Feebly Interacting Massive Particles and their signatures

Geneviève Bélanger

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

Nikhef, Amsterdam, 23/11/2018

Outline

Motivation

Relic density

Fimps in direct detection

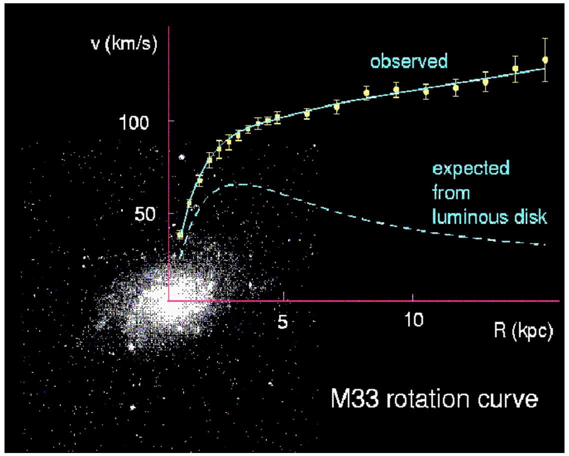
Fimps at colliders

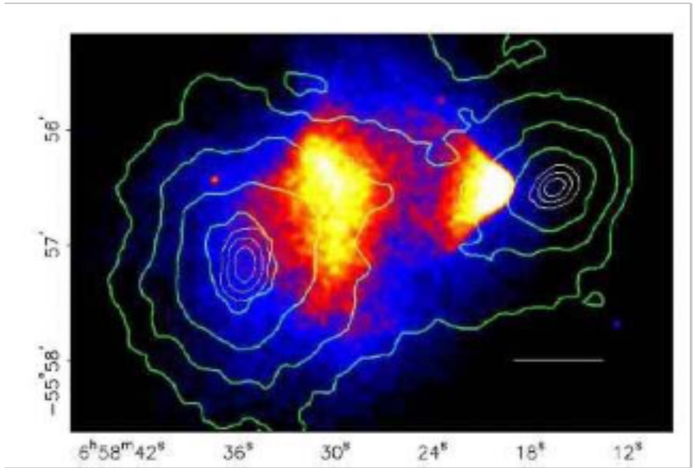
Intro

What do we know about dark matter?

It has gravitational interactions (galaxies – rotation curves- galaxy clusters, - Xray, gravitational lensing)

No electromagnetic interactions

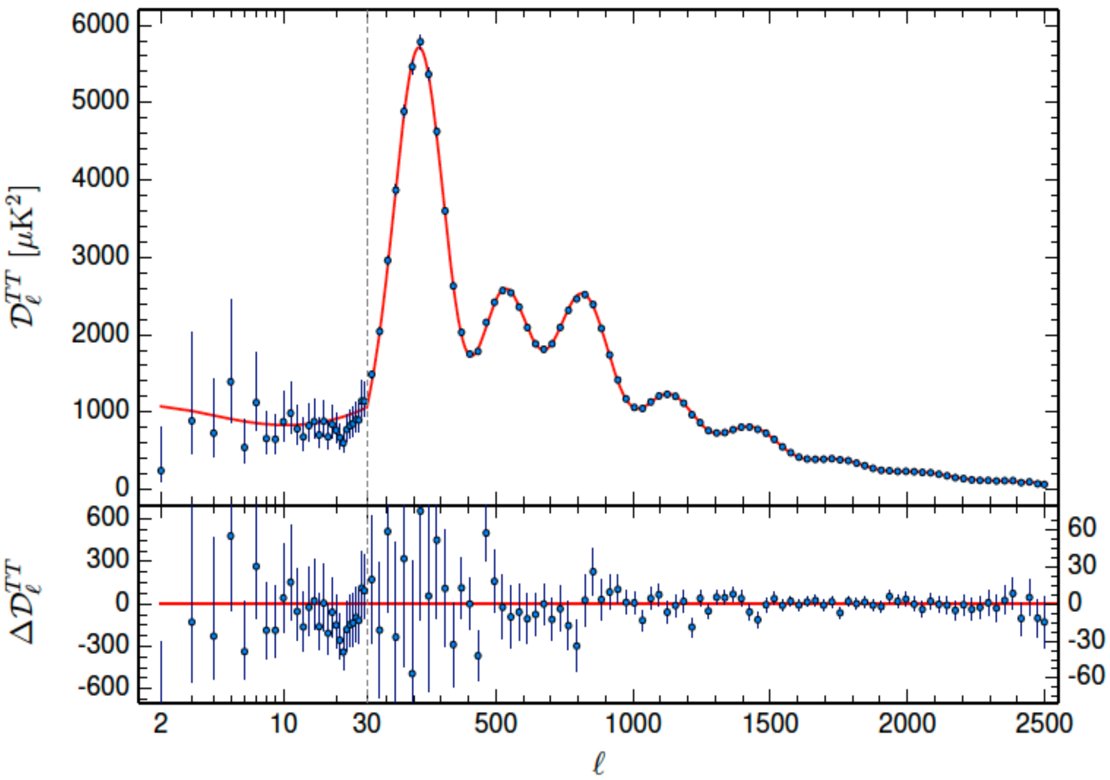




It is cold (or maybe warm) and collisionless (or not)

Within ΛCDM model – precisely know its relic density

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



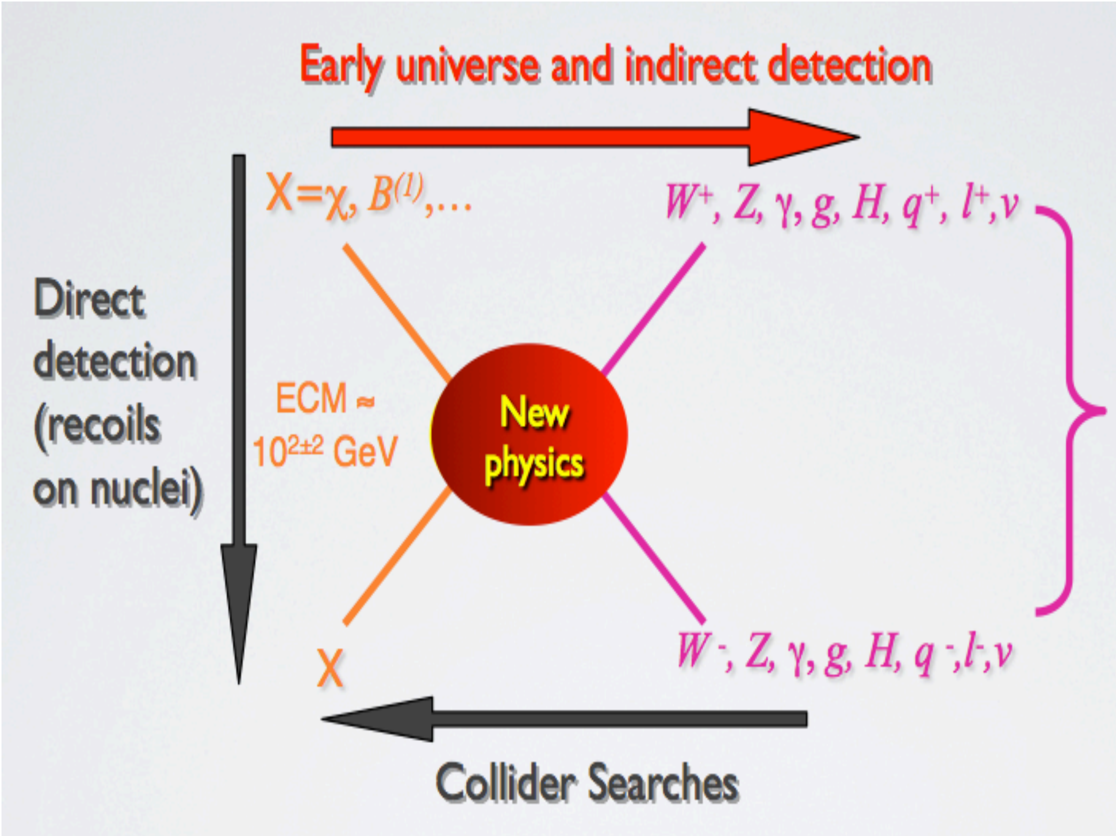
Leaves us with a lot of possibilities for dark matter

