The SIMP Miracle

Jay Wacker
SLAC
December

With:
Tomer Volansky
Eric Kuflik
Yonit Hochberg

The Universe is Dark

The biggest unexplained mystery of the Universe is

Dark Matter

It is physics strictly beyond the Standard Model

It requires at least one new degree of freedom to exist

At least one incredibly long lived particle
that exists in our galaxy today

DM Lifetime > 10^7 Age of Universe

The Long List of Dark Matter Properties

1.) Dark Matter has 5 times the mass density of Baryons

$$\frac{\rho_{\rm dm}}{\rho_{\rm b}} \equiv \xi \simeq 5$$

2.) It is a massive particle

of unknown mass

3.) It has suppressed interactions with QED & QCD

could have milli-charge

or interact through higher dim operators

4.) It doesn't strongly self-interact

Limits on $\sigma/m_{dm} < 1$ barn/GeV

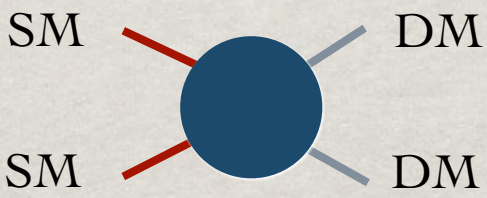
neutron scattering is 0.1 barn/GeV

Outline

- Lee-Weinberg & WIMPs
- The SIMP Miracle
- The Search For SIMPs
- Outlook

Early Universe Cosmology and Dark Matter

Lee & Weinberg in 1977 elegantly
linked Dark Matter genesis
and Early Universe Cosmology



If a new stable particle has 2-to-2 interactions with SM,
and Universe has hotter than its mass,
there will be a relic density left over

Dark Matter Freeze Out

$$\dot{n} + 3Hn = (\cancel{n_{\rm eq}^2} - \cancel{n^2})\langle\sigma_{\rm ann} v\rangle$$

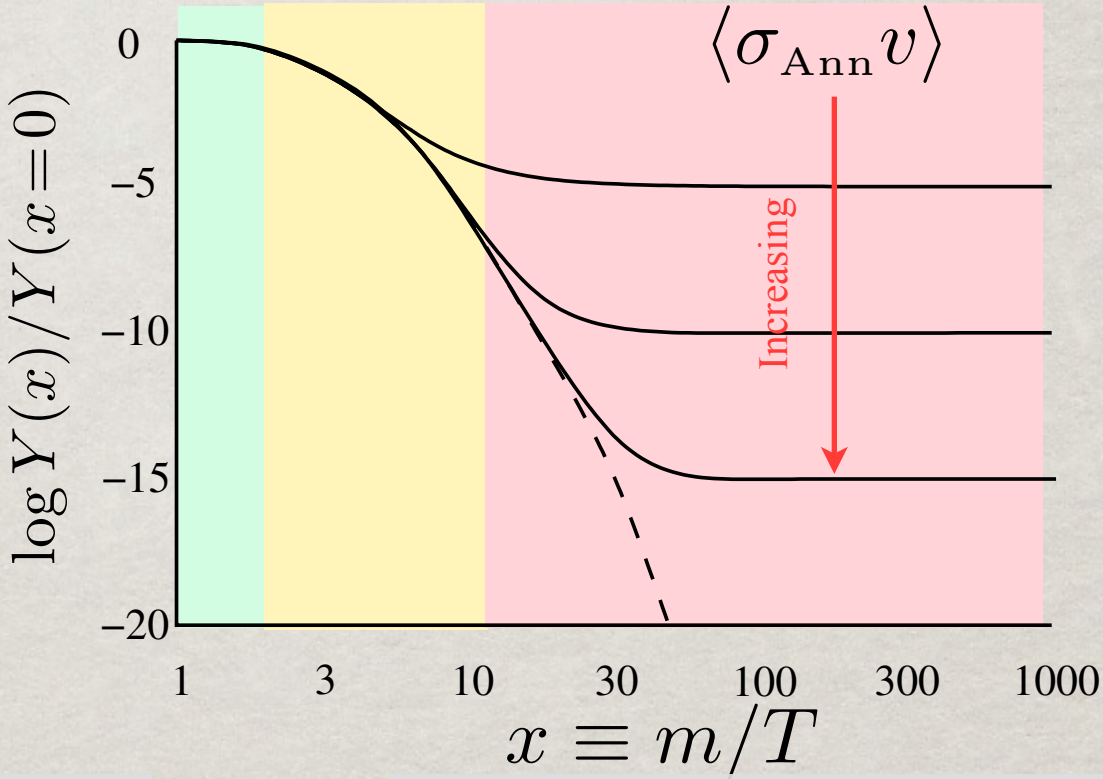
n ~ number of DM per volume

$$n_{\rm eq} \sim e^{-m/T}\ s$$

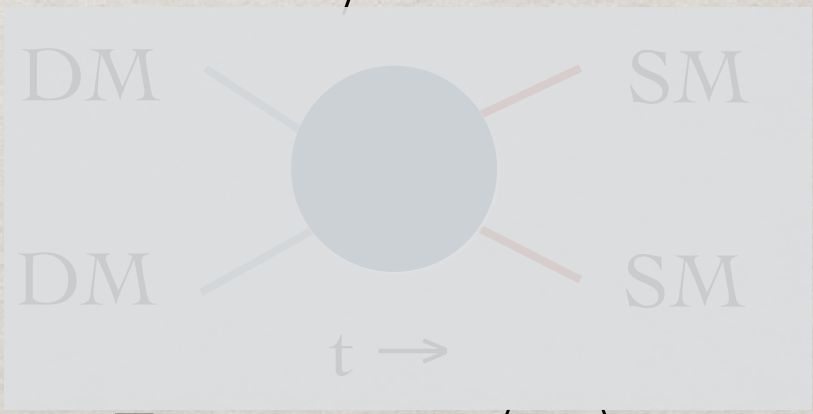
s ~ number of photons per volume

$$Y_{\rm dm} = n_{\rm dm}/s$$

number of DM per photon



$$\Gamma_{\rm pro} = n_{\rm sm}\langle\sigma v\rangle$$



$$\Gamma_{\rm ann} = n_{\rm dm}\langle\sigma v\rangle$$

WIMPs

If the interactions are through the weak interactions,

m_{dm} should be between 100 GeV and 3 TeV

Coincidence if the interactions are weak,
dark matter should be at the weak scale

WIMPs have been the dominant model for 35+years

Back of the Envelope Solution

$$\Gamma_{\rm ann} \simeq H\Big|_{\rm f.o.}$$

$$\Gamma_{\rm ann} \simeq n_{\rm dm}\langle\sigma_{\rm ann}v\rangle$$

$$H = \frac{T^2}{M_{\rm Pl}}$$

$$m_{\rm dm}n_{\rm dm} = \xi m_p n_{\rm b}$$

$$\langle\sigma_{\rm ann}v\rangle \simeq \frac{\alpha^2}{m_{\rm dm}^2}$$

$$n_{\rm b} = \eta_{\rm b} s$$

$$s \simeq T^3$$

$$T\Big|_{\rm f.o.} = \frac{m_{\rm dm}}{x_F}$$

$$\frac{\xi m_p \eta_{\rm b}\alpha^2}{x_F^3} \simeq \frac{m_{\rm dm}^2}{x_F^2 M_{\rm Pl}}$$

$$m_{\rm dm} \simeq \alpha\left(\xi\eta_{\rm b} m_p M_{\rm Pl}/x_F\right)^{\frac{1}{2}}$$

Examination of Lee-Weinberg

$$m_{\rm dm} \simeq \alpha \left(\xi \eta_{\rm b} m_p M_{\rm Pl} / x_F \right)^{\frac{1}{2}}$$

$T_{\rm eq} \simeq 1$ eV Matter-Radiation Equality Temperature

$$m_{\rm dm} \simeq \alpha \left(T_{\rm eq} M_{\rm Pl} / x_F \right)^{\frac{1}{2}}$$

Particle Physics

α unknown strength of 2-to-2 annihilation of DM to SM

Details of solving Boltzmann Equation

$20 \lesssim x_F \lesssim 30$

$$m_{\rm dm} \simeq \alpha \times 30 \text{ TeV}$$

TeV Scale Emerged

No Particle Physics went into

$$m_{\rm dm} \simeq \alpha \times 30 \text{ TeV}$$

$\alpha_{\rm weak} = 1/30$

WIMPs at 1 TeV emerged without input of scale

Truly a coincidence of scales

If interactions are suppressed, then DM could be lighter

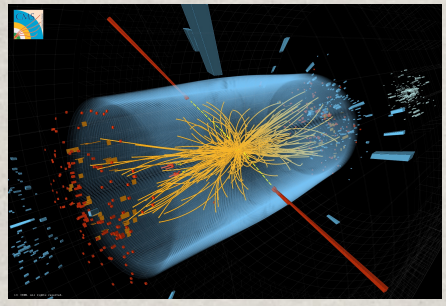
e.g. if DM is admixture of singlet & EW-charged state

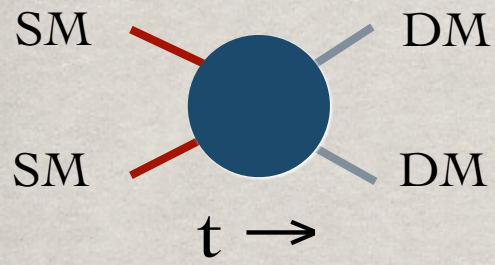
$$\alpha_{\rm eff} = \alpha_{\rm weak} \sin^2 \theta_{\rm mix}$$

