THE DARK SECTOR

Astroparticle Physics 2014: A Joint TeVPA/IDM Conference

Amsterdam

Jonathan Feng, UC Irvine and CERN

27 June 2014

DARK SECTORS AND DARK MATTER

- All evidence for dark matter is gravitational. Perhaps it's in a hidden sector, composed of particles with no SM gauge interactions (electromagnetic, weak, strong)

- This hidden sector may have a rich structure with matter and forces of its own

- It may also have non-gauge interactions with the SM

DARK SECTOR ETHICS

- Virtues
  - Can explain anomalies (self-interactions, 3.5 keV line, direct and indirect detection signals, …)
  - Can suggest new DM searches and signals to look for
  - Playground for interesting theoretical ideas

- Sins
  - Doesn’t address known problems of the SM
  - Doesn’t make use of nice features of the SM (WIMP miracle)
  - Not predictive, a game without rules
  - Needlessly baroque

- The sins are potentially serious. (“But the SM is baroque.” Yes, but not needlessly. “What if I came up with the SM in 1895?” You wouldn’t have, and everyone would have been right to ignore you. These are poor excuses for ugly models.) WIMPs, axions, etc. are well-motivated, and a dark sector should provide elegant solutions to real problems to merit attention.

OUTLINE

A Long History

Lee, Yang (1956); Kobsarev, Okun, Pomeranchuk (1966); Blinnikov, Khlopov (1982); Foot, Lew, Volkas (1991); Hodges (1993); Berezhiani, Dolgov, Mohapatra (1995); …

Effective Interactions

$$\underbrace{\mathcal{O}_4}_{N \quad A' \quad \phi_h} \qquad \underbrace{\mathcal{O}_5 \qquad \mathcal{O}_6}_{\text{DM ET}}$$

Full Models

$$\underbrace{\text{WIMPless} \quad \text{SIDM} \quad \text{XDM}}_{\text{A SIMPle Theory of DM}}$$

EFFECTIVE INTERACTIONS

- There are many ways the hidden particles could couple to us. Use effective operators as an organizing principle:

$$\mathcal{L} = \mathcal{O}_4 + \frac{1}{M}\mathcal{O}_5 + \frac{1}{M^2}\mathcal{O}_6 + \ldots$$

where the operators are grouped by their mass dimension, with [scalar] = 1, [fermion] = 3/2, [$F_{\mu\nu}$] = 2

- *M* is a (presumably) large "mediator mass," so start with dimension 4 operators. There are not too many:

Neutrino portal	Higgs portal	Photon portal
hLN	$h^\dagger h \phi_h^\dagger \phi_h$	$F_{\mu\nu} F_h^{\mu\nu}$

