Feebly Interacting Dark matter

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LAPTH Annecy-le-Vieux

See :

GB, Boudjema, Goudelis, Pukhov, Zaldivar, 1801.03509

GB, Desai, Goudelis, Harz, Lessa, No, Pukhov, Sekmen, Sengupta, Zaldivar, Zurita, 1811.05478

GB, Delaunay, Pukhov, Zaldivar, in preparation

ICTP, Sao Paulo, 23/10/2019

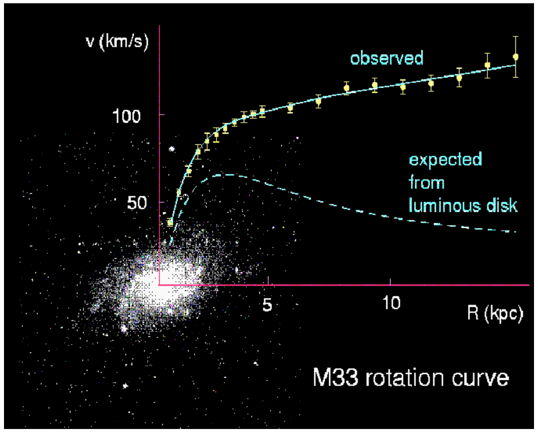
Outline

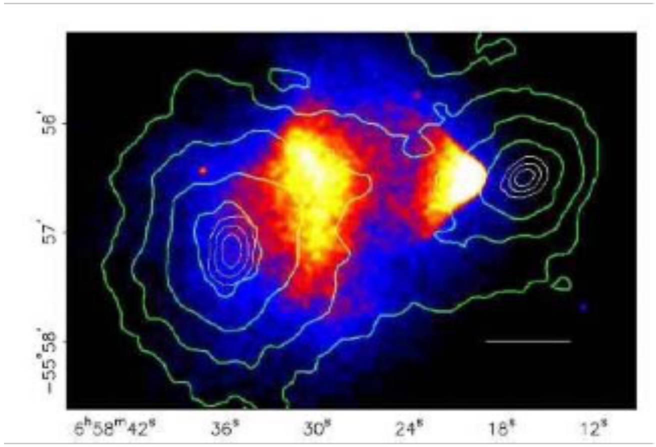
- Motivation
- Relic density of FIMPs
  - Generic case (Simplified model 1)
  - Production from out-of-equilibrium particles (Simplified model 2)
- Signatures
  - direct detection (simplified model 2)
  - LHC (simplified model 3)
- Summary

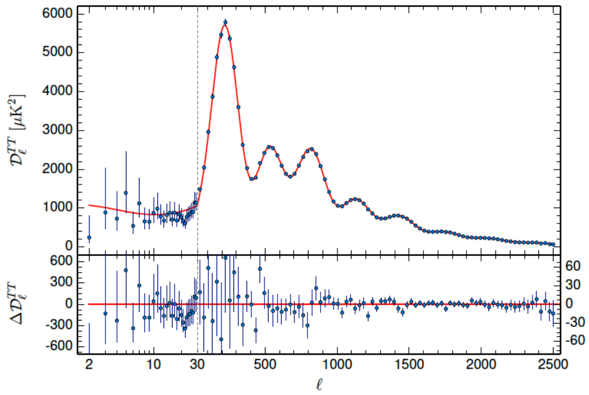
Introduction

What do we know about dark matter?

It has gravitational interactions (galaxies – rotation curves- galaxy clusters, - Xray, gravitational lensing) - no electromagnetic interactions - It is cold (or maybe warm)







Within ΛCDM model – precisely know its relic density

$\Omega_{cdm}\, h^2 = 0.1193 +/- 0.0014$ (PLANCK – 1502.01589)

Leaves lots of possibilities for dark matter

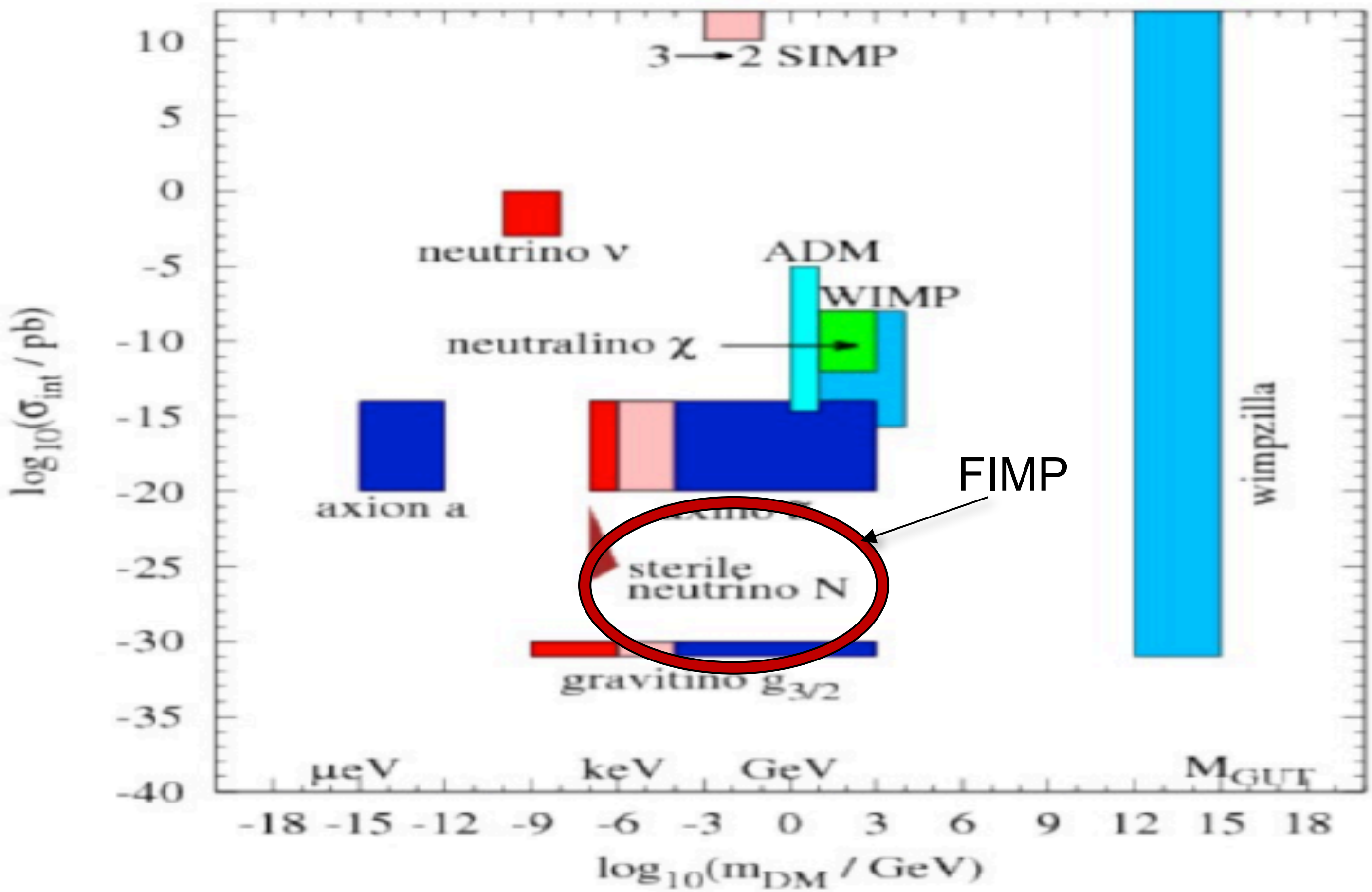
In particular from the particle physics point of view - Cannot be baryons, neutrinos (too hot)

- A new particle? Two DM? Mass scale? Interaction strength? large self-interactions? linked to baryon-antibaryon asymmetry?

