הטכניון
מכון טכנולוגי לישראל
TECHNION
Israel Institute of Technology

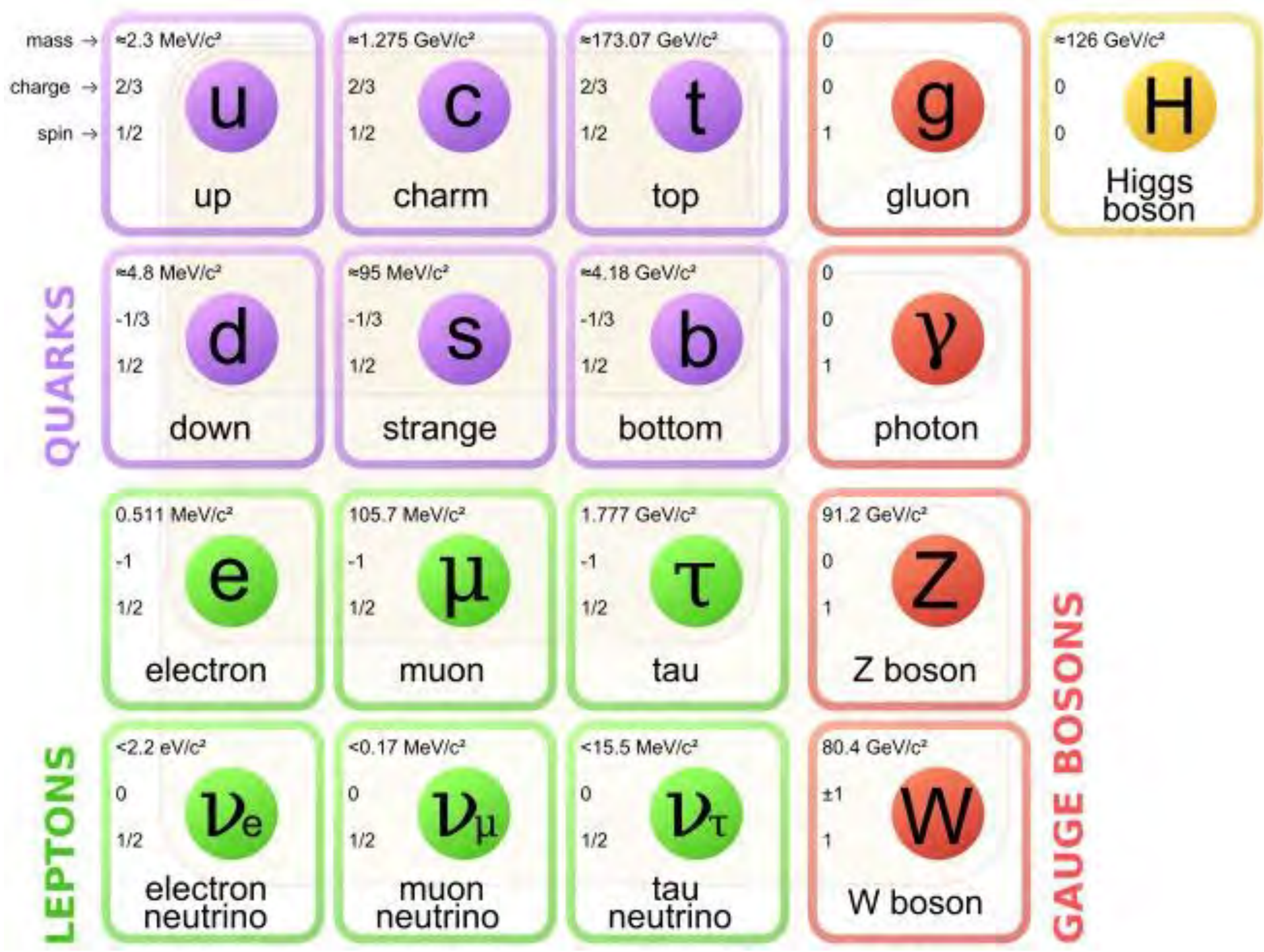
MSSM 4G scenario

Sho IWAMOTO（岩本　祥）

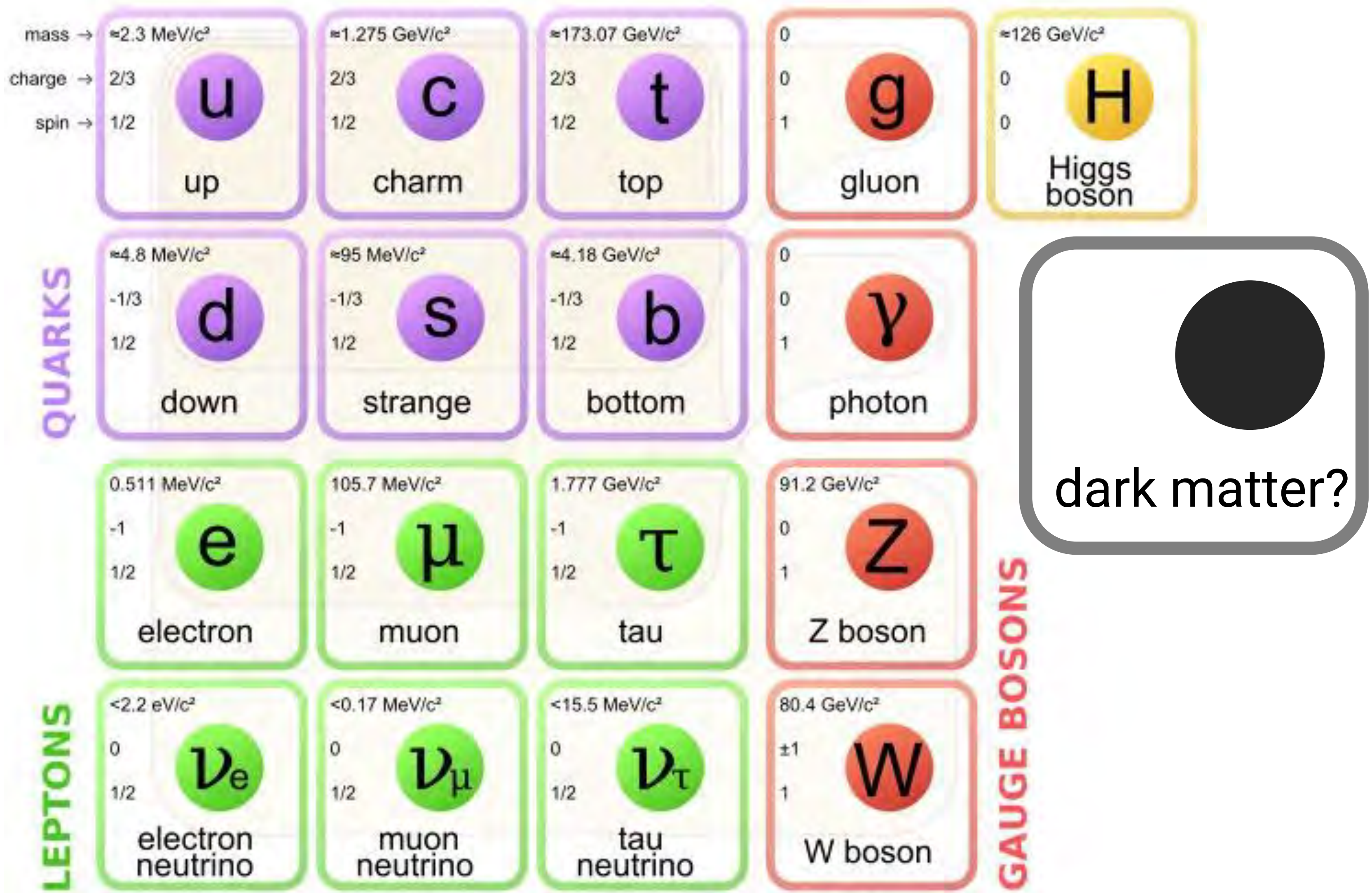
15 Sep. 2016
Seminar @ Osaka University

Based on [1608.00283] in collaboration with
M. Abdullah, **J. L. Feng**, and **B. Lillard** (UC Irvine)

Universe =


mass →
charge →
spin →
QUARKS
LEPTONS
GAUGE BOSONS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson

Universe =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dark matter?

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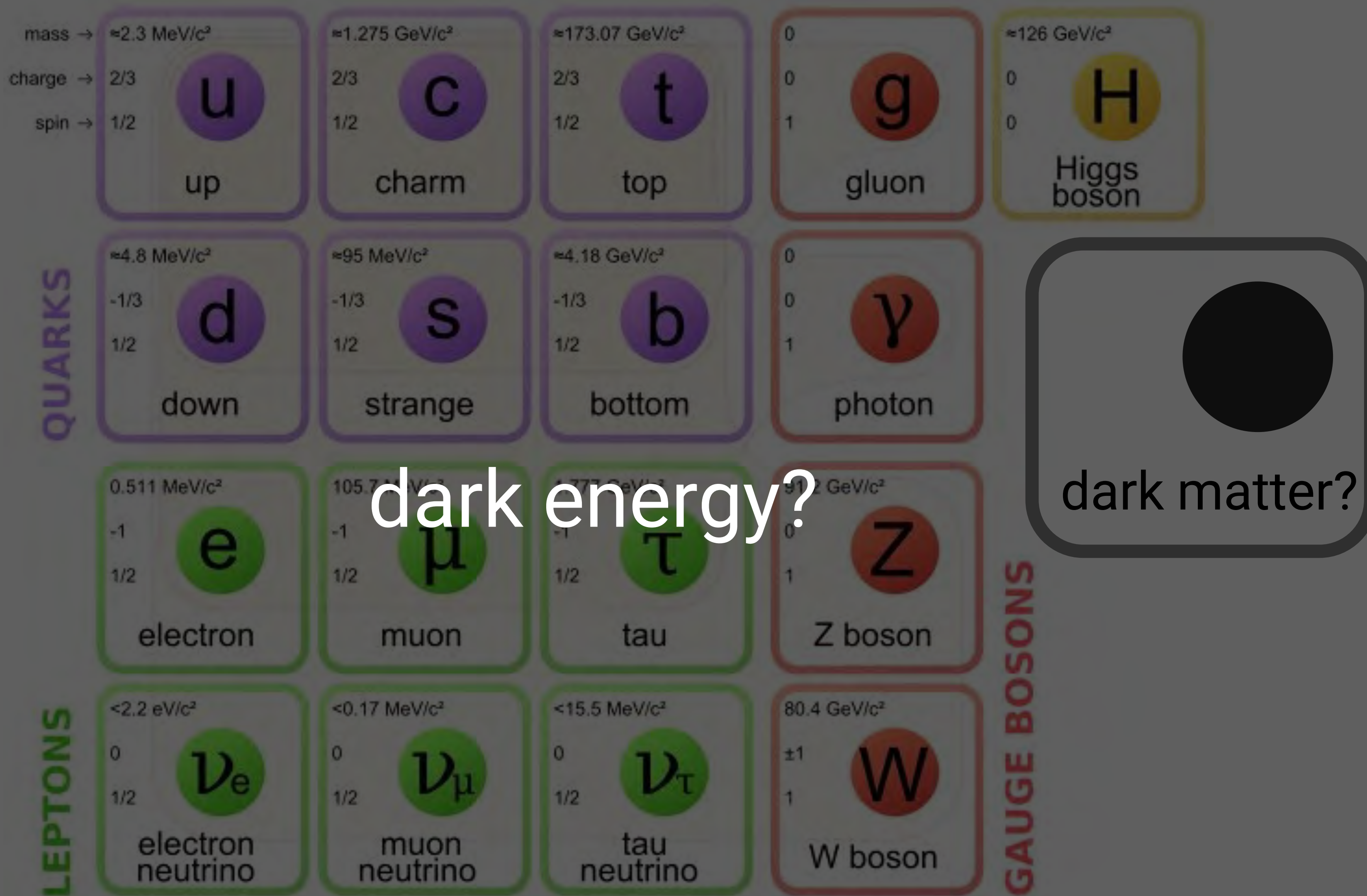
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dark energy?
dark matter?

Hints of "New Physics"

- Dark matter
- Dark energy
- Neutrino mass
- Gauge coupling unification
- Higgs mass ("naturalness")
- Muon "$g-2$"
- ...

New Physics Candidates

-
-
-
-

etc…

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- Dark matter
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New Physics Candidates

- SUSY [supersymmetry]
-
-
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etc…

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-
-

Please fill this list
with your models
/ models you like

etc…

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New Physics Candidates

- SUSY [supersymmetry]
- Gauge-Higgs unification
- Hidden strong SU(N)
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etc…

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[Standard Model]

- SM =

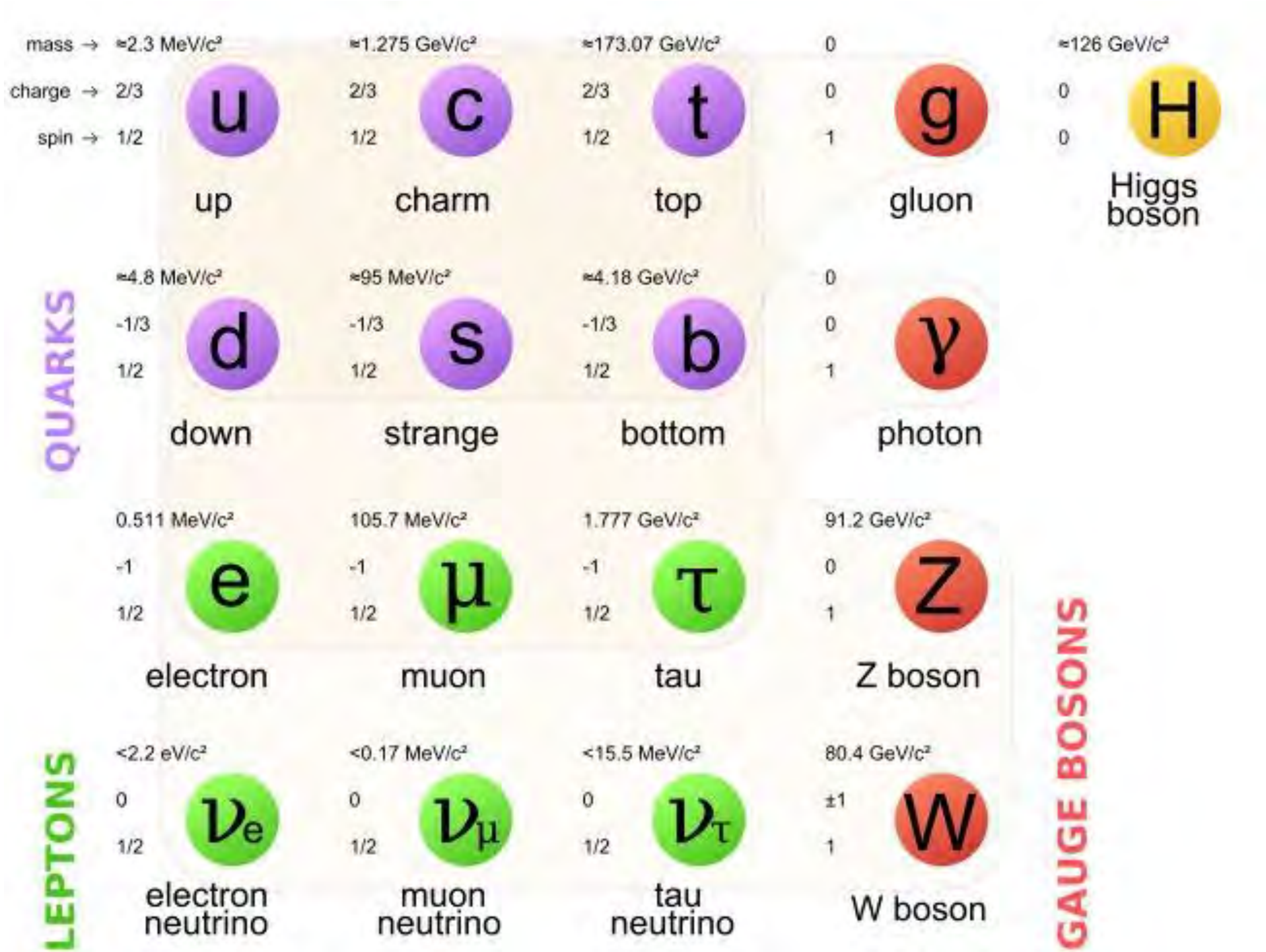
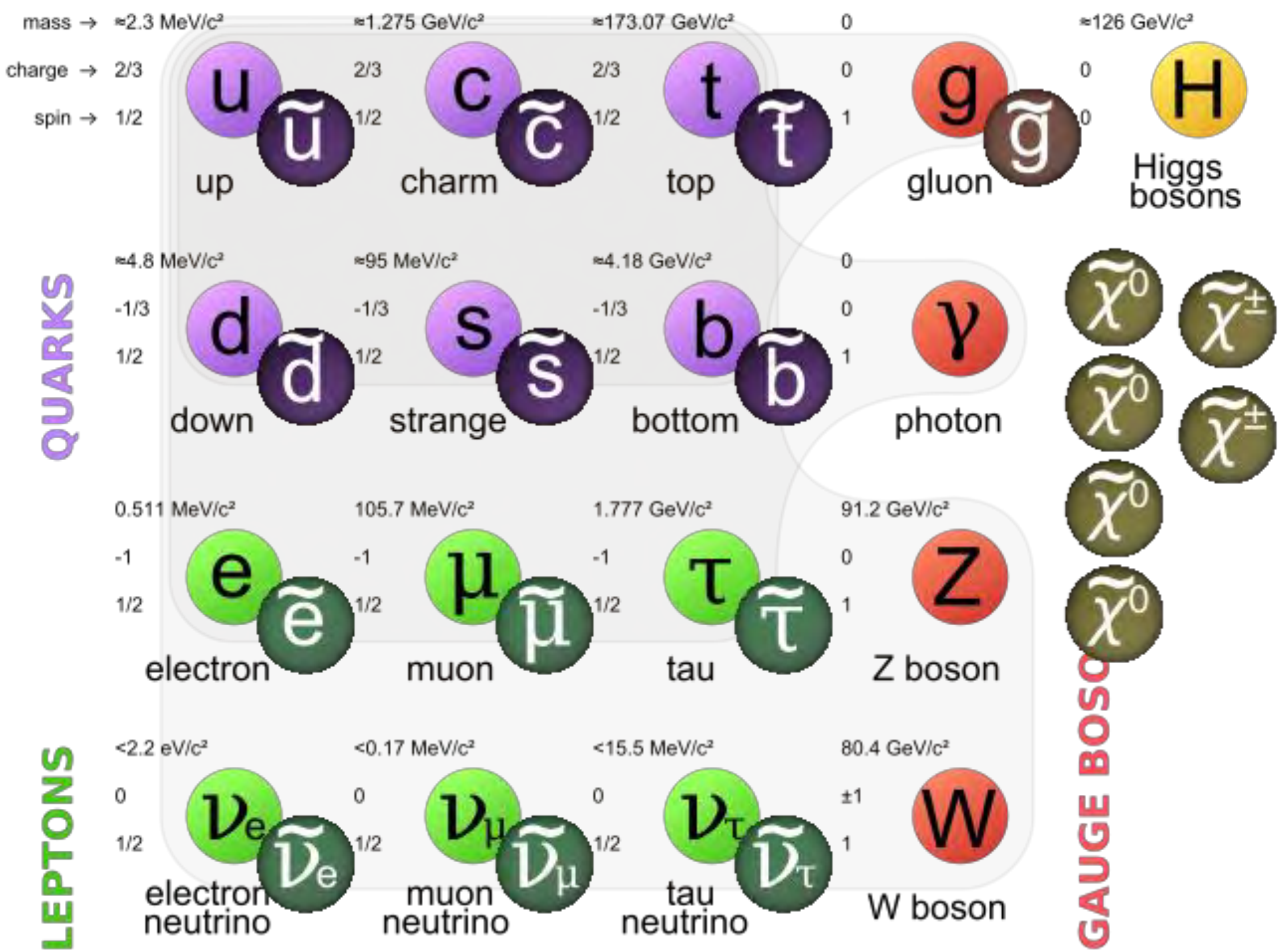


