Effectively Understanding Dark Matter Searches

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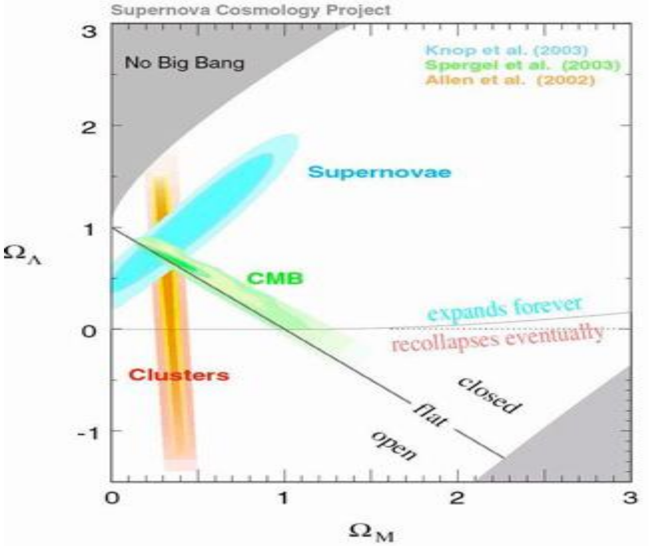
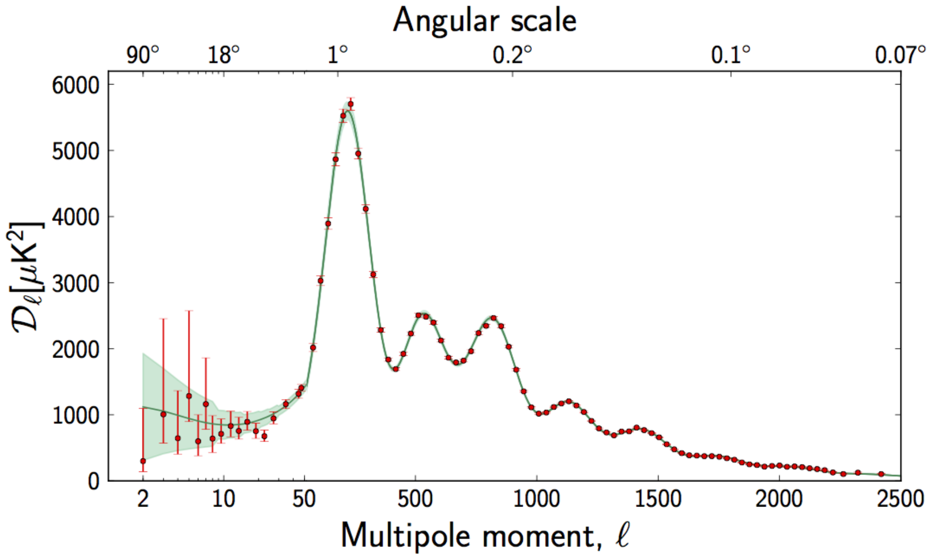
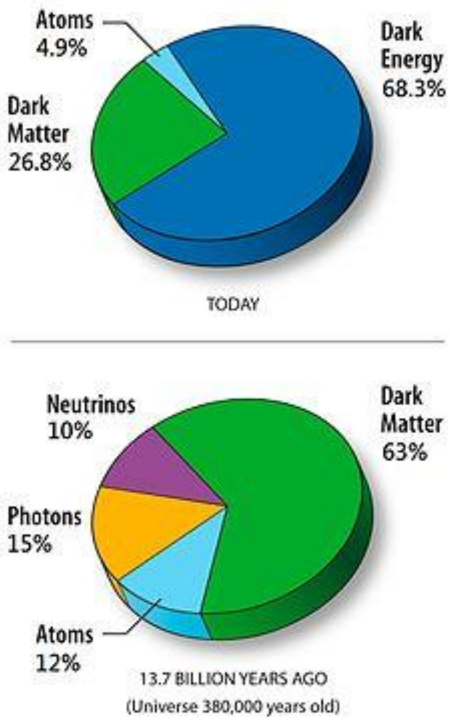
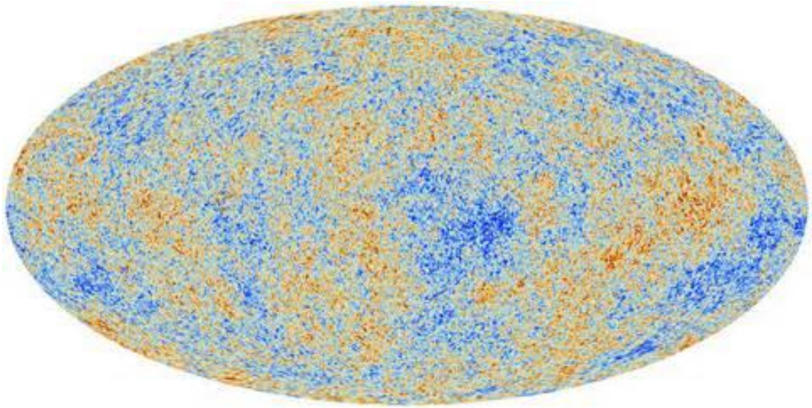
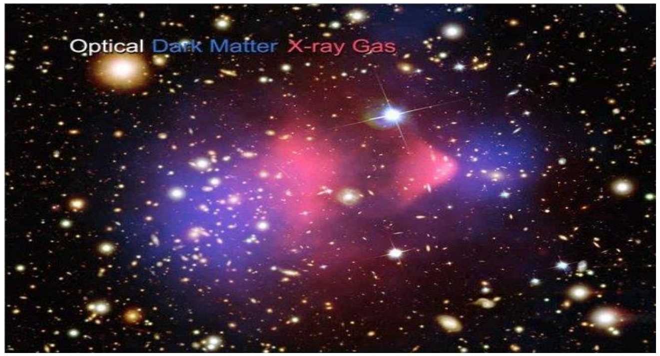
March 25, 2015


Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
$\mathcal{D}_\ell[\mu K^2]$
Multipole moment, ℓ


