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Stefano Profumo
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

An Introduction to Particle Dark Matter

Pre-SUSY Summer School
Melbourne, June 29-July 1, 2016

Quick **summary** of key concepts from Lecture 2

- There are several **caveats** to using the **pair-annihilation** at **freeze-out** as a proxy for the pair-annihilation **today**
- A **modified expansion rate** at freeze-out can have a huge **impact** on the thermal relic density [**quintessence**]
- After chemical decoupling, DM is in **kinetic** equilibrium, freeze-out must account for **multiple scattering**
- Kinetic decoupling sets the **scale** of the **smallest collapsed structures** in cold DM cosmologies
- Hot DM suppresses small-scale unacceptably, ruled out

Quick **summary** of key concepts from Lecture 2

- **Direct detection** is a tough business (such as neutrino detection)
- **E_{th}** ←→ **lowest DM mass** that can be detected ($v^2 \sim 10^{-5}$)
- Direct Detection: **sequence of EFT**:
  quark-gluon → nucleon → nuclei
- **Indirect** detection: $\Gamma_{\rm SM,\ ann} \sim \left(\int_V \frac{\rho_{\rm DM}^2}{m_\chi^2} {\rm d}V\right) \times (\sigma v) \times (N_{\rm SM,\ ann})\,,$
- **Final state**: no idea, model dependent:
  - SU(2) multiplet
  - couples to hypercharge
  - selection rule (e.g. Majorana fermion)

Annihilation (or decay) of DM can be **detected** or **constrained** in a variety of ways

Here's one possible **classification**:

1. **Very Indirect**: effects induced by dark matter on **astrophysical objects** or on **cosmological observations**

2. **Pretty Indirect**: probes that don't "trace back" to the annihilation event, as their trajectories are bent as the particles propagate: **charged cosmic rays**

3. **Not-so-indirect**: **neutrinos** and **gamma rays**, with the great added advantage of traveling in straight lines

Very indirect probes include e.g.

- **Solar Physics** (dark matter can affect the Sun's core temperature, the sound speed inside the Sun,...)
- **Neutron Star Capture**, possibly leading to the formation of black holes (notably e.g. in the context of asymmetric dark matter)
- **Supernova** and **Star** cooling
- **Protostars** (e.g. WIMP-fueled population-III stars)
- **Planets warming**
- **Big Bang Nucleosynthesis**, on the **cosmic microwave background**, on **reionization**, on **structure formation**…

Pretty Indirect Probes: **charged cosmic rays**

Good idea is to use **rare** cosmic rays, such as **anti-matter**

antiprotons, **positrons** relatively abundant
(mostly from inelastic processes CR p on ISM p)

Interesting probe: **antideuterons** (or even **anti-^{3}He** !!)

$$\bar{D}: \quad p+p \to p+p+\bar{p}+p+\bar{n}+n$$

large energy **threshold** (~17 GeV), so typically large momentum, while from DM produced at very low momentum! Select **low-energy antideuterons**

positrons (and in part antiprotons) have attracted attention because of "**anomalies**" reported by PAMELA, AMS-02

general scheme for Galactic CR's: **diffusion** (leaky-box) models

$$\frac{\mathrm{d}n}{\mathrm{d}E} = \psi\left(\vec{x}, E, t\right)$$

$$\frac{\partial}{\partial t}\psi = D(E)\Delta\psi + \frac{\partial}{\partial E}\left(b(E)\,\psi\right) + Q\left(\vec{x}, E, t\right)$$

Things can be made arbitrarily more **complicated/sophisticated**:

- *Cosmic-ray convection*; recipe: add: $\frac{\partial}{\partial z}(v_c \cdot \psi)$;
- *Diffusive re-acceleration*; recipe: add: $\frac{\partial}{\partial p}\, p^2\, D_{pp}\, \frac{\partial}{\partial p}\, \frac{1}{p^2}\psi$;
- *Fragmentation and decays*; recipe: add: $-\frac{1}{\tau_{\mathrm{f,d}}}\psi$.

Boundary conditions:

$$R \sim \mathcal{O}(1) \times 10 \text{ kpc},$$
$$h \sim \mathcal{O}(1) \times 1 \text{ kpc}.$$

$$D(E) \sim D_0 \left(\frac{E}{E_0}\right)^{\delta}$$

Useful to **simplify** the diffusion equation assuming steady-state, using typical diffusion and energy loss **time-scales**, defined by

$$\tau_{\text{diff}} \sim \frac{R^2}{D_0} \cdot E^{-\delta}, \qquad \tau_{\text{loss}} \sim \frac{E}{b(E)}$$

Diff. Eq. then looks like $$0 = -\frac{\psi}{\tau_{\text{diff}}} - \frac{\psi}{\tau_{\text{loss}}} + Q$$

with **solution** $$\psi \sim Q \cdot \min[\tau_{\text{diff}}, \tau_{\text{loss}}]$$

If the source is cosmic rays accelerated via a **Fermi mechanism**,

$$Q \sim E^{-2} \longrightarrow \quad \psi \sim E^{-2} \cdot E^{-\delta} \sim E^{-2.7}$$

…in agreement with **CR protons** (where en. losses are irrelevant)

For CR **electrons**, energy losses are efficient above a certain **energy**,

$$b_e(E) \simeq b^0_{\rm IC} \left(\frac{u_{\rm ph}}{1\ {\rm eV/cm^3}} \right) \cdot E^2 + b^0_{\rm sync} \left(\frac{B}{1\ \mu{\rm G}} \right)^2 \cdot E^2$$

$$b^0_{\rm IC} \simeq 0.76, \qquad b^0_{\rm sync} \simeq 0.025\ \ 10^{-16}\ {\rm GeV/s}$$

