SLAC NATIONAL ACCELERATOR LABORATORY

Instability of Lightest Visible Superpartner Points to Hidden Sector Dark Matter

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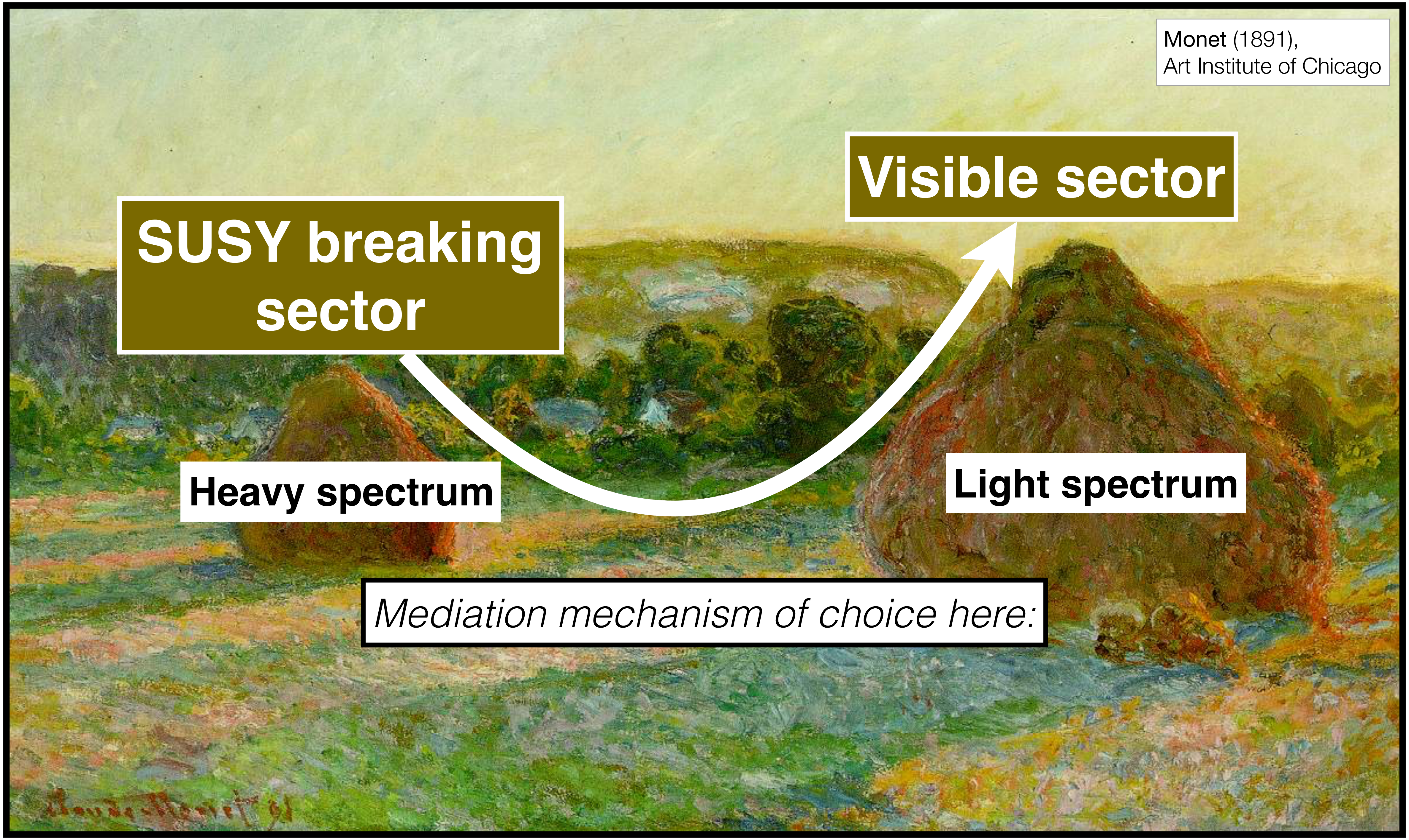
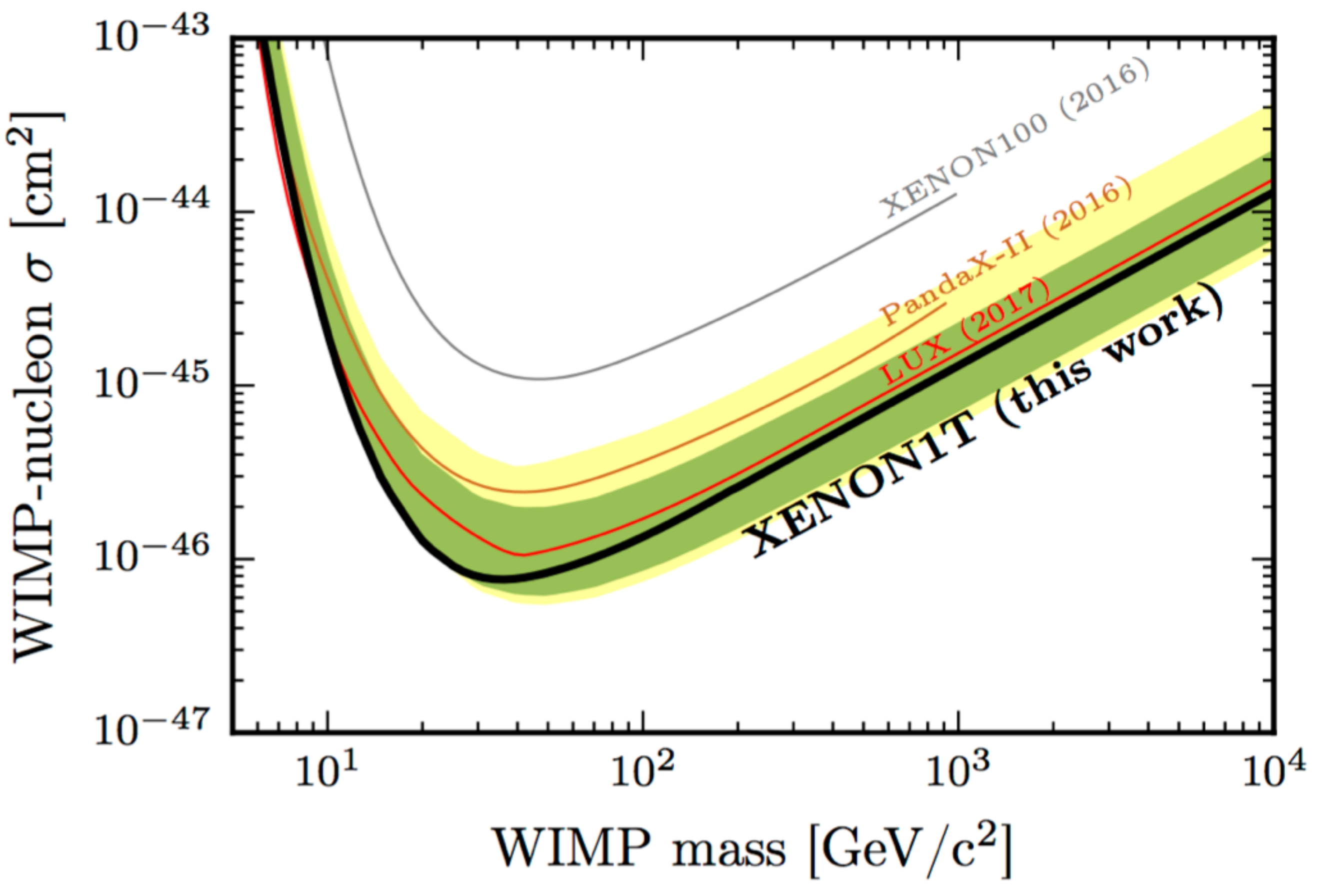
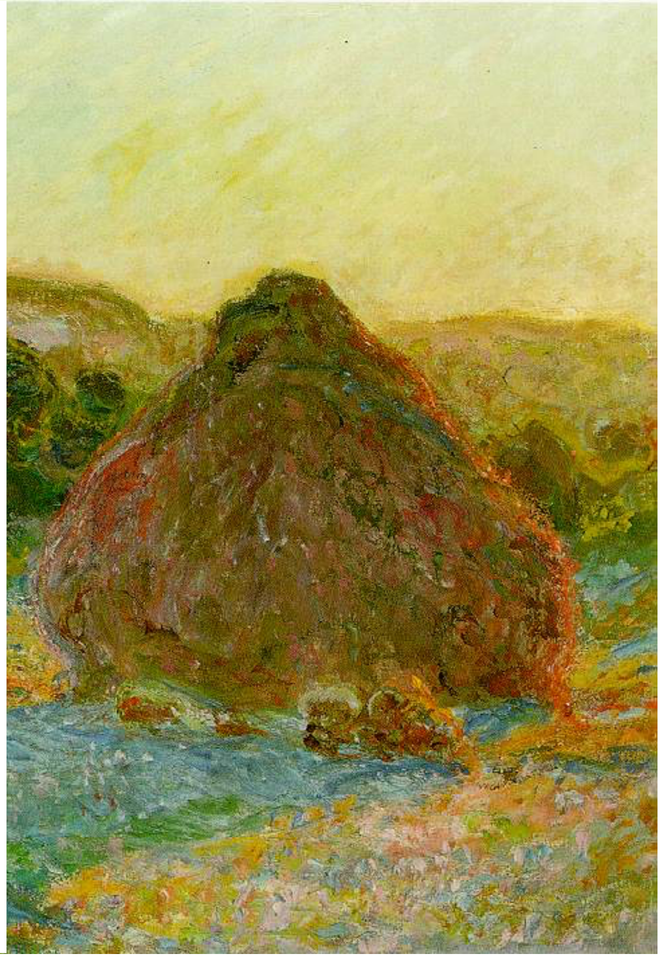
The usual setup of the MSSM



Looking in the wrong haystack?