NEUTRINO PORTAL

see Gonzalez-Garcia, Viel, Shaposhnikov talks

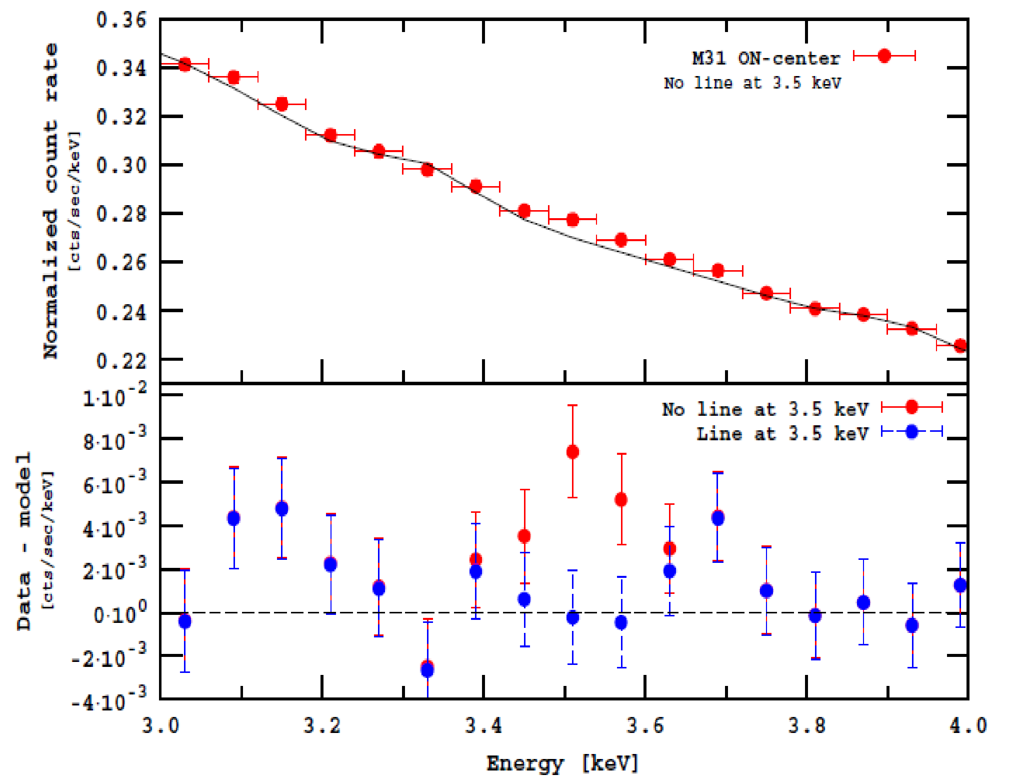
- One possibility is

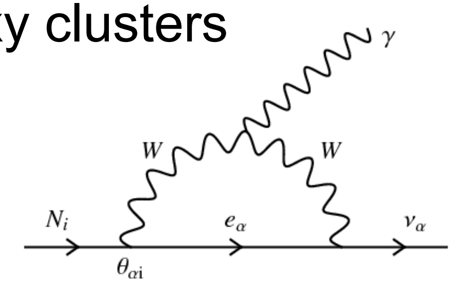
$$hLN$$

N is a total gauge singlet, the right-handed, or sterile, neutrino, and may be dark matter

- If N is dark matter, its favored mass range is ~keV

- This has received renewed attention from the 3.5 keV X-ray line seen from galaxies and galaxy clusters





Boyarsky, Ruchayskiy, Iakubovskyi, Franse (2014)
Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall (2014)
but see also Riemer-Sorensen (2014)

HIGGS PORTAL

Patt, Wilczek (2006); see Grojean talk

- Another possibility is

$$h^\dagger h \phi_h^\dagger \phi_h$$

where the *h* subscript denotes "hidden"

- When EW symmetry is broken, h → v + h, this leads to invisible Higgs decays

- A leading motivation for precision Higgs studies and future colliders, such as ILC, CLIC, FCC

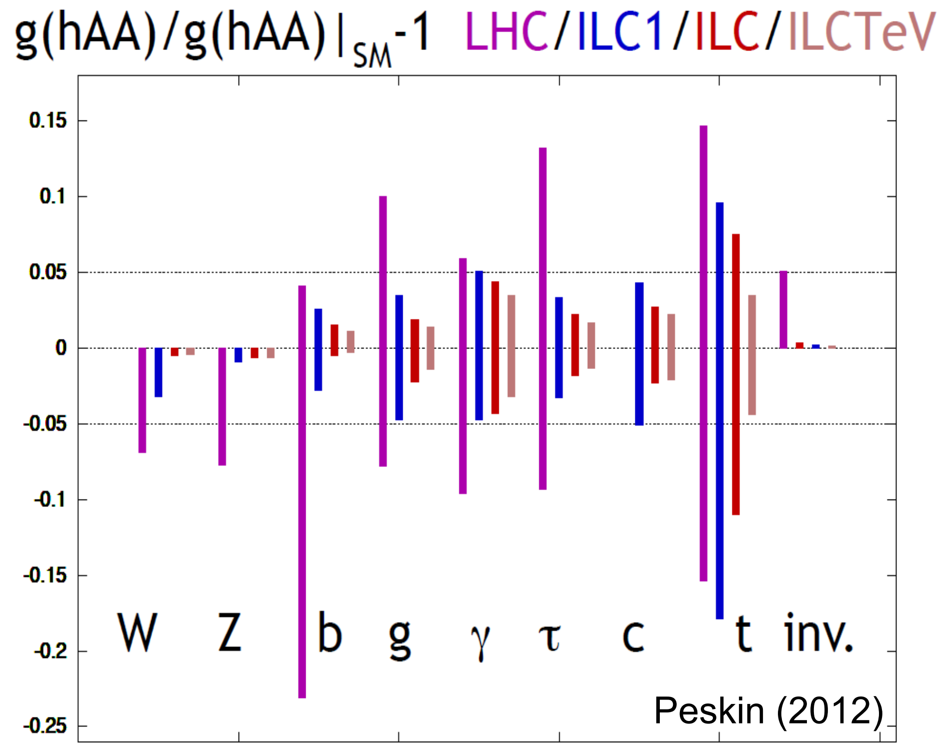


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

PHOTON PORTAL

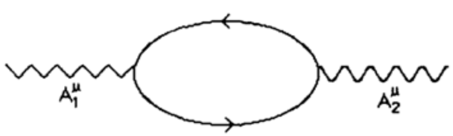
Holdom (1986)
Bjorken, Essig, Schuster, Toro (2009)