The Search for WIMPS

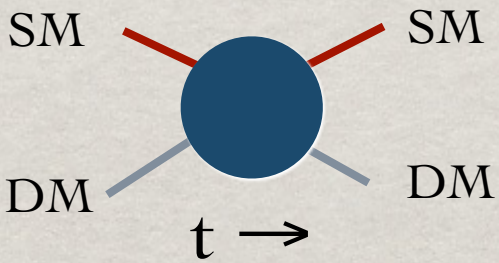
3 Pillars in the Search for DM

Direct Production

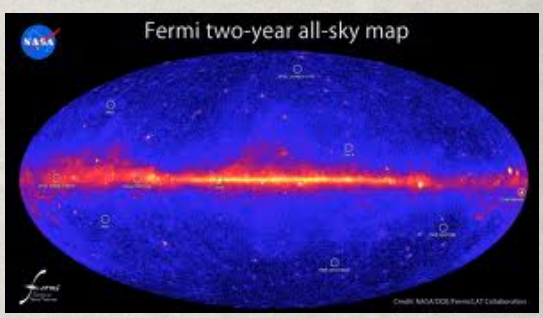


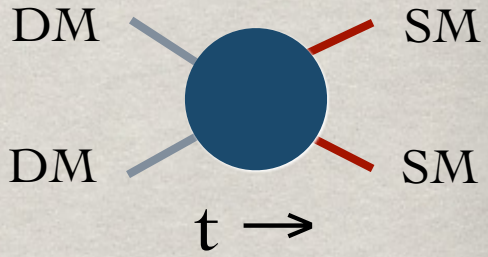


Direct Detection



Indirect Detection

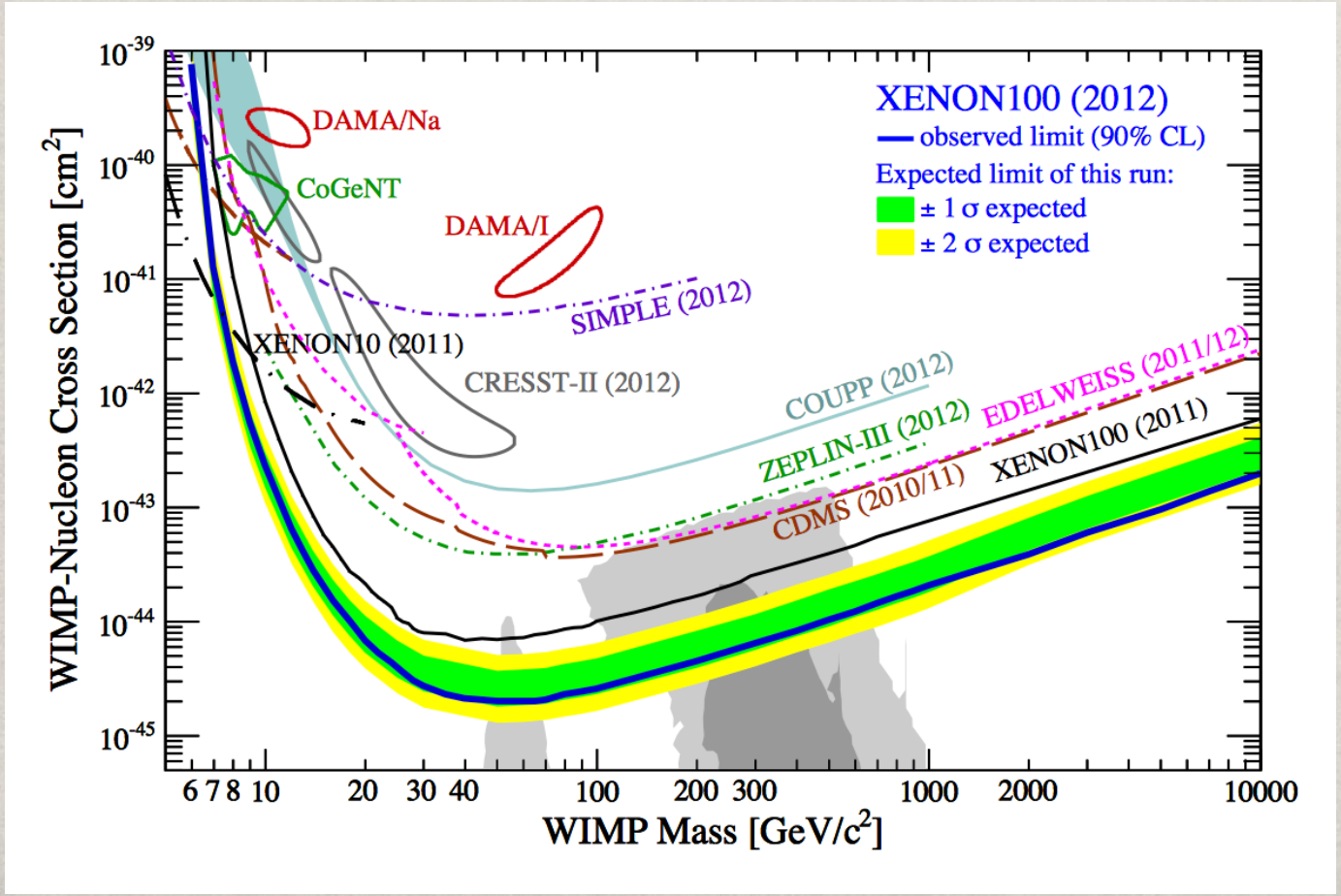


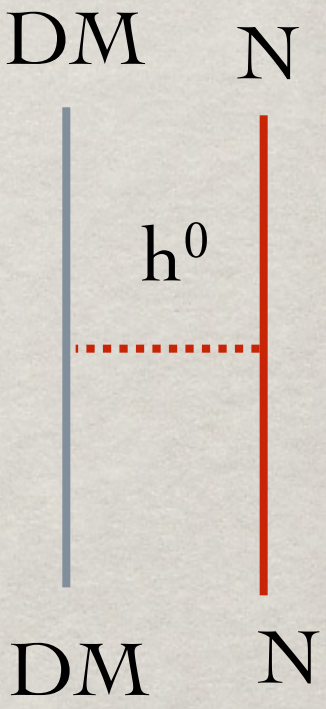


WIMPs Being Challenged

Spin independent Z^0-mediated interactions long ruled out

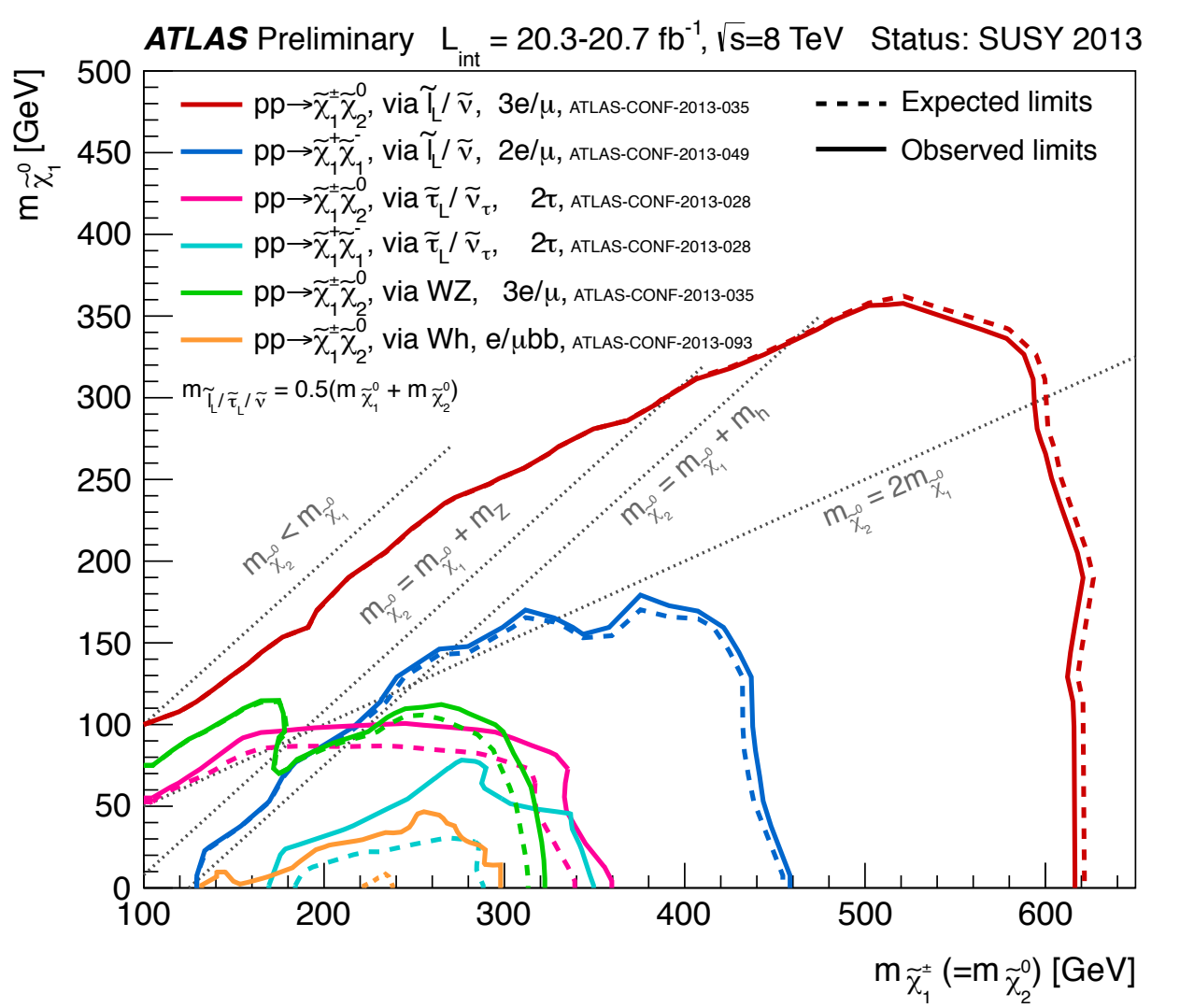
Xe100 greatly constrained h^0-mediated interactions