- WIMPs – long time favourite : good theoretical motivation, typical annihilation cross-section leads to correct relic density
- WIMPs : elaborate search strategies from astroparticle/cosmo/colliders - but no signatures so far
- Important to consider alternative DM production and to explore new signatures

Beyond WIMPs

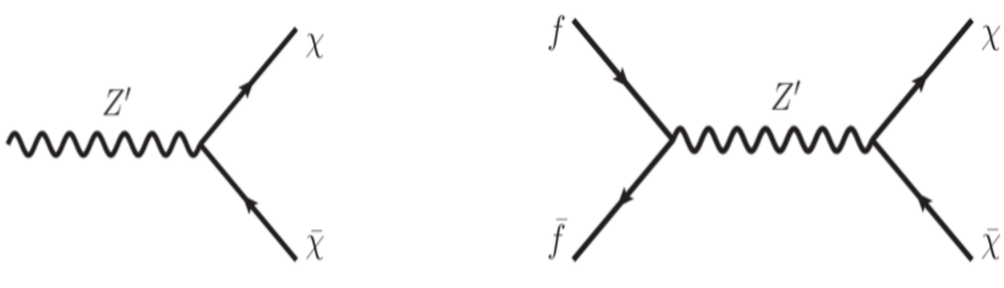
- Consider much weaker interaction strength and maybe mass scale



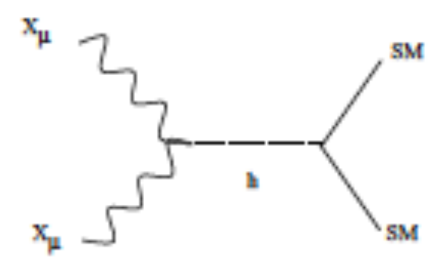
L. Roszkowski

FIMPS (Feebly interacting MP)

- Freeze-in (McDonald, PRL88, 091304 (2002); Hall et al, 0911.1120): in early Universe, DM so feebly interacting that never reach thermal equilibrium
- Assume that after inflation abundance DM very small, interactions are very weak but lead to production of DM



Freeze-in



Freeze-out

FIMPS (Feebly interacting MP)

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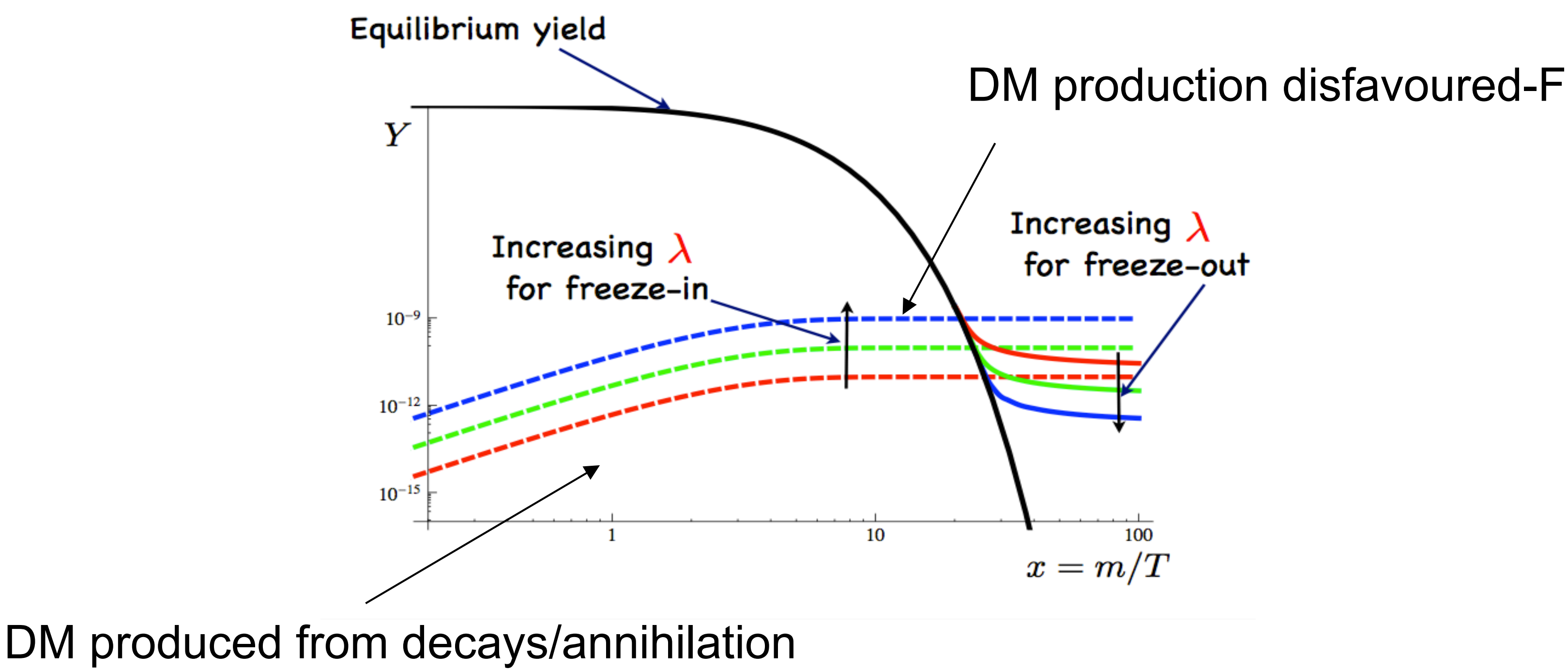
- T~M, DM 'freezes-in' - yield increase with interaction strength



Freeze-in

- DM particles are NOT in thermal equilibrium with SM
- Recall

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(\cancel{(n_\chi)^2} - (n_\chi^{eq})^2 \right)$$

Depletion of χ due to annihilation

Creation of χ from inverse process

- Initial number of DM particles is very small

$$\dot{n}_\chi + 3Hn_\chi = \langle \sigma v \rangle_{X\bar{X} \to \chi\bar{\chi}}(T) n_{eq}^2(T) + n_{eq}(T) \Gamma_{Y \to \chi\chi}(T)$$

annihilation

Decay (X,Y in Thermal equilibrium with SM)

$$n = \int \frac{d^3p}{(2\pi)^3} f(p)$$

Solving for relic density (annihilation)

- Boltzmann eq, 2->2:

$$\frac{dn}{dt} + 3Hn = \int \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_a}{(2\pi)^3 2E_a} \frac{d^3p_b}{(2\pi)^3 2E_b} \times (2\pi)^4 \delta^4(p_1 + p_2 - p_a - p_b) |\mathcal{M}|^2 f_1 f_2 (1 \mp f_a)(1 \mp f_b)$$

- For particles in kinetic equilibrium with SM

$$f_i = \frac{1}{\left(e^{\frac{(E_i - \mu_i)}{T}} \pm 1\right)} = \frac{\eta_i}{e^{\frac{E_i}{T}} + \eta_i} \qquad \eta_i = \pm e^{\mu_i/T}$$

- T larger than for freeze-out ($m_{DM}/3$ or $m_{Med}/3$), cannot always make approximation Maxwell-Boltzmann distribution

$$\frac{dn}{dt} + 3Hn = \frac{g_1 g_2}{8\pi^4} T |\eta_1 \eta_2| C_{12} \int ds\, p_{\mathrm{CM}}^2 \sqrt{s} \sigma(s) \tilde{K}_1(\sqrt{s}/T, x_1, x_2, 0, \eta_1, \eta_2)$$

$$\tilde{K}_1(x_1, x_a, x_b, \eta_1, \eta_a, \eta_b) = \frac{1}{4 p_{\mathrm{CM}} T |\eta_1|} \int dE_+ dE_-\; f_1 (1 \mp f_a)(1 \mp f_b)$$

- Effect of statistical treatment : up to a factor 2 (for bosons) ~25% for fermions
- Solve for Y=n/s →

