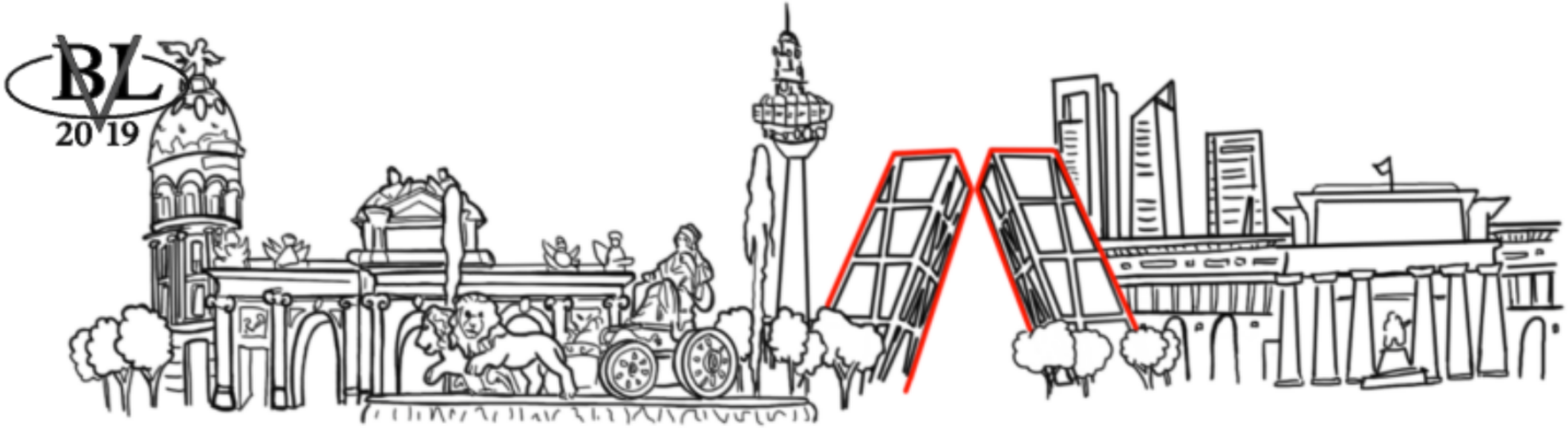
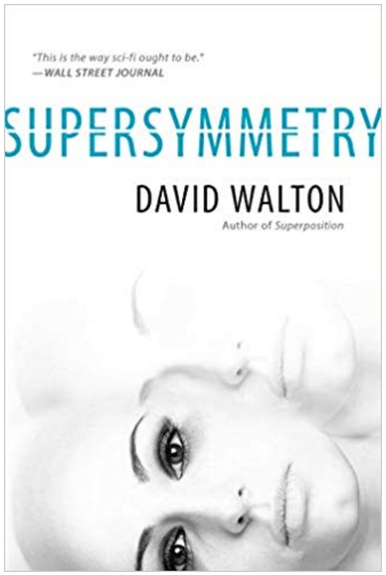


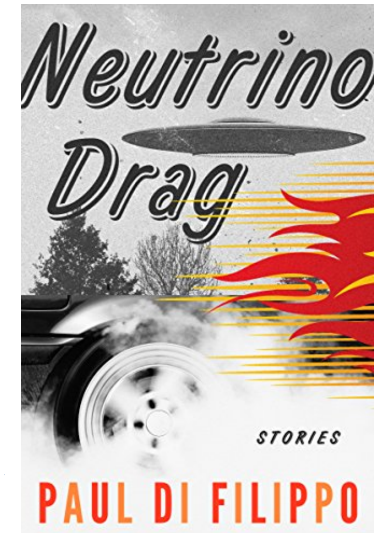
Long-lived particles in BSM

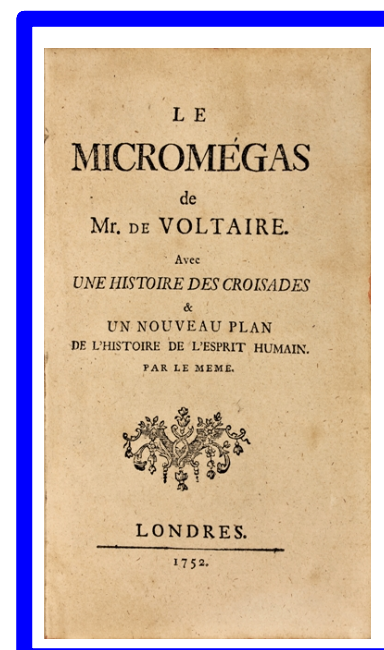
Bryan Zaldívar
UAM
23/10/2019

Motivation for Long-Lived Particles

Plenty of theoretical reasons to believe in the existence of LLPs:





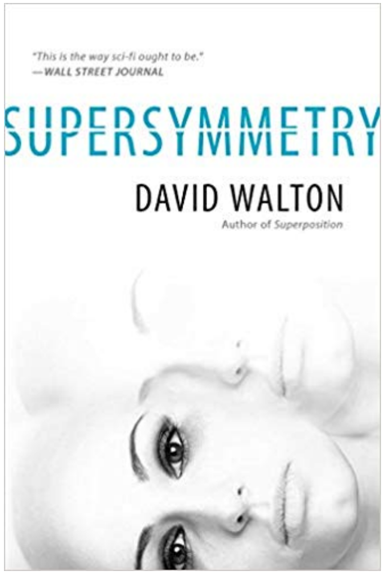

LE
MICROMÉGAS
de
Mr. DE VOLTAIRE.
Avec
UNE HISTOIRE DES CROISADES
&
UN NOUVEAU PLAN
DE L'HISTOIRE DE L'ESPRIT HUMAIN.
PAR LE MEME.