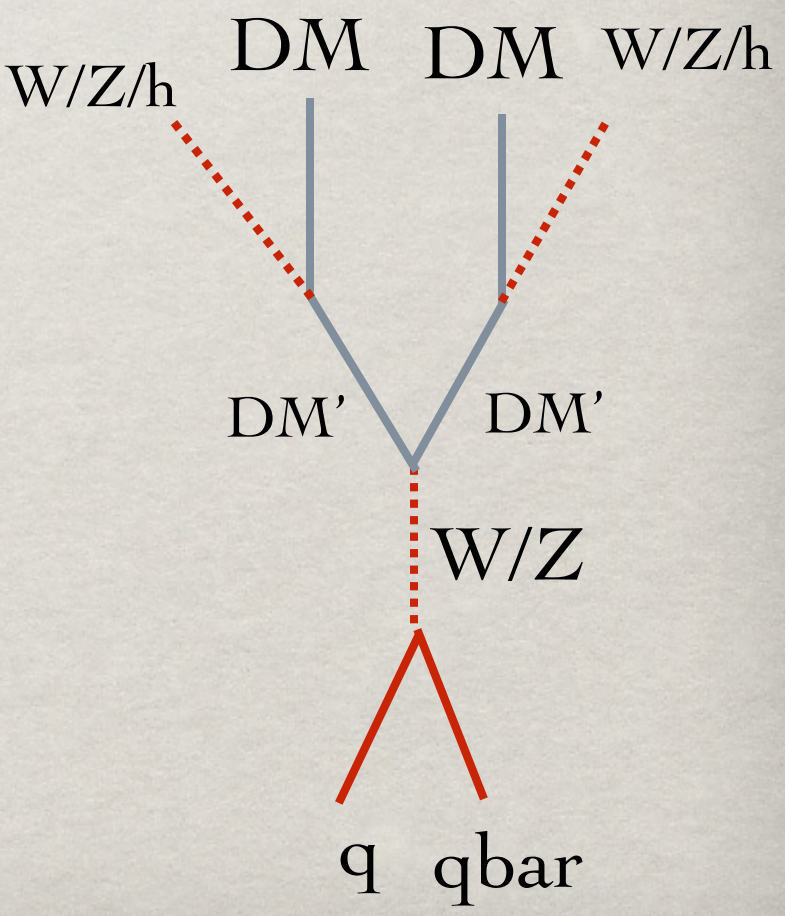




WIMPs Being Challenged

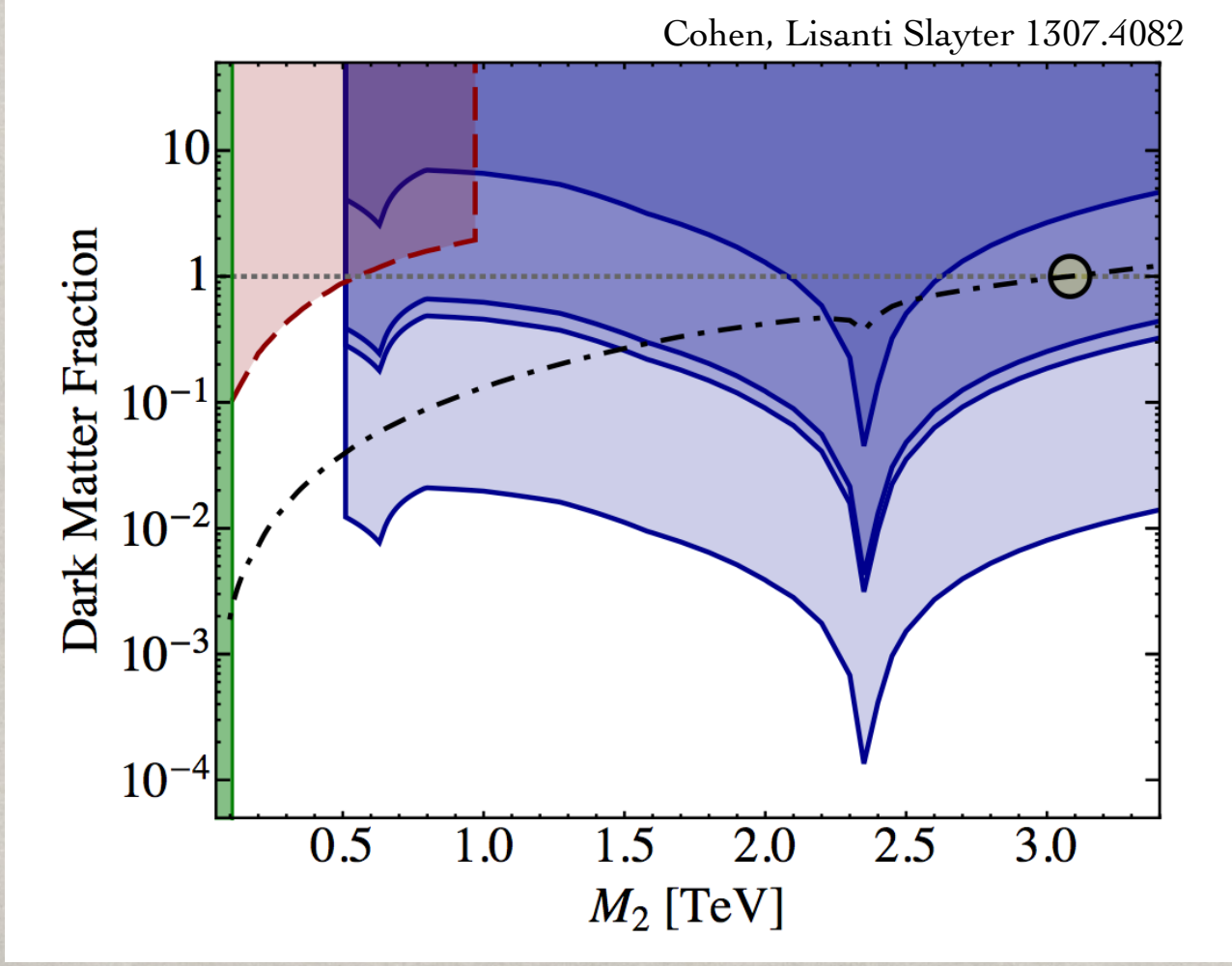
LHC extending searches for EW DM

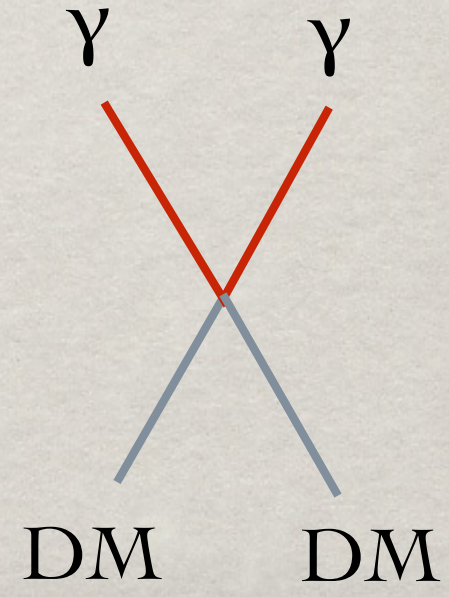




WIMPs Being Challenged

HESS ruled out thermal Wino





WIMPs in 2013

Dominant paradigm in DM is being challenged

Lots of non-thermal/quasi-thermal mechanisms

Asymmetric DM

Freeze-In DM

Axion DM

Gravitino DM

Is there another simple thermal mechanism that gives qualitatively different signatures?

Outline

- Lee-Weinberg & WIMPs
- The SIMP Miracle
- The Search For SIMPs
- Outlook

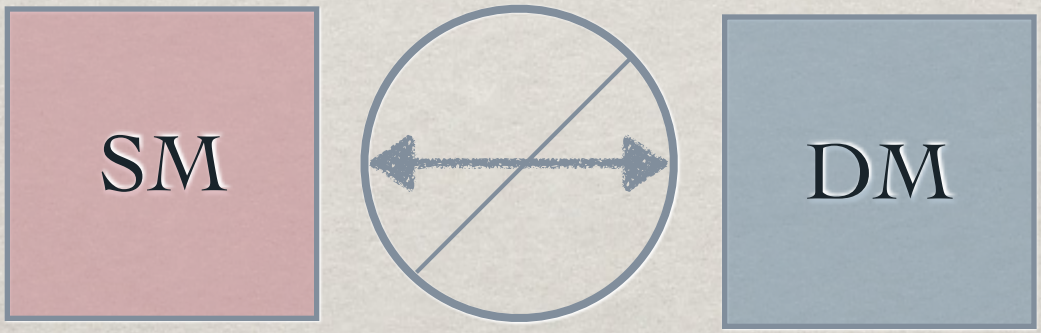
An Alternate Paradigm

Lee-Weinberg assumed unsuppressed interactions with the SM

DM is really part of enlarged SM sector

SM & DM charged under same interactions

What if DM was completely sequestered from SM?

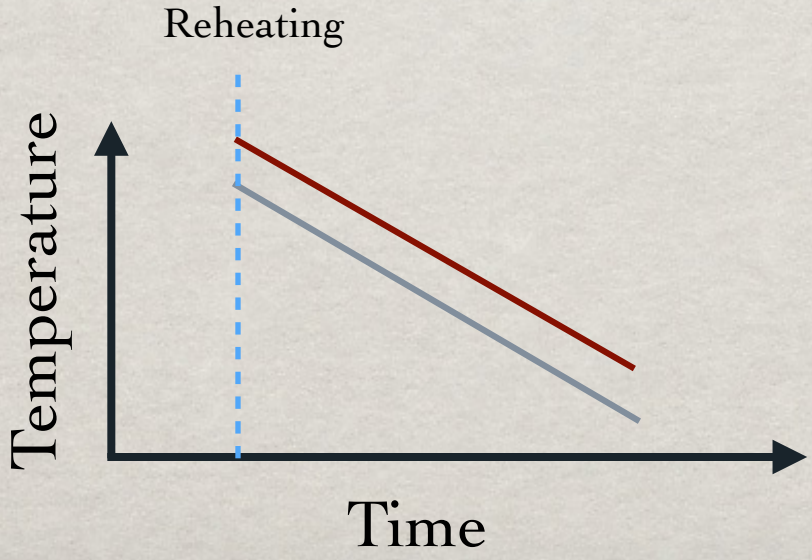


A Hot Hidden Sector

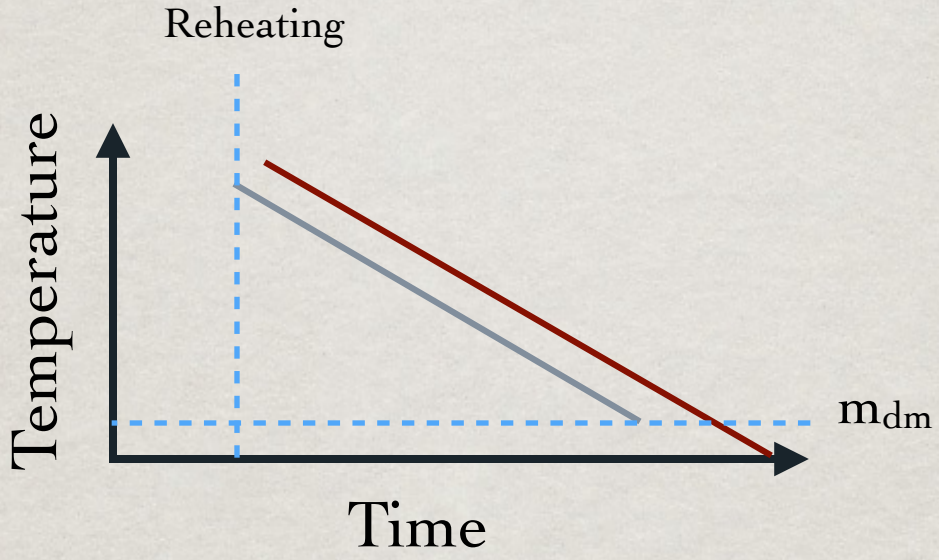
Dark Matter is the lightest state in a hot Hidden Sector