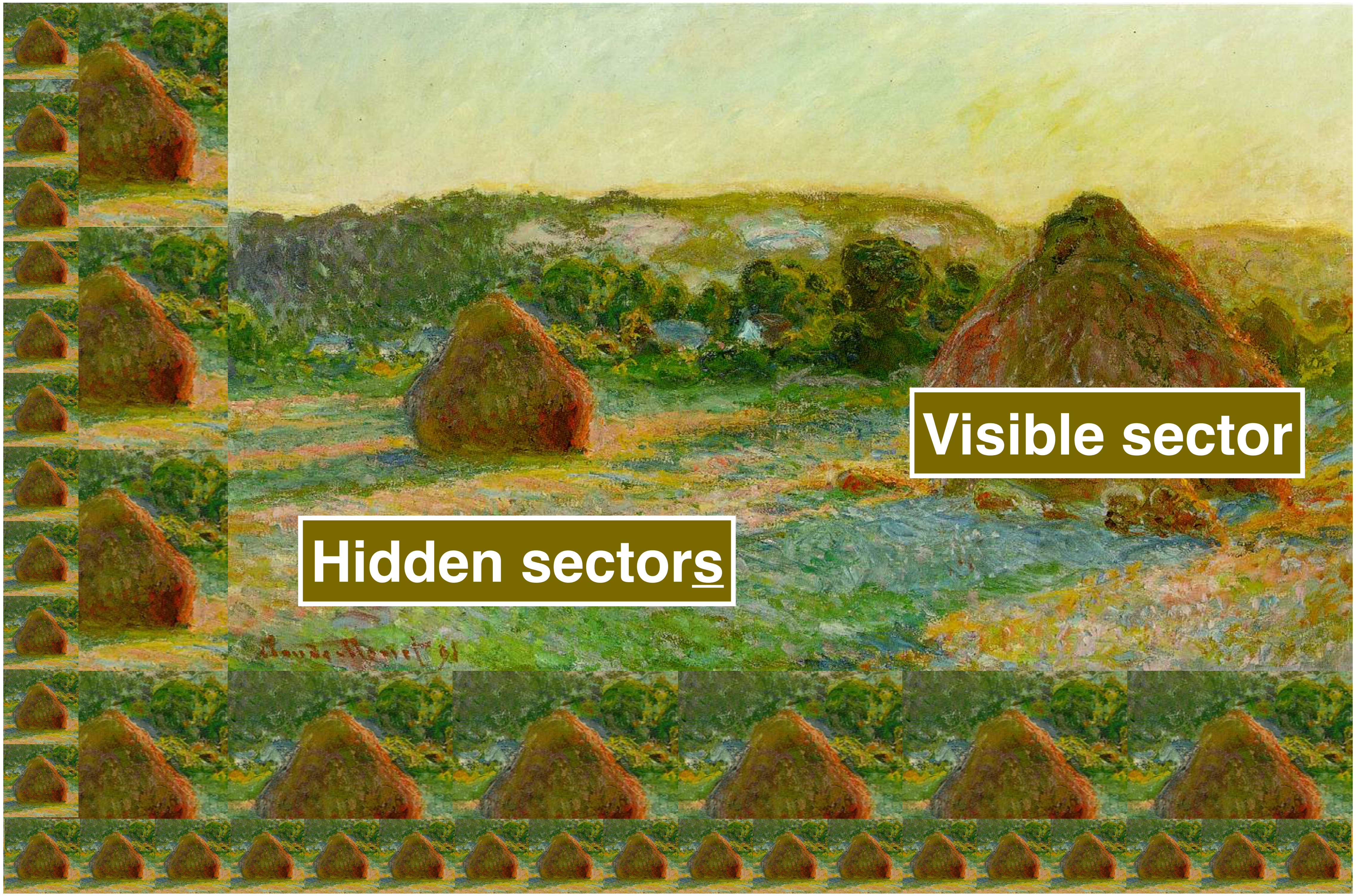


Monet (1891),
Art Institute of Chicago

Talks by: **Mahapatra, Flaecher, Weniger**

Complete the picture with insight from String Theory?

Insight from String Theory



Insight from String Theory

- Hidden Sector:

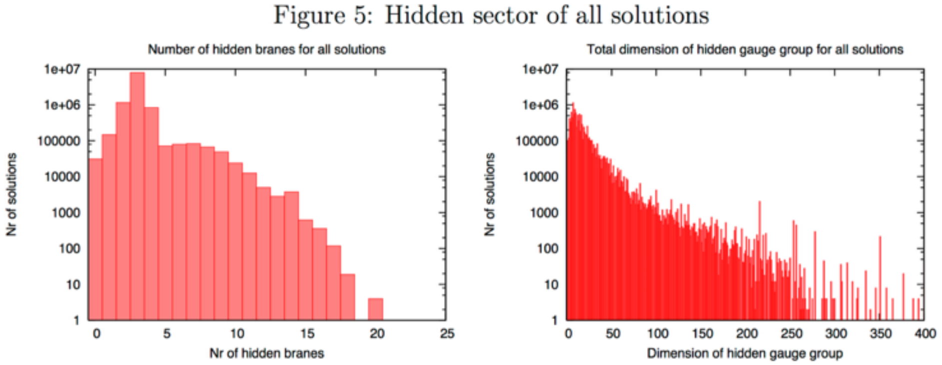
Contains states that are not charged at tree-level under the SM gauge symmetries, but can be charged under their own symmetry group G_{HS}

- In String Theory:
  - ➡ Required to ensure consistency of the theory
  - ➡ Existence demonstrated in many corners of string-scape
  - ➡ Large number, even O(100)

See e.g.
Blumenhagen *et al* (2005)
Dijkstra *et al* (2005)
Dienes (2006)
Gmeiner *et al* (2007)
Douglas & Taylor (2007)
Dienes *et al* (2007)
Taylor & Wang (2015)
Braun and Schafer-Nameki (2017)

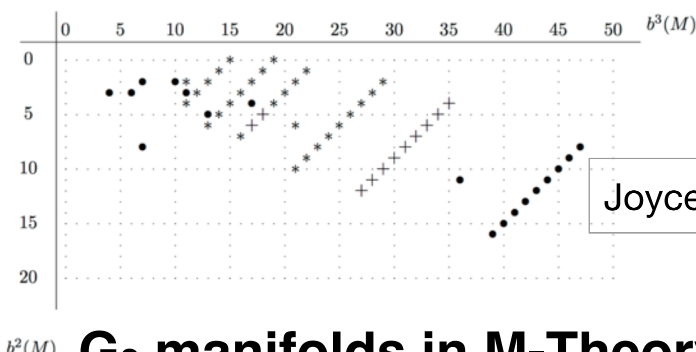
Insight from String Theory

Figure 5: Hidden sector of all solutions



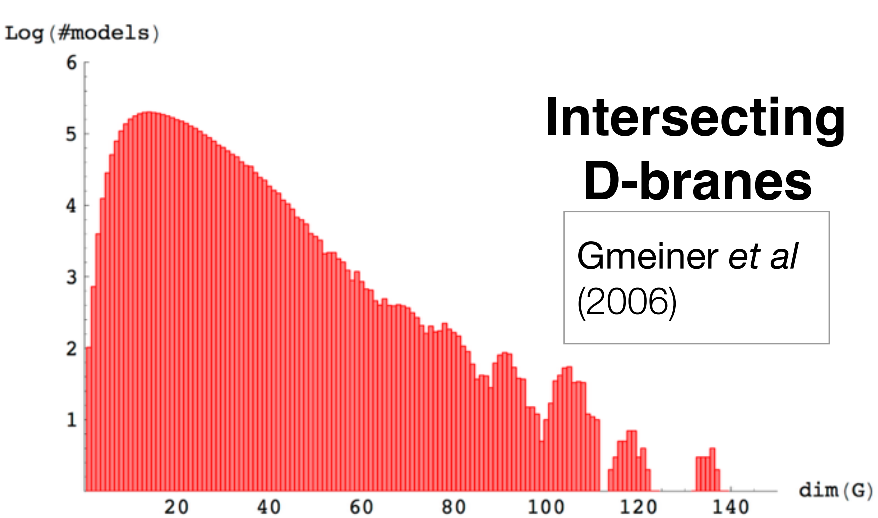
Dijkstra *et al* (2005)