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

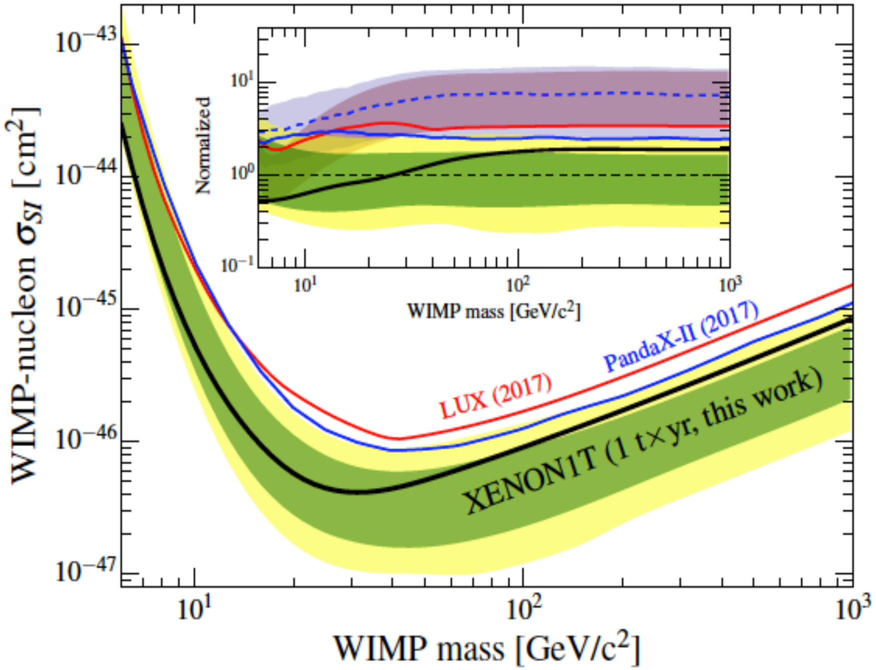
Probing the nature of WIMPs

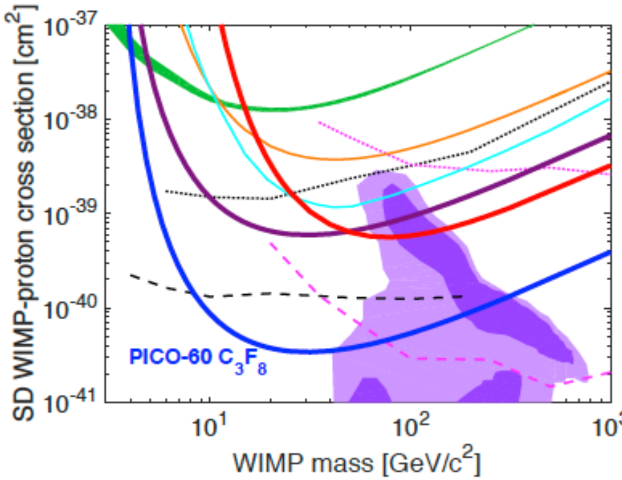


- All determined by interactions of WIMPS with Standard Model
- Specified within given particle physics model

