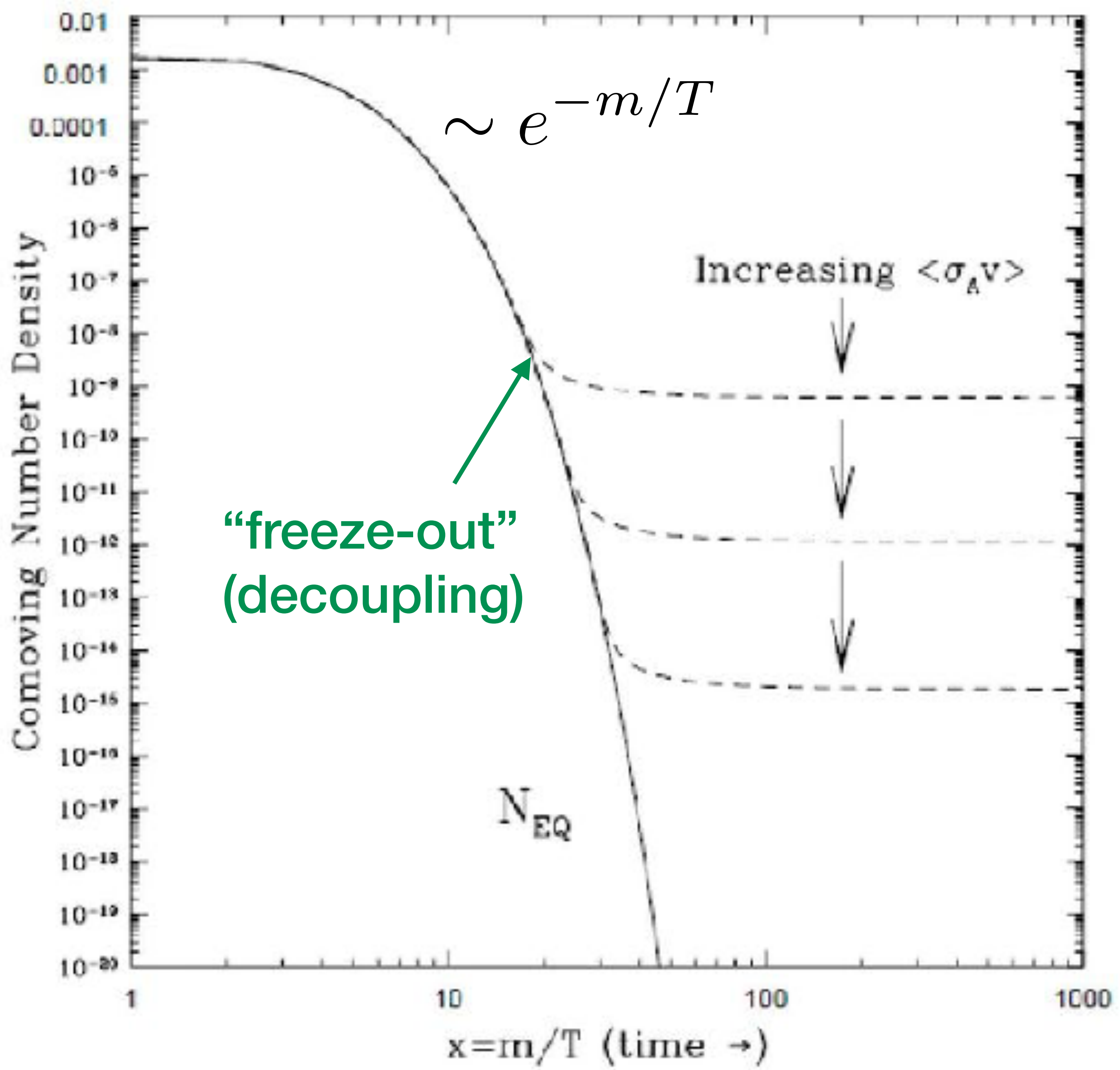
WIMP miracle

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle \sim \frac{g^4}{m^2}$$

$$g \sim 0.1, \quad \Omega h^2 = 0.12$$

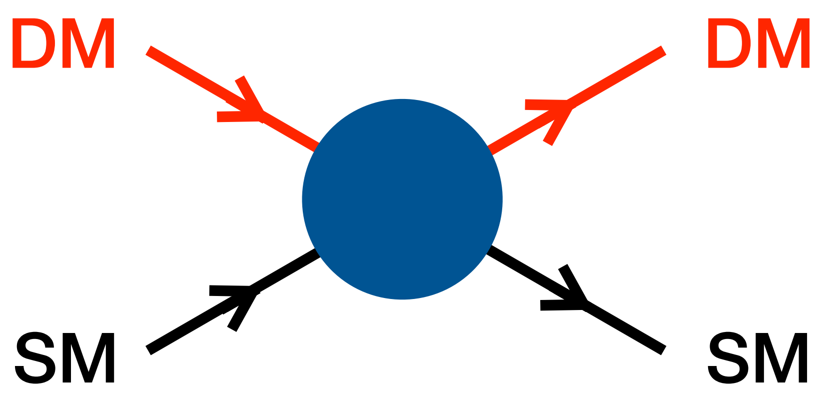
$$\Rightarrow \quad \boxed{m \sim 100\,\mathrm{GeV}}$$

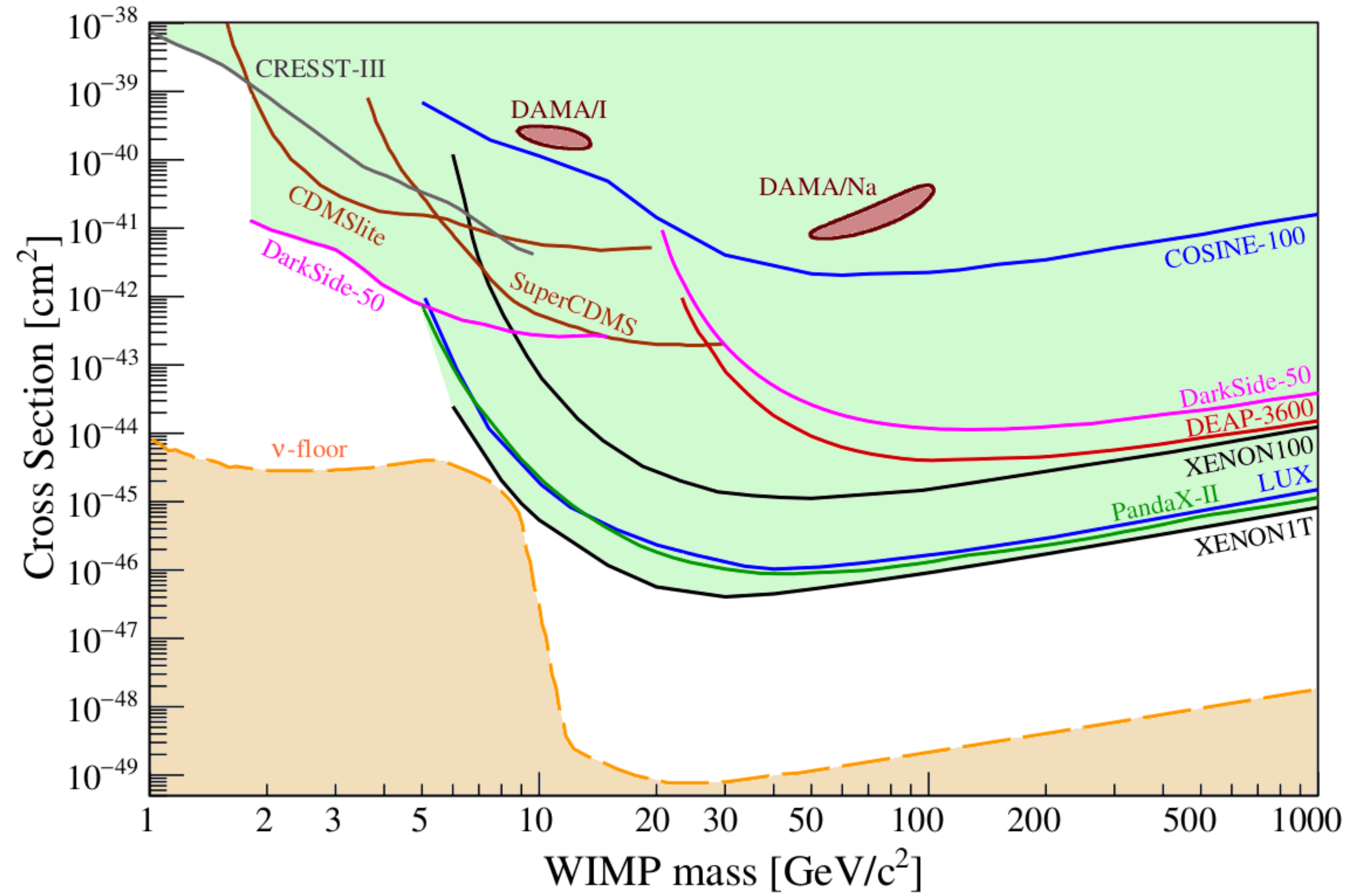


within the reach of LHC!

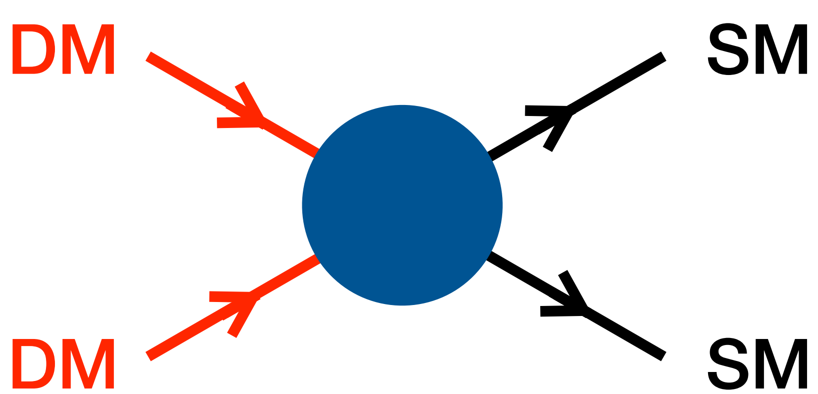
something to do with hierarchy problem?

Direct Detection:



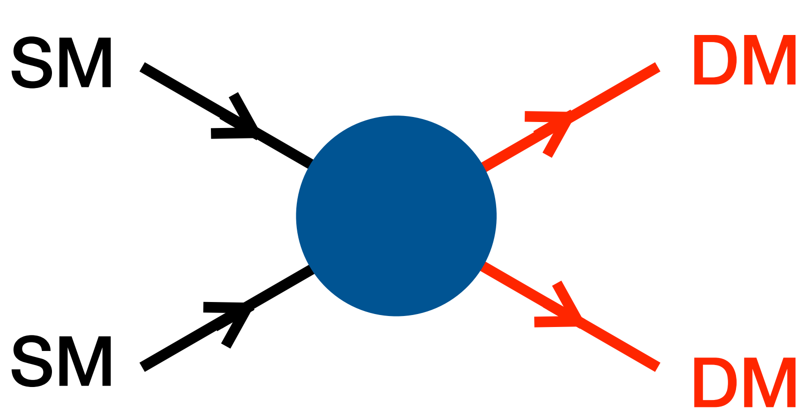


Indirect Detection:



No DM signature is found anywhere.

Collider (LHC):



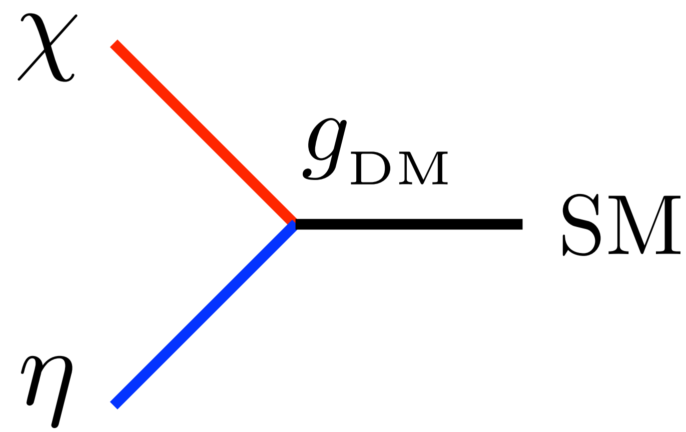
Why?

Co-annihilation

χ : Dark Matter (DM): → **singlet**

η : Co-Annihilation Partner (CAP): → **coloured or weakly charged**

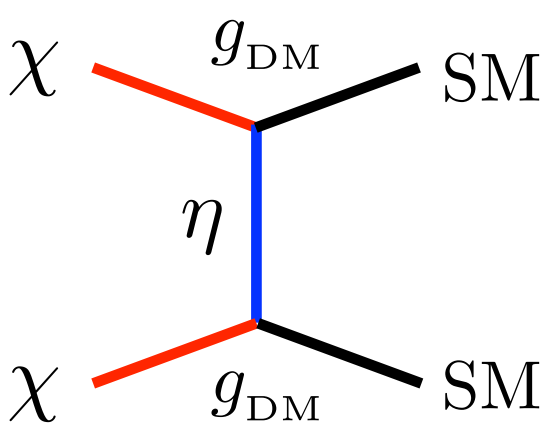
$$\mathcal{L} \supset g_{\rm DM} \cdot \chi\, \eta\, ({\rm SM})$$



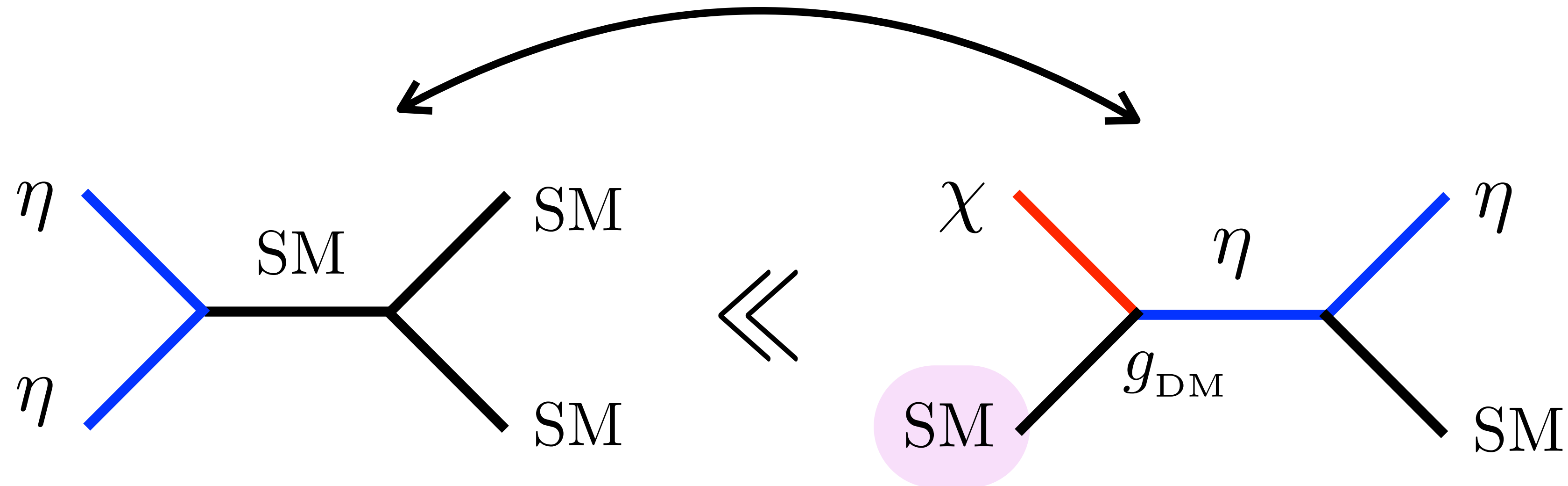
$$\mathbb{Z}_2 \begin{cases} \eta \to -\eta \\ \chi \to -\chi \end{cases}$$

For small g_{DM}, $\Delta m = m_\eta - m_\chi$

These two processes are enough to keep χ in the thermal bath



$\ll$



gauge interaction (unsuppressed)

not Boltzmann suppressed

$$\sigma_{\text{eff}}\, v = \frac{1}{(\text{g}_\chi + \bar{\text{g}}_\eta)^2} \Big[\text{g}_\chi^2 \cdot \sigma(\chi\,\chi \to \tau^+\tau^-) + \text{g}_\chi \bar{\text{g}}_\eta \cdot \sigma(\chi\,\eta \to SM \text{ particles}) + \bar{\text{g}}_\eta^2 \cdot \sigma(\eta\,\eta \to SM \text{ particles}) \Big]\, v$$

$$T_* \sim \frac{m_\chi}{25}$$

$$\bar{\text{g}}_\eta = \text{g}_\eta \left(\frac{m_\eta}{m_\chi}\right)^{3/2} \exp\left(-\frac{\Delta m}{T}\right)$$

Boltzmann factor of η:
We want this to be order 1

$$\frac{\Delta m}{m_\chi} \ll \frac{1}{25}$$

$$\text{g}_\chi \sim \text{g}_\eta \sim \mathcal{O}(1)$$

mass degeneracy is required

Experimental Signatures

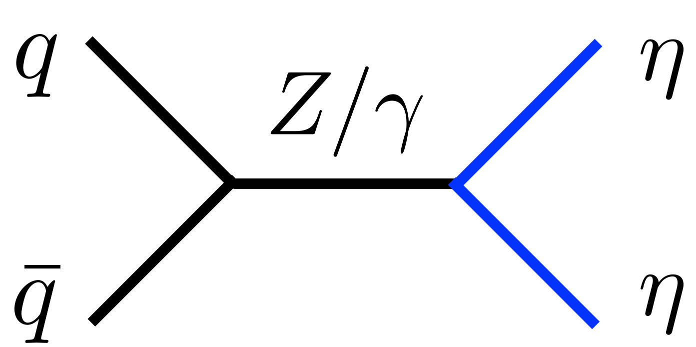
$$\mathcal{L} \supset g_{\rm DM} \cdot \chi\, \eta\, ({\rm SM})$$

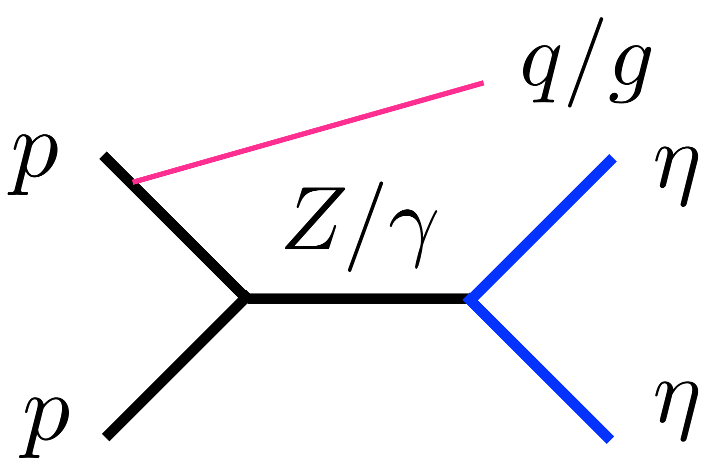
- For small $g_{\rm DM}$, the interaction between DM and SM becomes very weak.

- The sensitivities for direct and indirect detections are very low.

- The production rate for direct DM production at the LHC is also very small.

- Since CAP is charged under the SM gauge group, the production rate for CAP is unsuppressed at the LHC.

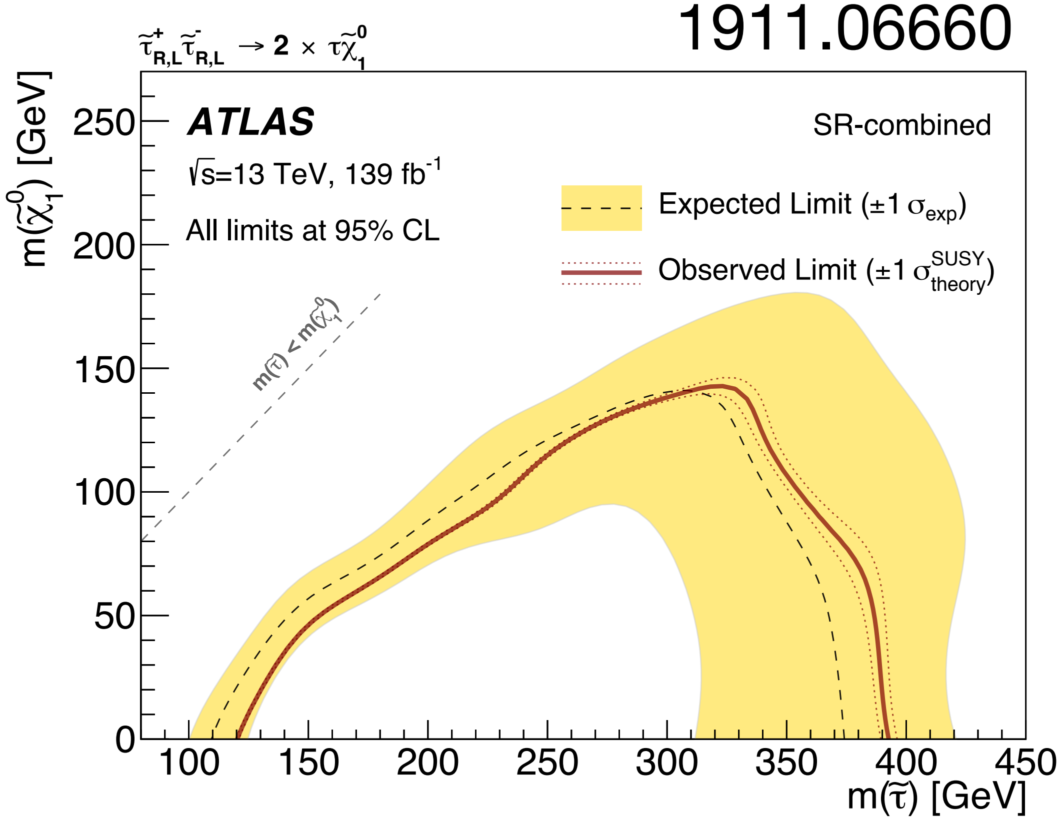




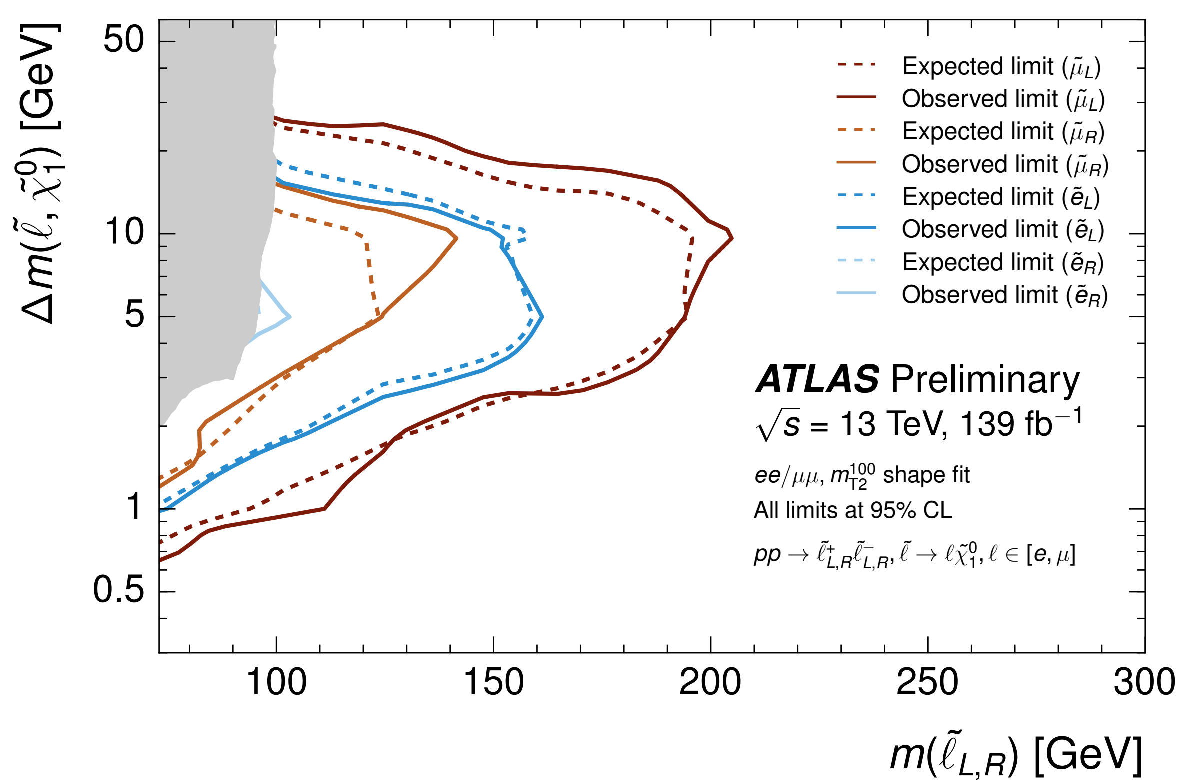
Collider Signature

- Once CAP is produced, it will decay into DM + SM with $\mathcal{L} \supset g_{\rm DM} \cdot \chi\, \eta\, ({\rm SM})$
- Since co-annihilation requires small mass difference ($\Delta m/m_\chi$ << 4%), the SM particles from the decay is very soft.
- In this case, the LHC search relies on the mono-jet channel and sensitivity is very weak in general.