Therefore (as observed) we expect a **broken power-law**

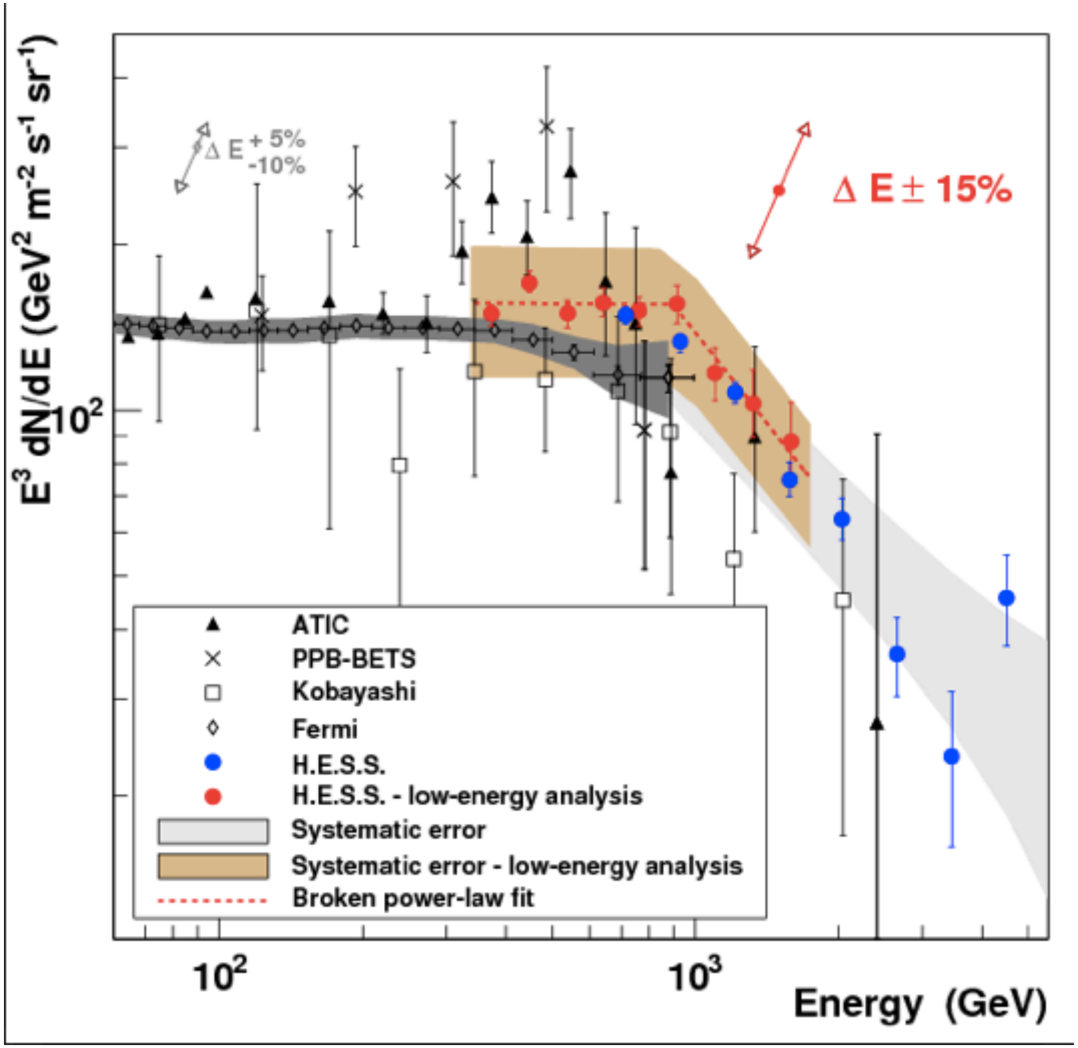
$$\psi_{\rm primary,\ low-energy} \sim \ Q \cdot \tau_{\rm diff} \sim E^{-2} \cdot E^{-\delta} \sim E^{-2.7}$$

$$\psi_{\rm primary,\ high-energy} \sim \ Q \cdot \tau_{\rm loss} \sim E^{-1} \cdot \frac{E}{E^2} \sim E^{-3}$$

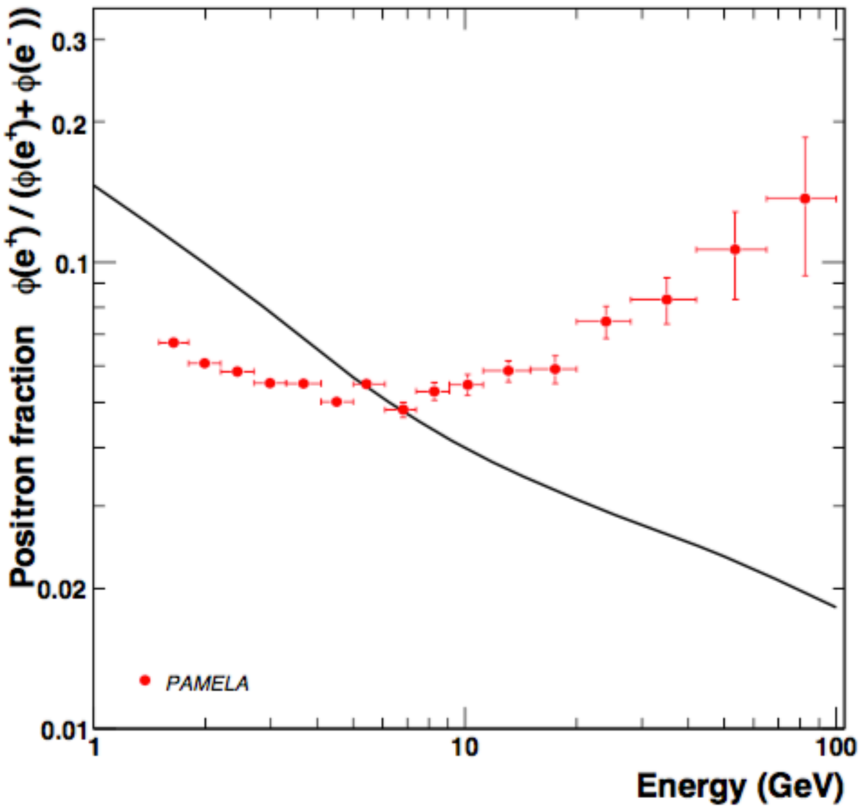
Also, **secondary-to-primary** ratios are generically

$$\frac{\psi_{e^+}}{\psi_{e^-}} \sim \ E^{-\delta},$$

Electron spectrum looks pretty good



but the **secondary-to-primary ratio** prediction is at **odds** with observed rising positron fraction



Much **hype** about this possibly being from **DM** – but very **problematic**

- No excess **anitprotons** – must be "leptophilic" (possible but not generic)

- No observed **secondary radiation** from brems or IC

- Needed **pair-annihilation rate** very large for thermal production, leads to unseen gamma-ray or radio emission

$$\langle \sigma v \rangle \sim 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \cdot \left(\frac{m_\chi}{100\ \mathrm{GeV}} \right)^{1.5}$$

Alternate explanation: nearby **point source** injecting a burst of **positrons** (a.k.a. Green's function, a.k.a. **PSR**)

$$\psi \propto Q \cdot \exp\left(-\left(\frac{r}{r_{\rm diff}}\right)^2\right)$$

Estimate **Age** and **Distance** of putative source

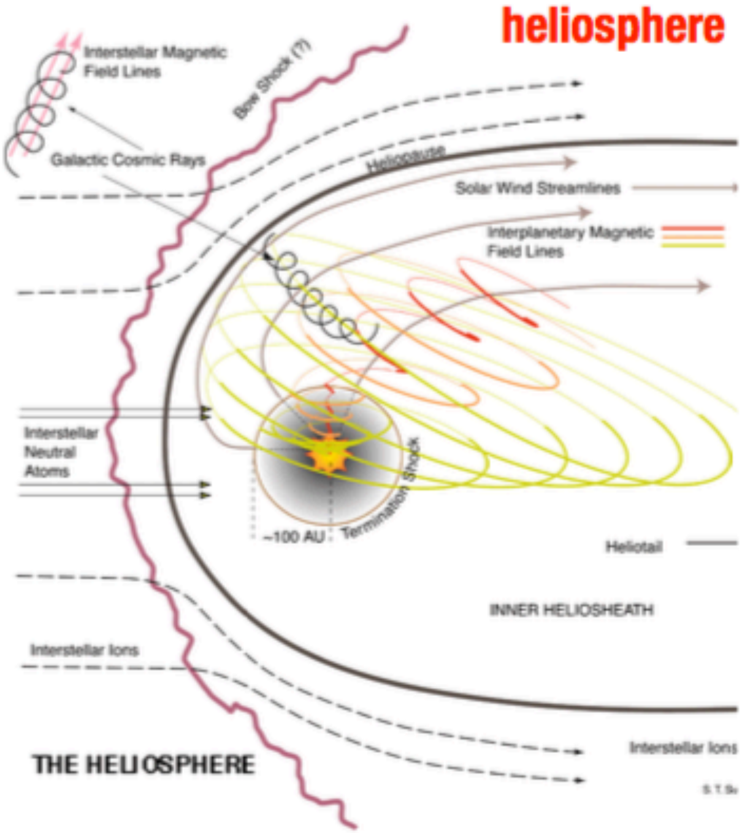
$$t_{\rm psr} \ll \tau_{\rm loss} = \frac{E}{b(E)};\ \text{for } E = 100\ {\rm GeV}, \tau_{\rm loss} \sim \frac{100}{10^{-16}\cdot 100^2}\ {\rm s} \sim 10^{14}\ {\rm s} \sim 3\ {\rm Myr.}$$

$$r_{\rm diff} \simeq \sqrt{D(E)\cdot t}.$$

$$\sqrt{D(E)\cdot t_{\rm psr}} \gg \text{ distance} \to \text{distance} \ll (3\times 10^{28}\cdot 100^{0.7}\cdot 10^{14})^{1/2}\ {\rm cm} \sim 10^{22}\ {\rm cm} \sim 3\ {\rm kpc.}$$

One possible way to **disentangle** PSR from DM: **anisotropy**

Complication: Larmor radius for **heliospheric** magnetic fields ***B~ nT***, is of the order of the **solar system size** (exercise)



Not-so-indirect DM detection: **neutrinos**!