But no signatures of WIMPs

Aprile, 1805.12562



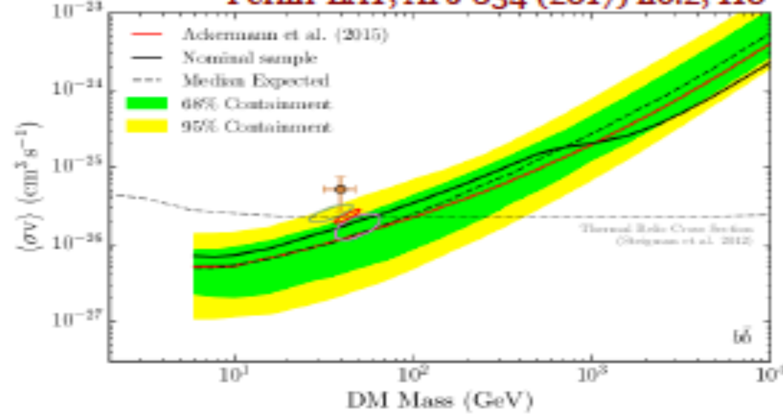


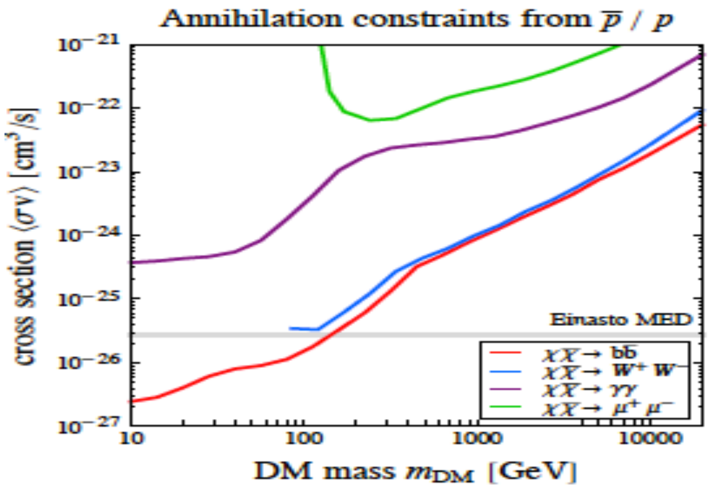
Amole et al, 1702.07666

Continuum

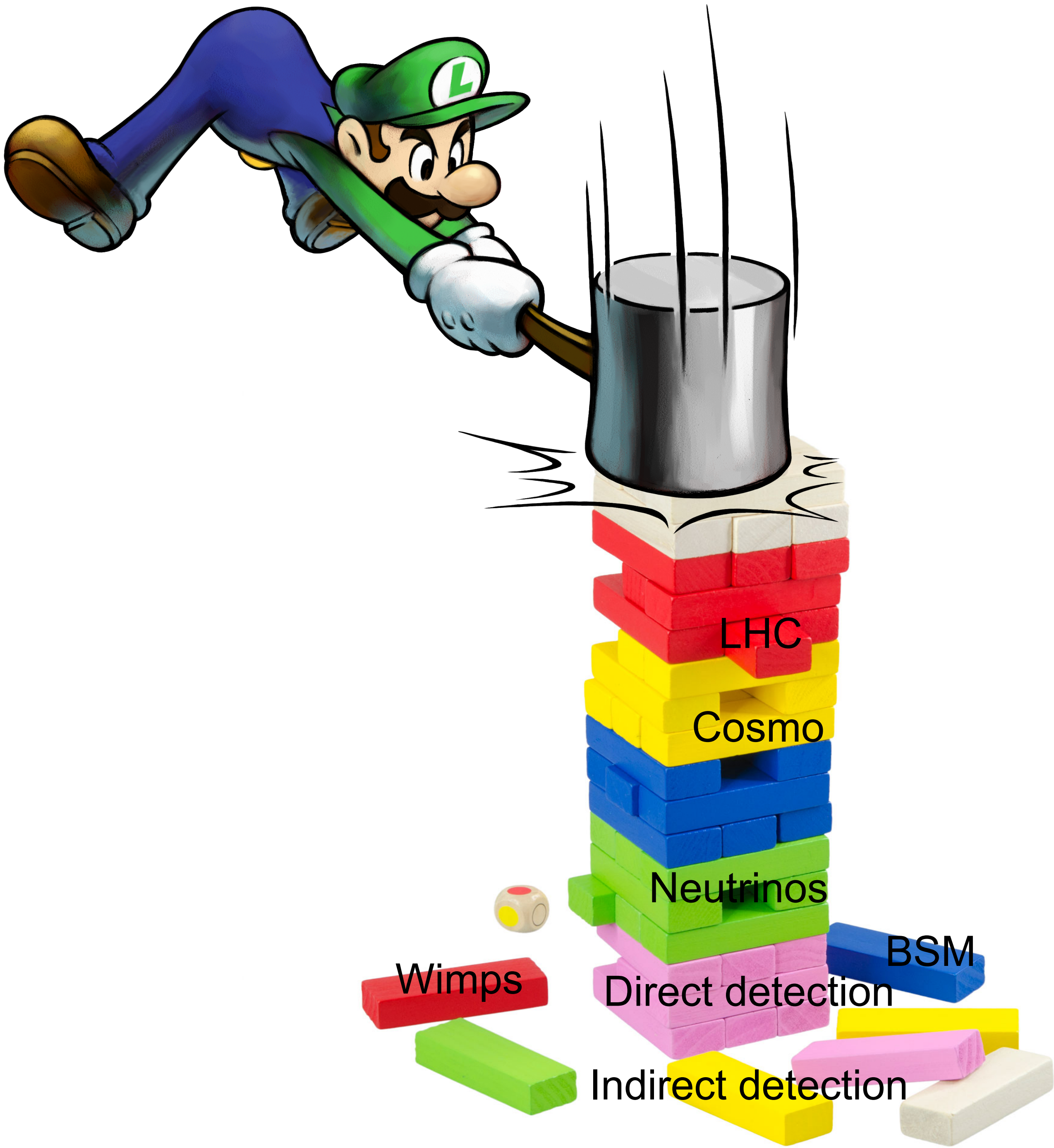
Fermi-LAT limit from dSPhs

Fermi-LAT, APJ 834 (2017) no.2, 110



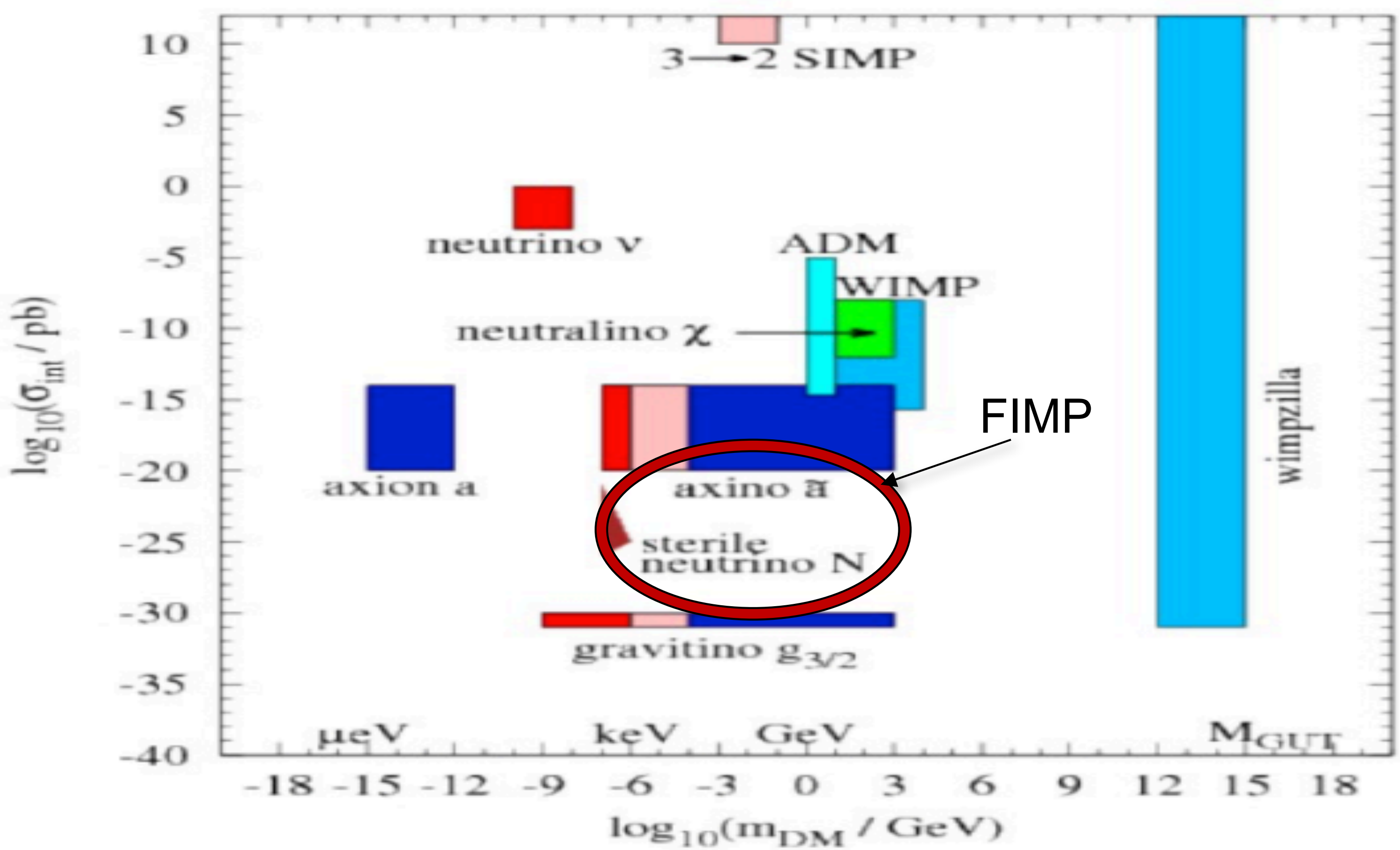


Giesen et al, 1504.04276


LHC
Cosmo
Neutrinos
BSM
Wimps
Direct detection
Indirect detection

Beyond WIMPs

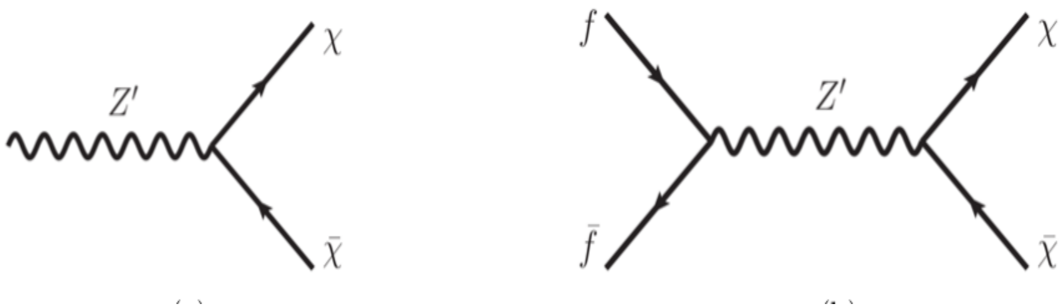
- Forget about WIMP miracle
- Consider much weaker interaction strength and maybe mass scale



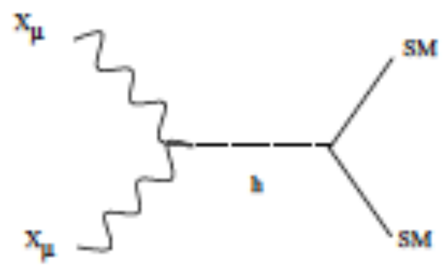
L. Roszkowski

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



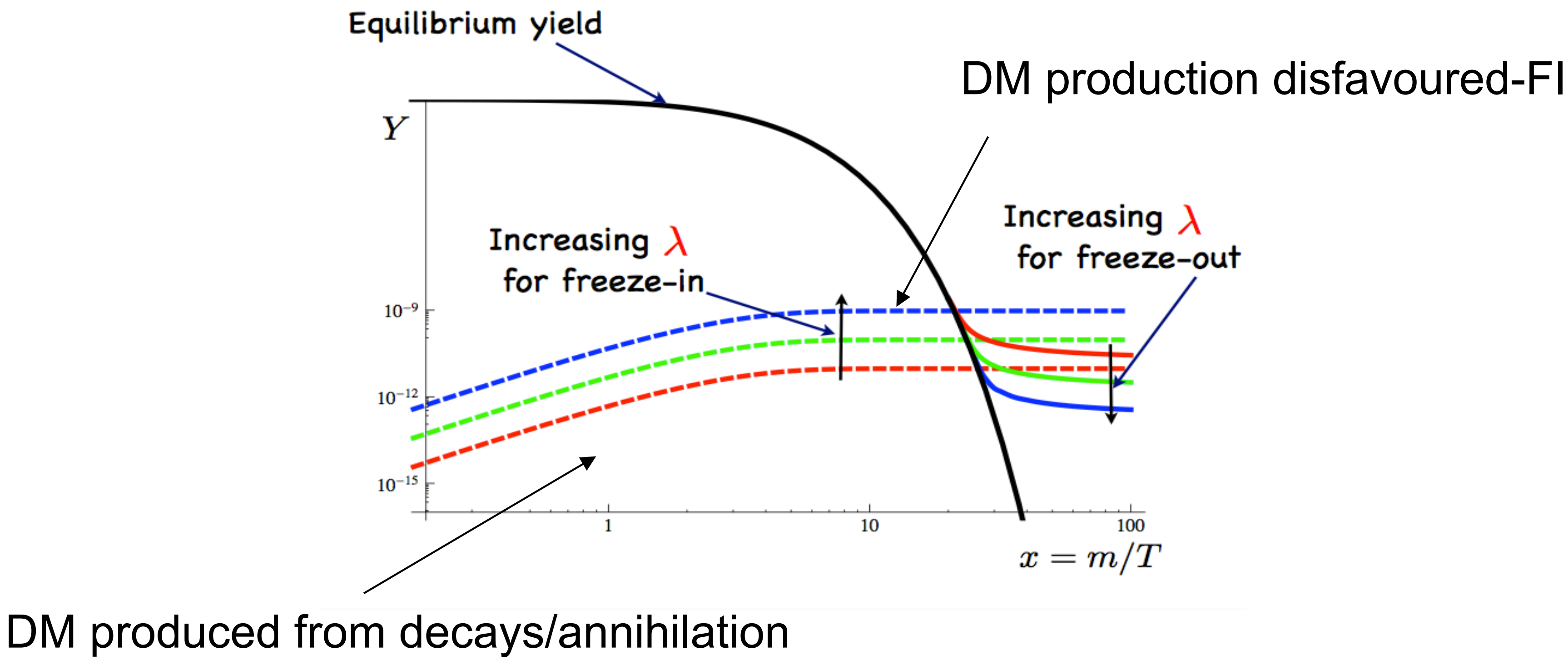
Freeze-in



Freeze-out

FIMPS (Feebly interacting MP)

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



In or Out

- Relic density depends on the initial conditions in FI, independent in FO since thermal equilibrium

- In FI: decay of heavier particles can dominate DM production, in FO only DM matters (except for coannihilation …)
  - Need to track evolution of heavier states (in equilibrium?) - dedicated Boltzmann equation

- Relevant temperature can be larger than for freeze-out,
  - FO : $m_{DM}/20$
  - FI : $m_{DM}/3$ or $m_{Med}/3$ or T_R -> cannot always make approximation Maxwell-Boltzmann distribution