Atoms 4.9%
Dark Energy 68.3%
Dark Matter 26.8%
TODAY
Neutrinos 10%
Dark Matter 63%
Photons 15%
Atoms 12%
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

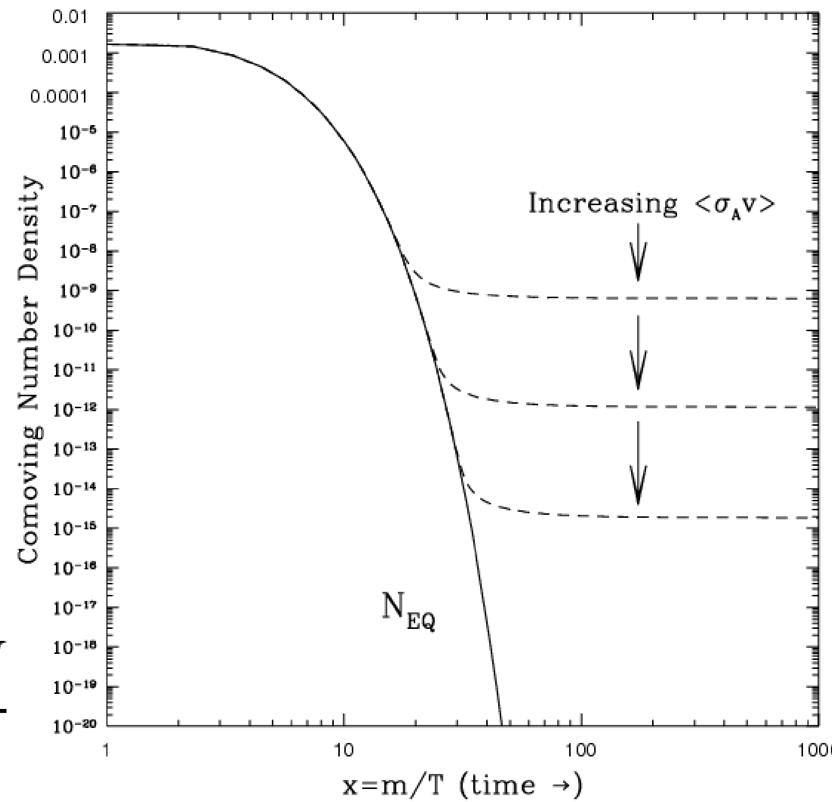



Optical Dark Matter X-ray Gas

WIMP Miracle

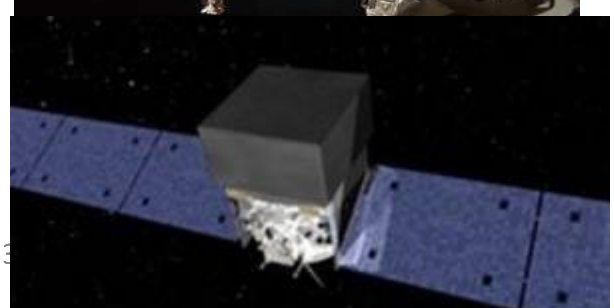
- If DM was in thermal equilibrium, then its current density is easily calculable.
- To match measurements,

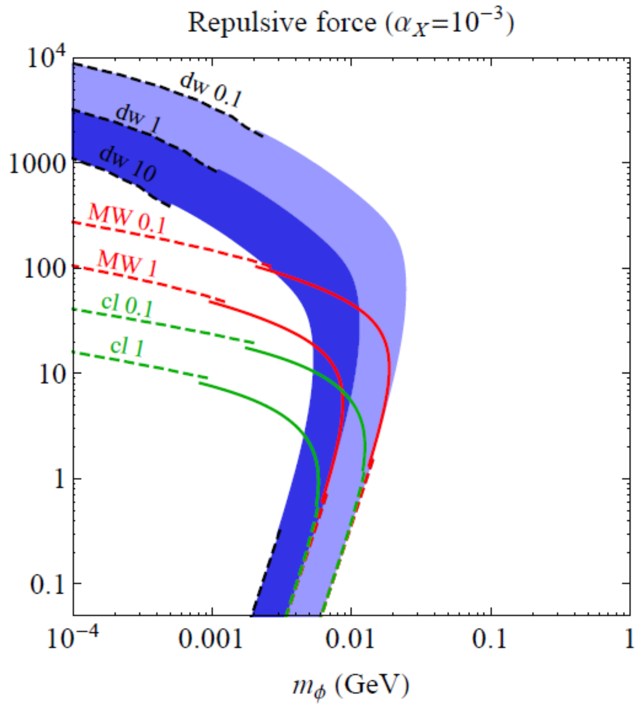
$$\frac{M_\chi}{\alpha} \sim \sqrt{T_{eq} M_{Pl}} \sim \frac{2.3\ \mathrm{TeV}}{0.03}$$