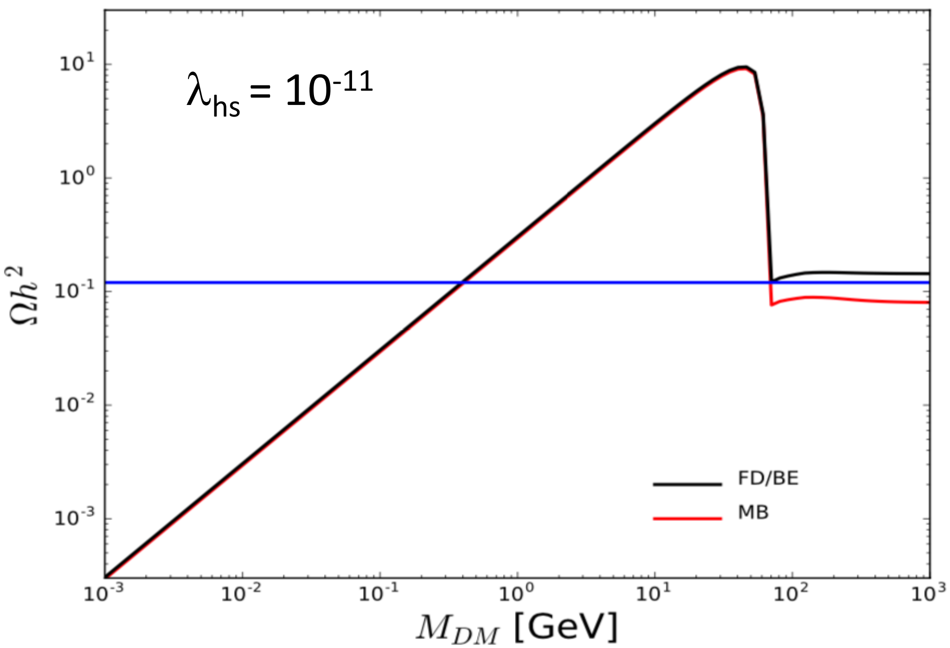
$$\Omega h^2 = \frac{m_\chi Y_\chi^0 s_0 h^2}{\rho_c}$$

Simplest example : singlet

- SM with real singlet (odd under and Z2 symmetry) (see also C. Yaguna 1105.1654)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\left(\partial_\mu S\right)\left(\partial^\mu S\right) + \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 - \lambda_{hs}\left(H^\dagger H\right)S^2$$

- Free parameters λ_{hs} and m_S ,



Higgs mediator

On-shell regime ($m_S \ll m_{Med}$)
$\Omega h^2 \sim \lambda_{hs}{}^2\, m_S$
DM can be light

Off-shell regime $2m_S > m_H$
Bose-Einstein/MB ~2
(DM production dominate by VV)

Out-of-equilibrium FIMP production

- Other possible contributions to FIMPs production beyond the simplest freeze-in mechanism (decay of a particle in thermal equilibrium or 2-2 scattering)
- Illustrate with a simple model, Dirac fermion (DM) with scalar mediator

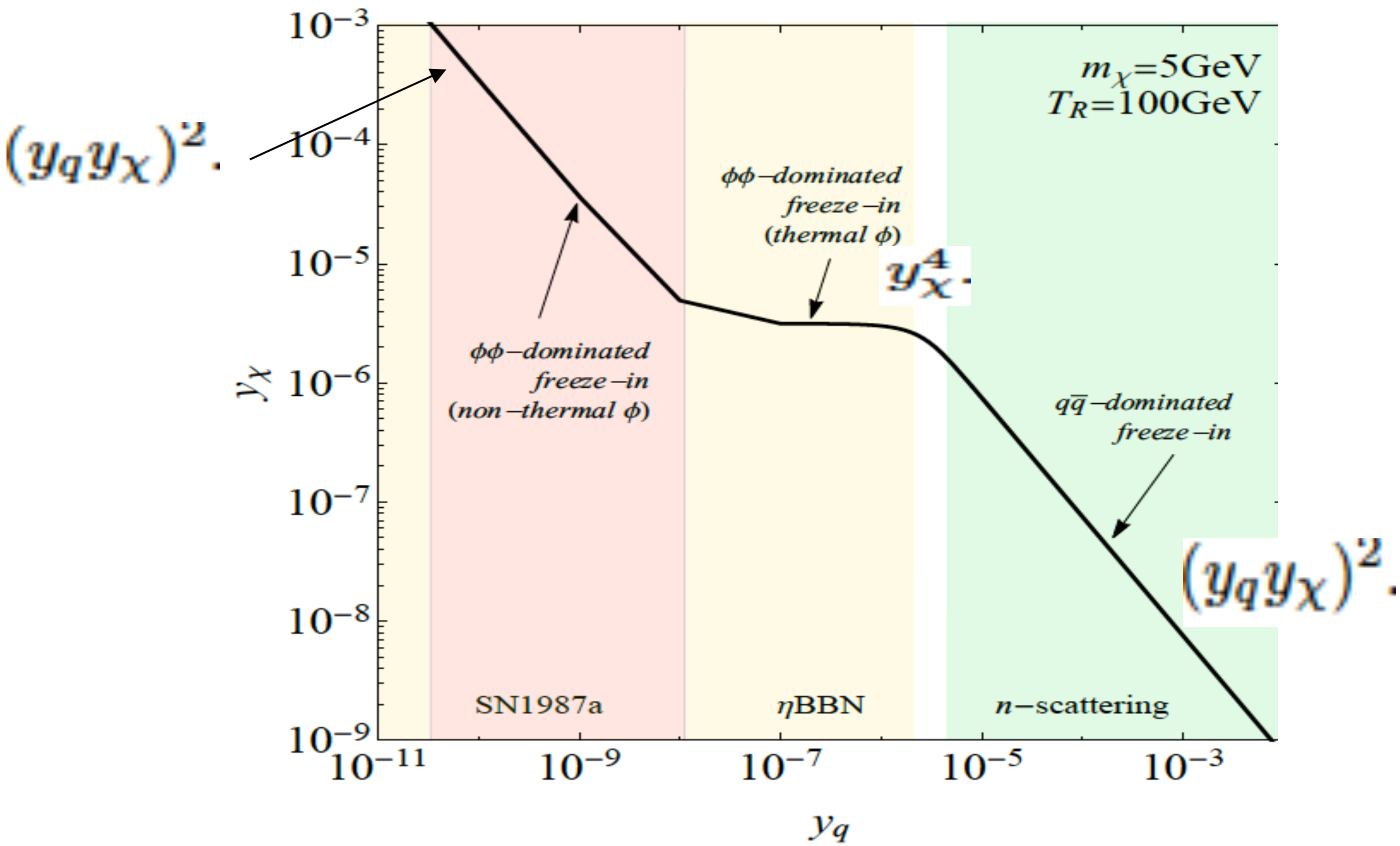
$$-\mathcal{L}_{\rm int} = y_\chi \phi \bar{\chi}\chi + y_q \phi \bar{q} q$$

- Consider case where ϕ is light (say 1 MeV) – 1) possibility to solve cluster anomalies 2) enhance direct detection (see later) 3) illustrate new DM production mechanism
- Two DM production processes

$$q\bar{q} \to \chi\bar{\chi} \quad \text{and} \quad \phi\phi \to \chi\bar{\chi}$$

$$(y_q y_\chi)^2. \qquad\qquad y_\chi^4.$$

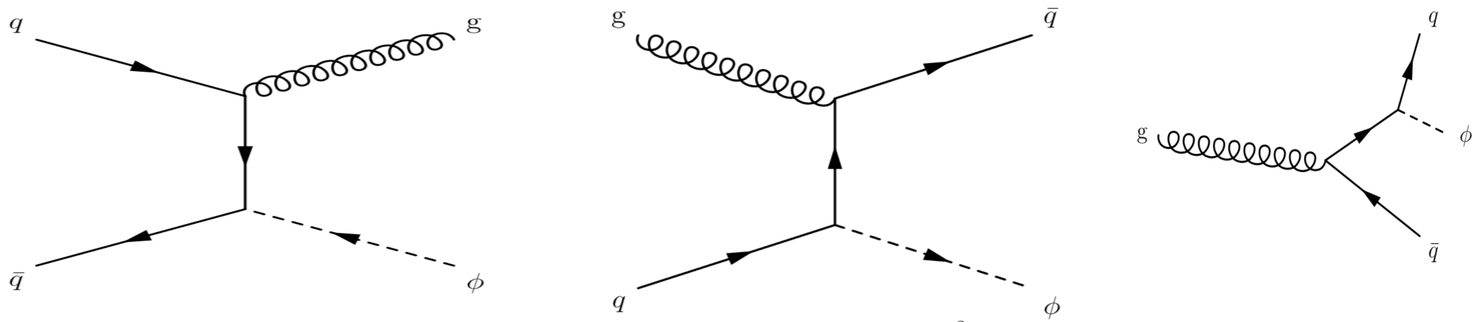
Relic density through freeze-in



- For small values of y_q the mediator is out-of-equilibrium during DM production – still contribute to DM production $\phi\phi \to \chi\chi$ suppressed by $(f_\phi/f_{eq})^2$ – can even be dominant