Image by MissBJ [CC BY 3.0], via Wikimedia Commons
(changes were made by S.I)

[Minimal Supersymmetric Standard Model]

- MSSM =



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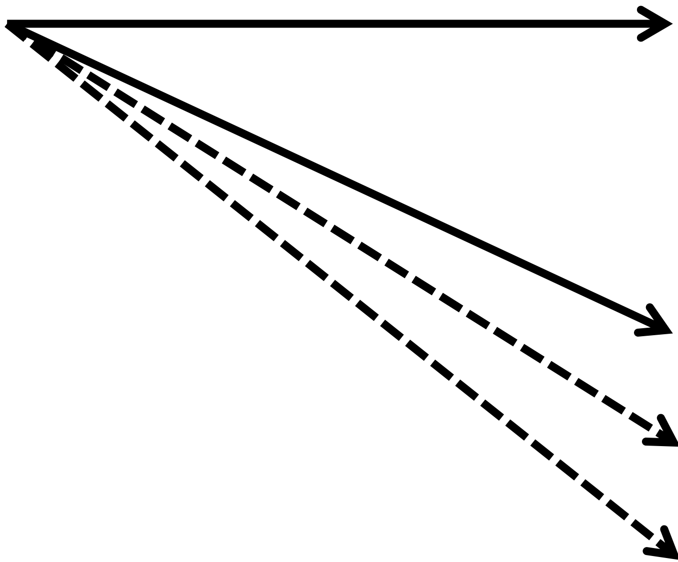
New Physics Candidates

- SUSY



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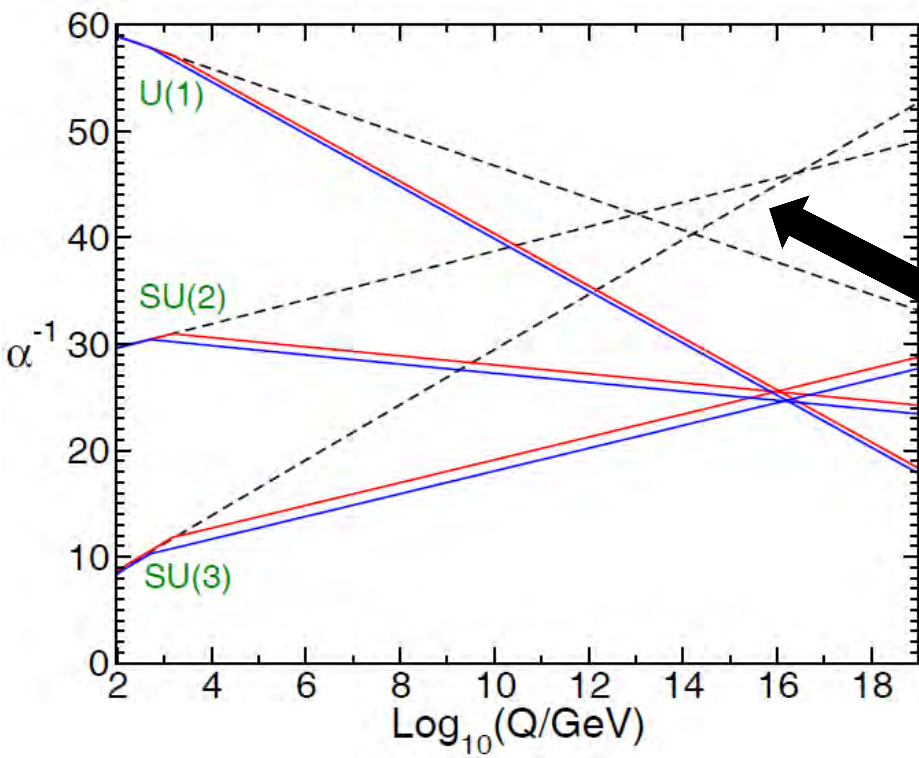
- SM ∋ 3 forces : U(1), SU(2), SU(3) [Why three?]

measured theoretical prediction



- Gauge coupling unification

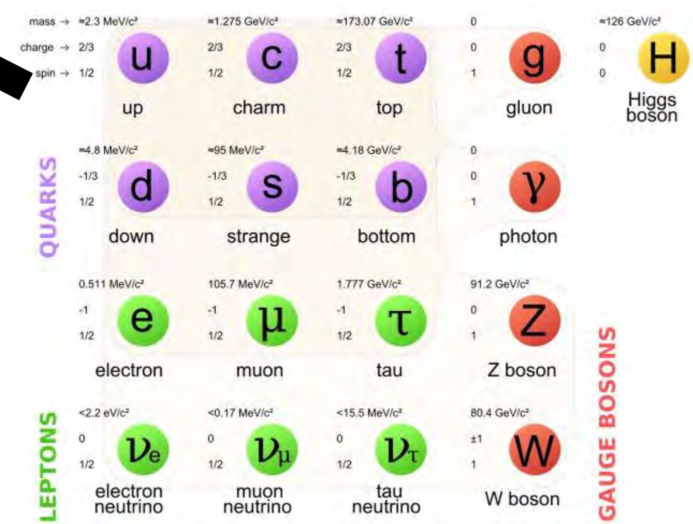


Figure from S. P. Martin, *A Supersymmetry Primer*, hep-ph/9709356

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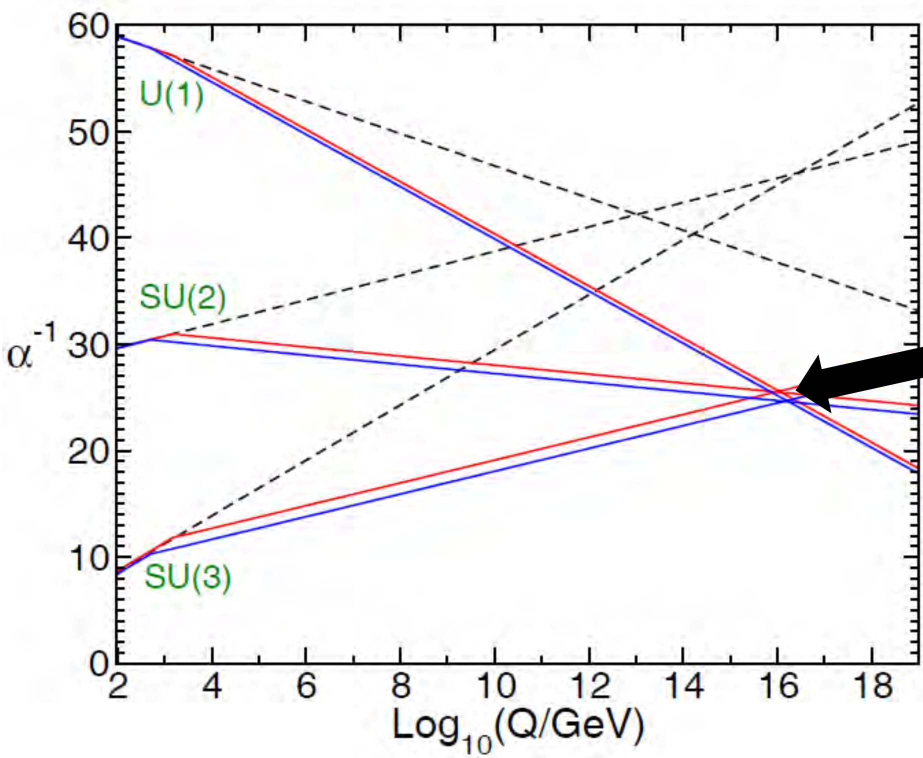

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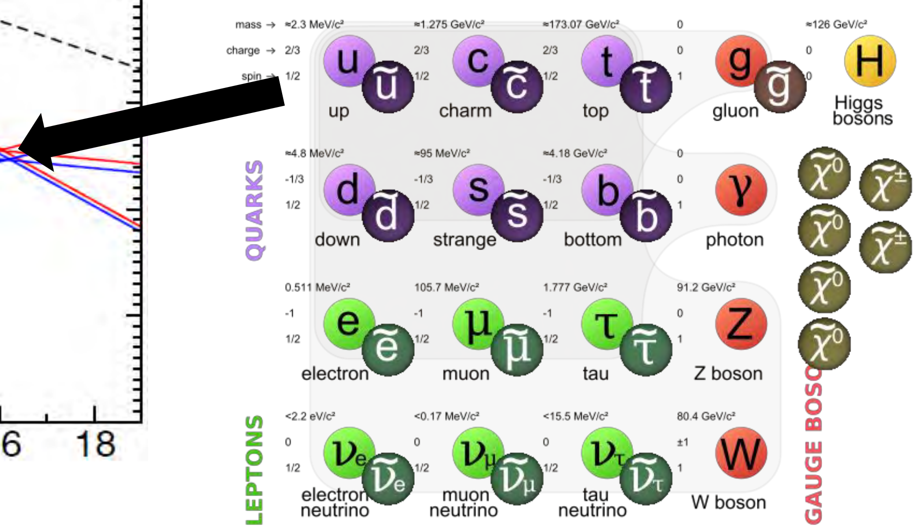

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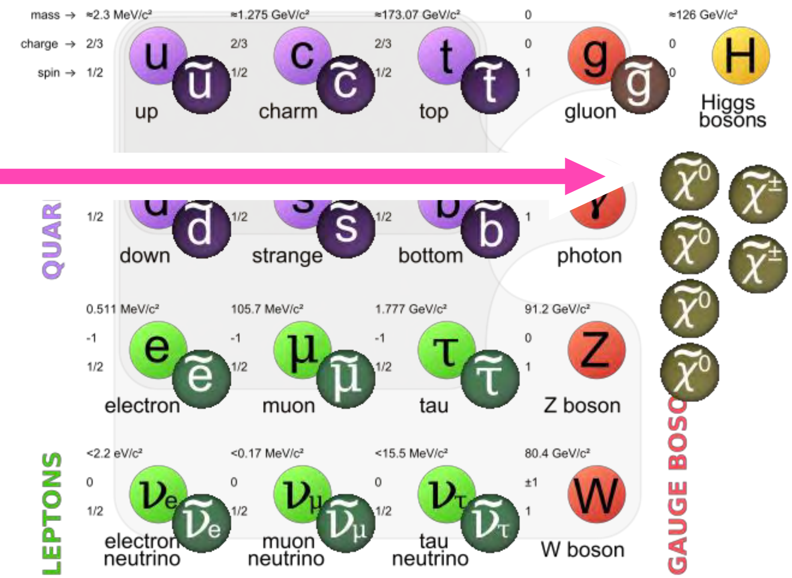
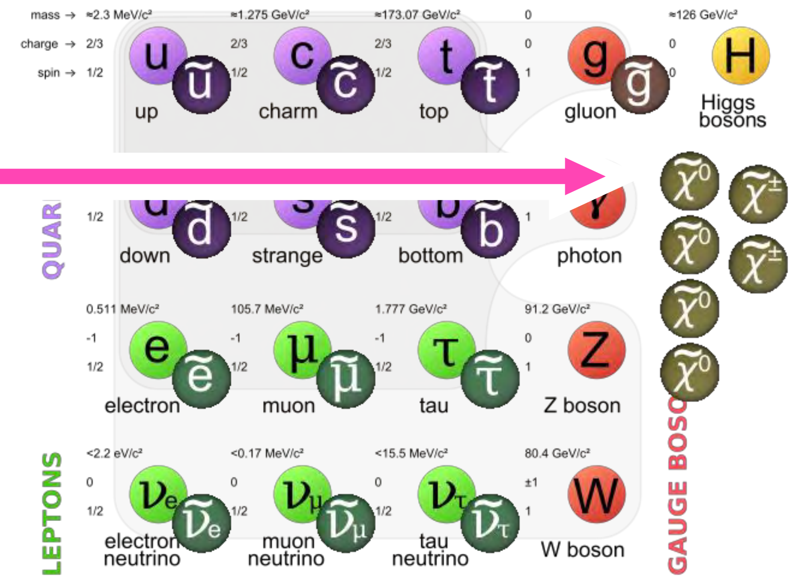
- MSSM ⊃ Dark matter candidate



- Dark matter?
  - stable (at least 1010 yr)
  - ✓ charge neutral
  - density $\Omega h^2 = 0.12$
  - not detected by astrophysics / direct search / LHC

- MSSM ∋ Dark matter candidate



- Dark matter?

if we introduce R-parity

  - ✓ stable (at least 1010 yr)
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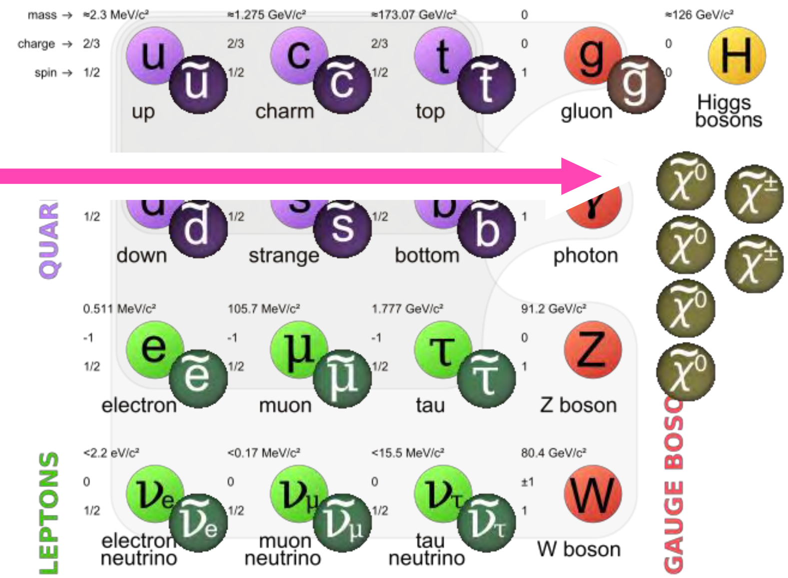

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$$\tilde{\chi}^0 = \tilde{B} \oplus \widetilde{W}^0 \oplus \tilde{H}^0_{\mathrm{d}} \oplus \tilde{H}^0_{\mathrm{u}}$$

- $\tilde{B}$-like? → "overabundant" problem

$$\Omega h^2 \gg 0.12$$

- $\widetilde{W}$-like?
- $\tilde{H}$-like?

$$\widetilde{\chi}^0 = \widetilde{B} \oplus \widetilde{W}^0 \oplus \widetilde{H}^0_{\mathrm{d}} \oplus \widetilde{H}^0_{\mathrm{u}}$$

- $\widetilde{B}$-like? → "overabundant" problem
- $\widetilde{W}$-like?
- $\widetilde{H}$-

h^2 0.12

MSSM 4G model
solves this problem!

Introduction: why overabundant?

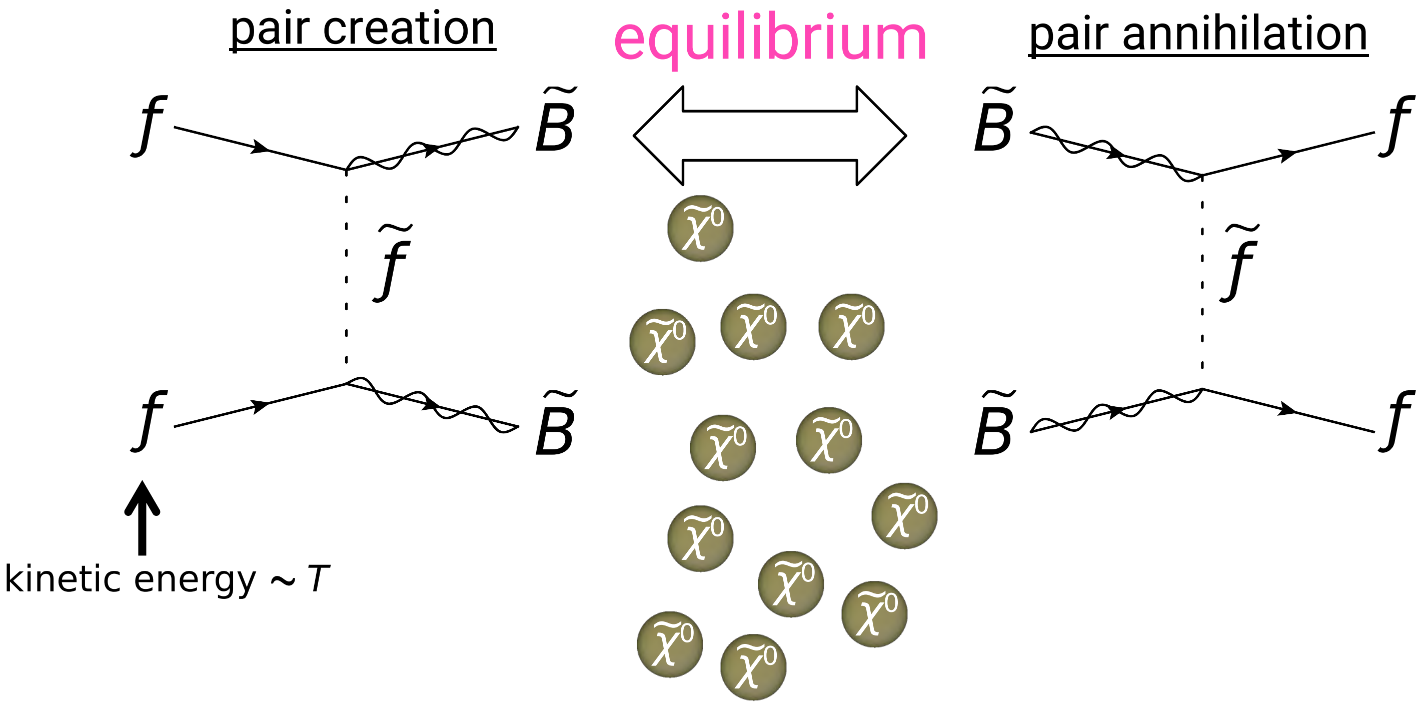
Model: **MSSM4G** solves overabundance.