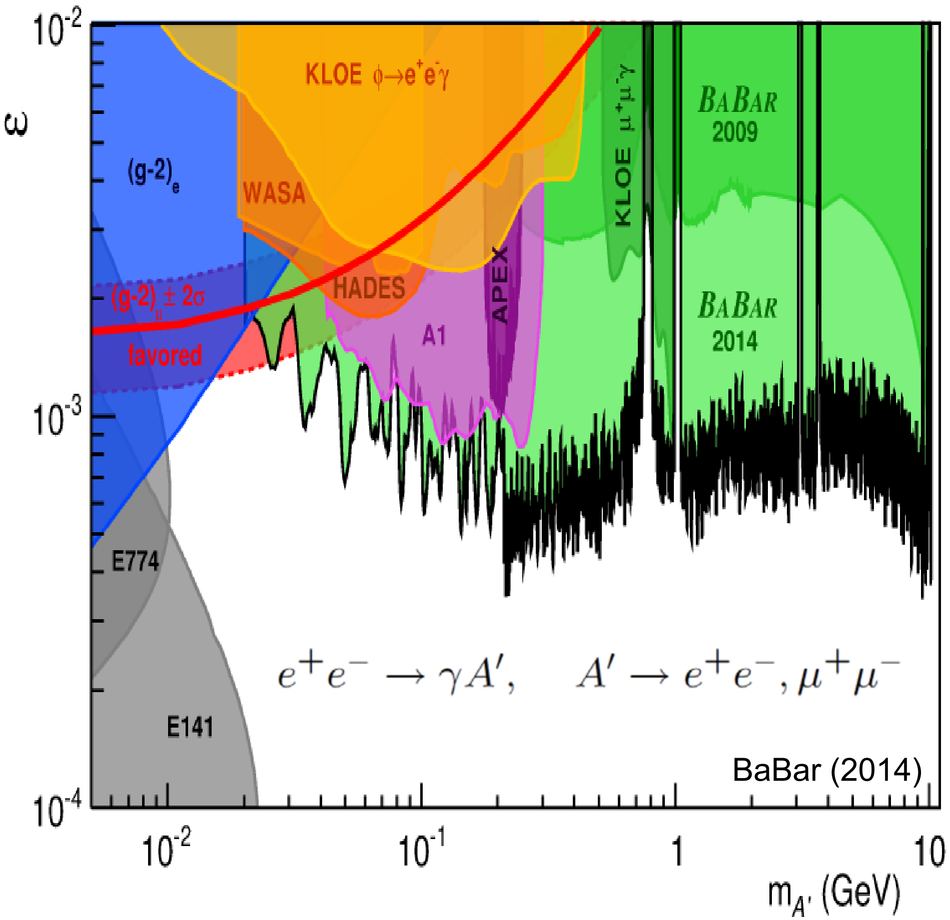
- Another possibility is $\epsilon F_{\mu\nu} F_h^{\mu\nu}$

  which leads to kinetic mixing between the SM photon and a hidden photon A', which must have a mass

- Diagonalizing, one finds that SM particles have hidden charge proportional to ε

- $\varepsilon \sim 10^{-3}$ from 1-loop effects, even for arbitrarily heavy particles in the loop (non-decoupling)





- A' cannot be DM, but may be a portal to the dark sector, motivates searches at the "intensity frontier"

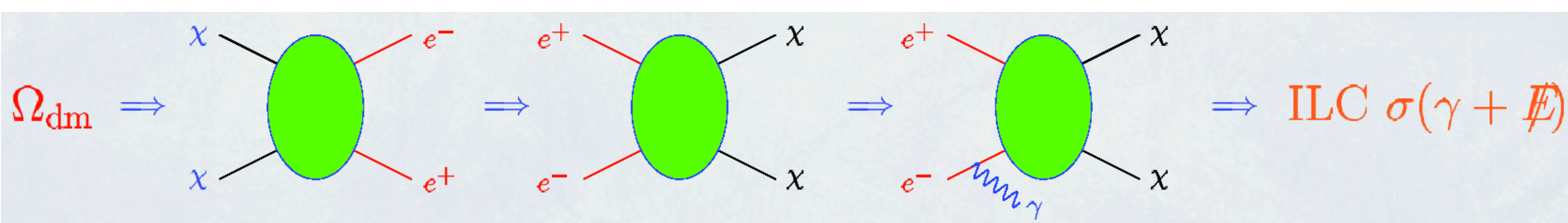
DM EFFECTIVE THEORY

see Tait, Giangiobbe, Brooke talks

- At mass dimension 5 and higher, have 4-point interactions suppressed by heavy mediators. DM effective theory allows one to compare relic density and direct, indirect, and collider probes.

- At colliders, DM pair production is invisible, so must radiate something
  - Mono-photons at the ILC
  - Mono-jets at the LHC

Birkedal, Matchev, Perelstein (2004); Feng, Su, Takayama (2005)