LONDRES.
1752.

Motivation for Long-Lived Particles

- Naturalness

New physics expected to appear not much above EW scale, otherwise fine-tunning



i) SUSY, e.g. Gauge-Mediation with gravitino LSP

$$c\tau(\tilde{\chi}^0 \to \tilde{G} + \mathrm{SM}) \sim 100\mathrm{m}(F/10^{14}\mathrm{GeV})^2$$ [Giudice, Rattazzi, 9801271]

ii) Neutral Naturalness (e.g. discrete symmetries à la Twin Higgs, with SM Higgs decays to hidden sector)

$$c\tau(0^{++} \to \mathrm{SM\ SM}) \sim 20\mathrm{m}(f/750\mathrm{GeV})^4$$ [Craig, Katz, Strassler, Sundrum, 1501.05310]

iii) Relaxion

Long-lived Decay via Higgs-mixing with small ($\lesssim 10^{-3}$) mixing angle

[Graham, Kaplan, Rajendran, 1504.07551]

- Baryogenesis (see talks by T. Konstandin and A. Long)

Origin of the matter-antimatter asymmetry

iv) WIMP Baryogenesis

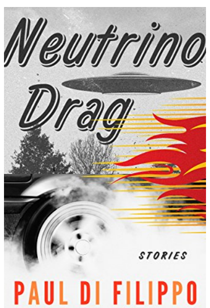
WIMPy with CPV, BV decays after freeze-out (but before BBN)

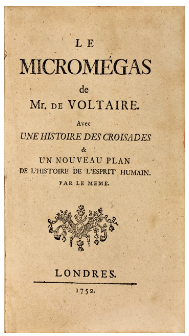
[Cui, Sundrum 1212.2973]

$$1\mathrm{cm}(100\mathrm{GeV}/M_X)^2 \lesssim c\tau_X \lesssim 10^8\mathrm{m}$$

Motivation for Long-Lived Particles

- Baryogenesis & Neutrino Masses & Dark Matter





v) low-scale leptogenesis

νMSM [Asaka, Shaposhnikov, 0505013]
[Boyarsky, Ruchayskiy, Shaposhnikov, 0901.0011]

SM augmented by 3 RH sterile neutrinos
- two heavier give mass to the active neutrinos
- " " are responsible for baryogenesis through their CPV oscillations
- lightest one is the DM candidate (keV to GeV)
  produced out-of-eq. from active-sterile oscillations
  (à la freeze-in) [Dodelson, Widrow, 9303287]
- production at the LHC via e.g. W-decays

- Neutrinos & Dark Matter

vi) Scotogenic FIMP [Hessler, Ibarra, Molinaro, Vogl, 1611.09540] (see also talk by A. Vicente)

SM augmented by 3 RH neutrinos, plus 1 scalar doublet, odd under new Z2 symm.

- neutrino masses generated at 1-loop [Ma, 0601225]
- DM (lightest RH neutrino) produced à la freeze-in from small Yukawa with odd scalar
- odd scalars produced at LHC via Higgs-mixing, then decaying (long-lived) to DM

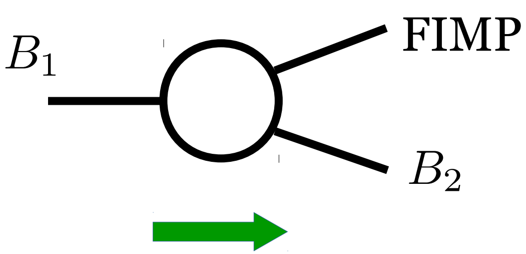
Motivation for Long-Lived Particles

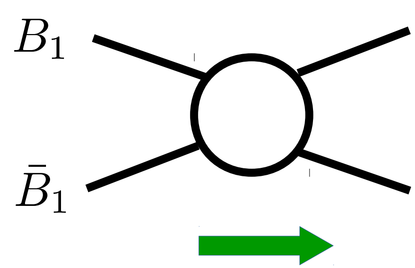
Freeze-in and Dark Matter (see talk by A. Goudelis)

Named and popularized from [Hall, Jedamzik, March-Russell, West, 0911.1120]