1911.06660



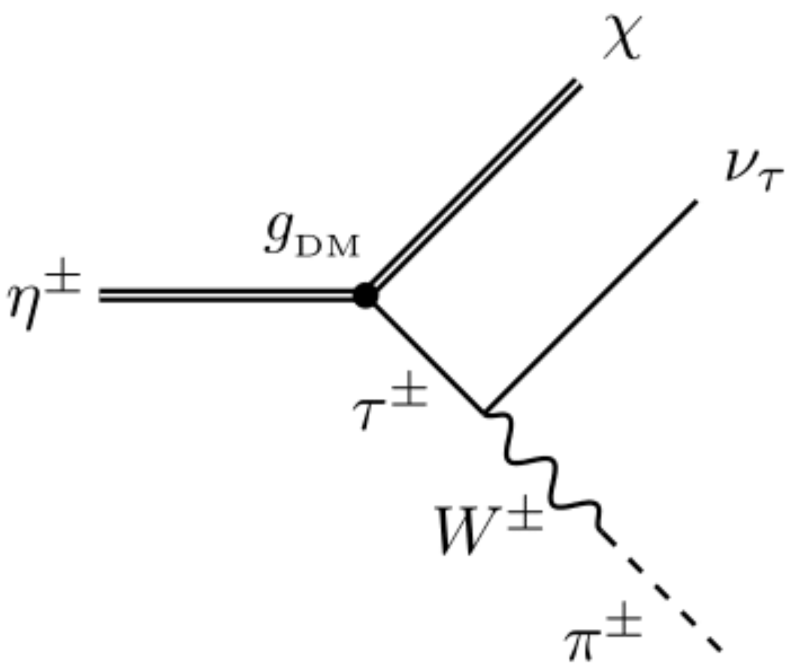
ATLAS-CONF-2019-014



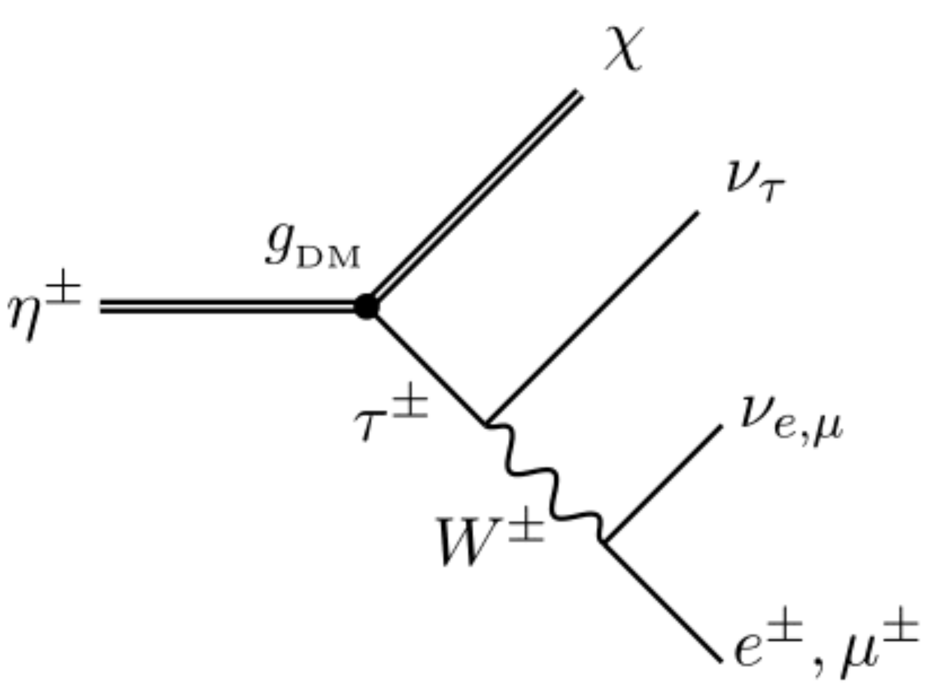
- If DM is exclusively coupled to the **tau-lepton** and **$\Delta m < m_\tau$**, the decay is further suppressed and CAP becomes **long-lived**.

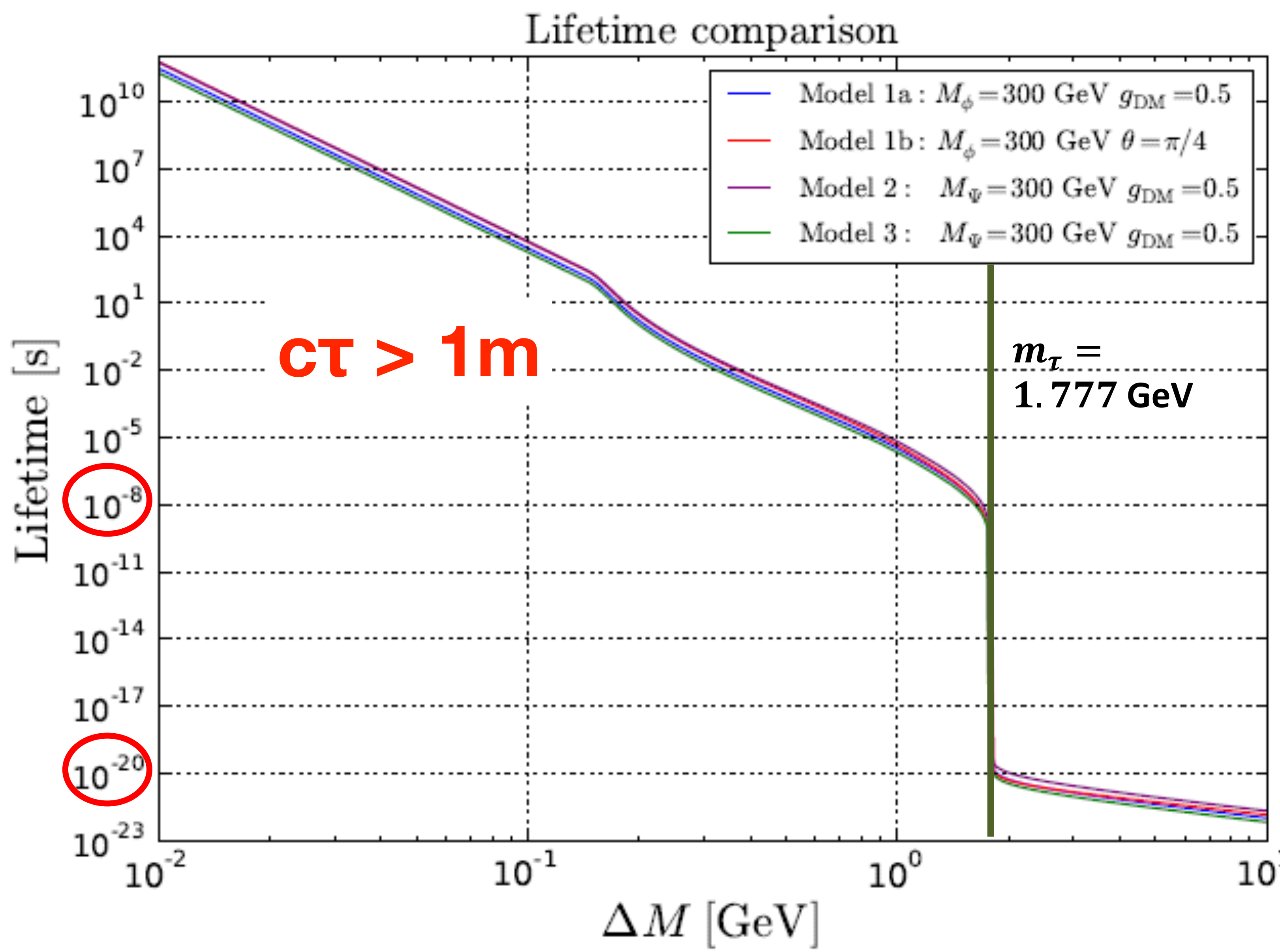
Lifetime in tau-philic models

$$\mathcal{L} \supset g_{\mathrm{DM}} \cdot \chi\, \eta\, \tau$$



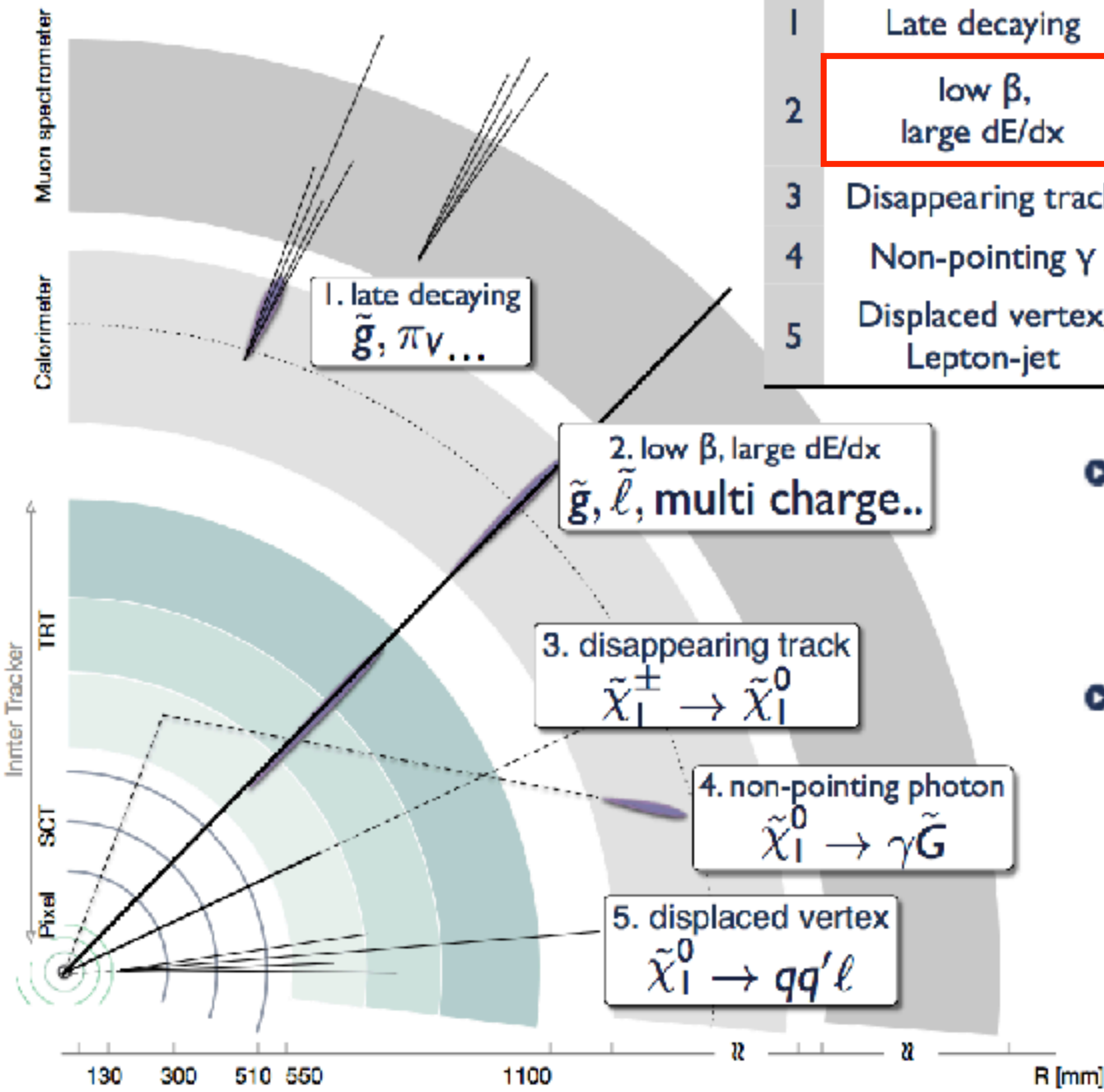
Also ρ and a_1 mesons





Long-Lived Signatures

	Signature	Scenario	decay-length sensitivity
1	Late decaying	split SUSY, Hidden Valley	—
2	low β, large dE/dx	GMSB, Split-SUSY, Stealth SUSY, Multi-charged	>1000mm
3	Disappearing track	AMSB (wino-LSP)	O(100-1000)mm
4	Non-pointing γ	GMSB	O(100-1000)mm
5	Displaced vertex, Lepton-jet	RPV, GMSB, Hidden Valley	O(10-100)mm



- Comprehensive searches in ATLAS, covering almost all possible experimental signatures with innovative analysis techniques.
- Few SM background process in general, but instrumental background dominates. The searches require full understanding of
  - material effects
  - alignment
  - timing calibration
  - non-collision background

slide taken from Shinpei Yamamoto @ LHCP 2014

Simplified Models (SMS)

- A standard signature to search for dark matter at colliders is the mono-X (or multi-jets) plus missing energy.

- These searches are being exploited and interpreted in terms of simplified dark matter models with mediators.

Dark Matter + mediator	+	Standard Model particles

- [A growing number of the analyses are also dedicated to the direct search of the mediators which can decay back to the SM.]

- We consider instead an alternative DM scenario characterised by simplified models without mediators.

Dark Matter + co-annihilation partner	+	Standard Model particles

- Our dark sector includes a co-annihilation partner (CAP) particle instead of a mediator (in addition to the cosmologically stable DM).

SMS for long-lived coannihilationing DM with tau

Model-1a			
Component	Field	Charge	Interaction
DM	Majorana fermion (χ)	$Y = 0$	$\phi^*(\chi\tau_R) + \text{h.c.}$
CAP	Complex scalar (ϕ)	$Y = -1$	

fermonic DM, scalar CAP

e.g. neutralino-stau (SUSY)

Model-2			
Component	Field	Charge	Interaction
DM	Real scalar (S)	$Y = 0$	$S(\overline{\Psi}P_R\tau) + \text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y = -1$	

scalar DM, fermonic CAP

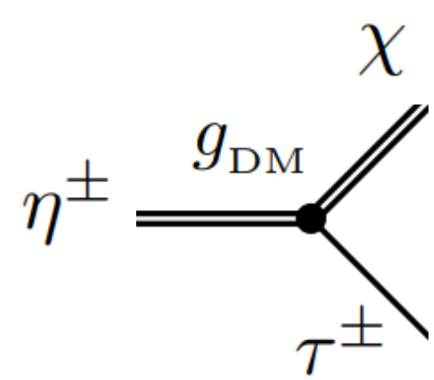
e.g. dilaton, KK-tau (extra-dim)

Model-3			
Component	Field	Charge	Interaction
DM	Vector (V_μ)	$Y = 0$	$V_\mu(\overline{\Psi}\gamma^\mu P_R\tau) + \text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y = -1$	

vector DM, fermonic CAP

e.g. KK-photon, KK-tau (UED)

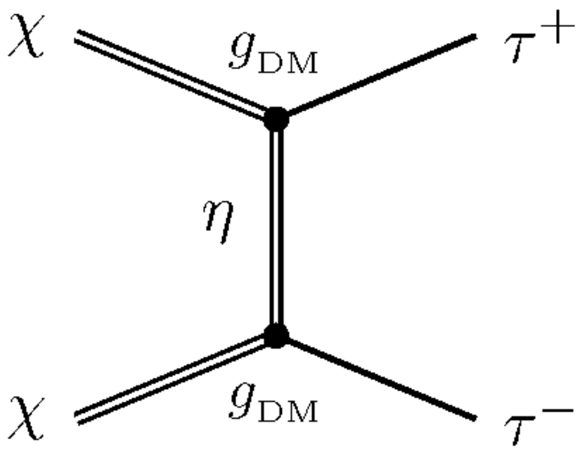
3 free parameters: $m_\chi,\ \Delta m,\ g_{\text{DM}}$



$\chi = \{\chi,\ S,\ V_\mu\}$

$\eta = \{\phi,\ \Psi\}$

DM annihilation



$$(\sigma v)^{s\text{ wave}}_{\rm ann} \sim \frac{g^4_{\rm DM}}{32\pi}\frac{m^2_\tau}{m^4_\chi}$$

In model-1 and -2, the DM is a Majorana fermion and a real scalar, respectively.

For those dark matters, the initial state is s-wave (spin-0) (Pauli blocking for the fermion case), therefore the s-wave part of this annihilation cross-section is chiral suppressed by the tau-lepton mass.

→ **Coannihilation is very important**

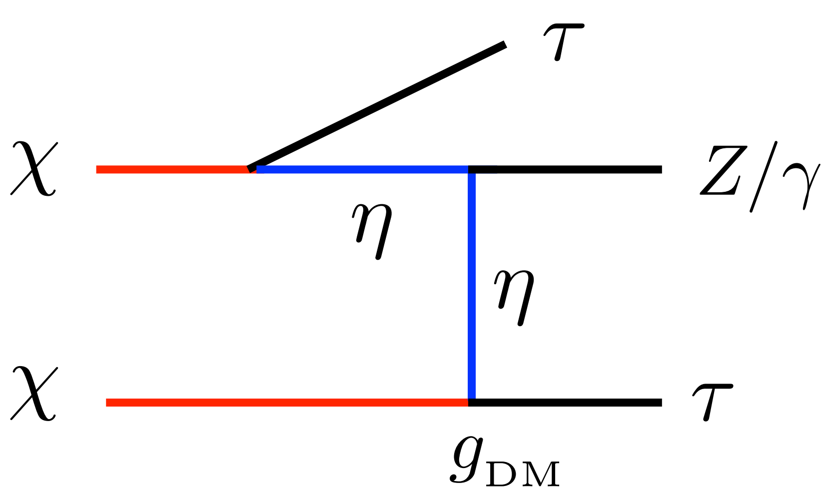
Other than s-wave:

$\sigma v \propto v^2$	$\sigma v \propto v^4$
p-wave suppressed for Majorana DM	d-wave suppressed for scalar DM

[v/c << 1 at the present Universe]

→ **indirect detection not promising(?)**

Indirect Detection

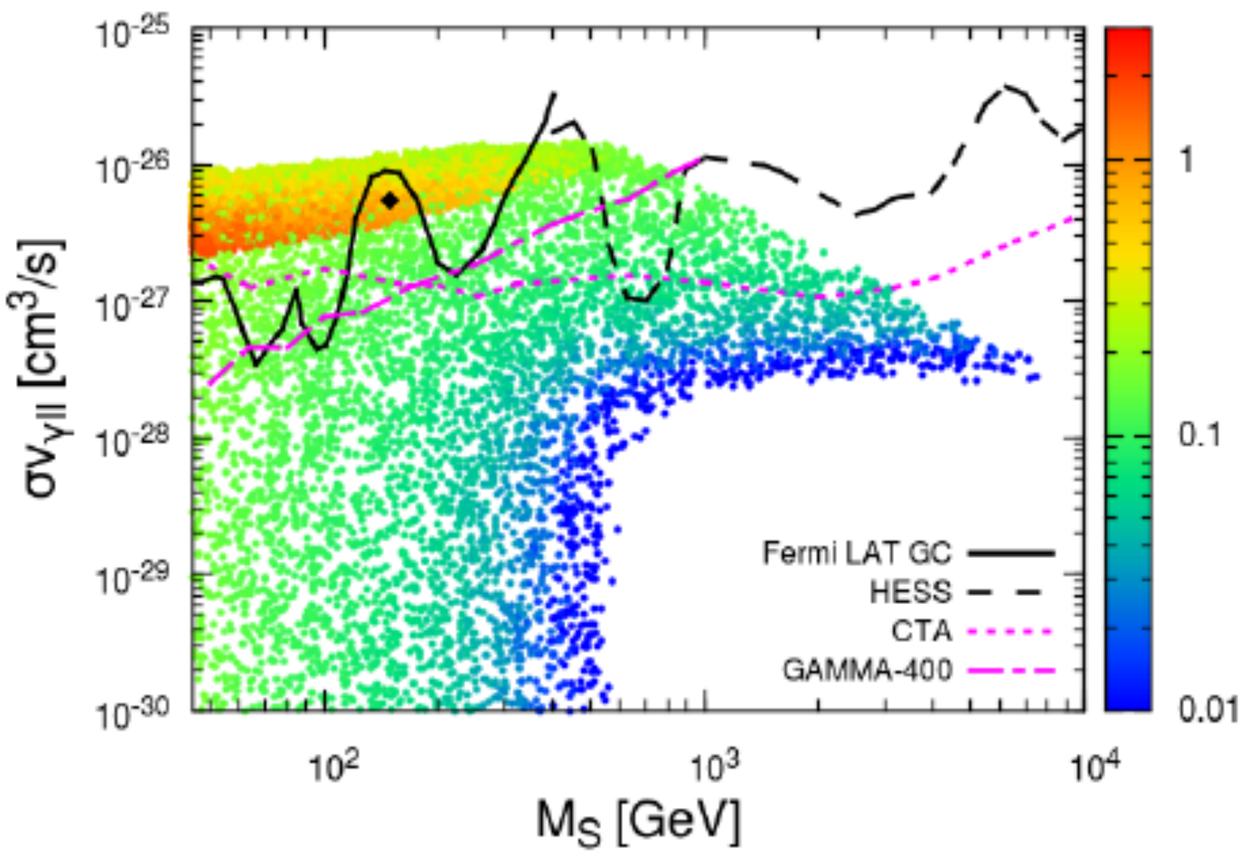


The DM can be converted into a slightly off-shell CAP by emitting a soft tau, the CAP then co-annihilates with another DM into a pair of SM particles.