Only **two** observed astrophysical sources of neutrinos!

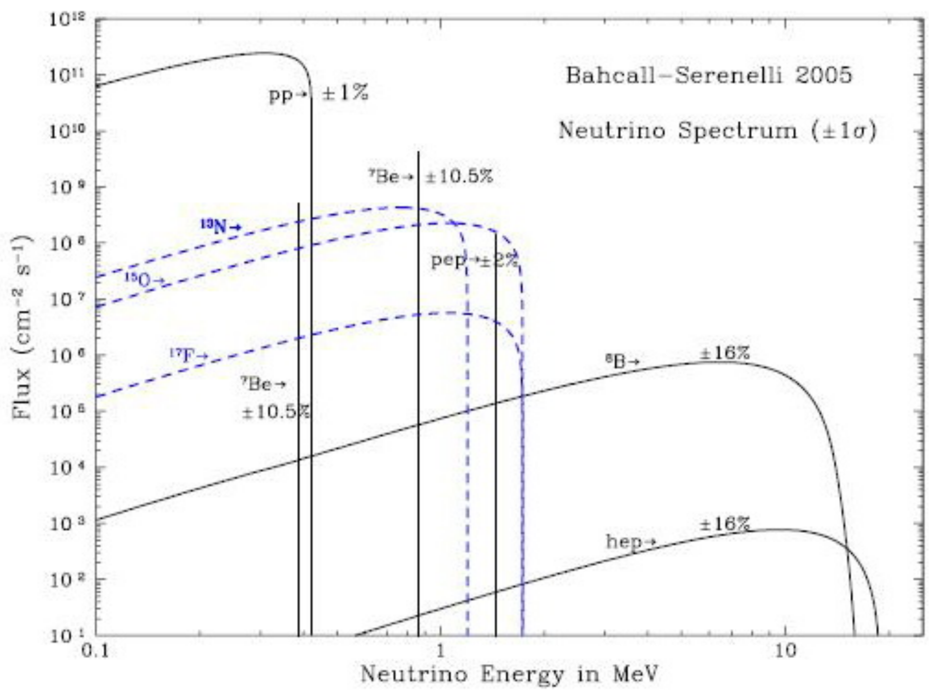
Hard (but not impossible) to detect particles

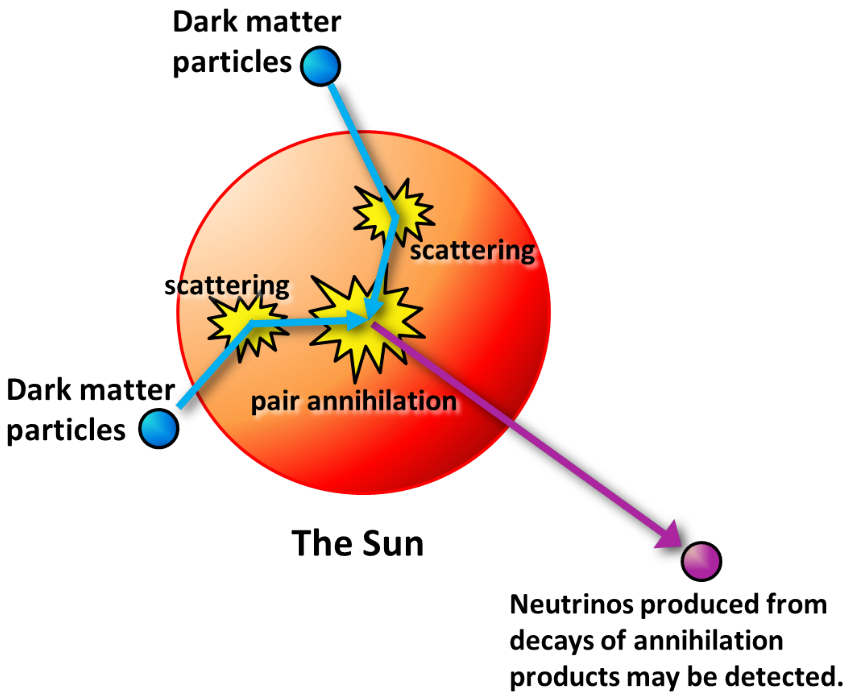
flip side: neutrinos have very **long mean free paths** in matter!

idea: DM can be **captured** in celestial bodies, **accrete** in sizable densities, start pair-annihilating

if the process of capture and annihilation is in **equilibrium**, large **fluxes** of neutrino can escape

best target: **Sun**! Large, **nearby**, **low-E** neutrino emission





Dark matter particles

scattering

scattering

pair annihilation

Dark matter particles

The Sun

Neutrinos produced from decays of annihilation products may be detected.

Estimate the process **quantitatively**!

First: **capture rate**

$$C^{\odot} \sim \phi_\chi \cdot \left(\frac{M_\odot}{m_p}\right) \cdot \sigma_{\chi-p}, \qquad \phi_\chi \sim n_\chi \cdot v_{\rm DM} = \frac{\rho_{\rm DM}}{m_\chi} \cdot v_{\rm DM}$$

$$\begin{aligned} \sigma_{\chi-p}^{\text{spin dependent}} &\lesssim 10^{-39}\ \text{cm}^2, \\ \sigma_{\chi-p}^{\text{spin independent}} &\lesssim 10^{-44}\ \text{cm}^2. \end{aligned}$$

$$C^{\odot} \sim \frac{10^{23}}{\text{s}} \left(\frac{\rho_{\rm DM}}{0.3\ \text{GeV}/\text{cm}^3}\right) \cdot \left(\frac{v_{\rm DM}}{300\ \text{km}/\text{s}}\right) \cdot \left(\frac{100\ \text{GeV}}{m_\chi}\right) \cdot \left(\frac{\sigma_{\chi-p}}{10^{-39}\ \text{cm}^2}\right)$$