B_i : particles in the thermal bath

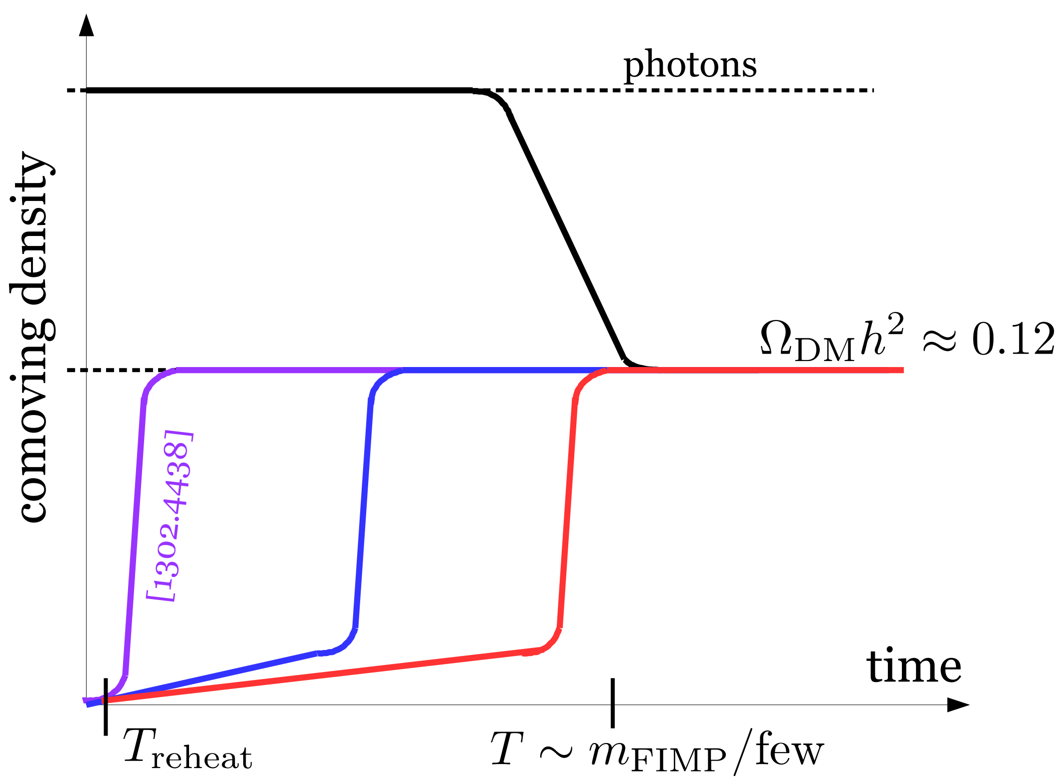
however see [McDonald, 0106249]





out-of-equilibrium

$\Gamma_{\rm inv.proc} < H$



Production happens sooner or later, depending on the scales of the model

$m_{\rm FIMP}\,,\, M_{\rm mother}\,,\, T_{\rm reheat}$

[Blennow, Fernandez-Martinez, BZ, 1309.7348]

Requiring obs. relic abundance

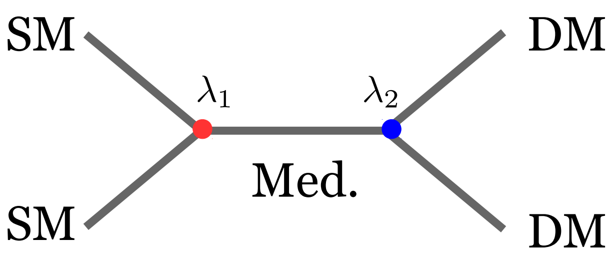
Couplings:

$$\lambda_1 \lambda_2 \sim 10^{-12}$$ (2-to-2 s-scatt.)

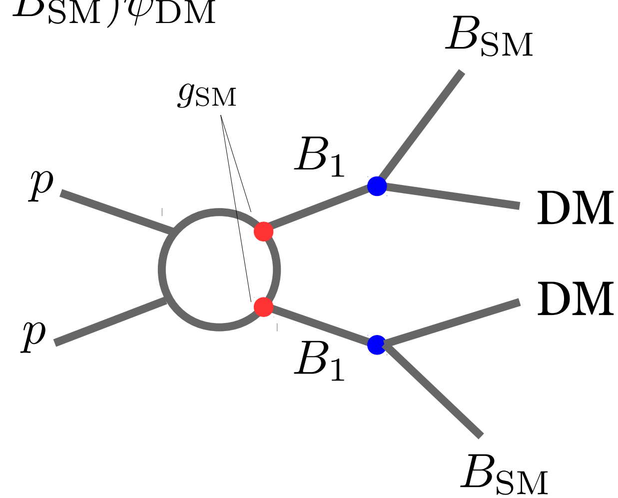
$$\lambda \sim 10^{-13} \sqrt{\frac{m_{\rm mother}}{m_{\rm DM}}}$$ (decay)

FIMP Dark Matter and LLPs at LHC

Freeze-in via s-channel scatt.
almost hopeless at the LHC:



Freeze-in via decay much more promising:
$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \lambda(\bar{B}_1 \cdot B_{\rm SM})\psi_{\rm DM}$



- $B_1, \psi_{\rm DM}$ odd under Z2 symmetry

- representation and spins of $B_1, B_{\rm SM}$ depends on the model

[Co, D'Eramo, Hall, Pappadopulo, 1506.07532]
[Evans, Shelton, 1601.01326]
[Hessler, Ibarra, Molinaro, Vogl, 1611.09540]
[Calibbi, Lopez-Honorez, Lowette, Mariotti, 1805.04423]
[Bélanger et al, 1811.05478]

- But 10^{-13} coupling…
  an LLP of ~ TeV requires coupling ~ 10^{-9}, how to get it?

$$\lambda \sim 10^{-13} \underbrace{\sqrt{\frac{m_Y}{m_{\rm DM}}}} \underbrace{\left(\frac{3\pi/2}{\int_{x_{\rm min}}^{x_{\rm max}} dx\ x^3 K_1(x)} \right)^{1/2}}$$

Change production time lapse / cosmological history
Increase mass-ratio as much as possible