Analysis:

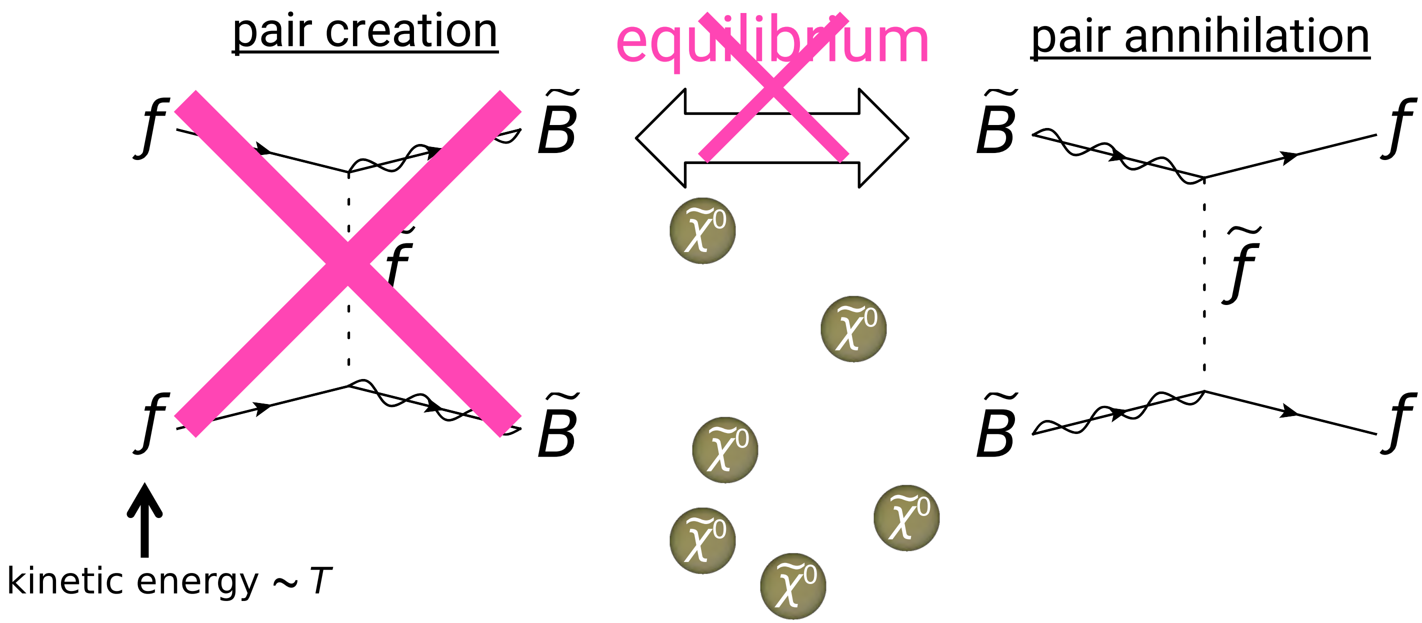
- cosmic rays (CTA, Fermi, MAGIC)
- colliders (LHC)
- direct detection (LUX)

Summary with discussion seeds

- Early Universe with $T > m_{\tilde{B}}$



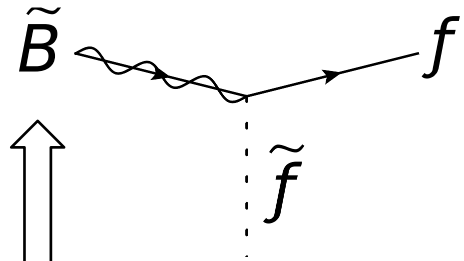
- Early Universe with $T \lesssim m_{\tilde{B}}$

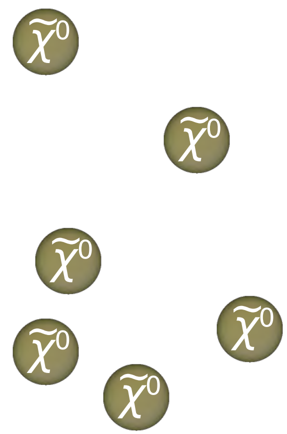


- Early Universe with $T \lesssim m_{\tilde{B}}/20$

pair creation

pair annihilation

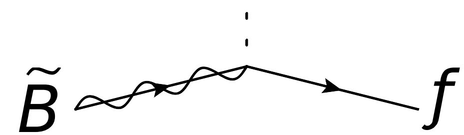




“relic density”

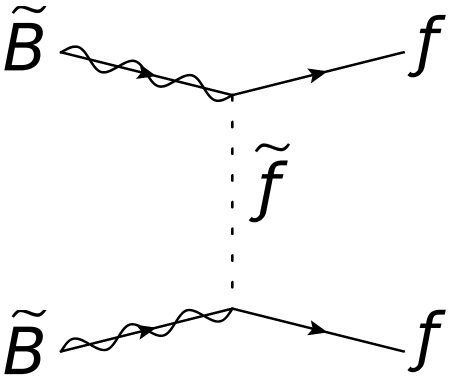
far apart due to

- pair annihilation
- Universe’s expansion



- "observed" relic density Ωh^2

⇦ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM



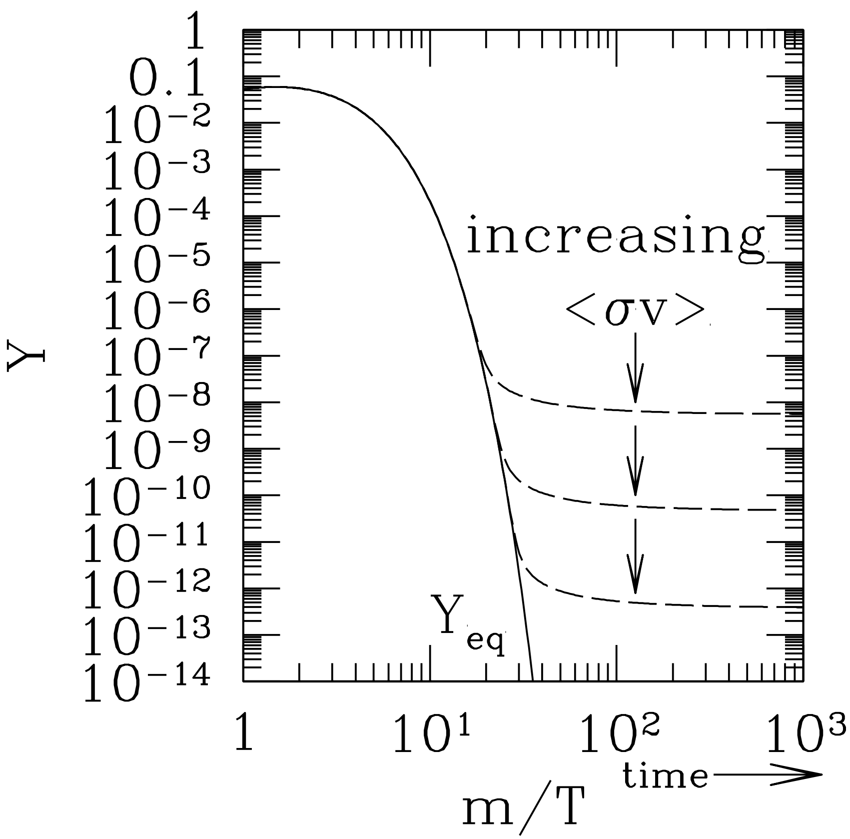
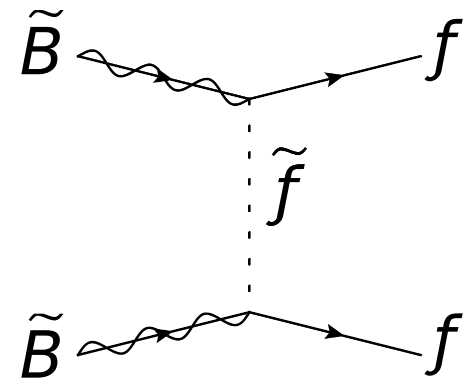


Figure from Gelmini and Gondolo, [1009.3690]

- "observed" relic density Ωh^2

$\Leftarrow$ "proper" crosssection $\langle \sigma v \rangle$ of (DM)(DM)→SM



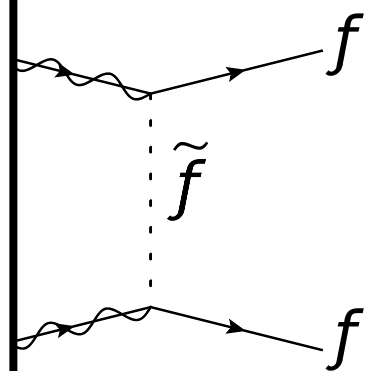
- pure $\tilde{B}$-DM (i.e., LSP $\tilde{\chi}^0$ is $\tilde{B}$-like)
  - $\langle \sigma v \rangle$ strongly depends on $m_{\tilde{f}}$

↳ $m_{\tilde{f}} \sim 100$ GeV

$$m_{\tilde{f}} \gg 100\ \text{GeV} \Longrightarrow \langle \sigma v \rangle \text{ too small}$$

$\Longrightarrow$ "overabundant" problem

- “obs ...)(DM)→SM



- pure

problem

An example in CMSSM:

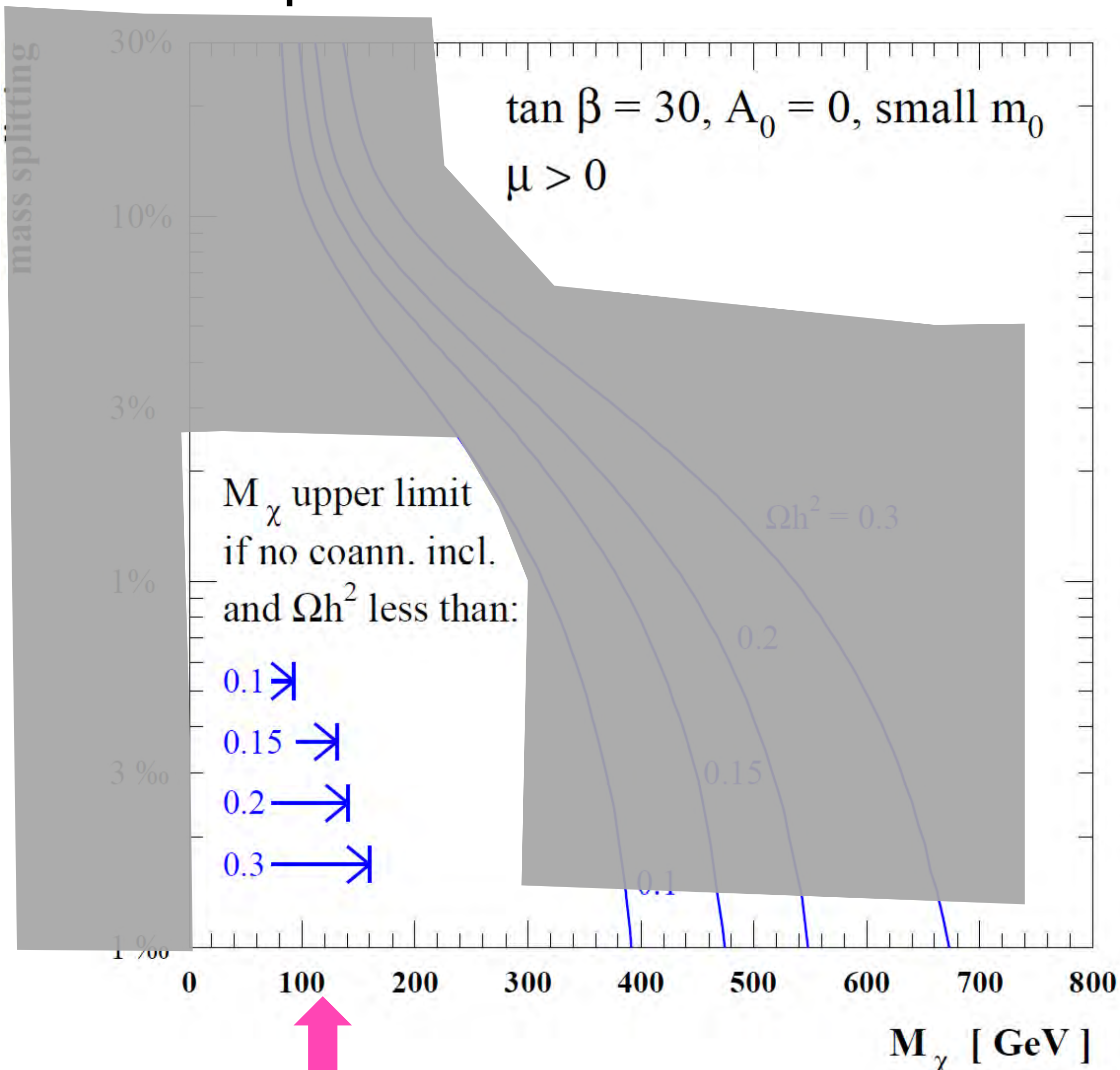
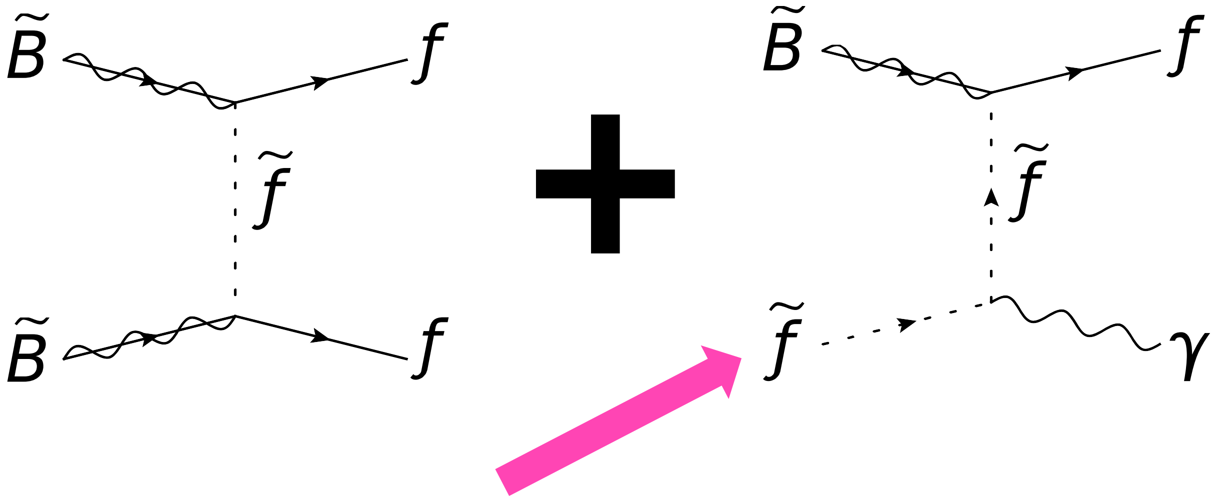


Figure from Edsjö, Schelke, Ullio, Gondolo, [hep-ph/0301106](hep-ph/0301106)

- An old solution to increase $\langle \sigma v \rangle$: “co-annihilation”



mass splitting $\dfrac{m_{\tilde{f}} - m_{\tilde{B}}}{m_{\tilde{B}}} \ll 1$

- An c … on”

An example in CMSSM:

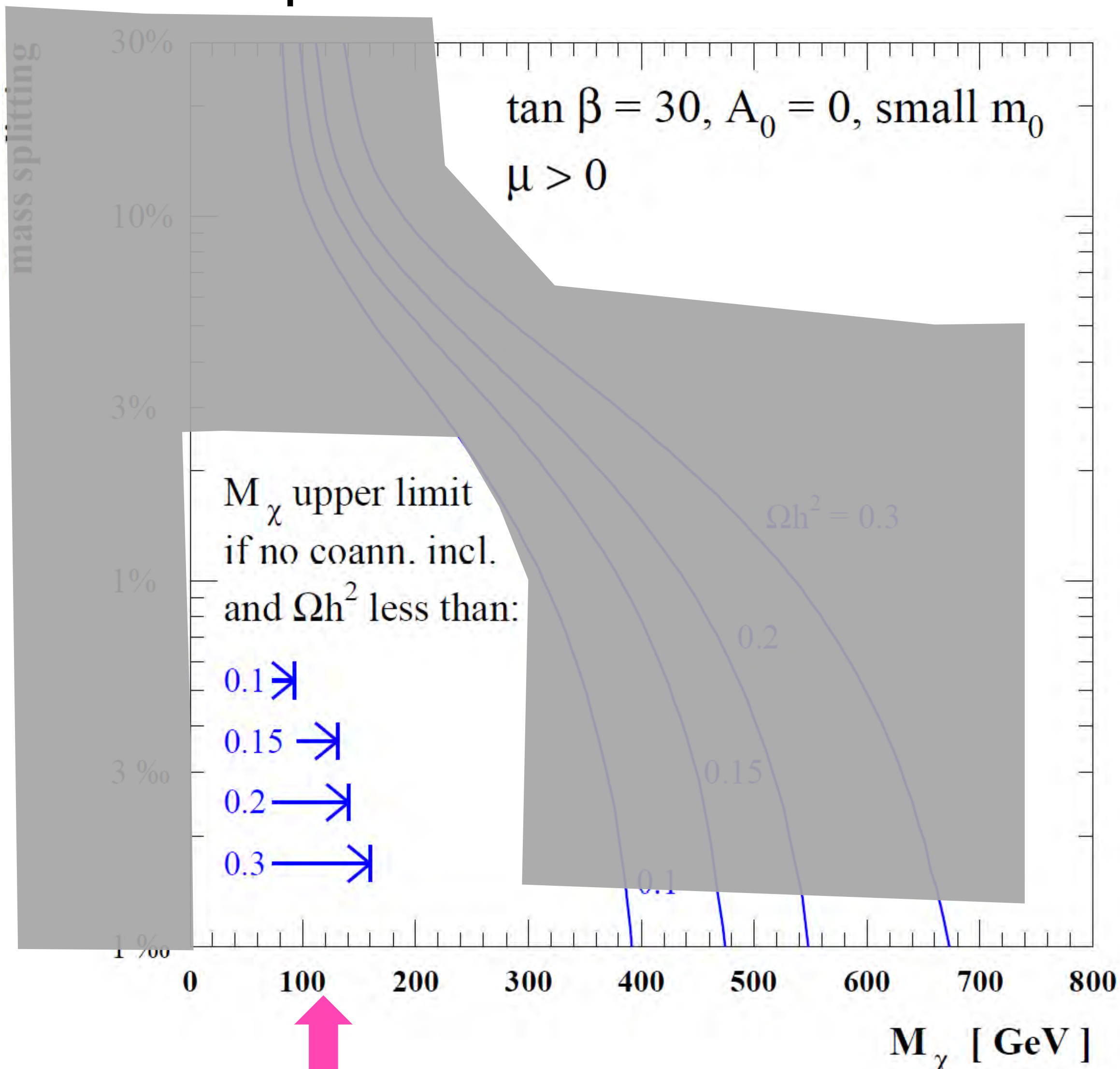


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Figure from Edsjö, Schelke, Ullio, Gondolo, [hep-ph/0301106](hep-ph/0301106)

- An c … on"

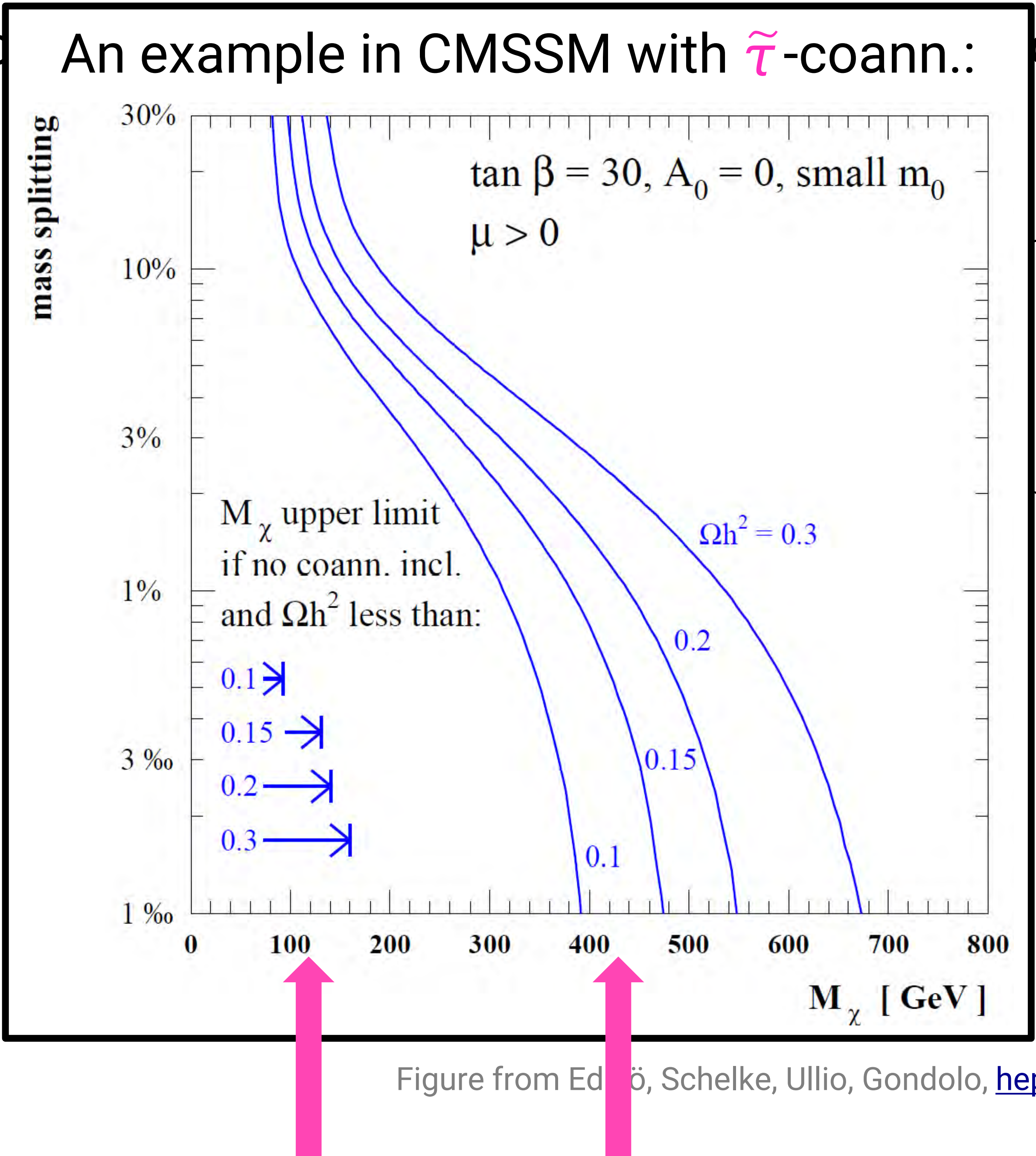

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Figure from Ed…ö, Schelke, Ullio, Gondolo, hep-ph/0301106

Introduction: why overabundant?