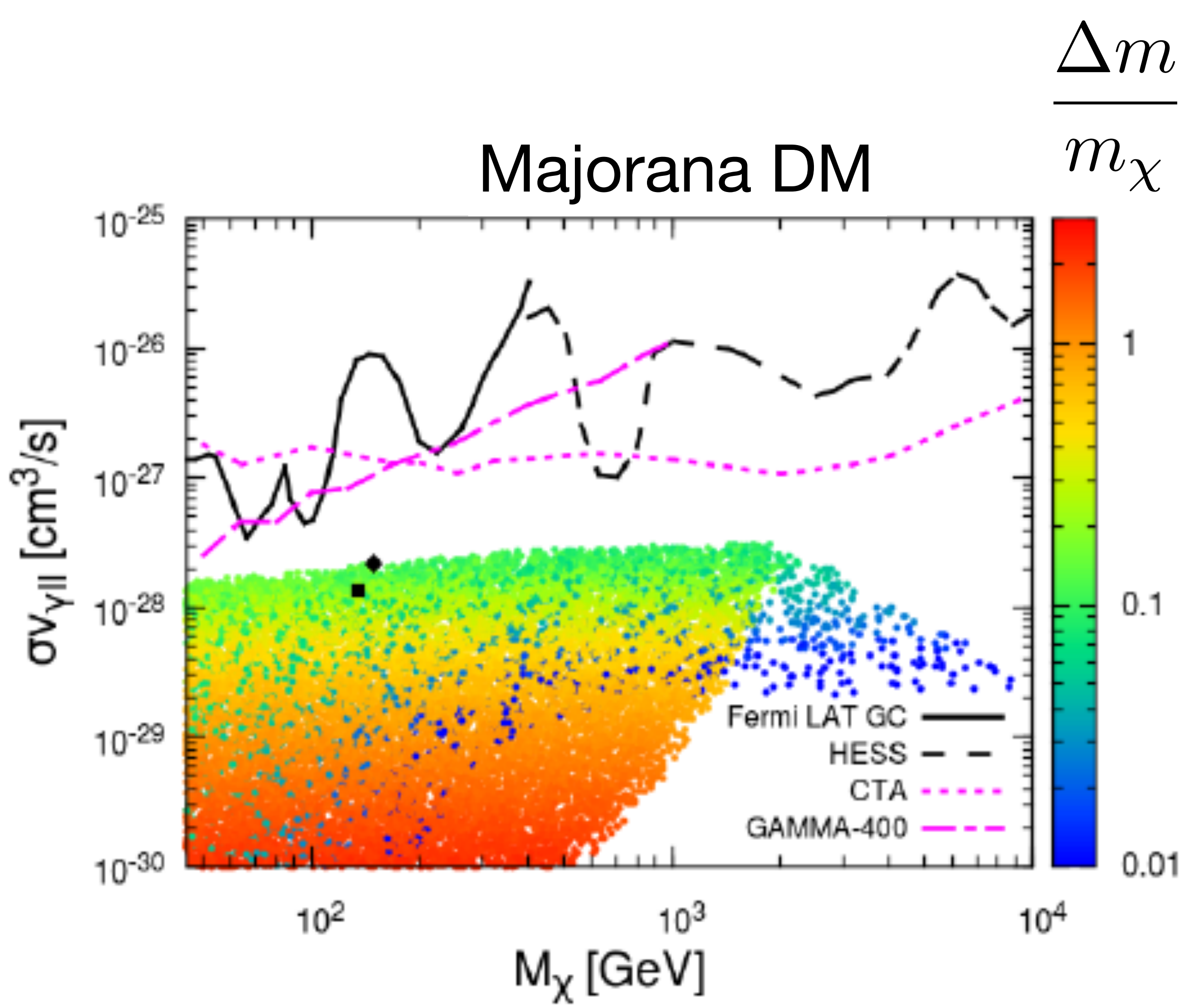
This channel is not chiral suppressed and turns out to be the dominant annihilation channel.

[Giacchino, Lopez-Honorez, Tytgat '13]

scalar DM

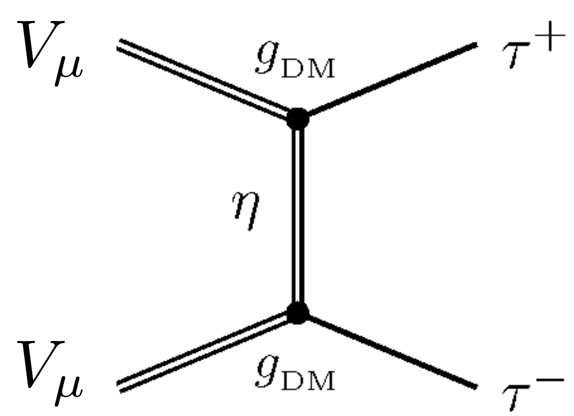


Majorana DM



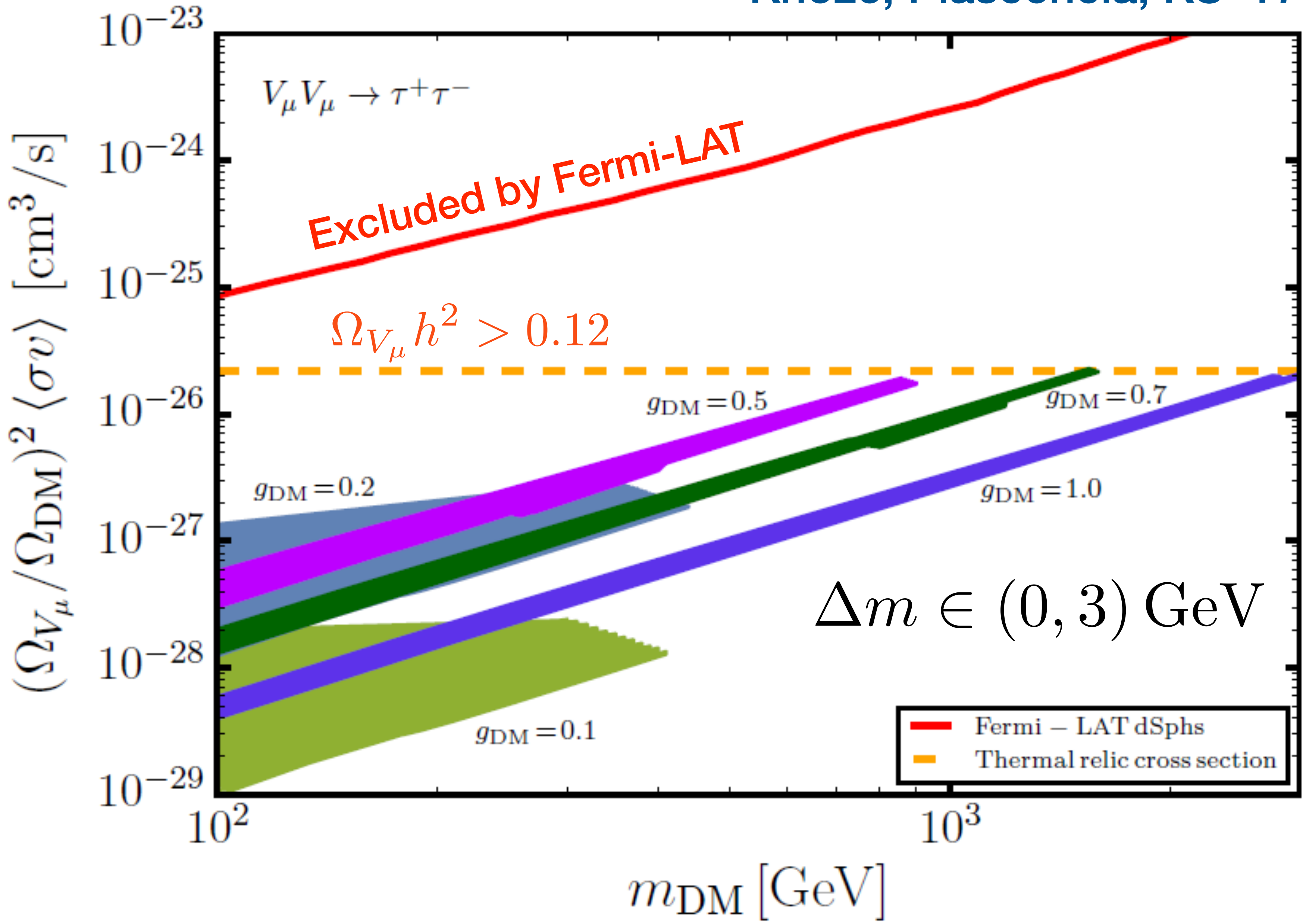
Blue points correspond to the parameter region of interest; $\Delta m/m_\chi$ << 4%.

Indirect Detection



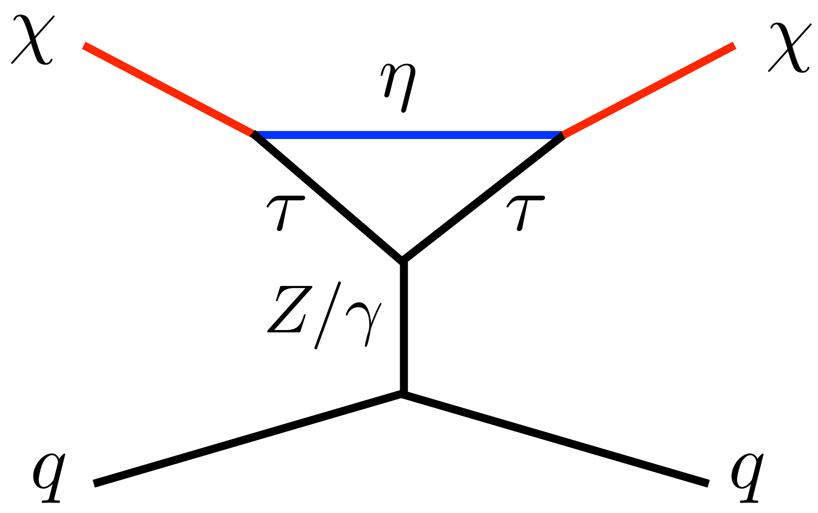
Vector DM annihilation is not chiral suppressed.

Khoze, Plascencia, KS ‘17



Direct Detection

- The anapole operator for direct detection is generated at 1-loop.



$$\mathcal{A}\,\bar{\chi}\gamma_\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$$

$$m_{\rm DM} \simeq 500\,{\rm GeV} \;\; {\rm and} \;\; \Delta M/m_\tau < 1,$$

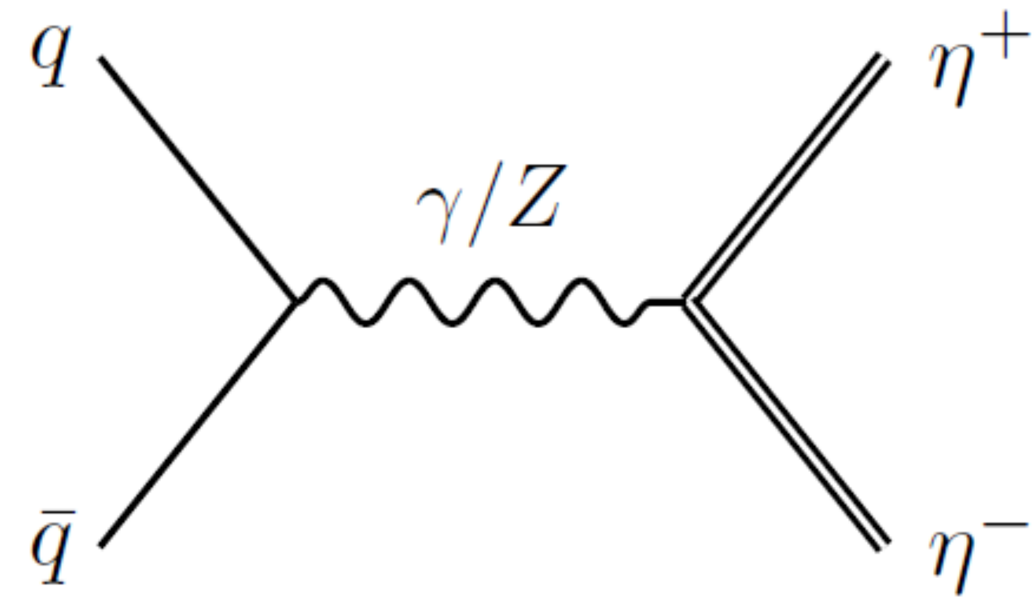
$$\mathcal{A}/g_{\rm DM}^2 \sim 8\cdot 10^{-7}\,[\mu_N\cdot{\rm fm}]$$

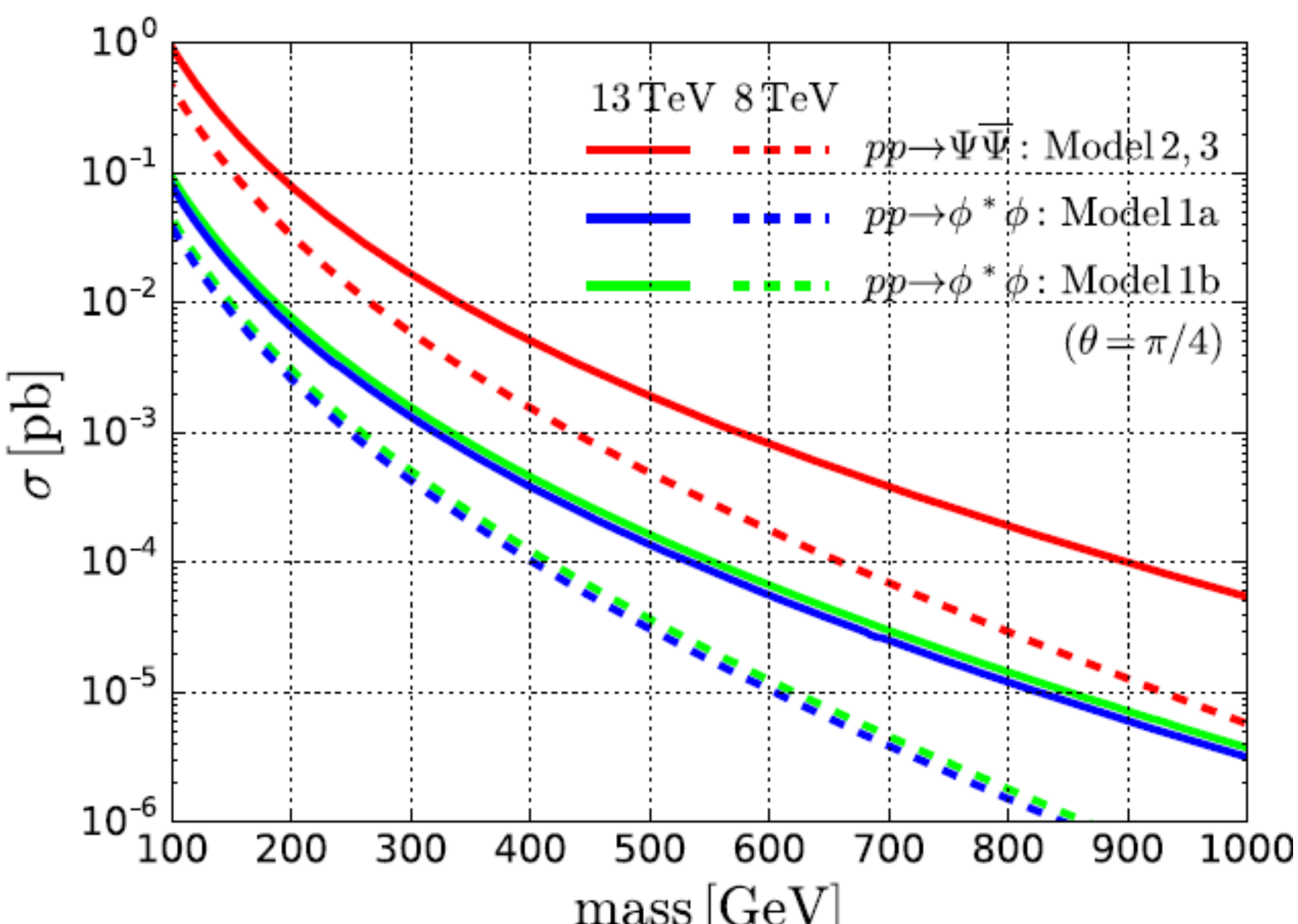
LUX $A > 2\times 10^{-5}\ [\mu_N\ \mathrm{fm}\ ]$

- The current limit is more than one order of magnitude smaller.

Direct Production at LHC

- Drell-Yann pair production of co-annihilation partner





- We study Dirac fermion and complex scalar as co-annihilation partners

Recasting HSCP analysis

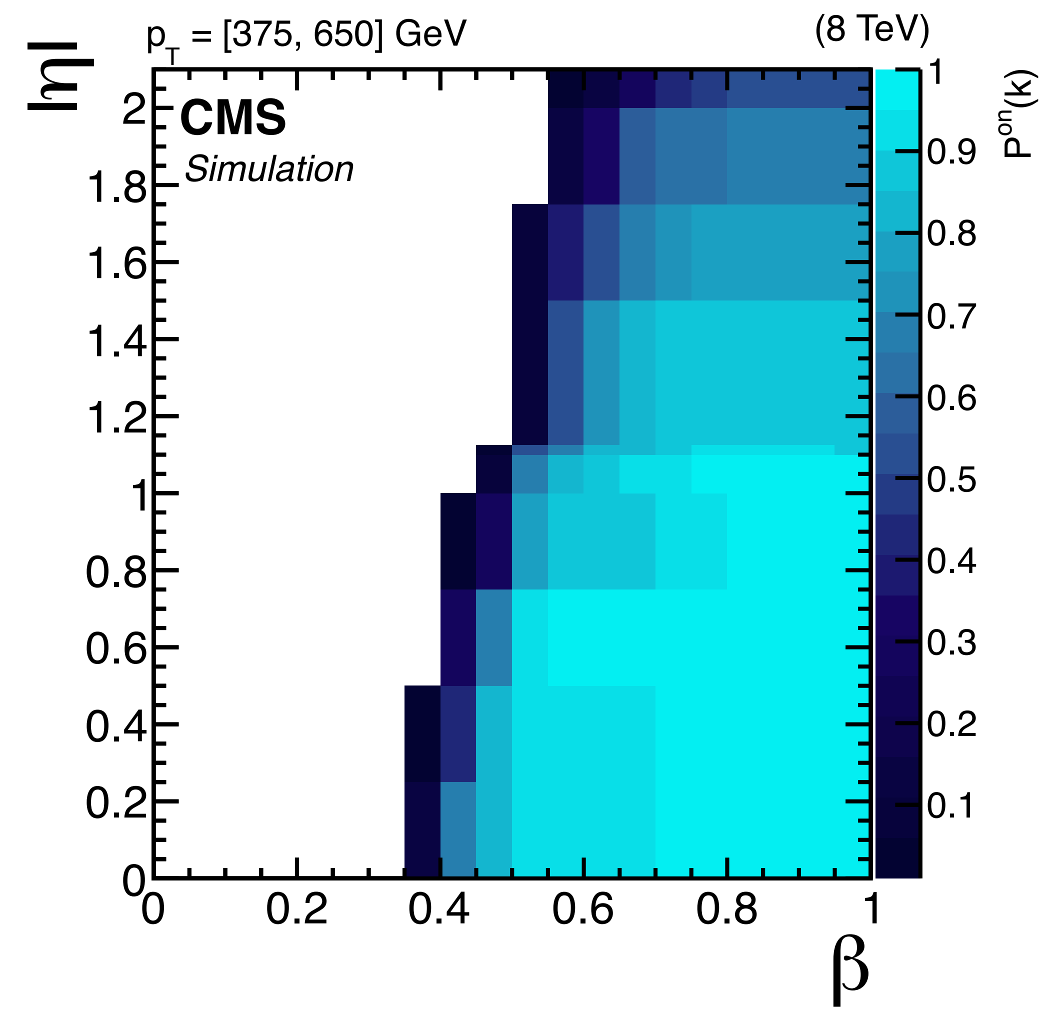
- In order to constrain the long-lived coaanihilating DM simplified models, we recast the heavy stable charged particle (HSCP) analysis by CMS (8TeV, 18.8 fb^{-1}) [1305.0491].

- We used the recipe provided by CMS [1502.02522] for recasting the HSCP analysis and used the efficiency maps provided in the paper.

[1305.0491]

	$\|Q\| < 1e$	tracker+TOF	tracker-only	$\|Q\| > 1e$
$\|\eta\|$	<2.1			
p_T (GeV/c)	>45			
d_z and d_{xy} (cm)	<0.5			
σ_{p_T}/p_T	<0.25			
Track χ^2/n_d	<5			
# Pixel hits	>1			
# Tracker hits	>7			
Frac. Valid hits	>0.8			
$\Sigma p_T^{trk}(\Delta R < 0.3)$ (GeV/c)	<50			
# dE/dx measurements	>5			
dE/dx strip shape test	yes			no
$E_{cal}(\Delta R < 0.3)/p$	<0.3			–
I_h (MeV/cm)	<2.8	>3.0		
ΔR to another track	$<\pi - 0.3$	–		

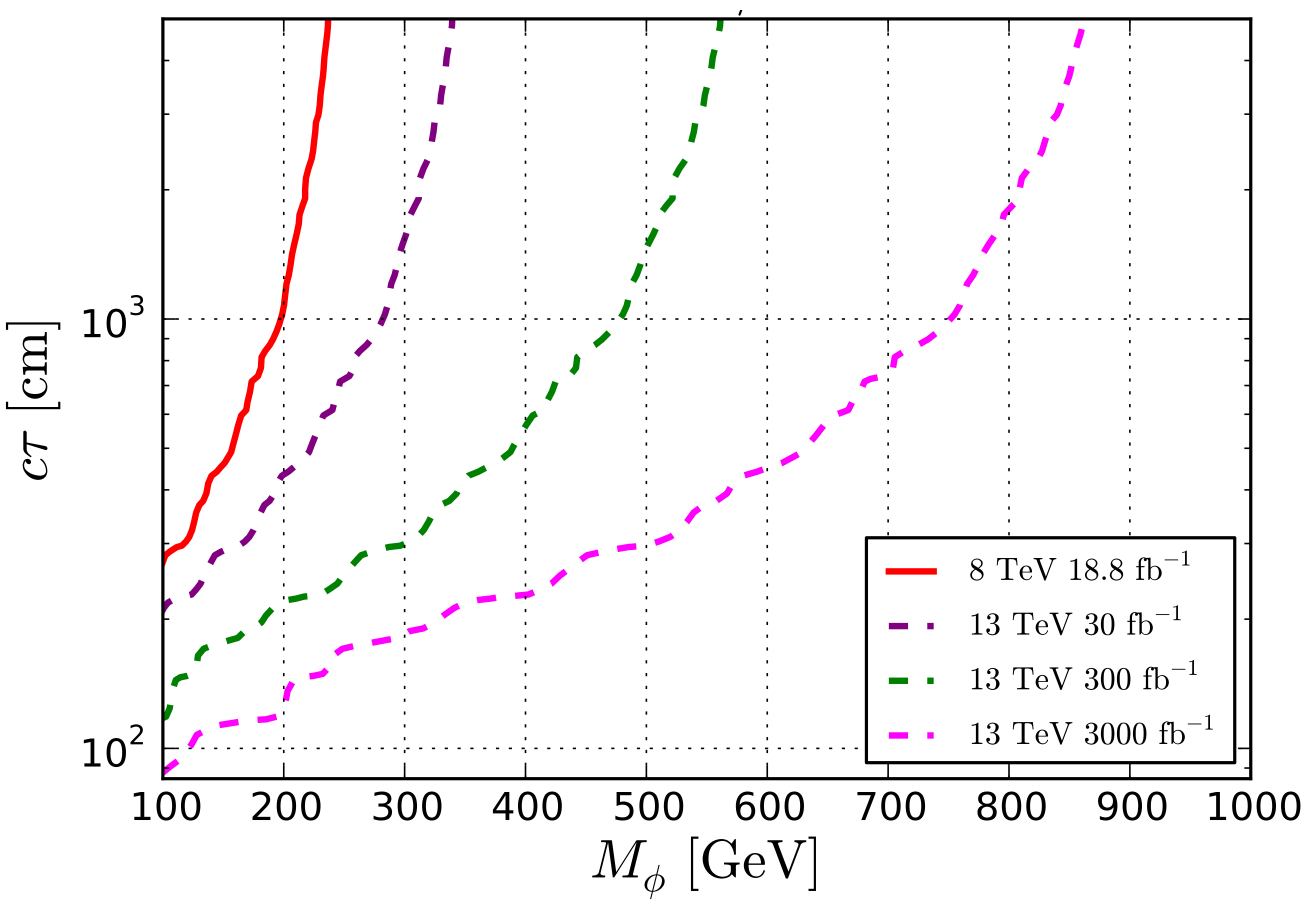
[1502.02522]