After Inflation, both SM & Dark Sector reheated to comparable temperatures

During Radiation Domination, both sectors cool together

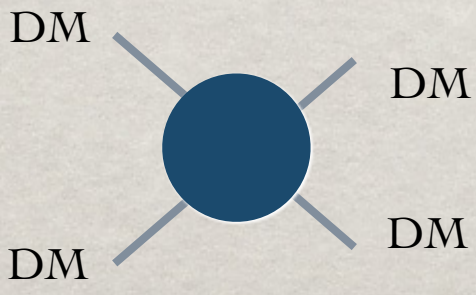


A Hot Hidden Sector



When $T_{dark} \simeq m_{dm}$, dark matter needs to annihilate

but



doesn't change the number density

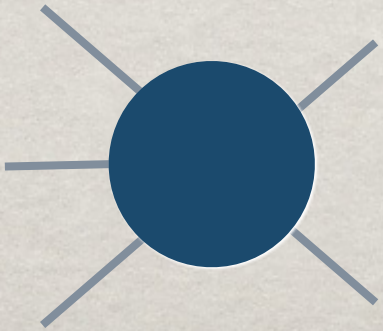
Life without 2-2 Annihilation

With no 2-to-2 annihilation possible,
is the story is over? $\frac{n_{\rm dm}}{s} \sim 1$

No…

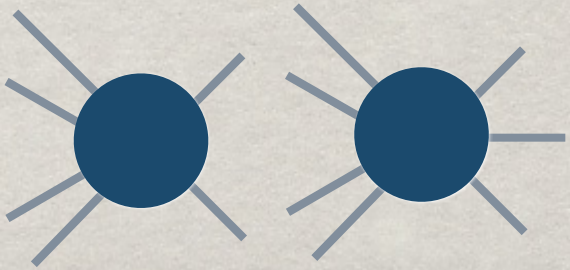
2-to-2 is the leading interaction that can change number density
Always absent in a closed system

The first process that can change number density in a closed system is a 3-to-2 interaction



t →

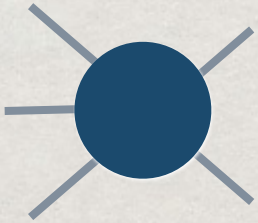
4-to-2 4-to-3 etc.



(only 3-to-2 will be viable)

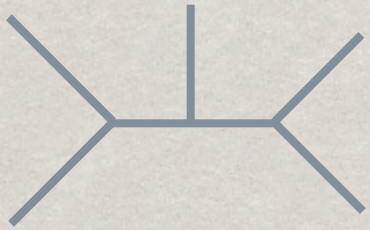
5-point Interactions

5-point interactions are a little unfamiliar

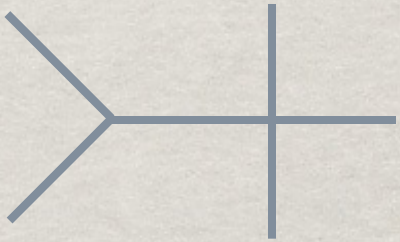


Consider a $\mathbb{Z}_3$ -symmetric model $\mathcal{L} \sim m^2|\phi|^2 + \kappa\phi^3 + \lambda|\phi|^4$

DM is stable (proof-in-principle) $\phi \to e^{\frac{2\pi i}{3}}\phi$



$$\mathcal{M} \sim \frac{\kappa^3}{m^4}$$



$$\mathcal{M} \sim \frac{\kappa\lambda}{m^2}$$

For single-scale models $\kappa \sim gm \quad \lambda \sim g^2$ $\mathcal{M} \sim \frac{g^3}{m}$

Redoing Lee-Weinberg

$$\Gamma_{\rm ann} \simeq H\Big|_{\rm f.o.}$$

$$\Gamma_{\rm ann} \simeq n_{\rm dm}^2 \langle \sigma_{3\to 2} v^2 \rangle \qquad H = \frac{T^2}{M_{\rm Pl}}$$

$$\langle \sigma_{3\to 2} v^2 \rangle \simeq \frac{\alpha^3}{m_{\rm dm}^5} \qquad \alpha \sim \frac{g^2}{4\pi}$$

$$m_{\rm dm} \simeq \alpha \left({T_{\rm eq}}^2 M_{\rm Pl} / x_F^4 \right)^{\frac{1}{3}}$$

The GeV Scale emerges for Strongly Interacting DM

$$m_{\rm dm} \simeq \alpha \times 100 \text{ MeV}$$

The SIMP Miracle

The Lee-Weinberg mechanism leads to the WIMP Miracle

This leads to the SIMP Miracle

Self Interacting Massive Particle

Strongly Interacting Massive Particle

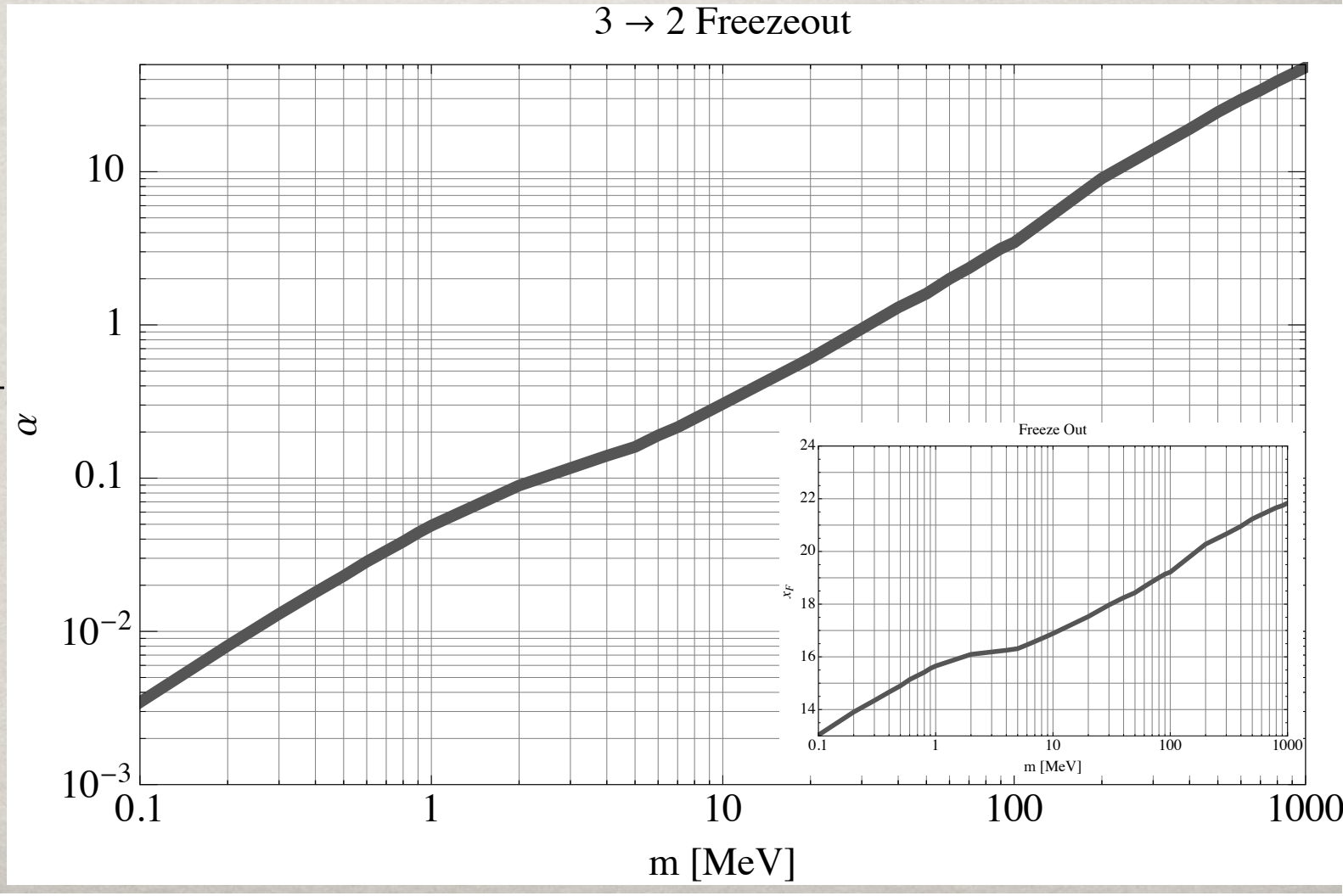
No particle physics went into the derivation of this scale

"The second thing you should think of in
Big Bang Cosmology leads to Dark Matter"

Boltzmann Equation (Part 1)

$$\dot{n} + 3Hn = (n^2 n_{\rm eq} - n^3)\langle\sigma_{3\to 2} v\rangle$$

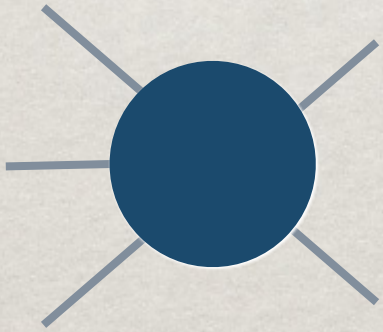
$$\langle\sigma_{3\to 2} v\rangle = \frac{\alpha^3}{m_{\rm dm}^5}$$



Caveat

Everything about the SIMP Miracle is a not quite right...