DM EFFECTIVE THEORY

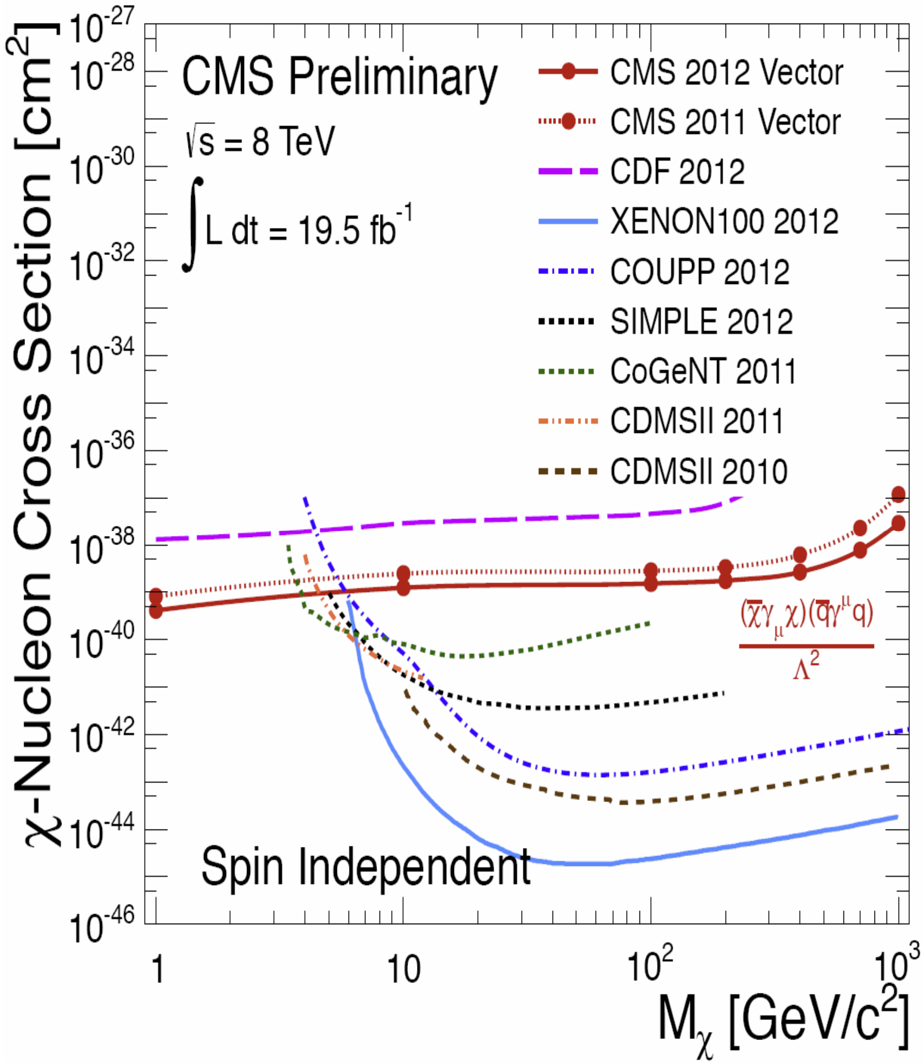
- This approach received a huge boost when hints of light DM motivated a hierarchy between the DM and mediator masses

Beltran, Hooper, Kolb,Krusberg, Tait (2006)
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

- There is now a mono-γ,j,b,t,W,Z,h industry, probing dark sectors at the LHC one operator at a time

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$

⋮



FULL MODELS

- Effective interactions, taken one at a time, allow comparisons between different probes, motivate new signals. But we don't expect just one operator. Full models allow one to address some bigger picture problems, find correlations between different interactions.

- For example:

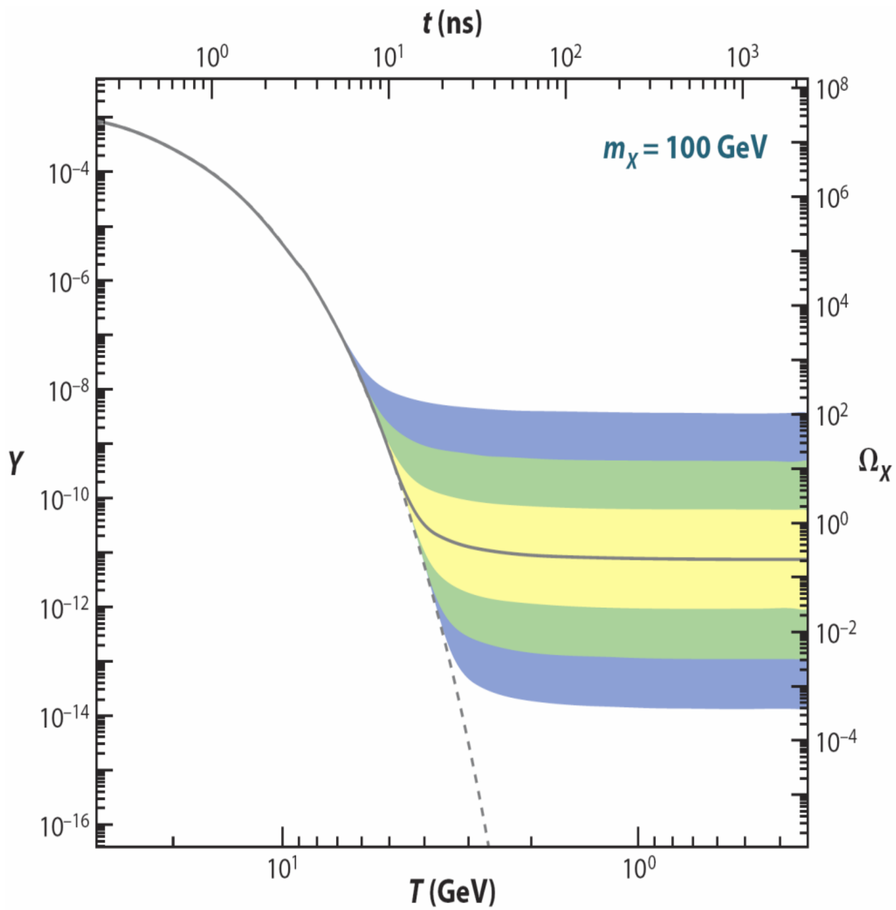
  WIMP miracle: Can we preserve this?

  Self-interacting DM: Can we accommodate this?

  3.5 keV line: Can we explain this?