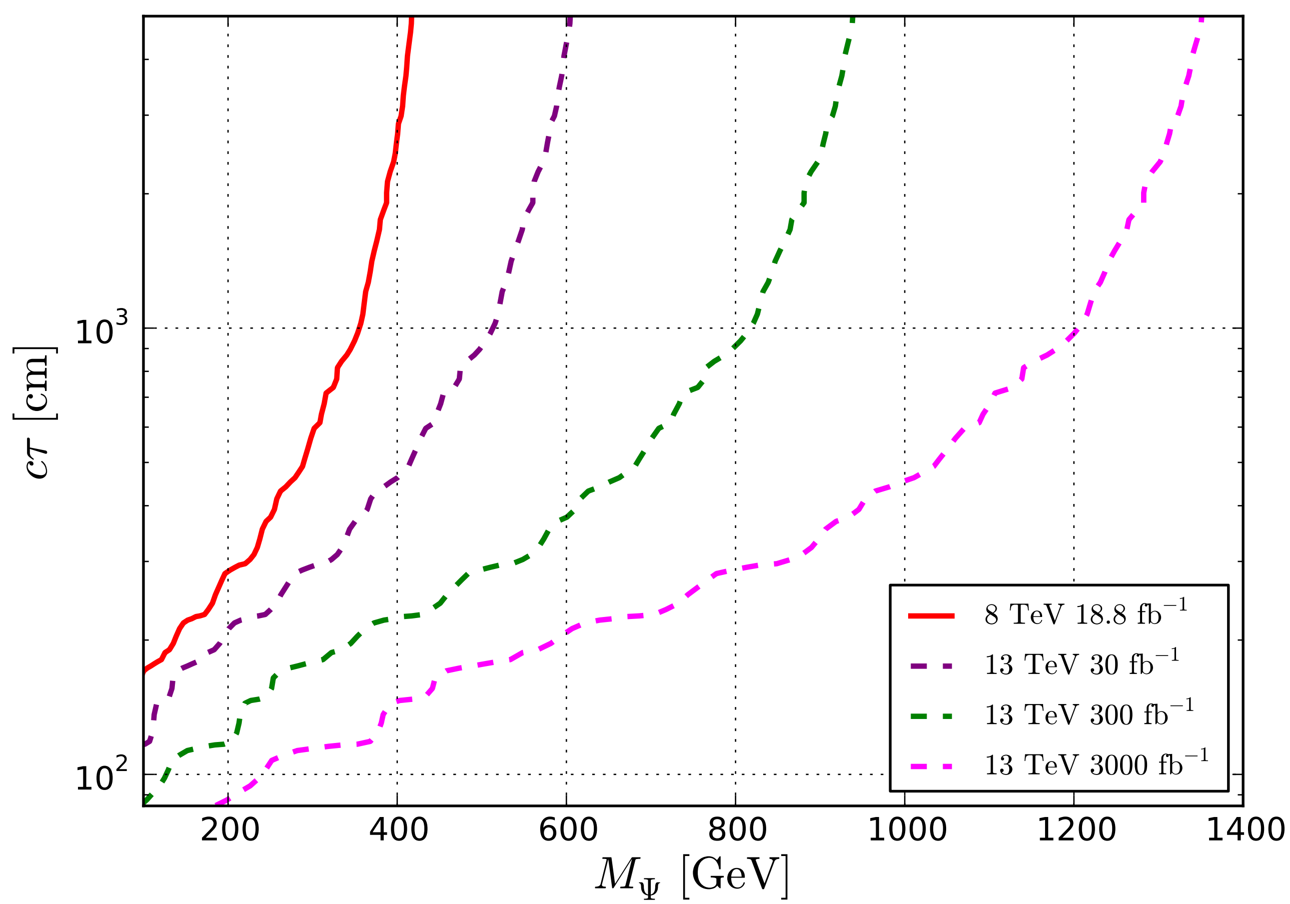
Recasting HSCP analysis

- In order to constrain the long-lived coaanihilating DM simplified models, we recast the heavy stable charged particle (HSCP) analysis by CMS (8TeV, 18.8 fb^{-1}) [1305.0491].
- We used the recipe provided by CMS [1502.02522] for recasting the HSCP analysis and used the efficiency maps provided in the paper.

Scalar CAP (Model-1)



Fermionic CAP (Model-2, 3)



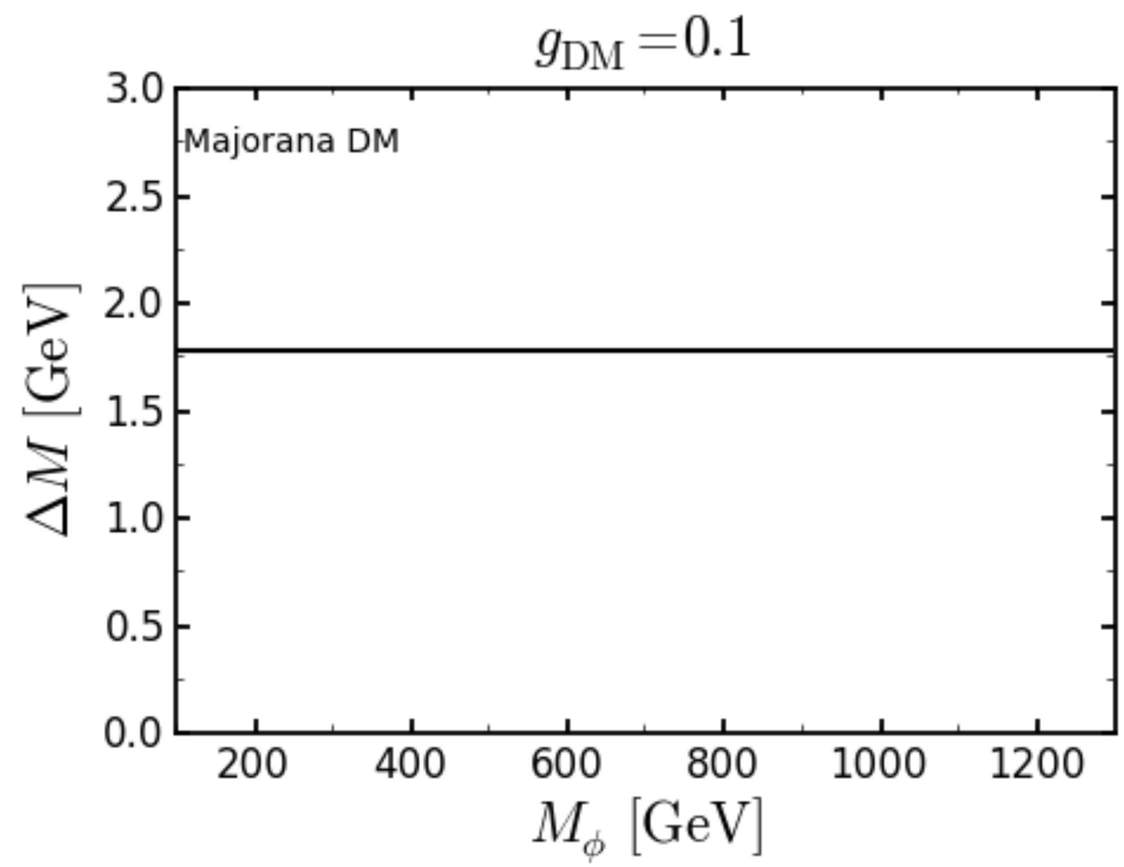
Majorana Dark Matter

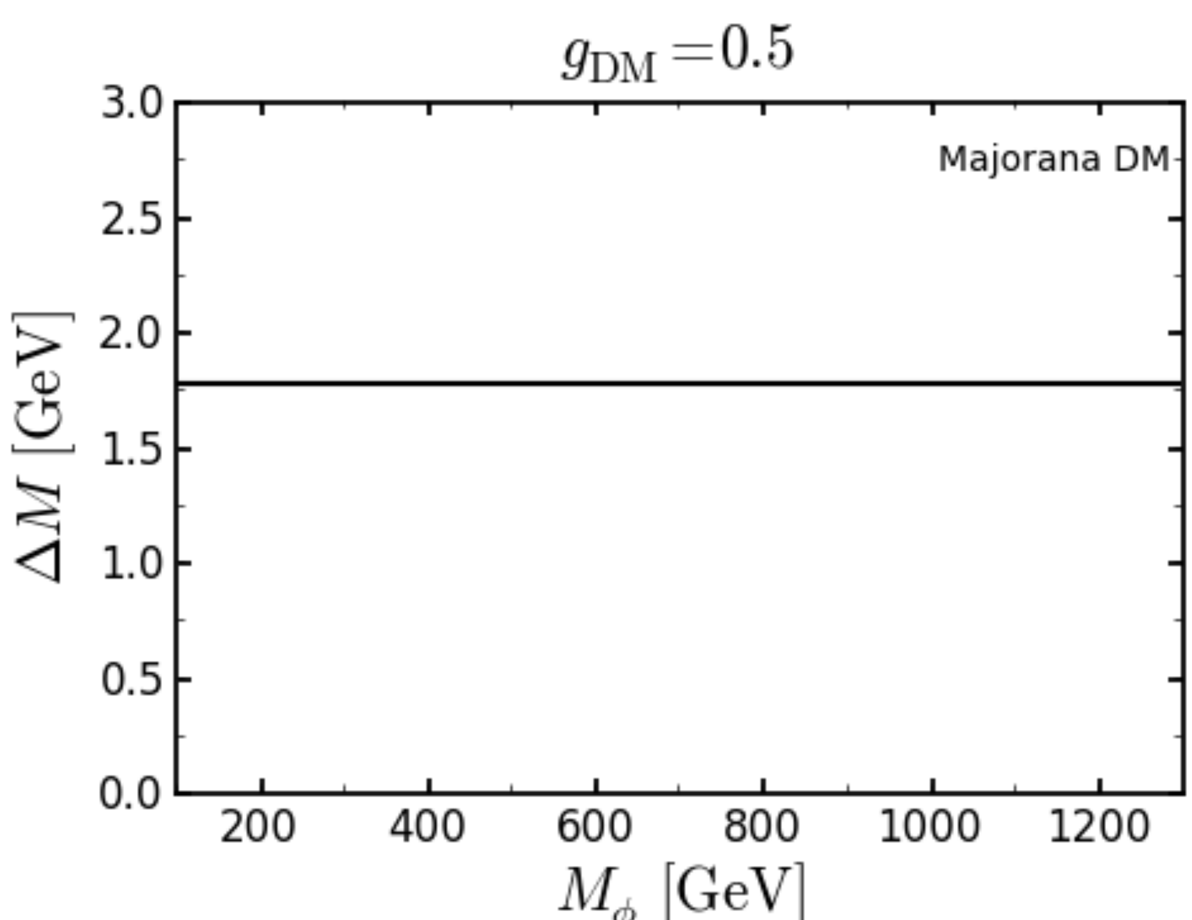
DM χ

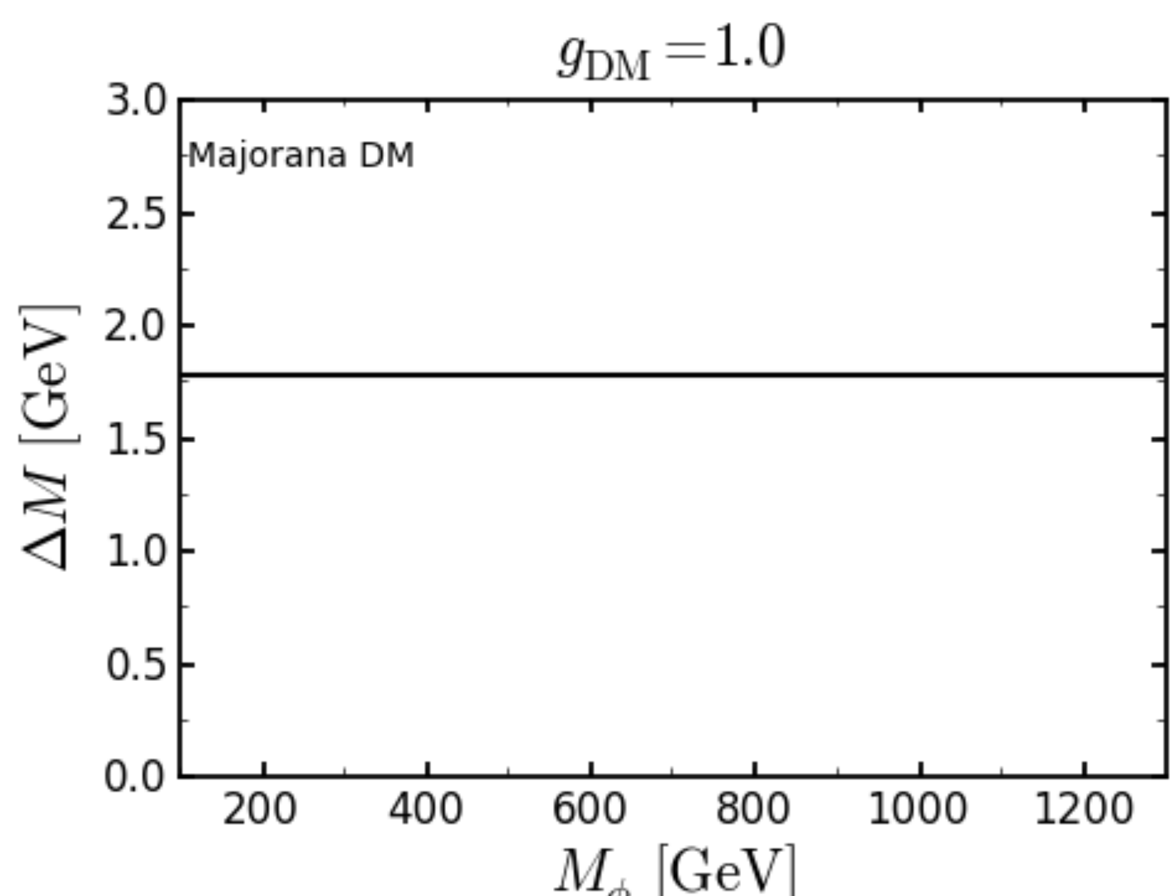
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