Tacitly assumed that the DM temperature
was following SM temperature

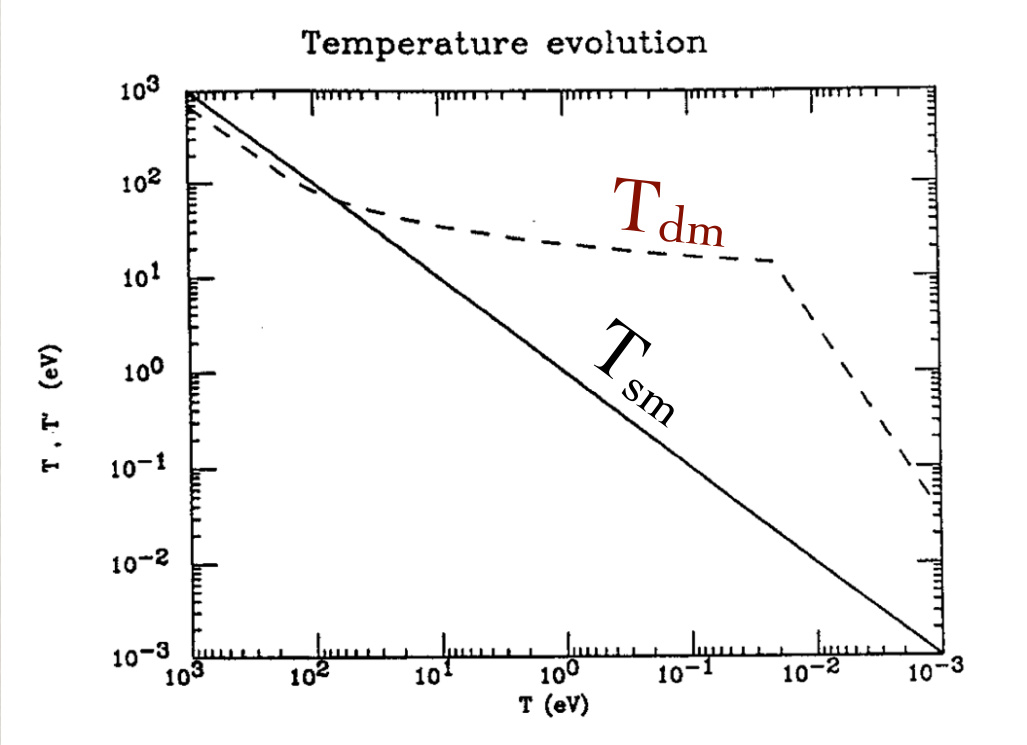
Cold  Hot

Temperature is approximately constant while freezing out

$$n_{\rm dm}(t) \propto \exp(-m_{\rm dm}/T_{\rm dm}) \neq \exp(-m_{\rm dm}/T_{\rm sm})$$

Carlson-Hall-Machacek

Selfinteracting dark matter
Eric D. Carlson (Harvard U.), Marie E. Machacek (Northeastern U.), Lawrence J. Hall (UC, Berkeley & LBL, Berkeley). Mar 1992. 31 pp.
HUTP-91-A066, LBL-32016, UCB-92-06, NUB-3042-92-TH

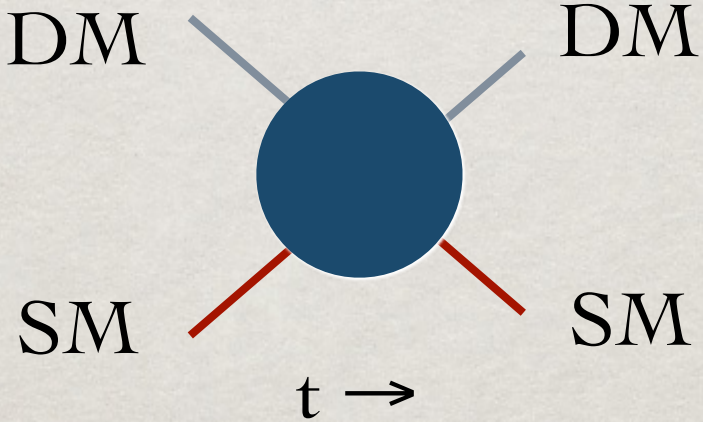


Predicts Light Hot Dark Matter

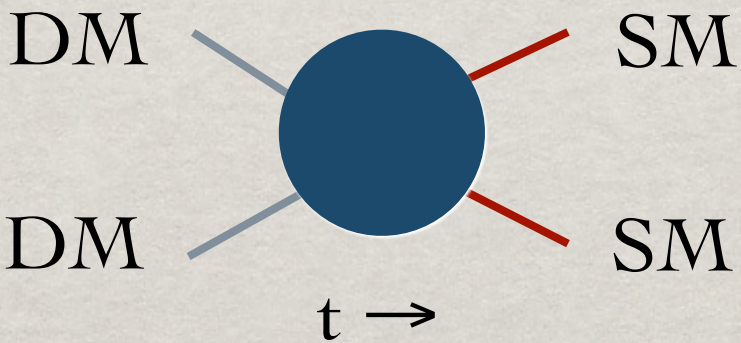
Disaster! Thoroughly ruled out

Keeping DM & SM in Thermal Equilibrium

Want to cool dark sector

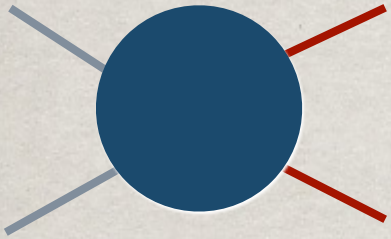


However, don't want Lee-Weinberg Mechanism



Is this possible?

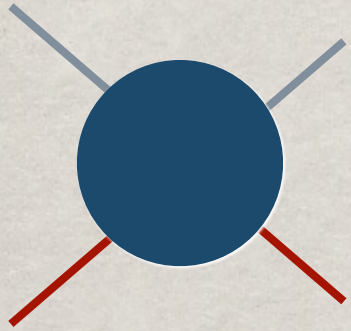
Cooling but not annihilating



t →

$$\Gamma_{\rm ann} = n_{\rm dm} \langle \sigma_{\rm ann} v \rangle$$

$$\frac{n_{\rm dm}}{n_{\rm sm}} \sim e^{-m_{\rm dm}/T}$$



t →

$$\Gamma_{\rm cool} = n_{\rm sm} \langle \sigma_{\rm ann} v \rangle$$

Need to scatter off light SM species:

e, γ, ν

Model of SIMP Interactions

Simple model for the interaction

$$\sigma_{\text{SM int}} = \frac{\epsilon^2}{m_{\text{dm}}^2}$$

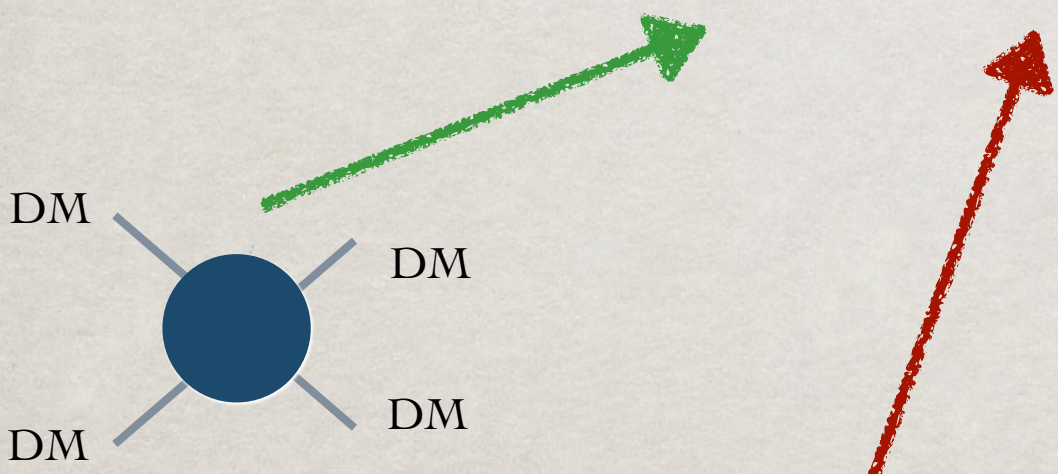
Assume DM dominantly interacts with electrons

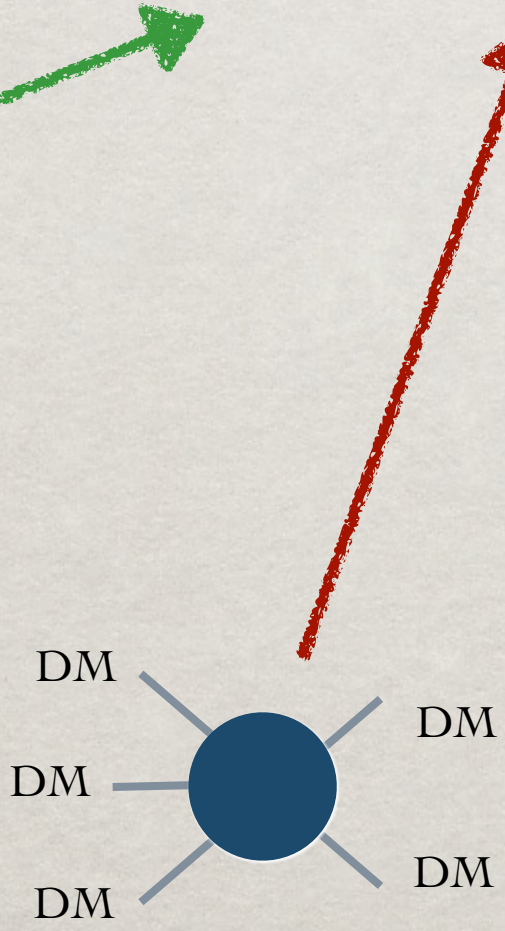
$$\mathcal{L}_{\text{int}} \simeq \frac{\epsilon}{m_{\text{dm}}} |\phi|^2 \, \bar{e}e$$