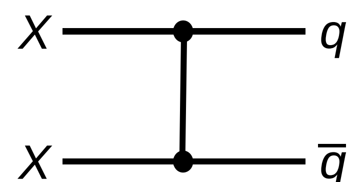
  Can we do all of these in one model?

WIMPLESS DARK MATTER



- Recall the WIMP miracle: the relation between Ω_X and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



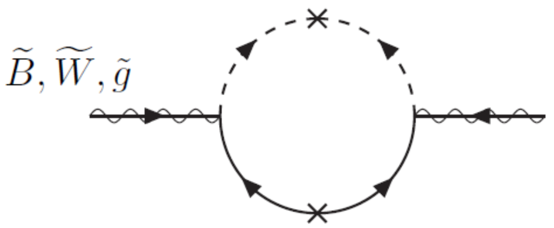
- m_X ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

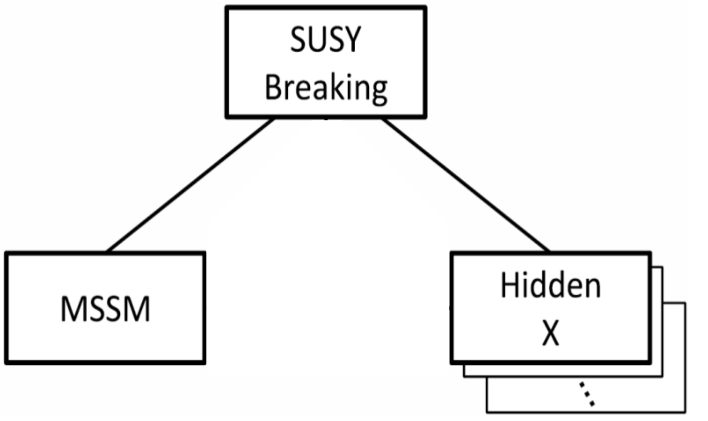
WIMPLESS DARK MATTER

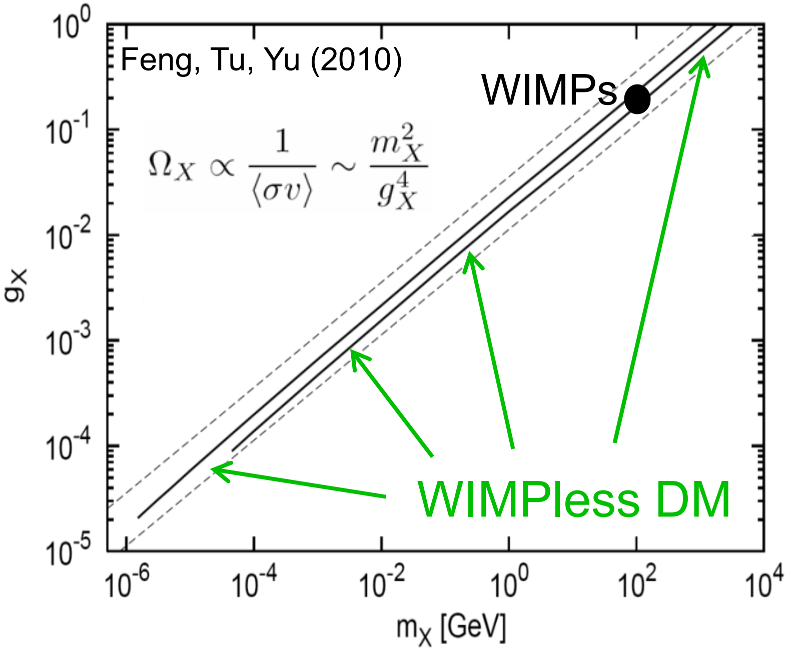
Feng, Kumar (2008)

- Can dark sectors have a WIMP miracle?
- Consider SUSY, which necessarily contains different sectors
- The flavor problem → SUSY models (AMSB, GMSB) with $m_X \sim g_X^2$



- If this applies also in hidden sectors, these will have DM with the correct relic density
- Restores
  - Particle physics motivations
  - Structure, predictivity
  - WIMP miracle without WIMPs