FIMP production from ϕ

- Processes that bring ϕ in equilibrium with SM



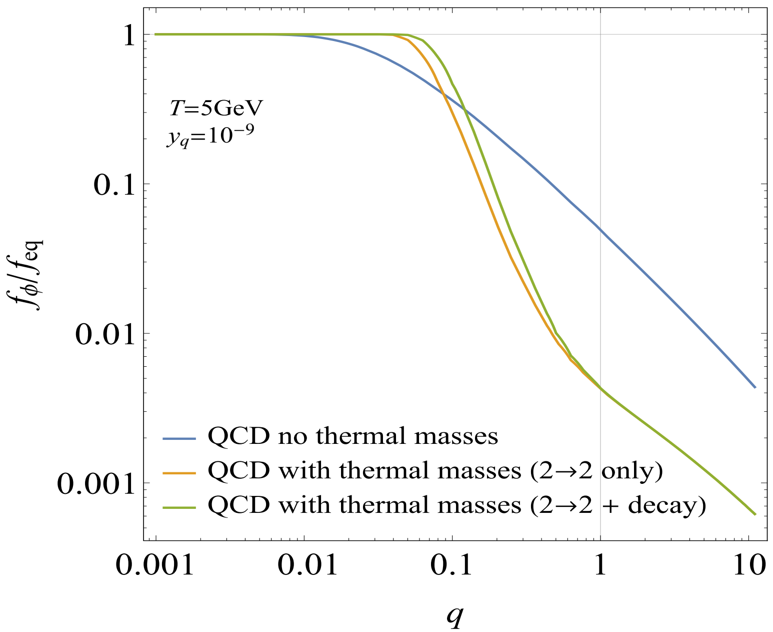
- To compute contribution to DM production from $\phi\phi \to \chi\chi$ need $f_\phi(p,T)$, for this solve Boltzmann equation for ϕ
- Thermal corrections are important – new channels (g decay) – thermal mass in the propagator, ($m_g > m_q$)

$$\frac{m_g^2(T)}{T^2} = \frac{g_s^2}{6}\left(N_c + \frac{n_f(T)}{2}\right) \qquad \frac{m_q^2(T)}{T^2} = \frac{g_s^2}{6} + \frac{e^2 Q_q^2}{8}$$

- Thermal masses Dvorkin, Lin, Schutz 1902.08623 (photon), Hambye et al 1908.09864 (gluons)

FIMP production from ϕ

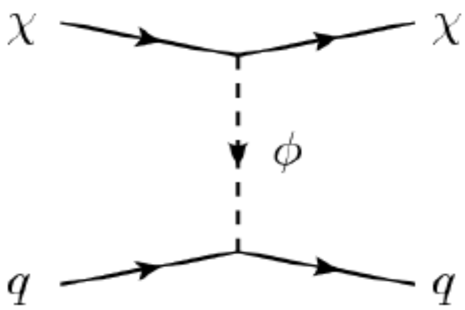
- Density of ϕ with large momentum (needed for production of DM) is suppressed – still can be dominant
- Impact of thermal masses important at large q



$$q = \frac{p}{T_0}\left(\frac{s(T_0)}{s(T)}\right)^{\frac{1}{3}}$$

- What about signatures?

Direct detection



$$\sigma_{SI} \propto \frac{g_\chi^2 g_q^2}{(q^2 - M_\phi^2)^2} \to \frac{1}{M_\phi^4}$$ for heavy mediator

$$\to \frac{1}{(2m_N E_R - M_\phi^2)^2}$$

For light mediator

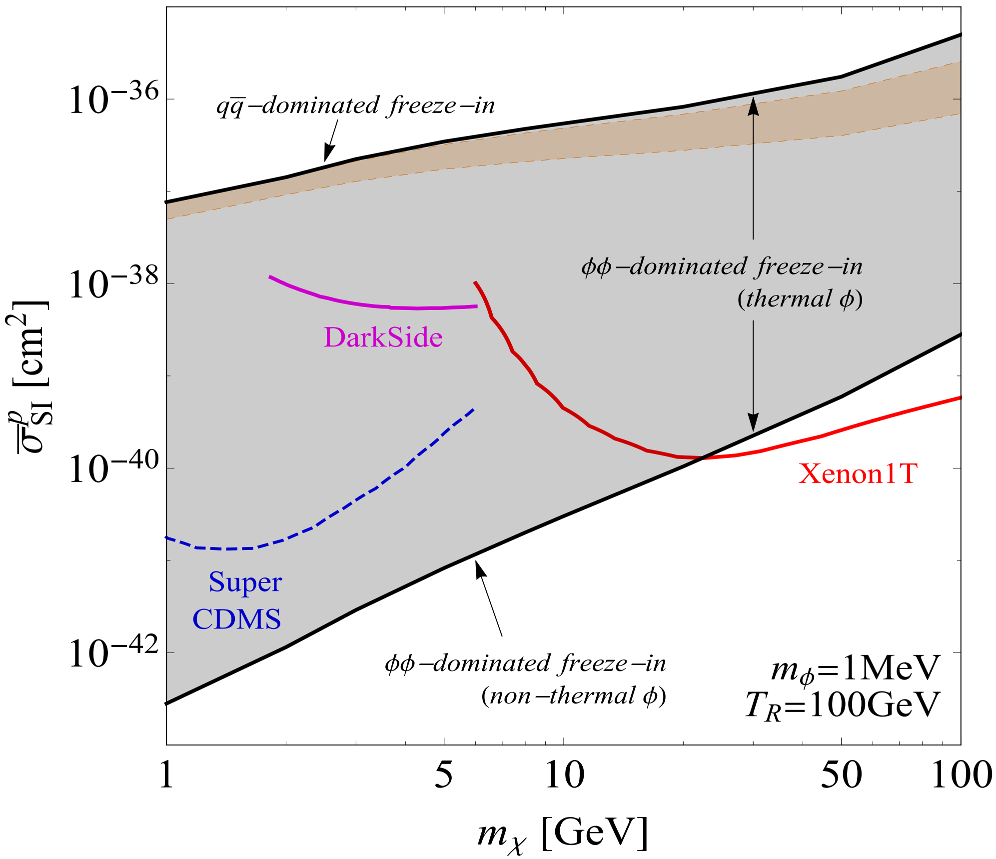
- Note for Xenon $2m_N E_R \sim (22\text{MeV})^2$ at detector threshold
- For very light mediator $\sigma \sim 1/E_R^2$, recoil spectrum peaks at low recoil energies - see also Hambye et al, 1807.05022

$$\frac{dR}{dE_R} = \frac{\rho_0 \bar{\sigma}_{\rm SI} N_A}{\sqrt{\pi} v_0 m_\chi \mu_{\chi N}^2} F^2(q) \eta(q^2) \times \frac{m_\phi^4}{(q^2 + m_\phi^2)^2}$$

Velocity distribution

- Re-interpretation of DD limits from Xenon, Darkside, … (micrOMEGAs_5.0.20 - GB,Mjallal, Pukhov)

Direct detection



GB, Delaunay, Pukhov, Zaldivar, in preparation

- A large part of FI region is/will be probed by DD even for DM at GeV scale
- See also other models, e.g. Hambye et al, 1807.05022