Minimal freeze-in models for LLP searches

[Bélanger, Desai, Goudelis, Lessa, No, Pukhov, Sekmen, Sengupta, BZ, Zurita, 1811.05478]

(see talk by A. Goudelis)

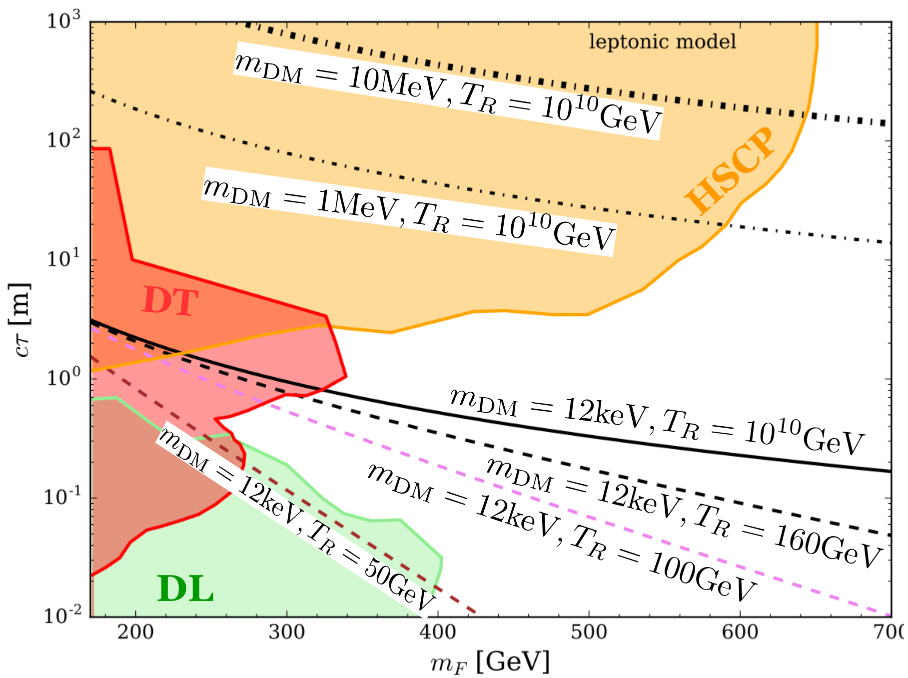
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \lambda(\bar{B}_1 \cdot B_{\rm SM})\psi_{\rm DM}$$

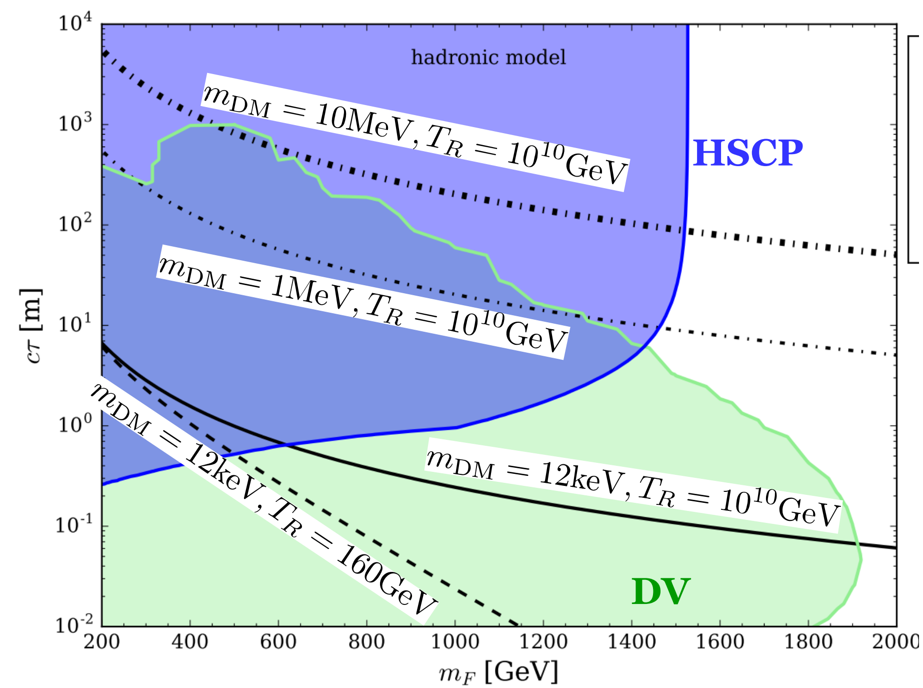
$\psi_{\rm DM}$ is a real scalar SM singlet

$$c\tau_{B_1} \sim 4.5 \text{ m} \left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)\left(\frac{m_{\rm DM}}{100\text{keV}}\right)\left(\frac{200\text{GeV}}{m_{B_1}}\right)^2$$

B_1 is vector-like SU(2) singlet fermion (electrically charged)
- heavy lepton (model 1)
- heavy up-type quark (model 2)

LHC constraints coming from:
- Heavy Stable Charged Particle (HSCP) searches [CMS 1305.0491, CMS-PAS-EXO-16-036]
- Disappearing Tracks (DT) [ATLAS 1712.02118, CMS 1804.07321]
- Displaced leptons (DL) (model 1) [CMS 1409.4789, CMS-PAS-EXO-16-022]
- Displaced vertices (DV) + MET (model 2) [ATLAS 1710.04901]





Freeze-in Dark Matter with Neutral LLPs

including thermal corrections!