Number of **accreted** DM **particles** *N*

$$\frac{\mathrm{d}N}{\mathrm{d}t} = C^{\odot} - A^{\odot}[N(t)]^2 - E^{\odot} N(t)$$

$$A^{\odot} \simeq \frac{\langle \sigma v \rangle}{V_{\mathrm{eff}}} \qquad \frac{m_\chi \, \phi_{\mathrm{grav}}(R_{\mathrm{eff}})}{T^{\odot}} \simeq 1$$

$$V_{\mathrm{eff}} \sim 10^{28}\ \mathrm{cm}^3 \ \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^{3/2}$$

$$\Gamma_A = \frac{1}{2} A^{\odot} [N(t^{\odot})]^2 = \frac{C^{\odot}}{2} \left[\tanh(\sqrt{C^{\odot} A^{\odot}}\ t^{\odot}) \right]^2$$

$$t^{\odot} \sim 4.5\ \mathrm{Byr} \sim 10^{17}\ \mathrm{s}$$

$$t^{\rm eq} \equiv \frac{1}{\sqrt{C^{\odot} A^{\odot}}} \ll t^{\odot} \qquad\qquad C^{\odot} \sim 10^{23}\ {\rm s}^{-1} \left(\frac{\sigma_{\chi-p}}{10^{-39}\ {\rm cm}^2}\right)$$

$$A^{\odot}_{\rm eq} \gg \frac{1}{(t^{\odot})^2\, C^{\odot}} = \frac{1}{10^{34}\cdot 10^{23}\ {\rm s}} \sim 10^{-57}\ {\rm s}^{-1}$$

$$A^{\odot} = 3\times 10^{-54}\ {\rm s}^{-1} \left(\frac{\langle\sigma v\rangle}{3\times 10^{-26}\ {\rm cm}^3/{\rm s}}\right)$$

So yes thermal DM is in **equilibration** as long as WIMP-nucleon cross section is **larger** than $10^{-41}\ {\rm cm}^2$

With **equilibration**, flux of neutrinos only depends on **capture rate**!

$$\Gamma_A = \frac{1}{2} A^{\odot} [N(t^{\odot})]^2 = \frac{C^{\odot}}{2} \left[\tanh(\sqrt{C^{\odot} A^{\odot}}\, t^{\odot}) \right]^2 \qquad \Gamma_A \simeq \frac{C^{\odot}}{2}$$

flux of **neutrinos** is then

$$\frac{\mathrm{d}N_{\nu_f}}{\mathrm{d}E_{\nu_f}} = \frac{C^{\odot}}{8\pi (D^{\odot})^2} \left(\frac{\mathrm{d}N_{\nu_f}}{\mathrm{d}E_{\nu_f}} \right)_{\mathrm{inj}}$$

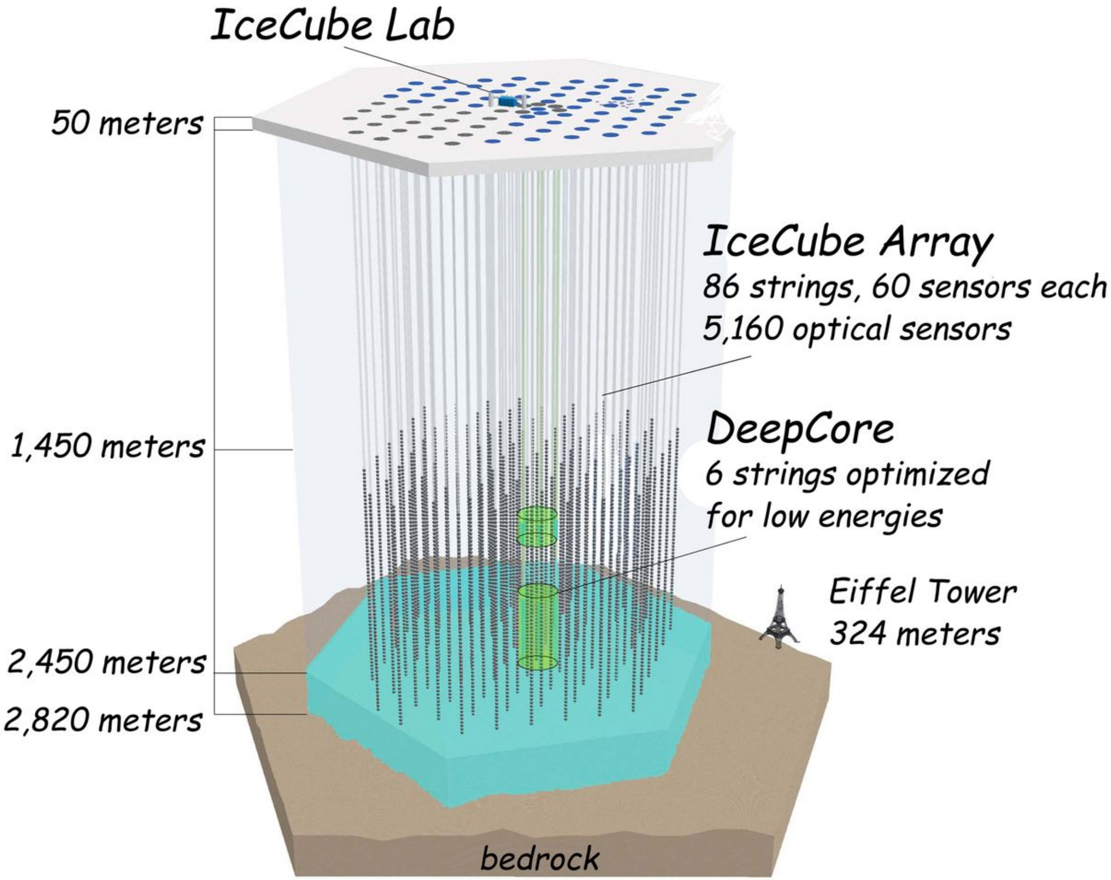
...and the number of **events** at **IceCube**

$$N_{\mathrm{events}} = \int \mathrm{d}E_{\nu_\mu} \int \mathrm{d}y \left(A_{\mathrm{eff}} \cdot \frac{\mathrm{d}N_{\nu_\mu}}{\mathrm{d}E_{\nu_\mu}} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}y}(E_{\nu_\mu}, y) \cdot (R_\mu(E_{\nu_\mu})) \right)$$

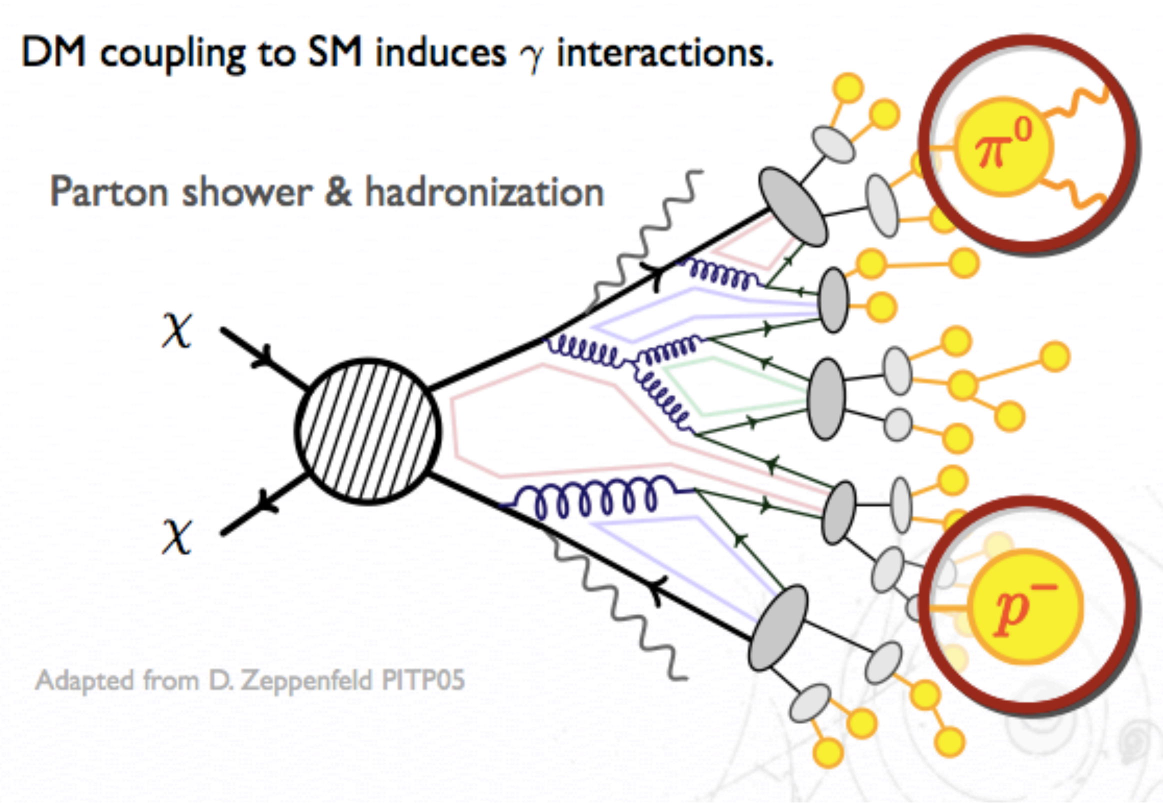
Best **final states**: *WW*, *ZZ*, or leptophilic