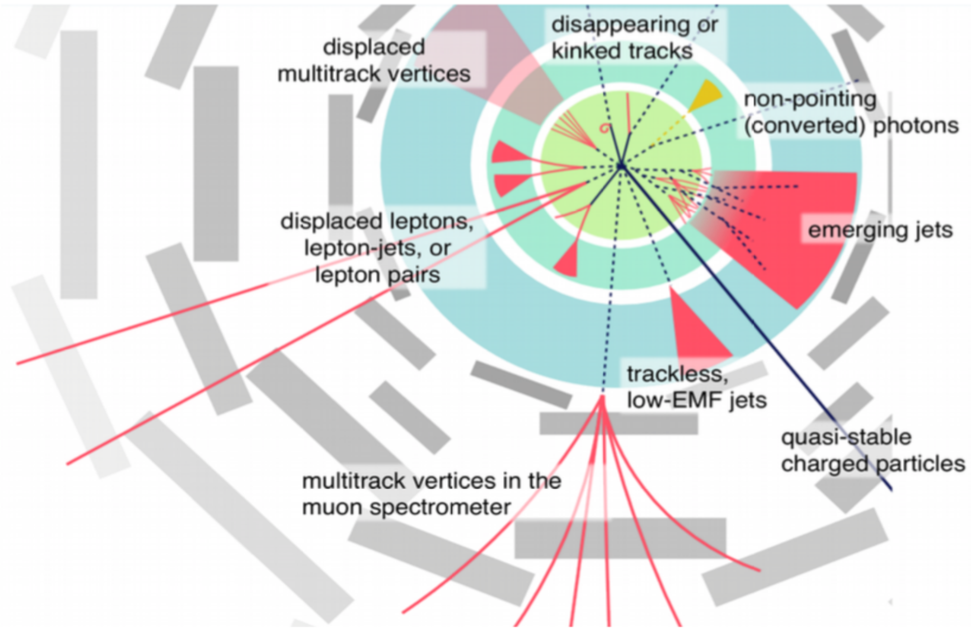
Other Signatures of FIMPs

- Typical couplings $y_q y_\chi \sim 10^{-10}$ - 10^{-12}
- Which such weak coupling can we expect any signal in standard DM searches : direct/indirect detection at colliders?
- Direct detection : possible with light mediator
- Indirect detection – a few possibilities with decaying DM
  - Freeze-In production of PeV scalar that decays into neutrinos (Icecube) Roland et al 1506.08195
  - Light Frozen-in DM can lead to Xray/γ-ray signatures
    - E.g. Baek, Po,Park 1405.3730, Essig et al, 1309.4091
- Collider signatures

FIMPs at colliders

- Despite small couplings could lead to some interesting LHC phenomenology
- Most relevant for colliders : DM is produced from the decay of a heavier particle (Y) in thermal equilibrium with thermal bath (eg Y is a WIMP but DM is FIMP)
- Y copiously produced, but small coupling→ long-lived
- Long-lived particles (either collider stable or displaced vertices)

The "LLP zoo"



H. Russell, LHC LLP workshop

Few examples of displaced vertices in FI:
Co, d'Eramo, Hall, Pappadopoulo, 1506.07532
Evans, Shelton 1601.01326
Hessler, Ibarra, Molinaro, Vogl, 1611.09540

Minimal freeze-in model

- Only one FIMP : DM, discrete Z_2 symmetry → stable DM
- DM is a SM gauge singlet – no thermalization in the early universe
- Minimality: smallest number of exotic fields (Y) but require some collider signature
    - Higgs portal y $H^2\,\chi^2$, DM production depends on y - no observable signature
- Y : Z_2 odd otherwise mostly coupled to SM suppressed decay to DM pairs
- Consider F vector-like fermion SU(2) singlet, DM : scalar singlet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\;\partial^\mu s - \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4 + \lambda_{sh}s^2\left(H^\dagger H\right)$$
$$+\bar{F}\left(i\not{D}\right)F - m_F\bar{F}F - \sum_f y_s^f\left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right)f + \text{h.c.}\right)$$

- Free parameters : m_s, m_F, y_s^f (assume λ_s, $\lambda_{sh} \ll 1$)
- Model also considered for FO, Giacchino et al 1511.04452, Colucci et al, 1804.05068, 1805.10173

Relic density

- DM mainly produced from decay of F (F-> f s)
- F can be either lepton or quark
- DM yield (assuming Maxwell-Boltzmann statistics)

$$Y_s \approx \frac{45\,\xi\,M_{\rm Pl}}{8\pi^4\cdot 1.66}\frac{g_F}{m_F^2}\Gamma\int_{m_F/T_R}^{m_F/T_0} dx\; x^3\,\frac{K_1(x)}{g_*^s(m_F/x)\sqrt{g_*(m_F/x)}},$$

- Γ : partial width to DM , depends on y_s^f
- DM abundance

$$\Omega_s h^2 \approx \frac{m_s Y_s}{3.6\times 10^{-9}\ \text{GeV}}$$

- F lifetime

$$c\tau[\text{m}] \approx 4.5\,\xi\,g_F\left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \text{keV}}\right)\left(\frac{200\ \text{GeV}}{m_F}\right)^2$$

- FI naturally leads to Long-lived particles

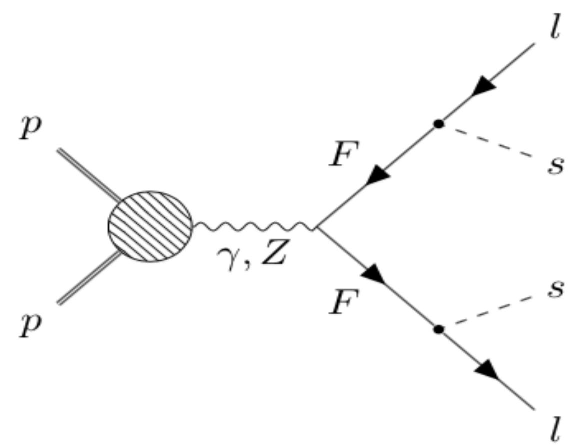
Relic density

- Lower bound on m_S (m_S>12keV)
  - Wash-out of small and intermediate scale structures if DM has non-negligible velocity dispersion – bound from Lyman-α forest observation
- Lowering reheating temperature - > shorter lifetime

$$Y_s \approx \frac{45\,\xi\,M_{\rm Pl}}{8\pi^4\cdot 1.66}\frac{g_F}{m_F^2}\Gamma\int_{m_F/T_R}^{m_F/T_0} dx\; x^3\,\frac{K_1(x)}{g_*^s(m_F/x)\sqrt{g_*(m_F/x)}},$$

- *Lifetime from cm to many meters*

Production at LHC

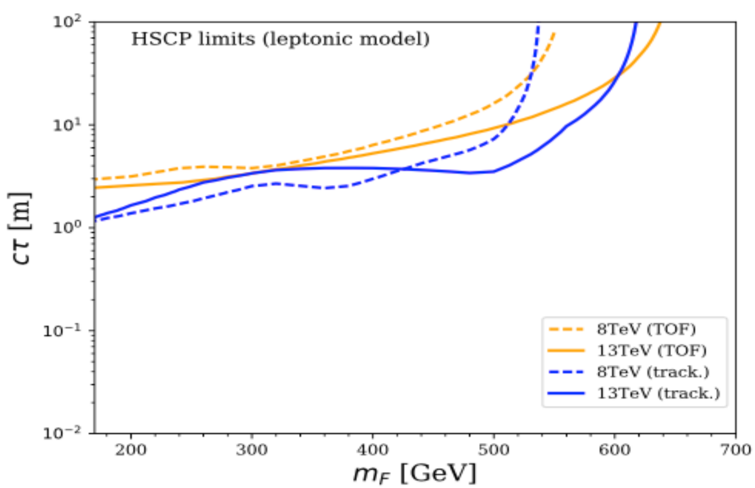


LLP signatures at colliders

- Heavy stable charged particles (HSCP)
- Disappearing tracks
- Displaced leptons
- Displaced vertices

Heavy stable charged particles

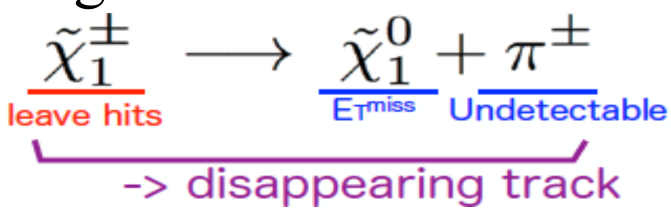
- F colour neutral : anomalous ionizing track in inner tracker
- F colour triplet : hadronisation in neutral or charged hadrons (R-hadrons)
- HSCP velocity $\beta<1$ (can distinguish HSCP from SM) :
  - charged particle produces ionizing track with higher ionization energy loss than SM
  - Time of flight measured with hits in muon chamber is larger than for relativistic muons
- If F has low $c\tau$, a fraction can decay within the tracker, rescale the production cross section