- Only one public code for freeze-in :   micrOMEGAs5.0: freeze-in GB, Boudjema, Goudelis, Pukhov, Zaldivar, arXiv:1801.03509

Freeze-in

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

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

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 Th.eq. with SM)

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

Solving for relic density (annihilation)

- Boltzmann eq, 2->2:

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

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

- T larger than for freeze-out, cannot always make approximation Maxwell-Boltzmann distribution

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

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

- Effect of statistical treatment : up to a factor 2 (for bosons) smaller for fermions
- Solve for Y=n/s → $\Omega h^2 = \frac{m_\chi Y_\chi^0 s_0 h^2}{\rho_c}$

Simple example : vector portal

- Z' portal with vector couplings to fermion DM and SM

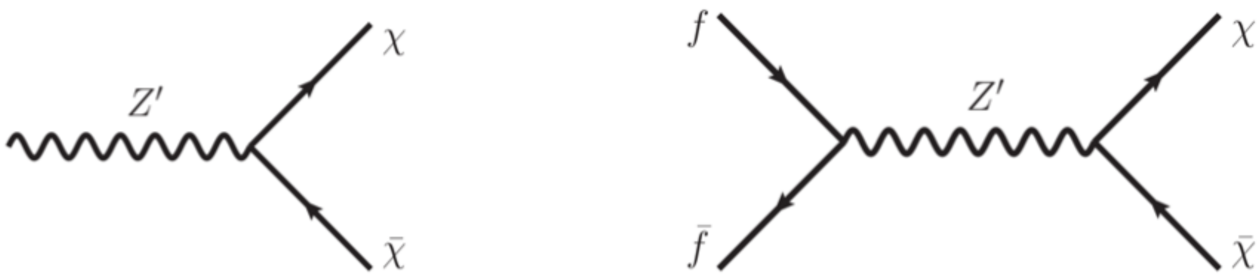
$$\mathcal{L}_{\rm int} = -g_\chi Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum g_q Z'_\mu \bar{q}\gamma^\mu q$$

- 3 regimes

$$m_{Z'} < 2m_\chi < T_R$$

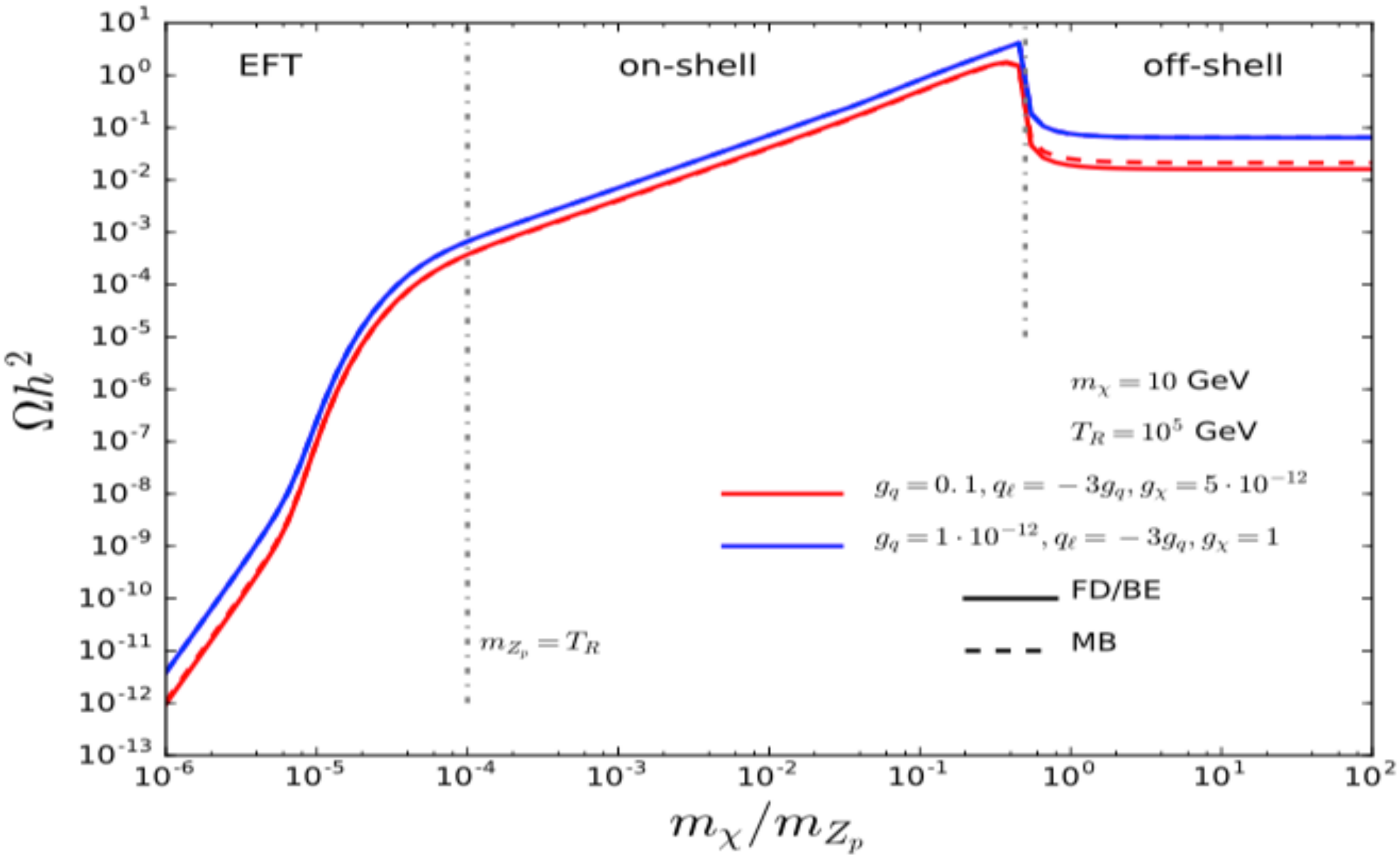
$$2m_\chi < T_R < m_{Z'}$$

regime	$\sigma(s)$	Y_χ
off-shell	$\frac{g_u^2 g_\chi^2}{s}$	$g_u^2 g_\chi^2 M_{\rm Pl}/m_\chi$
on-shell	$\frac{g_u^2 g_\chi^2 m_{Z'}}{\Gamma}\delta(s-m_{Z'}^2)$	$g_u^2 g_\chi^2/\Gamma$
EFT	$g_u^2 g_\chi^2 s/m_{Z'}^4$	$g_u^2 g_\chi^2 T_R^3/m_{Z'}^4$



$g_q\, g_\chi \sim 10^{-10}$ - 10^{-12}

Simple example : vector portal



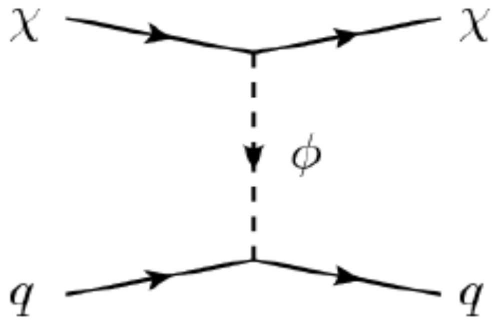
Typically get expected relic density both in off-shell ($m_\chi \sim m_{Med}$) and on-shell regime ($m_\chi << m_{Med}$) - DM can be very light

Signatures from the sky

- Typical couplings $g_q g_\chi \sim 10^{-10} - 10^{-12}$

- Which such weak coupling can we expect any signal in direct or indirect detection?
- 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
- Direct detection : introduce a light mediator to boost the rate

Direct detection



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

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

For light mediator

- Typical $q^2 \sim 100$MeV (M_{DM}=100GeV)
- For very light mediator $\sigma \sim 1/E_R^2$ ($M\phi$<40MeV), recall typical threshold on recoil energy ~5keV
- Spectrum peaks at low recoil energies