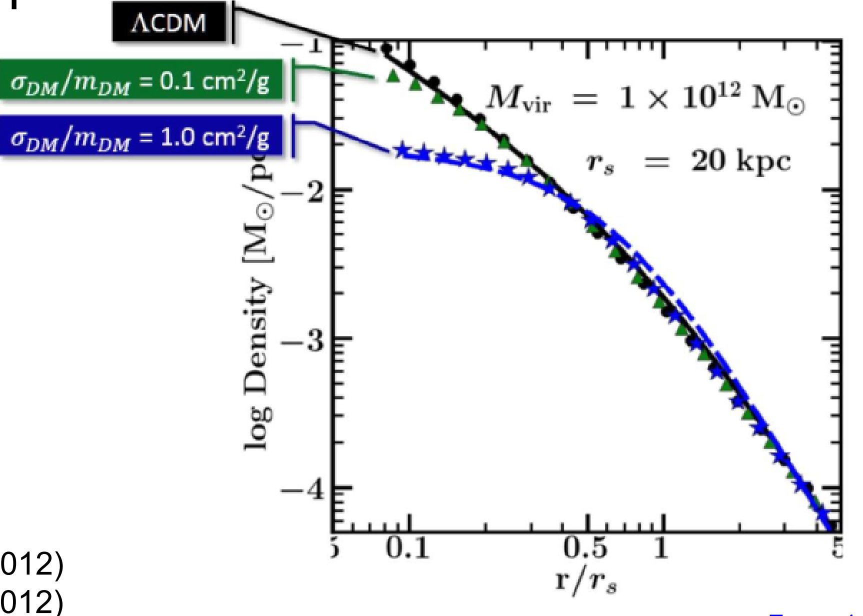
SELF-INTERACTING DARK MATTER

see Brooks, Yu talks

- If dark matter is completely hidden, can we learn anything about it?
- The Bullet Cluster and similar systems constrain self-interactions; DM passes through unperturbed →

  $\sigma_T/m < 1$ cm^2/g (or barn/GeV)

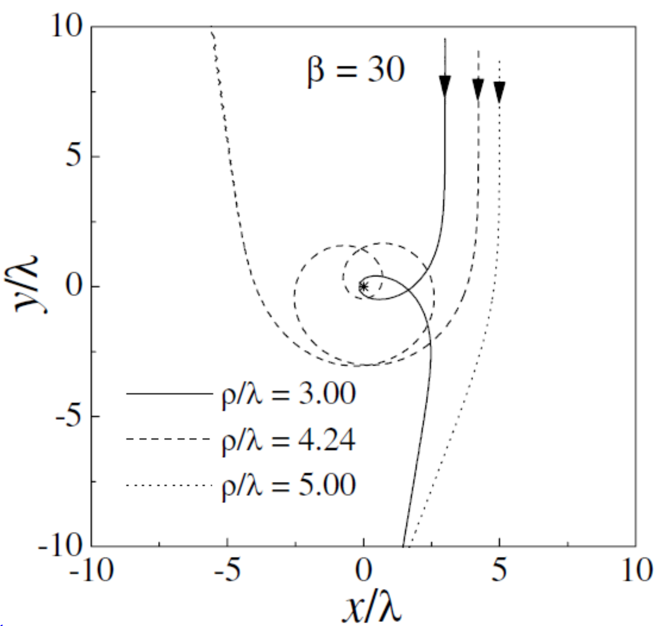
- But there are discrepancies between CDM simulations and observations on small-scales
  - Cusps vs. cores
  - Missing satellites problem
  - Too big to fail problem
  - Cluster collisions
- These indicate need for baryons in simulations or DM self-interactions near the bounds



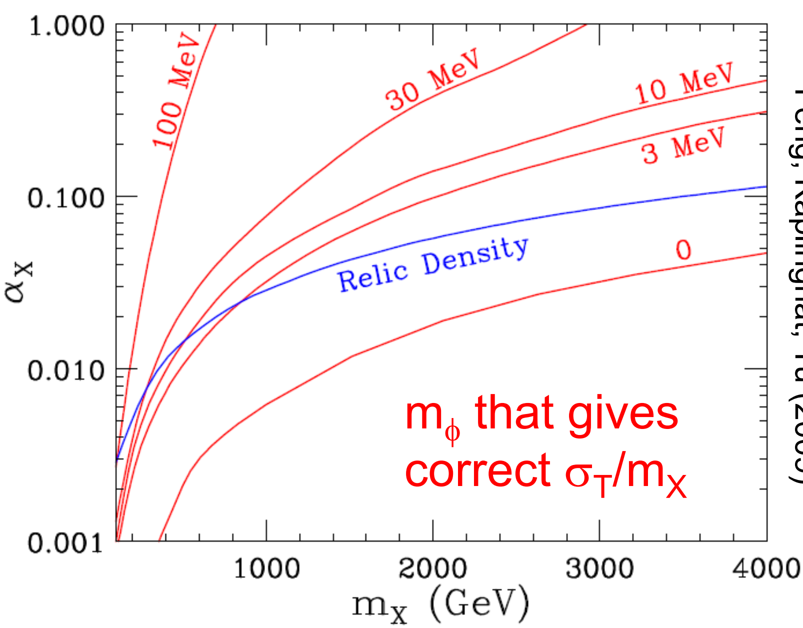
Rocha et al. (2012), Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)

SELF-INTERACTING DARK MATTER

- What sort of dark sector models can give the right self-interactions?
- Assume DM X interacts through massive photon ϕ with coupling α_X
- Yukawa potential produces weird trajectories: not conic sections!
- Luckily, plasma physicists studying trajectories of charged particles in screened Coulomb potentials have approximated their potentials as Yukawa potentials –exactly our case! Can use their numerical results.