$$\phi^* \, (\chi \, \tau_R) \subset \mathcal{L}$$

Gauge-invariant and renormalizable, no problems of unitarity







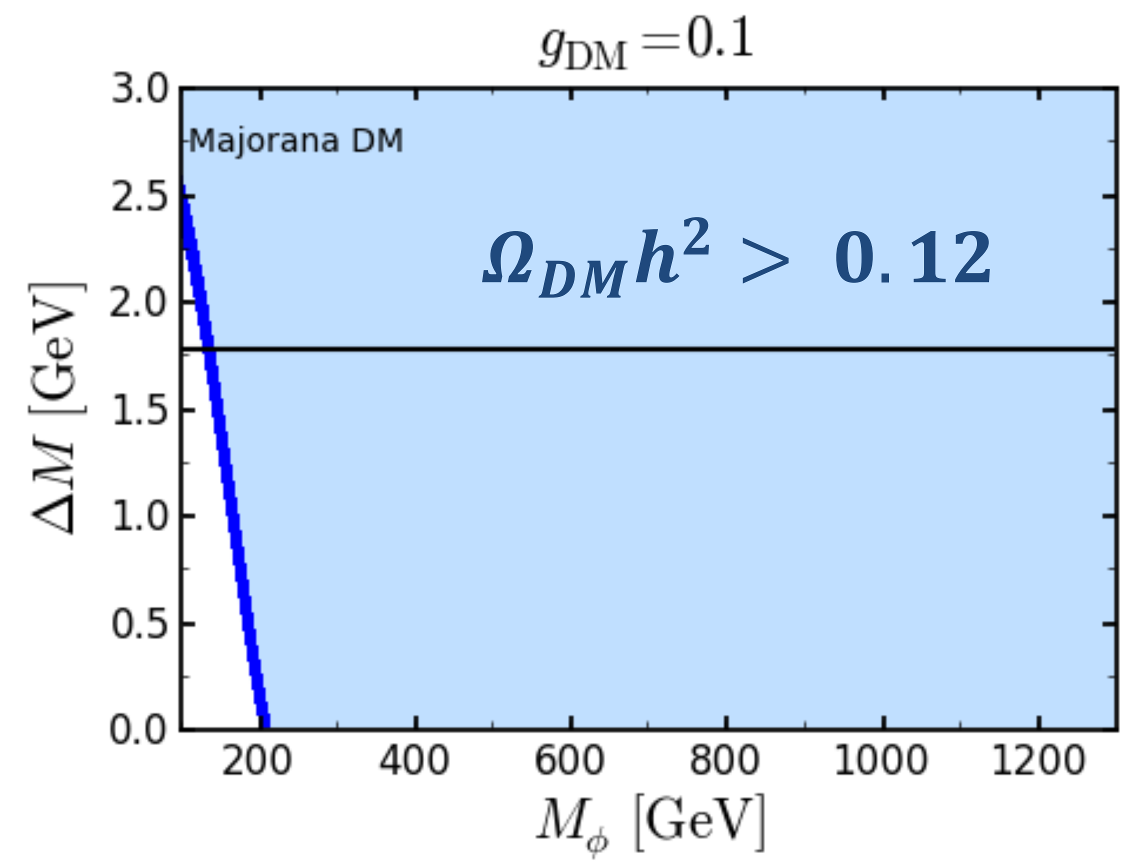
Majorana Dark Matter

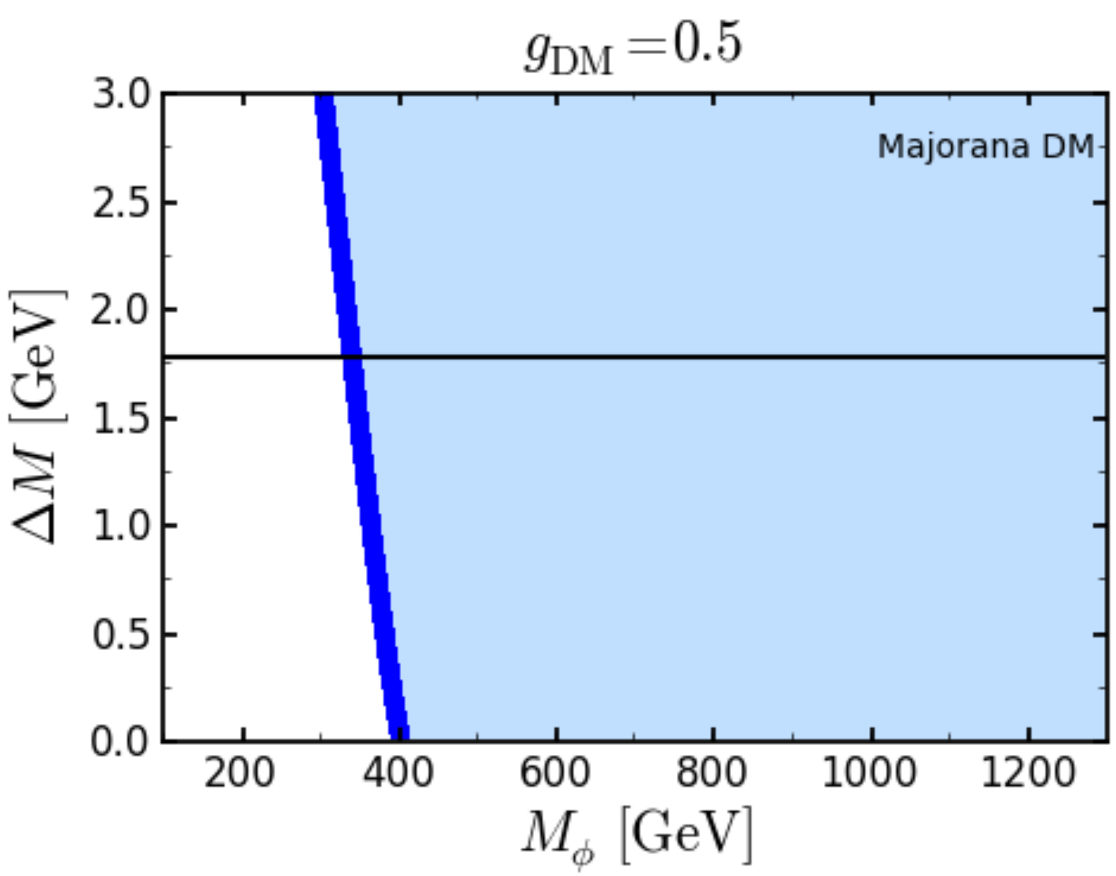
DM **CAP (Y=-1)**

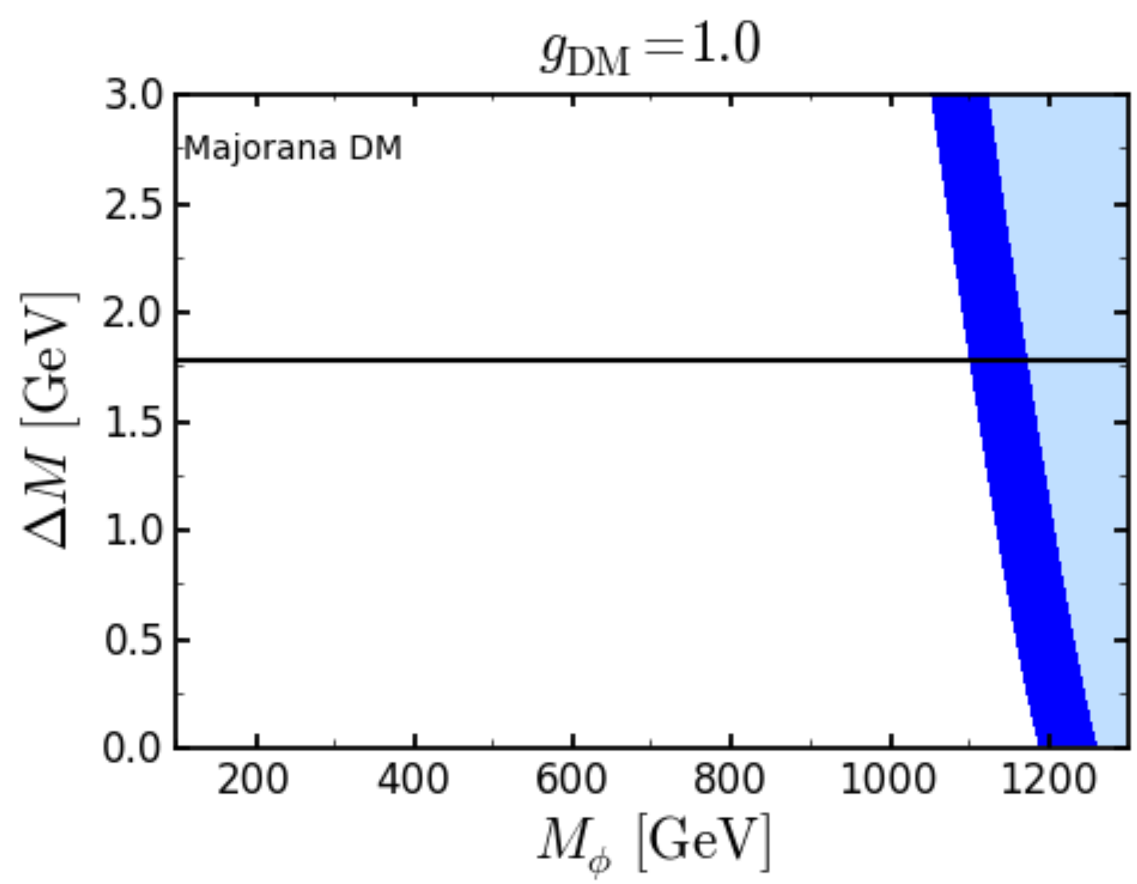
χ ϕ

$$\phi^* \left(\chi\, \tau_R\right) \subset \mathcal{L}$$

Gauge-invariant and renormalizable, no problems of unitarity





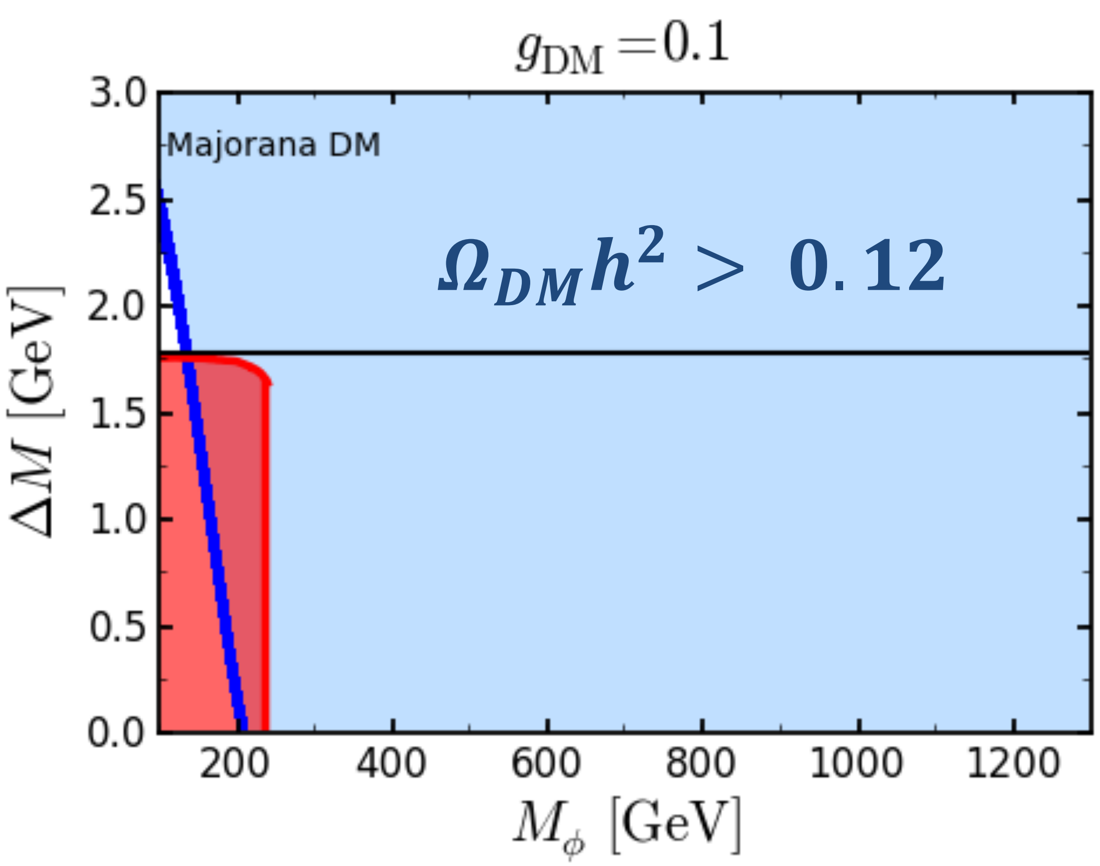


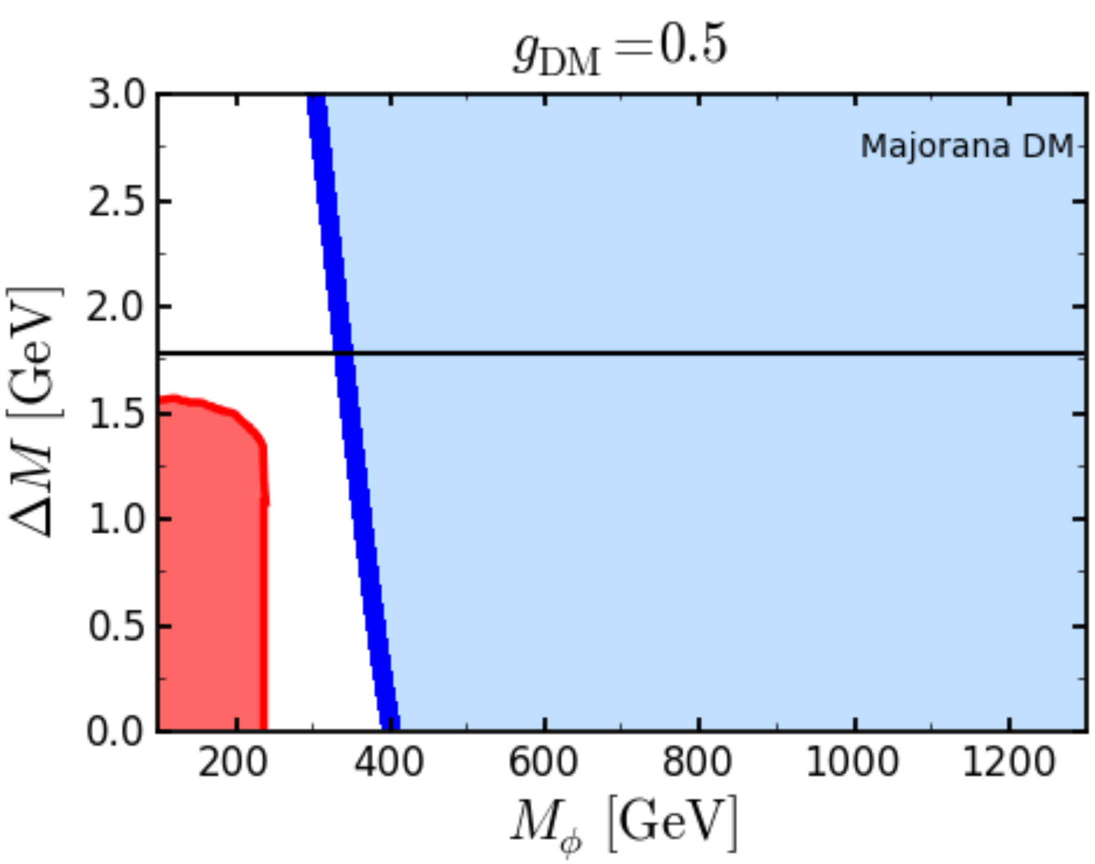
Majorana Dark Matter

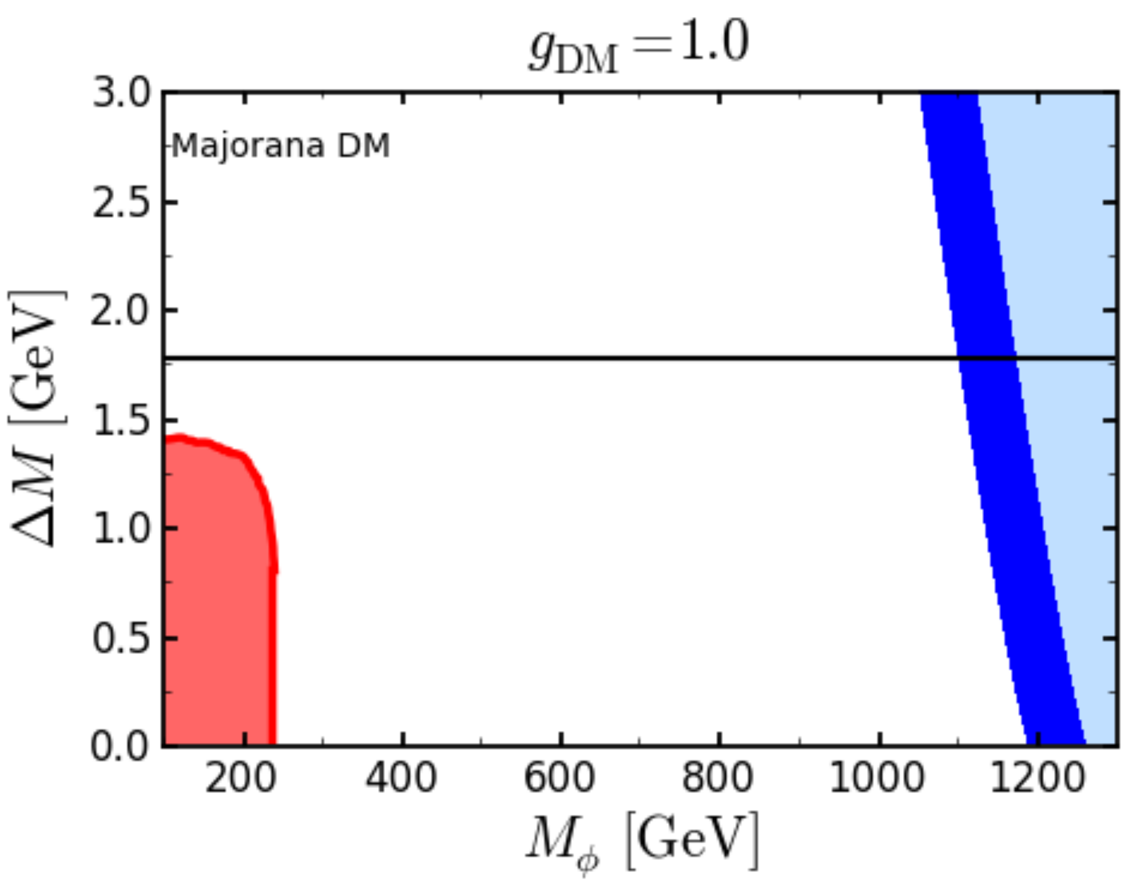
DM	CAP $(Y = 1 \;\; L_\tau = 1)$
χ	ϕ

$$\phi^* (\chi \, \tau_R) \subset \mathcal{L}$$

CMS 8 TeV 18.8 fb $^{-1}$







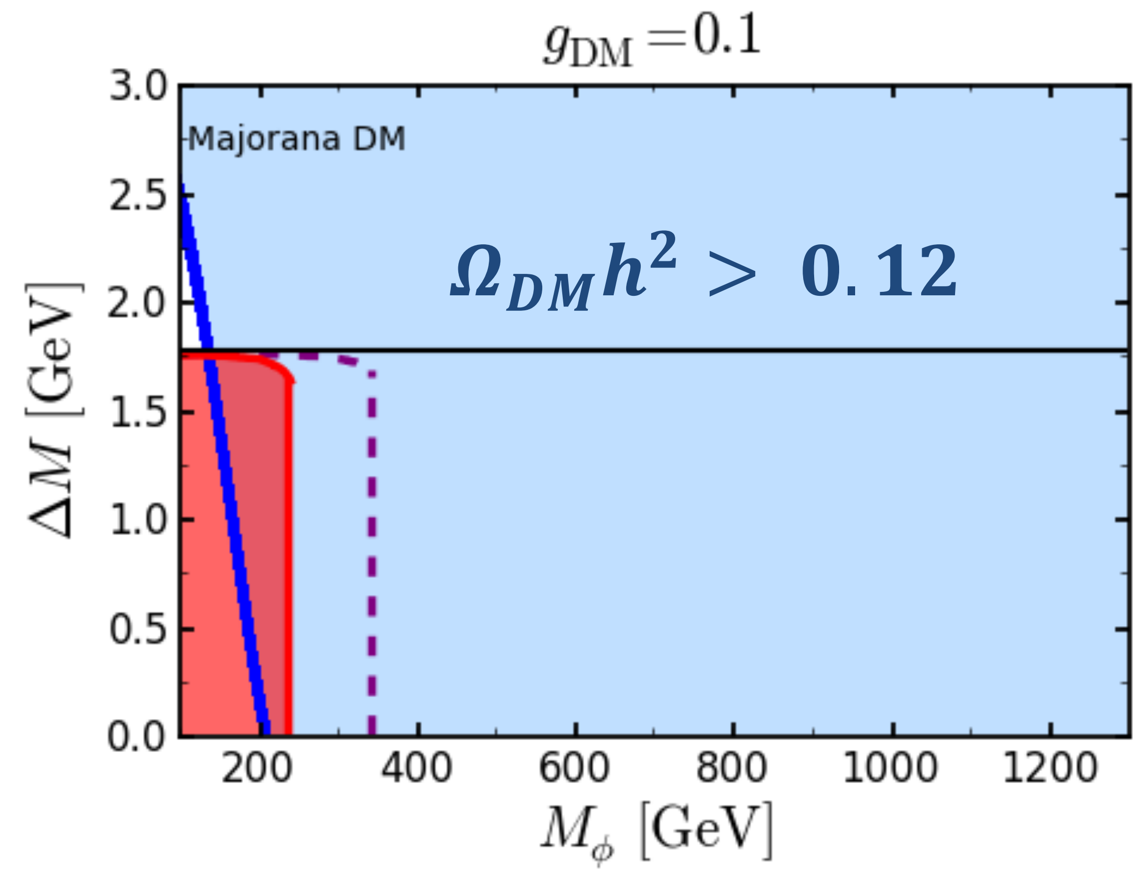
Majorana Dark Matter

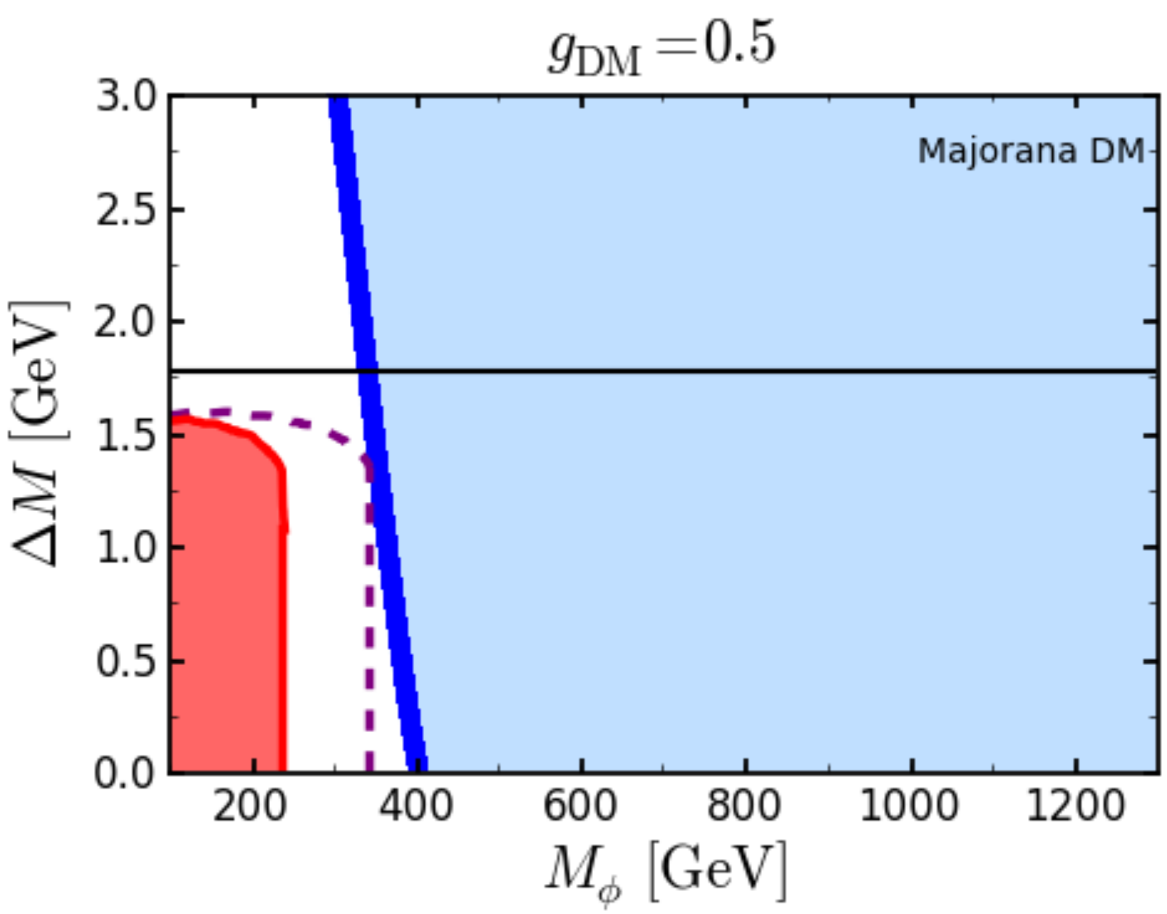
DM χ

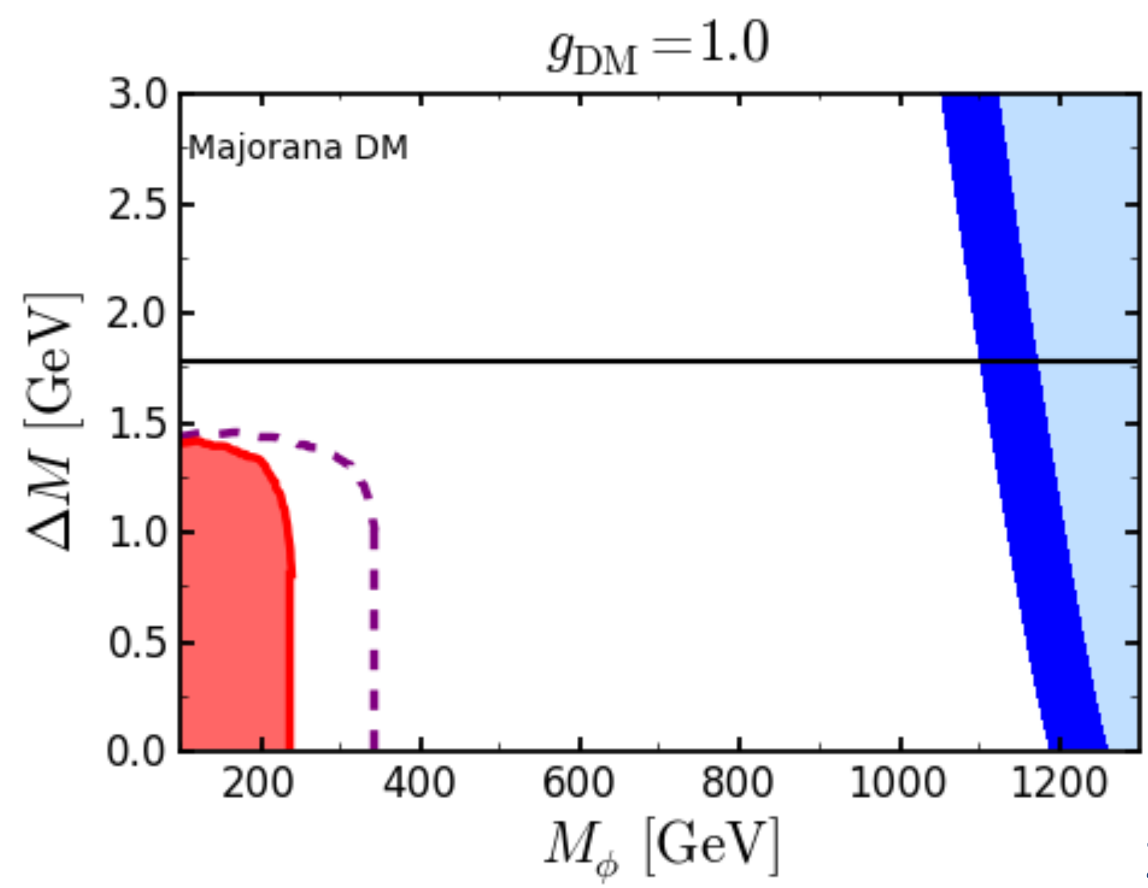
CAP $(Y = 1\ \ L_\tau = 1)$ ϕ

$$\phi^* \, (\chi\, \tau_R) \ \subset \ \mathcal{L}$$

13 TeV 30 fb $^{-1}$