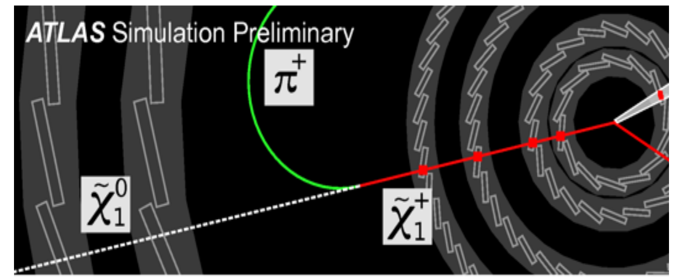


- Recast of CMS 8 TeV (18.8fb^{-1}) and 13 TeV (12.9fb^{-1}) searches:
  - Tracker only (decay outside tracker)
  - TOF: Tracker + time-of-flight (decay outside muon chamber)

Disappearing tracks

- First designed for wino-LSP (chargino lifetime .15-.25 ns)

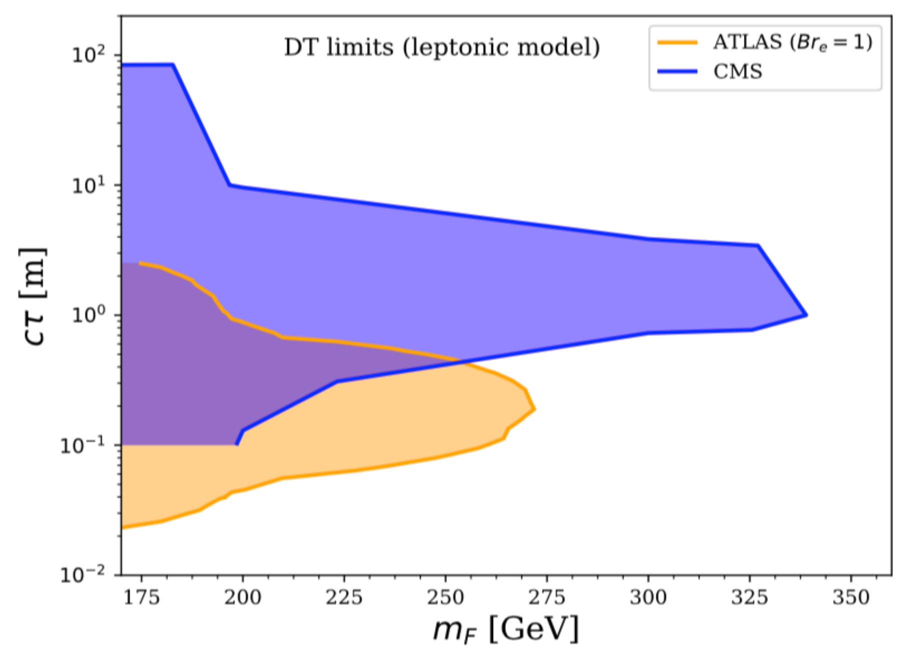




- Trigger: one disappearing track + one ISR jet (p_T>100GeV)

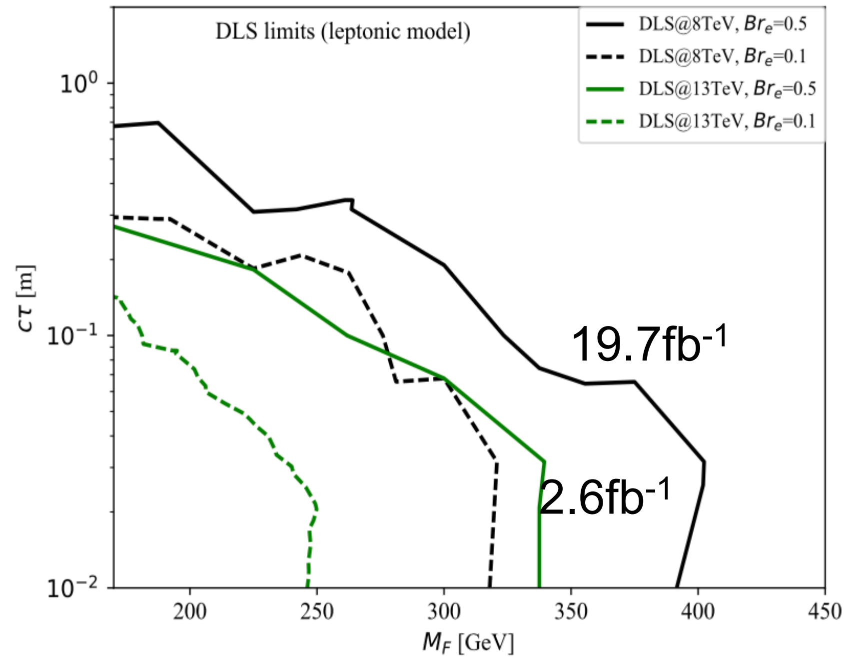
- ATLAS can reconstruct tracks down to 12 cm (25 cm for CMS)