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

Velocity distribution

- Re-interpretation of DD limits from Xenon …

Example : a minimal model

- Simplified model with Dirac fermion (DM) with scalar mediator

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

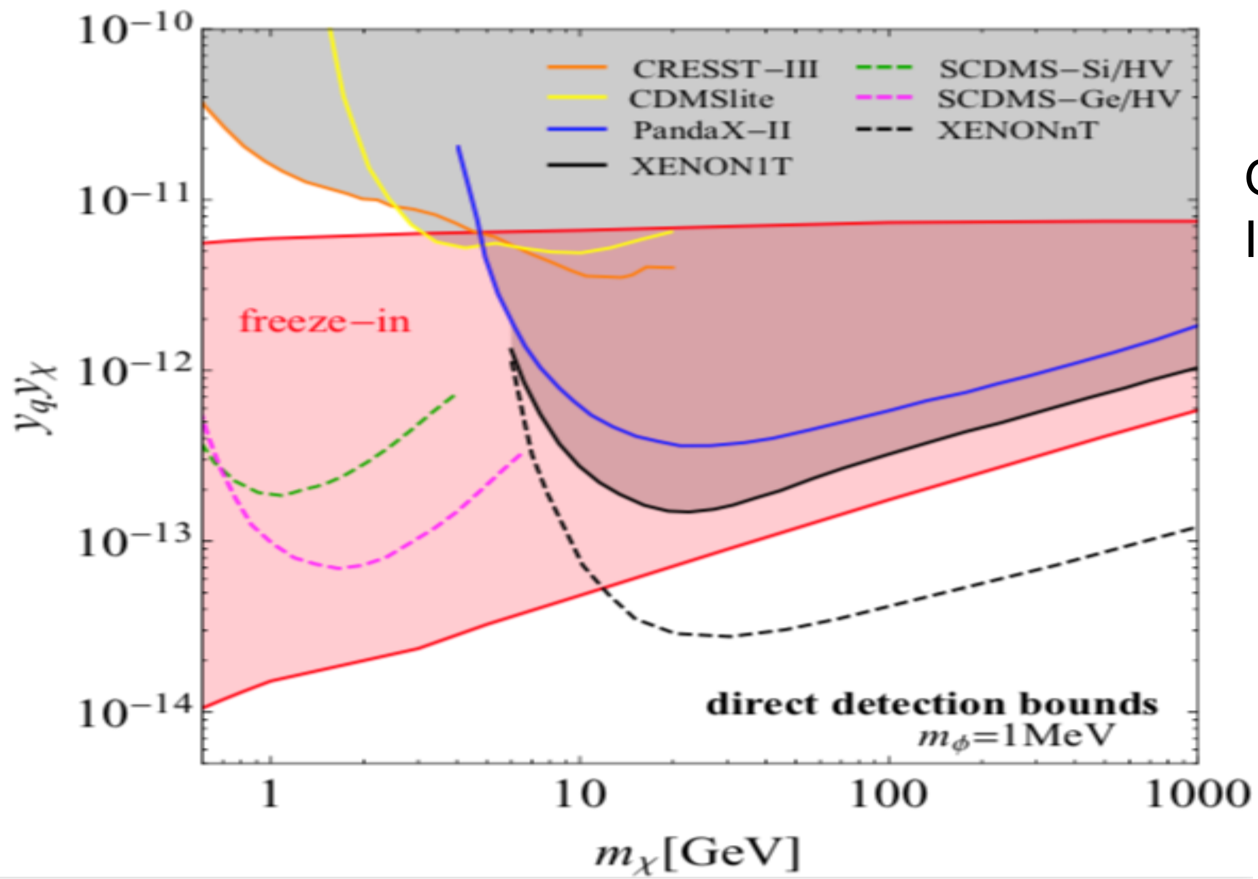
- Two DM production processes (relative contribution depends on couplings and on whether ϕ is in equilibrium with SM)

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

- Solve for FI : m_χ,m_ϕ, y_q, y_χ
- Can DD probe the region of parameter space that reproduces the relic density?

Direct detection

PRELIMINARY

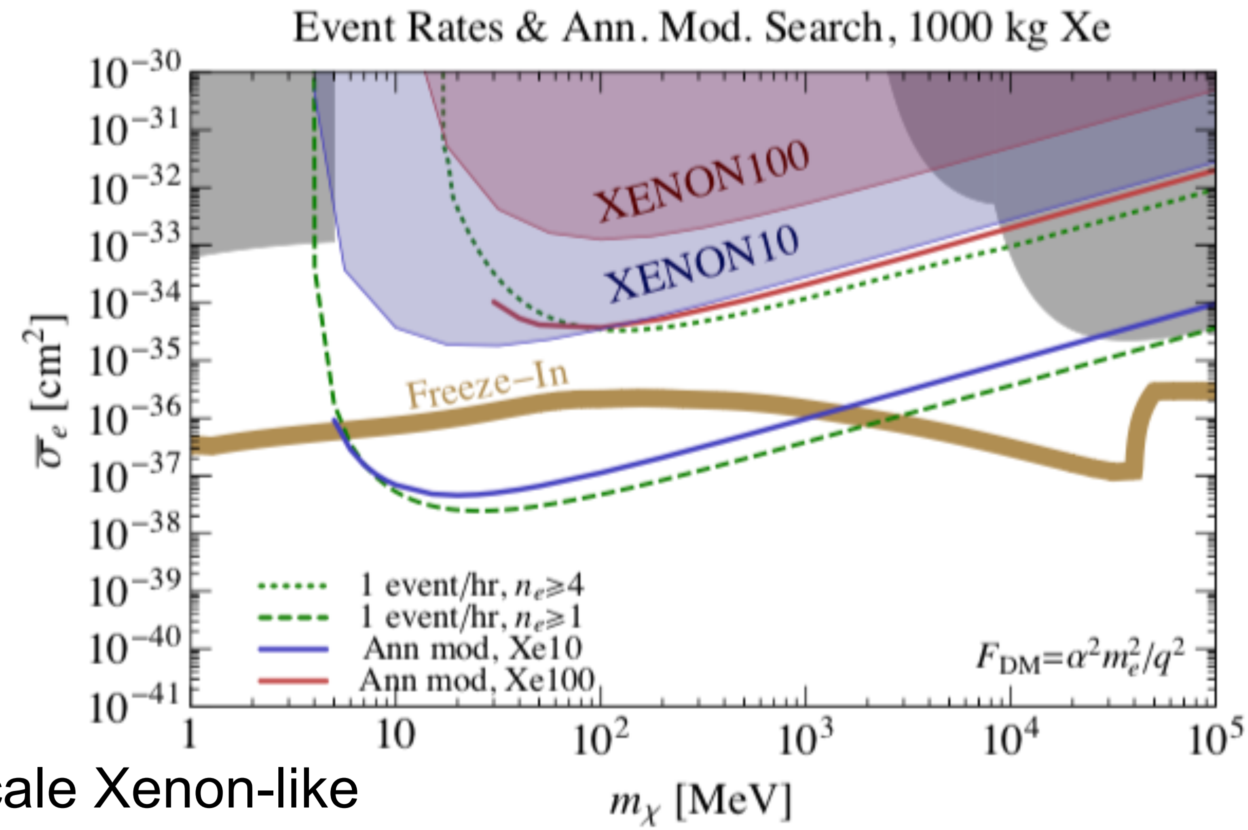


GB, Delaunay, Zaldivar,
In preparation

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

Direct detection with light mediator

- DM-electron scattering provides an alternative probe – results from Xenon, and from SENSEI : a dedicated detector, 1804.00088



Projection ton-scale Xenon-like

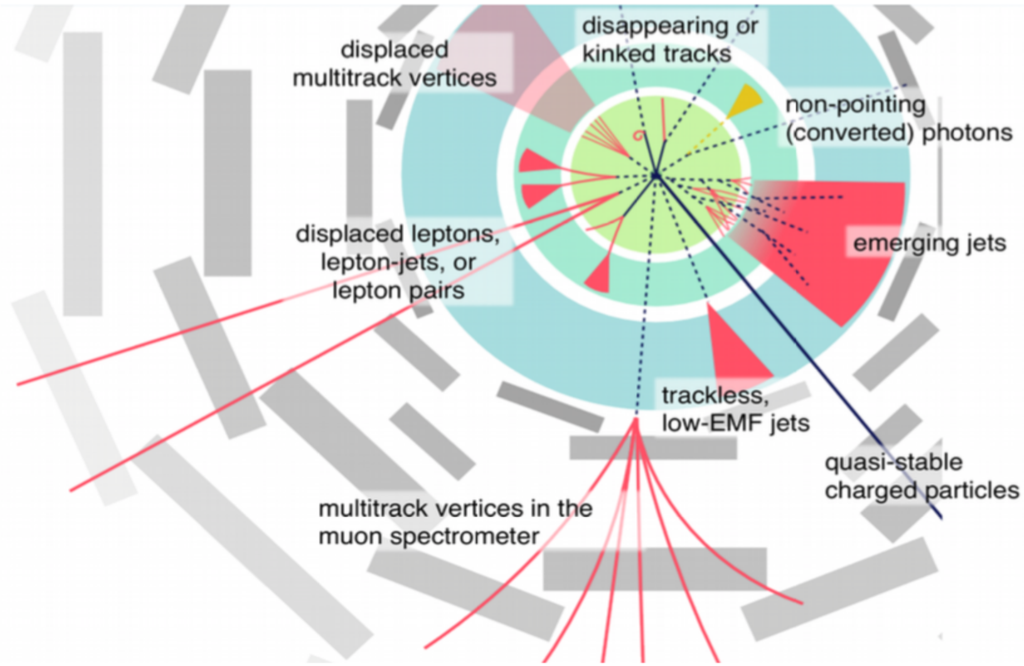
Essig et al 1703.00910

What about the LHC?