Model: MSSM4G solves overabundance.

Analysis:

- cosmic rays (CTA, Fermi, MAGIC)
- colliders (LHC)
- direct detection (LUX)

Summary with discussion seeds

- MSSM = **3G**enerations

+

extra vector-like
4th-Generation lepton

=

MSSM4G

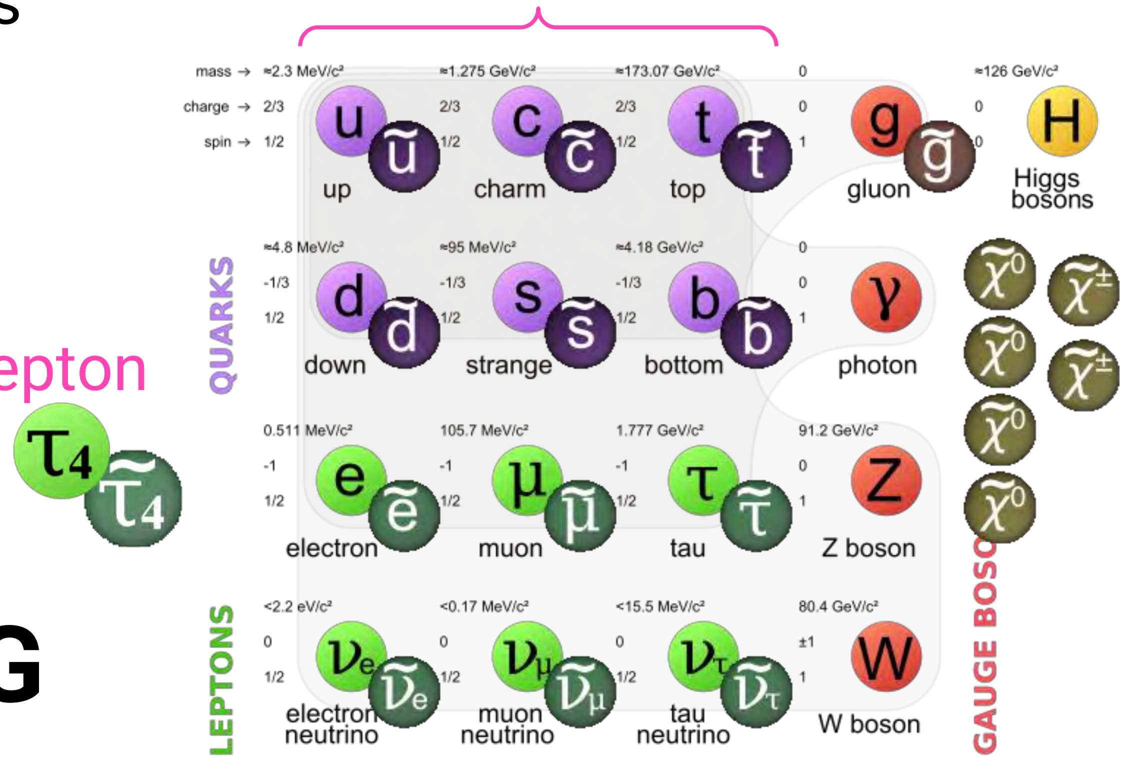
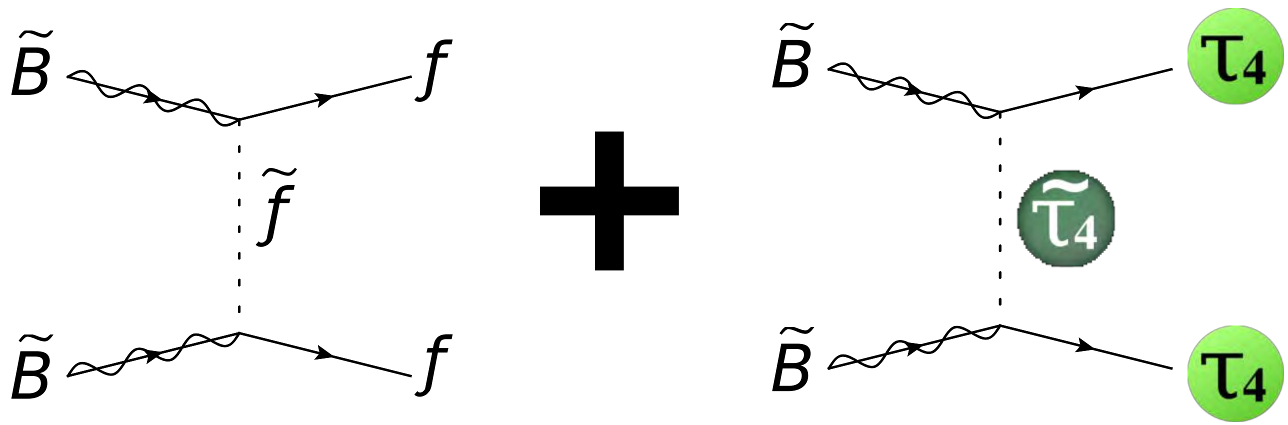


Image by MissBJ [CC BY 3.0], via Wikimedia Commons
(changes were made by S.I)

- A new solution to increase $\langle \sigma v \rangle$: MSSM4G



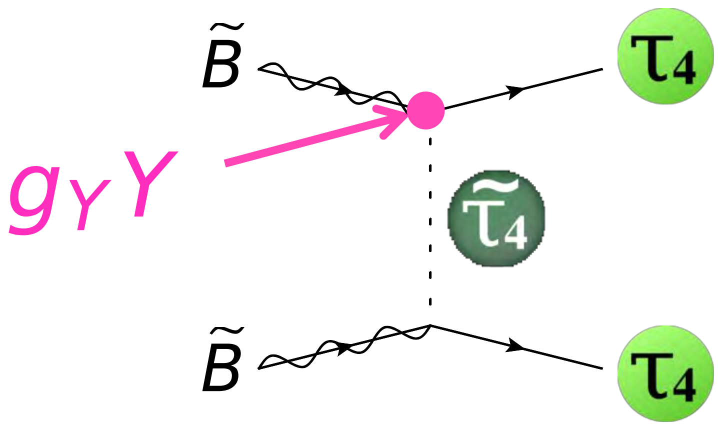
extra annihilation channel
→ larger Ωh^2
→ "proper" $\langle \sigma v \rangle$

if $\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$

$$(Q_i, \bar{U}_i, \bar{D}_i, L_i, \bar{E}_i) + (H_{\mathrm{u}}, H_{\mathrm{d}})$$ [MSSM]

$(i = 1 \ldots 3)$

$$+(E_4, \bar{E}_4)$$ [MSSM4G]



$$\Longrightarrow \langle \sigma v \rangle \propto Y^4$$

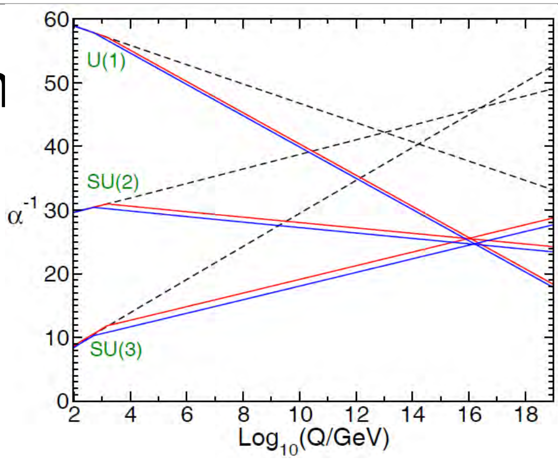
	$\mathrm{SU}(3)_{\mathrm{color}}$	$\mathrm{SU}(2)_{\mathrm{weak}}$	$\mathrm{U}(1)_Y$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$\bar{U}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\bar{E}_i$	$\mathbf{1}$	$\mathbf{1}$	1
$\bar{D}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
H_{u}	$\mathbf{1}$	$\mathbf{2}$	$1/2$
H_{d}	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\bar{E}_4$	$\mathbf{1}$	$\mathbf{1}$	1
E_4	$\mathbf{1}$	$\mathbf{1}$	-1

$$W = Y_{\mathrm{u}} H_{\mathrm{u}} Q \bar{U} + Y_{\mathrm{d}} H_{\mathrm{d}} Q \bar{D} + Y_{\mathrm{e}} H_{\mathrm{d}} L \bar{E}$$

$$+ M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_{\mathrm{d}} L_i \bar{E}_4$$

[vector-like mass] [mixing with SM leptons]

- MSSM + $E\bar{E}$ → breaks coupling unification



- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$
  - ✓ gauge coupling unification
  - ✓ SU(5) GUT
  - extra $H_u Q_4 \bar{U}_4$ interaction → m_h UP

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$
  - ✓ gauge coupling unification
  - ✗ SU(5) GUT
  - extra $H_d Q_4 \bar{D}_4$ coupling → m_h slightly UP

- MSSM + $E\bar{E}$ → breaks coupling unification

- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$

⇨ MSSM + $T_4, B_4, t_4, \tau_4,$

$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ MSSM + $T_4, B_4, b_4, \tau_4, \tau_5,$

$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{b}_{4L}, \tilde{b}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

- MSSM + $E\bar{E}$ → breaks coupling u

- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$

⇨ MSSM + ~~$T_4, B_4, t_4,$~~ $\tau_4,$

~~$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R},$~~ $\tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

assumed to be "decoupled" (very heavy) and we will ignore them.

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ MSSM + ~~$T_4, B_4, b_4,$~~ $\tau_4, \tau_5,$

~~$\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{b}_{4L}, \tilde{b}_{4R},$~~ $\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

Other working assumptions

- $M_1 \ll \mu \ll M_2$
  → LSP $\tilde{\chi}_1^0$ is $\tilde{B}$-like
- All the other SUSY particles & extra Higgses are decoupled.

- MSSM + $E\bar{E}$ → breaks coupling u

- QUE model : MSSM + $Q\bar{Q}U\bar{U}E\bar{E}$

⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4, $\tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

assumed to be equal-mass

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4, τ_5, $\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

assumed to be equal-mass (τ_4, τ_5)

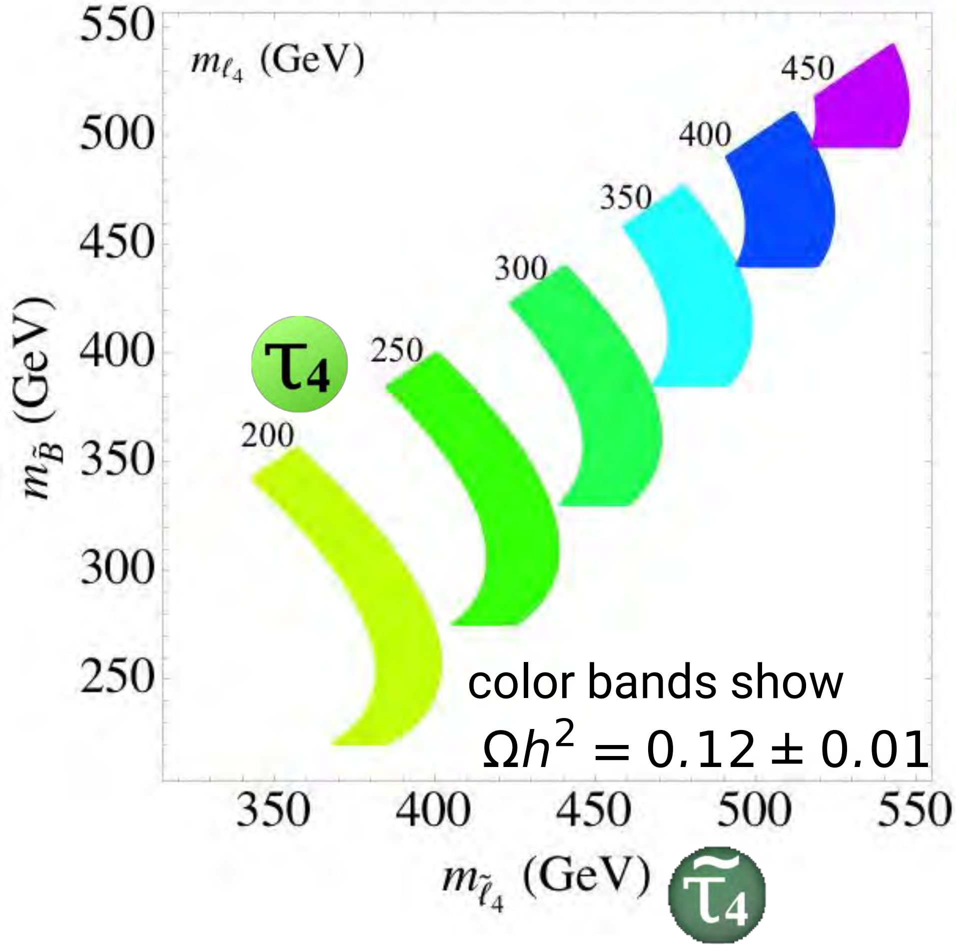
assumed to be equal-mass ($\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$)

Other working assumptions

- $M_1 \ll \mu \ll M_2$
  → LSP $\tilde{\chi}_1^0$ is $\tilde{B}$-like
- All the other SUSY particles & extra Higgses are decoupled.

Abdullah, Feng [1510.06089]

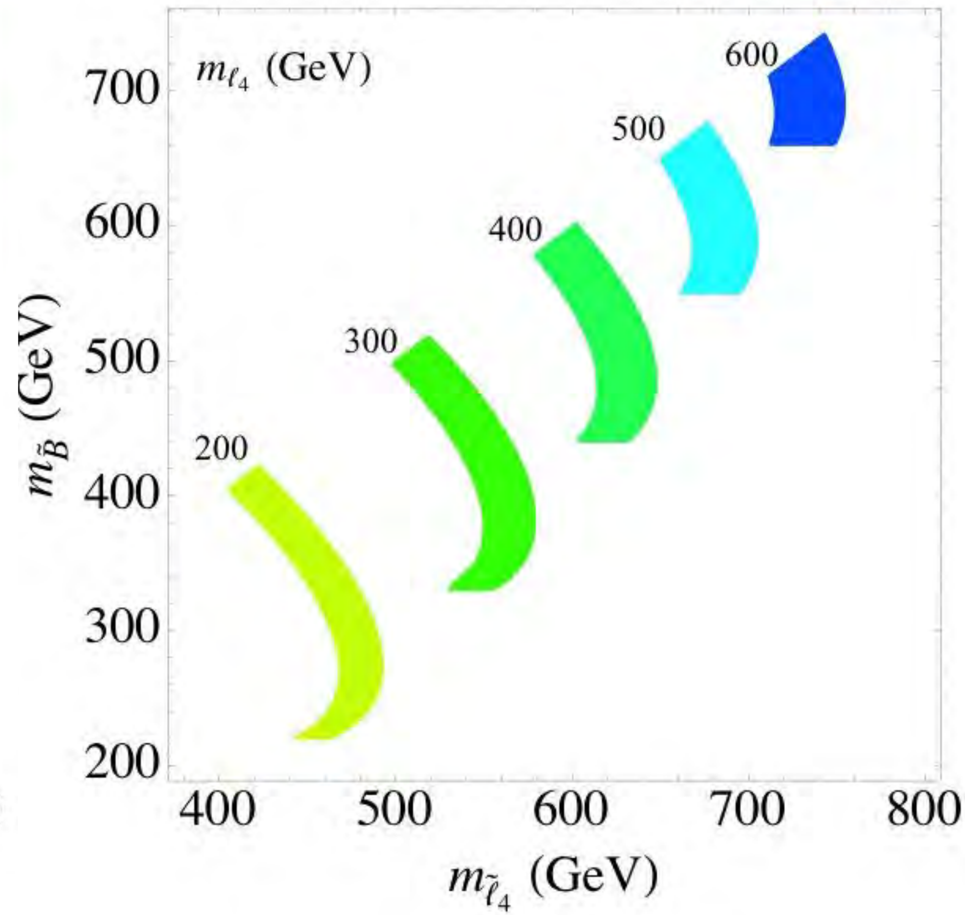
QUE model



color bands show

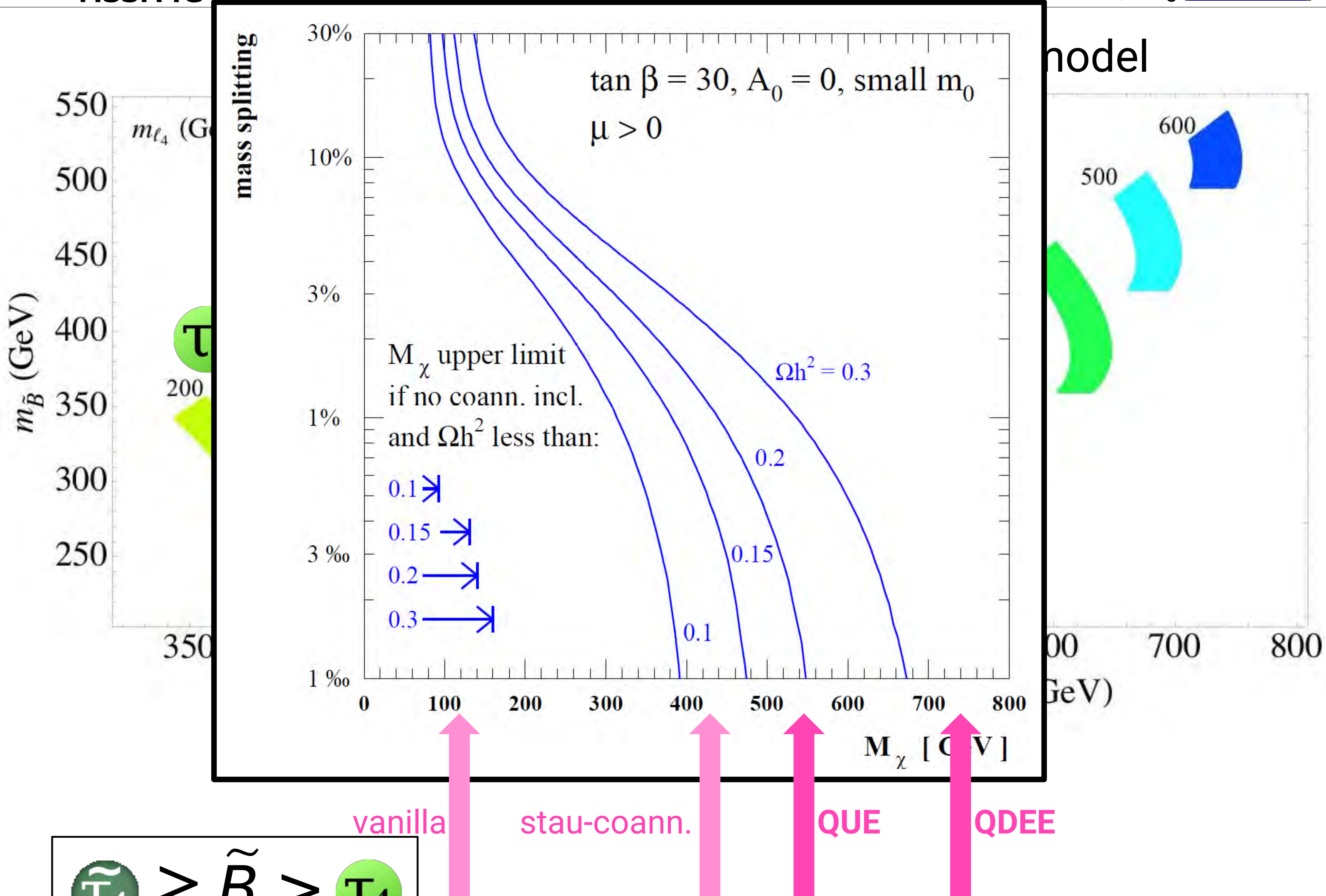
$\Omega h^2 = 0.12 \pm 0.01$

QDEE model



$$\tilde{\tau}_4 \gtrsim \tilde{B} > \tau_4$$

Abdullah, Feng [1510.06089]



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Introduction: why overabundant?