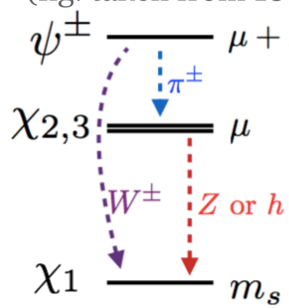
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \lambda(\bar{B}_1 \cdot B_{\rm SM})\psi_{\rm DM}$$

"singlet-doublet", "bino-higgsino", ...

$\psi_{\rm DM}$ is a -mostly singlet- fermion
B_1 is a -mostly doublet- fermion
$B_{\rm SM}$ is the SM Higgs or the Z

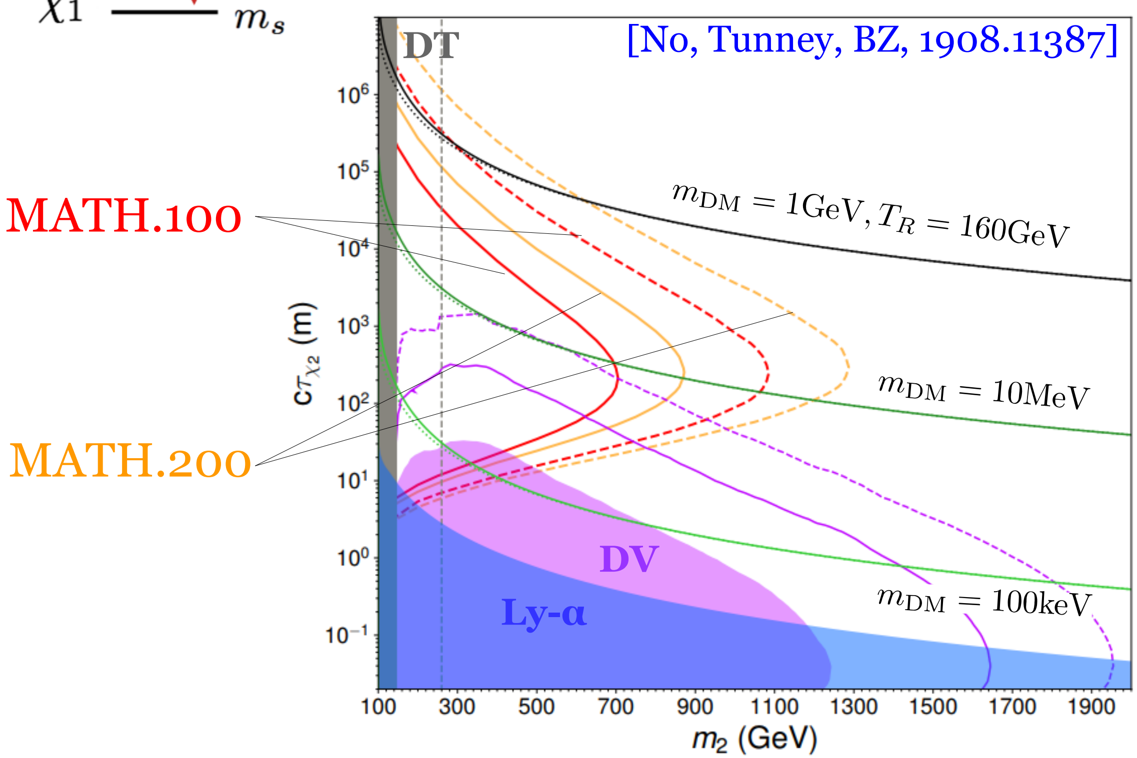
[Calibbi, Mariotti, Tziveloglou, 1505.03867], [Co, D'Eramo, Hall, Pappadopulo, 1506.07532]
[Calibbi, Lopez-Honorez, Lowette, Mariotti, 1805.04423], [No, Tunney, BZ, 1908.11387]

(fig. taken from 1805.04423)