Khrapak, Ivlev, Morfill, Zhdanov (2003)

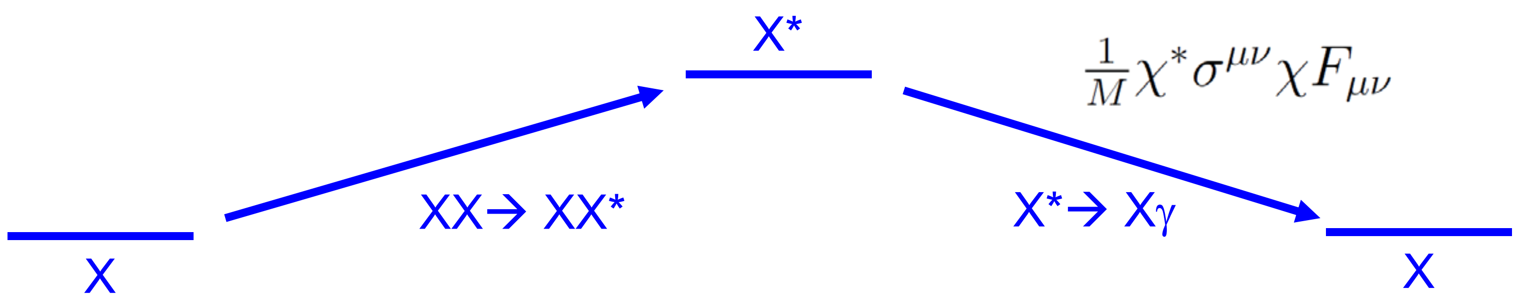


Feng, Kaplinghat, Yu (2009)

EXCITING DARK MATTER

Finkbeiner, Weiner (2007, 2014)

- Alternative dark sector explanation of the 3.5 keV line
- WIMP dark matter X with a nearly degenerate state X*
- X* created in collisions with $m_X v^2 > \Delta m$

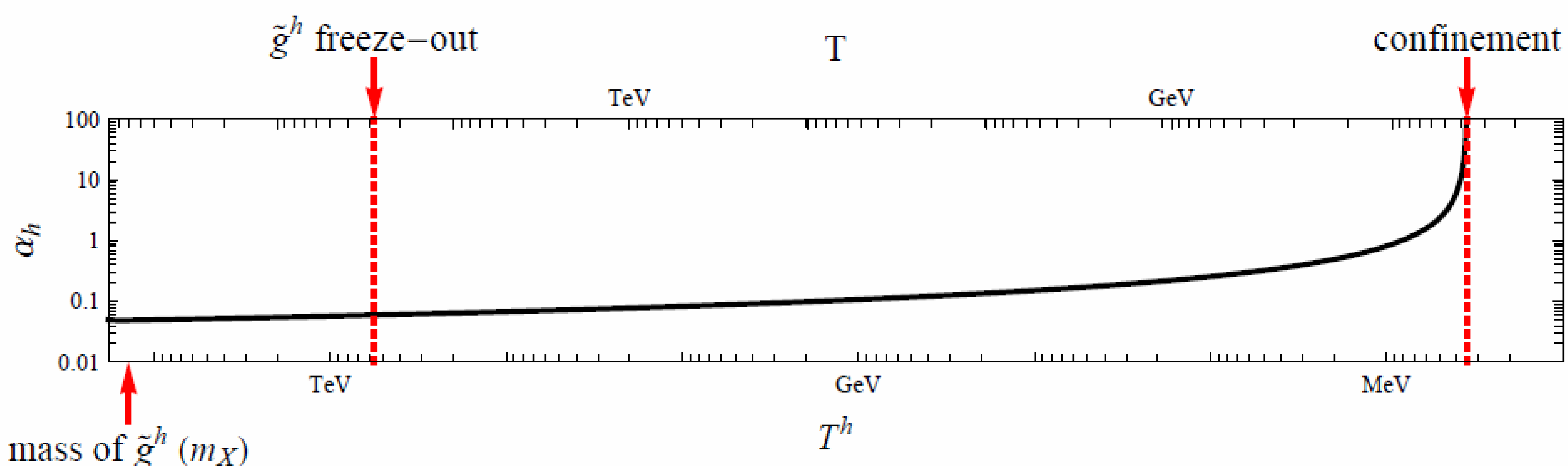


- Ingredients
  - m_X ~ TeV to get correct relic density
  - A dark photon with small mass ~ 100 MeV from Higgs mechanism to get correct flux
  - A highly-degenerate state X* with even smaller mass splitting Δm ~ 3.5 keV to get correct E_γ
  - Dipole operator to give visible photon

A SIMPle THEORY OF DARK MATTER

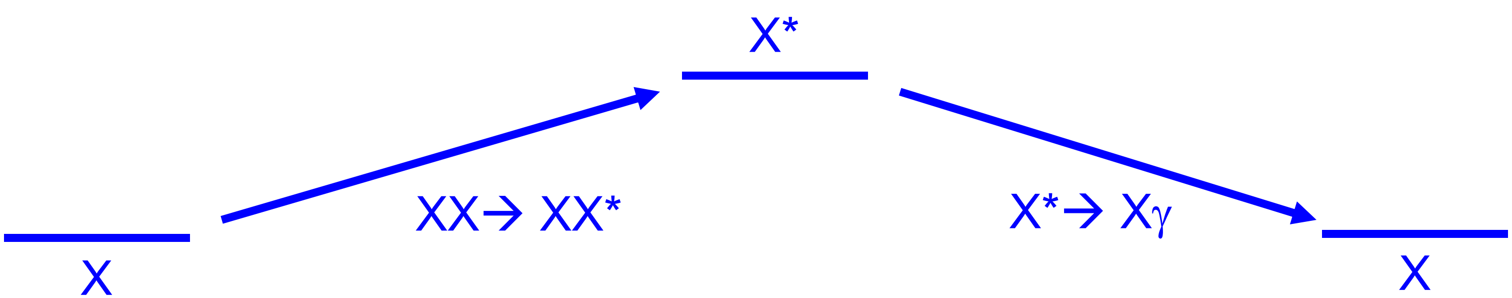
Boddy, Feng, Kaplinghat, Shadmi, Tait (2014, in prep)

