Dark matter and colliders

GGI conference "Collider Physics and the Cosmos"
Florence, Italy

Andreas Goudelis
LPTHE - Jussieu

The first two weeks of the GGI workshop

· XX participants

· 14 talks/presentations (more in the weeks that followed)

· Main topics:

1) WIMPs:
- models (portals, SUSY, X-dim, bound states)
- searches (LHC, future colliders searches, direct detection)
- connections to flavour

2) Non – WIMPs:
- freeze-in theory
- models
- self-interactions
- LHC searches and signatures

· ...and lots of discussions!

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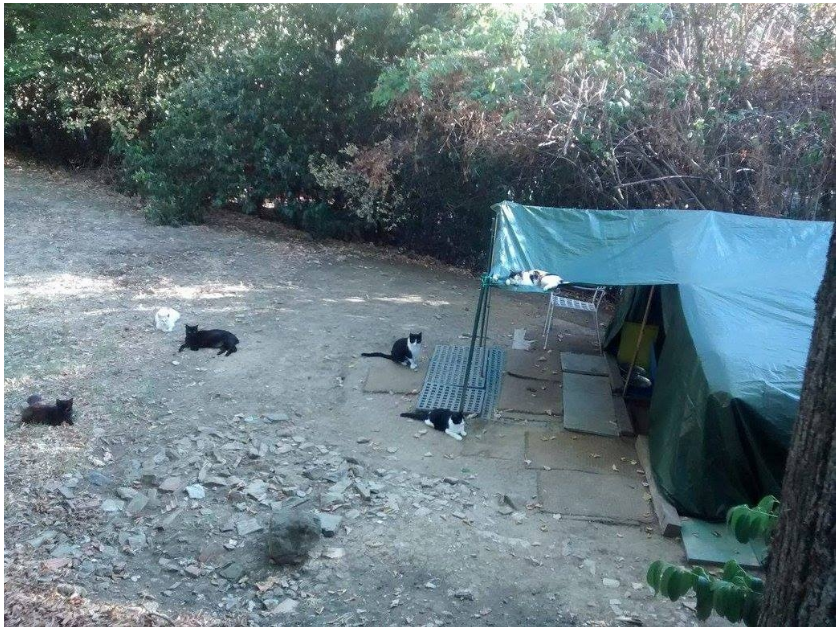
And cats, lots of cats



Status of the field

cf G. Bélanger's talk

We know a few main things about dark matter :

· It gravitates

· It doesn't interact with photons (much)

· Its abundance within vanilla ΛCDM cosmology

· If it's made out of ("particle physics") particles, they have to be BSM ones

Given the pressure on WIMP models, alternative possibilities are (re-)gaining ground :

· Self-interactions

In principle orthogonal, although: N. Bernal *et al*, arXiv:1510.08063,
N. Bernal, X. Chu, arXiv:1510.08527

· Primordial black holes

Esp. after LIGO events + TH developments,
e.g. A. M. Green arXiv:1609.01143

· Sterile neutrinos

cf S. Gariazzo's talk

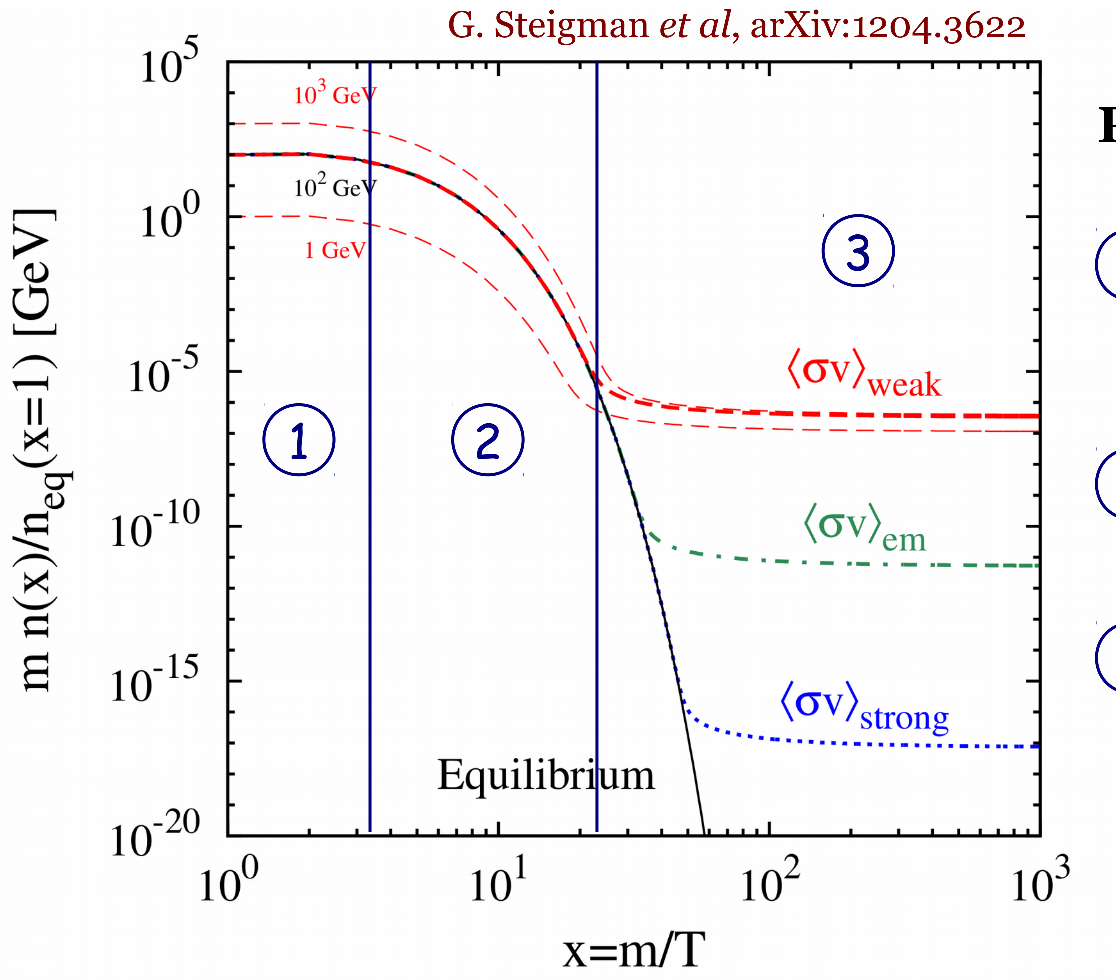
· FIMPs

Main focus of the 2nd week

Week 1: Freeze-out

The standard thermal freeze-out

Number density evolution for strong enough DM-SM interactions



Physically:

1. DM + DM ↔ SM + SM efficient in both directions.

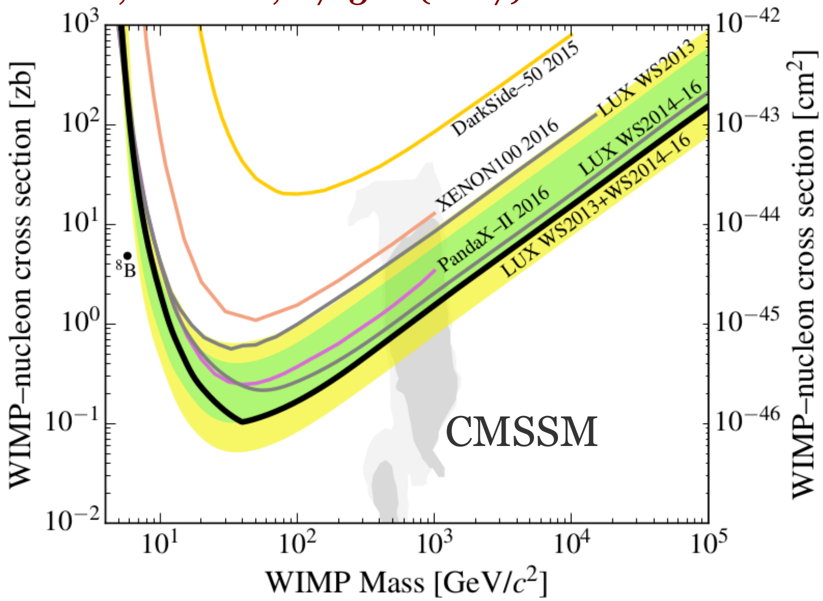
2. DM + DM ← SM + SM disfavoured.

3. n_{DM} <σv> < H : Equilibrium lost → Freeze-out.

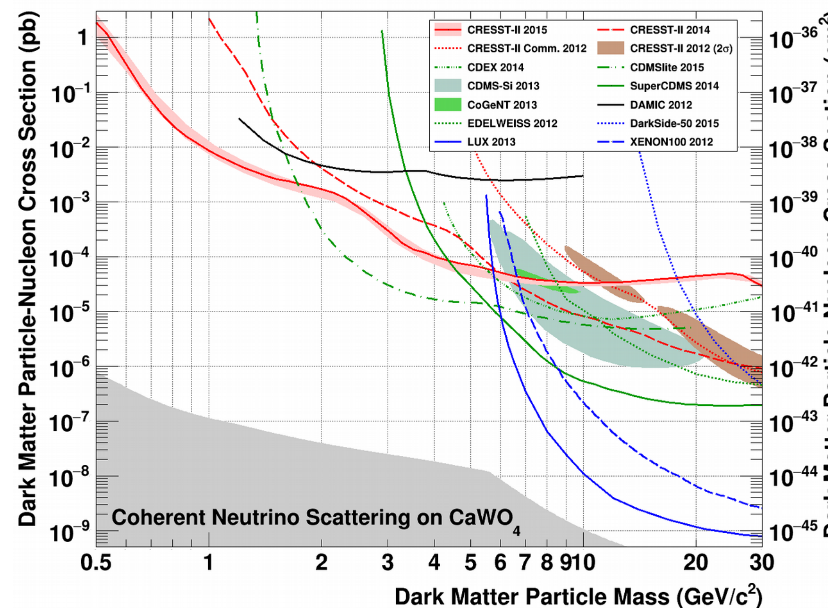
WIMPs: Direct Detection

Conventional searches (spin-independent scattering)

LUX, PRL 118, 021303 (2017)
PANDA-X, PRL 118, 071301 (2017)

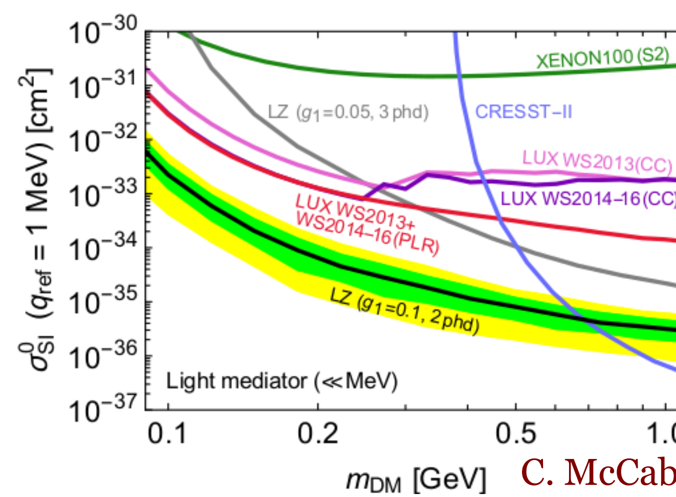


CRESST-II, EPJC (2016) 76:25



+ proposals on how to probe lower masses, e.g. through nuclear recoil bremsstrahlung