So far **no anomalous events** from Sun observed; **Earth** less promising

Opportunities with
lower-energy
threshold sub-detectors
DeepCore, **PINGU**

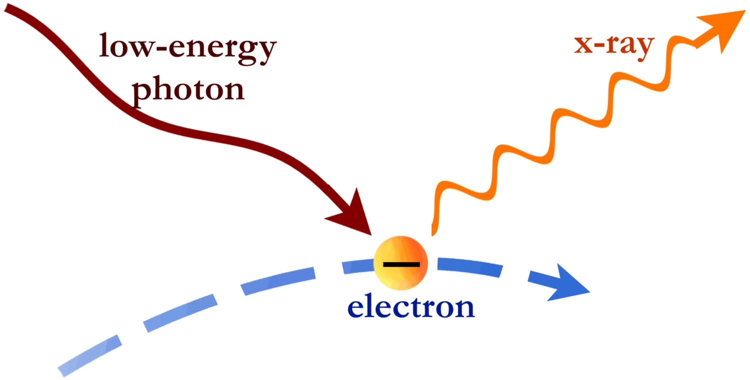


Light from **dark matter**!



Primary photons: prompt, or internal brems; just run Pythia (if you can!)

Secondary photons: IC, synchrotron

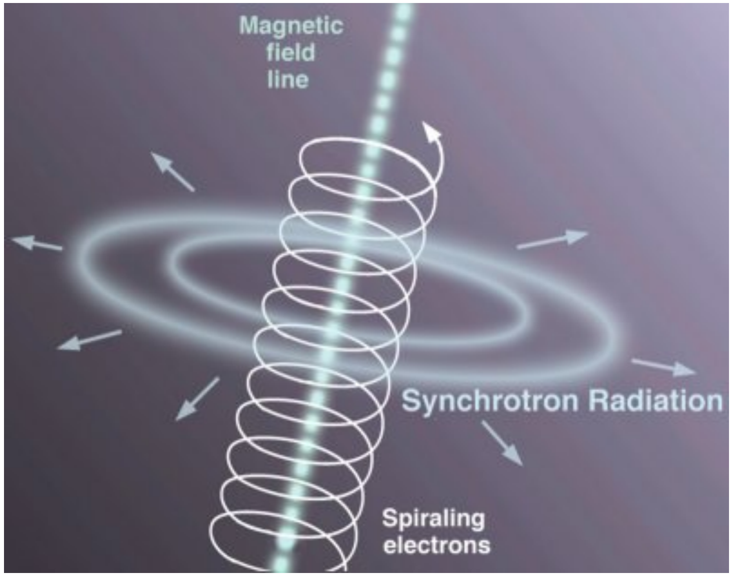


$$\langle E_0' \rangle \sim \frac{4}{3}\gamma_e^2 \, E_0.$$

$$\textbf{CMB} : E_0 \sim 2 \times 10^{-4} \text{ eV}$$
$$\textbf{starlight} : E_0 \sim 1 \text{ eV}$$
$$\textbf{dust} : E_0 \sim 0.01 \text{ eV}$$

$$E_e \sim \frac{m_\chi}{10} \rightarrow \gamma_e \sim 2 \times 10^4 \left(\frac{m_\chi}{100 \text{ GeV}}\right)$$

$$E'_{\text{CMB}} \sim 10^5 \text{ eV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2$$



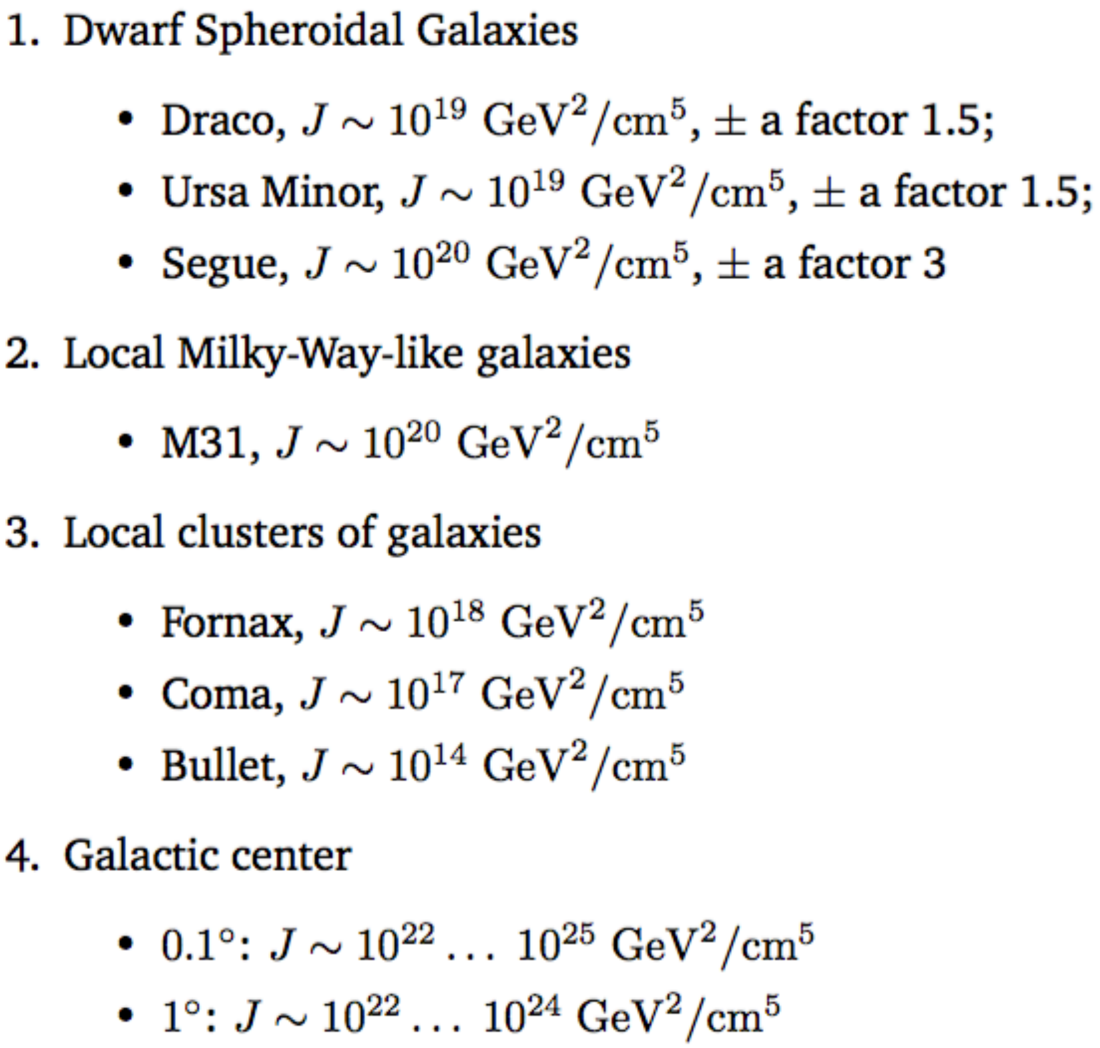
$$\frac{\nu_{\rm sync}}{\rm MHz} \simeq 10 \cdot \left(\frac{E_e}{\rm GeV}\right)^2 \left(\frac{B}{\mu{\rm G}}\right) \simeq 2.8 \cdot \left(\frac{\gamma_e}{1000}\right)^2 \left(\frac{B}{\mu{\rm G}}\right)$$