Gepner models



Joyce (1996)

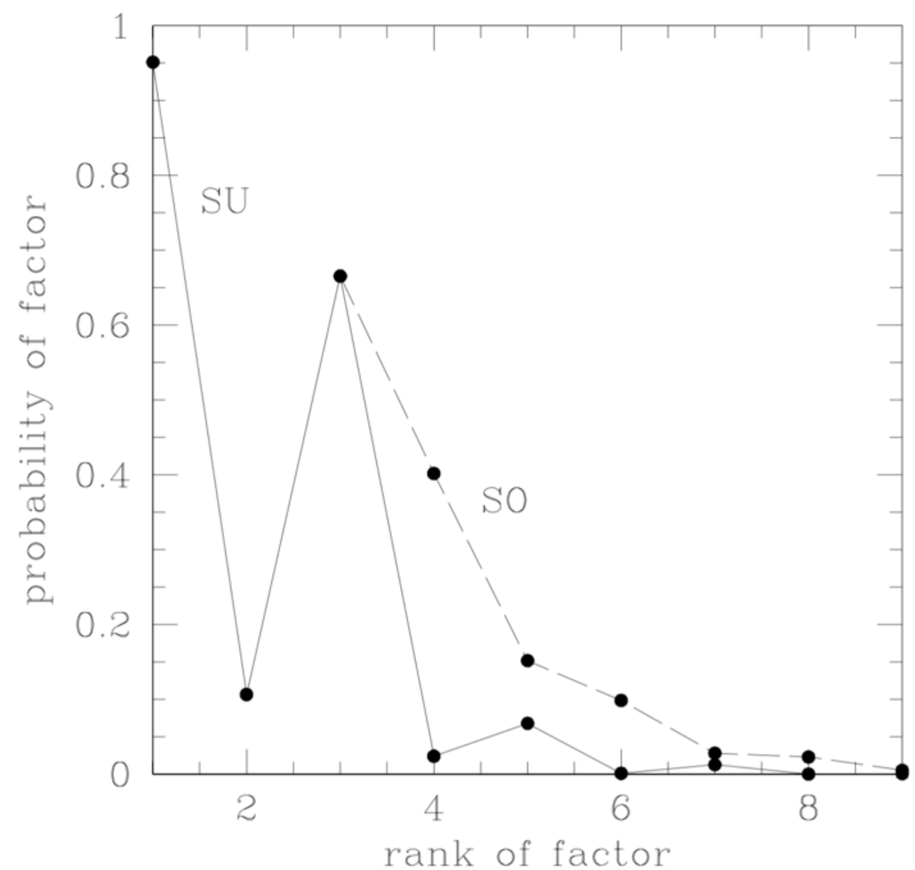
G_2 manifolds in M-Theory



Intersecting D-branes

Gmeiner *et al* (2006)

- Many hidden sectors in explicit constructions
- ~ 90+% are U(1)'s



Dienes (2006)

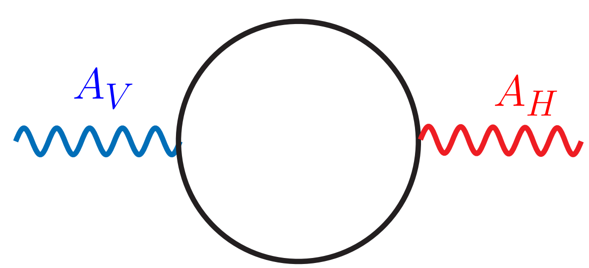
Portals in String Theory

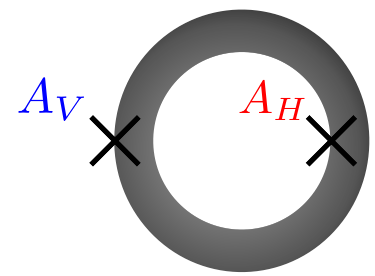
- Many possible portals - *Kinetic mixing*[i], *Higgs*[j], *Neutrino*[k], *Axion*[l]

i Holdom (1986) j Schabinger & Wells (2005) k Falkowski et al (2009) l Nomura & Thaler (2008)

- Kinetic mixing:

$$\mathcal{L}_{gauge} = -\frac{1}{4}F_V^2 - \frac{1}{4}F_H^2 + \frac{\epsilon}{2}F_V F_H$$





$$\epsilon = \frac{g_a g_b}{12\pi^2}\,\mathrm{Tr}\left(T^a T^b \log\left(\frac{M_{ab}^2}{M^2}\right)\right)$$

$$\epsilon = \frac{g_a g_b}{6\pi^2}\,(Q^a Q^b)\,\log\left(\frac{M + \Delta m_{ab}}{M}\right)$$

$$\epsilon \sim \boxed{10^{-3}} \div 10^{-13}$$

- Non-zero mixing of Visible $\mathrm{U(1)_V}$ with Hidden $\mathrm{U(1)_H}$

See e.g.
Dienes, Kolda, March-Russell (1996)
Lukas & Stelle (2000)
Blumenhagen *et al* (2005)
Abel et al (2008)
Goodsell *et al* (2009)
Goodsell *et al* (2012)

Implications of Hidden U(1)s

- Take a concrete model w/ one extra U(1)

$$\mathcal{L}_{gauge} = \boxed{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}\boxed{-\frac{1}{4}G^{\mu\nu}G_{\mu\nu}} + \frac{\epsilon}{2}\boxed{F^{\mu\nu}}\boxed{G_{\mu\nu}}.$$

$$\begin{pmatrix} Y_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon/\sqrt{1-\epsilon^2} \\ 0 & 1/\sqrt{1-\epsilon^2} \end{pmatrix} \begin{pmatrix} B_\mu \\ Z'_\mu \end{pmatrix}$$

After EWSB:

$$A_\mu = \hat{c}_W B_\mu + \hat{s}_W W^3_\mu \qquad m_A^2 = 0$$

$$s_W c_W m_Z = \hat{s}_W \hat{c}_W m_{\hat{Z}}$$

See e.g.
Babu, Kolda & March-Russell (1997)

Implications of Hidden U(1)s

- Gaugino masses:

$$\mathcal{L}_{G.\,mass} = -\frac{1}{2}M_2\tilde{W}^a\tilde{W}^a - \frac{1}{2}M_Y\tilde{Y}\tilde{Y} - \frac{1}{2}M_X\tilde{X}\tilde{X} - M_{XY}\tilde{X}\tilde{Y} + h.c.$$
$$= -\frac{1}{2}M_2\tilde{W}^a\tilde{W}^a - \frac{1}{2}M_1\tilde{B}\tilde{B} - \frac{1}{2}M_{\tilde{Z}'}\tilde{Z}'\tilde{Z}' - M_{BZ'}\tilde{B}\tilde{Z}' + h.c.$$

