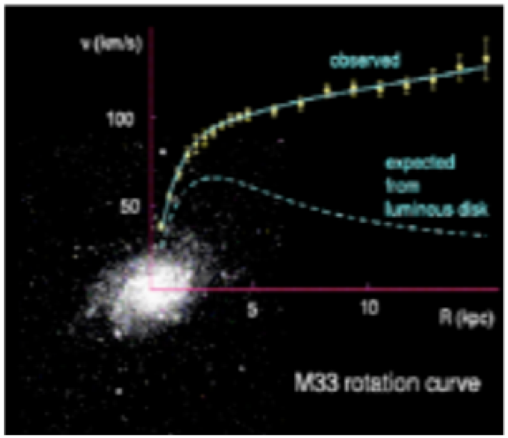
Dark matter candidates:
from weak to feeble

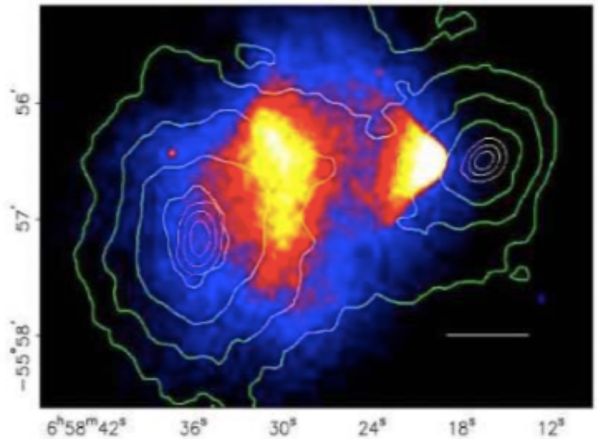
G. Bélanger

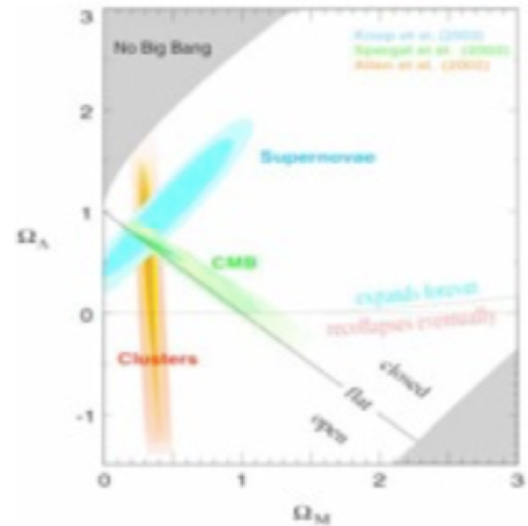
LAPTh, Annecy-le-Vieux

Karlsruhe, 11/03/2024

Introduction

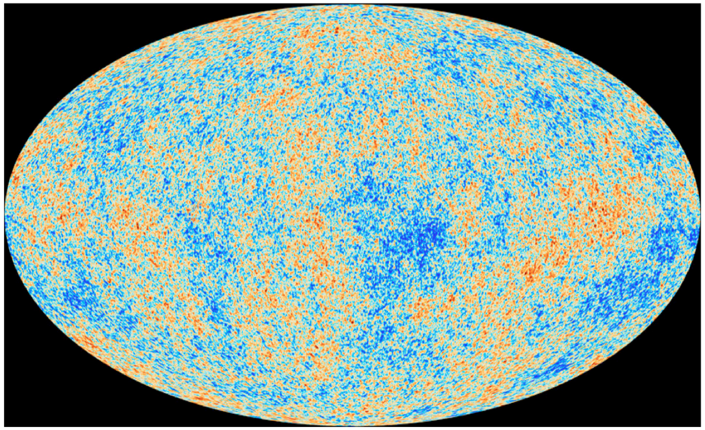


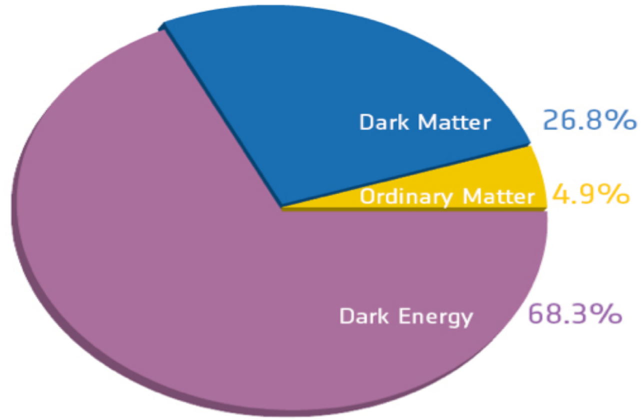




- Strong evidence for dark matter from many scales
  - The galactic scale (rotation curves)
  - Scale of galaxy clusters: mass to light-ratio, gravitational lensing, Bullet cluster
  - Cosmological scales
    - DM required to amplify the small fluctuations in Cosmic microwave background to form the large scale structure in the universe today
- Dark Matter a new particle?

WMAP and PLANCK





The universe contains ~27% of cold dark matter

*Cold: non-relativistic during structure formation otherwise with erase structure

Since DM is non relativistic at the time of 'last scattering' when photons decoupled –> M>10keV : neutrino cannot be main DM component

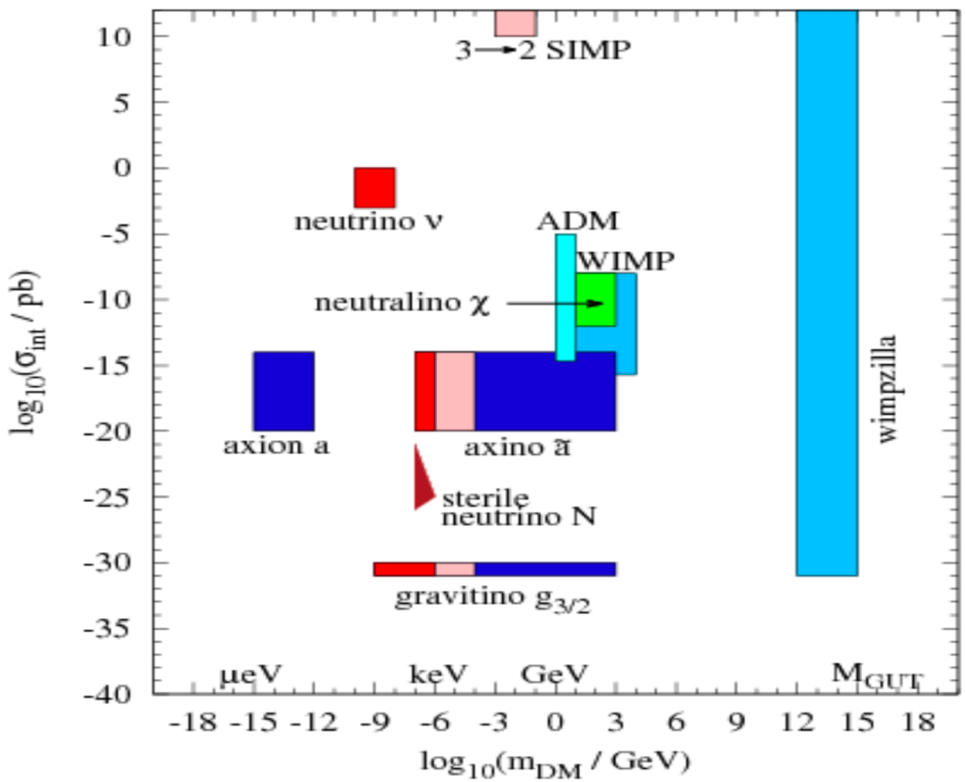
DM a new particle : what are its properties?