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

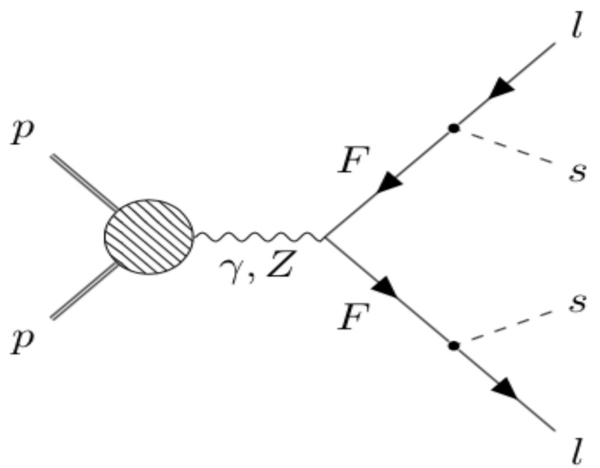
Relic density

- 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

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

- For very low reheating temperatures – possibility to falsify baryogenesis
- *Lifetime from cm to many meters*

Production at LHC



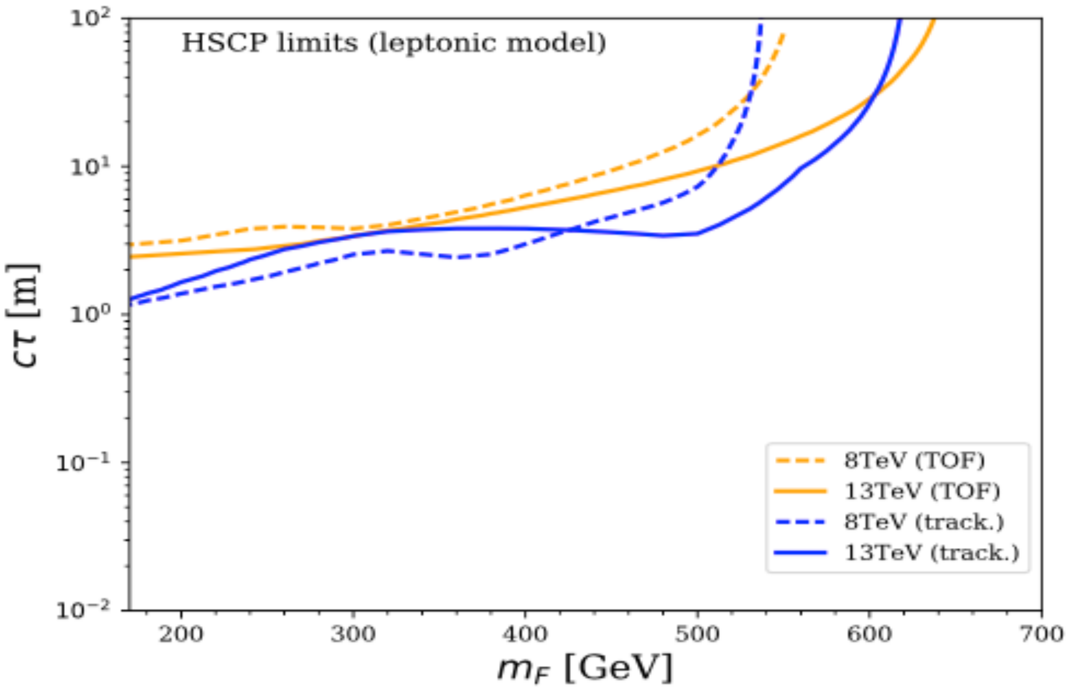
LLP signatures at colliders

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

HSCP

- 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
- Note if F has low $c\tau$, a fraction can decay within the tracker, rescale the production cross section

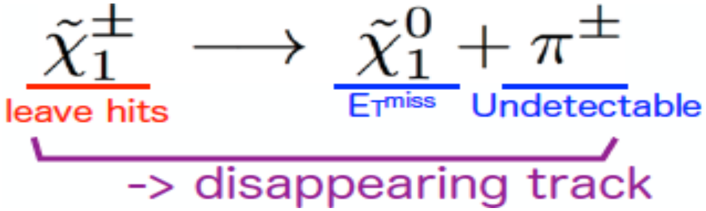
HSCP limits

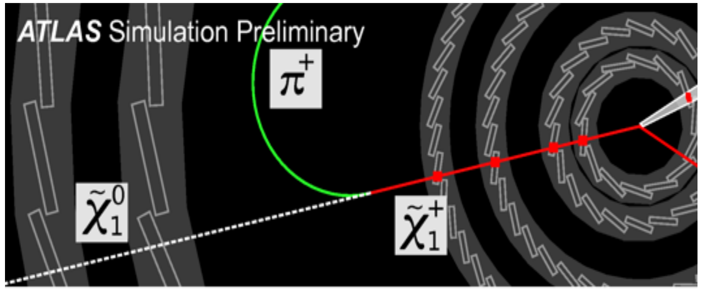


- Recast of CMS 8 TeV (18.8fb-1) and 13 TeV (12.9fb-1) searches:
  - Tracker only (decay outside tracker)
  - TOF: Tracker + time-of-flight (decay outside muon chamber)
- GB et al, 1811.05478

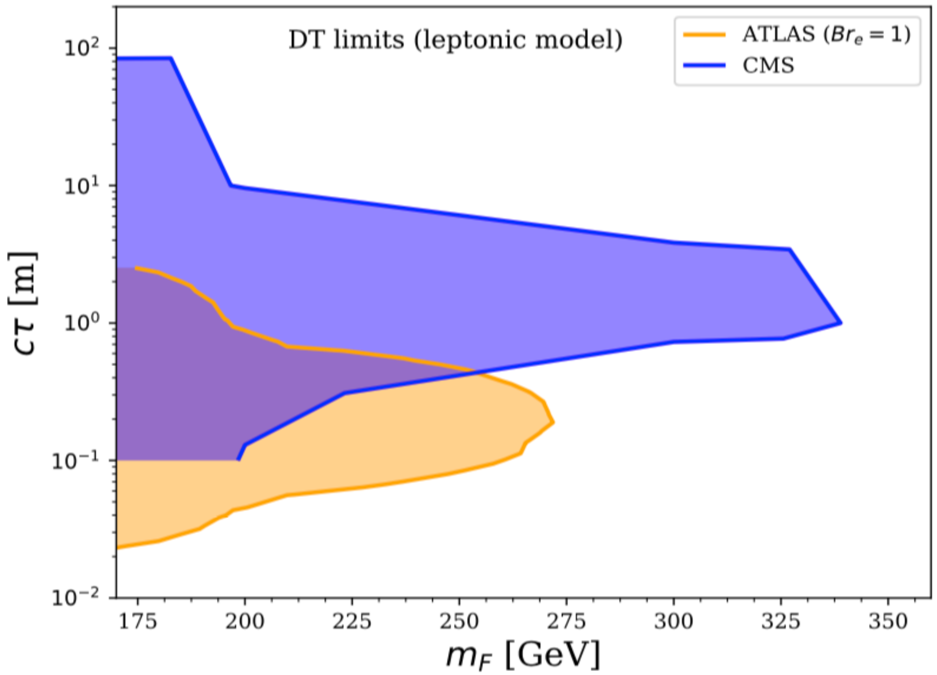
Disappearing tracks

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





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

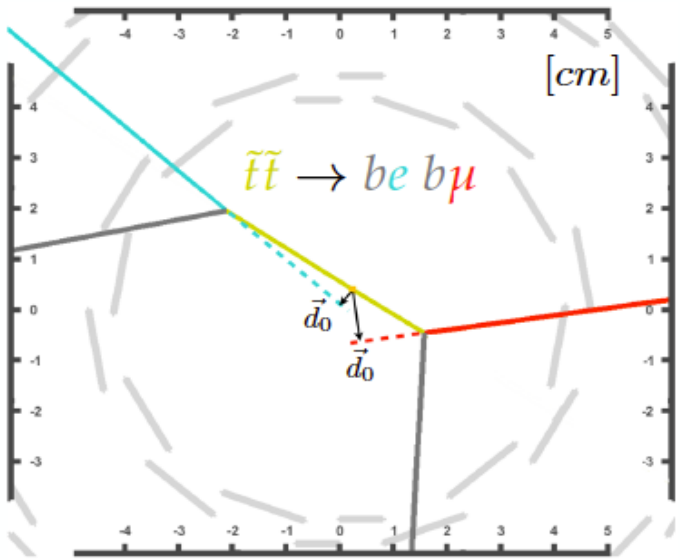


- ATLAS can reconstruct tracks down to 12 cm (25 cm for CMS)
- Not as sensitive as HSCP but covers shorter lifetimes