Model: **MSSM4G** solves overabundance.

Analysis:

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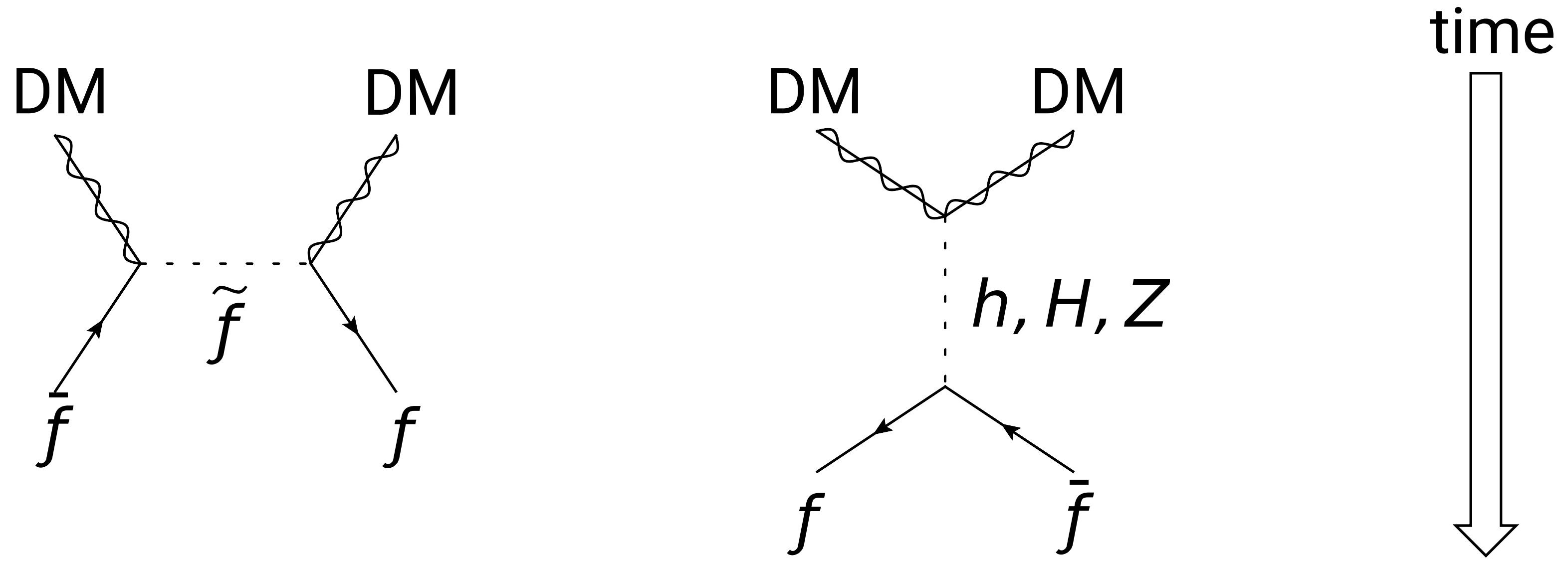
Summary with discussion seeds

- DM indirect detection (= searches for DM annihilation)



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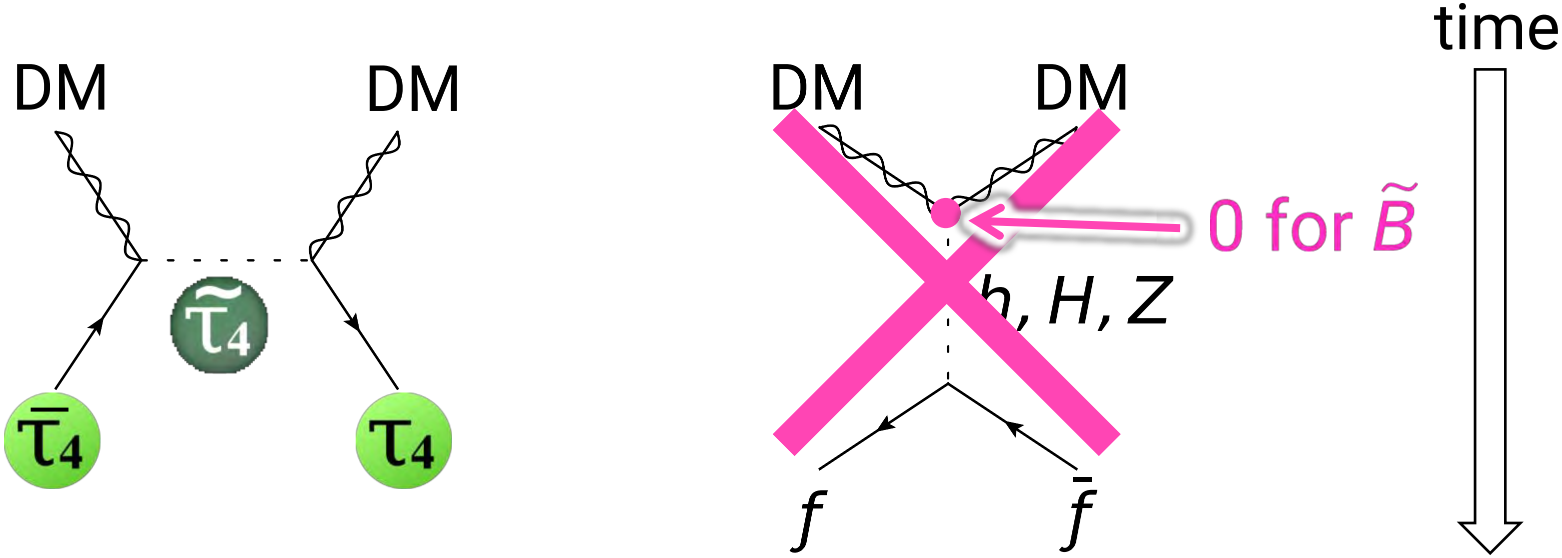
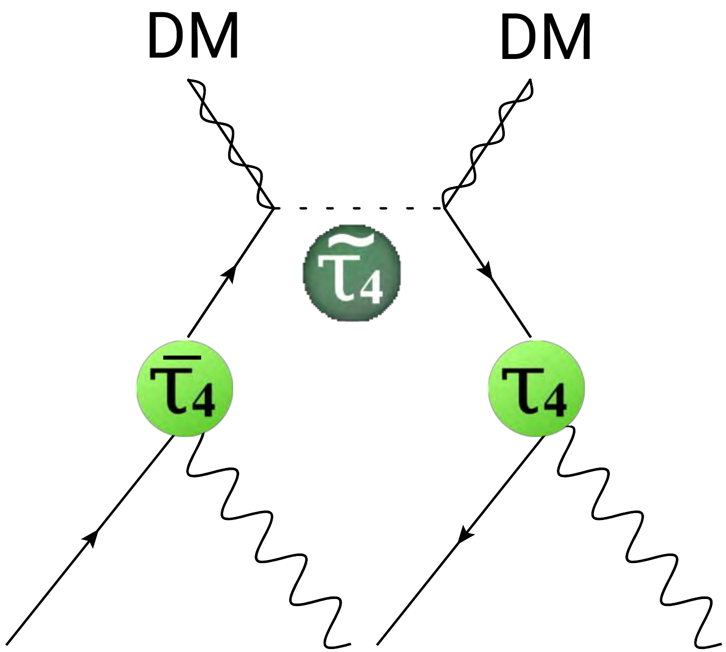


$$\langle \sigma v \rangle = \frac{g_Y^4 Y_L^2 Y_R^2}{2\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

(in convention of $Q = T_3 + Y$)

- DM indirect detection (= searches for DM DM $\to \tau_4 \bar{\tau}_4$)



$$\tau_4 \longrightarrow \begin{cases} W + \nu \\ Z + l \\ h + l \end{cases} \qquad \begin{pmatrix} \nu = \nu_e, \nu_\mu, \nu_\tau \\ l = e, \mu, \tau \end{pmatrix}$$

$$W\nu : Zl : hl \sim 2 : 1 : 1$$

$$W \ni Y_e H_d L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_d L_i \bar{E}_4$$

[vector-like mass] [mixing with SM leptons]

$$\langle \sigma v \rangle = \frac{g_Y^4 Y_L^2 Y_R^2}{2\pi} \frac{m_f^2}{m_{\widetilde{B}}} \frac{\sqrt{m_{\widetilde{B}}^2 - m_f^2}}{\left(m_{\widetilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

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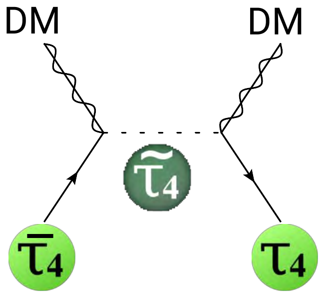

	DM DM→				
$\tau_{4(5)}$ mixes with e	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	e^+e^-
$\tau_{4(5)}$ mixes with μ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\mu^+\mu^-$
$\tau_{4(5)}$ mixes with τ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\tau^+\tau^-$

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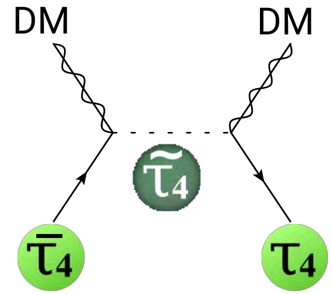


$W\nu : Zl : Hl \sim 2 : 1 : 1$

insensitive (IceCube)

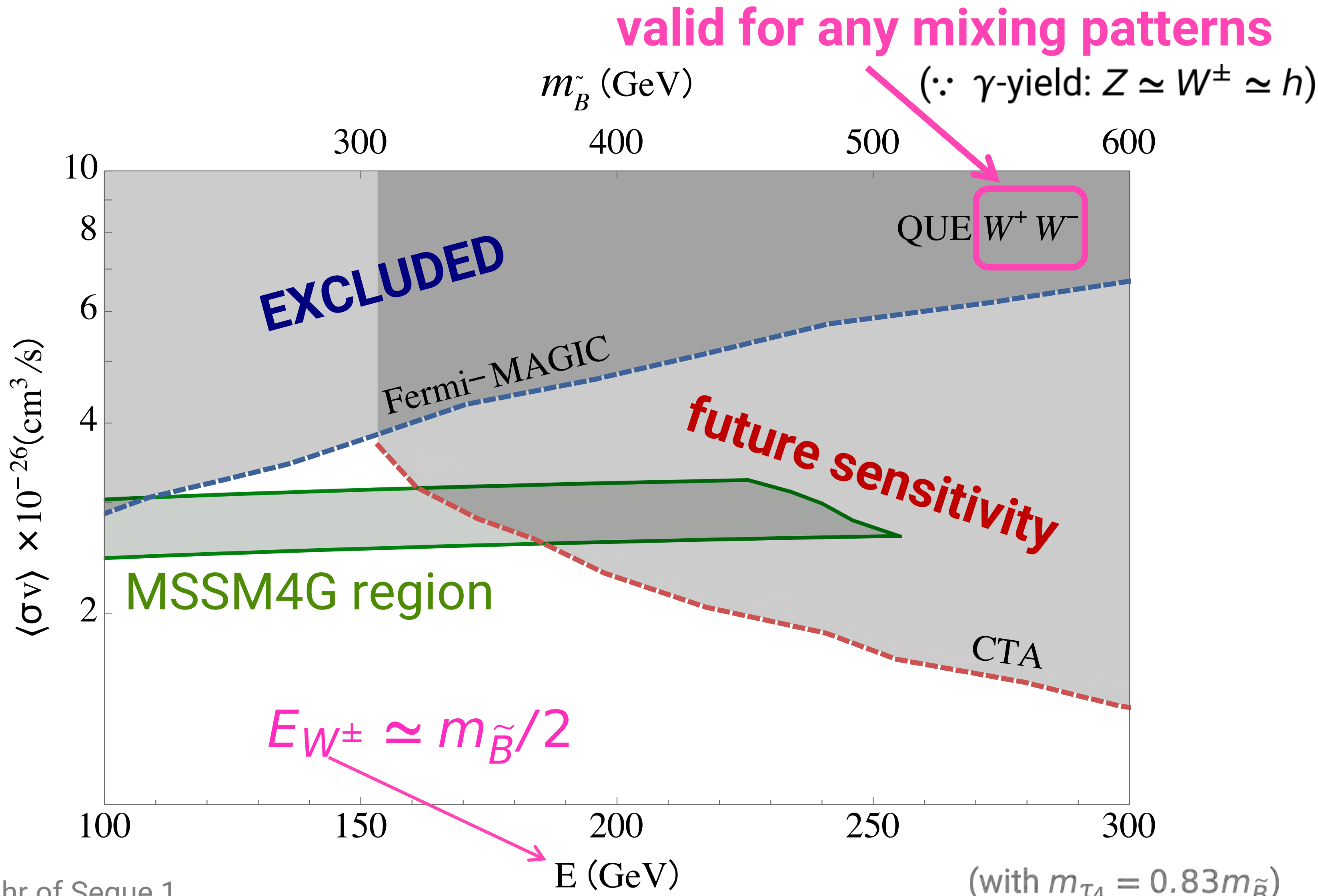
less sensitive / large BKG uncertainty

	DM DM→				
$\tau_{4(5)}$ mixes with e	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	e^+e^-
$\tau_{4(5)}$ mixes with μ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\mu^+\mu^-$
$\tau_{4(5)}$ mixes with τ	W^+W^-	ZZ	hh	$\nu\bar{\nu}$	$\tau^+\tau^-$

$\rightarrow \pi^0 \rightarrow \gamma$

$\rightarrow \cdots \rightarrow \gamma$

Abdullah, Feng, SI, Lillard [1608.00283]



MAGIC: 158 hr of Segue 1

Fermi-LAT: 6 yr of 15 dSph (incl. Segue 1)

DM profile: NFW

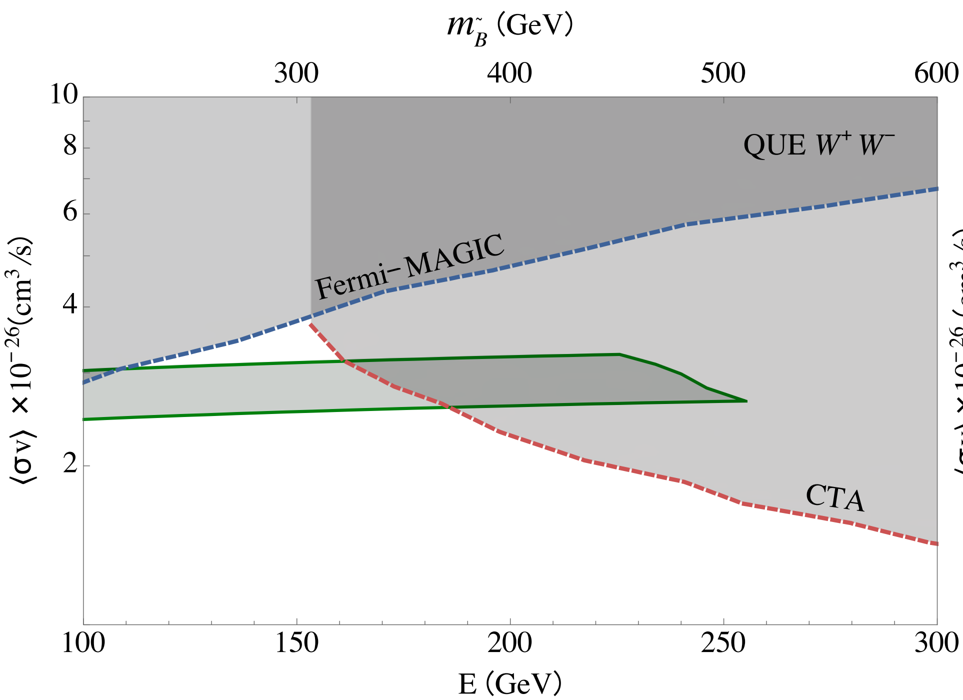
Fermi-LAT dominates MAGIC in almost all *E*-range.

CTA prospect : 500hr of Milky Way

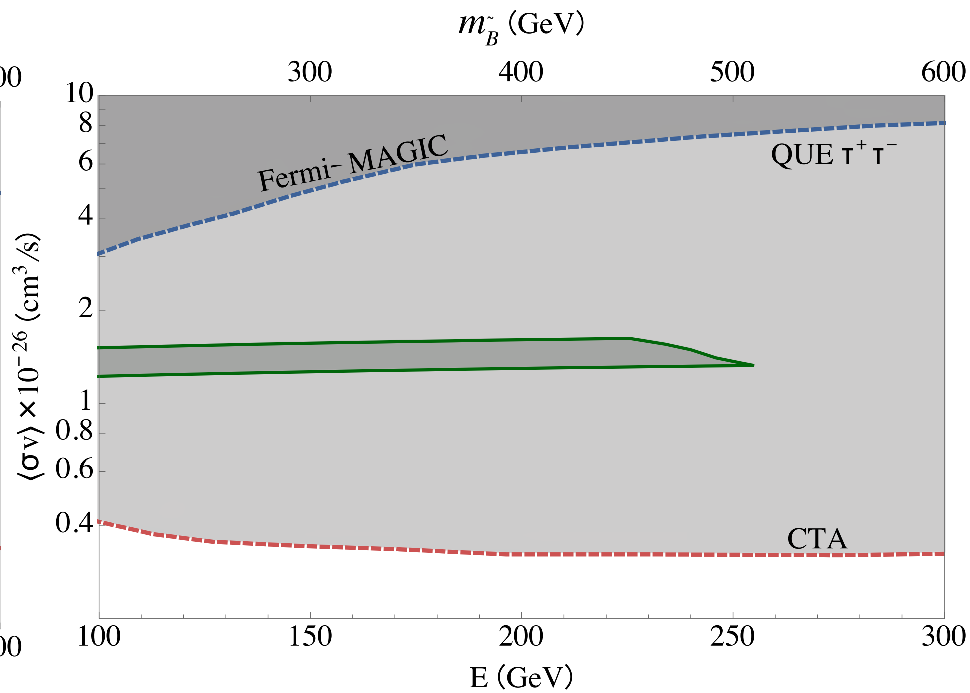
DM profile: Einasto

No syst. unc. (stat only)

WW (any mixing pattern)



ττ (only for τ-mixing cases)