Prompt emission simply depends on **annihilation** final state, and **target** of choice

$$\phi_\gamma = \frac{\Delta\Omega}{4\pi} \boxed{\left\{ \frac{1}{\Delta\Omega} \int \mathrm{d}\Omega \int \mathrm{d}l(\psi) \;\; (\rho_{\mathrm{DM}})^2 \right\}} \frac{\langle\sigma v\rangle}{2m_\chi^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$

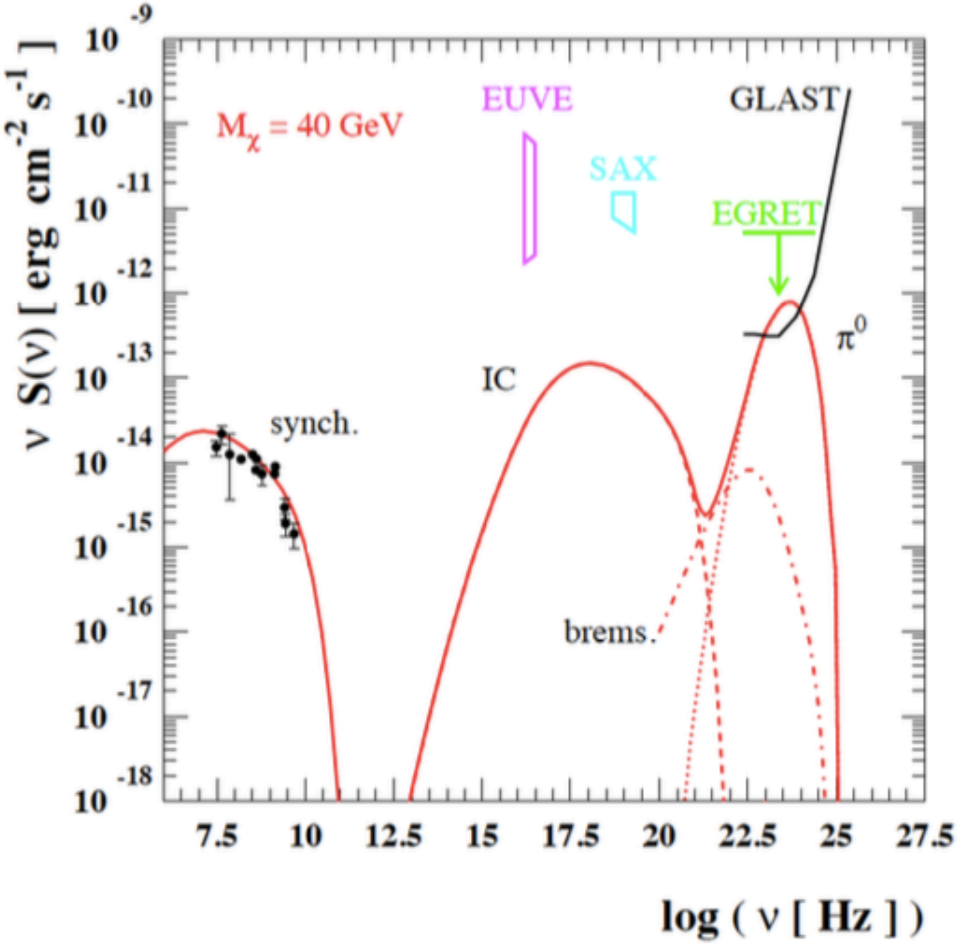
$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = \sum_f \frac{\mathrm{d}N_\gamma^f}{\mathrm{d}E_\gamma}$$

Angular region varies from 1 degree, to 0.1 degrees (10^{-3}, 10^{-5} sr, resp)

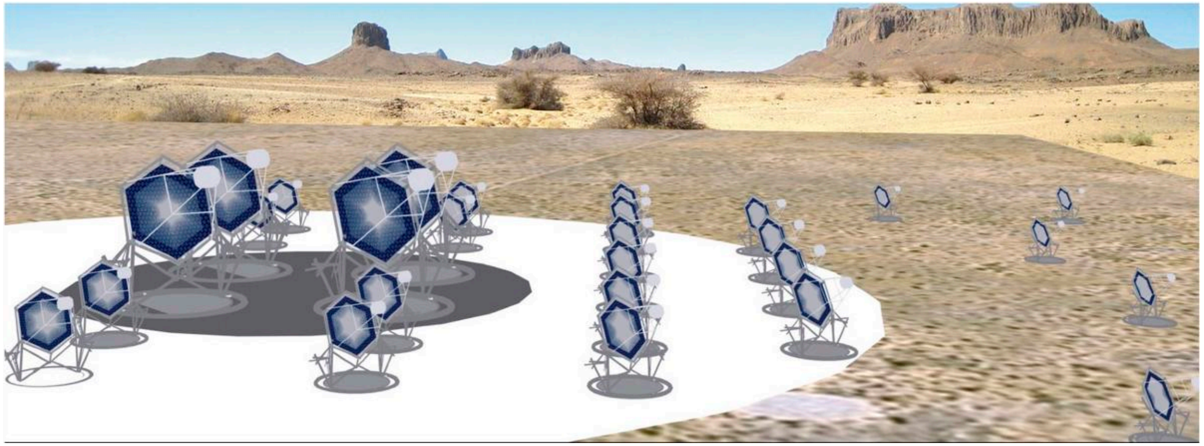


1. Dwarf Spheroidal Galaxies
    - Draco, $J \sim 10^{19}\ \mathrm{GeV}^2/\mathrm{cm}^5$, ± a factor 1.5;
    - Ursa Minor, $J \sim 10^{19}\ \mathrm{GeV}^2/\mathrm{cm}^5$, ± a factor 1.5;
    - Segue, $J \sim 10^{20}\ \mathrm{GeV}^2/\mathrm{cm}^5$, ± a factor 3
2. Local Milky-Way-like galaxies
    - M31, $J \sim 10^{20}\ \mathrm{GeV}^2/\mathrm{cm}^5$
3. Local clusters of galaxies
    - Fornax, $J \sim 10^{18}\ \mathrm{GeV}^2/\mathrm{cm}^5$
    - Coma, $J \sim 10^{17}\ \mathrm{GeV}^2/\mathrm{cm}^5$
    - Bullet, $J \sim 10^{14}\ \mathrm{GeV}^2/\mathrm{cm}^5$
4. Galactic center
    - 0.1°: $J \sim 10^{22} \ldots\ 10^{25}\ \mathrm{GeV}^2/\mathrm{cm}^5$
    - 1°: $J \sim 10^{22} \ldots\ 10^{24}\ \mathrm{GeV}^2/\mathrm{cm}^5$