C. Kouvaris, J. Pradler, arXiv:1607.01789



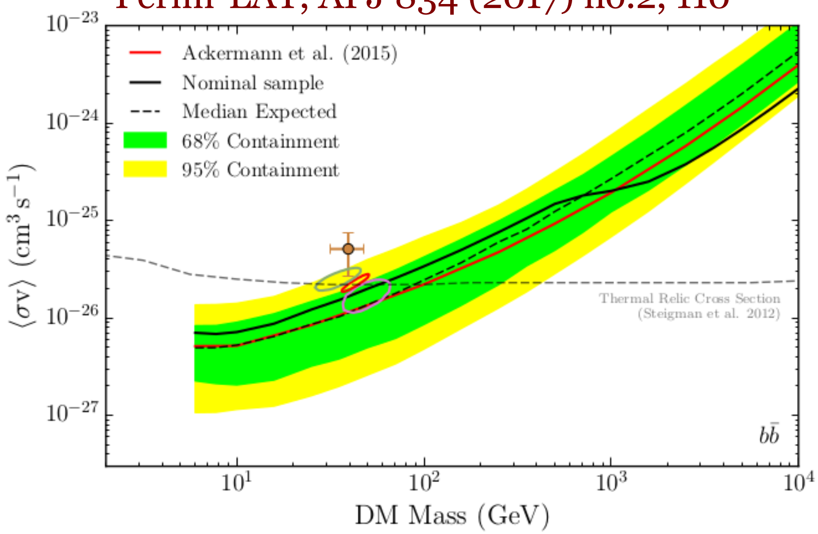
C. McCabe, arXiv:1702.04730

WIMPs: Indirect Detection

Continuum

Fermi-LAT limit from dSPhs

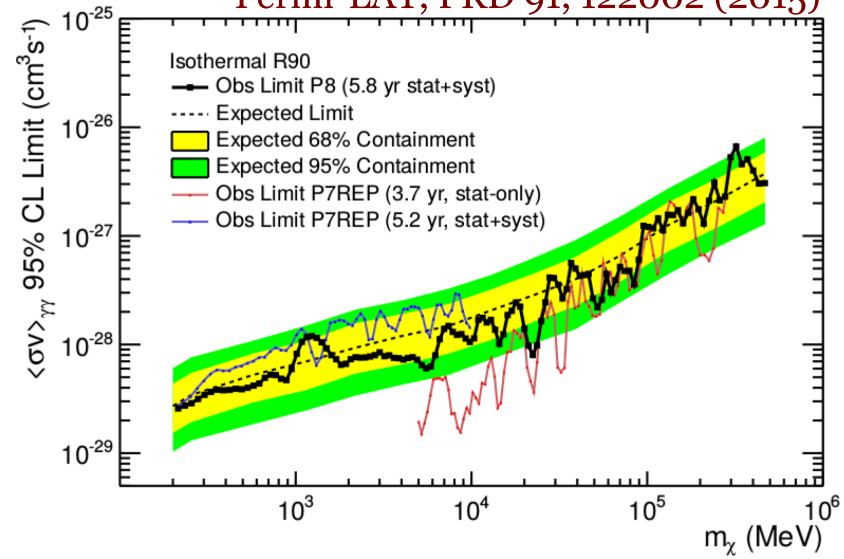
Fermi-LAT, APJ 834 (2017) no.2, 110



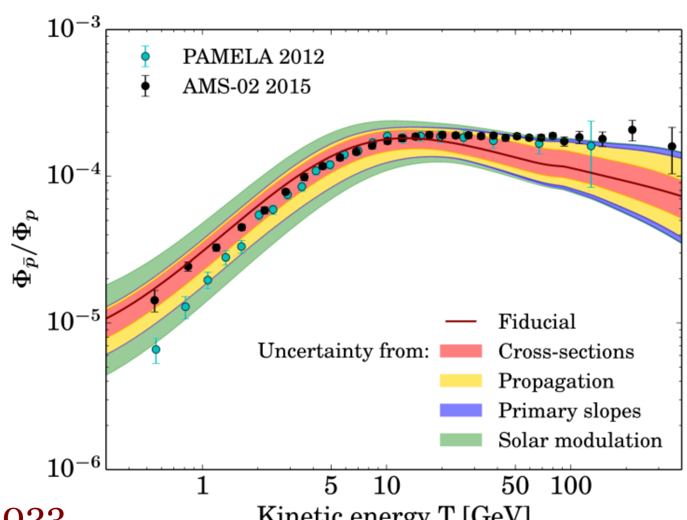
Spectral features

Fermi-LAT limit from Galactic Centre

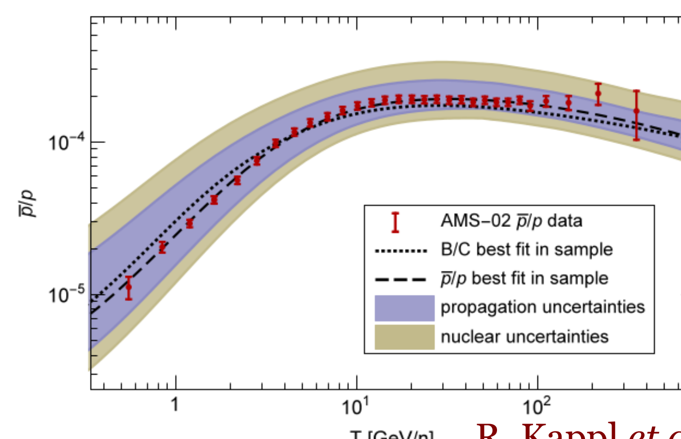
Fermi-LAT, PRD 91, 122002 (2015)