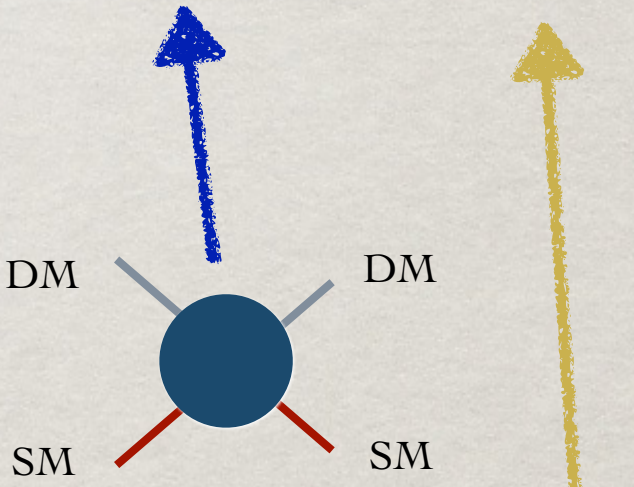
(note: does not have to lead to DM decay)

Boltzmann Equation (Part 2)

$$E\partial_t f - Hp^2\partial_E f = \gamma_{\text{self kin}} + \gamma_{3\to 2} + \gamma_{\text{SM kin}} + \gamma_{\text{ann SM}}$$

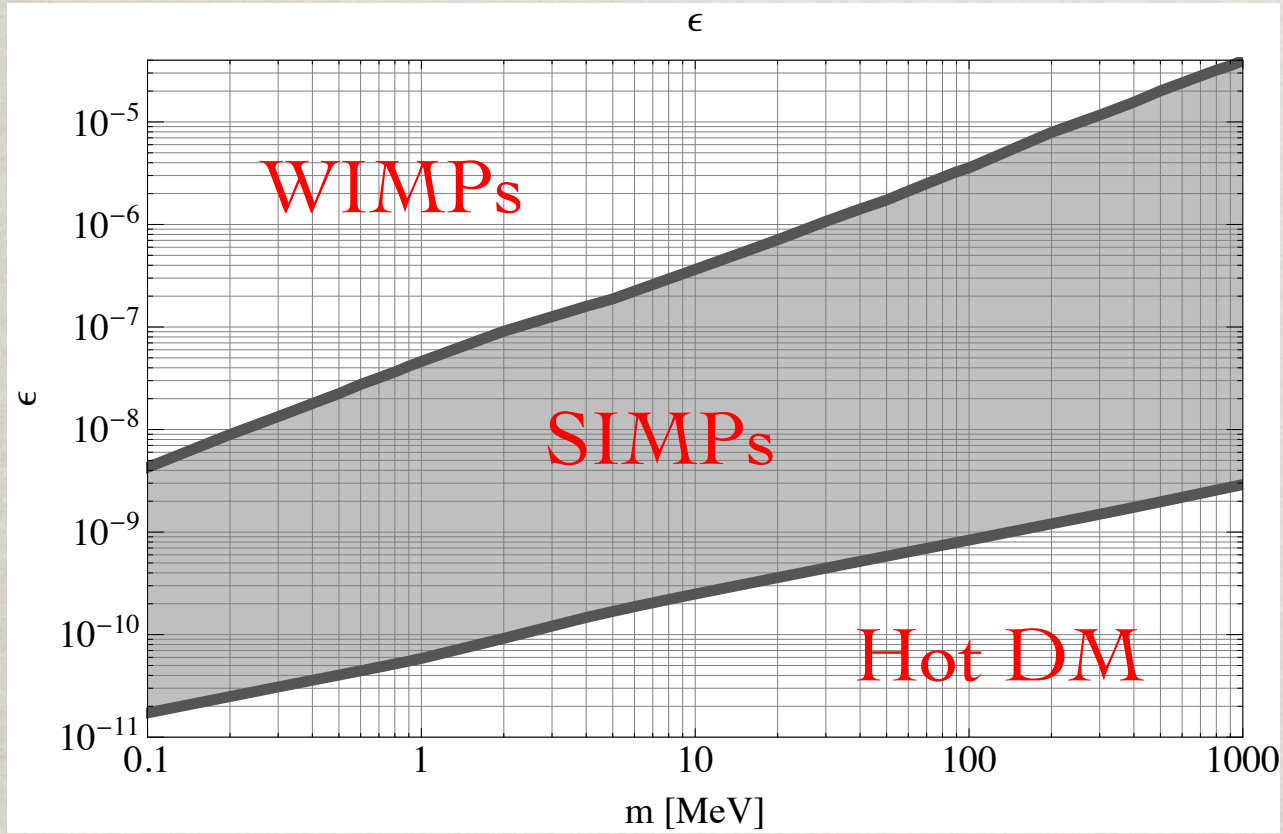






Needed Size of ε

Points to new physics in the 10 GeV to 10 TeV



$$\mathcal{L}_{\rm int} \simeq \frac{\epsilon}{m_{\rm dm}} |\phi|^2 \, \bar{e}e$$

$$\Lambda_{\rm NP} \sim \sqrt{m_{\rm dm} m_e / \epsilon}$$

Could be Higgs portal interaction

$$\mathcal{L} \sim \mu \, s \, |h|^2 + y_e \, h \, \bar{e}e + \kappa \, s \, |\phi|^2$$

The SIMP Miracle Requires SM Interactions

Dark Matter cannot be completely sequestered from the SM

Some residual interactions, smaller than WIMPs,
but not arbitrarily small

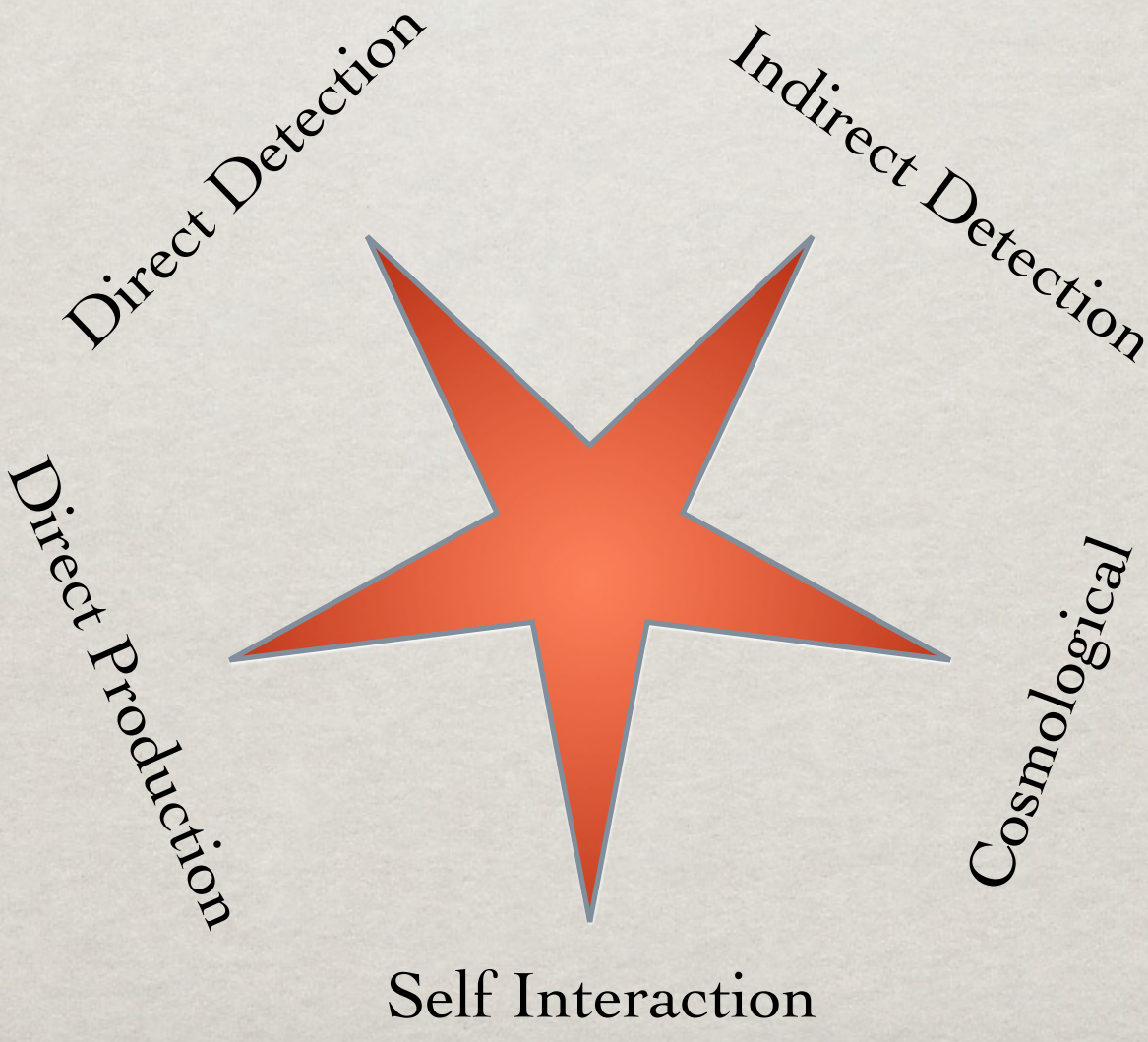
SIMPs are visible through cadre of standard experiments,
but a lower interaction rates than standard WIMPs