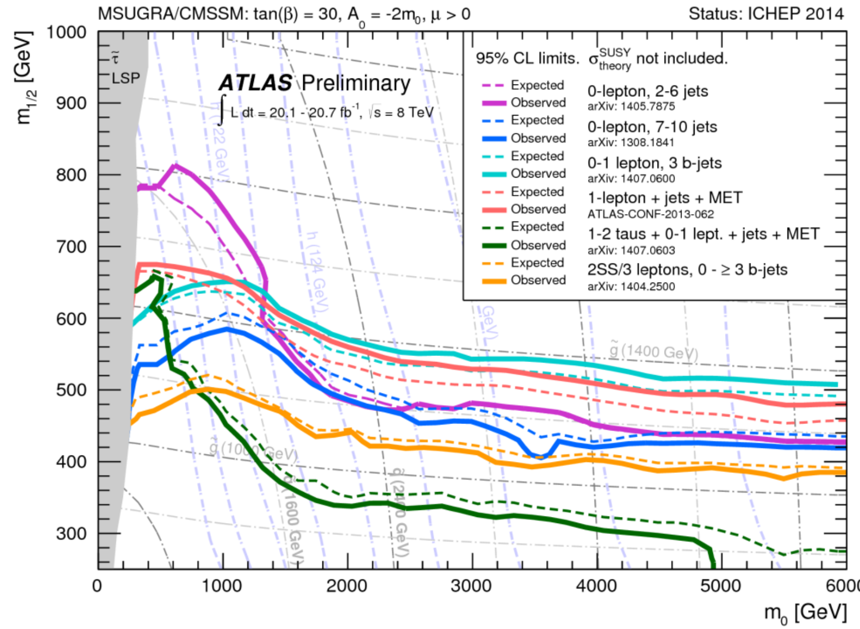


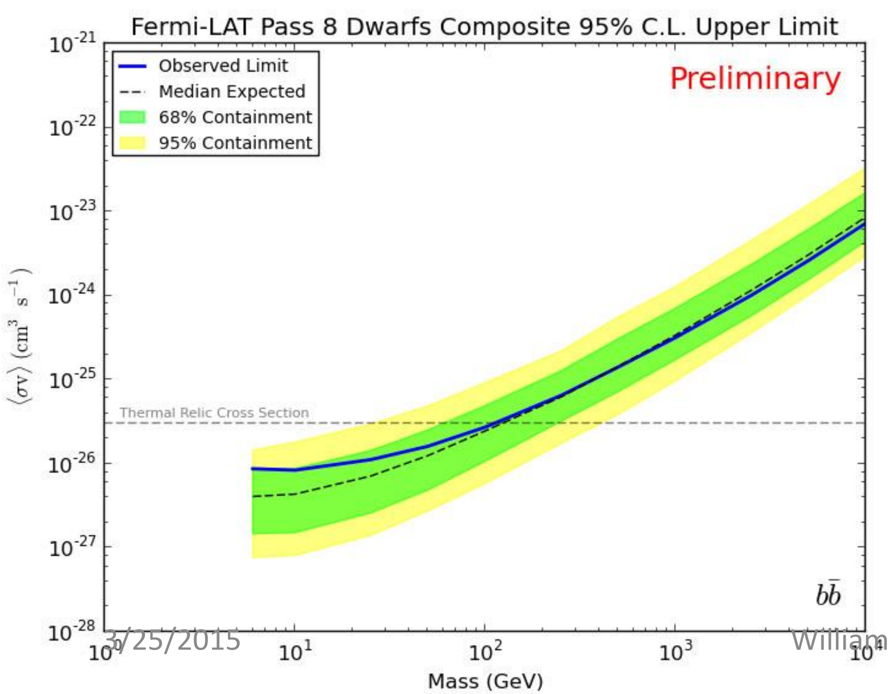
WIMP Search Strategies

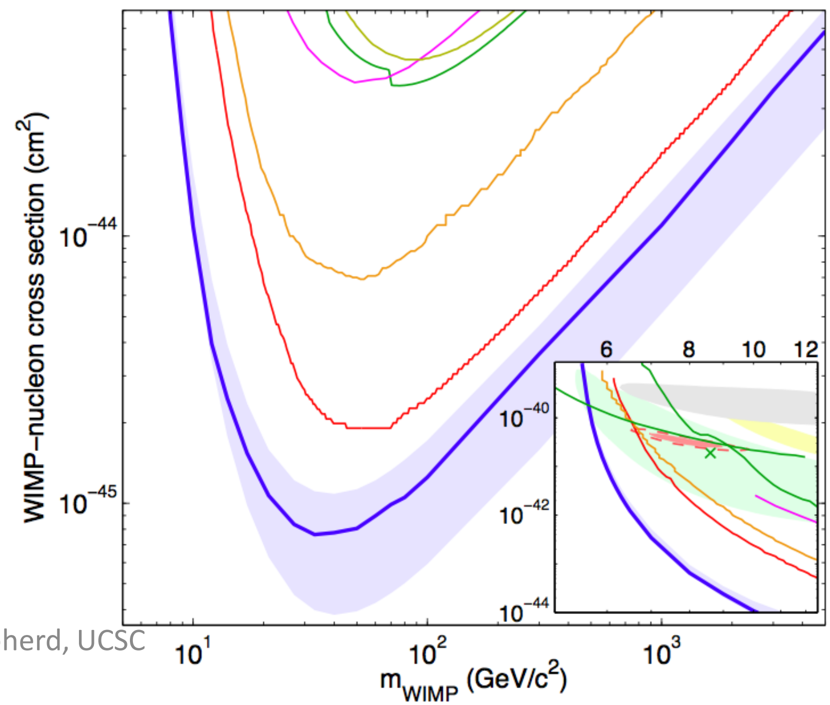
Y. YEPES (UNIVERSIDAD AUTÓNOMA DE MADRID) / K. RIEBER (POTSDAM)