- cold, neutral (or very small charge), stable, non-baryonic, weak interactions with standard model (or feeble)

- Relic density of DM known precisely (PLANCK)

$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010\,,$$

- Leaves lots of possibilities for DM of different mass and interaction strength - a new stable WIMP is most studied candidate - despite strong experimental programs – no signs of WIMPs but the searches continue



Baer et al, 1404.0071

- Well-motivated New Physics model has yet to be singled out
- 30 years ago, had a very good idea what would be this new particle : neutralino in SUSY – despite the large parameter space clear paths for DM searches (direct and indirect searches and production at colliders)
- Same strategy applies for other WIMPs – a new stable neutral weakly interacting particle
- Many possibilities for dark matter, classified by:
  - Dark matter production mechanisms : in thermal equilibrium in early universe or not – interaction strengths (WIMPs, FIMPs, SIMPs, SIDM etc..) – mass…
  - Theoretically motivated beyond the standard model (e.g. naturalness)
  - Expt-motivated extension of the Standard model : neutrino, anomaly (B, g-2…); baryogenesis
  - Extension of SM with DM candidate (e.g. simplified model)
- Underlying theoretical model allow to best exploit connections between search strategies – range of masses, coupling strengths, spin of DM, nature of mediator(s)
- Mediator(s) : coupling between DM and SM – e.g. H or new particle

The case of WIMPs

WIMP DM

- Most studied hypothesis: a new stable neutral weakly-interacting massive particle – WIMP – why are they good DM candidates?
- In thermal equilibrium when T of Universe much larger than its mass
- Equilibrium abundance maintained by processses

$$\chi\bar{\chi} \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, W^+W^-, ZZ$$

- As well as reverse processes, inverse reaction proceeds with equal rate
- As Universe expands T drops below m_χ, n_{eq} drops exponentially, production rate is suppressed (particles in plasma do not have sufficient thermal energy to produce $\chi\chi$) χ start to decouple – can only annihilate $dn/dt=\sigma v\ n^2$
- Eventually rate of annihilation drops below expansion rate $\Gamma < H$ – not enough χ for annihilation - > fall out of equilibrium and freeze-out (at T_{FO}~m/20), density depends only on expansion rate

$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

WIMP DM

- Why WIMP
- In thermal e … han its mass
- Equilibrium … $\bar{q}, W^+W^-, ZZ$
- As well as r … ith equal rate
- As Universe … ntially, production rate is suppr … ent thermal energy to produce χ … n/dt=σv n^2
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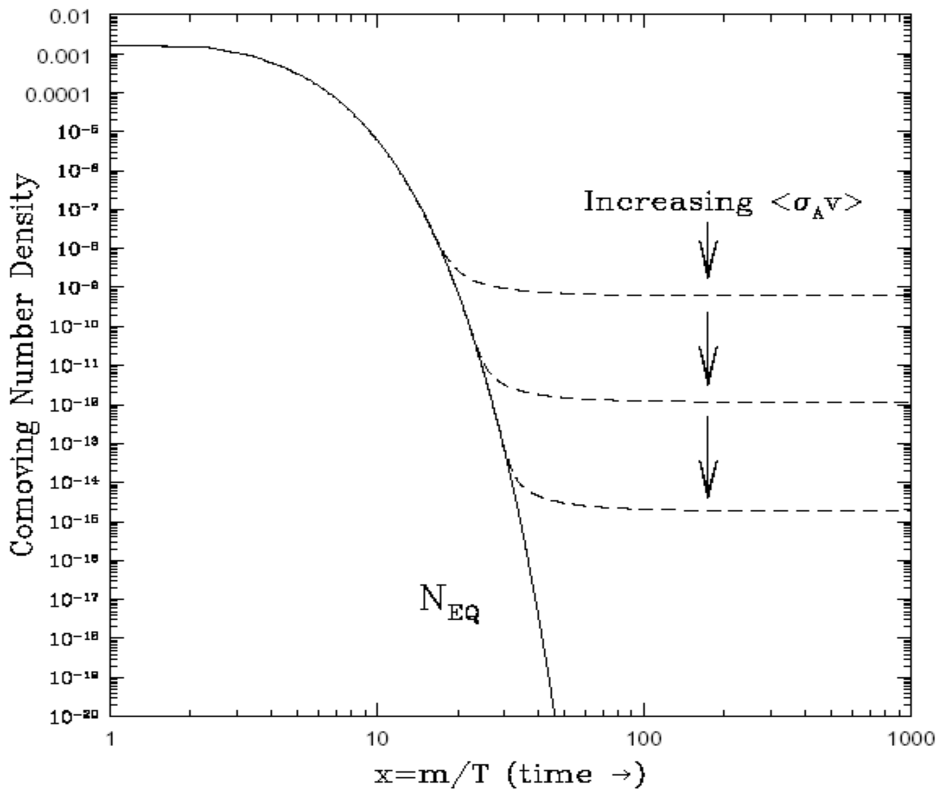


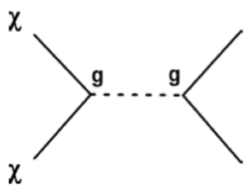
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

Dark matter: a WIMP?

In standard cosmological scenario, relic abundance

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} .$$

WIMP at EW scale has 'typical' annihilation cross section for $\Omega h^2 \sim 0.1$ (PLANCK)



$$< \sigma v > \sim \frac{g^4}{32 \pi m_{DM}^2}$$

$\sim 3\ 10^{-26}$ cm^3/s (or $\sigma \sim 1$pb)

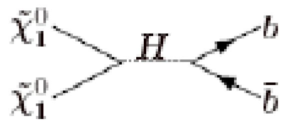
Remarkable coincidence : particle physics independently predicts particles with the right density to be dark matter (WIMP miracle)

This is simple estimate – possible variations by orders of magnitude

Mass and interaction strength for thermal DM ?

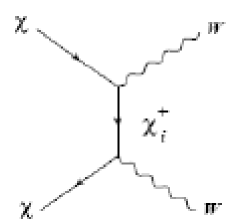
Miracle?

- Relic density puts strong constraint on combination of mass/couplings
- Will any weakly interacting particle lead to the 'miracle' ?
- Resonance



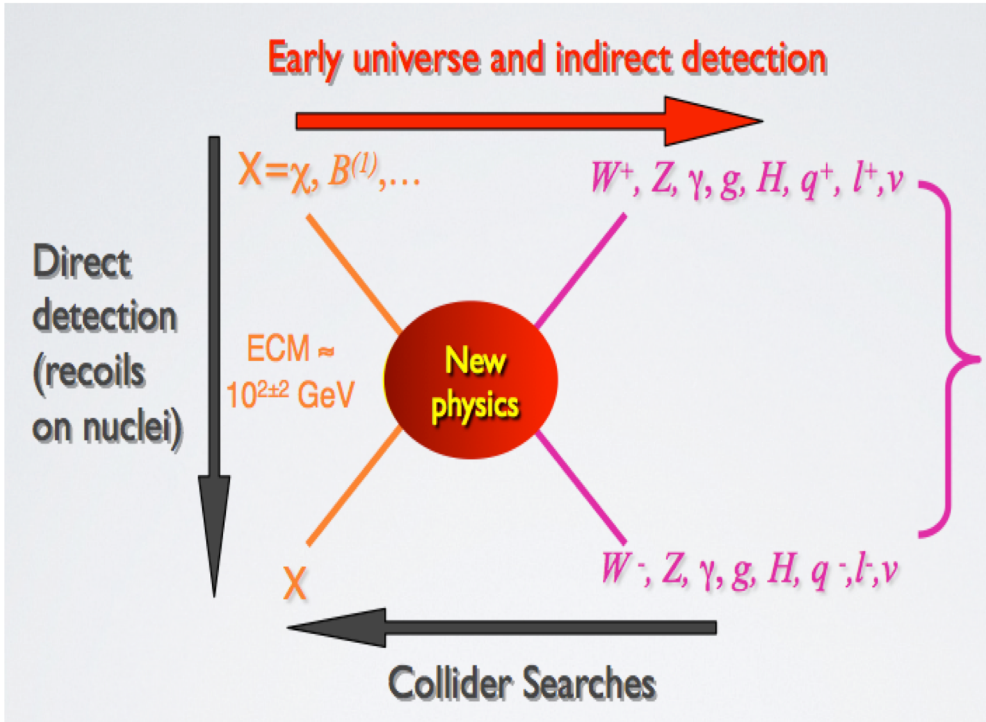
$$\sigma v \propto m_{\tilde{\chi}}^2/(4m_{\chi}^2 - m_H^2)^2$$

  - much weaker coupling required when $2m_\chi \sim m_H$
- New channels : increase of cross section if W/Z/h/t channels kinematically open, also larger cross sections for spin 1
- t-channel : enhancement when small mass splitting



- Other processes can contribute to DM formation, eg coannihilation

Probing the nature of dark matter



- All determined by interactions of WIMPS with Standard Model
- Strong connection relic/ID (only difference is v)
- Relic density and direct detection put severe constraints on WIMP models
- Not necessarily the same particles/process play dominant role, eg annihilation into dark sector can dominate relic – no effect on collider searches