Outline

- Lee-Weinberg & WIMPs
- The SIMP Miracle
- The Search For SIMPs
- Outlook

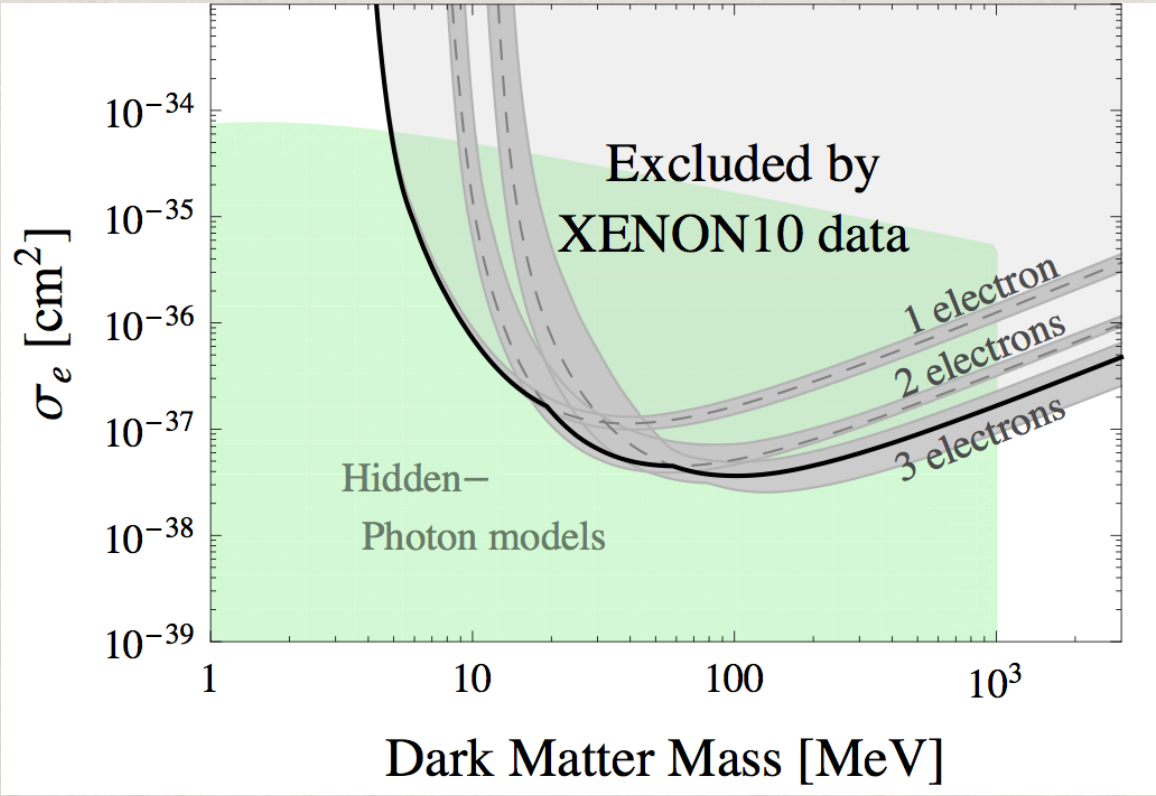
Limits on SIMP Interactions

5 Classes of Limits



Direct Detection

Nucleon scattering kinematically suppressed for $m_{dm} < 5$ GeV, better to scatter off electrons