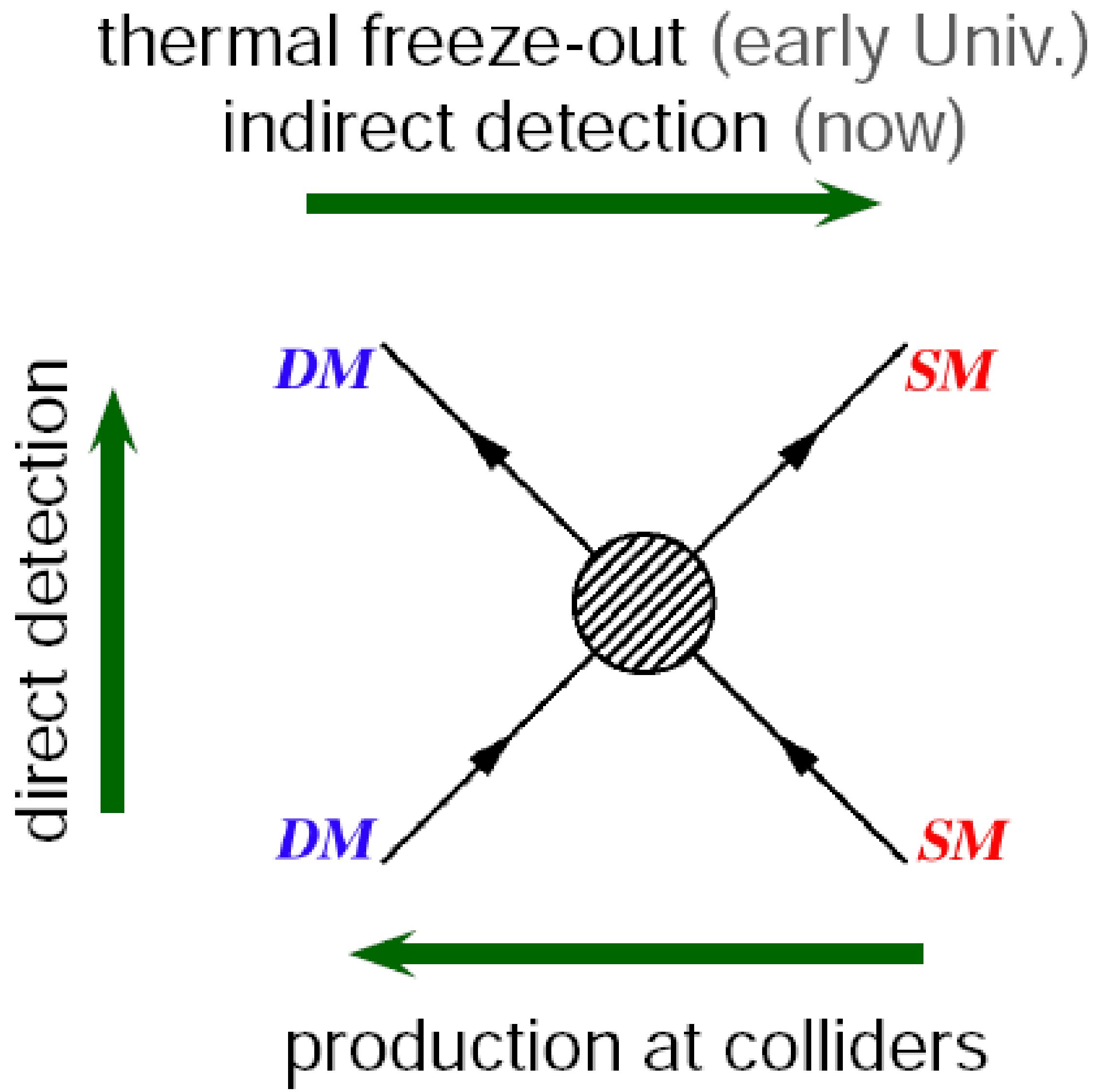



Repulsive force (α_X=10^{-3})
dw 0.1
dw 1
dw 10
MW 0.1
MW 1
cl 0.1
cl 1
10^4
1000
100
10
1
0.1
10^{-4}
0.001
0.01
0.1
1
m_ϕ (GeV)


MSUGRA/CMSSM: tan(β) = 30, A_0 = -2m_0, μ > 0
Status: ICHEP 2014
$\tilde{\tau}$ LSP
ATLAS Preliminary
$\int$ L dt = 20.1 - 20.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
95% CL limits. σ^{SUSY}_{theory} not included.
Expected
Observed
0-lepton, 2-6 jets
arXiv: 1405.7875
Expected
Observed
0-lepton, 7-10 jets
arXiv: 1308.1841
Expected
Observed
0-1 lepton, 3 b-jets
arXiv: 1407.0600
Expected
Observed
1-lepton + jets + MET
ATLAS-CONF-2013-062
Expected
Observed
1-2 taus + 0-1 lept. + jets + MET
arXiv: 1407.0603
Expected
Observed
2SS/3 leptons, 0 - ≥ 3 b-jets
arXiv: 1404.2500
$\tilde{g}$ (1400 GeV)
$m_{1/2}$ [GeV]
m_0 [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000


Fermi-LAT Pass 8 Dwarfs Composite 95% C.L. Upper Limit
Observed Limit
Median Expected
68% Containment
95% Containment
Preliminary
Thermal Relic Cross Section
$b\bar{b}$
$\langle \sigma v \rangle$ (cm^3 s^{-1})
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Mass (GeV)


WIMP–nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^{1}
10^{2}
10^{3}
m_{WIMP} (GeV/c^2)
6
8
10
12
10^{-40}
10^{-42}
10^{-44}



thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
DM
SM
DM
SM
production at colliders

What’s in the Middle?

- Many, many models have been proposed to explain dark matter, each with its own stabilizing symmetry and interactions with ordinary matter
  - Supersymmetry, Extra Dimensions, Inert Higgs…
- Analyses of each model are useful, but far from interchangeable
- We need a more general language for these translations between experiments

Effective Field Theory

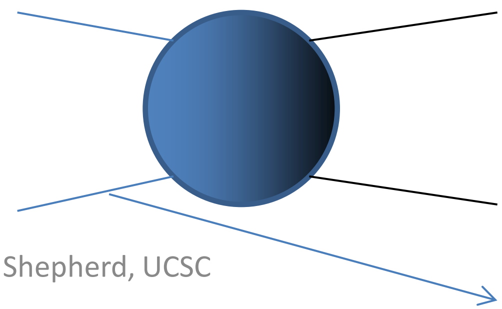
- In this case, let's imagine that whatever physics is responsible for dark matter interactions is very heavy compared to the scale our experiments can probe
- This leaves us with contact interactions between dark and ordinary matter
- Can be scalar-like or vector-like with various spin structures, of form $\frac{1}{\Lambda^2}\bar{\chi}\Gamma\chi\bar{q}\Gamma\mathrm{q}$

DM EFT

- Every interaction must have two DM particles in it, and it must respect the rules of the Standard Model
- This leaves a fair amount of freedom, but a manageable number of possibilities to explore
- The choice of interactions will impact the behavior of dark matter at each of our dark matter experiments