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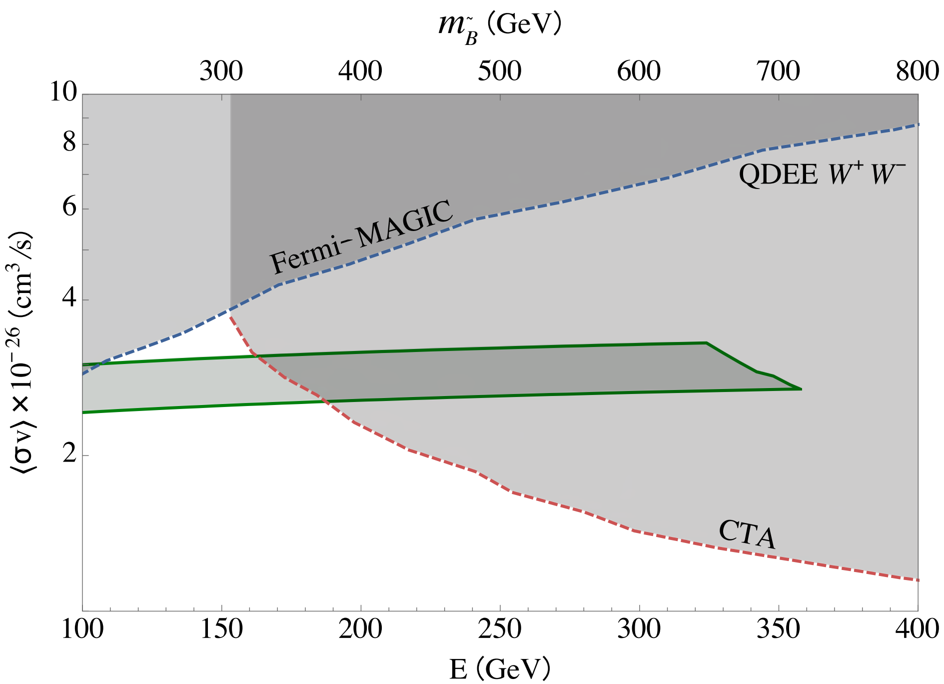

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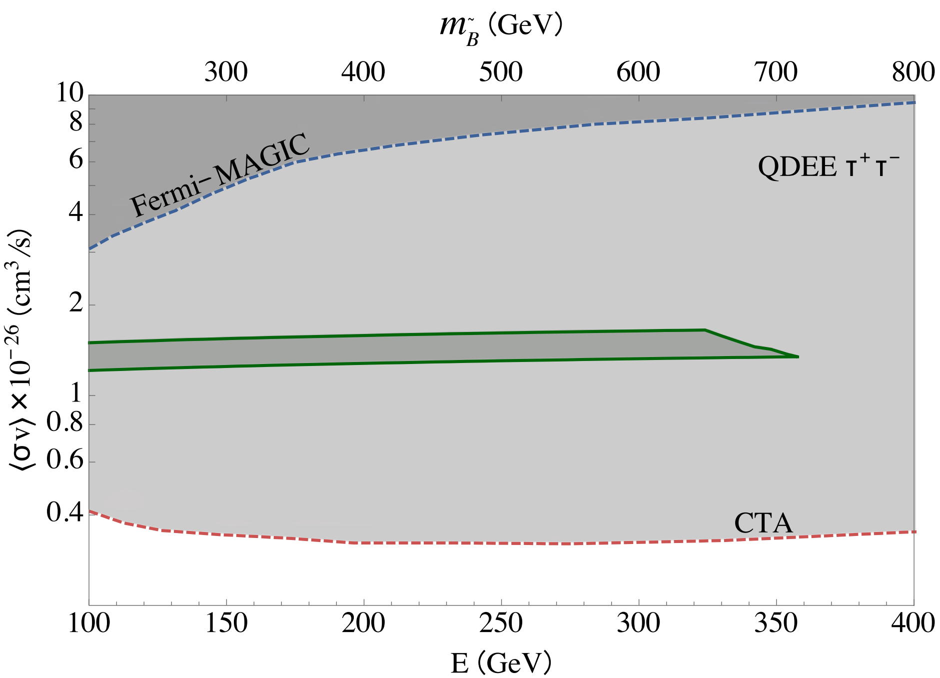

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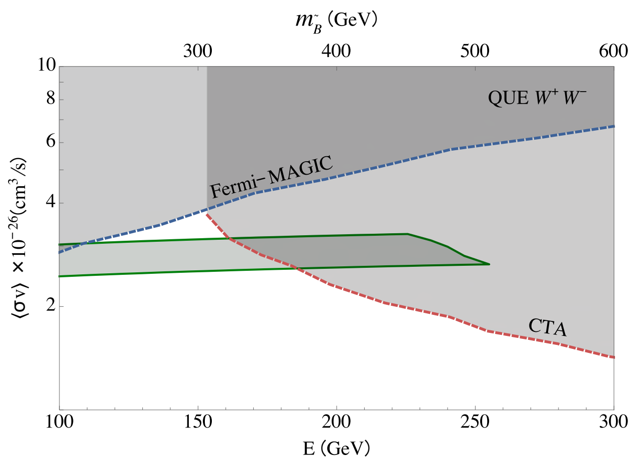
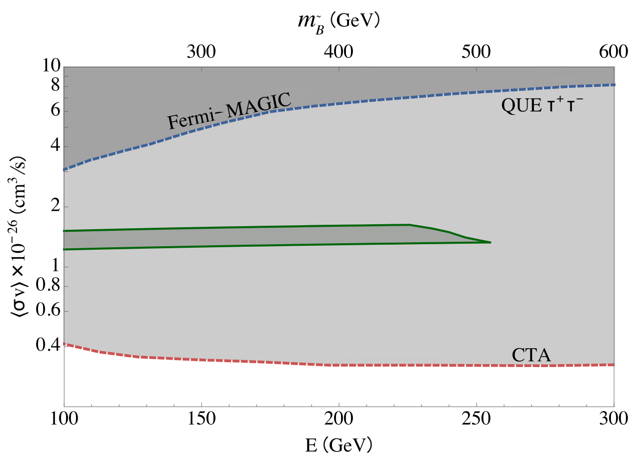
	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}} > 340\text{–}380$ GeV		**full coverage**
HL-LHC			

e/μ-mixing, QUE



τ/μ-mixing, QUE



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⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4,

$\underbrace{\tilde{\tau}_{4L}, \tilde{\tau}_{4R}}_{\text{assumed to be equal-mass}}$

- QDEE model : MSSM + $Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, $\overbrace{\tau_4, \tau_5}^{\text{assumed to be equal-mass}}$,

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⇨ SM + $\tilde{\chi}_1^0(\approx \tilde{B})$, τ_4,

$\tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

assumed to be equa

slepton search

$\tilde{\tau}_4 \nrightarrow \tau_4 + \tilde{B}$

$\longrightarrow (e, \mu, \tau) + \tilde{B}$

$\equiv 2(4) \times \tilde{l}_R$

extra lepton search

$\tau_4 \rightarrow W\nu, Zl, hl$

(as discussed before)

standard searches
for vectorlike leptons
(but 2x in QDEE)

$+ Q\bar{Q}D\bar{D}E\bar{E}E\bar{E}$

assumed to be equal-mass

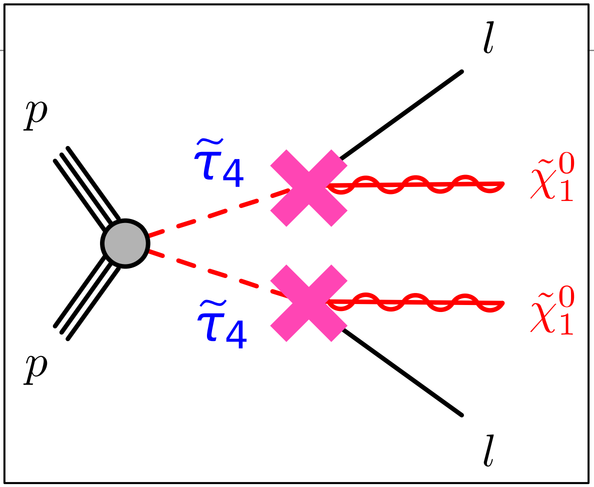
$\tau_4, \tau_5,$

$\tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

assumed to be equal-mass

$$pp \to \tilde{\tau}_{4(,5)}\tilde{\tau}^*_{4,(5)} \equiv pp \to \tilde{l}_R \tilde{l}^*_R$$

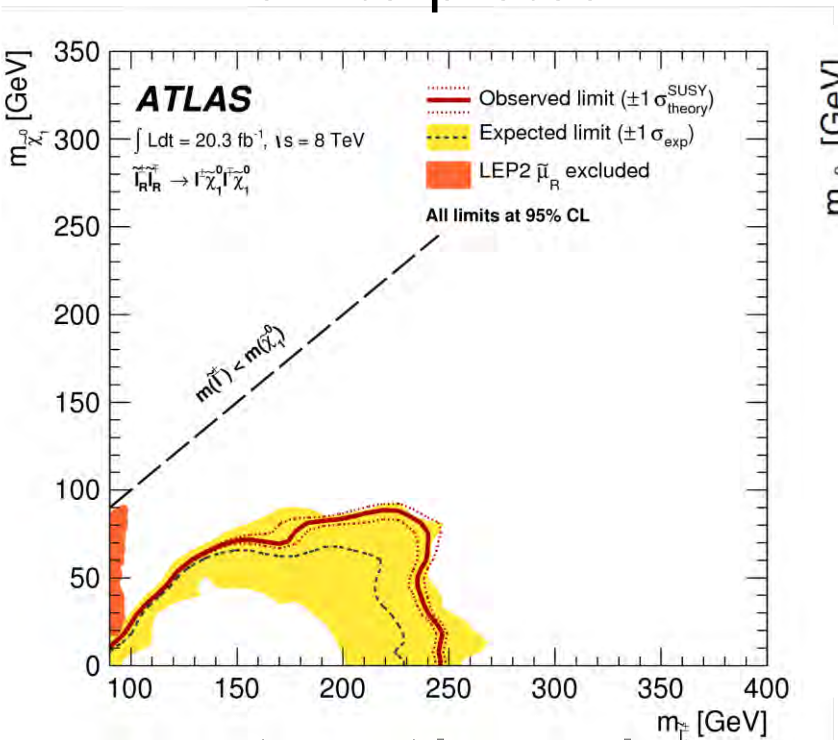
determined by mixing parameters



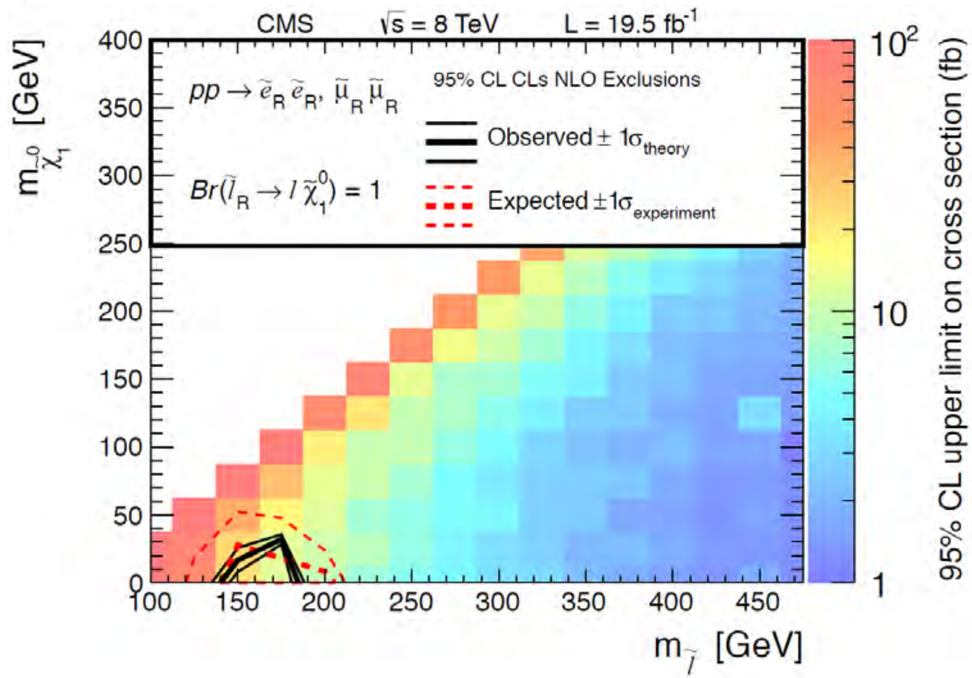
e/μ-mixing → slepton searches $(\tilde{e}_R, \tilde{\mu}_R)$ × 2 (4)

14 TeV prospects studied in 1408.2841 (Eckel, Ramsey-Musolf, Shepherd, Su)

→ re-interpreted



ATLAS (8TeV full) [1403.5294]



CMS (8TeV full) [1405.7570]

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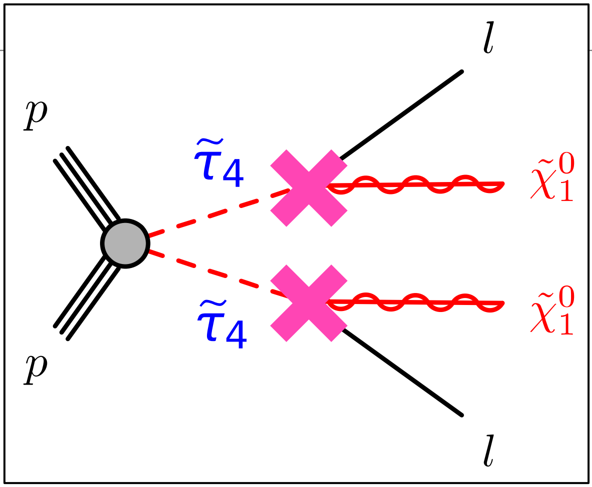
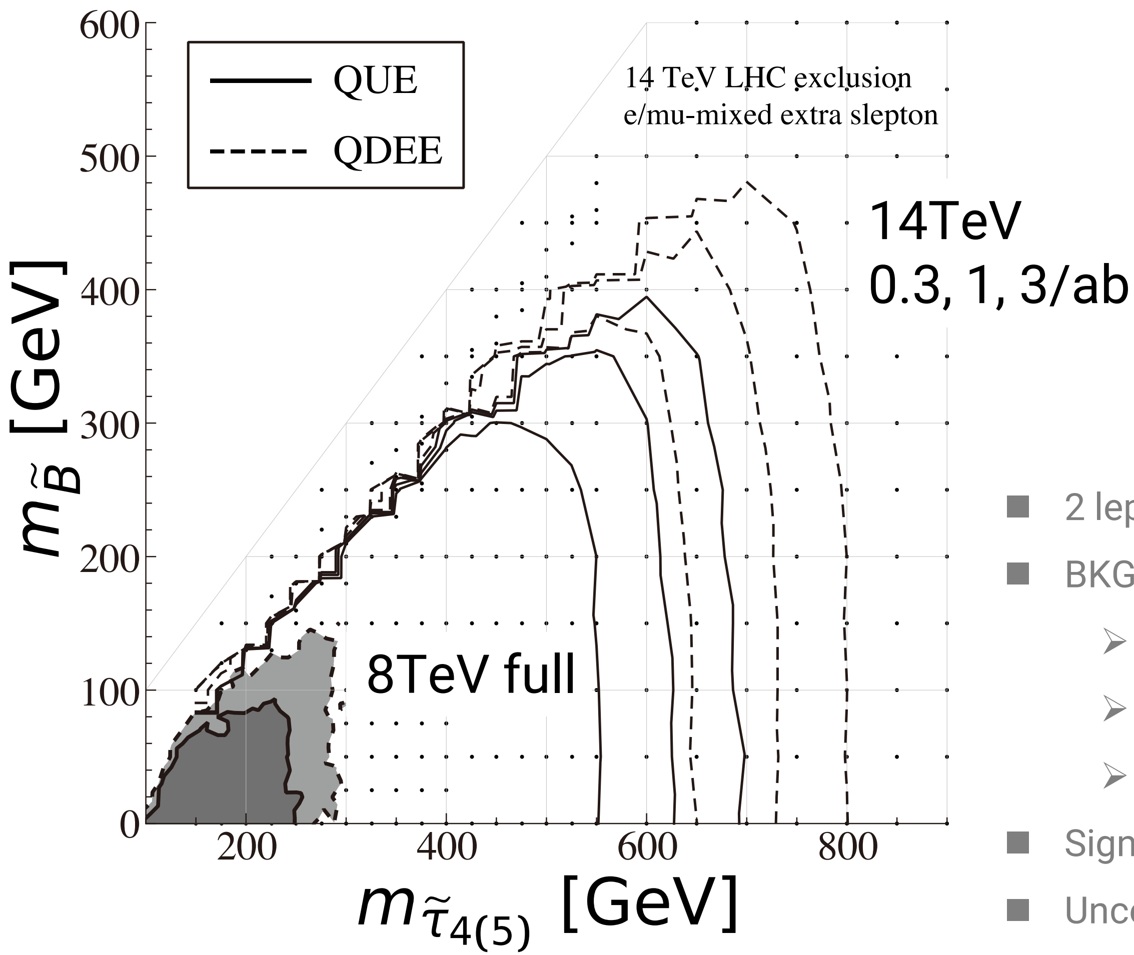
determined by mixing parameters

e/μ-mixing → slepton searches × 2 (4)
$(\tilde{e}_R, \tilde{\mu}_R)$



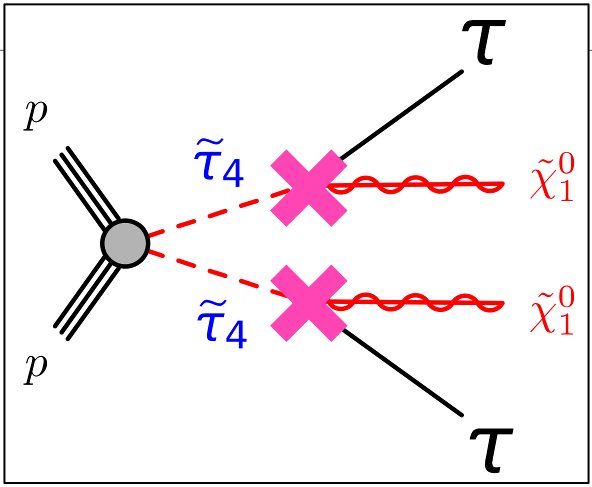


- 2 lepton + MET + mT2 + jet-veto
- BKG taken from 1408.2841
  - MG5−Pythia−Delphes (also for signal)
  - rescaled by NLO *K*-factor
  - di-boson dominates
- Signal events at LO level
- Uncertainties = stat. + 5% syst.

$$pp \to \tilde{\tau}_{4(,5)}\tilde{\tau}^*_{4,(5)} \equiv pp \to \tilde{l}_R \tilde{l}^*_R$$

↑ determined by mixing parameters

τ-mixing → stau searches × 2 (4)



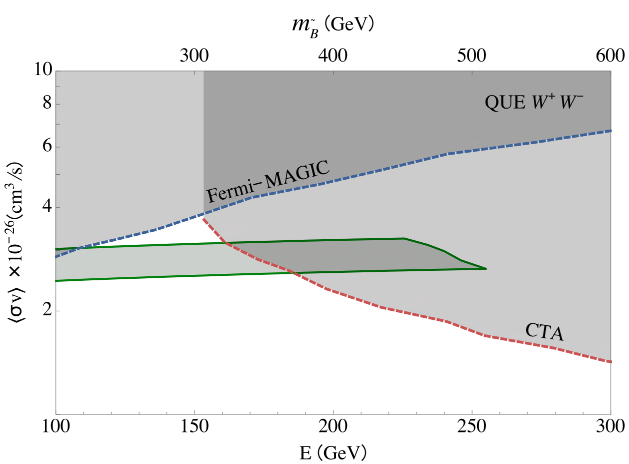
→ No constraint expected.

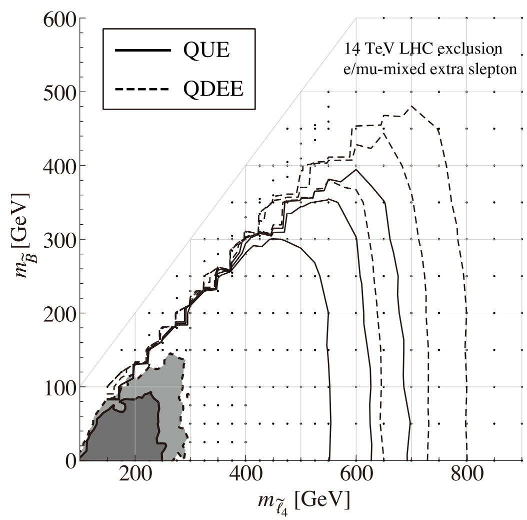
- LHC Run 1 provided no limit on MSSM stau mass.
- 14TeV, 3/ab LHC will not exclude MSSM4G parameter region.