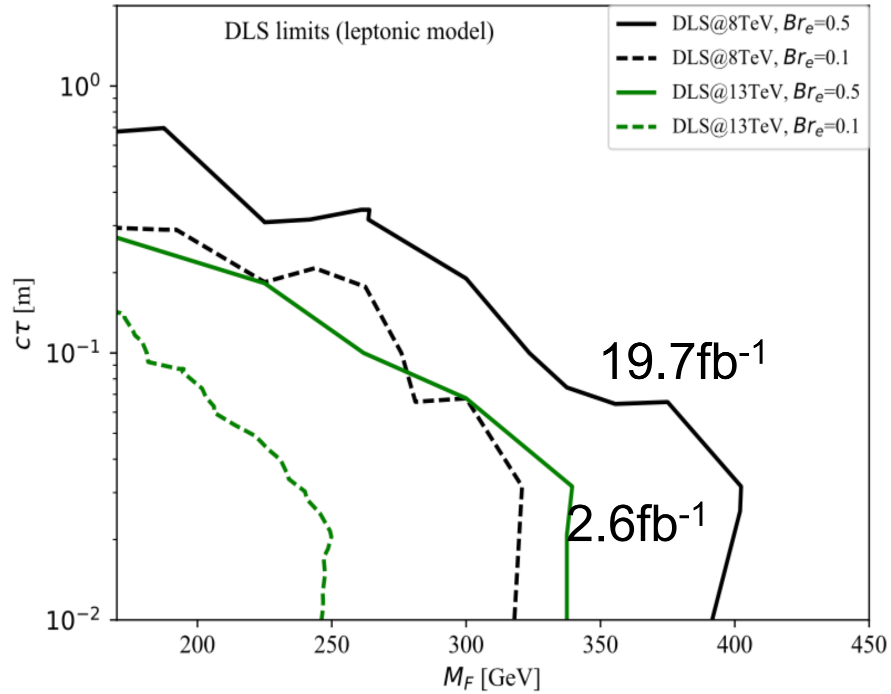
Displaced leptons

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

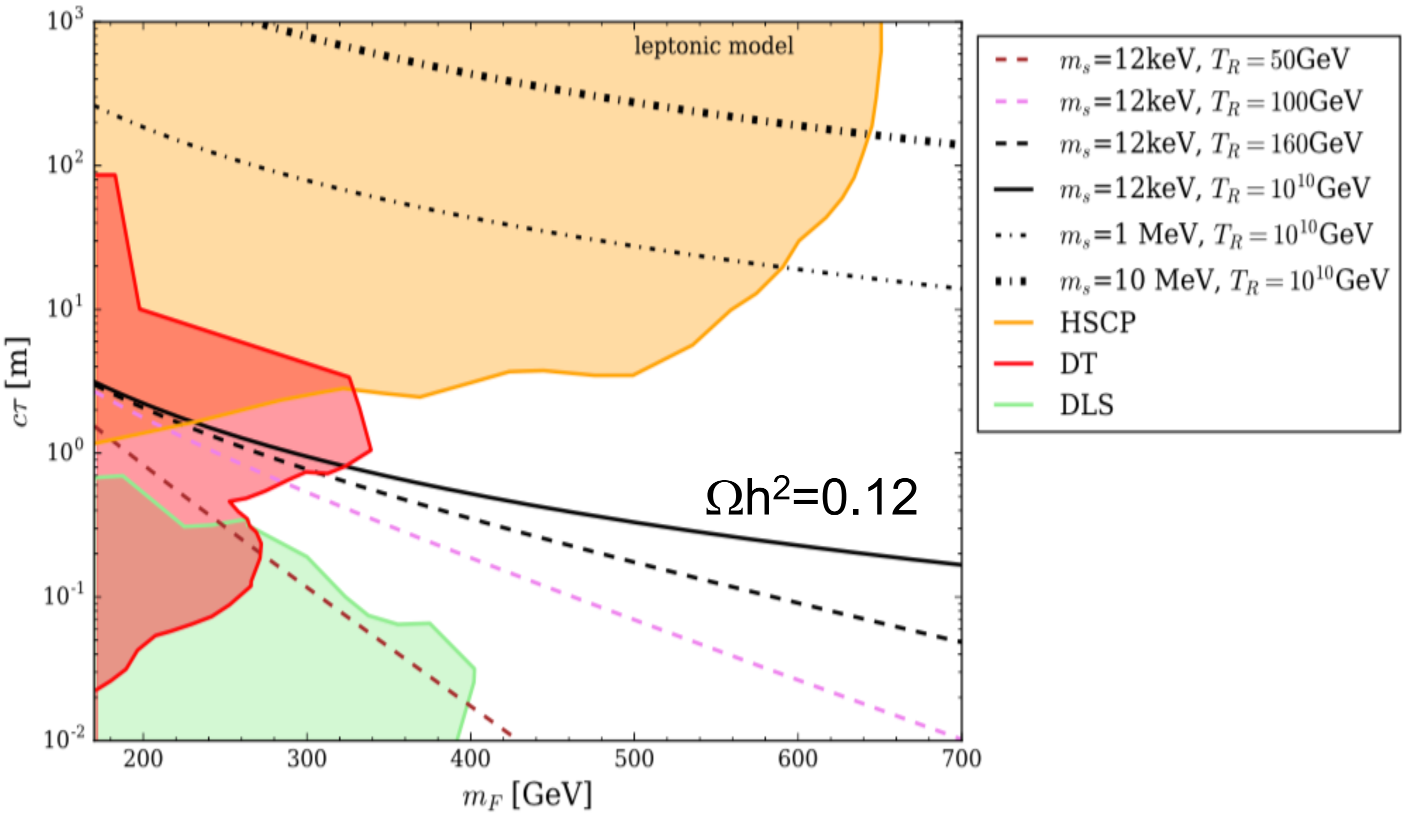
- Lepton transverse impact parameter - closest distance between beam axis and lepton track in transverse plane



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

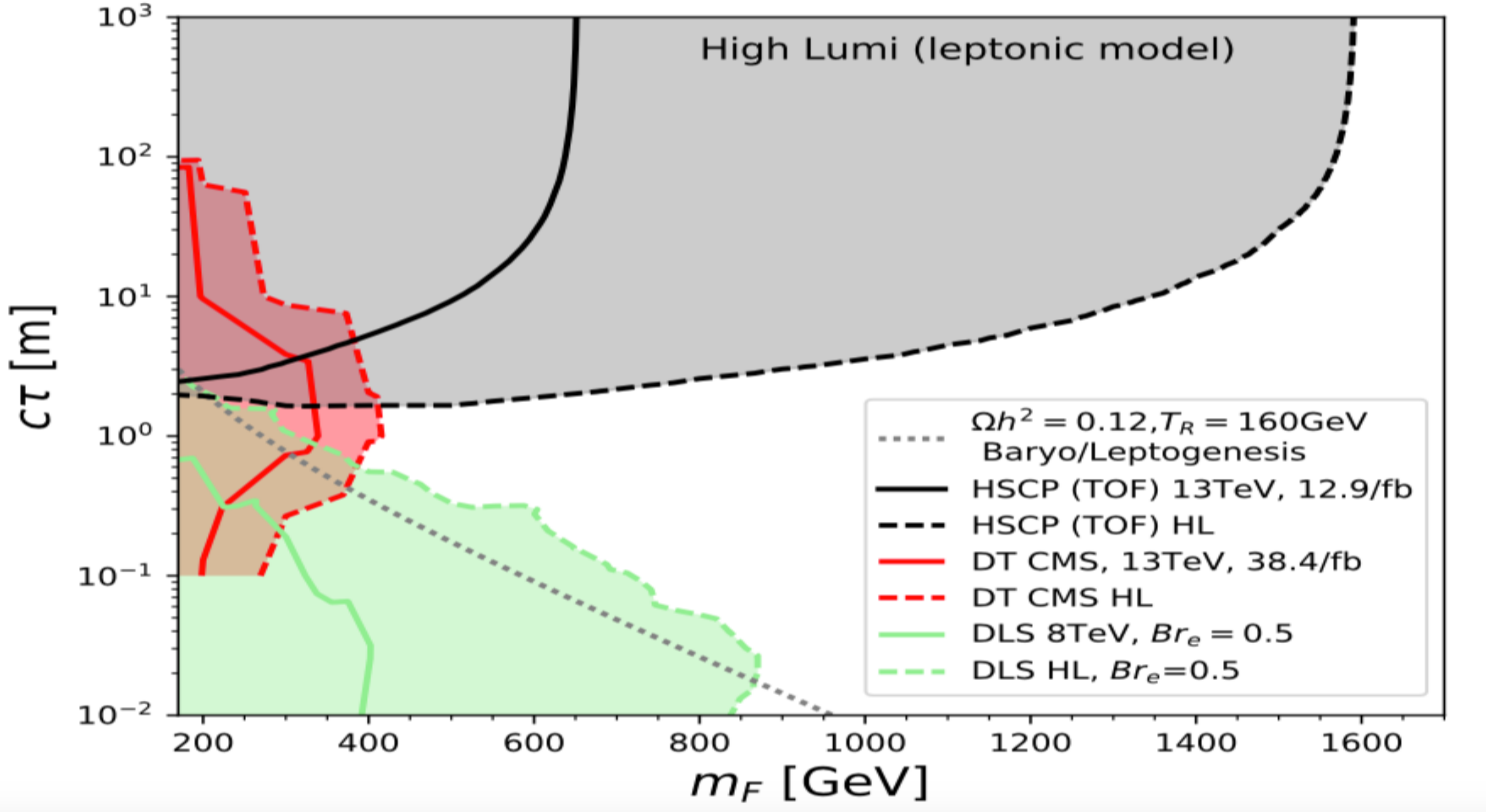


LHC constraints (lepton)