EFT at Colliders

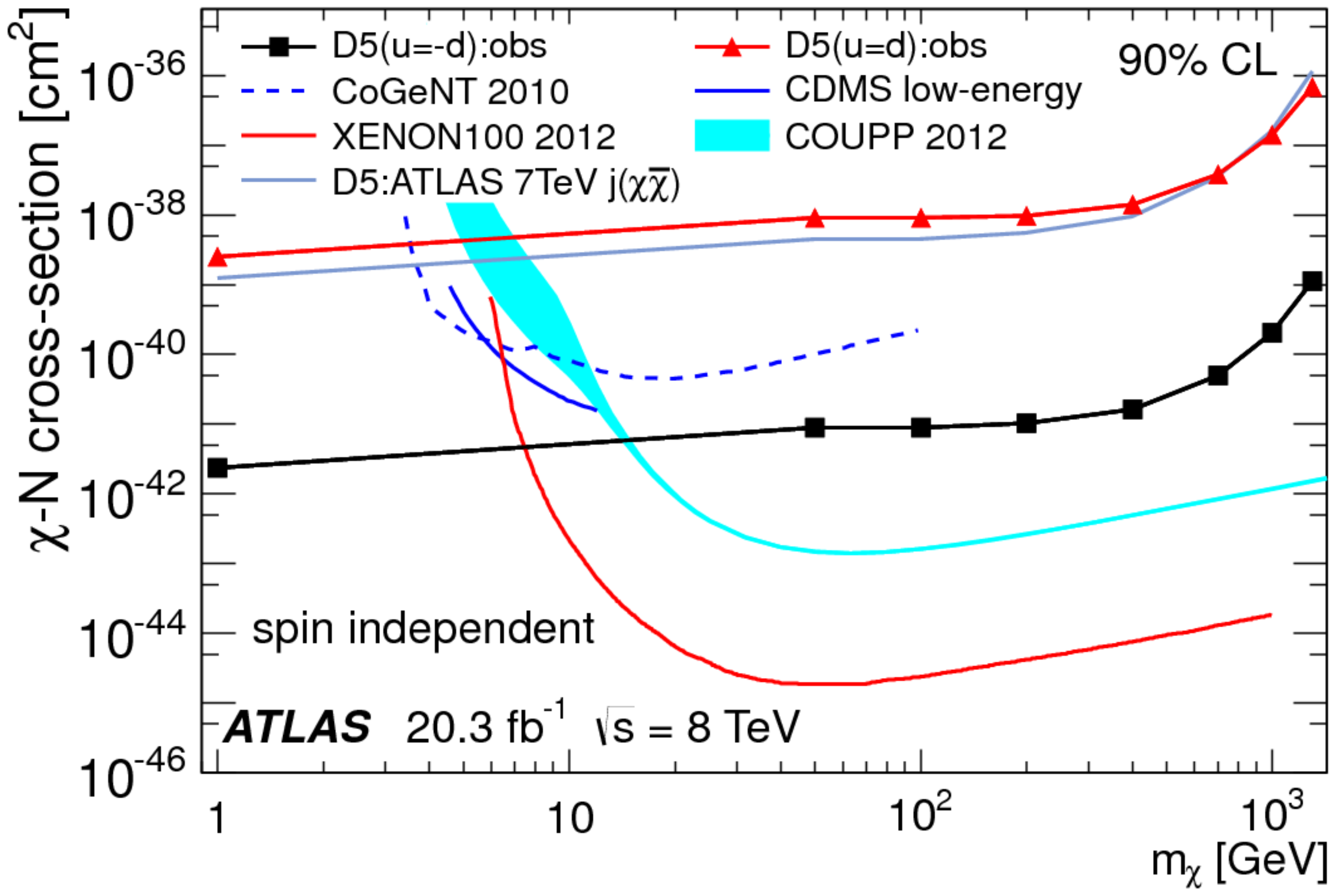
- The goal at colliders is to produce a pair of dark matter particles
  - Once made they won't interact with the detector
- Something we can see will have to be produced along with the DM
- The class of searches that are used to constrain these models are generically called mono-X searches



EFT at Colliders

- All the particles involved in a collision are relativistic, so that spin structures are not very important
- Interactions with light quarks and gluons are most strongly constrained
  - Some prefer heavier quarks, those are much harder to see at colliders

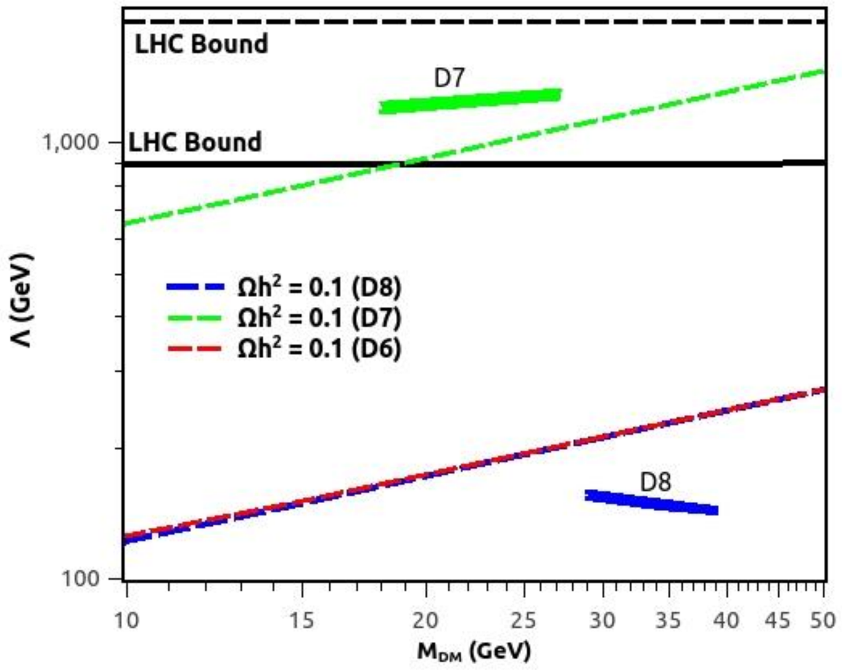
Collider Results vs Direct Detection



The Effective Hooperon

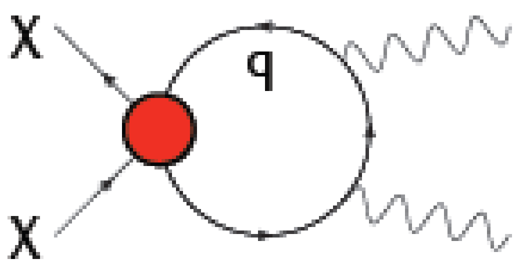
- Within the EFT picture, there are two main requirements to fit the Hooperon
  - Must annihilate efficiently enough
  - Must be able to have right relic density