- Diagonalised

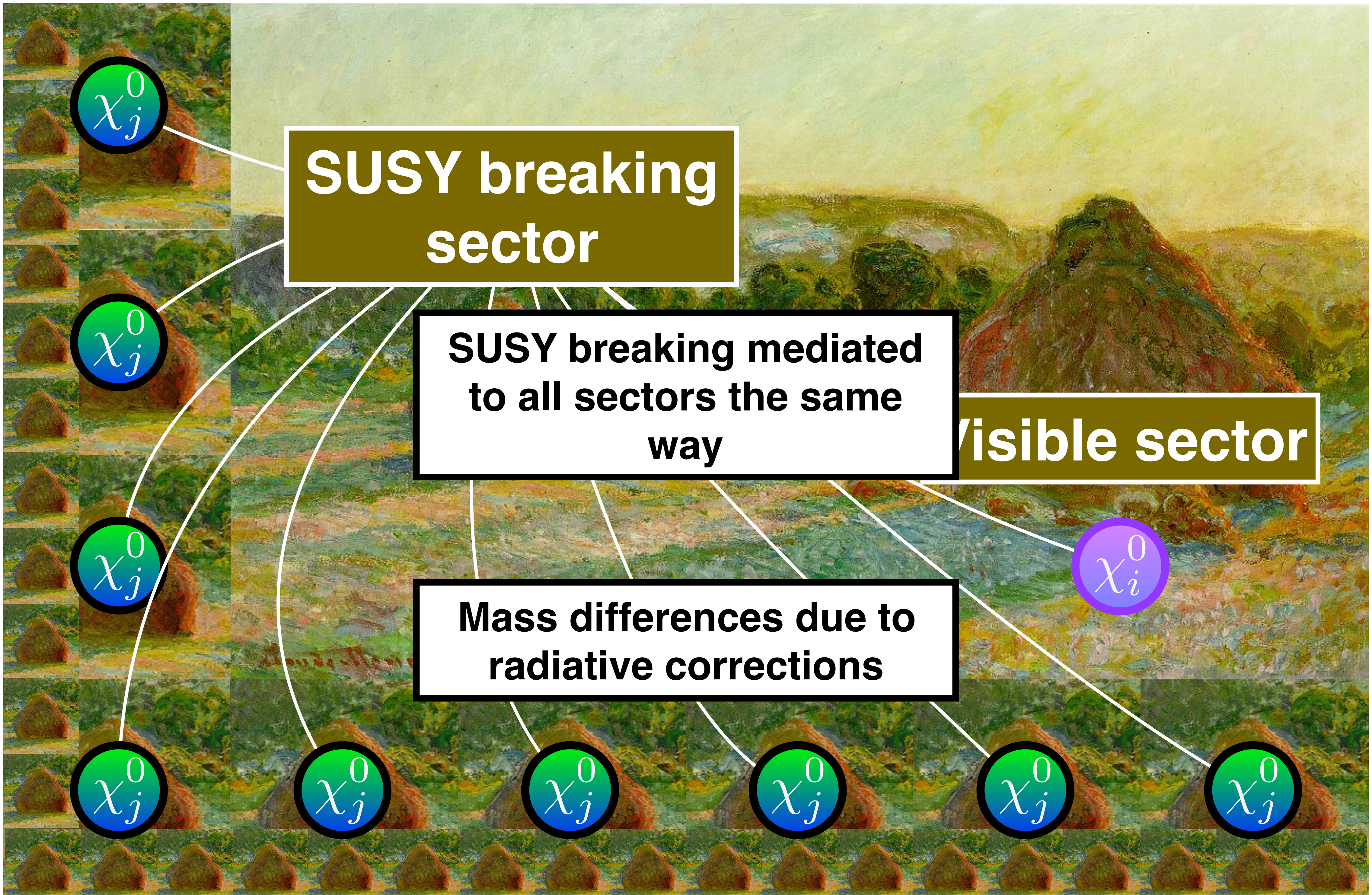
$$\begin{pmatrix}\tilde{Y}\\ \tilde{X}\end{pmatrix} = \begin{pmatrix}1 & \epsilon/\sqrt{1-\epsilon^2}\\ 0 & 1/\sqrt{1-\epsilon^2}\end{pmatrix}\begin{pmatrix}\tilde{B}\\ \tilde{Z}'\end{pmatrix}$$

$$\boxed{M_1 = M_Y;}\quad M_{\tilde{Z}'} = \frac{1}{1-\epsilon^2}\left(M_X + \epsilon M_{XY} + \epsilon^2 M_Y\right);\quad M_{BZ'} = \frac{1}{1-\epsilon^2}\left(M_{XY}\boxed{+\,\epsilon M_Y}\right)$$

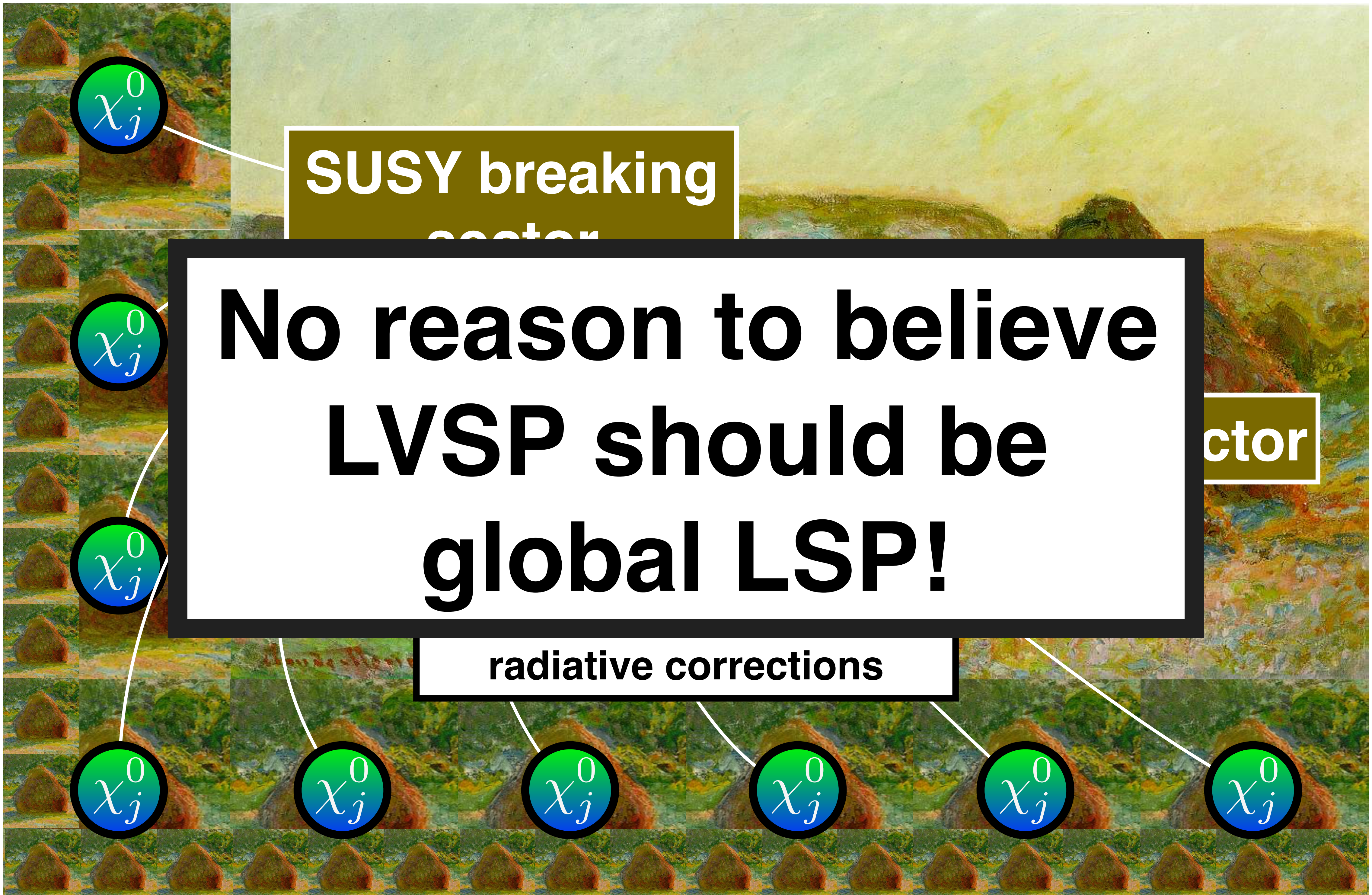
$$\mathcal{M}_N = \left(\begin{array}{cccc|c} & & & & M_{BZ'}\\ & \mathcal{M}_{N,\,4\times4} & & & 0\\ & & & & g_X v c_\beta Q_1\\ & & & & g_X v c_\beta Q_2\\ \hline M_{BZ'} & 0 & g_X v c_\beta Q_1 & g_X v s_\beta Q_2 & M_{\tilde{Z}'}\end{array}\right) \qquad Q_i = \frac{g_Y}{g_X}\epsilon Y_i$$

Acharya, SE, Kane, Nelson, Perry (2017)

Spectrum of HS -inos?