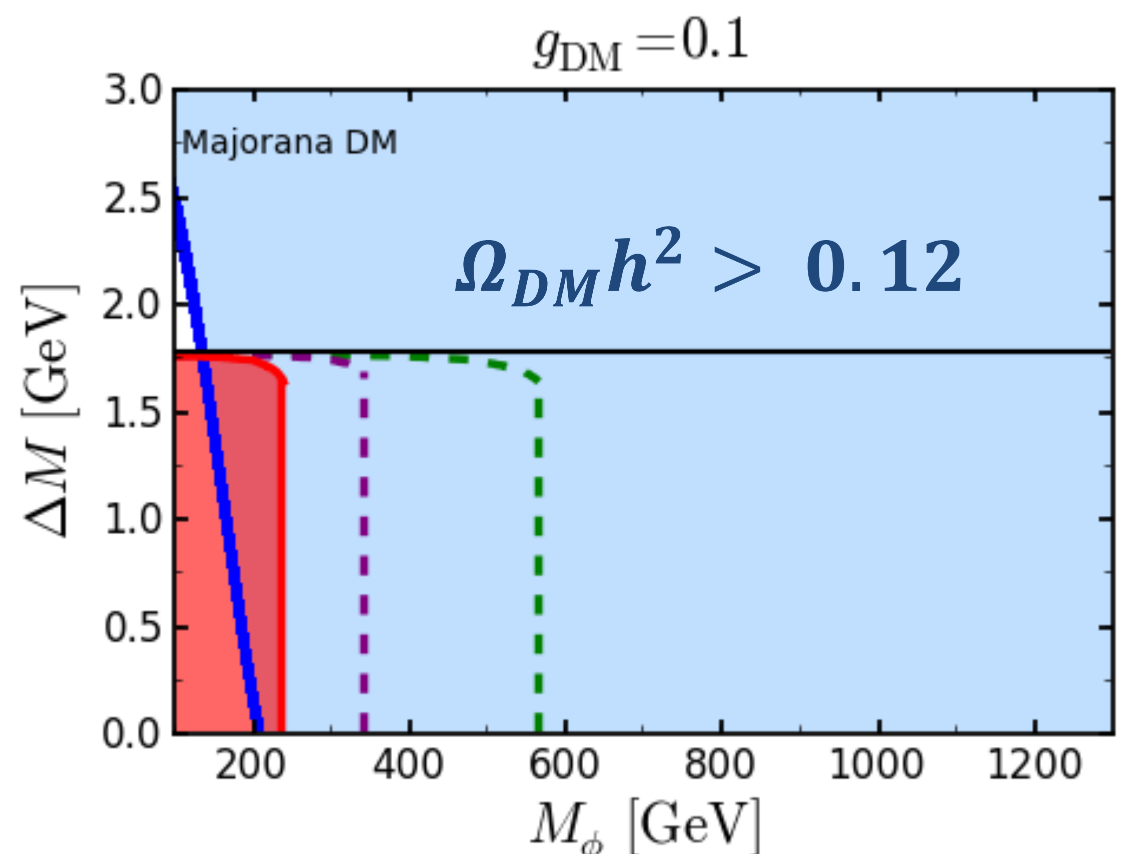
Majorana Dark Matter

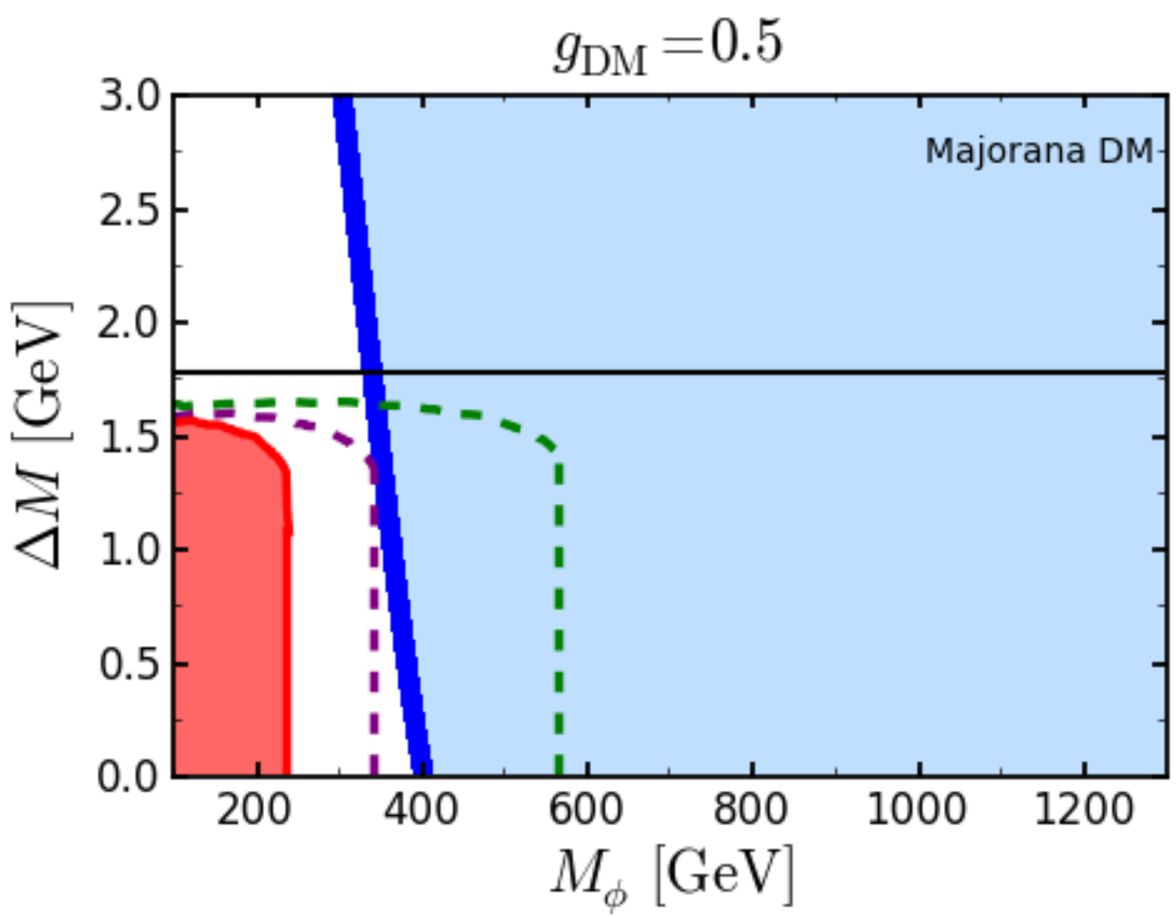
DM χ

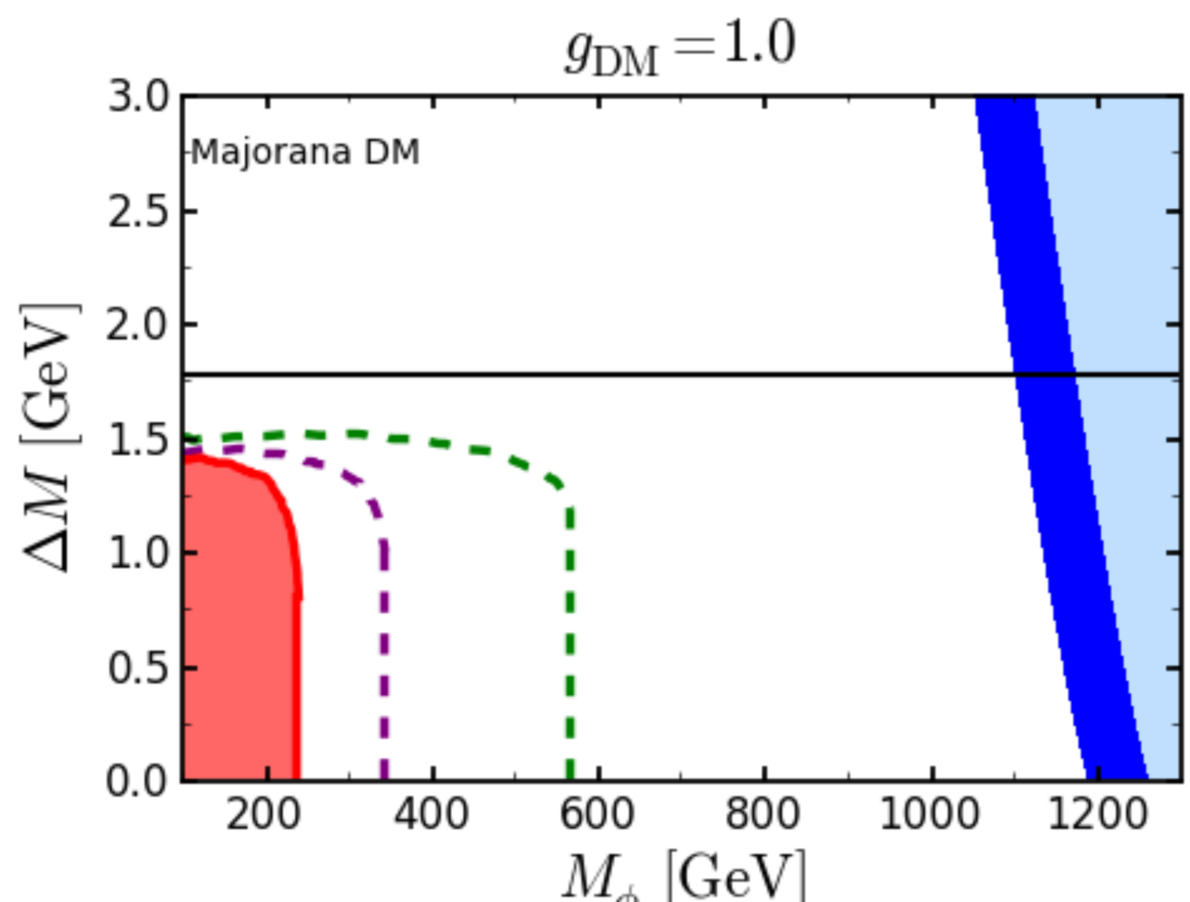
CAP $(Y = 1 \;\; L_\tau = 1)$ ϕ

$$\phi^* \, (\chi \, \tau_R) \;\subset\; \mathcal{L}$$

13 TeV 300 fb $^{-1}$





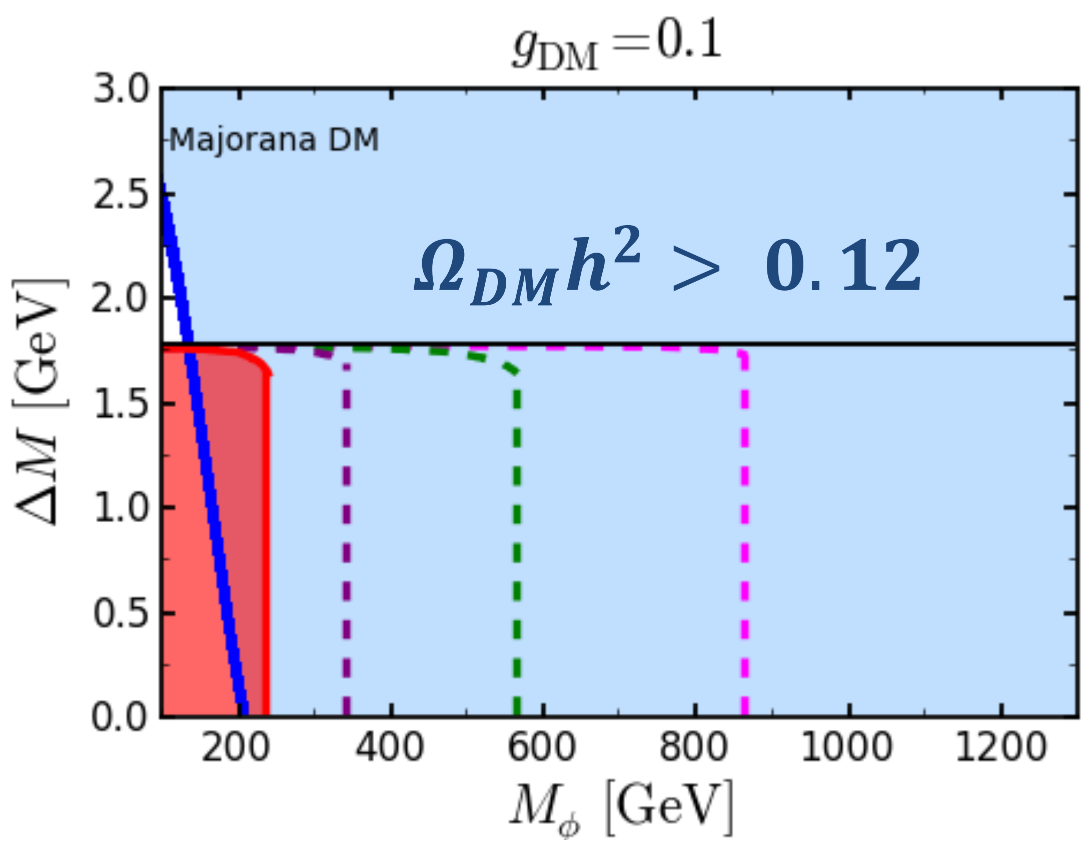


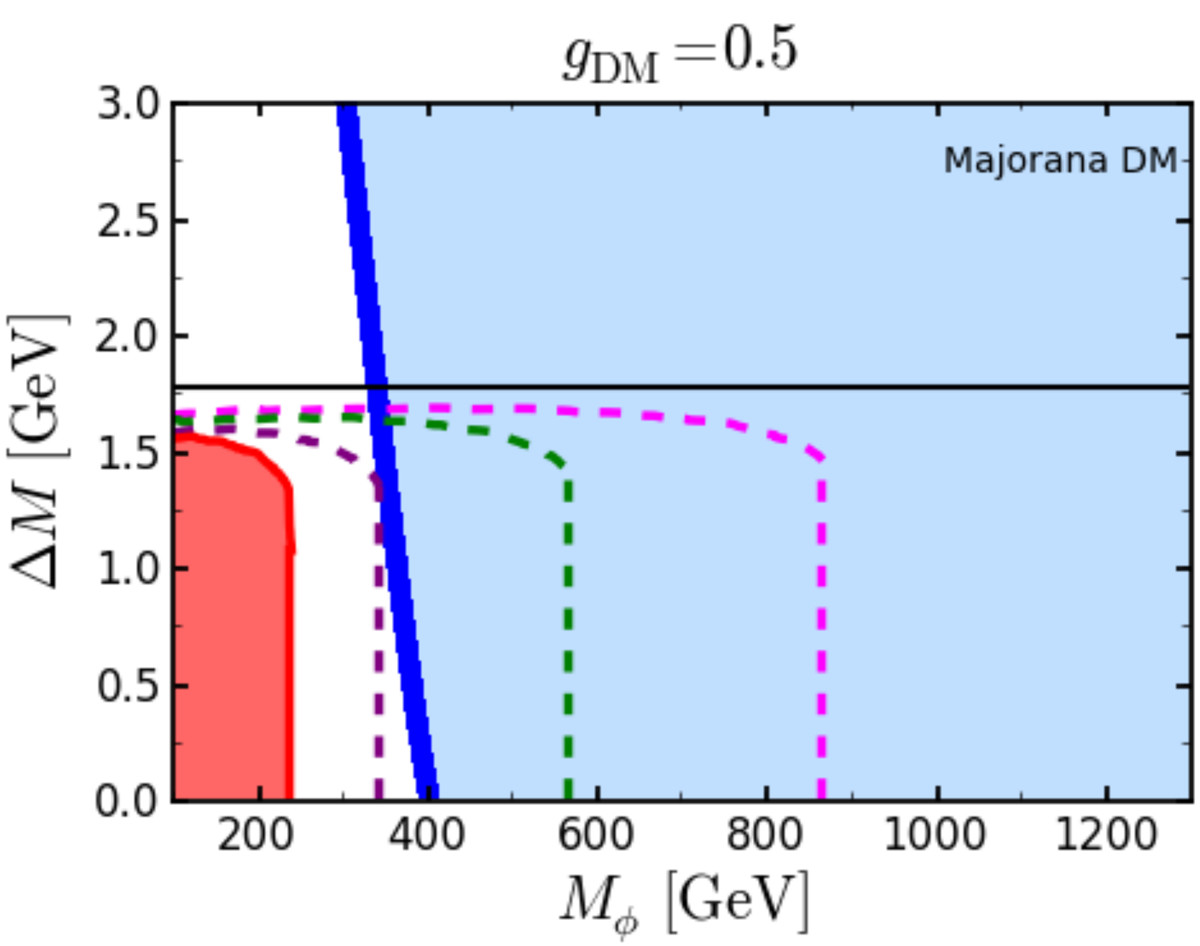
Majorana Dark Matter

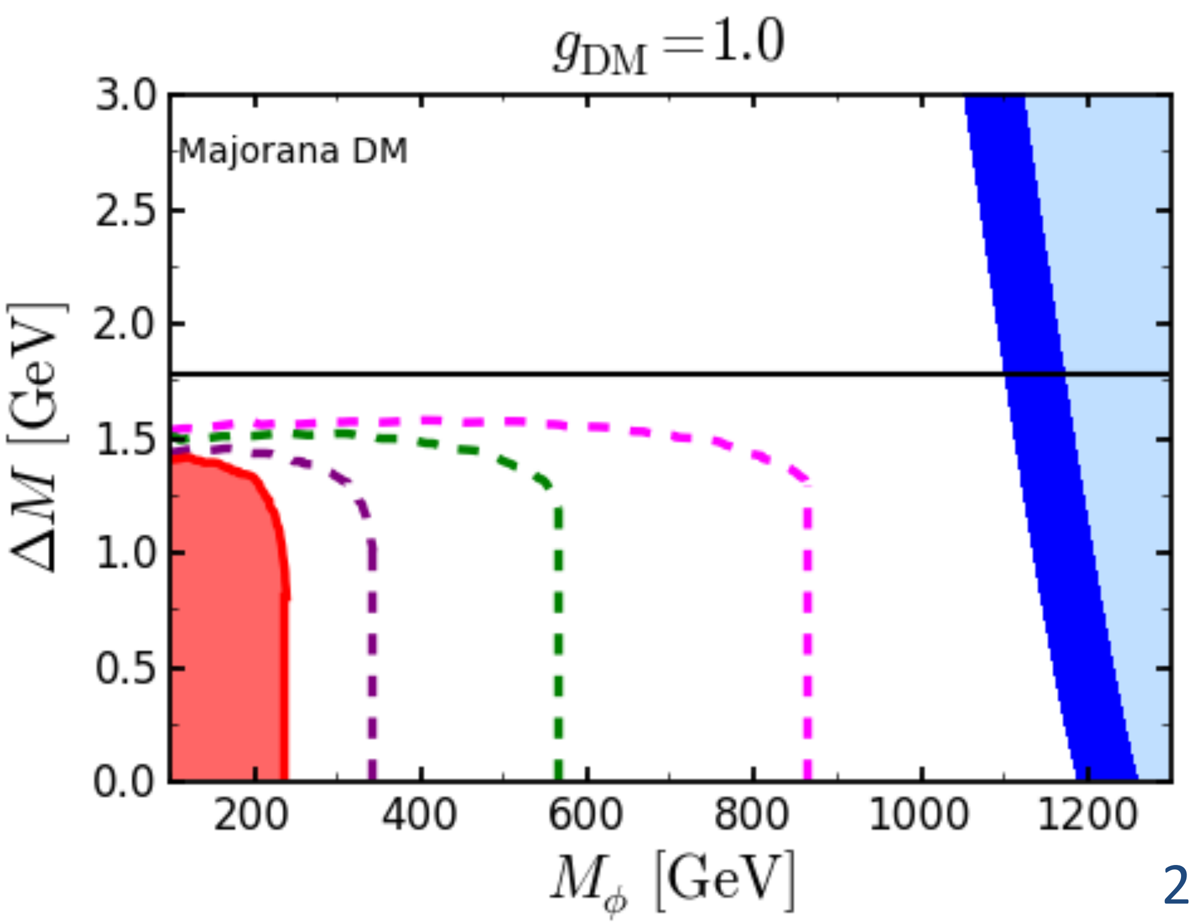
DM χ **CAP** $(Y = 1 \;\; L_\tau = 1)$ ϕ

$$\phi^* \, (\chi \, \tau_R) \;\; \subset \;\; \mathcal{L}$$

High Lumi 13 TeV 3000 fb $^{-1}$



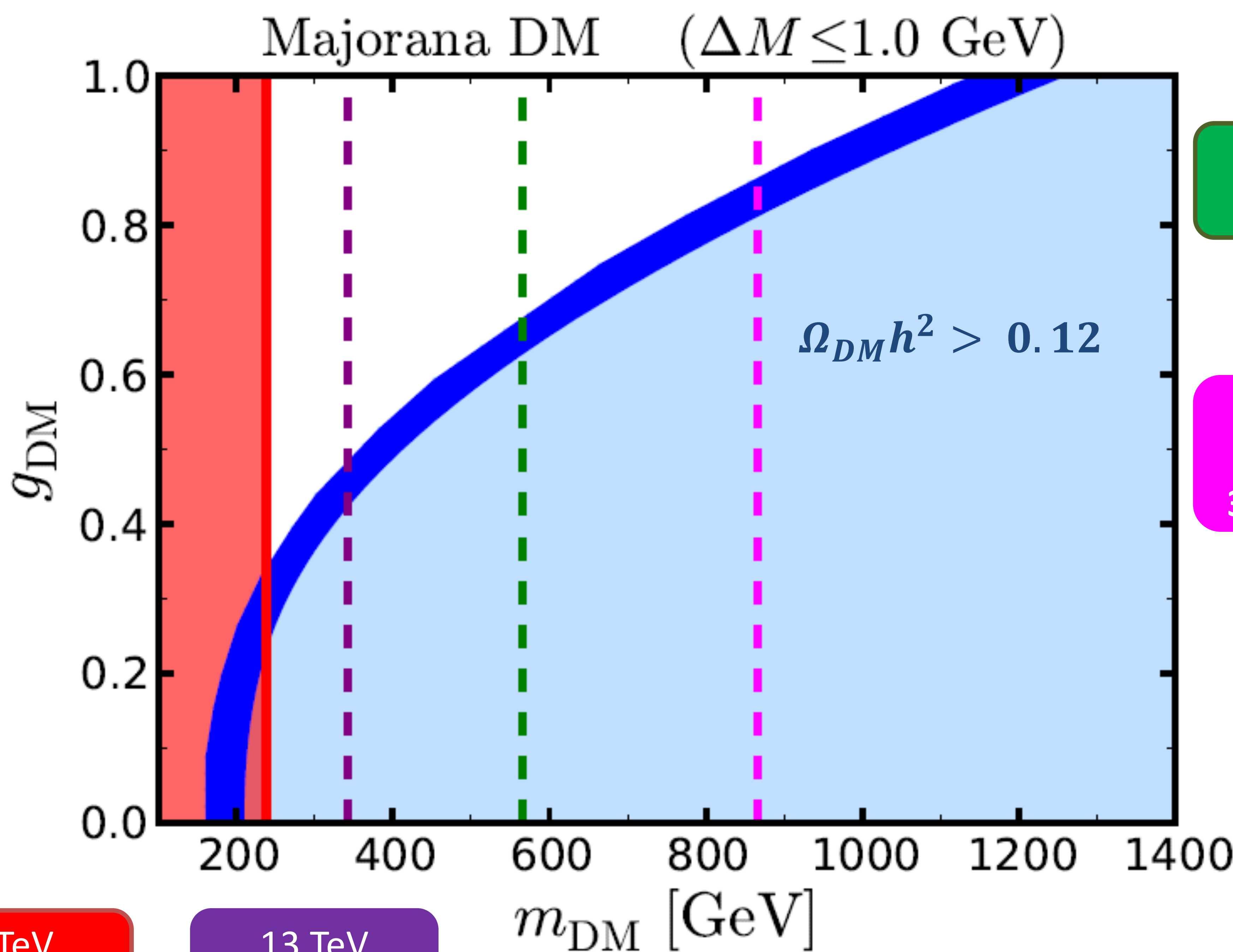




Model 1a

Majorana DM
Scalar CAP
e.g. neutralino-stau in SUSY

Now on the (gDM , mDM) plane:



13 TeV
300 fb $^{-1}$

High Lumi
13 TeV
3000 fb $^{-1}$

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

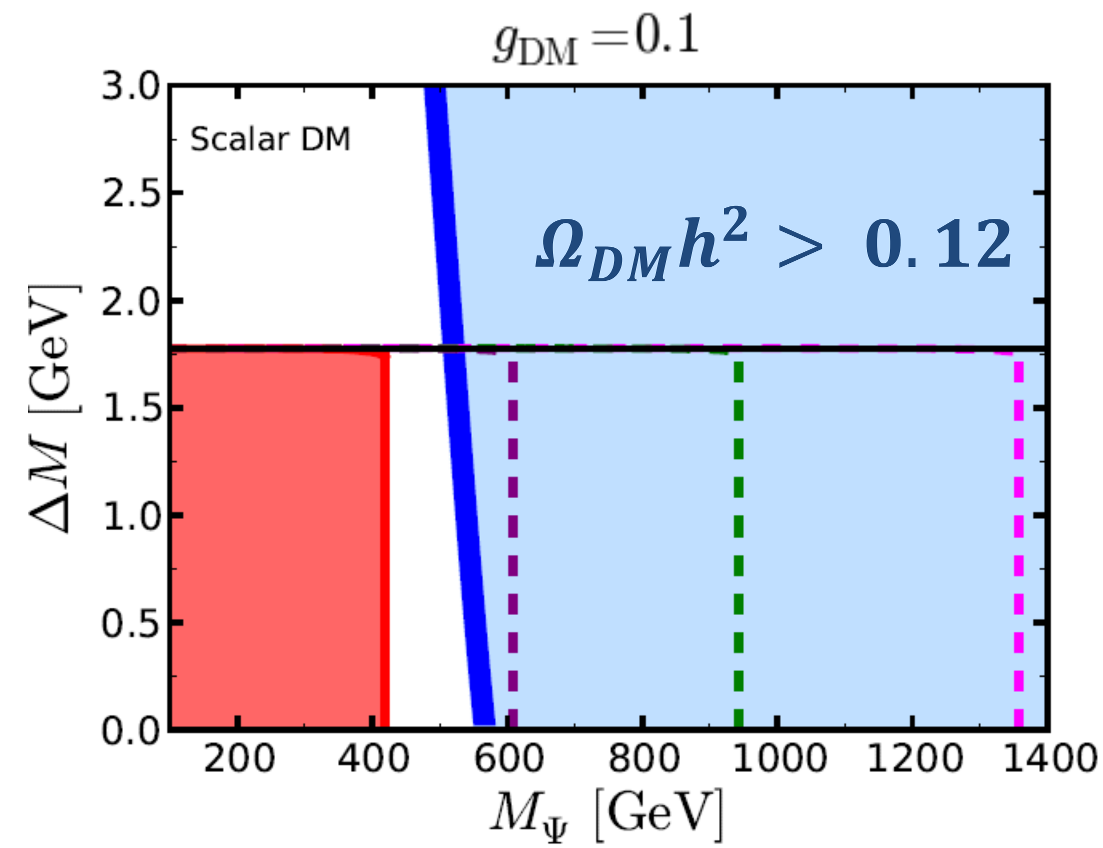
Model 2

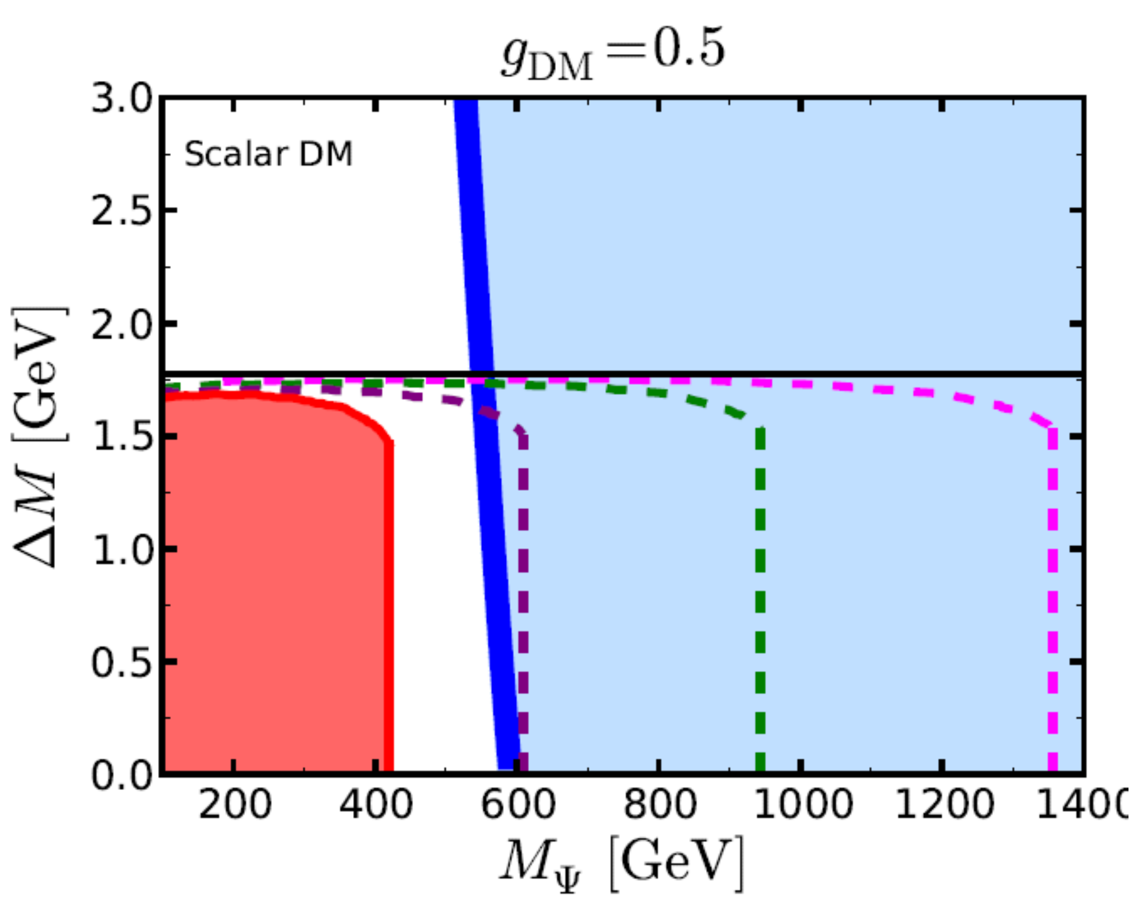
Scalar DM, **Fermion CAP**
e.g. dilaton, KK-tau