- Not as sensitive as HSCP but covers shorter lifetimes

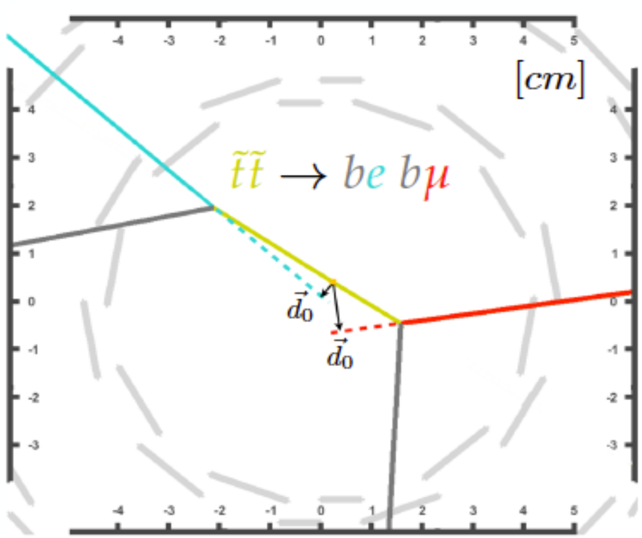


Displaced leptons

- Search for displaced eμ – only applies if F decays to both electrons and muons

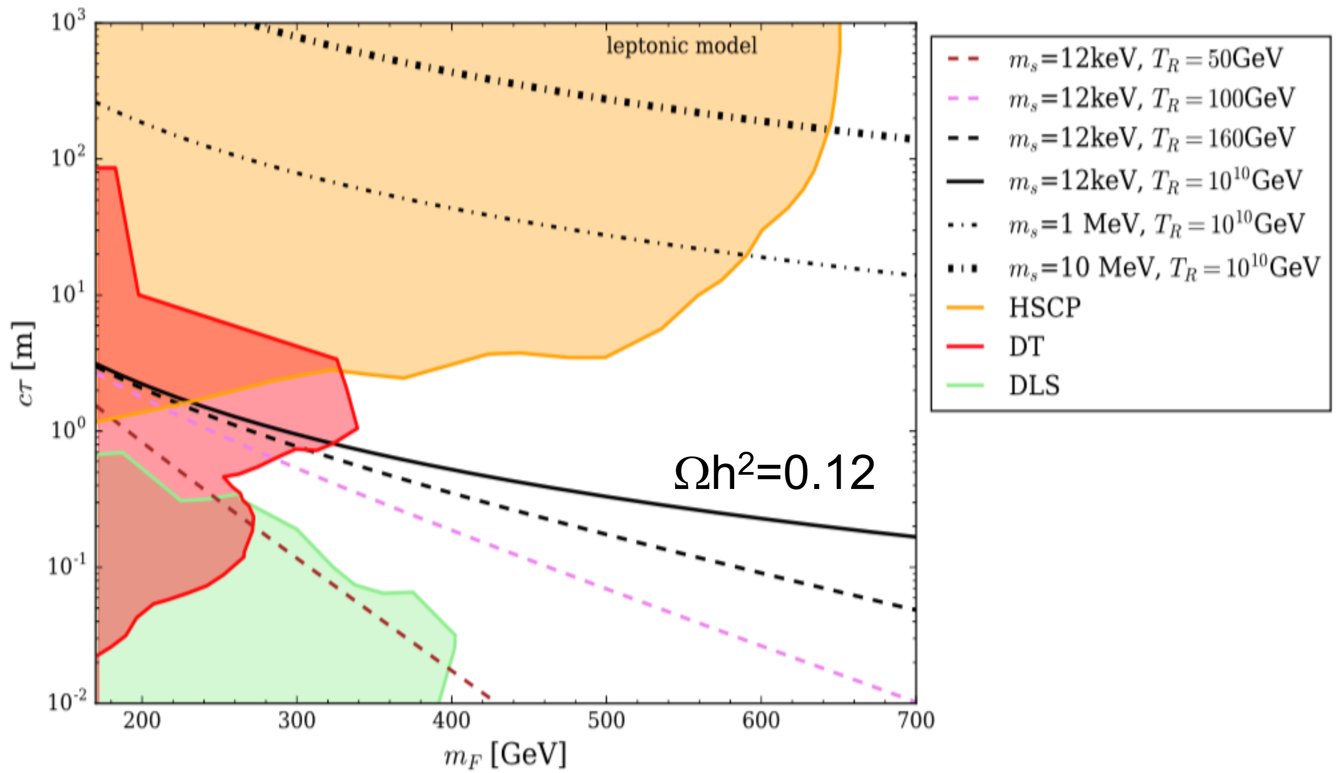


- Lepton transverse impact parameter - closest distance between beam axis and lepton track in transverse plane



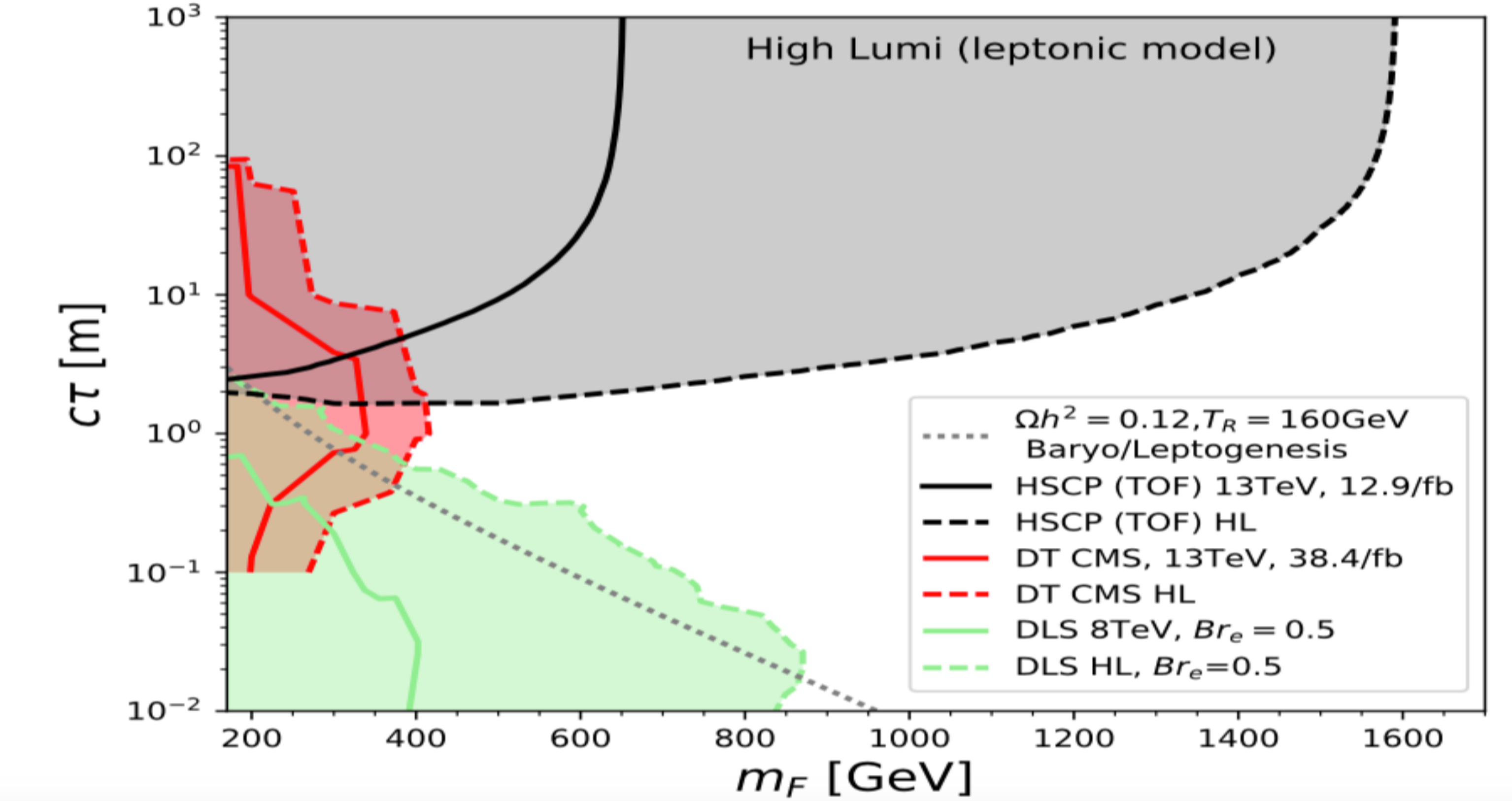
cds.cern.ch/record/2205146?ln=en

LHC constraints (lepton)



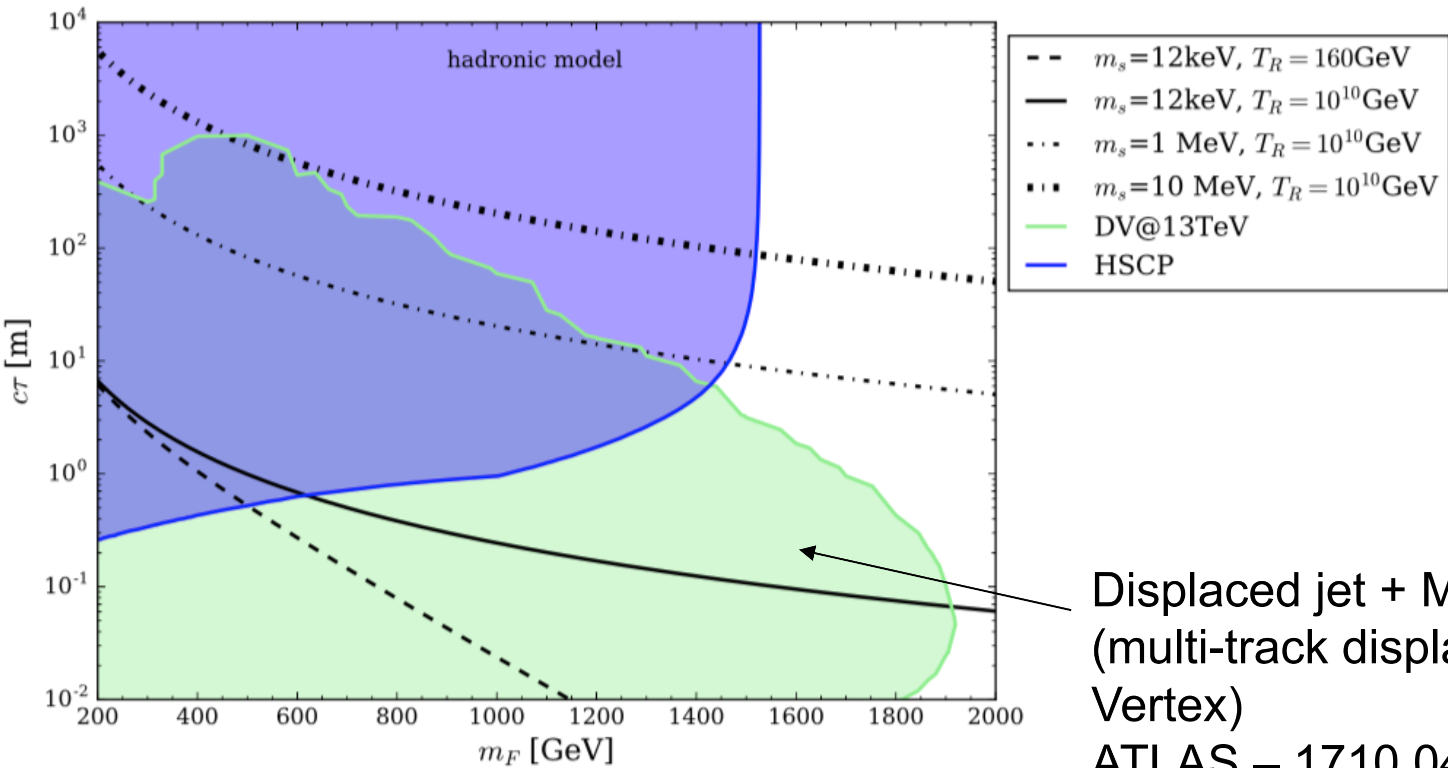
- As DM becomes heavier – only HSCP searches relevant
- Lower T_R : expect signatures for smaller $c\tau$