Antiprotons



G. Giesen *et al*,
JCAP 1509 (2015) 023

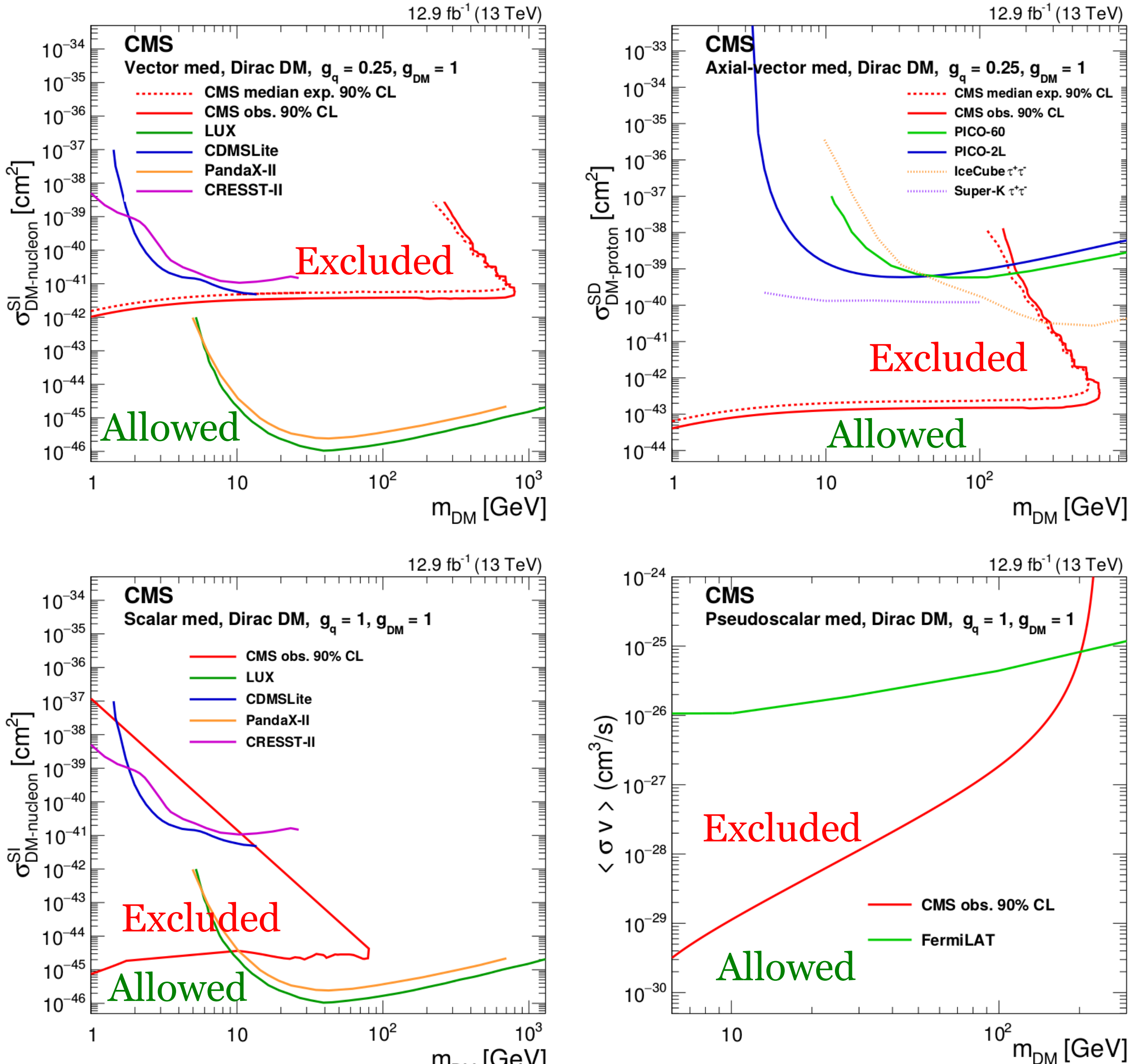


R. Kappl *et al*,
JCAP 1510 (2015) 034

WIMPs: Collider searches

cf C. Doglioni's talk

Most celebrated LHC dark matter searches: mono-X



CMS, arXiv:1703.01651

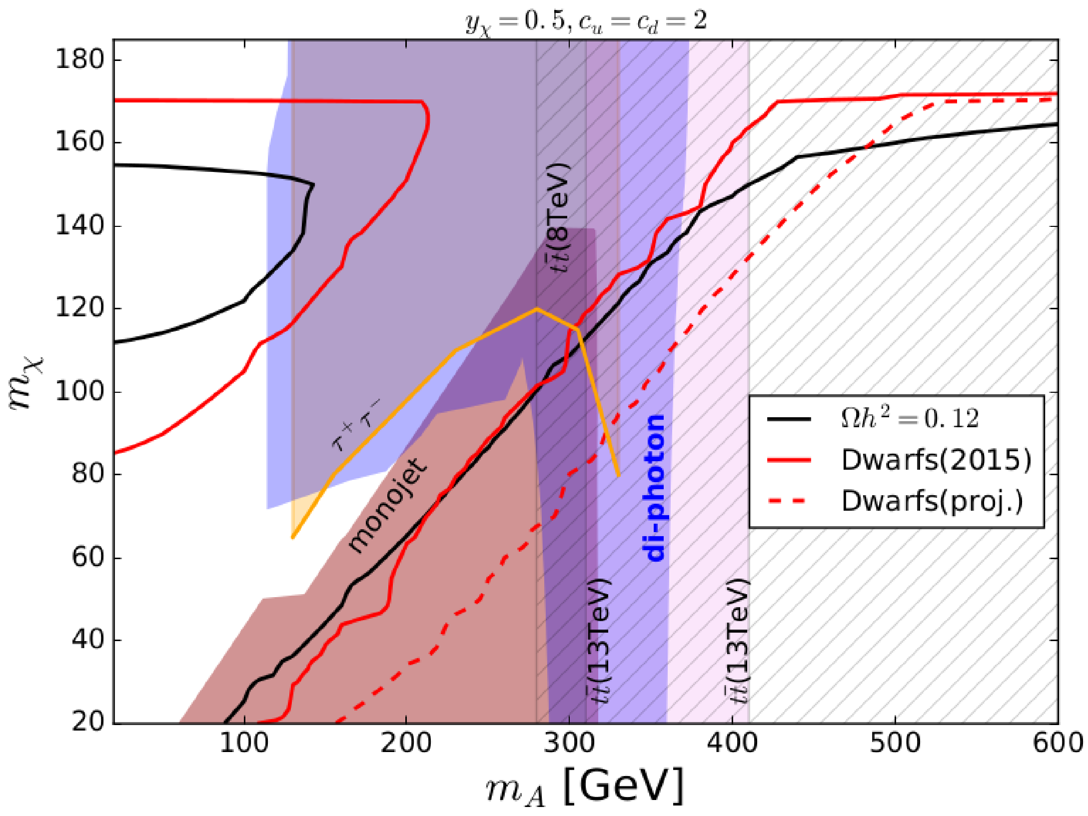
- Complete shift from EFTs.
- Four benchmark models: Dirac DM with vector, axial-vector, scalar and pseudoscalar mediator coupling to quarks.
- Robust handle on light DM.
- Crucial assumption: $m_{DM} < m_{Med}/2$.
  Otherwise limits vanish
- Relatively insensitive to the underlying Lorentz structure.
  Very strong point!
- When direct detection works, it dominates.
- Heavy DM: indirect detection.

WIMPs: Collider searches

What about the off-shell regime ($m_{DM} > m_{Med}/2$)?

Look for the mediator

LHC searches complementary with direct/indirect detection but also amongst *themselves*!



S. Banerjee, D. Barducci, G. Bélanger, B. Fuks, A. G., B. Zaldivar, arXiv:1705.02327

- Consider simple model of Majorana dark matter χ + Higgs-like pseudoscalar mediator *A*.

- Limits from: monojets, di-t/b + MET, di-t, di-τ, γγ, indirect detection.

- To keep in mind: light mediators are the trickiest ones.

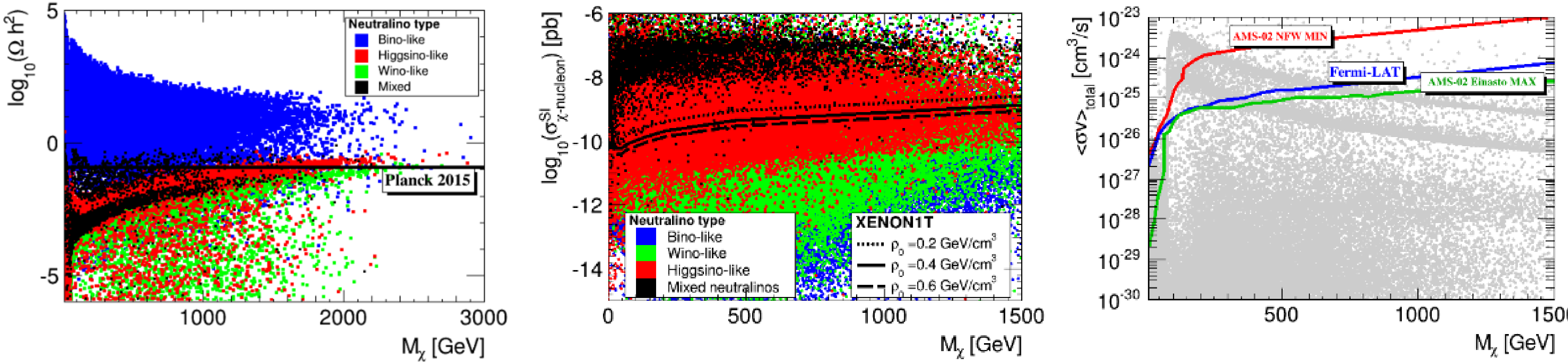
How robust are these limits?

cf A. Arbey's talk
(also this afternoon)

Looking for DM in its "natural habitat" is the opposite to what we learned in Exp. Phys. I

How well do we control all the uncertainties?

A. Arbey, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426



· Relic abundance: QCD equation of state (~5%), Sommerfeld (5% - 50%), NLO (5% - 50%), cosmological assumptions (could completely invalidate bounds).