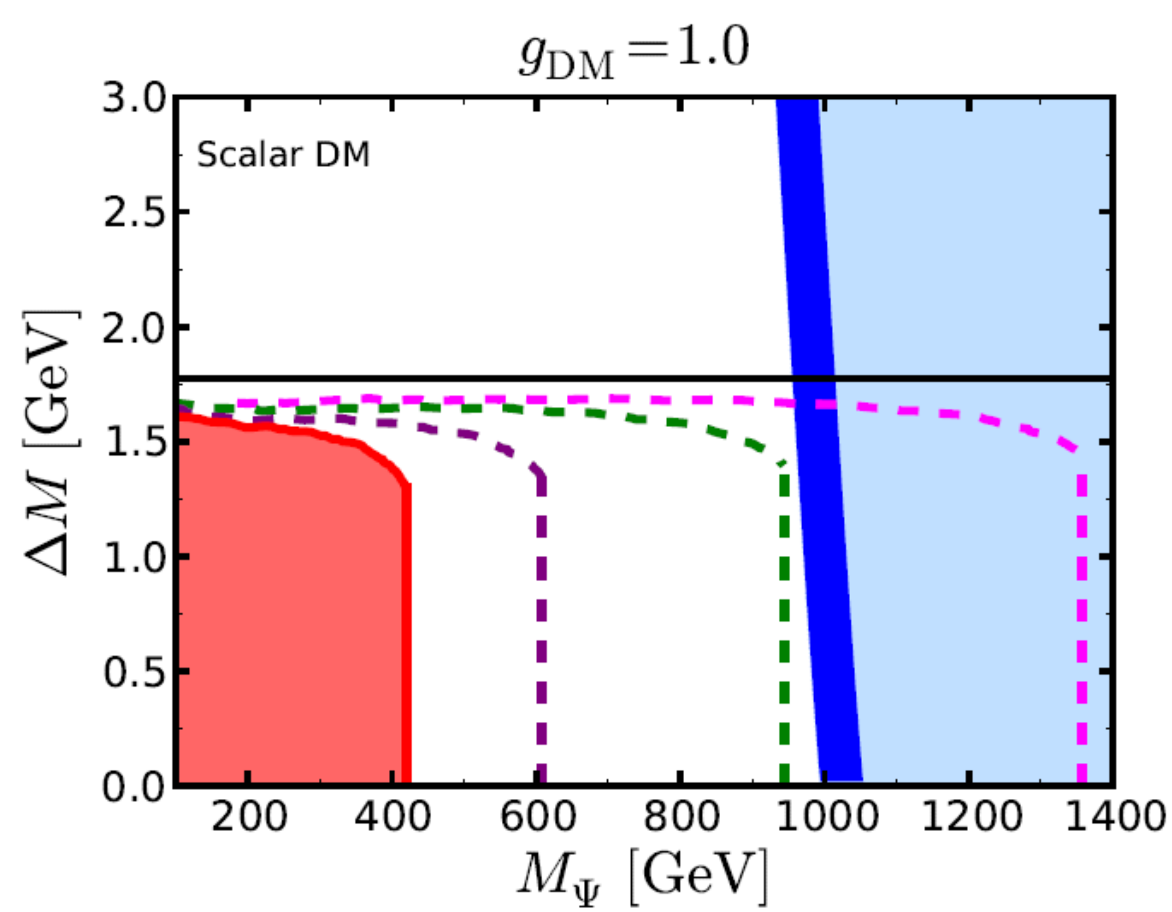
R Scalar	Dirac ferm
DM	**CAP** $(Y = 1 \;\; L_\tau = 1)$
S	Ψ