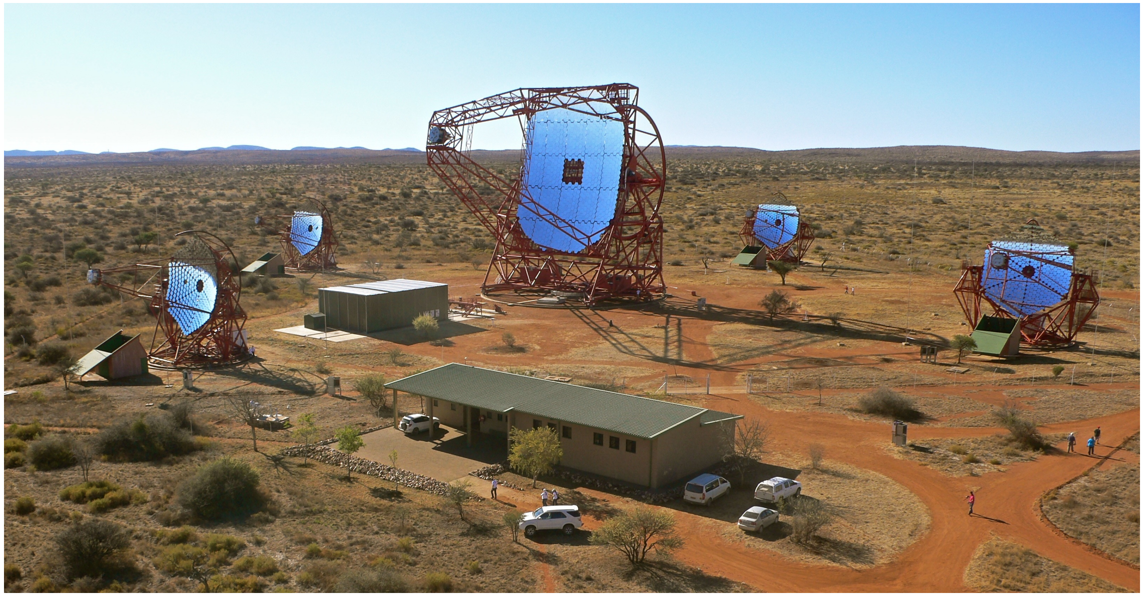
Overall **emission** looks like this, e.g. in a **cluster** of galaxies



here, **normalization** chosen to fit radio emission



	Fermi-LAT	H.E.S.S.	CTA
E_γ range $A_{\rm eff}$ $T_{\rm obs}$	0.1 to 300 GeV ~ 1 m^2 $\sim 10^8$ s	0.1 to 10 TeV $\sim 10^5$ m^2 $\sim 10^6$ s	10 GeV to 10 TeV $\sim 10^6$ m^2 $\sim 10^6$ s



to have a **detection**: collect **some photons**, beat **background** (S/N>>1)

$$\int \mathrm{d}E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \sim \frac{m_\chi}{\mathrm{GeV}}$$

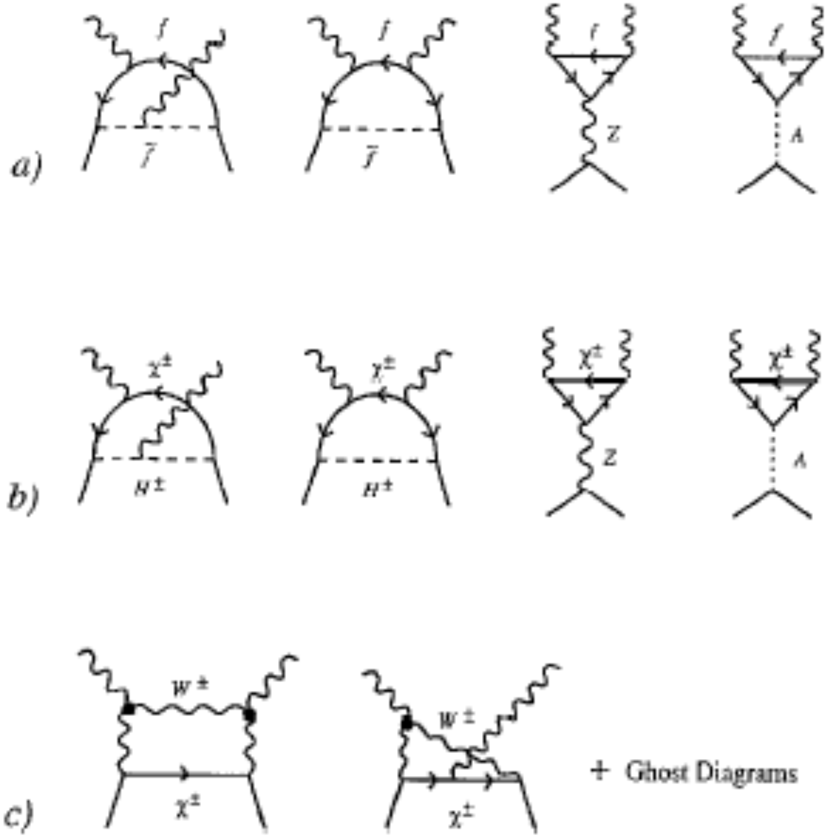
$$\phi_\gamma = (\Delta\Omega \cdot J)\, \frac{1}{8\pi}\, \frac{\langle \sigma v \rangle}{m_\chi^2} \cdot m_\chi \sim 10^{-32} \frac{1}{\mathrm{cm}^2\ \mathrm{s}} \left(\frac{J}{\mathrm{GeV}^2/\mathrm{cm}^5} \right)$$

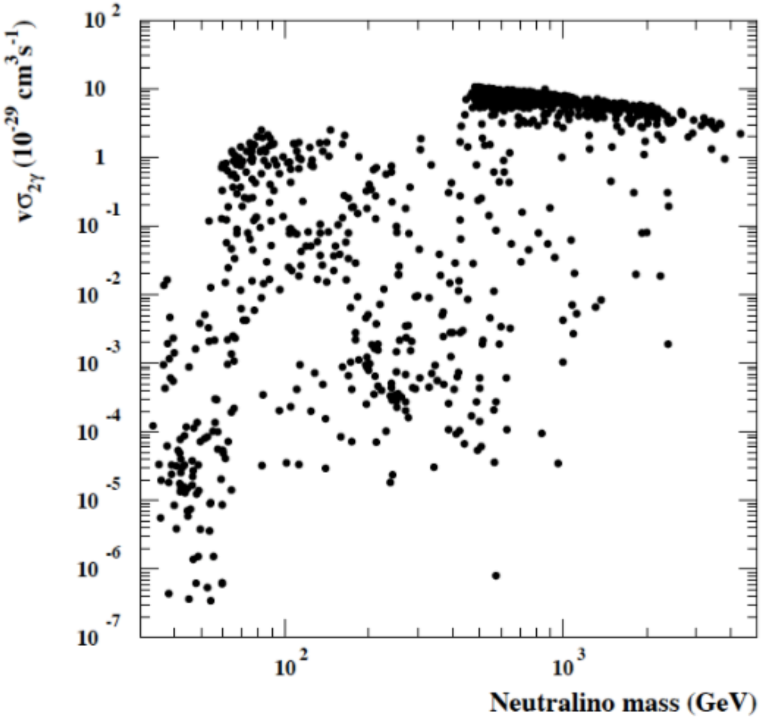
$$N_\gamma \sim A_{\mathrm{eff}} \cdot T_{\mathrm{obs}} \cdot \phi_\gamma \sim 10^{-20} \frac{J}{\mathrm{GeV}^2/\mathrm{cm}^5}$$

$$J^{\mathrm{tot}} \sim \mathrm{few} \times 10^{20}\ \mathrm{GeV}^2/\mathrm{cm}^5, \qquad \langle \sigma v \rangle_{\mathrm{lim}} \sim 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{30\ \mathrm{GeV}}{m_\chi} \right)$$