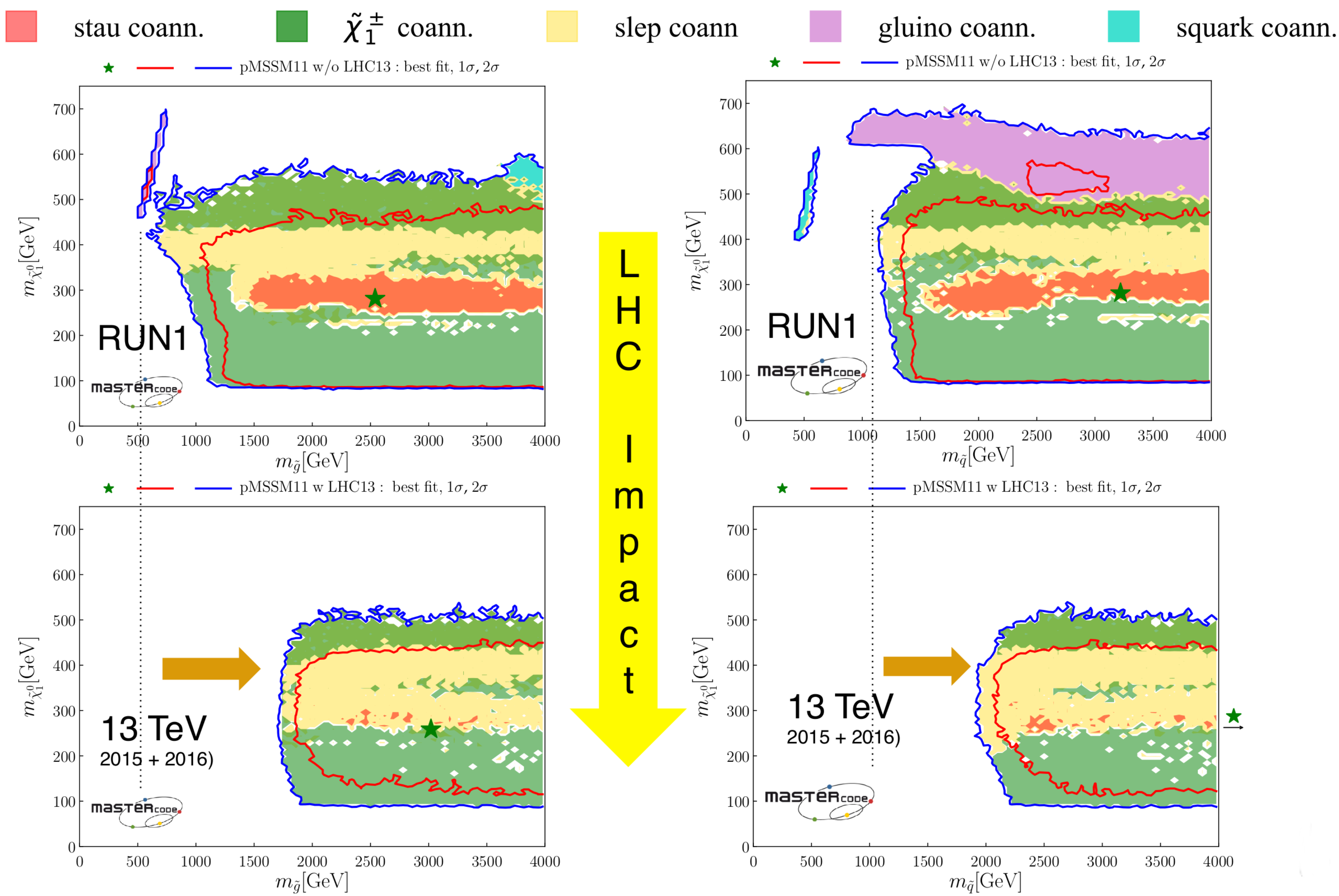
· Direct detection : Nuclear FFs (20% - 50%), v_{SOL} (~20%), ρ_o (factor 2).

· Indirect detection : Sommerfeld (up to factor 1000), propagation model (factor 10), dSph halo profile (factor 2).

Neutralino DM update

cf O. Buchmüller's talk
(also this afternoon!)

MasterCode collaboration update:



Dark matter @ future colliders

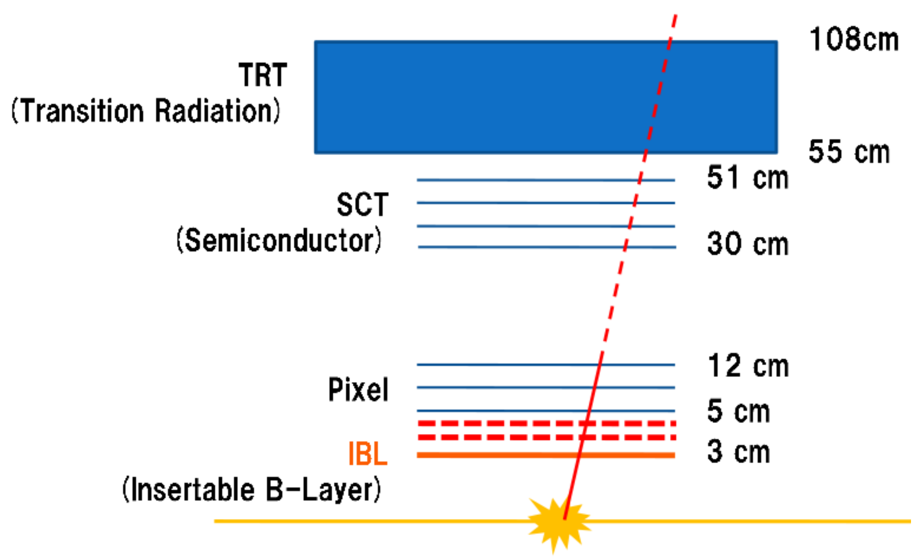
cf S. Shirai's talk

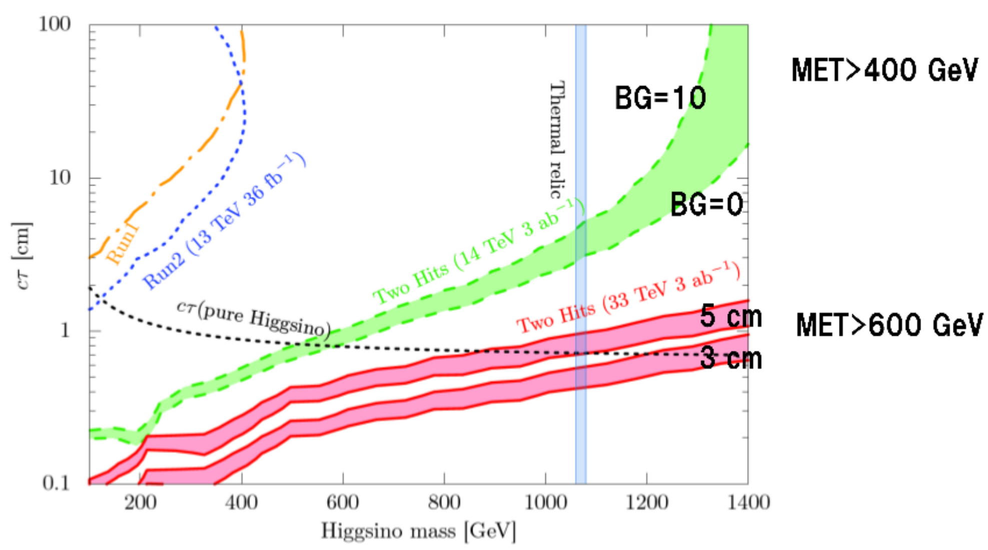
Slight digression from dark matter: Pure Higgsinos/Winos

· In the limit of a pure Higgsino/Wino LSP, the charged and neutral parts of the multiplet are degenerate @ tree-level and split through radiative corrections ($\delta m_H \sim 260 - 350$ MeV, $\delta m_W \sim 145 - 165$ MeV).

Macroscopic decay lengths

· Proposal for LHC upgrades: add tracker layers.