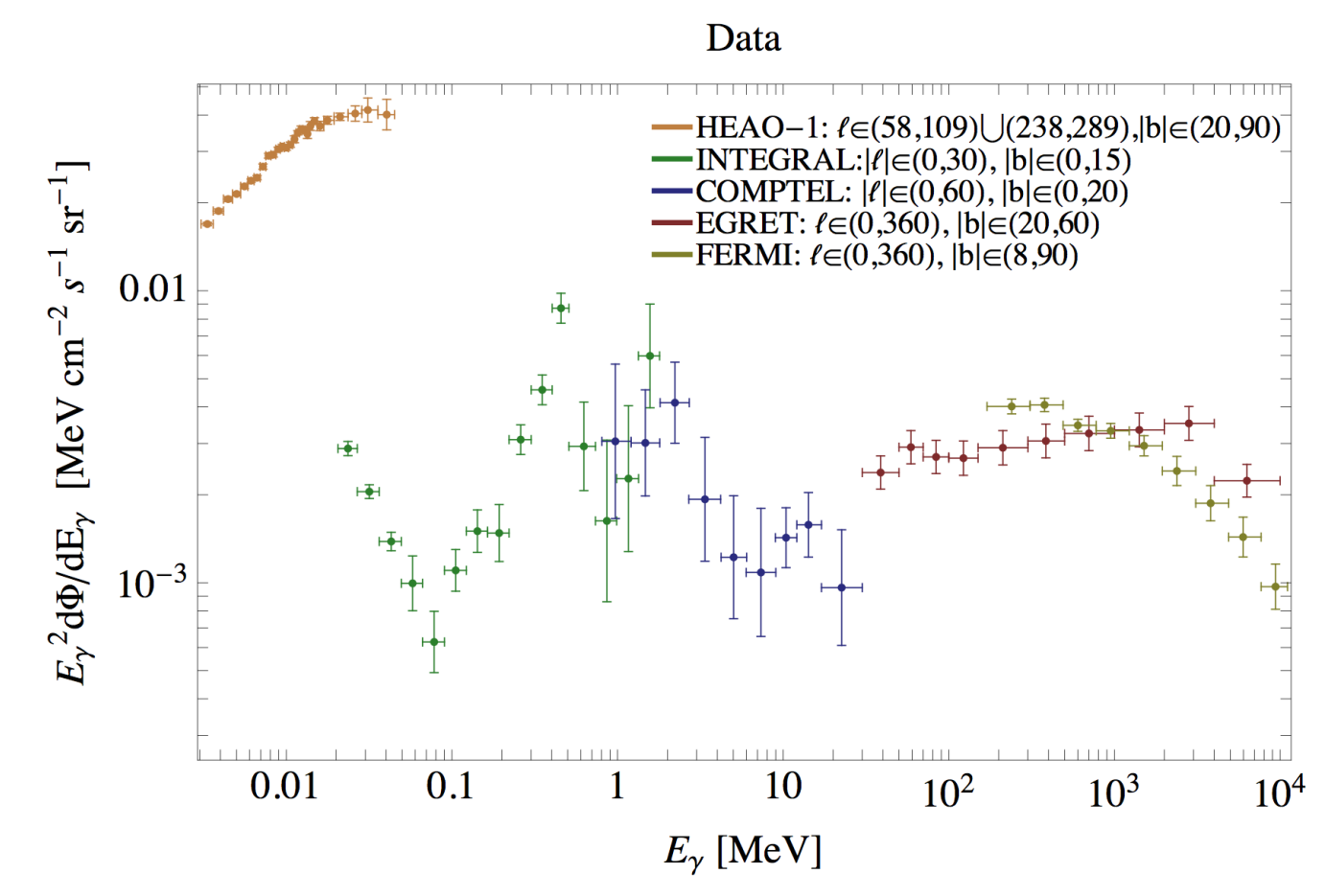


Essig, Manalaysay, Mardon, Soerensen, Volansky1206.2644

Indirect Detection

Cosmic Ray Flux Provides Limits

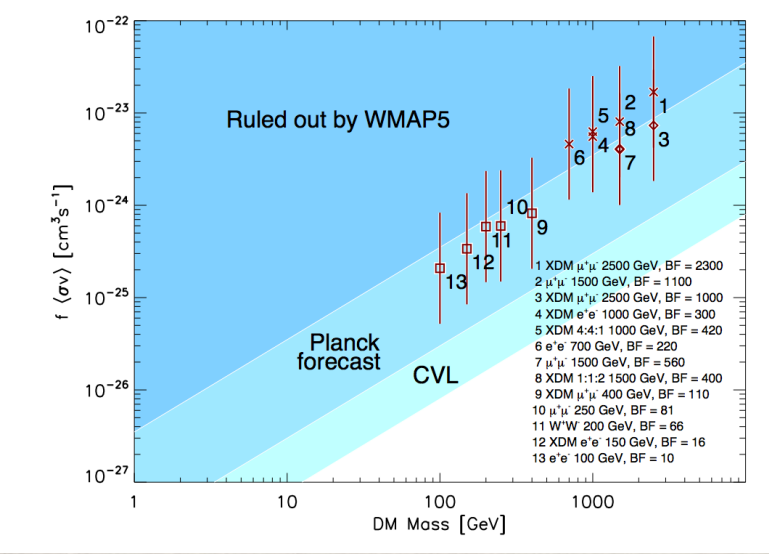
EGRET & COMPTEL provide best limits



Essig, Kuflik, McDermott, Volansky, Zurek 1309.4091

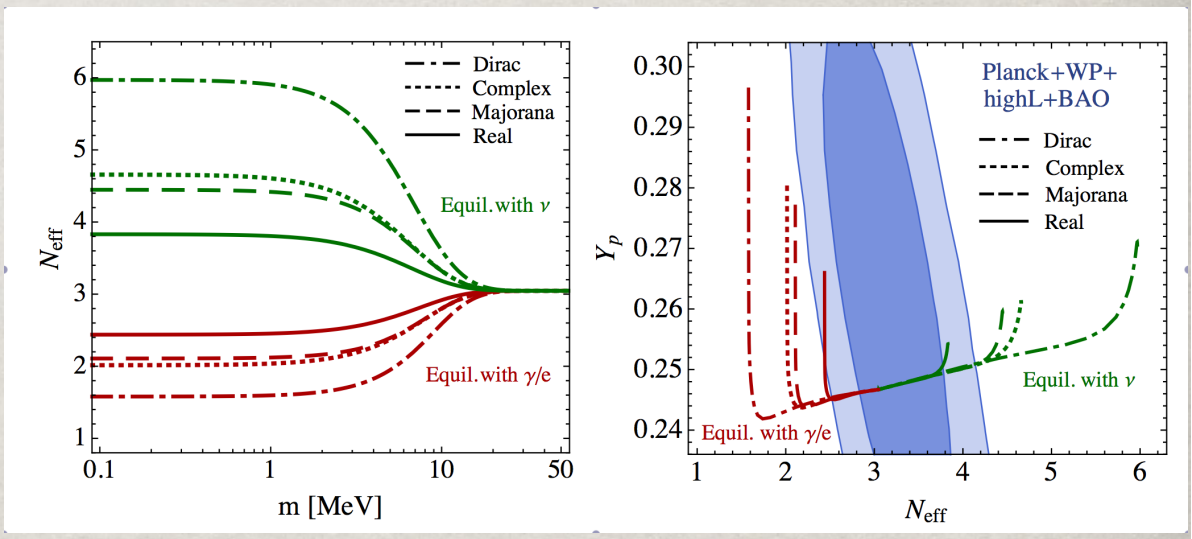
Cosmological Searches

CMB Distortion



Slatyer, Padmanabhan, Finkbeiner 0906.1197

$N_{\nu\,\mathrm{eff}}$ Modification

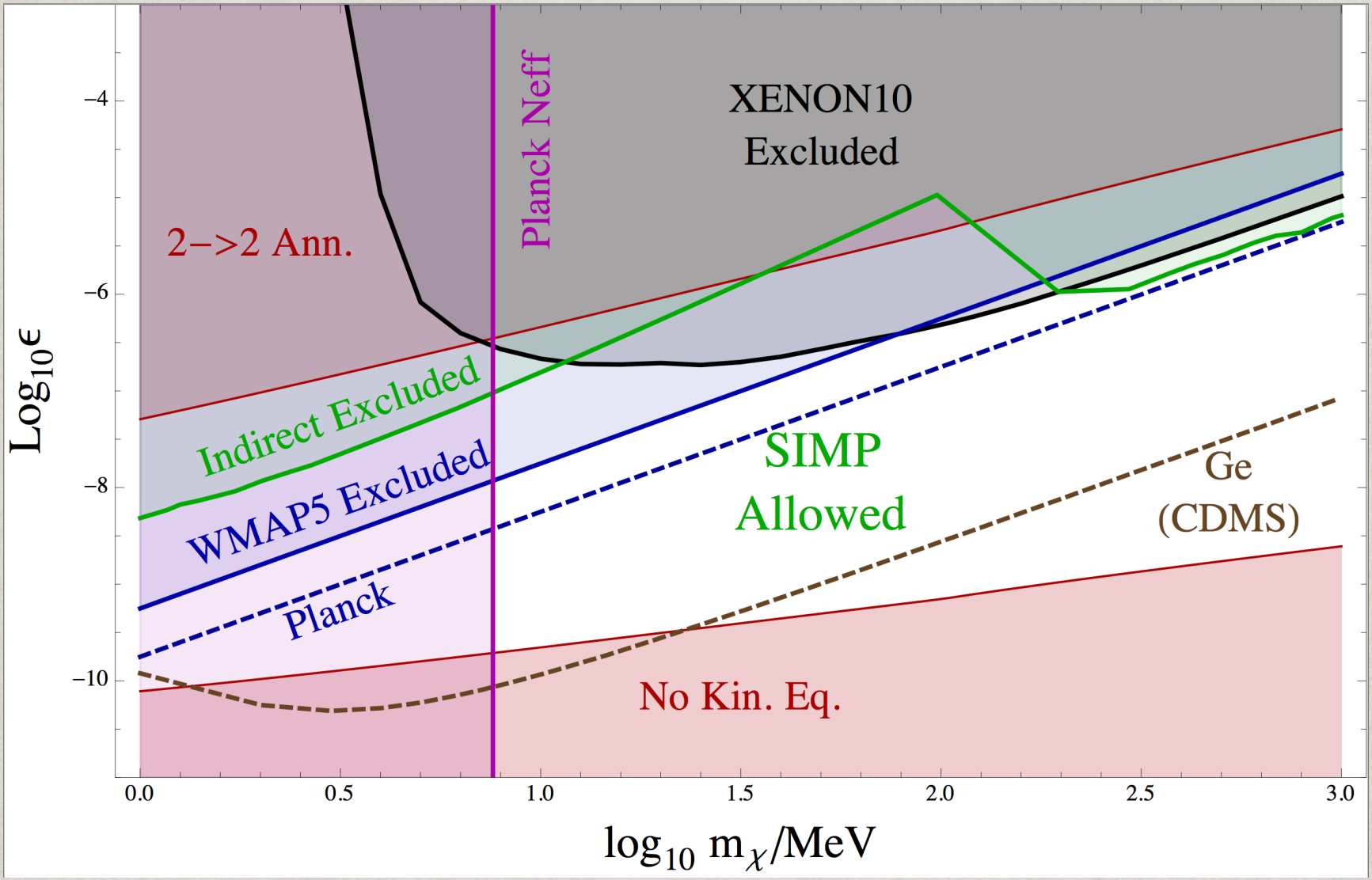


Boehm, Dolan, McCabe 1303.6270

Late DM annihilations add energy into CMB

If in equilibrium with QED sector beneath ν-freeze out $N_{\nu\,\mathrm{eff}}$ will be modified

Combined Limits



Self Interaction

Long standing structure formation problem

Cored DM Profiles & Missing Satellite (or now TBTF)

Recent analyses showed DM self-interaction of

$$\frac{\sigma}{m} \sim 0.2 \frac{\text{barn}}{\text{GeV}} \sim 500 \text{ GeV}^{-3}$$ can solve problem

and allowed by Galactic Shape analysis and Bullet Cluster bounds

Strong-Scale Cross Sections!

Just Perfect!

$$\frac{\sigma_{\text{int}}}{m_{\text{dm}}} \sim \frac{\alpha^2}{m_{\text{dm}}} \sim 500 \frac{1 \text{ GeV}}{m_{\text{dm}}}$$

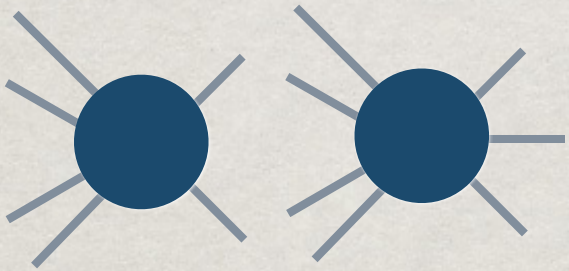
Outline

- Lee-Weinberg & WIMPs
- The SIMP Miracle
- The Search For SIMPs
- Outlook

Higher Point Interactions

What about higher point interactions?

4-to-2 4-to-3 etc.



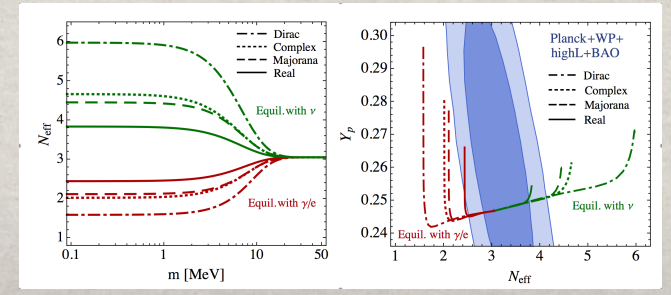
(only 3-to-2 will be viable)

6 point interactions automatically conserve $\mathbb{Z}_2$ symmetry

$$m_{\rm dm} \simeq \alpha \left({T_{\rm eq}}^{n-1} M_{\rm Pl} \right)^{\frac{1}{n}} \qquad \langle \sigma_{n\to 2} v \rangle = \frac{\alpha^n}{m^{2+3n}}$$

n=4 corresponds to 10 keV

dead by $N_{\nu\,\rm eff}$



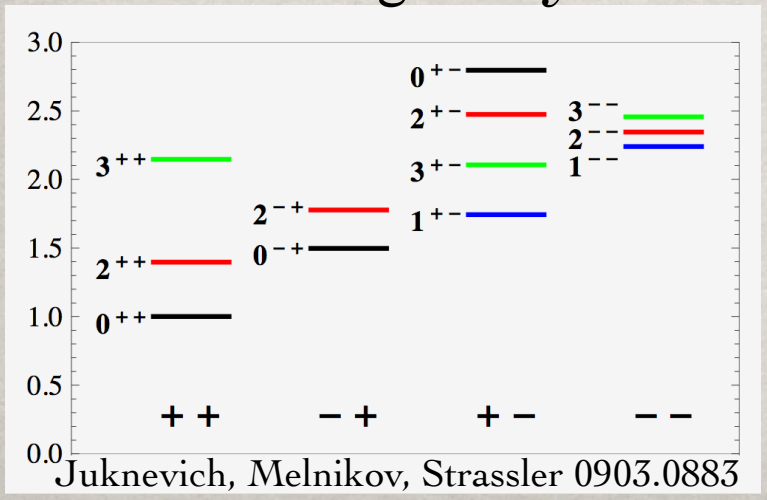
Hidden Glueball DM

Hidden pure SU(N) sector that confines

$$\mathcal{L}_{\rm dark} \sim G_{\mu\nu}^2 + (\partial a)^2 + m_a^2 a^2 + \frac{a}{f} G\tilde{G} + \frac{a}{f'} F\tilde{F}$$

Confines at $\Lambda_{\rm dark}$

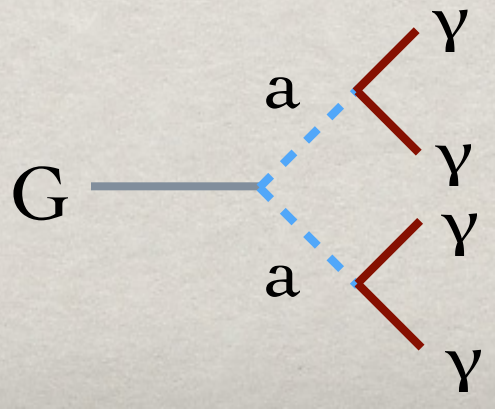
O(10) states stable to strong decays



Juknevich, Melnikov, Strassler 0903.0883

Axion heavier than glueball $\epsilon \sim \dfrac{\Lambda_{\rm dark}^4}{f f' m_a^2}$

Scalar Glueball decays through 4 body



~ε^4 borderline

10^{25} seconds

electrons safer

Outlook

SIMPs offer a new window to DM

Points to different physical scales

Truly a miracle that it isn't ruled out

Lighter DM that self-interacts

Discovery of the particle physics of DM
could be through long standing structure formation problems

New model building challenges

Simplest models still need to be discovered