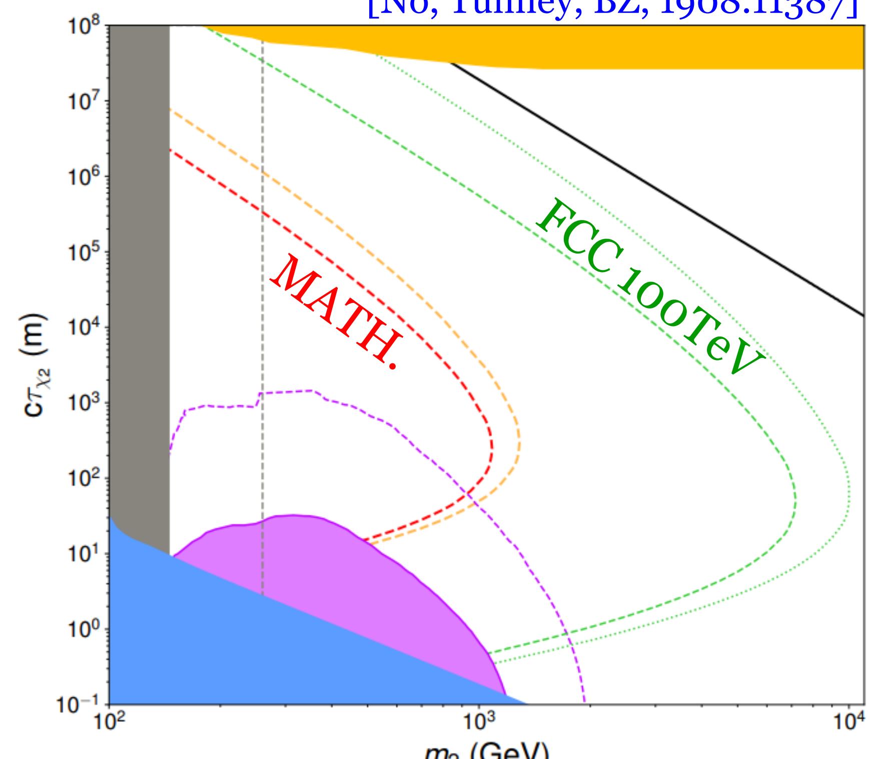


LHC constraints:
- disappearing tracks (DT)
- displaced vertices (DV) + MET
- prompt decays
- mono-X searches

Other collider-related constraints:
- MATHUSLA [Curtin et al, 1806.07396]
- forward LLP detector at a future collider (e.g. FCC-hh)



[No, Tunney, BZ, 1908.11387]



Conclusions

- The theoretical motivations for LLPs are linked to the most important problems in (astro)-particle physics

- If Dark Matter turns out to be a FIMP, it may very well be spotted through LLP signatures.

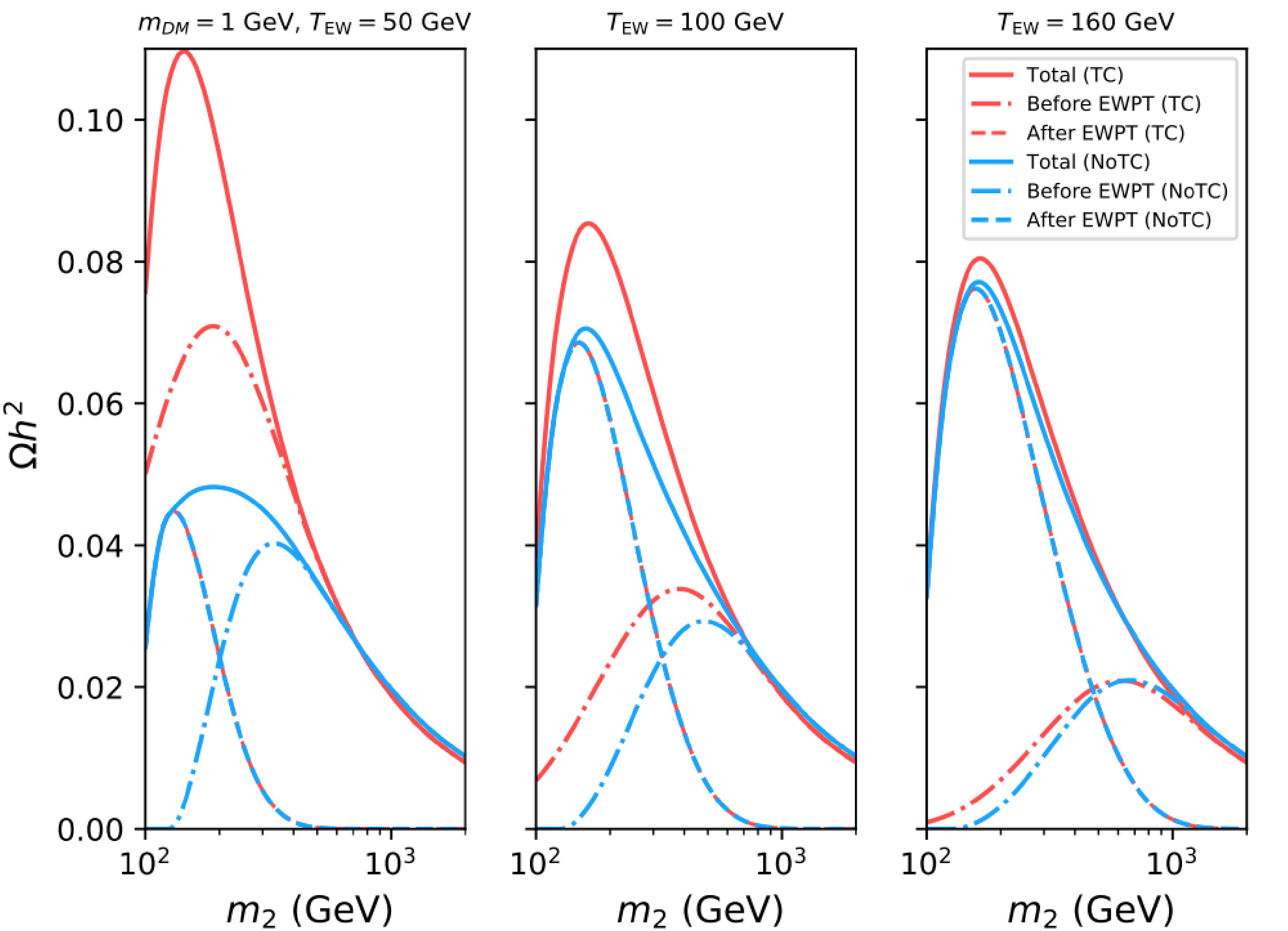
  Minimal models (three parameters)
  offer an attractive interpretation for experimental searches