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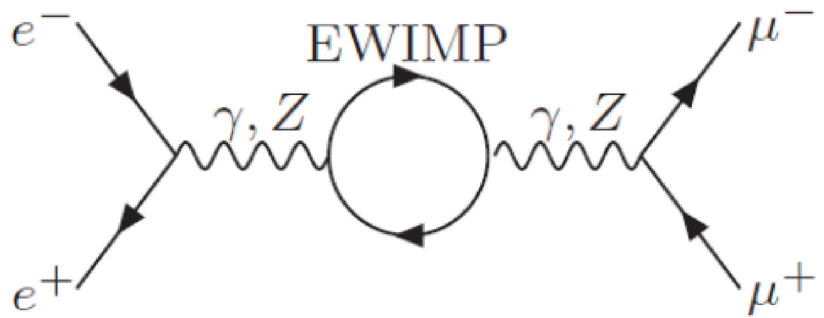
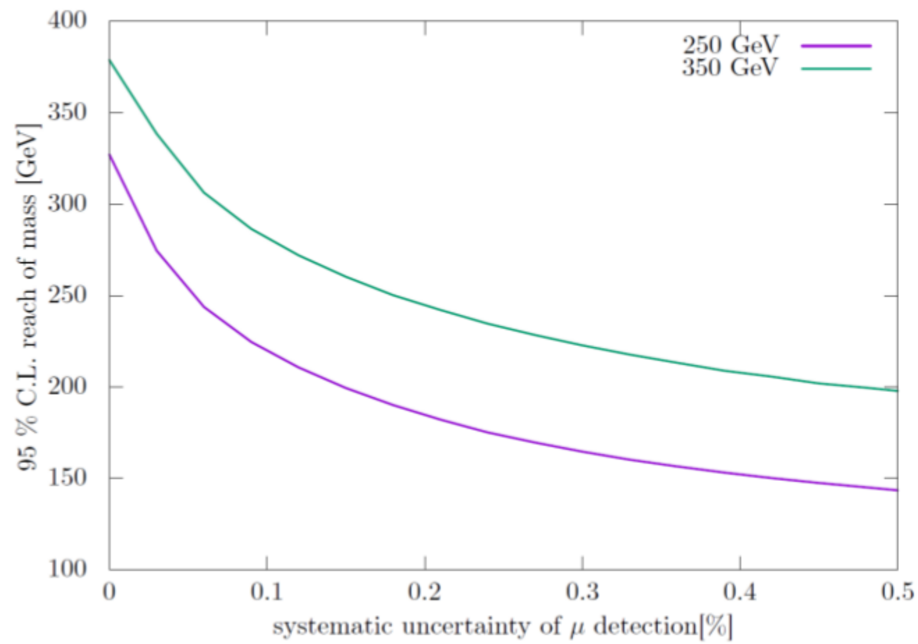
Can the ILC250/350 discover DM – motivated new physics not accessible at the LHC?



· Heavy states cannot be produced, but the ILC is a cleaner environment → more sensitive to EW radiative processes.



Week 2: Freeze-in

Beyond WIMPs: Freeze-in

cf A.G.'s and
Y. Mambrini's talks

Assume, that a particle species 1 possesses feeble (*very* weak) couplings with 2, 3 and 4.
Reasonable assumption (perhaps): its initial density is negligible.

arXiv:hep-ph/0106249,
arXiv:0911.1120, arXiv:1706.07442
...and many more

$$\equiv n(t)$$

$$\frac{d}{dt}\left[\int f_1(E,t)\frac{g_1 d^3p_1}{(2\pi)^3}\right] + 3H\int f_1(E,t)\frac{g_1 d^3p_1}{(2\pi)^3} =$$

$$-\sum_{\text{spins}}\int\left[f_1 f_2(1\pm f_3)(1\pm f_4)\left|\mathcal{M}_{12\to34}\right|^2 - f_3 f_4(1\pm f_1)(1\pm f_2)\left|\mathcal{M}_{34\to12}\right|^2\right]$$

$$\times(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)\times\prod_{i=1}^{4}\left(\frac{d^3p_i}{(2\pi)^3 2E_i}\right)$$

Ignore

Small density

Ignore

Feeble coupling + small density

$\sim f_3^{eq} \times f_4^{eq}$

Typically the SM particles, thermalize quickly

· No DM annihilation term.

· No equilibrium between 1 and the other particles.

Beyond WIMPs: Freeze-in

cf A.G.'s and
Y. Mambrini's talks

Grossly speaking, distinguish 3 scenarios:

I) Dark matter could be produced directly from 2 → 2 processes, annihilations of Standard Model (or other bath) particles: $a + b \to \chi + \chi$

IIa) Dark matter could be produced from the decay of a heavier particle in equilibrium with the thermal bath: $Y \to \chi + \chi$ (but χ is a FIMP)

IIb) Dark matter could be produced from the decay of a heavier particle which is *not* in equilibrium with the thermal bath: $Y \to \chi + \chi$ (both χ and Y are FIMPs, but where did Y come from?)

· Scattering scenarios seem to be more or less irrelevant for LHC phenomenology (barring model-dependent features).

· But if DM (or even Y) is produced through decays of some heavier, "strongly" coupled state, the latter could be produced at the LHC.

A playground for LHC phenomenology!

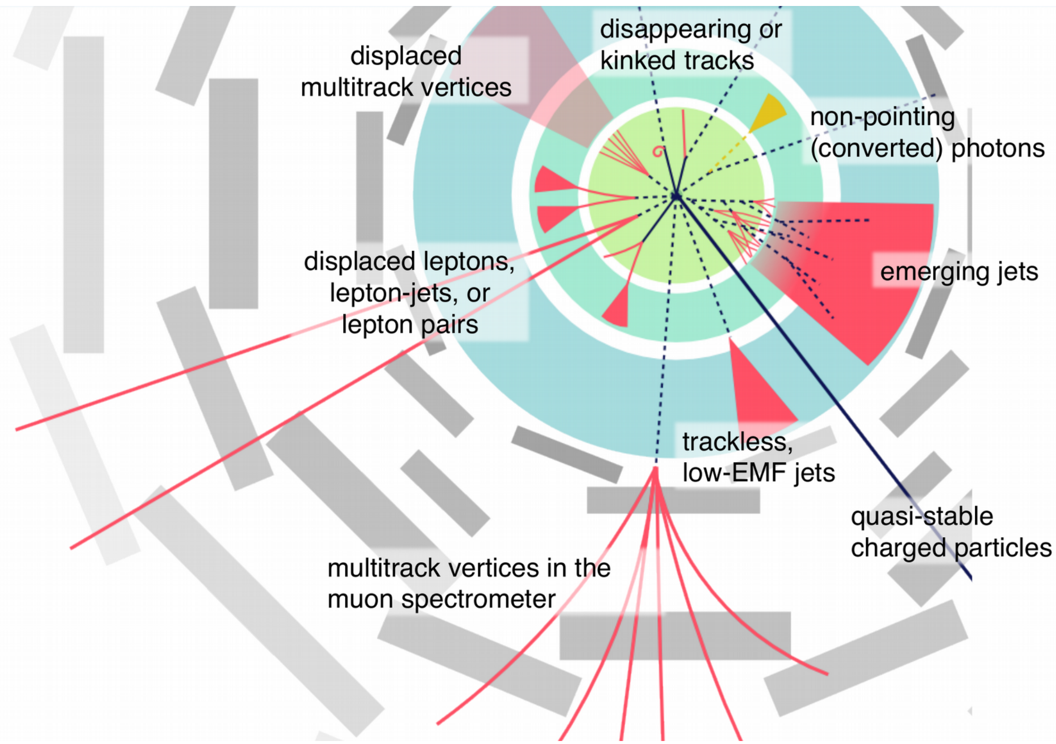
Freeze-in @ the LHC

cf talks by C. Doglioni, O. Buchmüller, A.G.