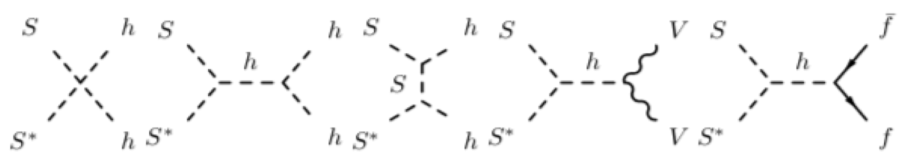
Illustration relic/DD constraints

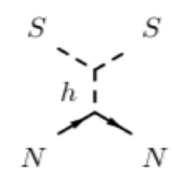
- Singlet scalar : Simplest SM extension : one singlet scalar + Z_2 symmetry
- Improves stability of Higgs sector
- Higgs portal : one coupling (to Higgs) drives all DM observables – relic,DD,ID

$$V_{Z_2} = \mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 + \lambda_{SH}|S|^2|H|^2$$

Direct detection

annihilation

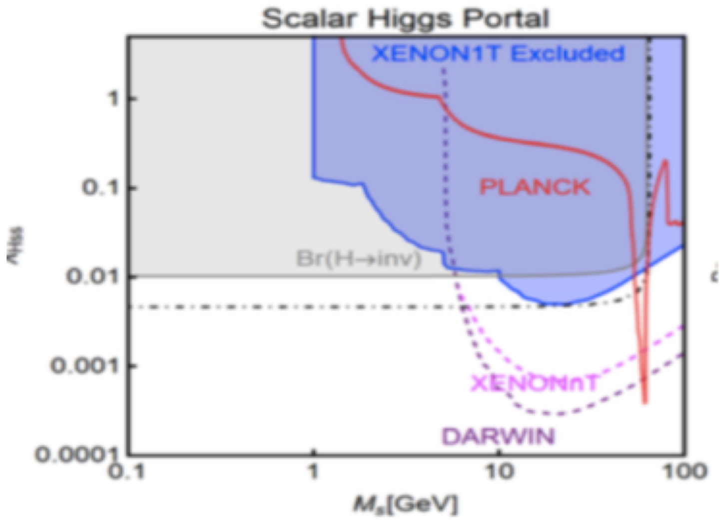


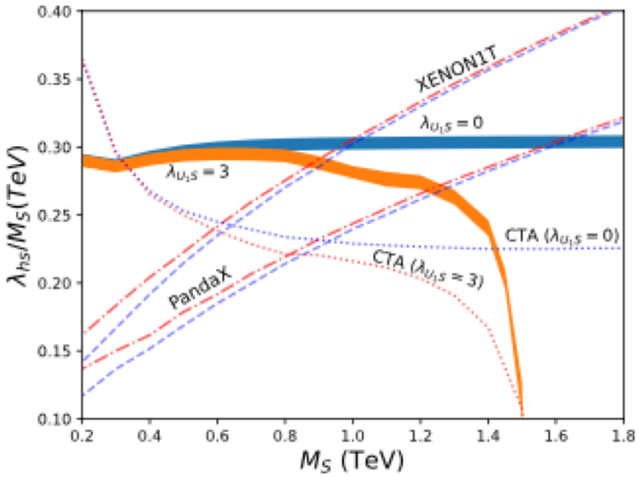


$m_s \gg m_i$	$\dfrac{\lambda_{SH}^2}{64\pi m_s^2}$	$\dfrac{\lambda_{SH}^2}{32\pi m_s^2}$	$\dfrac{\lambda_{SH}^2 m_f^2}{64\pi m_s^4}$
$m_s \ll m_h$			$\dfrac{\lambda_{SH}^2 m_f^2}{64\pi m_h^4}$

- Need large enough coupling for DM annihilation – but constraints from DD

Singlet scalar



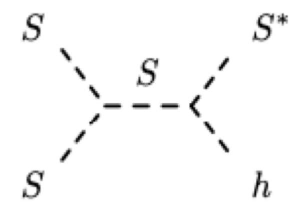


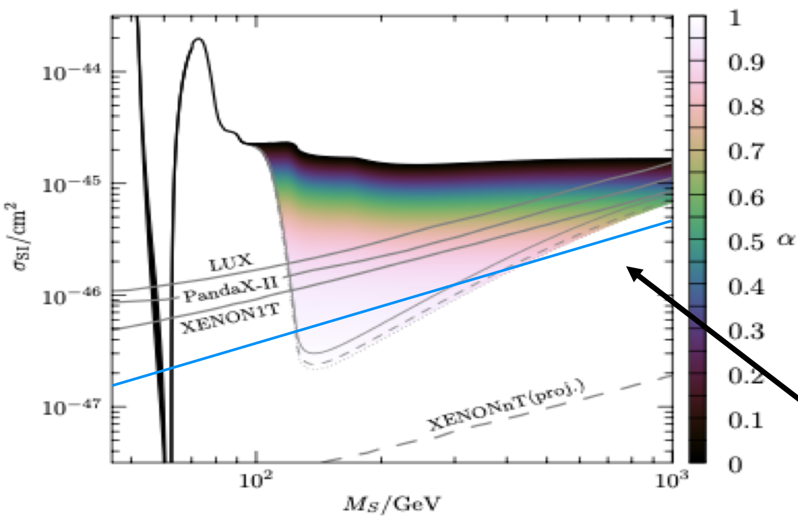
GB et al 2206.11305
Singlet scalar+ U1 LQ

Arcadi et al, 2101.02507

- If annihilation is efficient enough for relic density to be satisfied -> strong constraint from direct detection (unless DM mass >TeV, DM mass ~ mh/2)
- If $m_S<m_h/2$: Higgs invisible - Djouadi, Lebedev, Mambrini, Quevillon, 1112.3299
- *To relax constraints on WIMPs : uncorrelate relic density/ direct detection*
- Several ways to do that (beyond exploiting resonance effect)
  - New particles for relic (e.g. new processes not involving the Higgs)

- *To relax constraints on WIMPs : uncorrelate relic density/ direct detection*
  - New processes for relic (e.g. co-annihilation, semi-annihilation …)
  - Semi-annihilation: processes involving different number of dark particles (Hambye, 0811.0172; D'Eramo, Thaler 1003.5912)
    - Example : singlet scalar model with Z_3



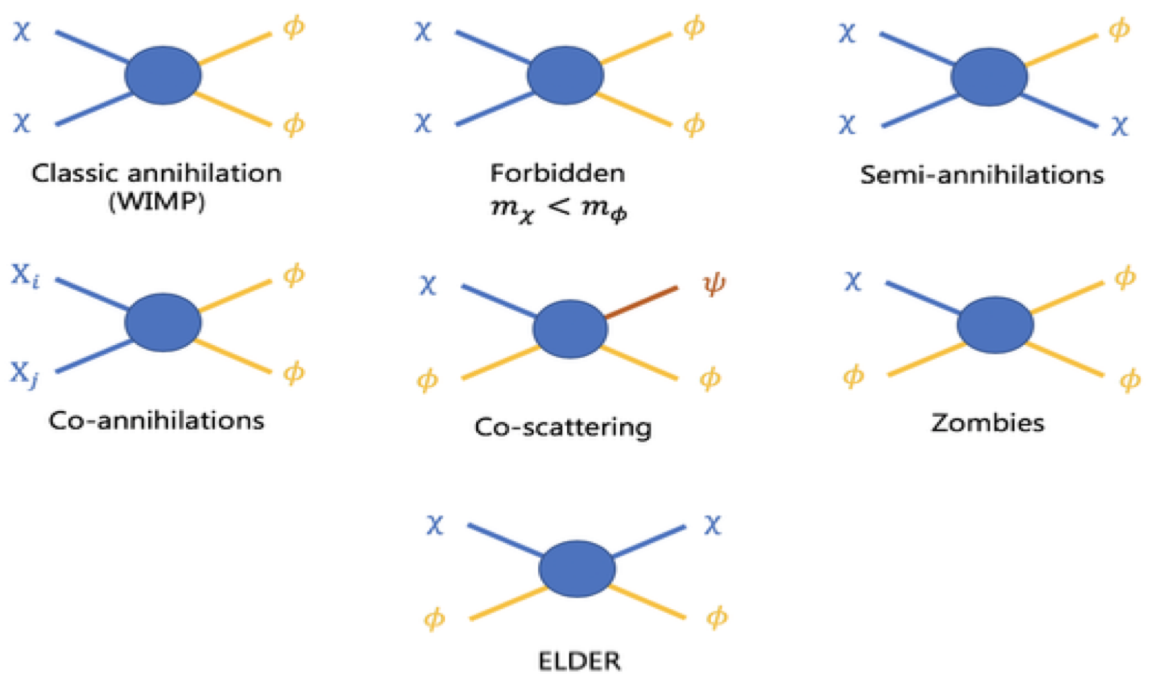


GB, Kannike, Pukhov, Raidal, 1211.1014
Hektor, Hryczuk, Kannike, 1901.08074

~LZ, 2207.02764

- Relax direct detection constraint of the singlet scalar – now under tension with LZ result