Summary

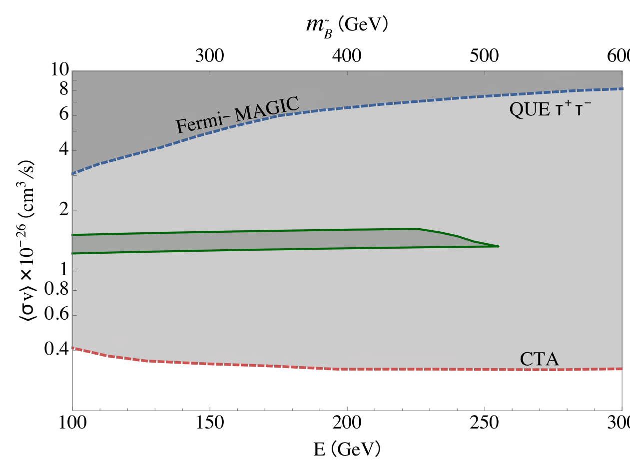
	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}}$ > 340–380 GeV		**full coverage**
HL-LHC (slepton)	covers $m_{\tilde{B}}$ < 400 (480) GeV (but not “degenerate” region)		–
HL-LHC (lepton)			

e/μ-mixing

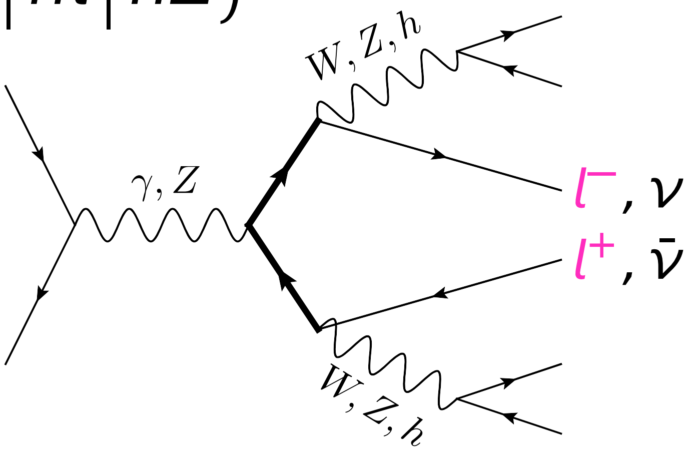




τ/μ-mixing, QUE



$$pp \to \tau^+_{4(,5)} \tau^-_{4,(5)} \to \left(W\nu \middle| hl \middle| Zl\right)\left(W\nu \middle| hl \middle| hZ\right)$$



e/μ-mixing case

"vectorlike lepton searches" by
multi-$\ell^\pm$ signature ($3-5\ell^\pm$)

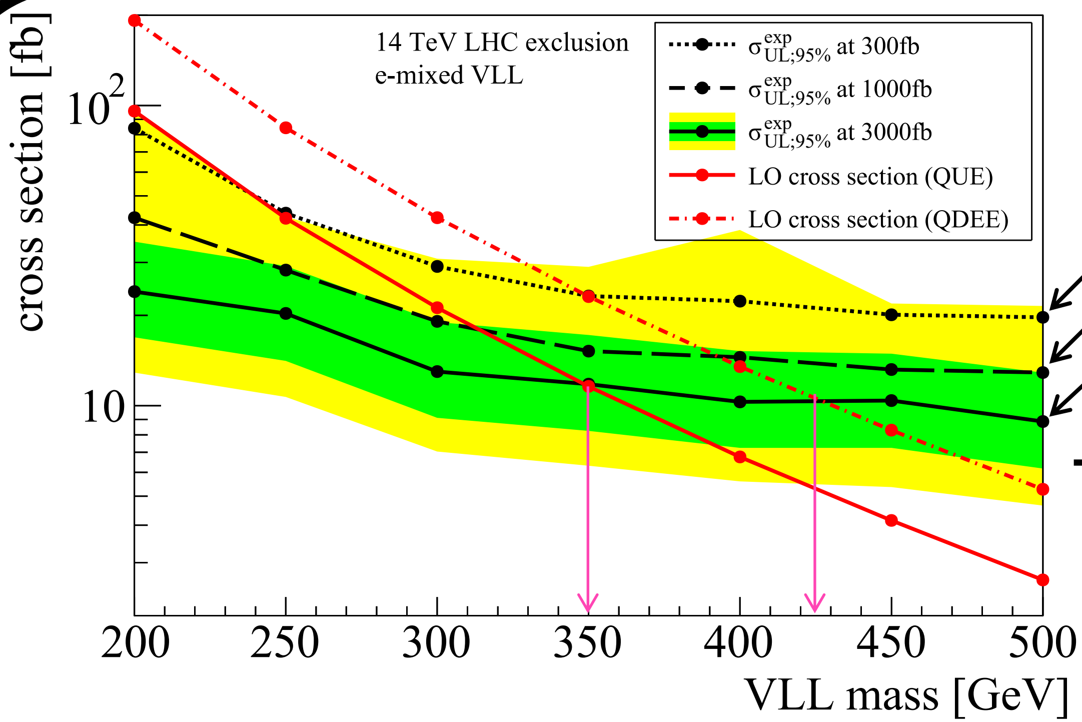
[Cf. ATLAS collaboration, 1506.01291]

$$\begin{cases} W\nu Z\ell \to 3\ell \ (1.3\%) \\ W\nu h\ell \to 3\ell \ (0.6\%) \\ h\ell Z\ell \to 3\ell \ (0.8\%) \\ h\ell h\ell \to 3\ell \ (0.8\%) \end{cases} \quad \begin{cases} W\nu Z\ell \to 4^+\ell \ (0.4\%) \\ h\ell Z\ell \to 4^+\ell \ (1.0\%) \\ Z\ell Z\ell \to 4^+\ell \ (0.8\%) \\ h\ell h\ell \to 4^+\ell \ (0.2\%) \end{cases}$$

→ Monte Carlo simulation

$$pp \to \tau^{+}_{4(,5)}\tau^{-}_{4,(5)} \to (W\nu|hl|Zl)(W\nu|hl|hZ)$$

e/μ-mixing case



0.3ab

1ab

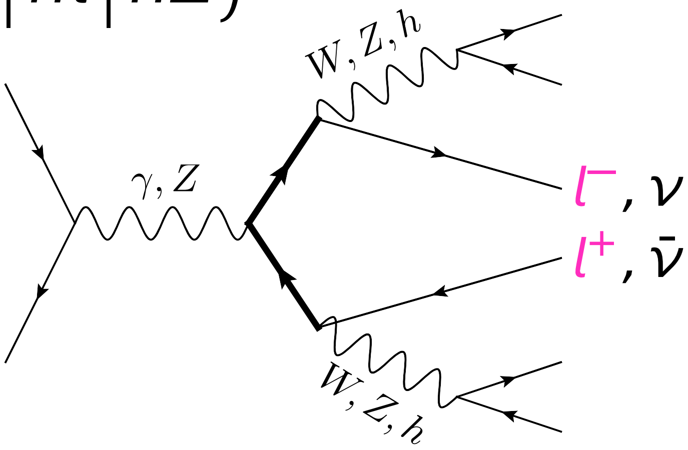
3ab (with 1&2σ band)

→ 14TeV, 3/ab covers m_{τ_4} < 350 (425) GeV

QUE QDEE

- Snowmass BKG set is used.
  - MG5−Pythia−Delphes + NLO *K*-factor
  - di-boson + *tt* dominated
- Signal by FR−MG5aMC−Pythia−Delphes (LO)
- SR dedicated for WZ / ZZ + leptons
  - 3L, 4L for WZ, and 4L, 5L for ZZ
  - tau-tag / b-tag not used (avoided)
- Uncertainties = stat. + 20% syst.

$$pp \to \tau^+_{4(,5)}\tau^-_{4,(5)} \to (W\nu|hl|Zl)(W\nu|hl|hZ)$$



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→ 14TeV, 3/ab covers m_{τ_4} < 350 (425) GeV
QUE QDEE

τ-mixing case

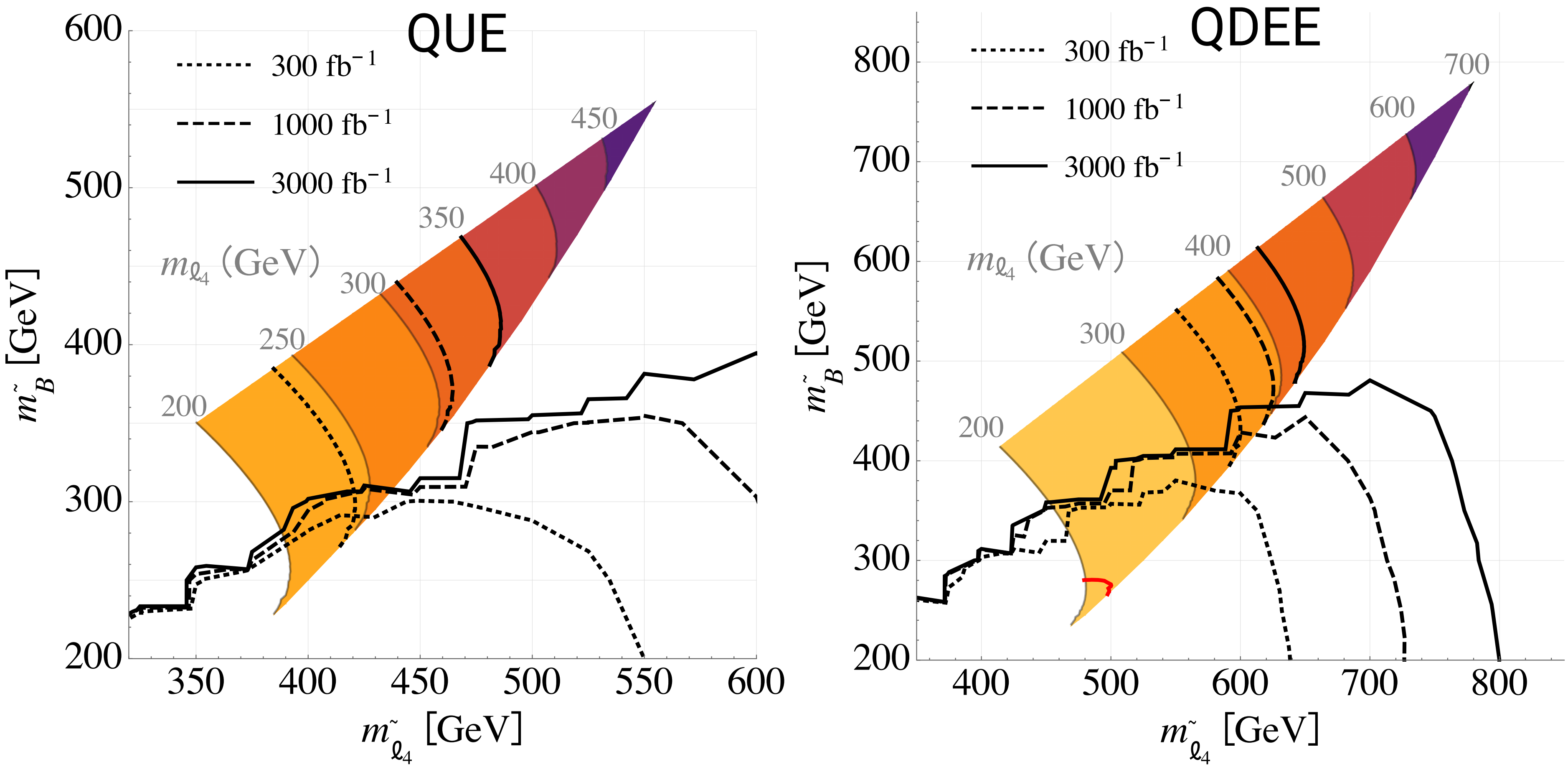
✓ 1510.03456 (Kumar and Matrin)

- SRs: 4(e, mu, had-tau)
- Signal and BKG by their MC (FR−MG5−Pythia−Delphes)
- no prospects for exclusion if BKG syst. unc. > 10%

→ 13 TeV, 3/ab covers m_{τ_4} < 234 (264) GeV

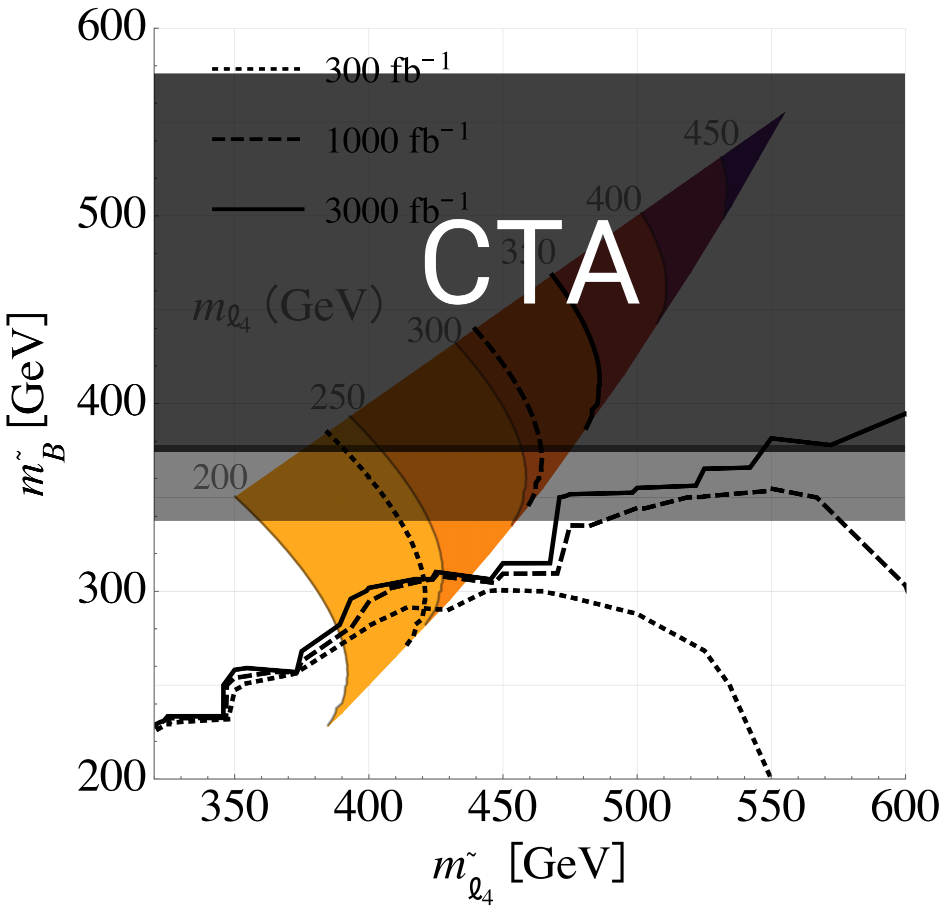
with "a very optimistic BKG estimation"

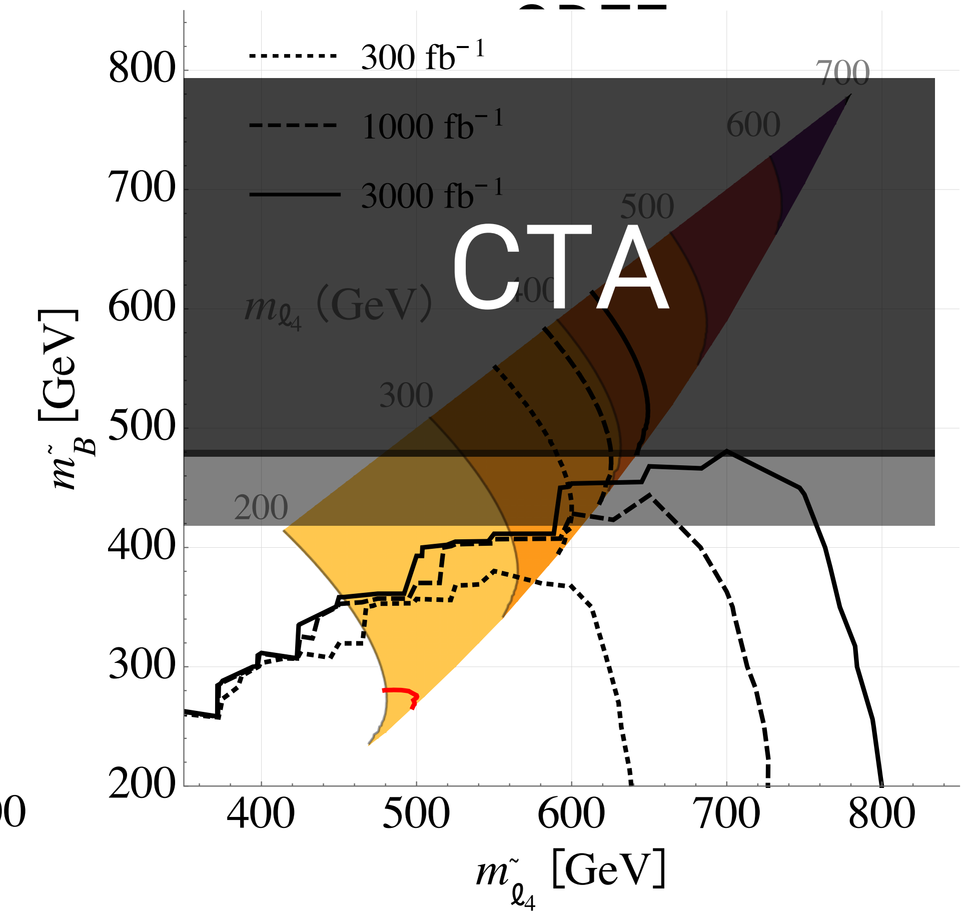
- e/μ-mixing cases



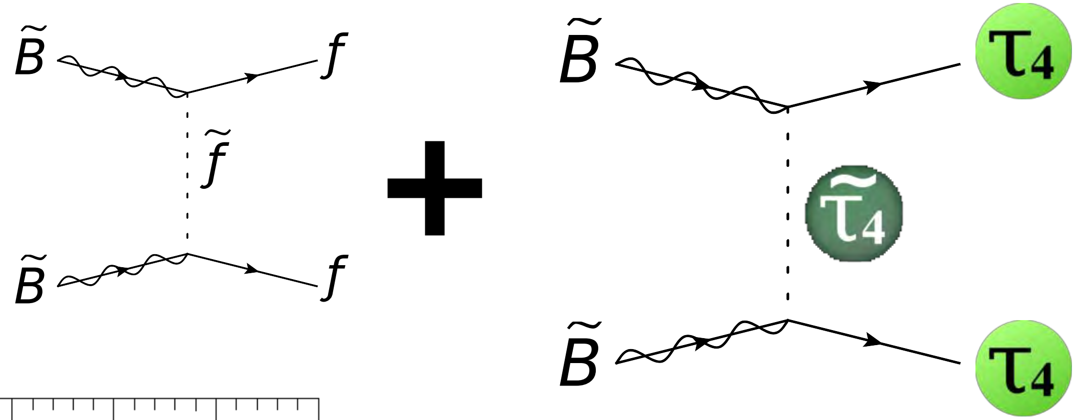
- τ-mixing case
  - LHC insensitive … (´・ω・`)