All collider searches for FIMPs (that I'm aware of!) rely on the production of some not-so-feebly coupled heavier state that can decay into the FIMP.

Very weak couplings imply long lifetimes for the parent particle

The "LLP zoo"



H. Russell, LHC LLP workshop

· Proliferation of possible signatures (extra parameter wrt prompt searches: τ_{LLP}).

e.g. TH vs EXP view of an e^-

· How do we define a set of "simplified models" (if we do)?

cf O. Buchmüller's talk

· What do freeze-in models actually predict?

· And do we have sufficient motivation for LLP searches altogether?

Freeze-in @ the LHC

All collider searches for FIMPs (that I'm aware of!) rely on the production of some not-so-feebly coupled heavier state that can decay into the FIMP.

Very weak couplings imply long lifetimes for the parent particle

But how long are these lifetimes? It turns out that freeze-in models mostly give rise to detector-stable particles. Two known exceptions:

· Freeze-in during a matter-dominated era: requires much larger couplings than standard freeze-in.

R. T. Co, F. D'Eramo, L. J. Hall, D. Pappadopulo, arXiv:1506.07532
J. A. Evans, J. Shelton, arXiv:1601.01326

· Cases of very light FIMPs, e.g. in the "scotogenic" model.

A. Hessler, A. Ibarra, E. Molinaro, S. Vogl, arXiv:1611.09540

$$c\tau(H^{\pm}) \simeq 8.3\text{m} \left(\frac{M_1}{10\text{keV}}\right) \left(\frac{100\text{GeV}}{m_{H^{\pm}}}\right)^2$$

New detectors might be needed

e.g. J. P. Chou, D. Curtin, H. J. Lubatti, arXiv:1606.06298

On motivation: Hell is other searches

One of the things I learned in this workshop:

Naïve theorist's view: they're a possibility we should look for them!

Experimentalist's reality: ok, whose bandwidth shall we use?

→ It's not just a question of manpower, it's also a question of priorities!

In other words: one needs some strong motivation to "get someone else's data"!

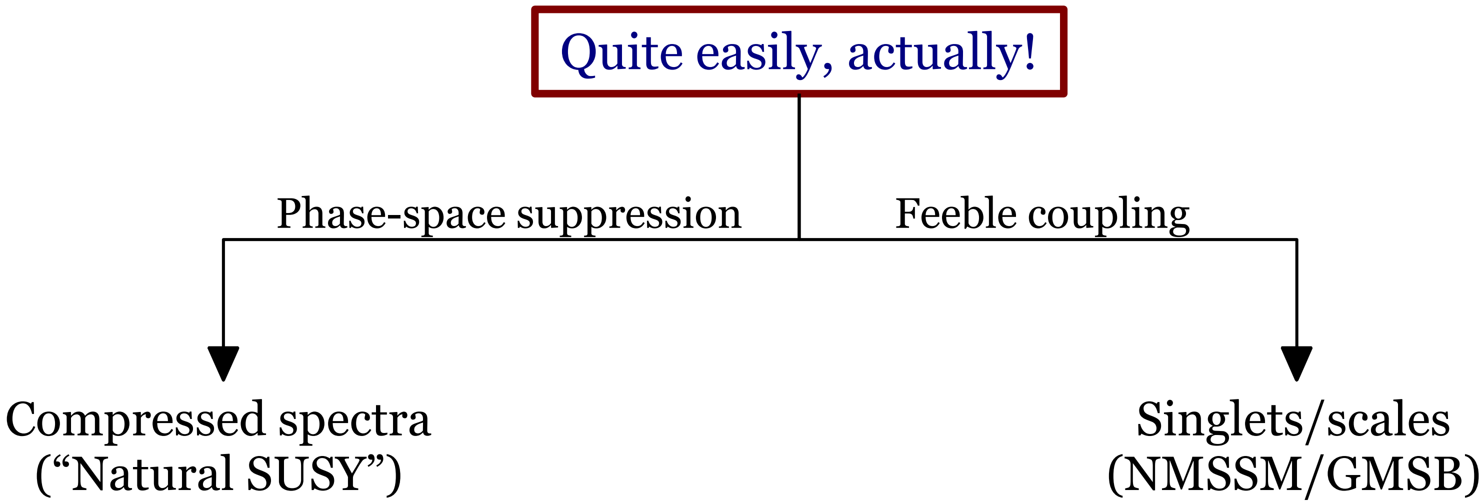
Situation similar to telescope observation times in indirect DM detection.

· Odds are some choices will have to be made, and these choices also depend on figuring out which signatures appear to be common in models involving LLPs (and have a relatively good sensitivity).

· Also: these are actually pretty complicated analyses, so we better actually have some relatively strong physics case before asking experimentalists to perform them!

On motivation: LLPs and SUSY

How easily do long-lived particles appear in UV-complete (“well-motivated”) BSM models, e.g. in supersymmetric scenarios?



· The two cases do share some common potential signatures, but they can also differ quite radically.

· Highly desirable to figure out what the potential signals could be in SUSY models: effort for benchmark scenarios during GGI workshop.

Orthogonal topics

Small-scale problems with CDM

cf B. Zaldivar's talk

The picture of collisionless CDM has had a massive success, but might only be providing part of the picture.

Some disagreement appears when comparing CDM halo simulations with actual observations...

Cusp vs core problem

CDM simulations strongly favour cusped DM halo profiles like NFW.

but

Actual observations in many galaxies rather suggest cored ones.

Missing satellite problem

CDM simulations predict $O(10^2)$ satellite galaxies orbiting the MW.

but

Only $O(10)$ have been observed.

+ self-similarity, too-big-to-fail

Solutions include:

- Baryonic effects → Can flatten out cusps (depending on m_B/m_{DM}), difficult to simulate!

- Warm dark matter → Larger free-streaming length, doesn't settle as much in gravitational wells.

- Self-interacting dark matter → Works for both, need $\sigma_{SI} \sim 10^{10}\, \sigma_{weak}$!