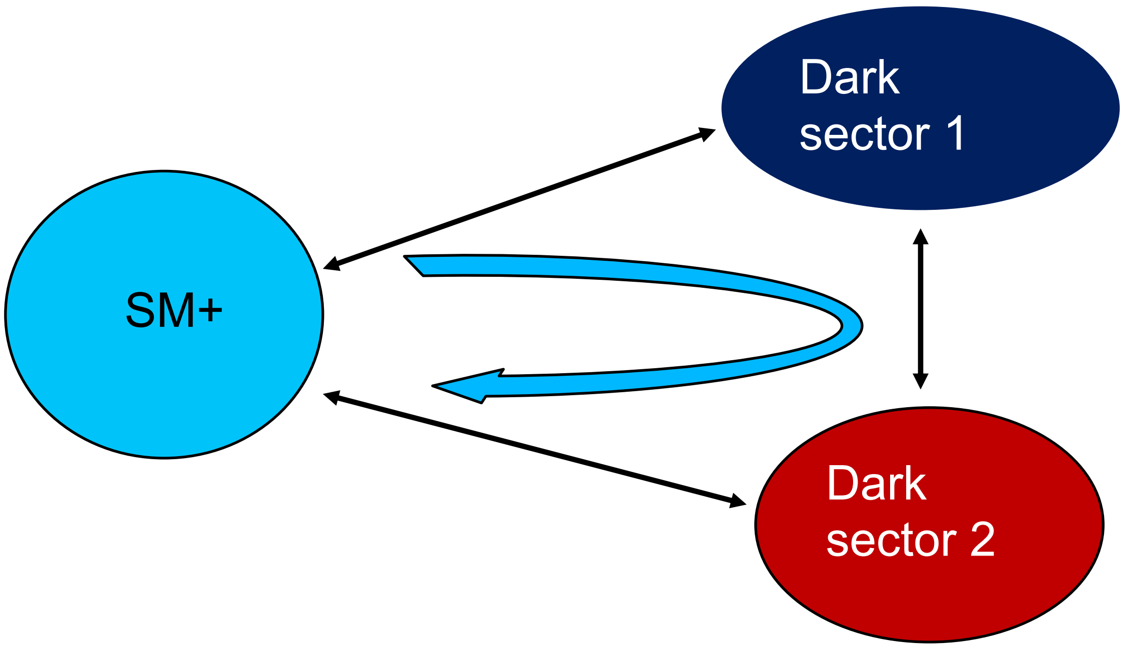
- To relax constraints on WIMPs : uncorrelate relic density/ direct detection
  - New processes for relic :



Hochberg, Les Houches
SciPost Phys. Lect. 2022

- To relax constraints on WIMPs : uncorrelate relic density/ direct detection
- Several ways to do that (beyond exploiting resonance effect)
  - New particles for relic (e.g. new processes not involving the Higgs)
  - New processes for relic (e.g. co-annihilation, semi-annihilation …)
  - Pseudoscalar mediator(s) - Banerjee, GB, Bhatia, Fuks, Raychaudhuri, 2110.15391
    - Relax DD constraints – potential signature of new pseudoscalar at LHC
    - Loop-induced contribution to DD much weaker, current experiments do not yet probe O(1) couplings -- Li, Wu , 1904.03407
  - Multi-component : no reason that the dark sector contains only one new particle – issue of stability

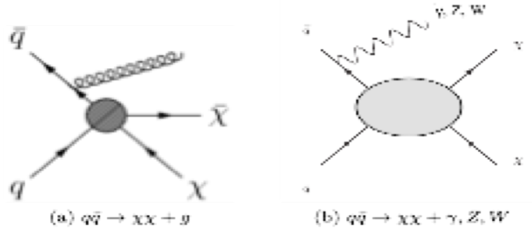
Multi-component : 2 dark sectors



- Assisted freeze-out : no interactions DS2-SM – interactions DS1-DS2 determine the abundance of DM2 (GB, JC Park, JCAP03 (2012) 038)
- DM conversion : include also DS2-SM
- WIMP models can be constructed to avoid certain constraints, but strategy of direct/indirect/collider searches offer powerful probes of WIMPs
- Zurek 0811.4429, Bhattacharya 1607.08461, Lu Wu Zhou, 1101.4148, Bas I Beneito, et al, 2207.02874, GB, Mjallal, Pukhov, 2108.08061

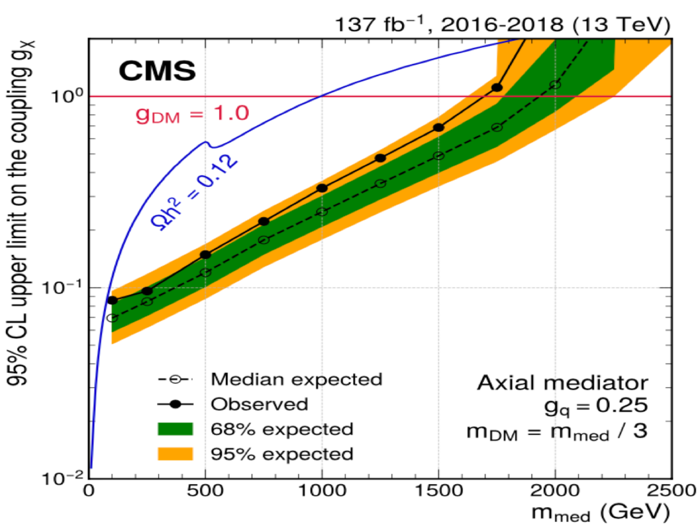
LHC searches for DM

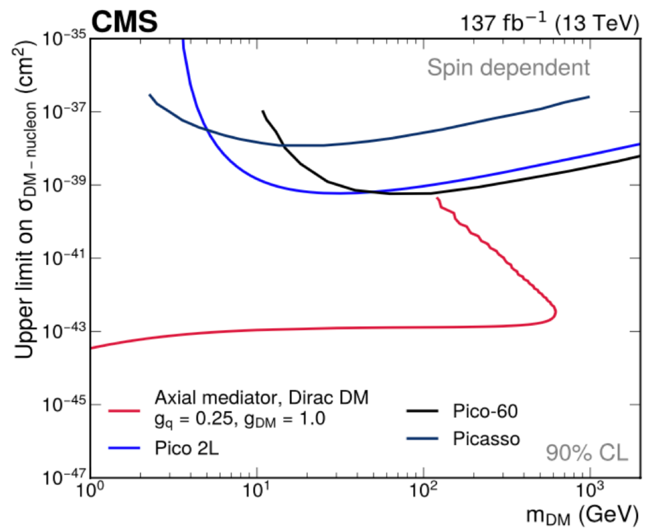
Model independent approach (monoX) MET+ jet, γ,W,Z



Also used for simplified model : mediator+DM

In some cases probe region compatible with relic, and higher sensitivity than DD experiments (mostly SD and low masses





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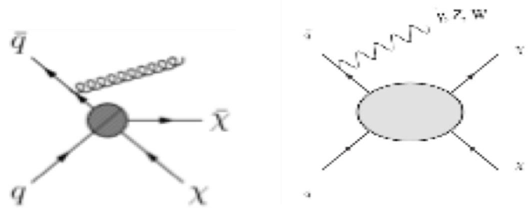
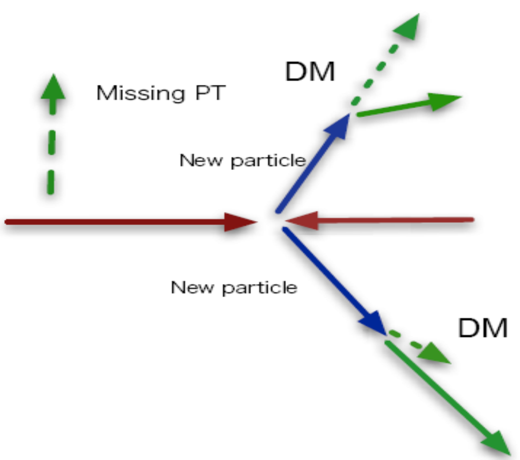