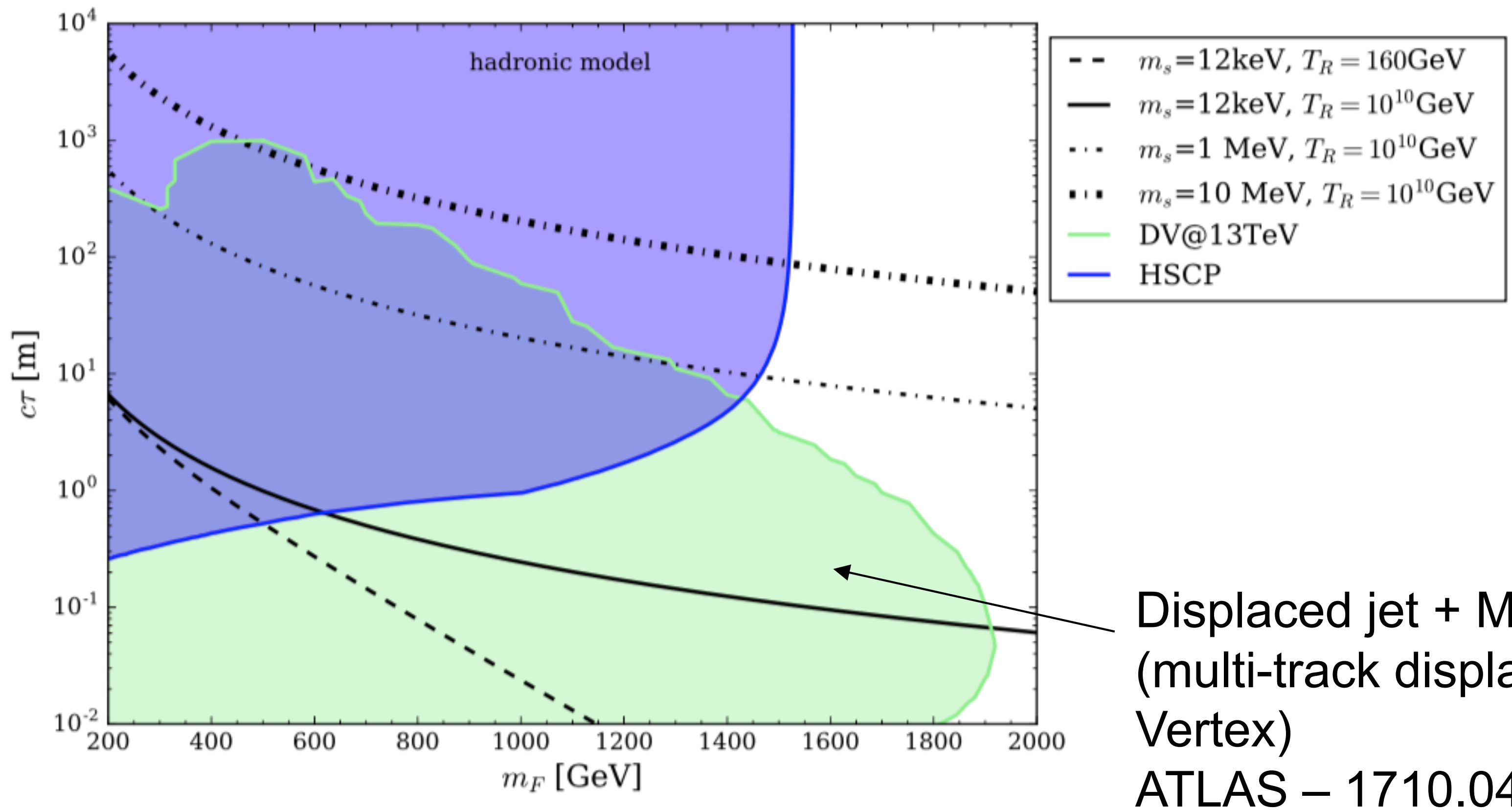
- As DM becomes heavier – only HSCP searches relevant
- Lower T_R : expect signatures for smaller $c\tau$

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

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

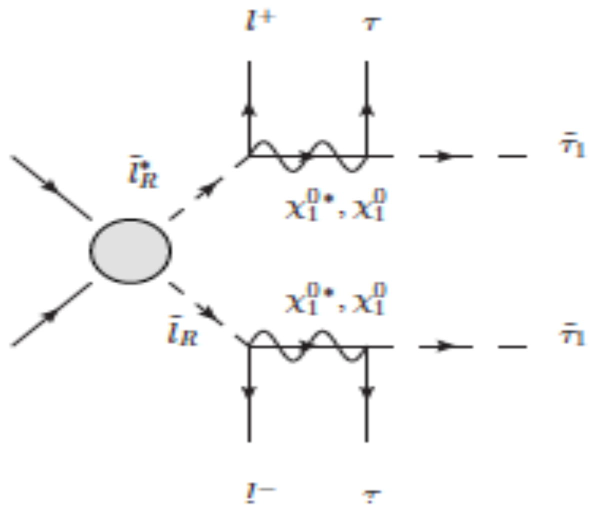
$$W = y_\nu \hat{H}_u \cdot \hat{L}\,\hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L}\,\hat{\ell}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u$$

- 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

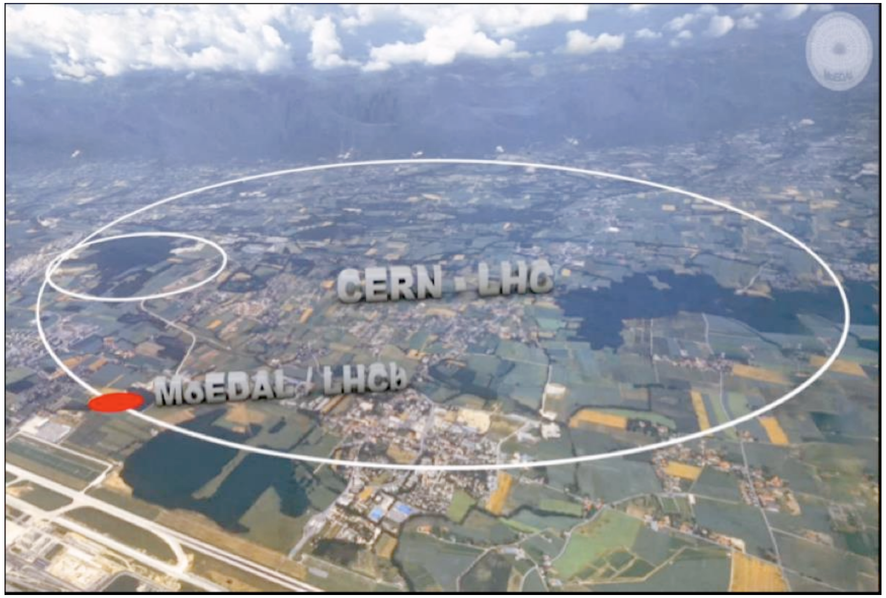
$$\Omega^{\rm FO}_{\tilde{\nu}_R} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}} \Omega_{\rm MSSM\text{-}LSP} \qquad\qquad \Omega^{FI}_{\tilde{\nu}_R} h^2 \simeq \frac{1.09 \times 10^{27}}{g^{*\,3/2}} m_{\tilde{\nu}_R} \sum_i \frac{g_i \Gamma_i}{m_i^2}$$

- 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

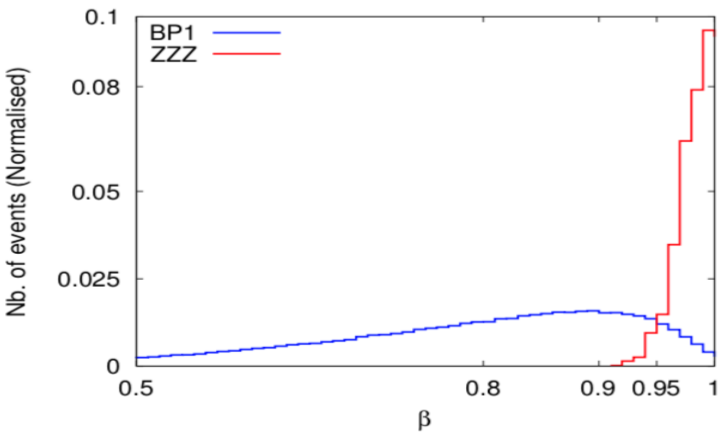
MoEDAL detector



- 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



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

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

Final remarks

- Made enormous progress in searching for DM with direct/indirect and collider searches with WIMPs
- With searches for long-lived and ‘collider-stable’ particles – powerful probes of another class of DM candidates : FIMPs
- Some FIMPs can be tested in (in)direct detection
- Many cosmological constraints on light particles (not in this talk)