- Very promising complementarity between LHC searches and the MATHUSLA proposal

- Impressive sensitivity of a forward detector at a 100 TeV collider

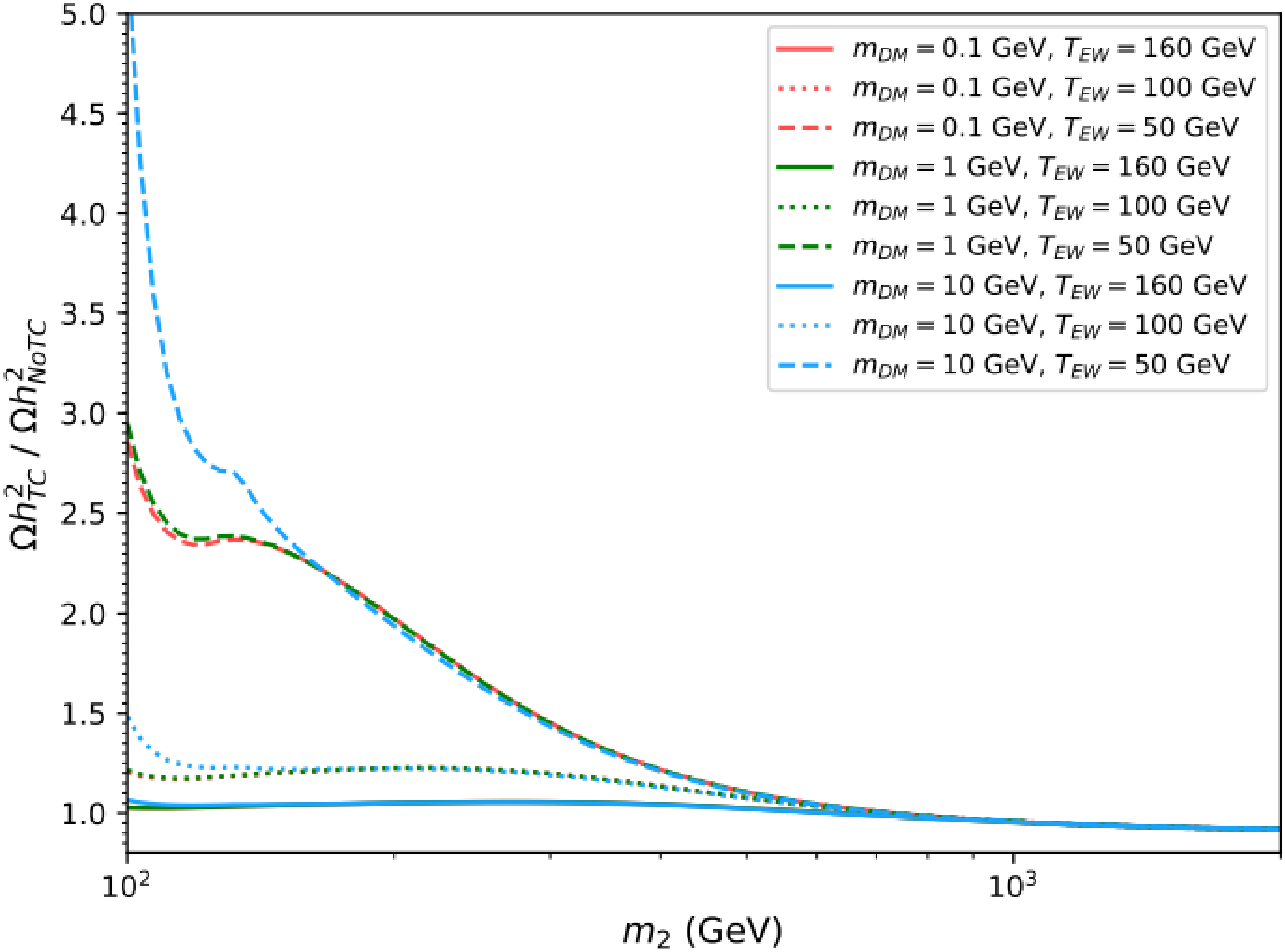
Thanks!

Thermal corrections



[No, Tunney, BZ, 1908.11387]

Thermal corrections



[No, Tunney, BZ, 1908.11387]

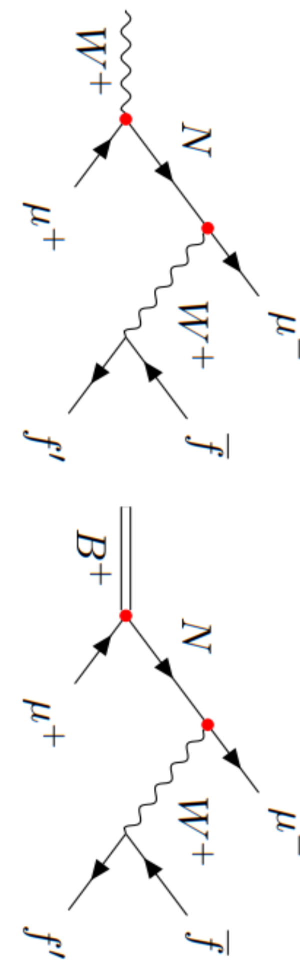
Baryogenesis with the nuMSM
9803255 (Akhmedov, Rubakov, Smirnov)

We suggest that the baryogenesis proceeds in the following way:

(i) In the course of the evolution of the Universe, singlet neutrinos are produced through their Yukawa couplings. The production mechanism of singlet neutrinos conserves CP, *i.e.* for each type equal numbers of particles and antiparticles (particles of opposite helicities in the Majorana case) are produced.