(a) $q\bar{q} \to \chi\chi + g$ (b) $q\bar{q} \to \chi\chi + \gamma, Z, W$

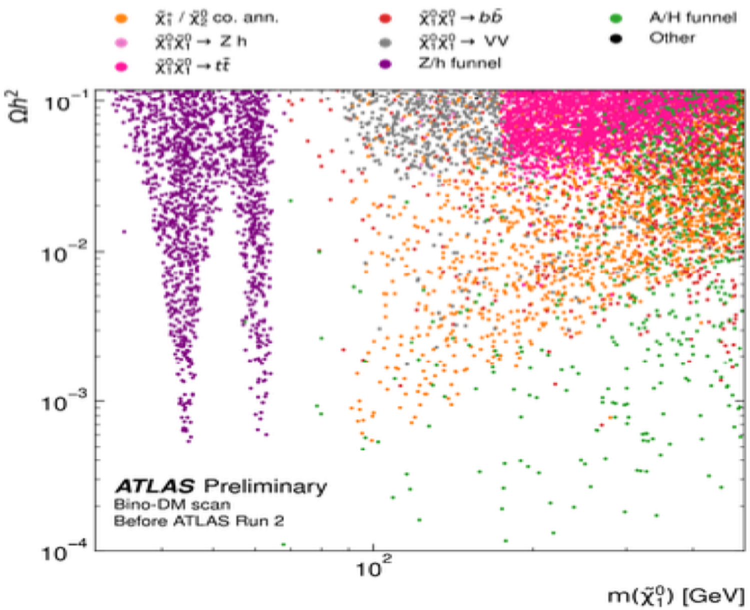
Model dependent approach:

- Production of new particles that decay in DM, signature : MET + l, q,….
- Invisible decays of the Higgs
- Charged tracks and displaced vertices
    - small mass splitting or very weak interactions
- Searches for new particles in SM final state
    - E.g. mediator – no connection to DM

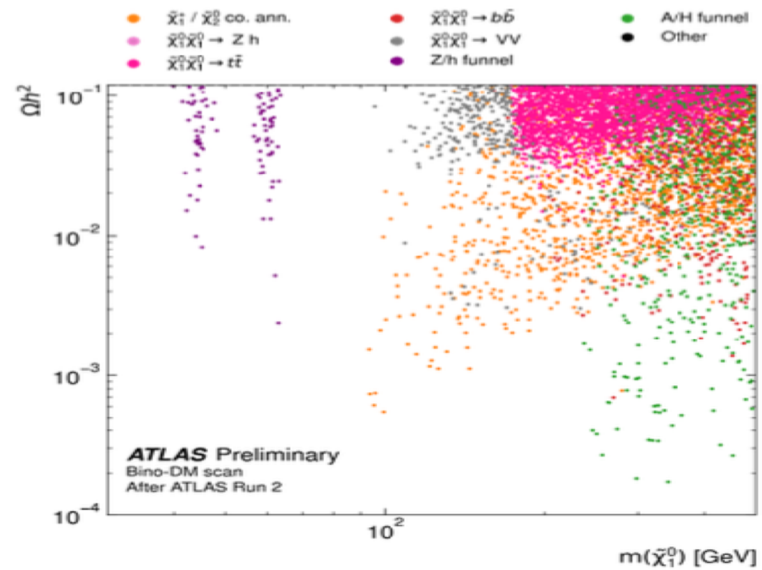


Status of SUSY after LHC and LZ

Searches for electroweakinos in RunII

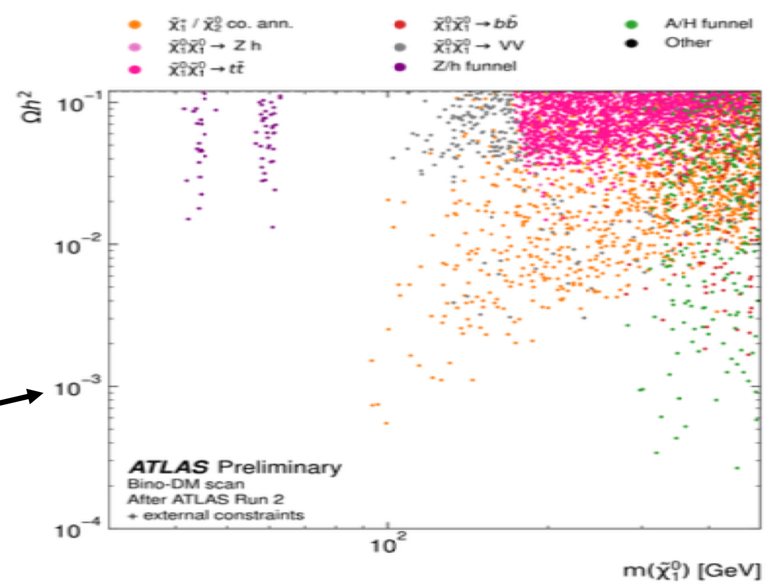


(a) All models



(b) Models not excluded by ATLAS

ATLAS-Conf-2023

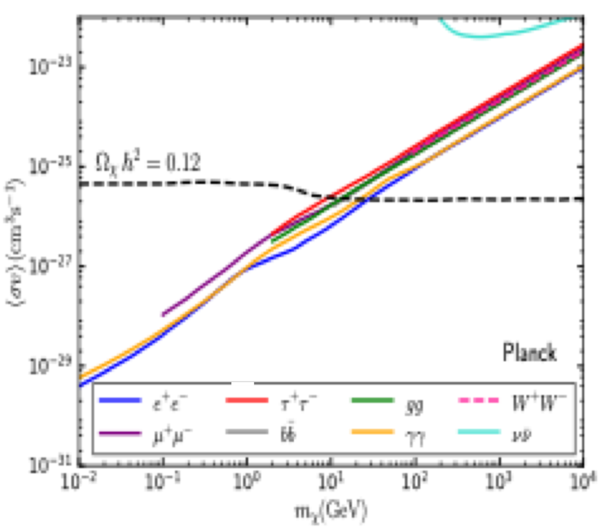


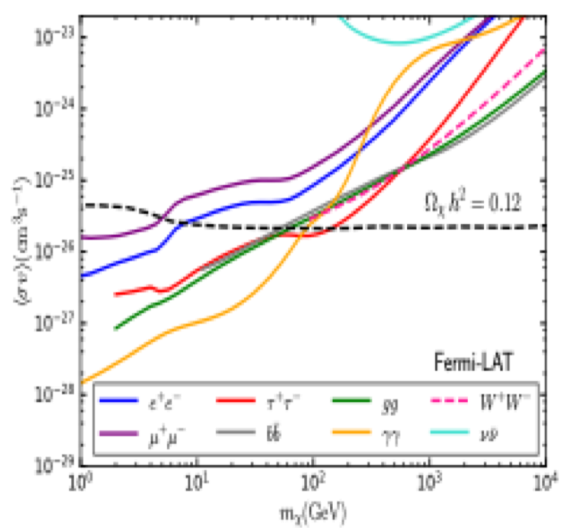
Still room for SUSY DM after Run2 and recent DM searches

Below the weak scale

- Light DM (below few GeVs)
  - For correct relic density and to escape current constraint, light DM usually couples also to some light mediator -> probes in high intensity low energy colliders
  - Strong constraints from CMB and Indirect detection
    - Ionizing particles ($e^+ e^- \gamma$) from DM annihilation change the ionization history of hydrogen gas-> perturbation of CMB anisotropies
    - Stringent limits on light DM assuming s-wave annihilation and 100%BR in given SM (neutrino annihilation channel escapes constraints)