$$S(\overline{\Psi}\,\tau_R) \;\subset\; \mathcal{L}$$

Gauge-invariant and renormalizable, no problems of unitarity



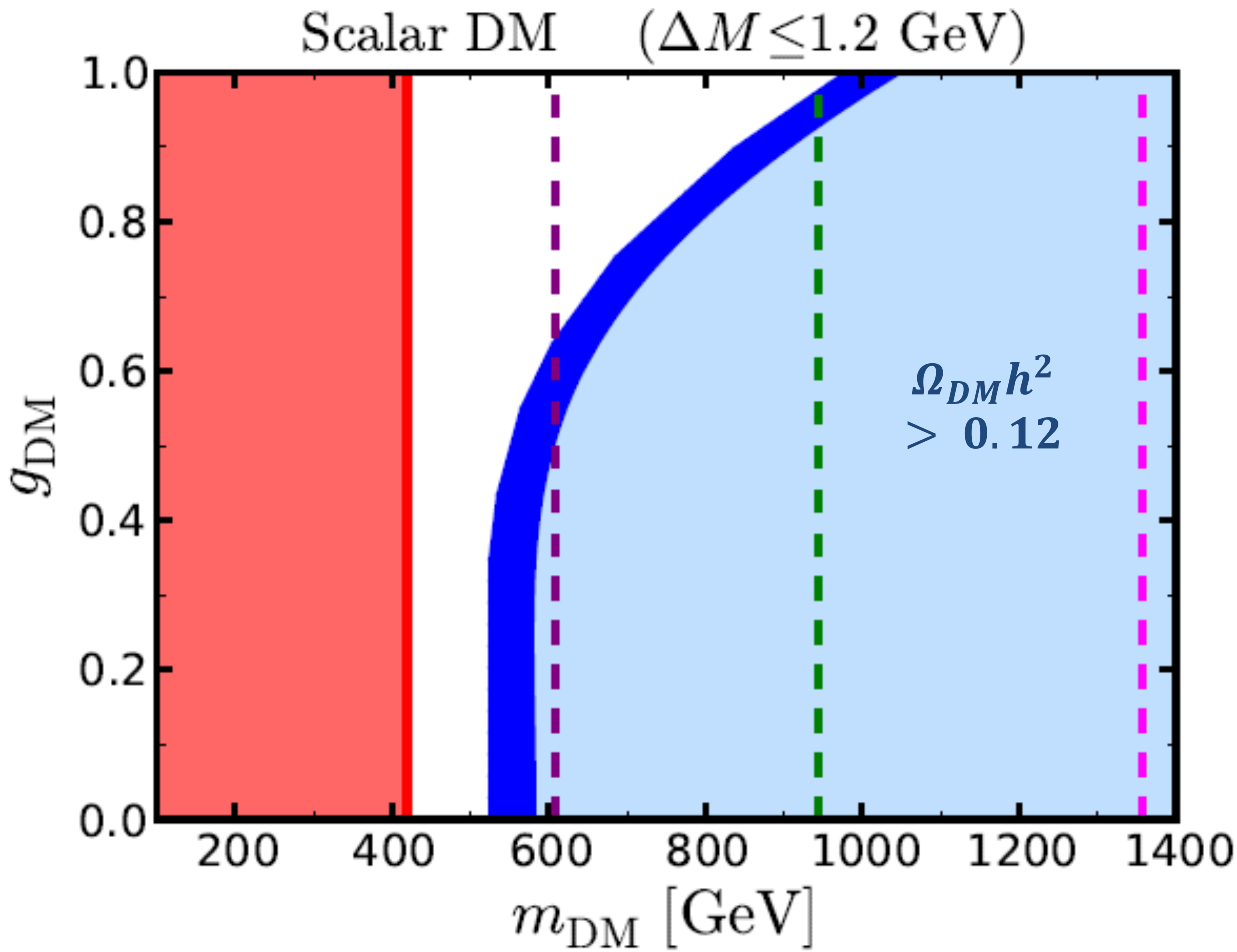




Model 2

Scalar DM, **Fermion CAP**

e.g. dilaton, KK-tau



13 TeV
300 fb $^{-1}$

High Lumi
13 TeV
3000 fb $^{-1}$

8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

Model 3

Vector DM, Fermion CAP
e.g. KK-photon, KK-tau

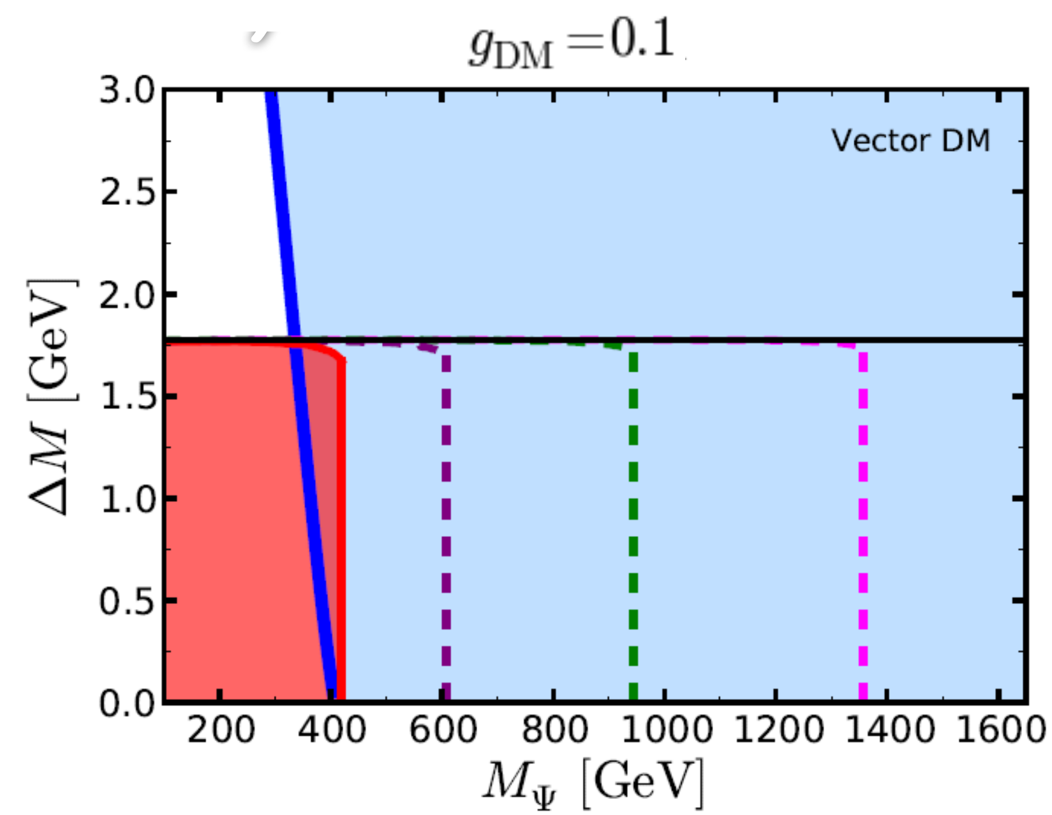
Vector Dirac ferm

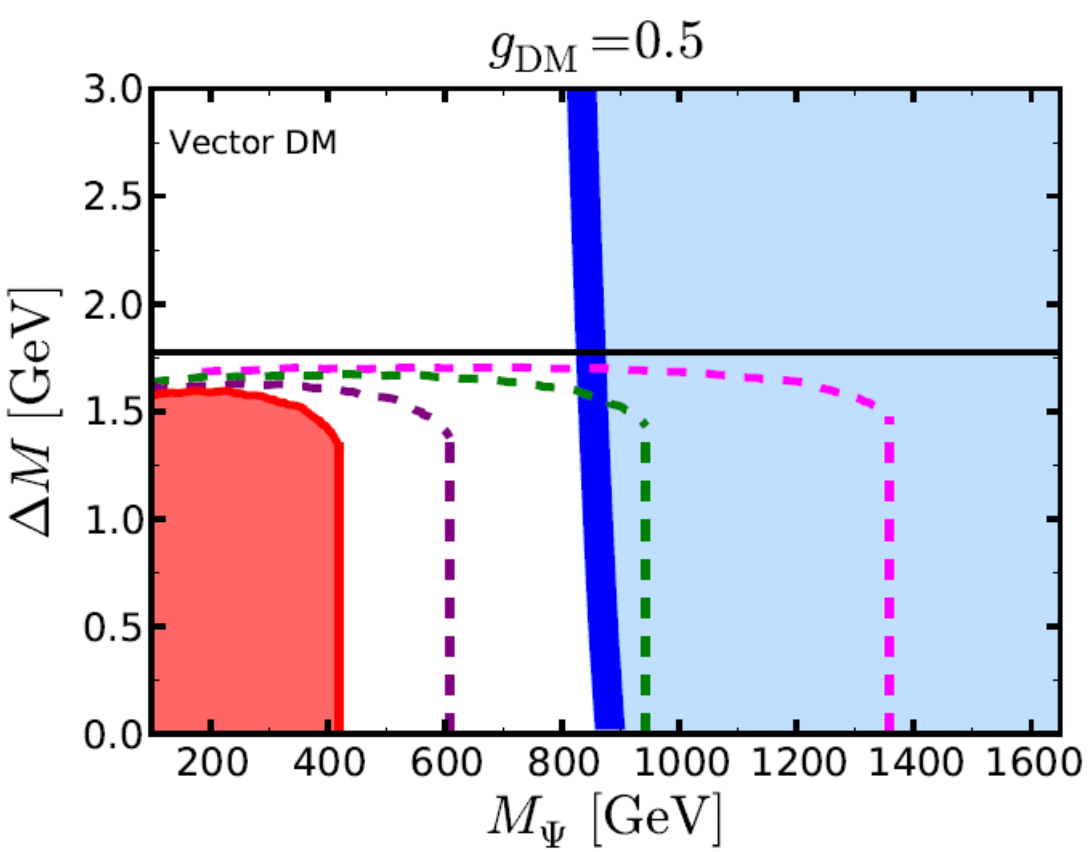
DM A_μ

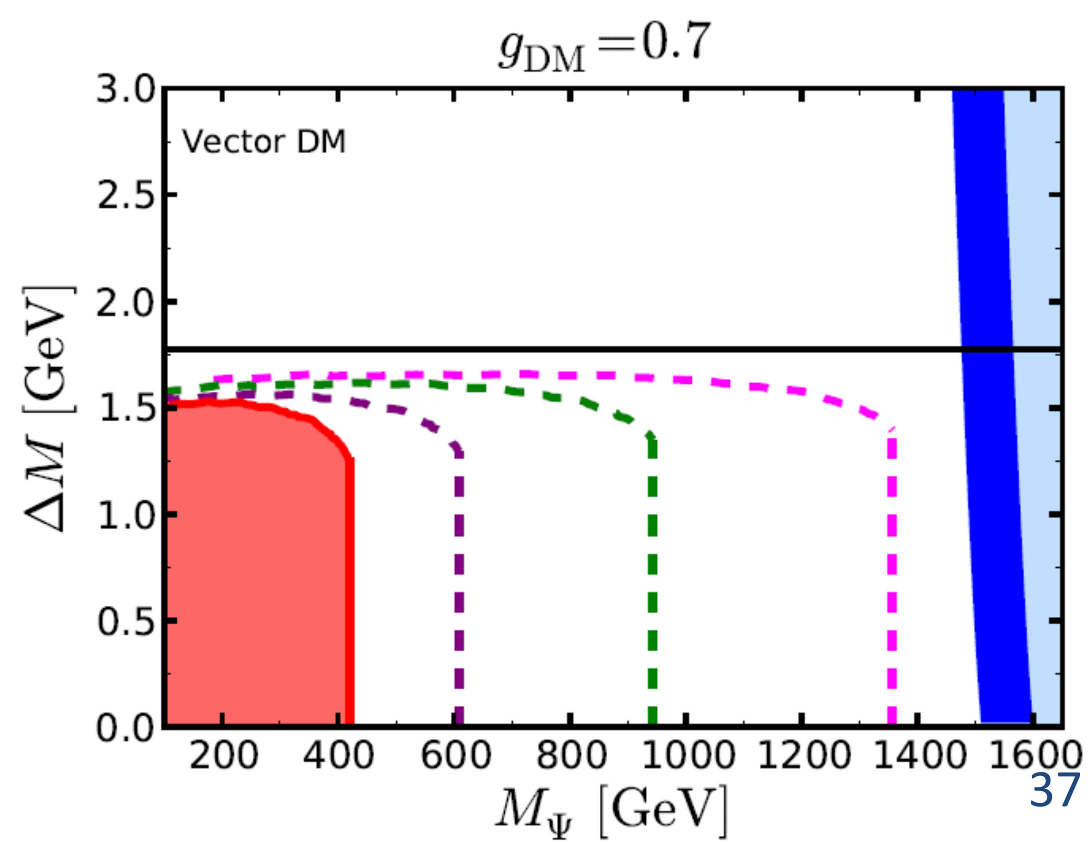
CAP $(Y = 1 \;\; L_\tau = 1)$ Ψ

$$A_\mu\,(\bar{\Psi}\,\tau_R) \;\subset\; \mathcal{L}$$

NOT gauge-invariant, requires UV-completion, e.g. Extra-Dimensions

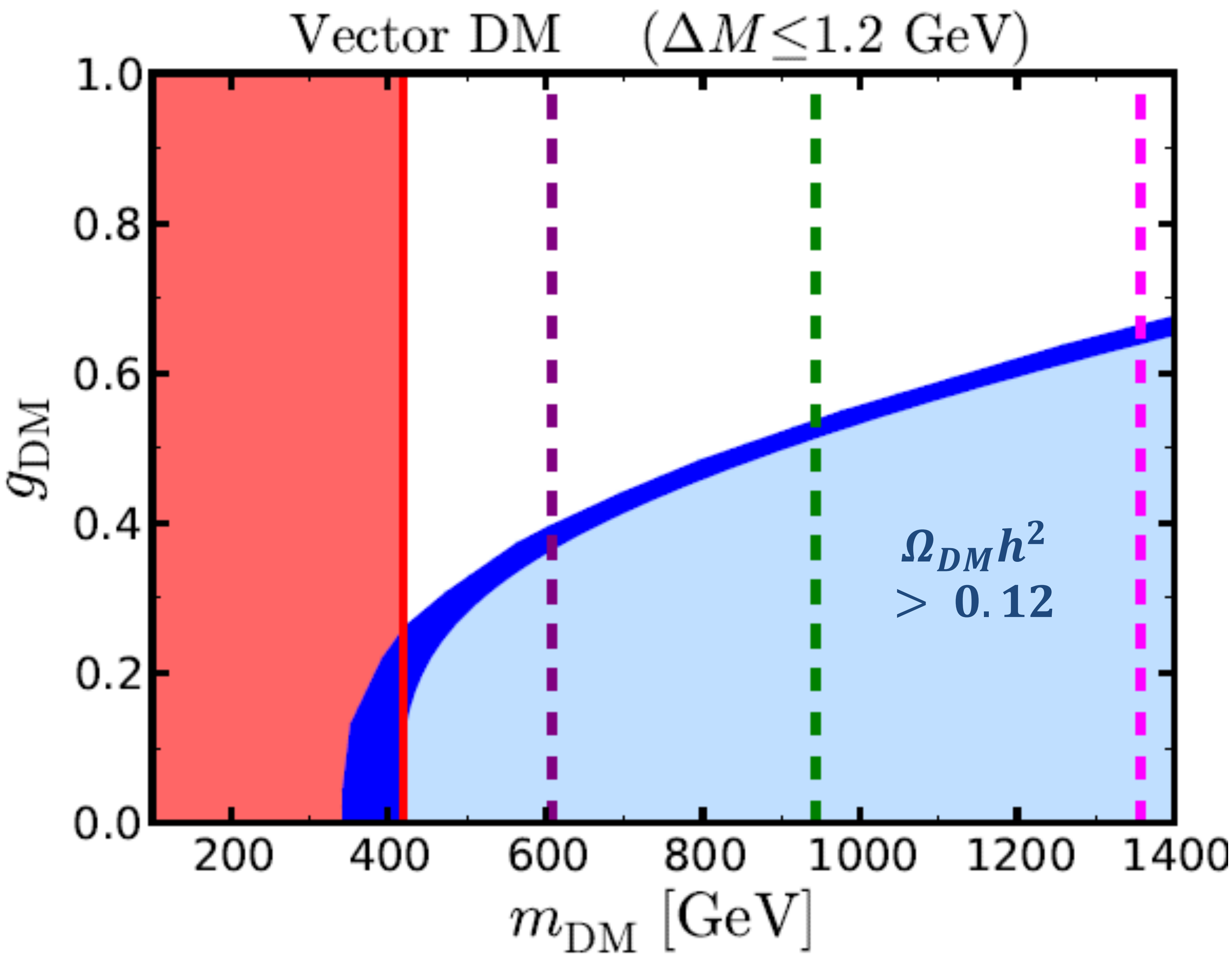






Model 3

Vector DM, **Fermion CAP**
e.g. KK-photon, KK-tau



13 TeV
300 fb $^{-1}$

High Lumi
13 TeV
3000 fb $^{-1}$

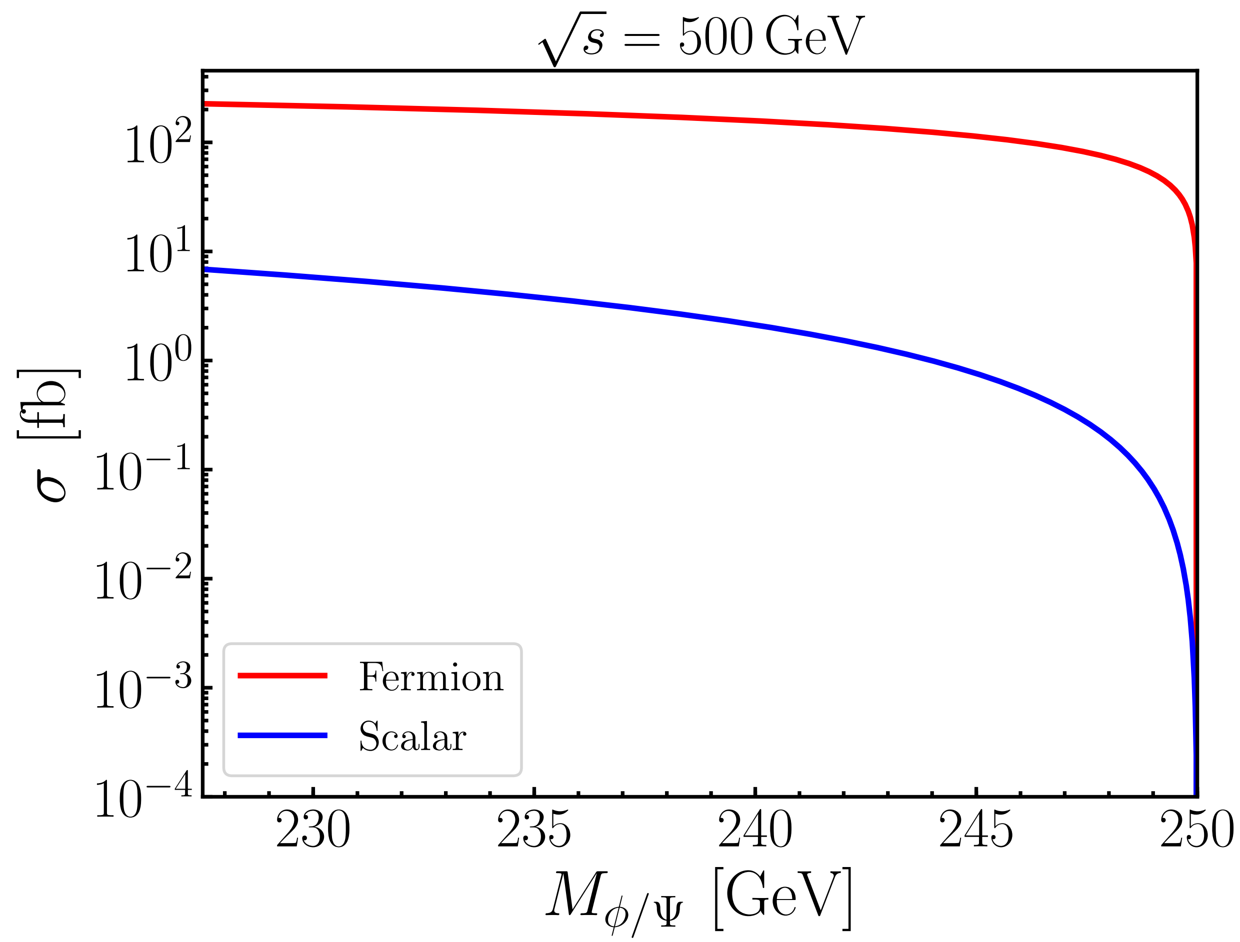
8 TeV
18.8 fb $^{-1}$

13 TeV
30 fb $^{-1}$

future e^+e^- collider

Cross-Section

$$e^+e^- \to \eta^+\eta^- \to \tau^+\tau^-\chi\,\chi$$



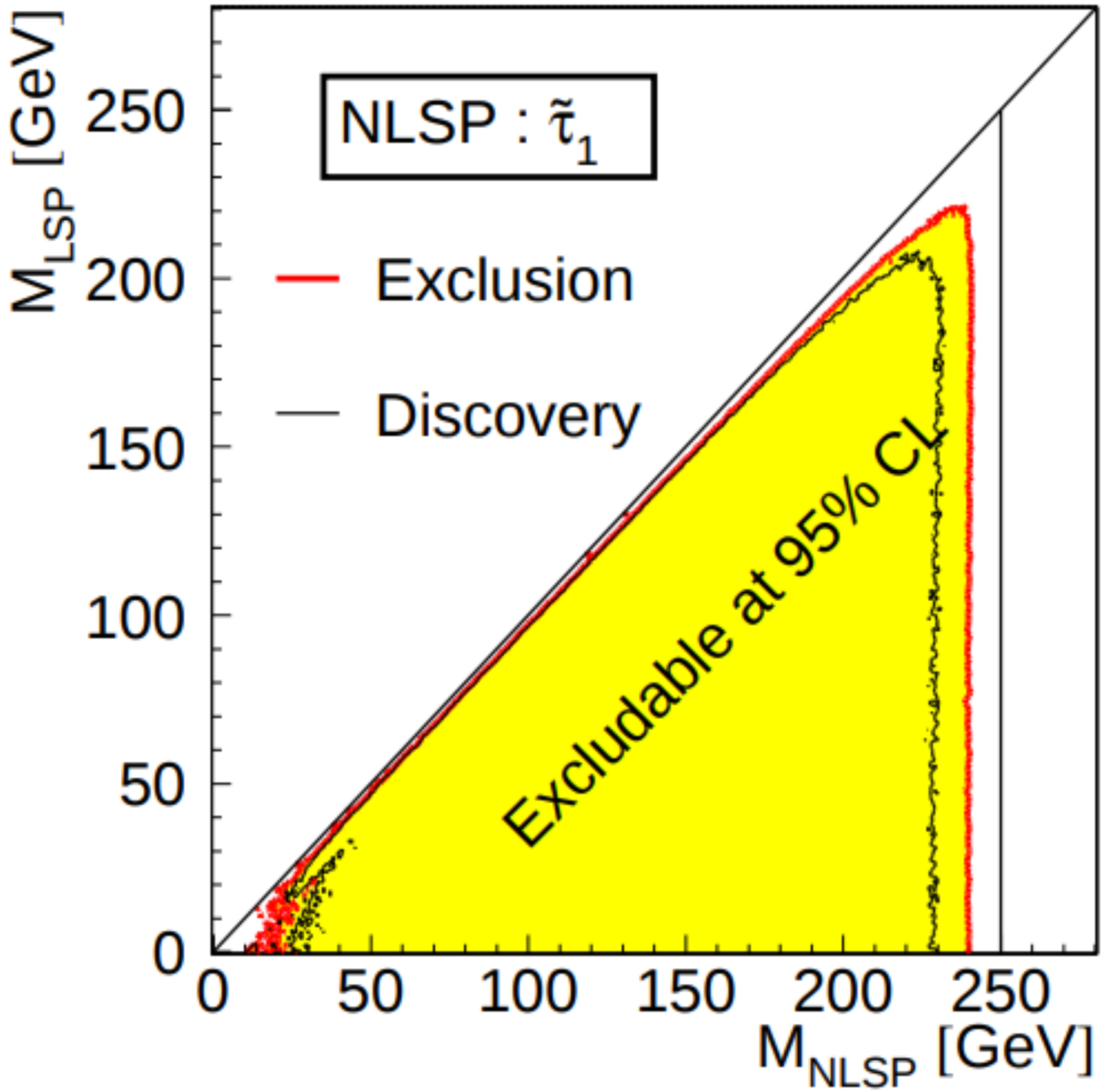
$$\sigma(e^+e^- \to \phi^+\phi^-) \;=\; \alpha^2\pi s\cdot\mathcal{A}\cdot\frac{1}{6}\beta^3,$$

$$\sigma(e^+e^- \to \Psi^+\Psi^-) \;=\; \alpha^2\pi s\cdot\mathcal{A}\cdot\beta\left(1-\frac{1}{3}\beta^2\right)$$

$$\mathcal{A} \;=\; \frac{2}{s^2}+\frac{2}{s}\frac{(g_L+g_R)g_R}{(s-m_Z^2)}+\frac{(g_L^2+g_R^2)g_R^2}{(s-m_Z^2)^2}, \qquad g_L=\frac{-\frac{1}{2}+s_W^2}{s_Wc_W}, \qquad g_R=\frac{s_W^2}{s_Wc_W}, \qquad \beta=\sqrt{1-\frac{4M_{\phi/\Psi}^2}{s}}$$

Prospects for CLIC

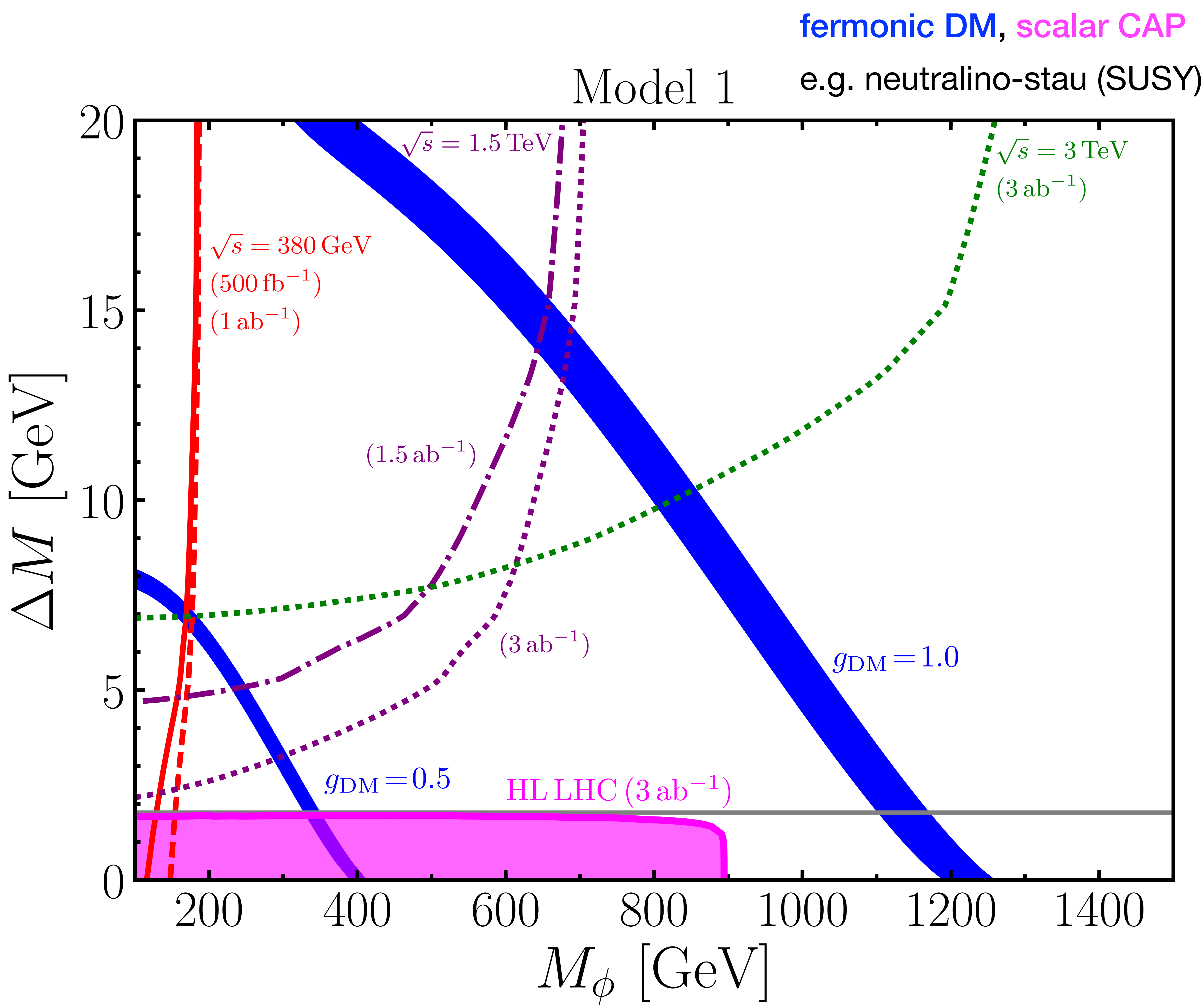
- **Example: Linear colliders can study compressed spectrum in SUSY**



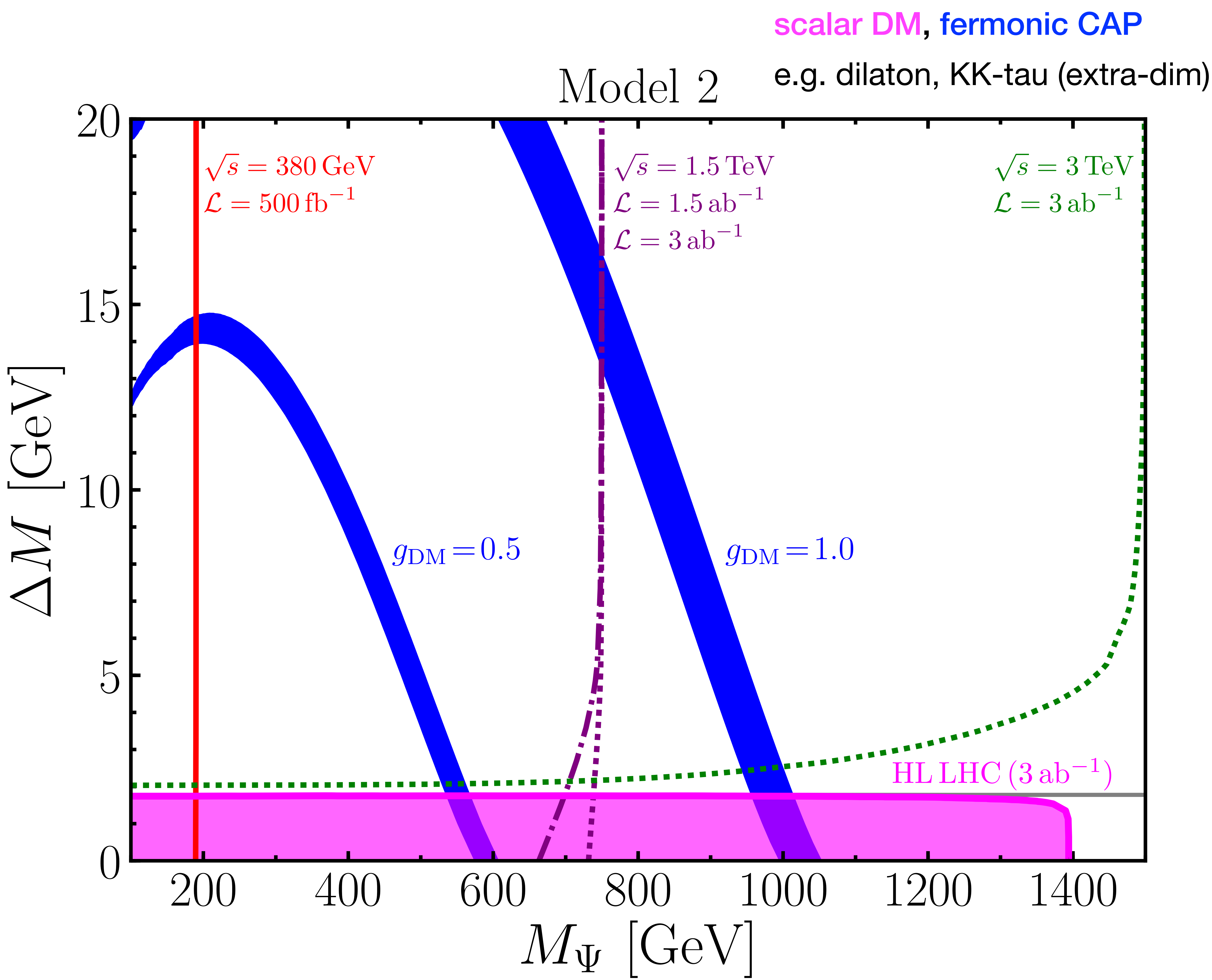
$\sqrt{s} = 500$ **GeV**

[Berggren 2013]

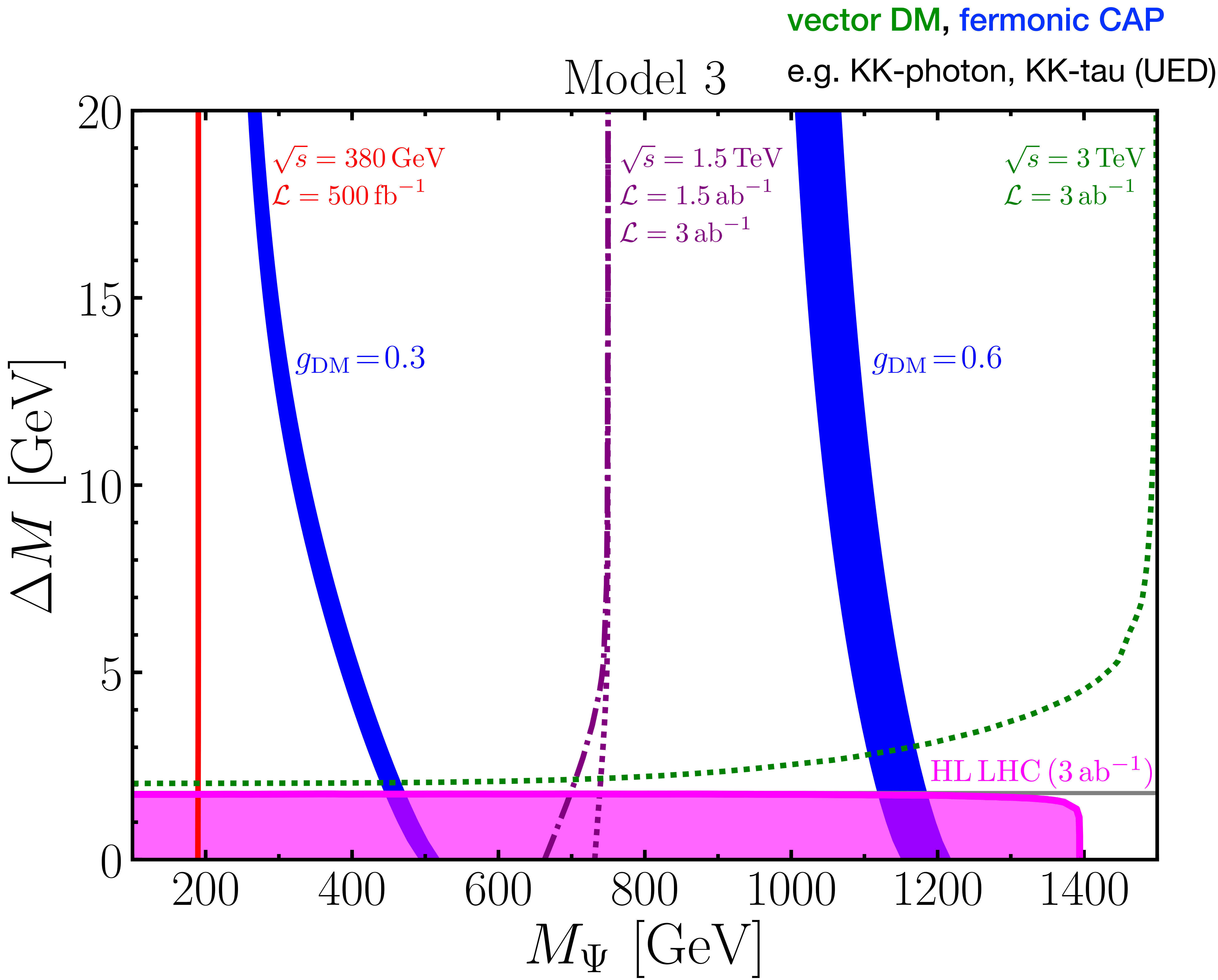
- Stau and neutralino, lightest supersymmetric states
- $\Delta M < 10$ GeV can be tested, virtual $\gamma\,\gamma$ becomes relevant background



fermonic DM, scalar CAP
e.g. neutralino-stau (SUSY)
Model 1
$\sqrt{s} = 1.5$ TeV
$\sqrt{s} = 3$ TeV
$(3\,\mathrm{ab}^{-1})$
$\sqrt{s} = 380$ GeV
$(500\,\mathrm{fb}^{-1})$
$(1\,\mathrm{ab}^{-1})$
$(1.5\,\mathrm{ab}^{-1})$
$(3\,\mathrm{ab}^{-1})$
$g_{\mathrm{DM}} = 1.0$
$g_{\mathrm{DM}} = 0.5$
HL LHC $(3\,\mathrm{ab}^{-1})$
ΔM [GeV]
M_ϕ [GeV]
0
5
10
15
20
200
400
600
800
1000
1200
1400



scalar DM, fermonic CAP
e.g. dilaton, KK-tau (extra-dim)
Model 2
$\sqrt{s} = 380\,\mathrm{GeV}$
$\mathcal{L} = 500\,\mathrm{fb}^{-1}$
$\sqrt{s} = 1.5\,\mathrm{TeV}$
$\mathcal{L} = 1.5\,\mathrm{ab}^{-1}$
$\mathcal{L} = 3\,\mathrm{ab}^{-1}$
$\sqrt{s} = 3\,\mathrm{TeV}$
$\mathcal{L} = 3\,\mathrm{ab}^{-1}$
$g_{\mathrm{DM}} = 0.5$
$g_{\mathrm{DM}} = 1.0$
HL LHC $(3\,\mathrm{ab}^{-1})$
ΔM [GeV]
M_Ψ [GeV]
0
5
10
15
20
200
400
600
800
1000
1200
1400


vector DM, fermonic CAP
e.g. KK-photon, KK-tau (UED)
Model 3
$\sqrt{s} = 380\,\mathrm{GeV}$
$\mathcal{L} = 500\,\mathrm{fb}^{-1}$
$\sqrt{s} = 1.5\,\mathrm{TeV}$
$\mathcal{L} = 1.5\,\mathrm{ab}^{-1}$
$\mathcal{L} = 3\,\mathrm{ab}^{-1}$
$\sqrt{s} = 3\,\mathrm{TeV}$
$\mathcal{L} = 3\,\mathrm{ab}^{-1}$
$g_{\mathrm{DM}} = 0.3$
$g_{\mathrm{DM}} = 0.6$
$\mathrm{HL\ LHC}\,(3\,\mathrm{ab}^{-1})$
ΔM [GeV]
M_Ψ [GeV]
0
5
10
15
20
200
400
600
800
1000
1200
1400

Conclusion

- We presented co-annihilating dark matter simplified models with long-lived signatures. There are 3-parameters: $m_\chi, \ \Delta m, \ g_{\rm DM}$

Model-1a			
Component	Field	Charge	Interaction
DM	Majorana fermion (χ)	$Y=0$	$\phi^*(\chi\tau_R)+\text{h.c.}$
CAP	Complex scalar (ϕ)	$Y=-1$	

fermonic DM, scalar CAP

e.g. neutralino-stau (SUSY)

Model-2			
Component	Field	Charge	Interaction
DM	Real scalar (S)	$Y=0$	$S(\overline{\Psi}P_R\tau)+\text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y=-1$	

scalar DM, fermonic CAP

e.g. dilaton, KK-tau (extra-dim)

Model-3			
Component	Field	Charge	Interaction
DM	Vector (V_μ)	$Y=0$	$V_\mu(\overline{\Psi}\gamma^\mu P_R\tau)+\text{h.c.}$
CAP	Dirac fermion (Ψ)	$Y=-1$	

vector DM, fermonic CAP

e.g. KK-photon, KK-tau (UED)

- In this class of models, direct detection is 1-loop suppressed, indirect detection is velocity suppressed (for Model-1 and 2). The collider has the best chance of detecting it, but it needs $\Delta m < m_\tau$ to have long-lived signature.

- These models can be used by ATLAS and CMS to present their results.