- We can put all of these together with a remarkably simple theory of dark matter: pure SUSY SU(N) with hidden gluons g and gluinos $\tilde{g}$
- At early times, interaction is weak, $\tilde{g}$ with m_X ~ TeV freezes out with correct Ω, in accord with the WIMPless miracle
- Then the Universe cools, the coupling runs, and the theory confines at Λ ~ 100 MeV, forming glueballs (gg) and glueballinos ($g\tilde{g}$)
- The glueballinos self-interact through glueball exchange with σ_T/m ~ 1 cm²/g



A SIMPle THEORY OF DARK MATTER

- The glueballino spectrum has hyperfine structure, with splitting $\Delta m \sim \alpha^4 \Lambda^2/m_X \sim \Lambda^2/m_X \sim$ keV



- A realization of XDM, where
  - m_X ~ TeV to get correct relic density ← set by WIMPless miracle
  - A dark photon with small mass ~ 100 MeV from Higgs mechanism to get correct flux ← confinement replaces Higgs mechanism, mediator mass scale Λ naturally small, set by RGEs, m_X, α_X, N
  - A highly-degenerate state X* with even smaller mass splitting Δm ~ 3.5 keV to get correct E_γ ← highly-degenerate state naturally even smaller, provided by hyperfine splitting, mass splitting set by Λ^2/m_X
  - Dipole operator to give visible photon

A SIMPle THEORY OF DARK MATTER

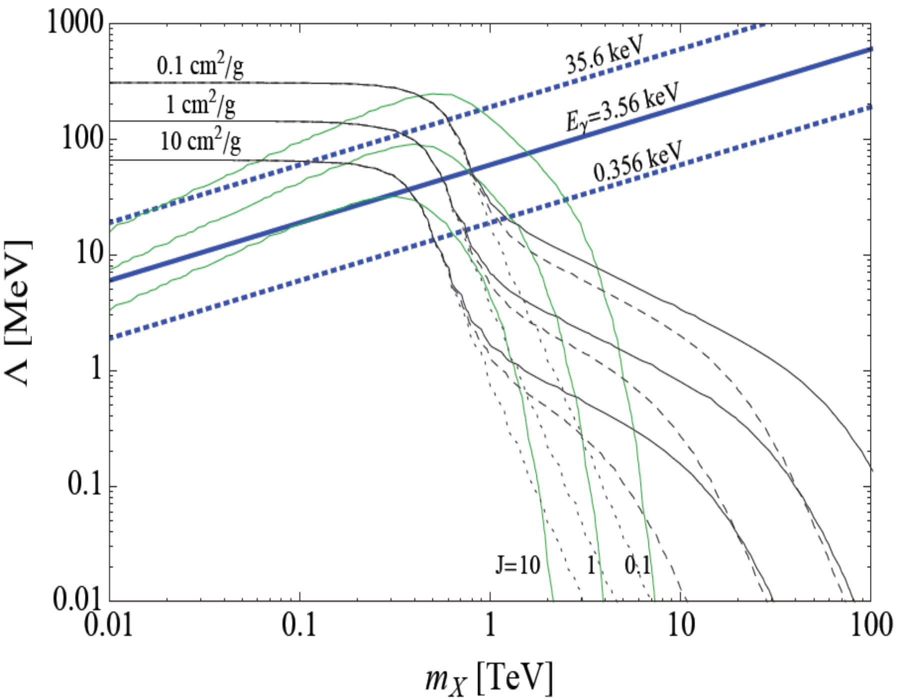
- Bottom line: hidden sector is simplest possible SUSY model: pure SU(N) with hidden gluons g and gluinos $\tilde{g}$
- Preserves WIMPless miracle, explains self-interactions, 3.5 keV line energy and flux in terms of a small number of parameters
- 3.5 keV line is the "21 cm line" for DM

Cline, Farzan, Liu, Moore, Xue (2014)

- Other important features
  - Typically requires large N, small T_h/T
  - No re-annihilation after hadronization
  - Not much cannibalization: glueballs eat their own rest mass to stay warm

$$XXX \rightarrow XX$$

Carlson, Machacek, Hall (1992)



Boddy, Feng, Kaplinghat, Shadmi, Tait (in prep)

CONCLUSIONS

- Dark sectors are a logical possibility, given what we know about dark matter so far
- Lots of recent activity, resulting in novel ideas to preserve virtues, avoid problems
- Effective operators have generated ideas for signals, allow for comparison across a wide range of dark matter searches
- SIMPle Theory of Dark Matter, pure SUSY SU(N), preserves WIMP miracle, gives self-interactions, and predicts correct energy and flux for 3.5 keV line