Slatyer, 1506.03811

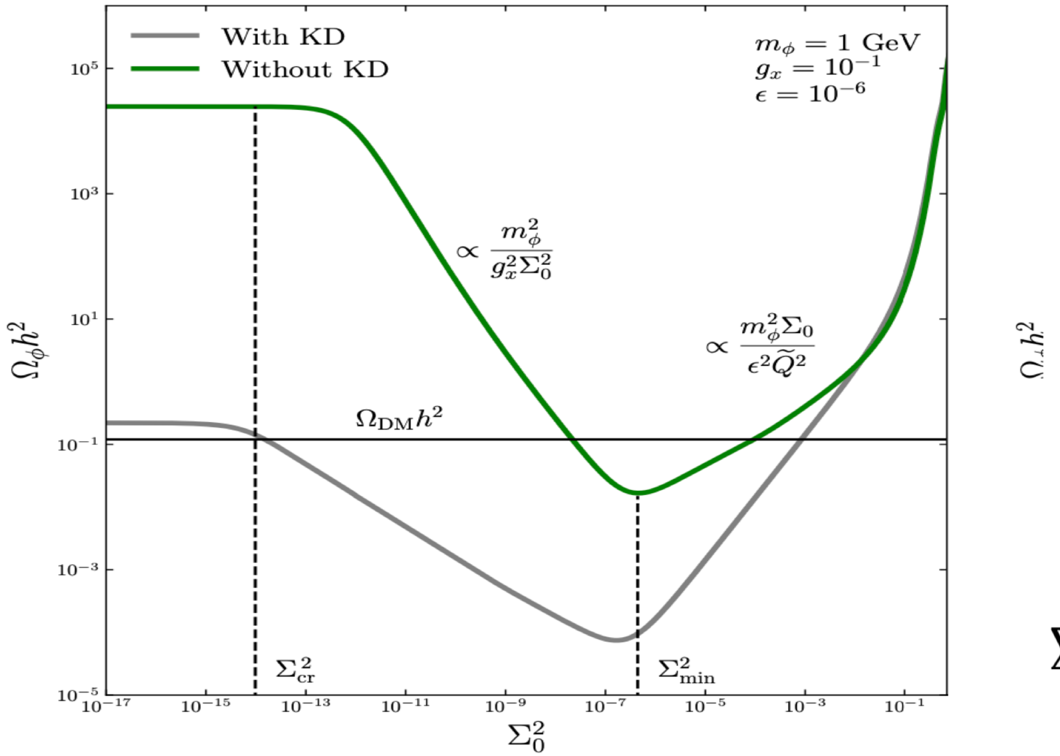




Dutta et al, 2212.09795

- Fermi-LAT searches for photons from DM annihilation in dSph's also strong constraints

- Light DM (below few GeVs)
  - Example : scalar DM coupled (gx) to dark photon - kinetic mixing (ε)
    - annihilation near resonance – Breit-Wigner enhancement and possible that σv (MW) >> σv (FO),
    - process is p-wave avoid strongest constraints from CMB ($v{\sim}10^{-8}$)



$$\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2$$

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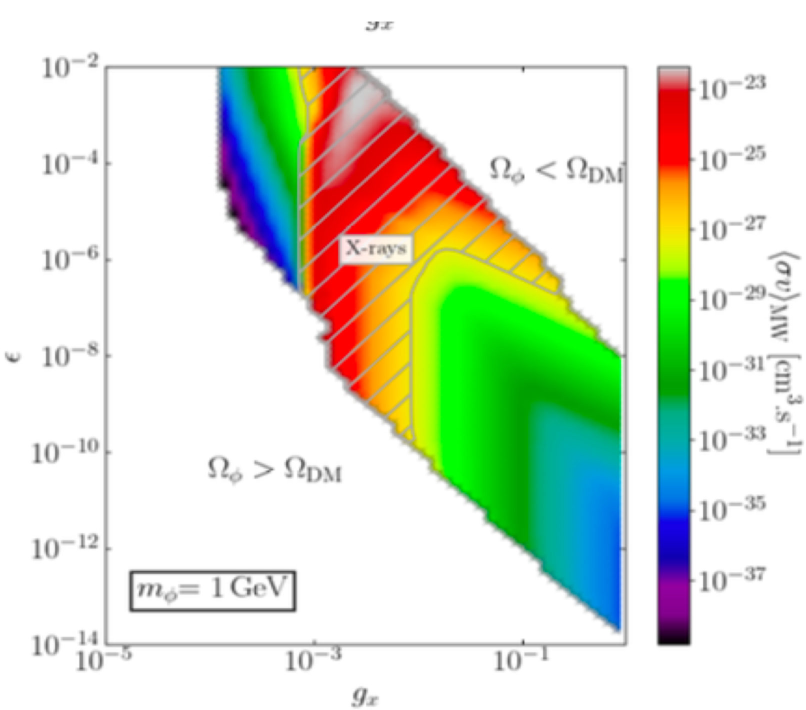

GB, Chakraborti, Genolini, Salati, 2401.02513 (M_{med}~$2M_\chi$)

e+e- from DM annihilation scattering on low energy photons in interstellar radiation field in Galaxy – generate Xray via Inverse Compton

Xray Constraints from XMM Newton, Cirelli et al 2303.08854

DM annihilation injects energy in plasma generate distortions from pure black body spectrum – constraints from FIRAS

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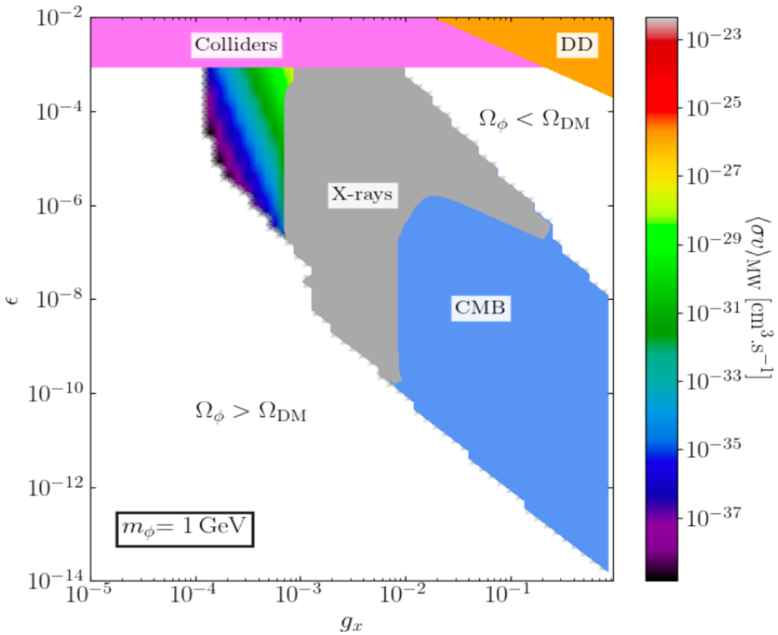

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Xray Constraints from XMM Newton, Cirelli et al 2303.08854

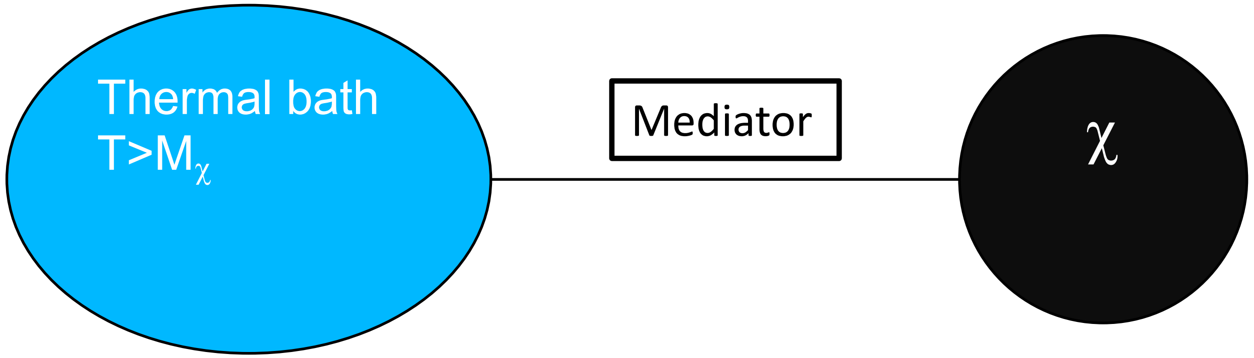
DM annihilation injects energy in plasma generate distortions from pure black body spectrum – constraints from FIRAS Redshift 10^6->10^4

- Below threshold for DD on nucleons, strong constraints from ID (Xray) and CMB, also colliders (here BABAR and LEP, e+e--> AA'-> invisible)

Weaker than weak : the FIMP case

FIMPS (Feebly interacting MP)

- Freeze-in (Hall et al 0911.1120, McDonald,J. hep-ph/0106249) relevant for FIMP
- In early Universe, χ so feebly interacting that χ is decoupled from plasma



- Interactions are feeble but lead to production of χ
- Review : Bernal et al, 1706.07442; GB, Chakraborti, Pukhov, 2309.00491