(ii) Once created, singlet neutrinos oscillate, and also interact with ordinary matter. None of these processes violates the total lepton number $L^{tot} = L + L_A + L_B + L_C$, where L is the usual lepton number (we assume that Majorana masses are small enough, see below). However, CP is not conserved due to mixing in the singlet neutrino sector. Therefore the initially created state with individual lepton numbers $L_A = L_B = L_C = 0$ evolves through the oscillations into a state in which $L_A \neq 0$, $L_B \neq 0$, $L_C \neq 0$ but still $L^{tot} = 0$. That is, the total lepton number gets unevenly distributed between different species.

(iii) Singlet neutrinos communicate their lepton asymmetry to ordinary neutrinos and charged leptons through their Yukawa couplings. We assume that the Yukawa



(a) Electroweak production.

(b) *B*-meson production.

1905.09828
(Drewes, Lucente, et al)

About 1811.05478, Julia Harz @ Moriond 2019

(In)direct constraints

Heavy lepton

- **Electroweak precision data**

  no mixing with SM fermions, $SU(2)_L$ singlets
  → no relevant contributions

  Ellis, Godbole, Gopalakrishna, Wells, 1404.4398

- **muon lifetime**

  $$\mu \to ess$$

  below current experimental limits

- **Lepton-Flavour-Violation**

$$Br(\mu \to e\gamma) \sim \frac{2v^4 (y_s^e)^2 (y_s^\mu)^2}{3 m_F^4 (16\pi)^2} \approx \mathcal{O}(10^{-46})$$

- **LEP**

  $$m_F > 104 \text{ GeV}$$

  OPAL, hep-ex/0507048

Heavy quark

- **Running of the strong coupling**

  $$m_F < \mathcal{O}(x \times 100\text{GeV})$$

  Llorente, Nachman, 1807.00894

- **Meson mixing / $K^+ \to \pi^+ ss$**

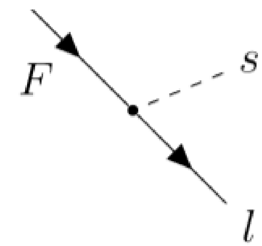
  suppressed by small couplings y_s^f

- **LHC searches** for multi-jet plus missing energy subdominant

About 1811.05478, Julia Harz @ Moriond 2019

Cosmological constraints

- **Big-Bang Nucleosynthesis**
  we consider 1cm < cτ < 10^4m → T~150 MeV
  → heavy fermions decay well before onset of BBN



- **Lyman-α forest**

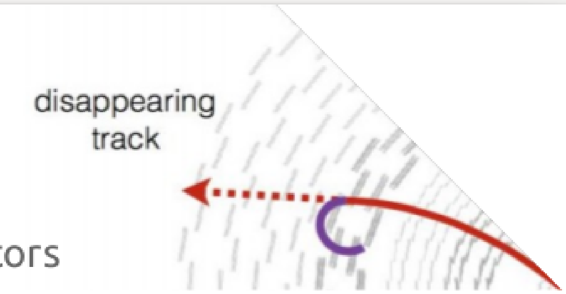
$$m_{\mathrm{DM}} \gtrsim 12\ \mathrm{keV} \left(\frac{\sum_i \mathrm{BR}_i \Delta_i^\eta}{\sum_i \mathrm{BR}_i} \right)^{1/\eta} \gtrsim 12\ \mathrm{keV}$$

$$\eta = 1.9$$

$$\Delta_i = 1 - m^2_{X^i_{\mathrm{SM}}} / m^2_Y$$

Boulebnane, Heeck, Nguyen, Teresi, 1709.07283

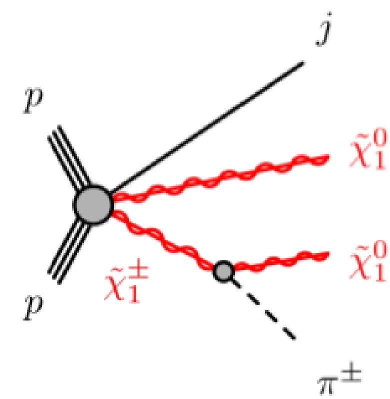
2 Disappearing Tracks (DT)



- **isolated track** reconstructed in the pixel and strip detectors without any hit in the outer tracker (CMS) or a track with only pixel hits (ATLAS)

- ATLAS can reconstruct tracks down to 12 cm (new innermost tracking layer "IBL"); CMS 25-30 cm
- CMS has better coverage for longer life times cτ > 1m

- **AMSB** motivated scenario with mass **degenerate lightest chargino** and **neutralino**



(a) $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_1^0 j$

- **Recasting** of two analyses of ATLAS and CMS

$$\mathcal{N} = \sigma_{\mathrm{pp}\to\mathrm{F}\bar{\mathrm{F}}} \times \varepsilon(m,\tau) \times \mathcal{L}$$

13 TeV ATLAS analysis 36.1 fb^{-1}
13 TeV CMS analysis 138.4 fb^{-1}

ATLAS Coll., Search for long-lived charginos based on a disappearing-track signature in pp collisions at √s= 13TeV with the ATLAS detector, JHEP06(2018) 022, [arXiv:1712.02118]

CMS Coll., Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at √s=13 TeV, arXiv:1804.07321