Alves, Profumo, Queiroz, WS 1403.5027



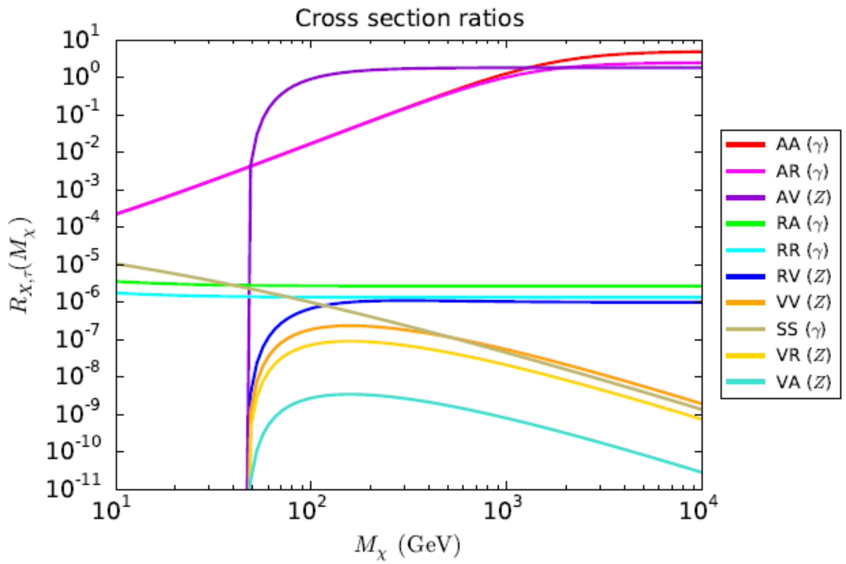
Gamma Ray Lines

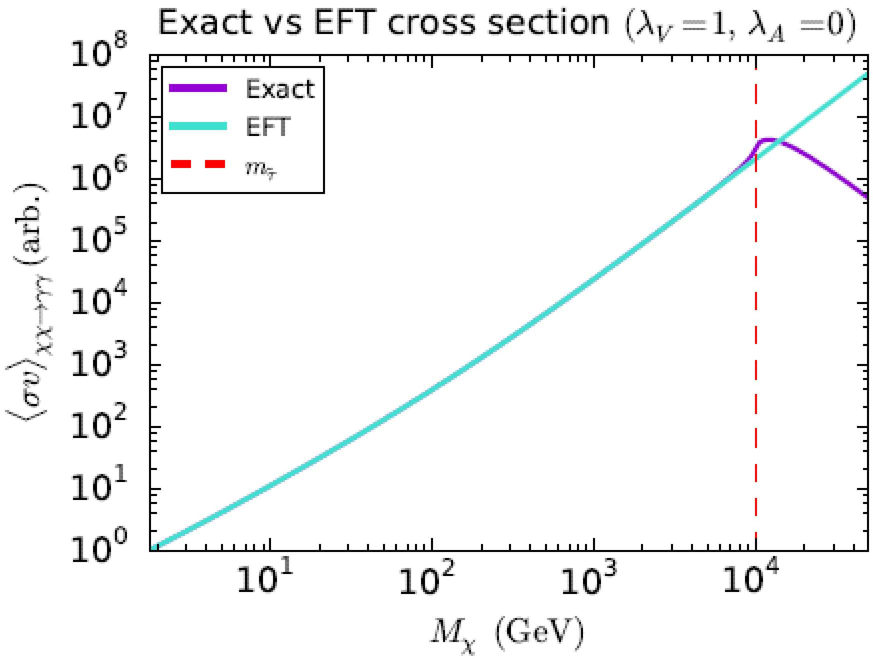
- Couplings of WIMPs to ordinary matter leads to higher-order couplings of WIMPs to photons and other force-carriers of the SM
- Allows the annihilation of WIMPs directly to photons, giving rise to a new gamma-ray spectral line



Gamma Ray Lines

Coogan, Profumo, WS, in preparation

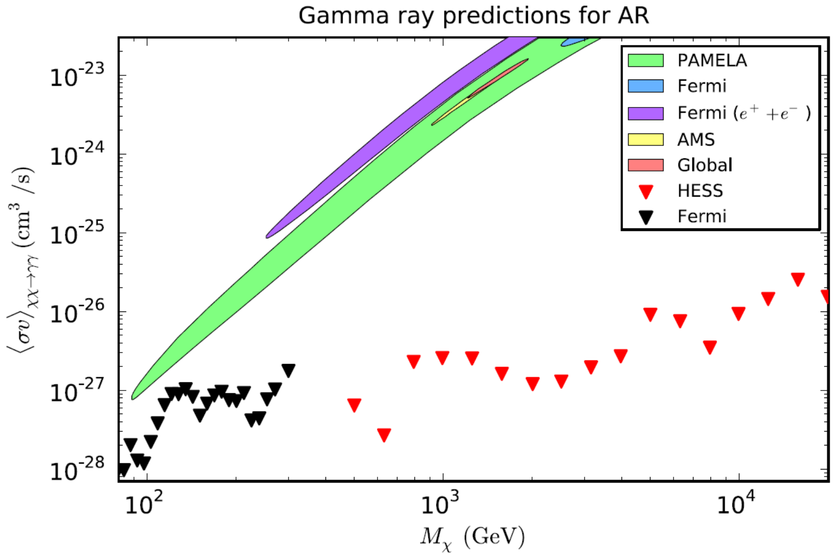




Positrons and Gamma Rays

- If cosmic ray positrons are due to DM annihilations we can predict the gamma-ray line flux
- This eliminates some coupling choices as possible explanations of the Pamela/AMS excess