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

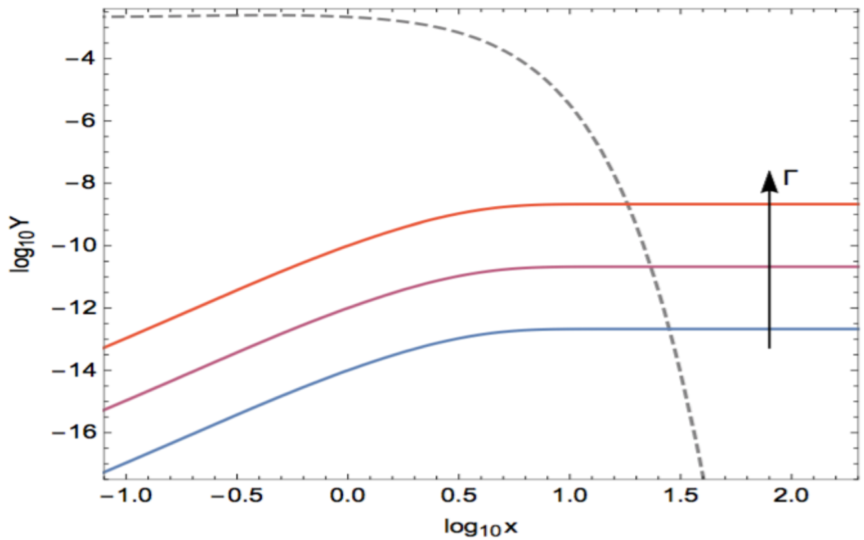
$$\dot{n}_\chi + 3Hn_\chi = \langle \sigma v \rangle_{X\bar{X} \to \chi\bar{\chi}}(T) n_{eq}^2(T) + n_{eq}(T) \Gamma_{Y \to \chi\chi}(T)$$

annihilation

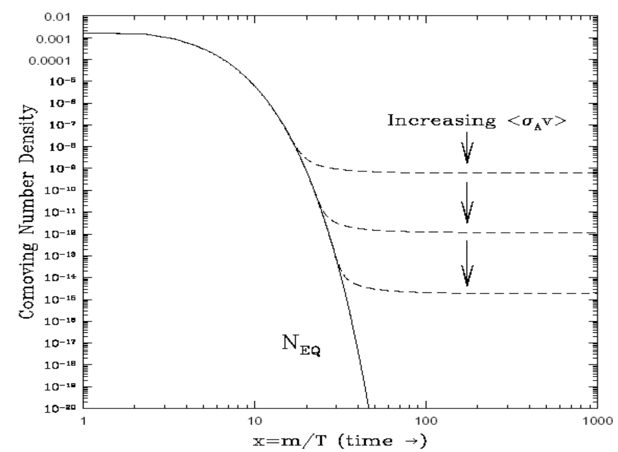
Decay
(X,Y in Th.eq. With SM)

FIMPS (Feebly interacting MP)

- DM production from SM annihilation (or decay) until number density of SM becomes Boltzmann suppressed - n_χ constant ‘freezes-in’
- T~ M, χ ‘freezes-in’ - yield increases with interaction strength, Y~λ



x=m/T



Comparison with WIMPs

- When decay possible, usually dominates
- Typical interaction strength : $10^{-12} – 10^{-10}$
- Mass range : from very light to above TeV scale

- Some possibilities for FIMPs:
  - FIMP is DM : pair production in annihilation of SM particles (or in decay of particle in thermal equilibrium)
  - FIMP is DM, next to lightest ‘odd’ particle has long lifetime freeze-out as usual then decay to FIMP – typically $\lambda \sim 10^{-12}$
    - a new long-lived particle with signature at collider (LLP) and/or also affect BBN or CMB depending on lifetime
  - FIMP can also be part of multi-component DM – if the WIMP is only a small fraction of DM its DD and ID signals are suppressed.
  - FIMP is not DM, freezes-in and then decay to WIMP DM increasing abundance of WIMP
    - Relic abundance and DM annihilation cross section no longer related, freeze-in produces DM abundance, DM annihilation can be large – freeze-out abundance small
    - Hard to identify the presence of the FIMP, but mismatch between properties of measured WIMP with value of relic density
    - Possible boost in indirect detection signals ($\sigma v > 3\ 10^{-26}$ cm^2/s)

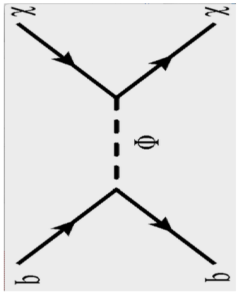
Probes of FIMPs

- FIMP in general a singlet under SM (to prevent reaching thermal equilibrium) - for example the singlet scalar model used for freeze-out but for a different choice of couplings
- Probes not as generic as for WIMPs
- Direct detection
  - On nucleons: detectable if mediator is light
  - On electrons
- Colliders
- Indirect detection
- Cosmology : BBN, energy injection…

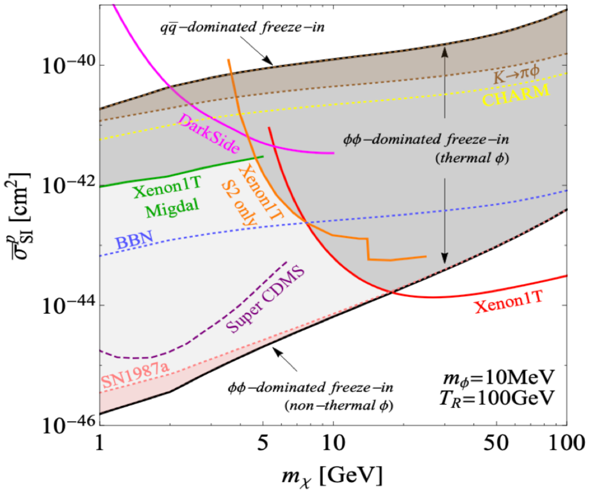
Direct detection

- FIMPs can be within reach of direct detection when rate is enhanced by presence of light mediator

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



where $\bar{\sigma}^p_{\rm SI} = \frac{y_p^2 y_\chi^2 \mu_{\chi p}^2}{\pi m_\phi^4}$ $\sigma_{\rm SI}$ at zero momentum transfer

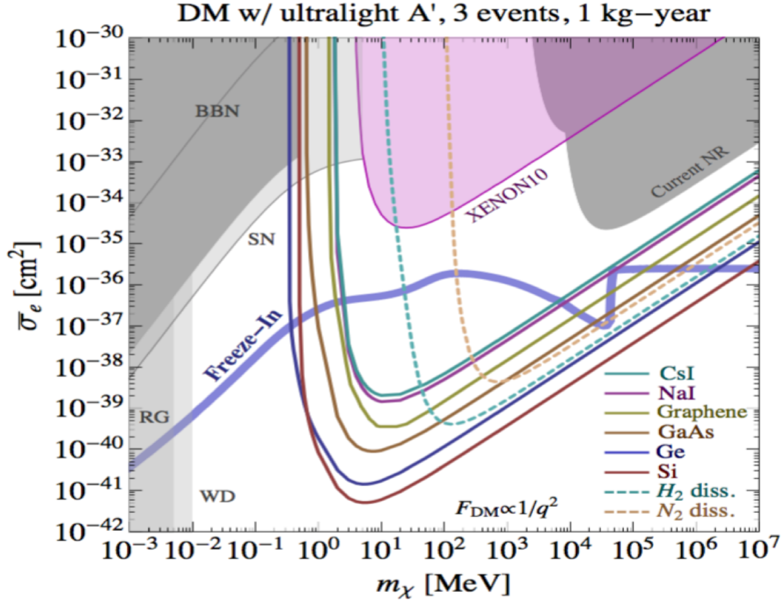


GB, Delaunay, Pukhov, Zaldivar, 2005.06294

FI can be tested in current DD when mediator is light

Direct detection – electrons

- DM can scatter off electrons – scattering ionize atoms in target leading to single electron signal, recoiling electron can also ionize other atoms if has sufficient energy – lead to few electron signals
- Allow to extend the sensitivity of DM detector below m~GeV where typical nuclear recoil energy is below threshold. $E_{nr} \sim m_{DM}^2 v^2 / 2m_N$
- Energy available, $E_{kin} = m_{DM}/2\ v^2$
- New projects to search for very light DM with different materials, eg. superconductors–