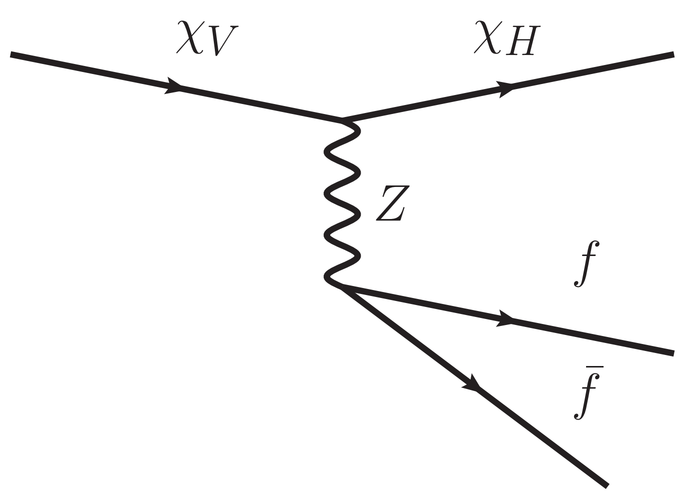


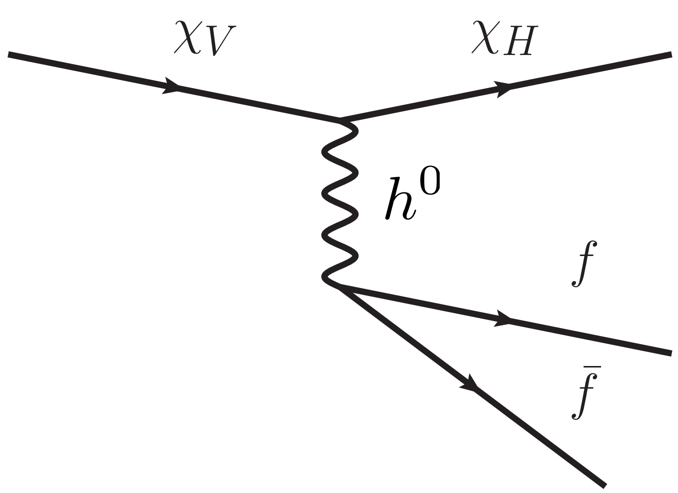
Spectrum of HS -inos?



Decay mode of LVSP

- Dominant decay modes if sfermions heavy:





$$\tau_{2-\mathrm{body}}^{\chi_i \to Z\ \chi_j} \sim \boxed{10^{-17}\ \mathrm{s}} \times \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{0.01}{|N_{i3}N_{j3}^* - N_{i4}N_{j4}^*|}\right)^2$$

$$\tau^{\chi_i \to h\ \chi_j} \sim \frac{c_w^2 H_{ij}^2}{|N_{i3}N_{j3}^* - N_{i4}N_{j4}^*|^2}\tau^{\chi_i \to Z\ \chi_j}$$

$$\tau_{3-\mathrm{body}}^{\chi_i \to Z\ \chi_j} \sim \boxed{10^{-12}\ \mathrm{s}} \times \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{0.01}{|N_{i3}N_{j3}^* - N_{i4}N_{j4}^*|}\right)^2 \left(\frac{\delta m}{50}\right)^5$$

$$\tau^{\tilde{H} \to Z\ \chi_j} \sim |N_{i3}N_{j3}^* - N_{i4}N_{j4}^*|\ \tau^{\tilde{B},\tilde{W} \to Z\ \chi_j}$$

$$H_{ij} = \frac{1}{2s_w}(N_{j2} - t_w N_{j1})(-s_\alpha N_{i3} - c_\alpha N_{i4}) + i \leftrightarrow j$$

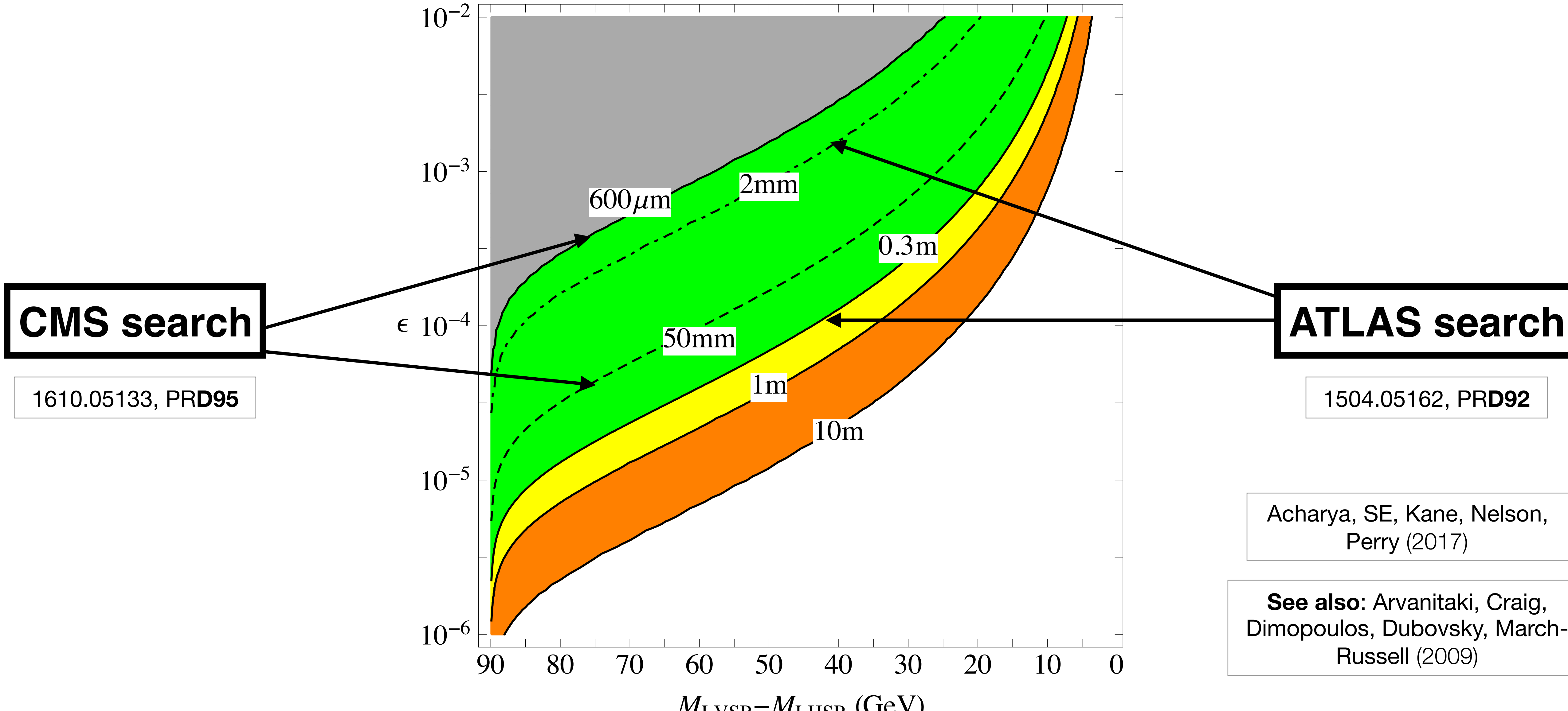
See also: Arvanitaki, Craig, Dimopoulos, Dubovsky, March-Russell (2009)

Acharya, SE, Kane, Nelson, Perry (2016, 2017)

Prompt decay

Phenomenology of LVSP decay

- Additional particles in final state
- 3-body decays: potential displaced vertex



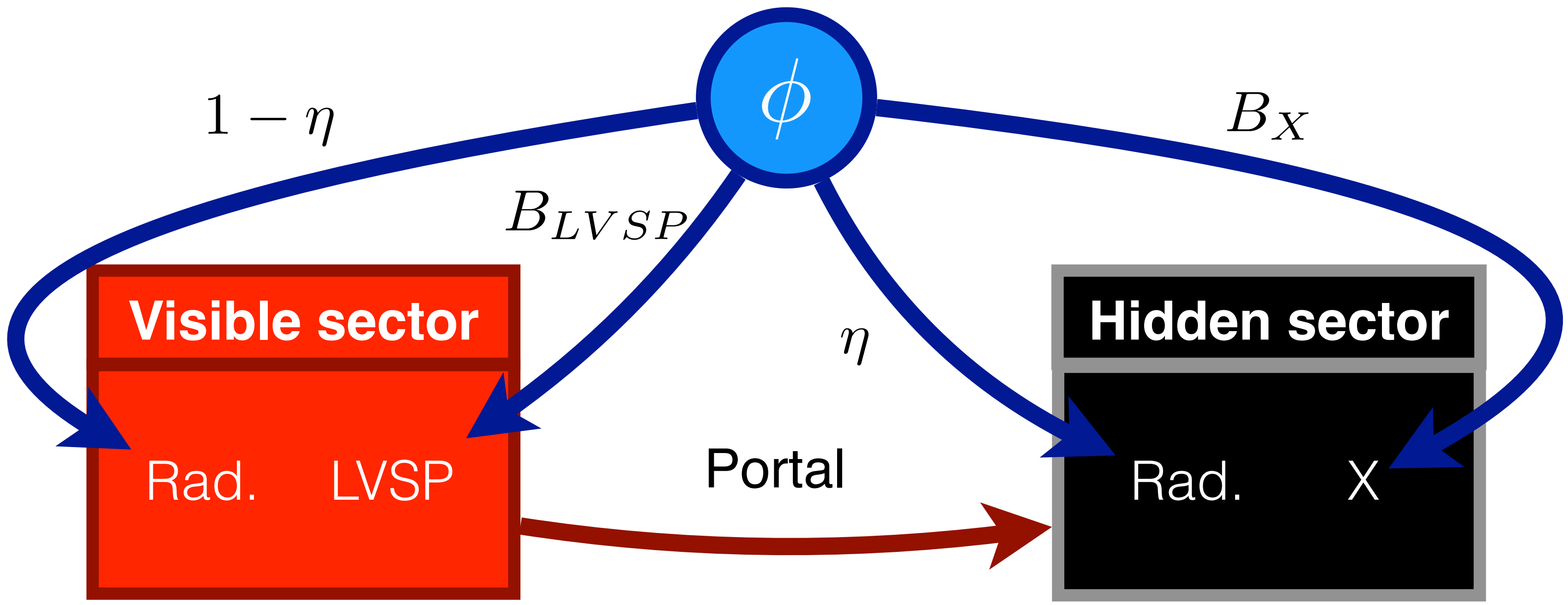
Acharya, SE, Kane, Nelson, Perry (2017)