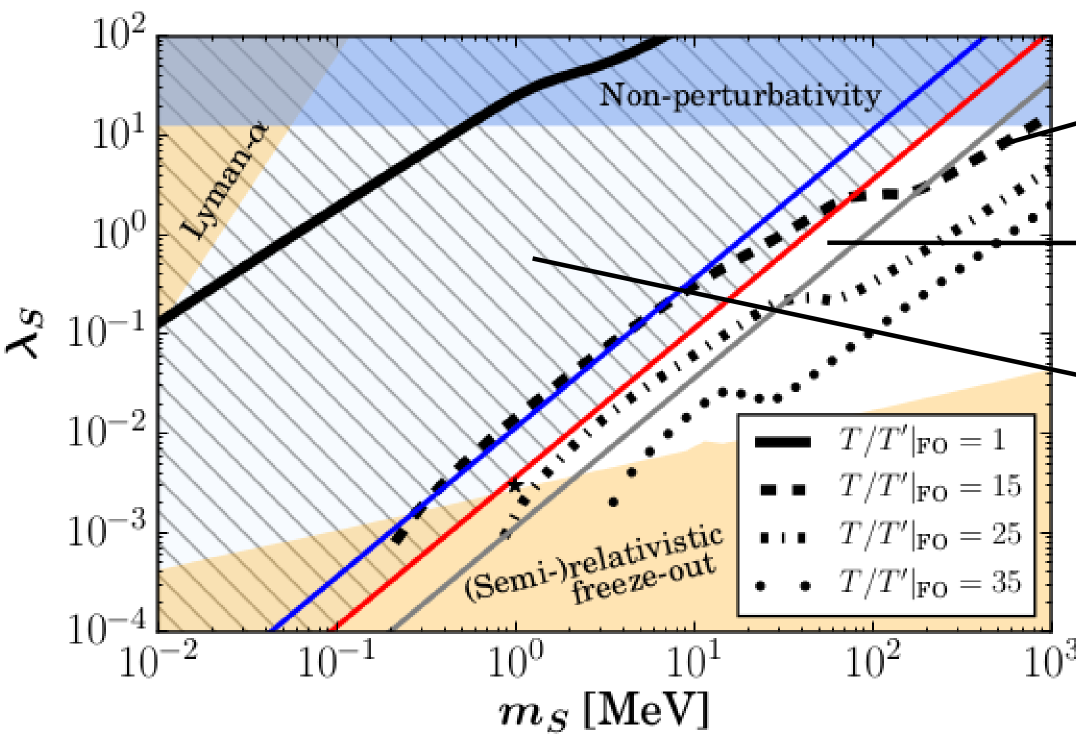
Possible corollary of self-interactions

Usually, when computing the dark matter abundance, only $2 \leftrightarrow 2$ processes are taken into account.

But what if the self-interactions are so strong that number-changing processes *within* the dark sector dominate?

One example from the Singlet Scalar Model: $V = V_{\rm SM} + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} |H|^2 S^2$

N. Bernal, X. Chu, JCAP 1601 (2016) 006
Cf also N. Bernal *et al*, JCAP 1603 (2016) 018



$\Omega_{\rm DM} = \Omega_{\rm Planck}$

Small-scale structure problems solved

Galaxy cluster limits on self-interactions

An unexpected link between the dark matter density and small-scale structure formation?

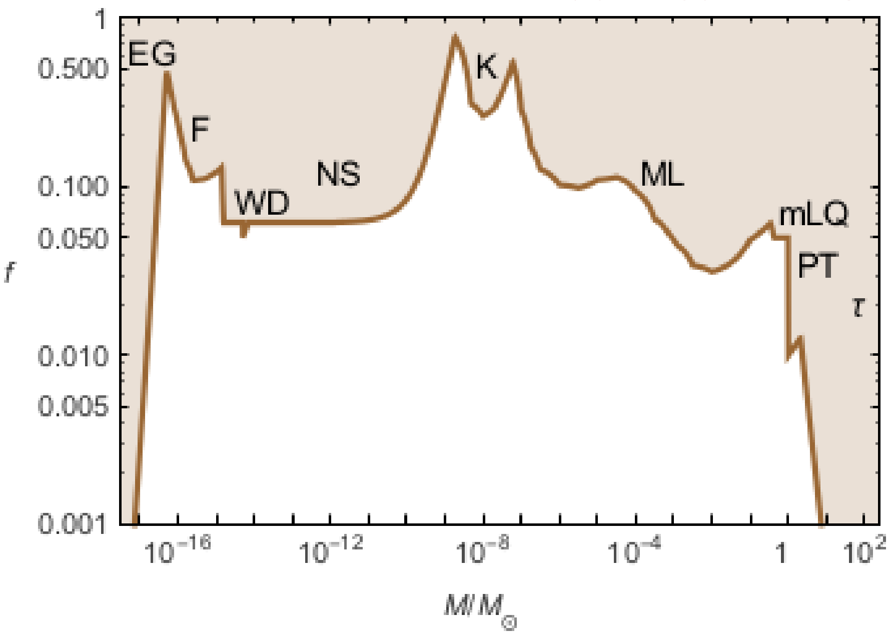
Primordial black holes as dark matter

Revived interest after the LIGO gravitational wave detection: could it be due to a merger of primordial black holes?

I. Cholis *et al*, PRL 116, 201301 (2016)

Assuming monochromatic mass function

F. Kühnel, K. Freese, PRD 95, 083508 (2017)

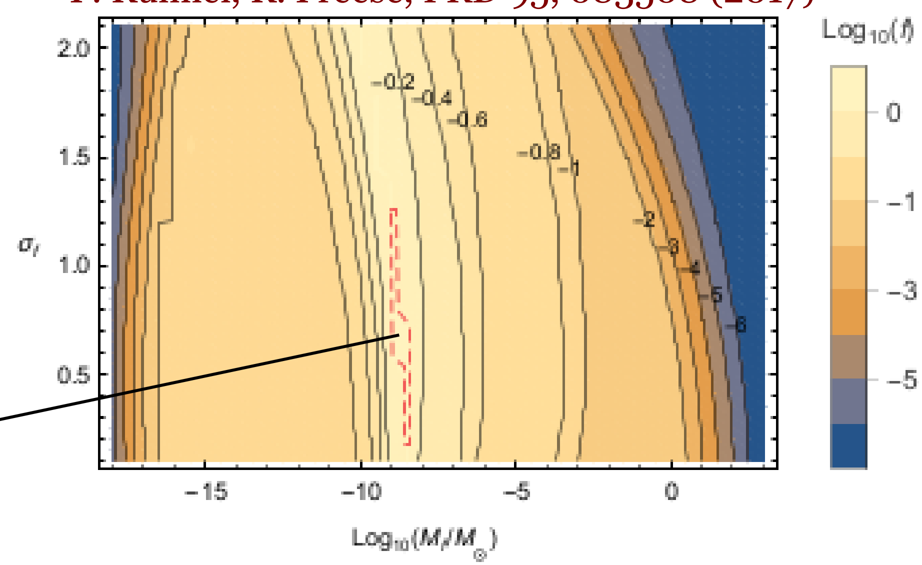


Assuming extended mass function as

$$\frac{dn}{dM} \equiv N \exp\left[-\frac{(\log M/M_f)^2}{2\sigma_f^2}\right]$$

A.M. Green, (PRD 2016) PRD 94, 063530 (2016)

F. Kühnel, K. Freese, PRD 95, 083508 (2017)



In this region PBHs could make up for the entire dark matter content in the Universe.

Elements of summary

· We don't know what DM is. So far we gain more and more knowledge about what it's not.

· Can we explain its abundance in the Universe? We have ideas, in fact quite a few! Freeze-out, freeze-in, dark freeze-out, "gravitational" production, asymmetric dark matter...

· All these ideas motivate searches: there is no model-independent, fully generic dark matter detection technique!

· Pressure on thermal freeze-out: envisage new searches

Can we exclude thermal FO? Most likely not, but we can render it much less attractive.

· A lot of effort is currently being dedicated to pinpoint the signatures of alternative dark matter generation mechanisms : LHC, astrophysics, cosmology, intensity frontier.

· On the model-building side : the traditional problem in dark matter physics is that we have no argument for some relevant mass scale.

Where can we find motivation?

Ideas include: experimental excesses, Naturalness, Flavour, Strong CP...