Coogan, Profumo, WS, in preparation

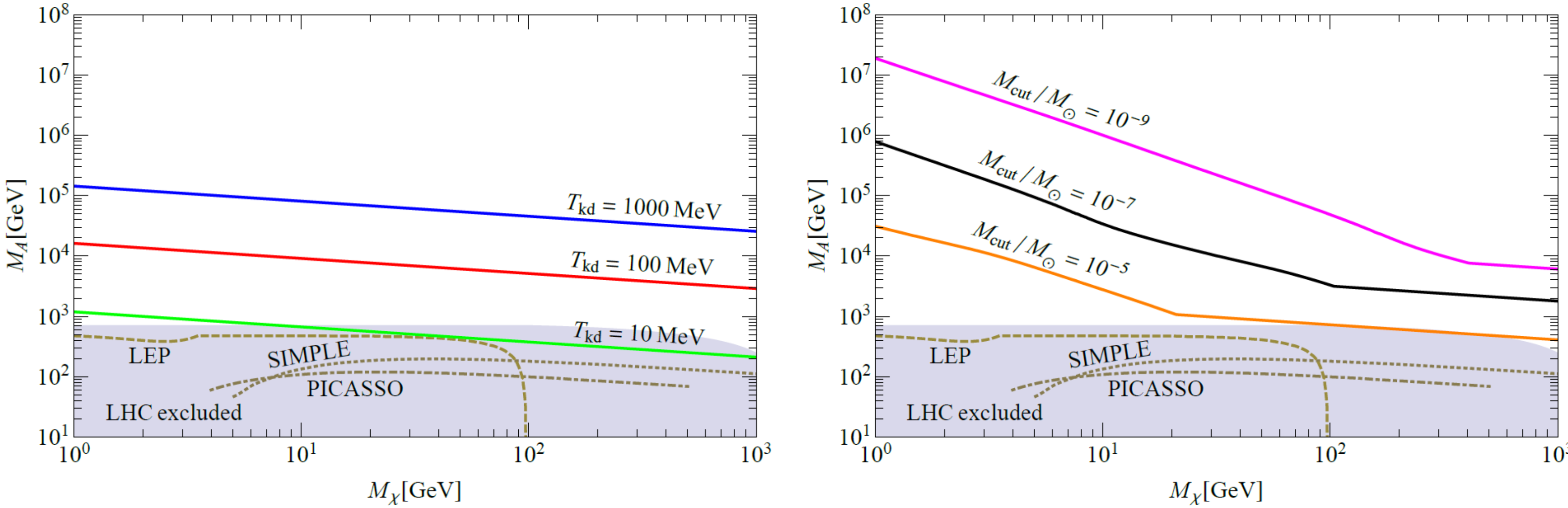


EFT Kinetic Decoupling

- Dark matter distribution through space is set by scattering interactions after the relic density is already set
  - Akin to direct detection processes
- Calculating the scattering rate in the early universe, we can find the smallest size allowed for dark matter haloes for any assumed interaction

EFT Kinetic Decoupling

Cornell, Profumo, WS, 1305.4676

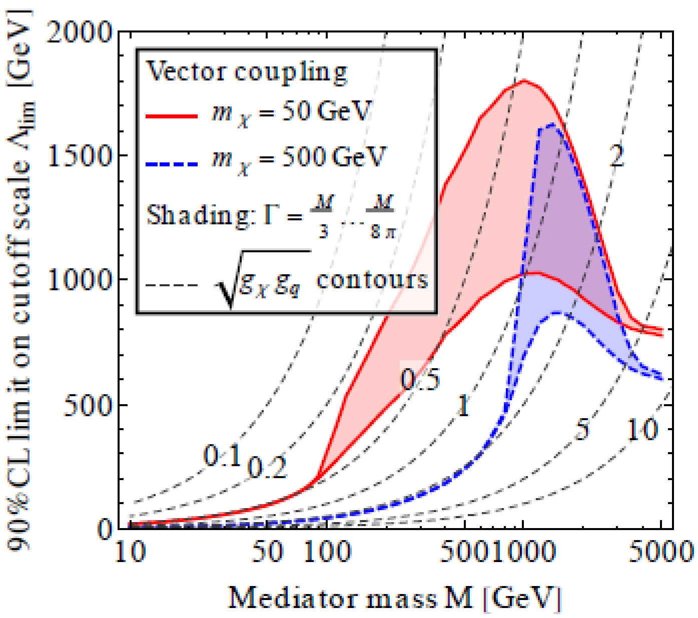


EFT Shortcomings

- We assumed we can’t see any new particles other than the dark matter candidate, but that certainly doesn’t have to be true
- If we can see the particle mediating interactions with dark matter then the rates we calculated can be changed
  - Biggest issue is at colliders, where we are probing high energies

Light Mediators

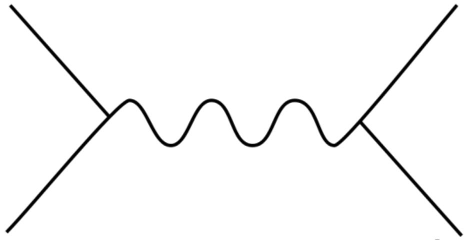
- Bringing the mediator mass down into range can have large effects!
- This is one possible cause of 'conflict' between different DM search techniques