See also: Arvanitaki, Craig, Dimopoulos, Dubovsky, March-Russell (2009)

Summary of LVSP decay

- LVSP **will** decay if conditions are met:
    - ✓ Hidden Sector exists
    - ✓ Portal exists connecting Visible to Hidden sector
    - ✓ Hidden Sector contains a particle lighter than LVSP
- Decay produces extra particles in final state
- Potentially detectable displaced vertices for small mass splitting
- What does this mean for SUSY dark matter?

Hidden Sector Dark Matter production



$$T_{RH} \equiv \left(\frac{45}{4\pi^3 g_*(T_{RH})}\right)^{1/4} \times \sqrt{\Gamma_\Phi M_{pl}}$$

$$T_D \approx T_{RH}(1-\eta)^{1/4} \quad \text{when} \quad H = \Gamma_\phi$$

$$T'_D \approx \eta^{1/4}\left(\frac{g_\star(T_D)}{g_\star(T'_D)}\right) T_{RH}$$

Kane, P. Kumar, Nelson, Zheng (2015)

$N_{\rm eff}$ constraint

$$\Delta N_{eff}(T_{BBN}) \lesssim 1.44, \qquad \Delta N_{eff}(T_{CMB}) \lesssim 0.4$$

Fields & Sarkar (2006) Planck Coll. (2013)

$$\eta(T_{BBN}) \lesssim 0.20, \quad \eta(T_{CMB}) \lesssim 0.06$$

CMB-S4 Next Generation CMB Experiment

$$\sigma(N_{eff}) = 0.020$$
$$\eta(T_{CMB}) \lesssim 0.004$$

Possible constraint on String Hidden Sector(s) model building?

Production mechanisms

Efficient Annihilation at T'_D

Kane, Kumar, Nelson, Zheng (2015)

$$T'_{FO} > T'_D$$

Quasi-static equilibrium solution (a.k.a. Non-Thermal Wimp “miracle”)

$$\Omega h^2{}_{QSE} \simeq 5.2\ (1-\eta)^{-3/4} \left(\frac{M_X}{10\ \mathrm{GeV}}\right) \left(\frac{10\ \mathrm{MeV}}{T_{RH}}\right) \left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}\right)$$

$$T'_{FO} < T'_D$$

Standard freeze-out during dark radiation domination

$$\Omega h^2{}_{FO^{rad}} \simeq 0.13 \left(\frac{\eta}{(1-\eta)^3 g_\star(T_{FO}) g'_\star(T'_{FO})}\right)^{1/4} \left(\frac{x_{FO}}{17.5}\right) \left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}\right) \ \text{if} \ \ x_{FO} \gtrsim 3$$

$$\Omega h^2{}_{FO^{rad}} \simeq 100 \left(\frac{\eta^3}{(1-\eta)^3 g_\star(T_{FO}) g'_\star(T'_{FO})^3}\right)^{1/4} \left(\frac{M_X}{1\ \mathrm{KeV}}\right) \ \text{if} \ \ x_{FO} \lesssim 3$$

$$x_{FO} \equiv M_X / T'_{FO}$$

Production mechanisms

Inefficient Annihilation at T'_D

Kane, Kumar, Nelson, Zheng (2015)

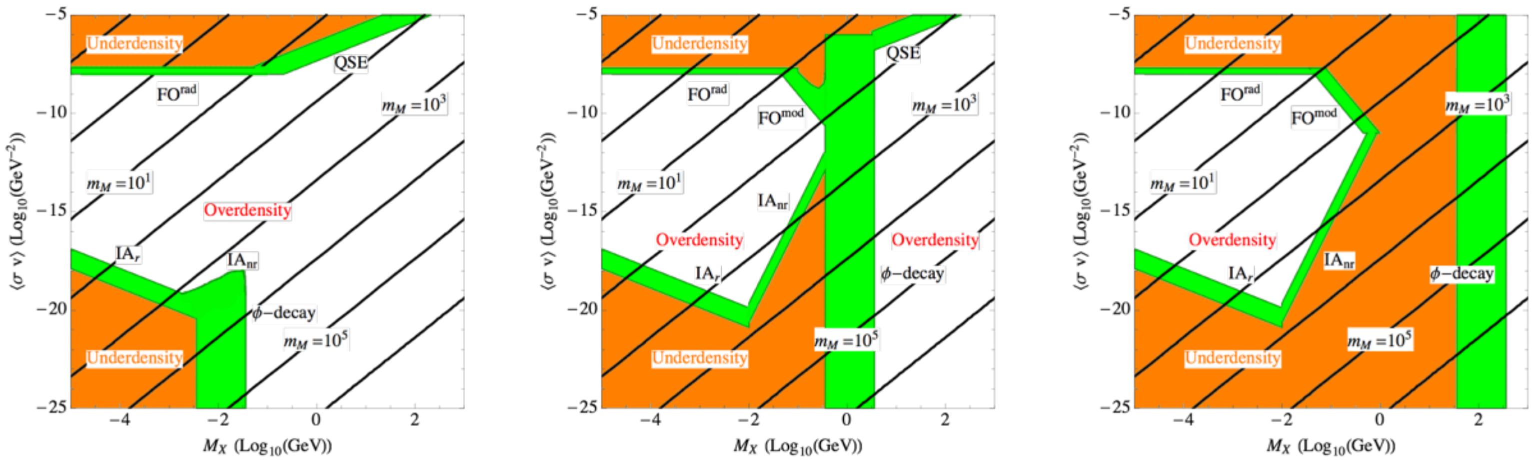
Modulus decay populates DM directly

$$\Omega h^2{}_{\phi-decay} \simeq 0.31 \times \left(\frac{B_X}{(1-\eta)^{3/4}}\right)\left(\frac{M_X}{10\,\mathrm{MeV}}\right)\left(\frac{T_{RH}}{10\,\mathrm{MeV}}\right)\left(\frac{50\,\mathrm{TeV}}{m_\phi}\right)$$

“Inverse annihilation” — dark radiation produces DM

$$\Omega h^2{}_{IA_r} \simeq 95\left(\frac{\eta^{3/2}}{(1-\eta)^{3/4} g'_\star (T'_D)^{3/2}}\right)\left(\frac{T_{RH}}{10\ \mathrm{MeV}}\right)\left(\frac{M_X}{1\ \mathrm{KeV}}\right)\left(\frac{\langle\sigma v\rangle}{10^{-16}\ \mathrm{GeV}^{-2}}\right)$$

Production mechanisms vs parameter space



$$\langle \sigma v \rangle \sim \frac{g_D^4}{8\pi} \frac{M_X^2}{M_M^4} \, , M_X \gg M_M \, ,$$