Extrapolating to higher luminosity



Naive extrapolation to 3000fb^{-1} (extrapolate current expected number of background events)

LHC constraints (quark)



Displaced jet + MET(>250GeV)
(multi-track displaced Vertex)
ATLAS – 1710.04901

- Region m_F< 1.5TeV fully covered
- Lower T_R : expect signatures for smaller $c\tau$

Summary

- Several viable scenarios for feebly interacting particles which leads to relic density ~0.11
- For a precise prediction include 1) Fermi-Dirac/Bose-Einstein distribution 2) when relevant thermal masses 3) production from out-of-equilibrium particles
- Some FIMPs can be tested in (in)direct detection
- Searches for long-lived and 'collider-stable' particles – useful probes of FIMP models
- Many cosmological constraints on light particles (not in this talk)

FI beyond simplified models

- FI can also occur in some of the common BSM models, e.g. in supersymmetry with RH sneutrino, gravitino, axino etc..
  - Cheung et al, 1103.4394; Hall et al, 1010.0245; Co et al 1611.05028…
- An example MSSM+RH sneutrino
  - Asaka et al, hep-ph/0612211, Banerjee et al, 1603.08834
- Neutrino have masses – RH neutrino + Susy partner well-motivated – if LSP then can be DM
- Example MSSM+3 RH neutrinos with pure Dirac neutrino mass
- Superpotential

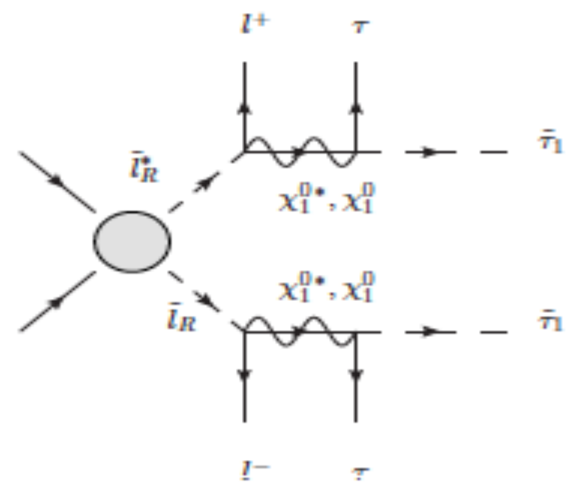
$$W = y_\nu \hat{H}_u \cdot \hat{L}\,\hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L}\,\hat{\ell}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u$$

- Small Yukawa couplings O(10^{-13}) (from neutrino oscillation and Planck+lensing +BAO)

- Sneutrino not thermalized in early universe - produced from decay of MSSM-LSP before or after freeze-out

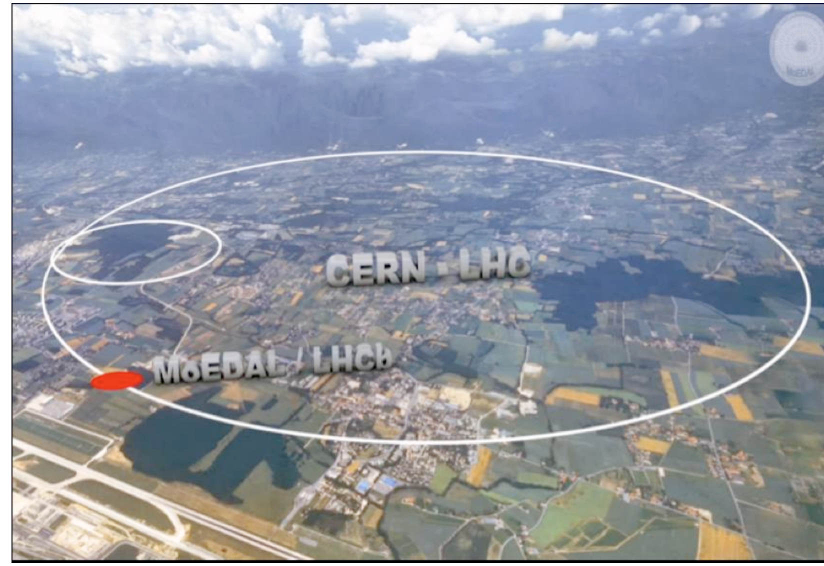
$$\Omega_{\tilde{\nu}_R}^{\rm FO} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}}\,\Omega_{\rm MSSM\text{-}LSP} \qquad \Omega_{\tilde{\nu}_R}^{FI} h^2 \simeq \frac{1.09\times 10^{27}}{g^{*\,3/2}} m_{\tilde{\nu}_R} \sum_i \frac{g_i \Gamma_i}{m_i^2}$$

- Consider stau as the NLSP - live from sec to min : decay outside detector
- LHC signature : stable charged particle NOT MET
- Constraints from BBN : lifetime of stau can be long enough for decay around or after BBN→ impact on abundance of light elements
- Decay of particle with lifetime > 0.1s can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes -Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)



- LHC Searches
  - Cascades : coloured sparticles decay into jets + SUSY→ N jets + stau
  - Pair production of two stable staus (model independent but lower cross section)
  - Passive search for stable particles
- Stable stau behaves like « slow » muons β=p/E<1
  - Use ionisation properties and time of flight measurement to distinguish from muon
  - kinematic distribution

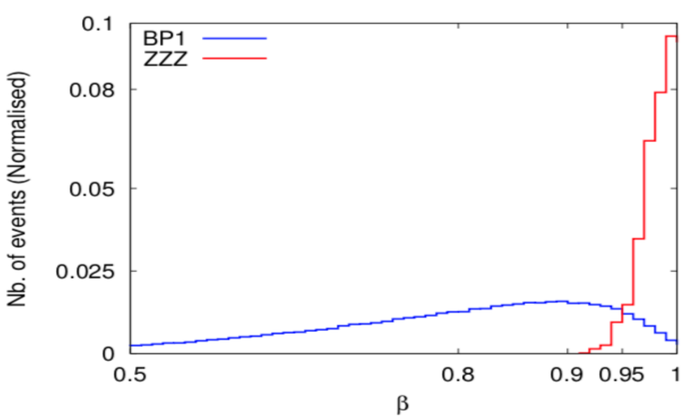
MoEDAL detector



- Passive detector
- Array of nuclear track detector stacks
- Surrounds intersection region point 8
- Sensitive to highly ionising particles
- Does not require trigger, one detected event is enough
- Major condition : ionizing particle has velocity $\beta<0.5$
- Enough to detect signal

B. Acharya et al, 1405.7662

Stau velocity distribution



$\mathcal{L} = 3000\ \mathrm{fb}^{-1}$

Benchmark	$m_{\tilde{\tau}_1}$ (GeV)	N_s
BP1	398	26
BP2	554	7
BP3	655	3
BP6	831	1

Banerjee et al, 1806.04488