Prospects to probe light FIMPs

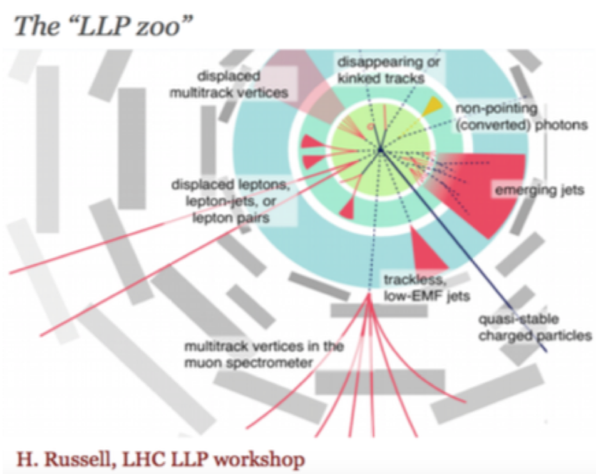
FIPS 2020 report : arXiv:2102.12143

Probes of FIMPs

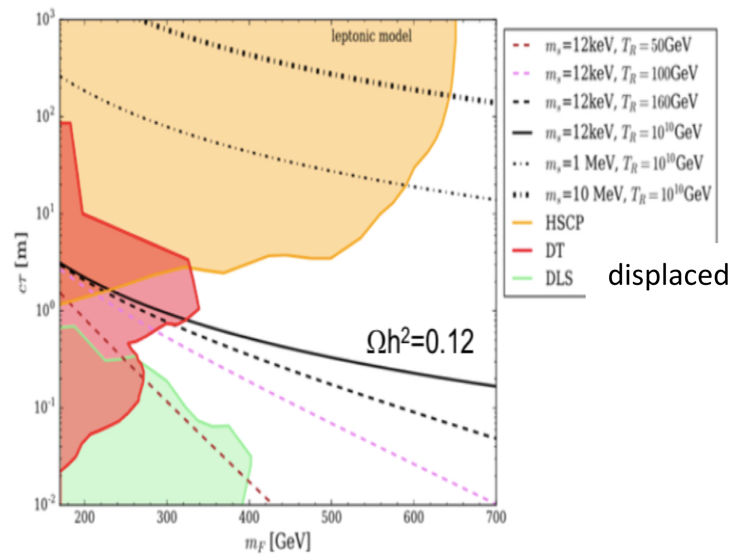
- Not as generic as for WIMPs
- Direct detection
- Colliders
  - need some other particle in dark sector with at least weak couplings, preferably charged : typical search for Heavy Stable Charged Particle and/or displaced signatures (especially for small reheating temperature)
  - most of standard DM searches at colliders useless, host of additional probes in ATLAS/CMS/LHCb,
  - If mass scale is low : in fixed targets, mesons decays (e.g at BESIII and KLOE) and e^+e^- collisions
  - Decays outside detector (MATHUSLA, FASER etc..)
- Indirect detection – relevant if LLP decays now
- Cosmology : BBN, energy injection ….

FIMPs at LHC

- DM is produced from the decay of heavier particle (F) whose interactions allow copious production at LHC
- F decays in FIMP+SM with very small coupling -> LLP (either colllider stable or displaced signatures)



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



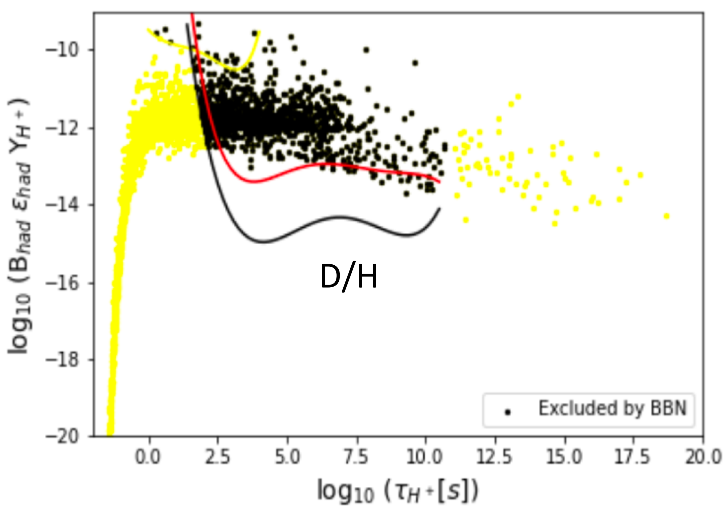
F: new vector fermion decays to FIMP+lepton
GB et al, 1811.05478

- As DM becomes heavier only HSCP becomes relevant

Big Bang Nucleosynthesis

- If particle with lifetime > 0.1s decays 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)
- Alteration of n/p ratio - for example
  - -> overproduction He^4
- Hadrodissociation of He^4 causes overproduction of D
  - $n+He^4 \to He^3+D, 2D+n, D+p+n$

- Key elements :
  - Bhad : hadronic BR of LLP
  - Evis: net energy carried away by hadrons
  - Y(WIMP) : yield



GB, Mjallal Pukhov, 2205.04104

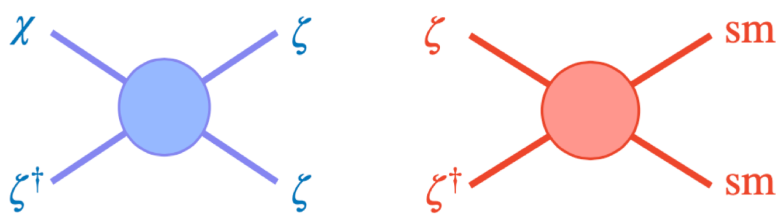
Conclusion

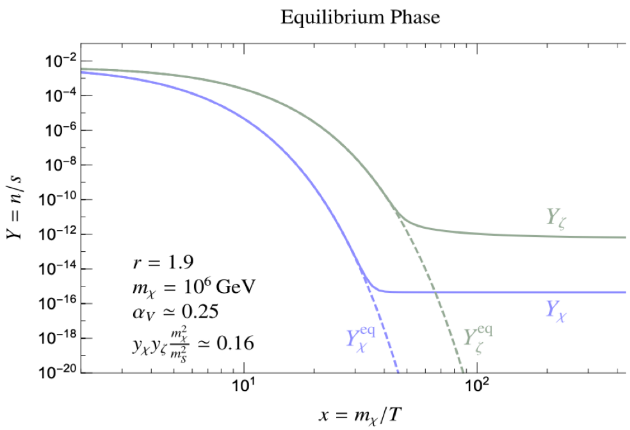
- Several processes can contribute to DM production – gives rise to a variety of DM models not necessarily tied to the electroweak scale or to weak interactions
- Although classical WIMP models are severely constrained from relic/LHC/direct detection/indirect detection – WIMPs are not dead
- WIMP models can be constructed to avoid certain constraints, but strategy of direct/indirect/collider searches offer powerful probes of DM
- New probes for light DM (e.g. DD or intensity frontier) or LLPs (colliders, cosmo)
- *After so many years, still in the dark about the nature of dark matter*

Extra

- General properties of thermal DM
- No naturalness -> mass scale extends from 10 MeV->100TeV
  - For FO mechanism from $\chi\chi$->SM SM
    - rate of DM annihilation $\Gamma=n<\sigma v>$, unitarity imposes upper limit on $<\sigma v>$-> lower bound on n at FO ($\Gamma\sim H$)
    - $\Omega h^2 \sim m_\chi n$ -> upper bound on m_χ
    - Or if DM is heavier than upper bound it will be overabundant
    - Remark : if DM is > few TeV : hard for LHC and for ID (CTA can reach high masses) but signal scales as $n^2 \sim \rho^2/m^2$
  - Note : with zombie can relax this constraint -> almost to Planck scale

- Note : with zombie can relax this constraint -> almost to Planck scale
- Kramer et al, 2003.04900 (assumes that $\chi\chi \to \zeta\zeta$ or SM SM small)





- DM is χ; $m_\zeta < m\chi < 3\, m_\zeta$ (to prevent $\chi \to \zeta\zeta\zeta$ decay)
- If ζ remains in equilibrium, at FO of χ, n_ζ large

$$\dot{n}_\chi + 3Hn_\chi = -n_\zeta^{eq}\langle\sigma_{\chi\zeta\to\zeta\zeta}v\rangle\left(n_\chi - n_\chi^{eq}\right) \ .$$

- Relaxes upper bound on $m\chi$
- Also if DM at weak scale - much smaller interaction rates than standard WIMPs