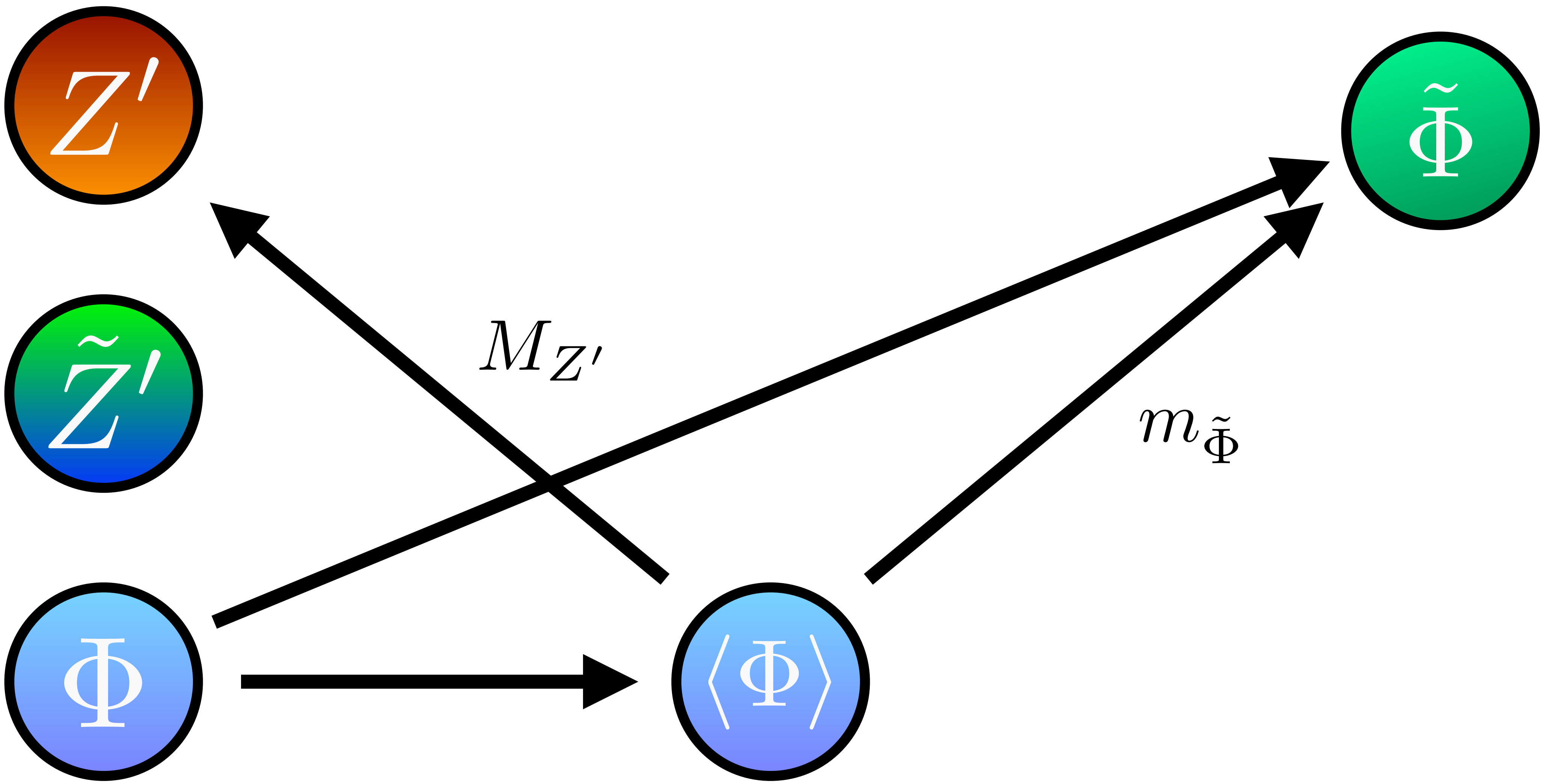
$$\langle \sigma v \rangle \sim \frac{g_D^4}{8\pi} \frac{1^2}{M_X^2} \sqrt{1 - \frac{M_M^2}{M_X^2}} \, , M_X < M_M$$

Acharya, SE, Kane, Nelson, Perry (2017)

Mechanism	Candidate	Mediator
QSE	*chiral fermion, (light) gaugino* $0.1 \lesssim M_X \lesssim 100$ GeV	*gauge boson* $10 \lesssim M_{Z'} \lesssim 100$ GeV
FO^{rad}	*chiral fermion* $M_X \lesssim 100$ MeV	*gauge boson* $M_{Z'} \lesssim 10$ GeV
Modulus decay $B_X \sim 10^{-1}$	*chiral fermion* $100 \lesssim M_X \lesssim 500$ MeV	*gauge boson, scalar* $1 \lesssim M_M \lesssim 100$ TeV
$B_X \sim 10^{-3}$	*chiral fermion* $0.5 \lesssim M_X \lesssim 5$ GeV	*gauge boson, scalar* $10 \lesssim M_M \lesssim 10^6$ GeV
$B_X \sim 10^{-5}$	*chiral fermion, gaugino* $50 \lesssim M_X \lesssim 500$ GeV	*gauge boson, scalar* $10 \lesssim M_M \lesssim 10^6$ GeV

Talk by: Acharya

Minimal content of a pure U(1) Hidden sector

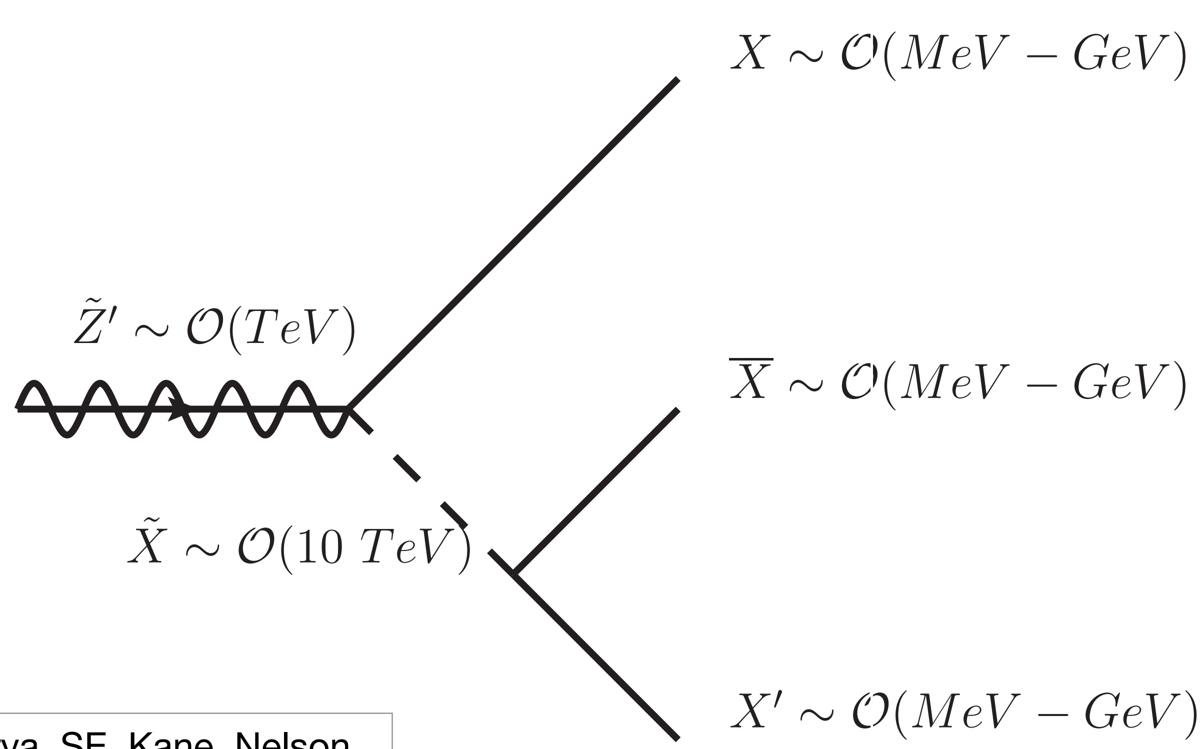


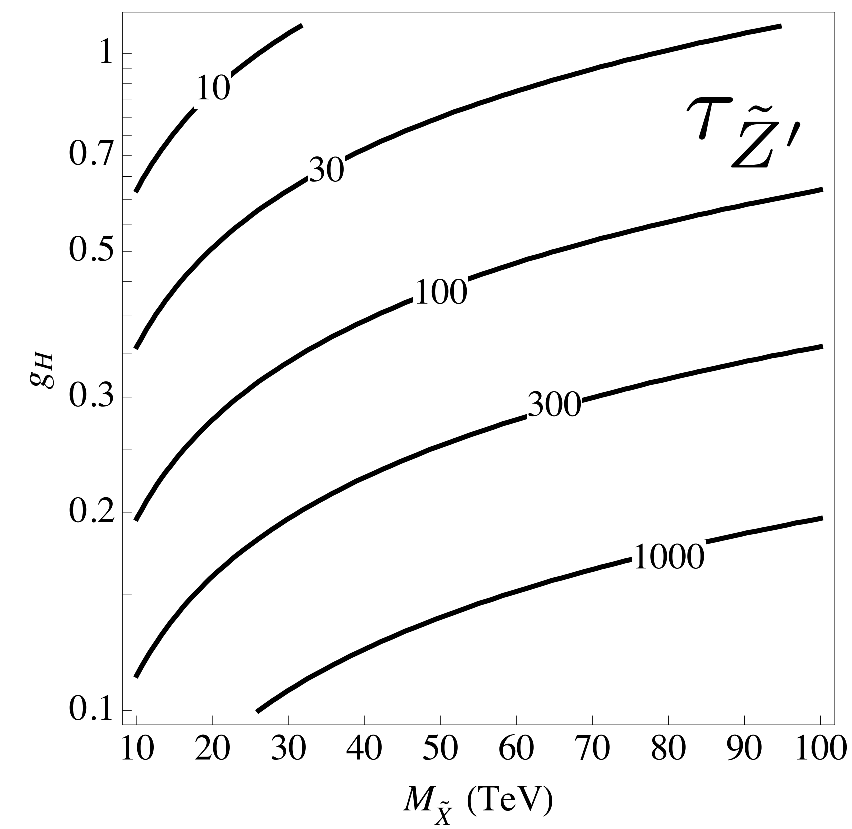
Getting chiral fermions in a Hidden Sector