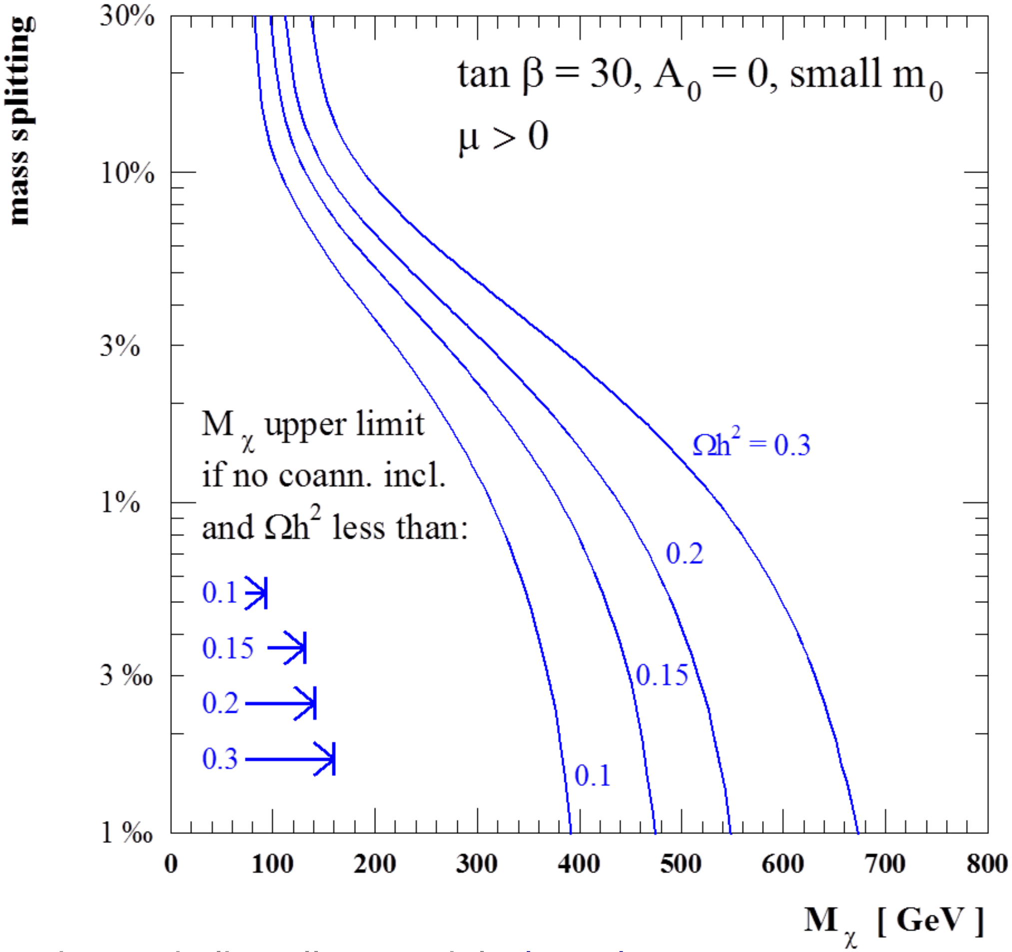
- e/μ-mixing cases





- τ-mixing case
  - LHC insensitive, but CTA covers full region





extra annihilation channel

→ larger Ωh^2

→ "proper" $\langle \sigma v \rangle$

if $\widetilde{\tau}_4 \gtrsim \widetilde{B} > \tau_4$

$$\langle \sigma v \rangle \propto Y^4 \Longrightarrow \text{MSSM} + E\bar{E}$$

$$Y_\mathrm{u} H_\mathrm{u} Q \bar{U} + Y_\mathrm{d} H_\mathrm{d} Q \bar{D} + Y_\mathrm{e} H_\mathrm{d} L \bar{E} + M_{E_4} E_4 \bar{E}_4 + \epsilon_i H_\mathrm{d} L_i \bar{E}_4$$

Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

	e-mixing	μ-mixing	τ-mixing
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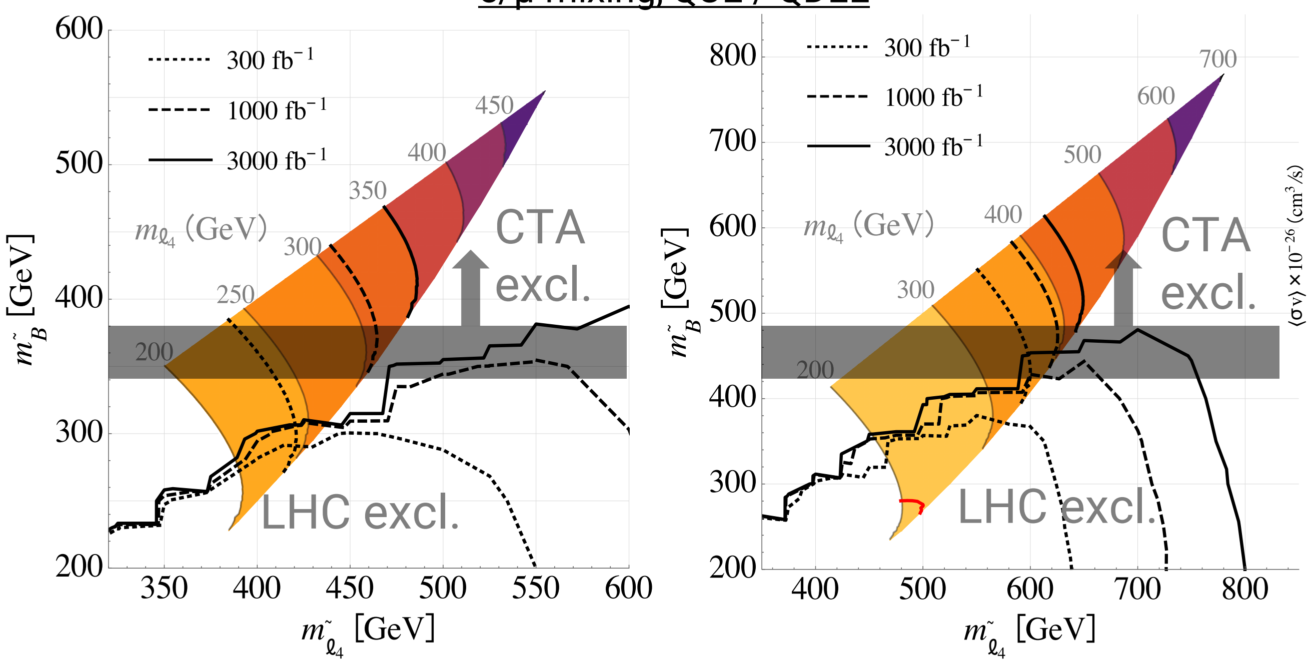
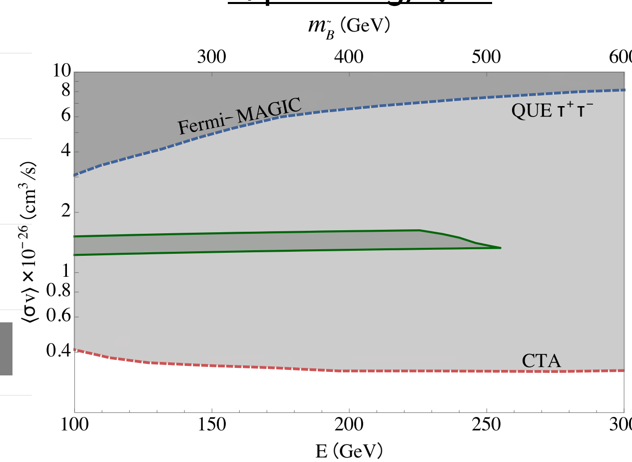
HL-LHC (slepton)	covers $m_{\tilde{B}}$ < 400 (480) GeV (but not “degenerate” region)		−
HL-LHC (lepton)	covers m_{τ_4} < 350 (430) GeV equivalent to $m_{\tilde{B}}$ < 380 (480) GeV		−

e/μ-mixing, QUE / QDEE



τ/μ-mixing, QUE



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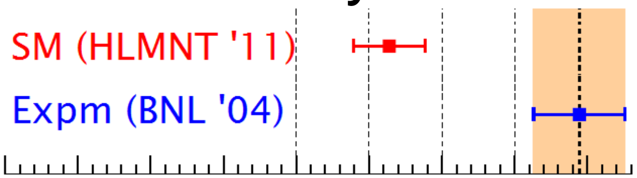
- colliders (LHC)
- direct detection (LUX)

Summary with discussion seeds

: "muon $g-2$ problem"

$$\left(a_\mu := \frac{g_\mu - 2}{2} \right)$$

■ $(g-2)_\mu$ anomaly



Hagiwara, Liao, Martin, Nomura, Teubner [1105.1439]

$$a_\mu^{\mathrm{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$

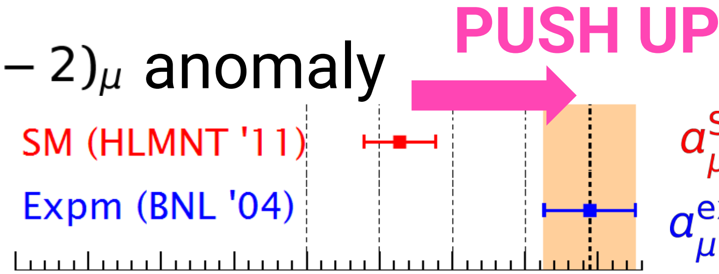
$$a_\mu^{\mathrm{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

3.3σ discrepancy

MSSM: extra contribution → MSSM **may** explain this anomaly.

$$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$$

- $(g-2)_\mu$ anomaly



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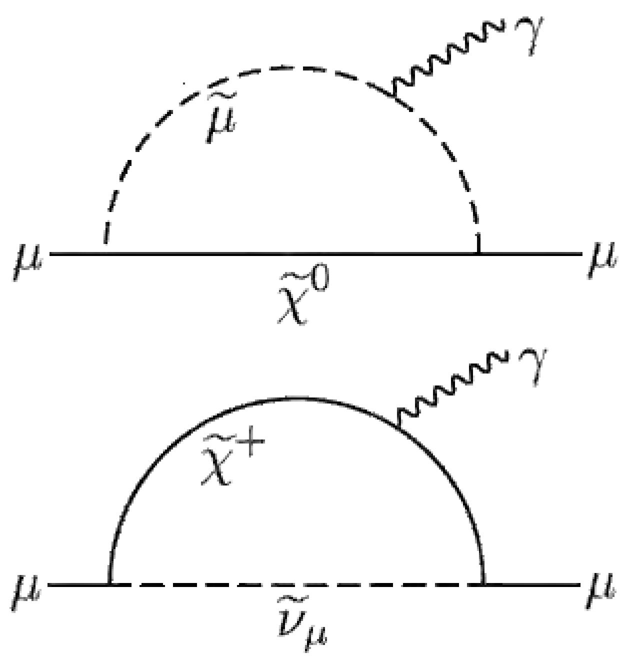
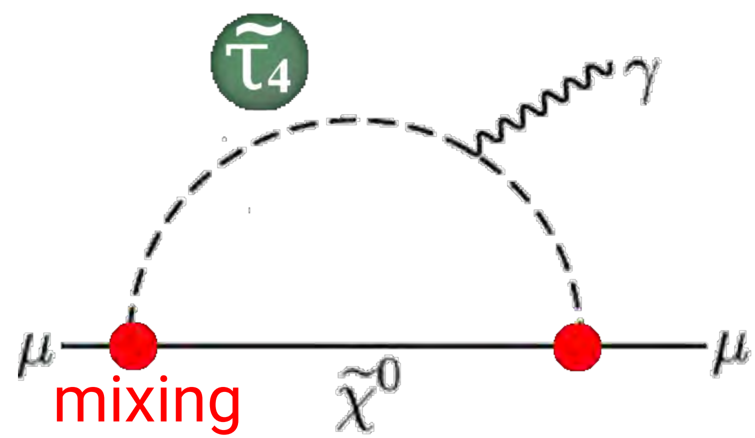


4G extra contribution?



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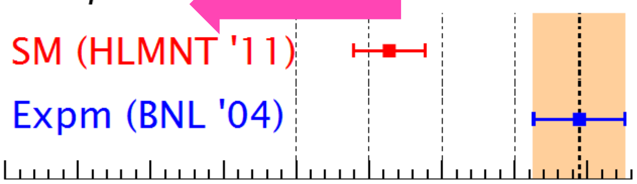
- $(g-2)_\mu$ anomaly

PUSH DOWN



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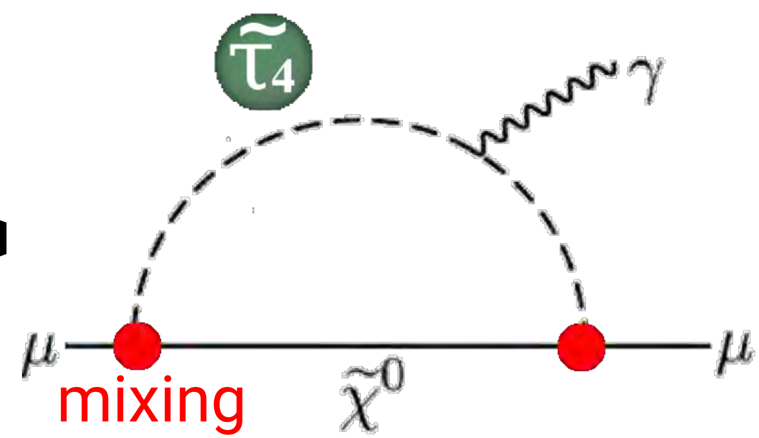
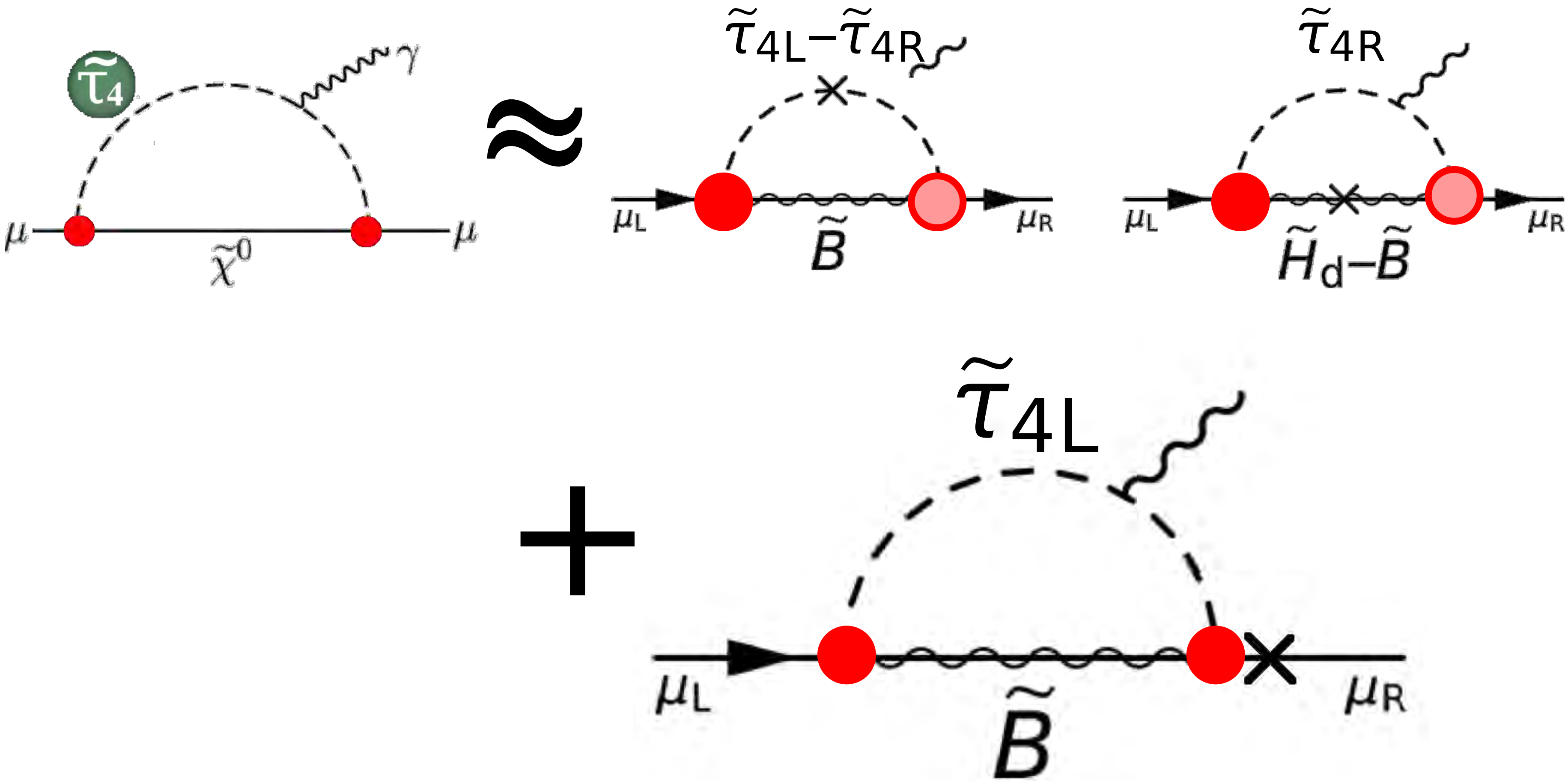


- Why always negative?

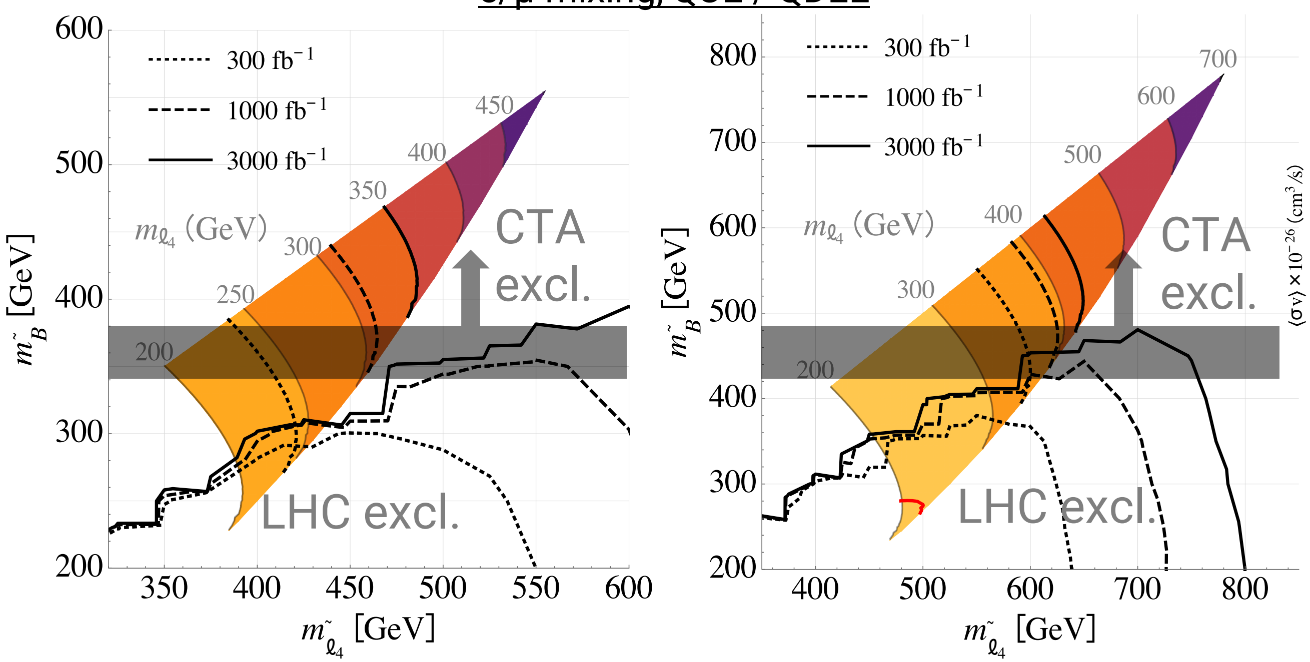


$$= -\frac{|\epsilon|^2}{16\pi^2}\frac{m_\mu^2}{6(|M_E|^2+m_{\widetilde{E}^c}^2)} N_1\left(\frac{\mu^2}{|M_E|^2+m_{\widetilde{E}^c}^2}\right)$$

Summary : Future prospects

	e-mixing	μ-mixing	τ-mixing
CTA 500hr	covers $m_{\tilde{B}}$ > 340−380 GeV		**full coverage**
HL-LHC (slepton)	covers $m_{\tilde{B}}$ < 400 (480) GeV (but not “degenerate” region)		−
HL-LHC (lepton)	covers m_{τ_4} < 350 (430) GeV equivalent to $m_{\tilde{B}}$ < 380 (480) GeV		−

e/μ-mixing, QUE / QDEE



τ/μ-mixing, QUE