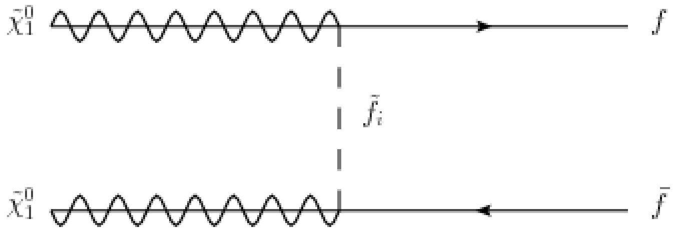


Fox, Harnik, Kopp, Tsai 1109.4398

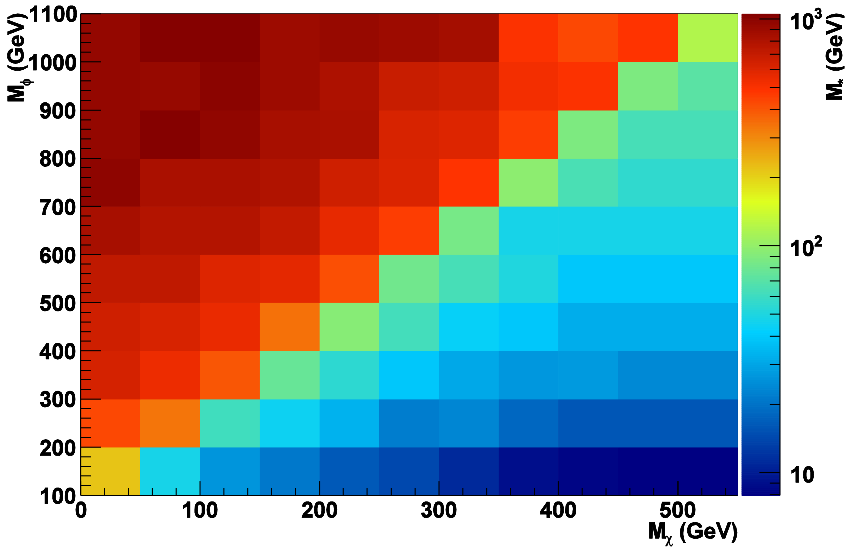
Simplified Models and Mappings

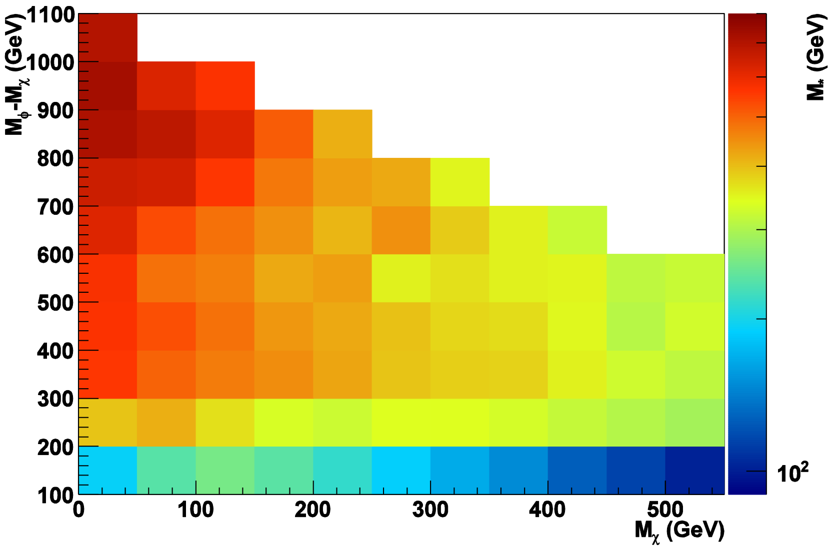
- Mediator can couple either to two or one dark matter particle at a time, giving very different behavior





Goodman and WS, 1111.2359





On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC

Giorgio Busoni[a,1], Andrea De Simone[a,b,2],
Enrico Morgante[c,3], Antonio Riotto[c,4]

On the Validity of the Effective Field Theory
for Dark Matter Searches at the LHC

Beyond effective field theory for dark matter searches at the LHC

O. Buchmueller,[a] Matthew J. Dolan,[b] and Christopher McCabe[b]

On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC

Beyond effective field theory for dark matter searches at the LHC

On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC Part II: Complete Analysis for the s-channel

Giorgio Busoni[a,1], Andrea De Simone[a,2], Johanna Gramling[b,3], Enrico Morgante[b,4], Antonio Riotto[b,5]

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On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC Part III: Analysis for the t-channel

Giorgio Busoni[a,1], Andrea De Simone[a,2],
Thomas Jacques[b,3], Enrico Morgante[b,4], Antonio Riotto[b,5]

On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC

Beyond effective field theory for dark matter searches at the LHC

On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC Part II: Complete Analysis for the s-channel

On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC Part III: Analysis for the t-channel

Characterising dark matter searches at colliders and direct detection experiments: Vector mediators

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Oliver Buchmueller,[a] Matthew J. Dolan,[b] Sarah A. Malik[a] and Christopher McCabe[c,d]

On the Validity of the Effective Field Theory
for Dark Matter Searches at the LHC

Beyond effective field theory for dark matter searches at the LHC

On the Validity of the Effective Field Theory
for Dark Matter Searches at the LHC
Part II: Complete Analysis for the s-channel

On the Validity of the Effective Field Theory
for Dark Matter Searches at the LHC
Part III: Analysis for the t-channel

Characterising dark matter searches at colliders and direct detection experiments: Vector mediators

Simplified Models for Dark Matter and Missing Energy Searches at the LHC

Jalal Abdallah,[1] Adi Ashkenazi,[2] Antonio Boveia,[3] Giorgio Busoni,[4] Andrea De Simone,[4] Caterina Doglioni,[5] Aielet Efrati,[6] Erez Etzion,[2] Johanna Gramling,[5] Thomas Jacques,[5] Tongyan Lin,[7] Enrico Morgante,[5] Michele Papucci,[8,9] Bjoern Penning,[3,10] Antonio Walter Riotto,[5] Thomas Rizzo,[11] David Salek,[12] Steven Schramm,[13] Oren Slone,[2] Yotam Soreq,[6] Alessandro Vichi,[8,9] Tomer Volansky,[2] Itay Yavin,[14,15] Ning Zhou,[16] and Kathryn Zurek[8,9]

Conclusions

- These EFTs are useful tools for understanding the interplay between different searches for dark matter
- It gives sensible and attainable targets for present and future experiments
- Guides us to understand what signals and phenomena are very difficult to obtain from generic dark matter dynamics
  - Either require more subtle model building or are less likely to be truly due to dark matter dynamics
- While EFT predictions are subject to very important caveats, any violation of the expectations they lead us to would be very exciting for future experiments