Can start from an E_8 singularity, resolved to SU(5):

$$W \supset y_X \mathbf{X}\mathbf{X}'\mathbf{X}''$$

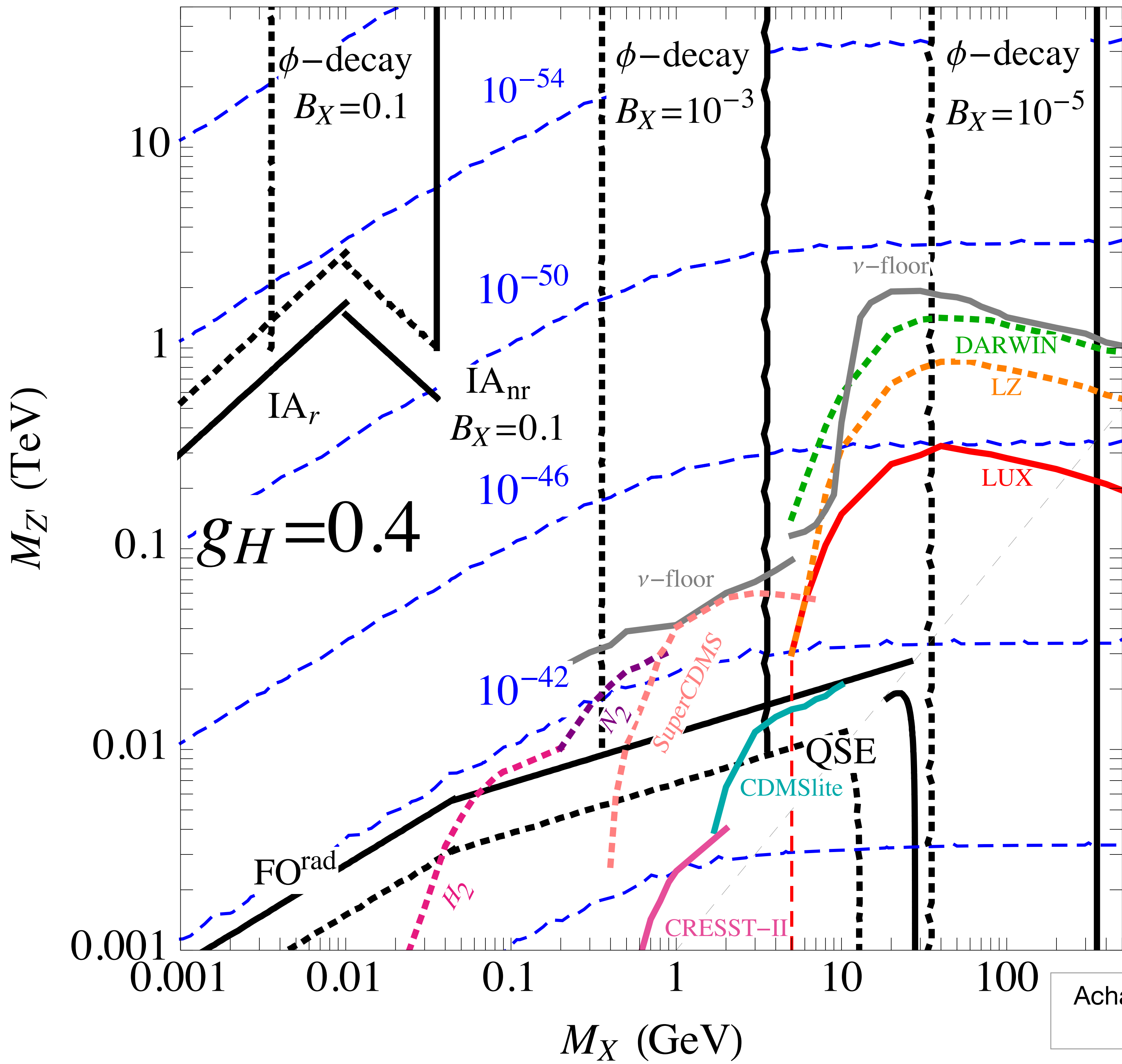
$$\mathcal{L}_{int.} \supset -i\sqrt{2}g_H \left(\tilde{X}^\dagger Q_X \tilde{Z}' X - \overline{X} Q_X \overline{\tilde{Z}'} \tilde{X}\right) - \left(y_X \tilde{X} X' X'' + h.c.\right)$$





Acharya, SE, Kane, Nelson, Perry (2017)

Direct detection prospects



Currently	—	LUX
	—	CDMSlite
	—	CRESST-II
Planned	···	superCDMS
	···	LZ
	···	Darwin
Future(?)	···	H_2
	···	N_2

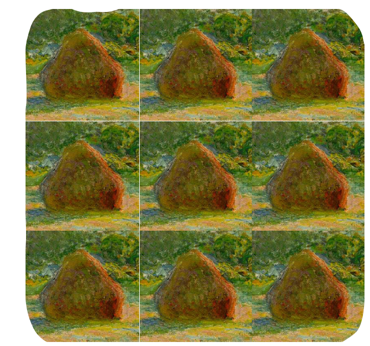
$$\sigma_{X-N} \simeq \frac{\epsilon^2 g_Y^2 g_H^2 \mu_{XN}^2}{\pi} \frac{\left(1-4s_w^2\right)^2}{M_{Z'}^4}$$

$$\sigma_{X-e} = \frac{4\mu_{Xe}^2 \alpha_{em} g_H^2 c_w^2 \epsilon^2}{M_{Z'}^4}$$

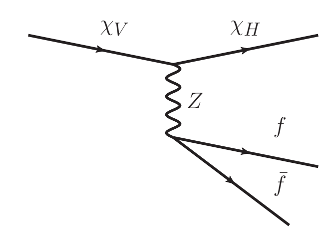
Acharya, SE, Kane, Nelson, Perry (2017)

Summary

- Null results in DM searches — wrong haystack?



- String insight:
    - ➡ Many sectors
    - ➡ Many U(1) factors
    - ➡ Generic Kinetic mixing between U(1) factors



LVSP unlikely to be stable

DM likely in a Hidden Sector

Summary

- Non-thermal DM in Hidden Sector — what can it be?

Mechanism	Candidate	Mediator	Current status	Future status
QSE FO^{rad}	*chiral fermion, (light) gaugino* $0.1 \lesssim M_X \lesssim 100$ GeV *chiral fermion* $M_X \lesssim 100$ MeV	*gauge boson* $10 \lesssim M_{Z'} \lesssim 100$ GeV *gauge boson* $M_{Z'} \lesssim 10$ GeV	LUX $M_X \lesssim 5$ GeV –	SuperCDMS $M_X \lesssim 500$ MeV –
Modulus decay $B_X \sim 10^{-1}$ $B_X \sim 10^{-3}$ $B_X \sim 10^{-5}$	*chiral fermion* $100 \lesssim M_X \lesssim 500$ MeV *chiral fermion* $0.5 \lesssim M_X \lesssim 5$ GeV *chiral fermion, gaugino* $50 \lesssim M_X \lesssim 500$ GeV	*gauge boson, scalar* $1 \lesssim M_M \lesssim 100$ TeV *gauge boson, scalar* $10 \lesssim M_M \lesssim 10^6$ GeV *gauge boson, scalar* $10 \lesssim M_M \lesssim 10^6$ GeV	– CDMSlite $M_{Z'} \gtrsim \mathcal{O}(10)$ GeV LUX $M_{Z'} \gtrsim \mathcal{O}(300)$ GeV	– SuperCDMS $M_{Z'} \gtrsim \mathcal{O}(100)$ GeV LZ $M_{Z'} \gtrsim \mathcal{O}(1)$ TeV
IA$_{nr}$ IA$_r$	*chiral fermion* $10 \lesssim M_X \lesssim 100$ MeV *chiral fermion* $M_X \lesssim 5$ MeV	*gauge boson* $100 \lesssim M_{Z'} \lesssim 10^4$ GeV *gauge boson* $10 \lesssim M_{Z'} \lesssim 5000$ GeV		

Extra motivation for sub-GeV?

see *US Cosmic Visions (2017)*