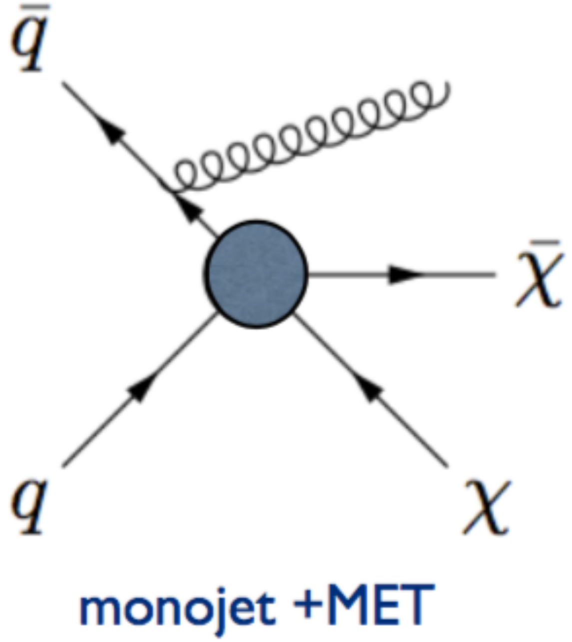
In addition, **monochromatic** photons $\chi\chi \to \gamma\gamma$

$$\frac{\langle\sigma v\rangle_{\gamma\gamma}}{\langle\sigma v\rangle_{\mathrm{tot}}} \sim \frac{\alpha^2}{16\pi^2}$$





DM particles can be produced at **colliders**, but at very **low rates** compared to Galactic DM fluxes... (see problem on next slide)



Idea: look for **anomalous** events with missing energy and **SM particles** (e.g. monojets, monophotons, etc)

Exercise We want to compare the Galactic dark matter flux at Earth with the flux of dark matter that might be expected from collider production.
Assume $\rho_{\rm DM}(r_\oplus) = 0.3~{\rm GeV/cm^3}$, $v = 220$ km/s. Assume that an LHC detector has an instantaneous luminosity $\dot{\mathcal{L}} = 5 \times 10^{33}~{\rm cm^{-2}s^{-1}}$.

(i) Get an expression for the flux of dark matter particles produced at the LHC detector under consideration at a distance R, assuming isotropic production (discuss how realistic this assumption is), as a function of the total dark matter pair-production cross section $\sigma_{\rm LHC} = \sigma(pp \to \chi\chi + \text{anything})$.

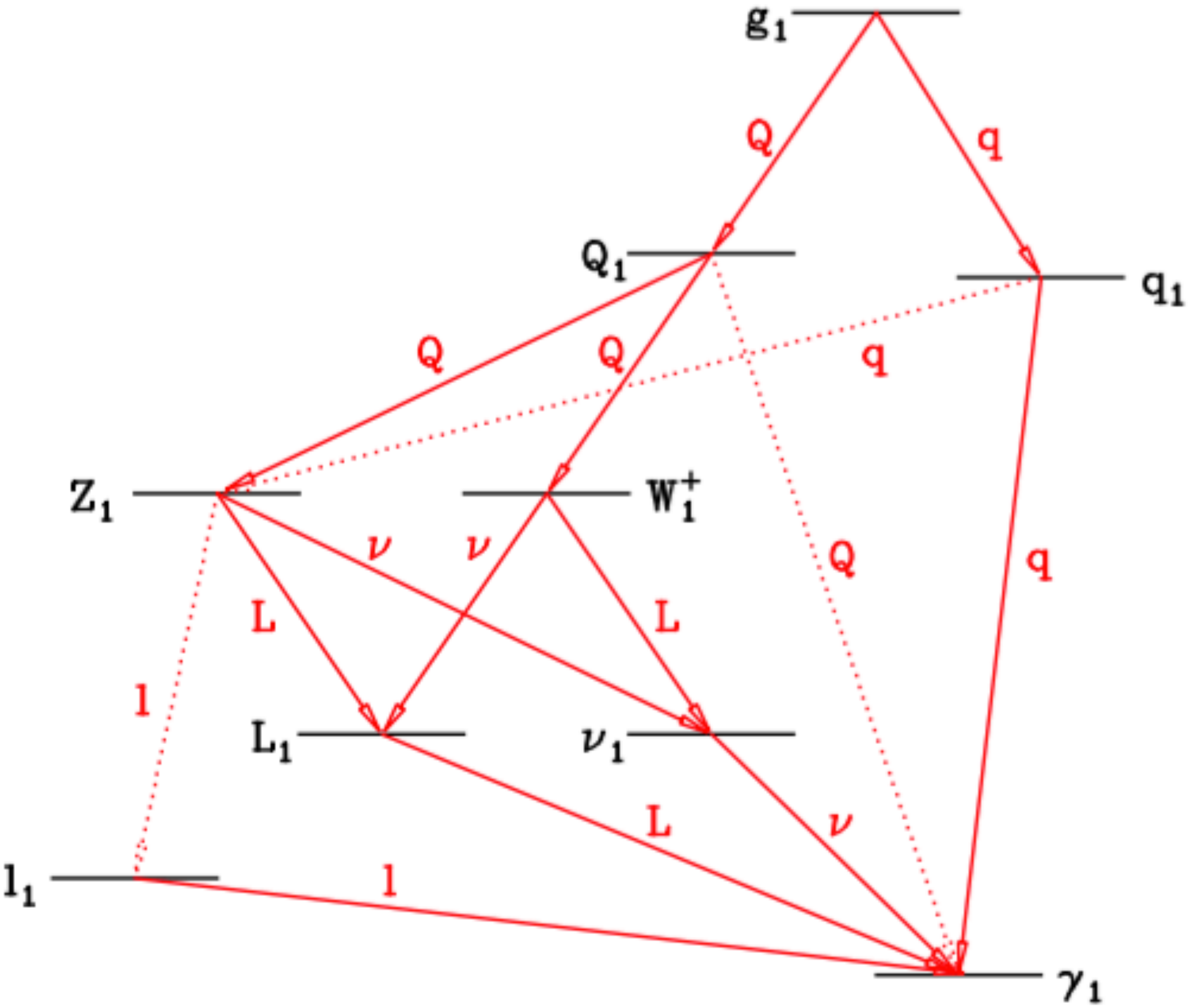
(ii) Assume $m_\chi = 100$ GeV, and a weak-interaction cross section $\sigma_{\rm LHC} = G_F^2 m_\chi^2$. Compare the flux from LHC production at $R = 10$ m with the Galactic flux.

(iii) For which $\sigma_{\rm LHC}$ are the two fluxes comparable?

Two possible **approaches**:

(i) **top-down**: pick a model, select best search strategies, optimize cuts, scan parameter space (e.g. SUSY, UED)

(ii) **bottom-up**: effective theory, or simplified model – sketch of how DM could manifest itself at colliders...


g_1
Q
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Q_1
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Q
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Z_1
W_1^+
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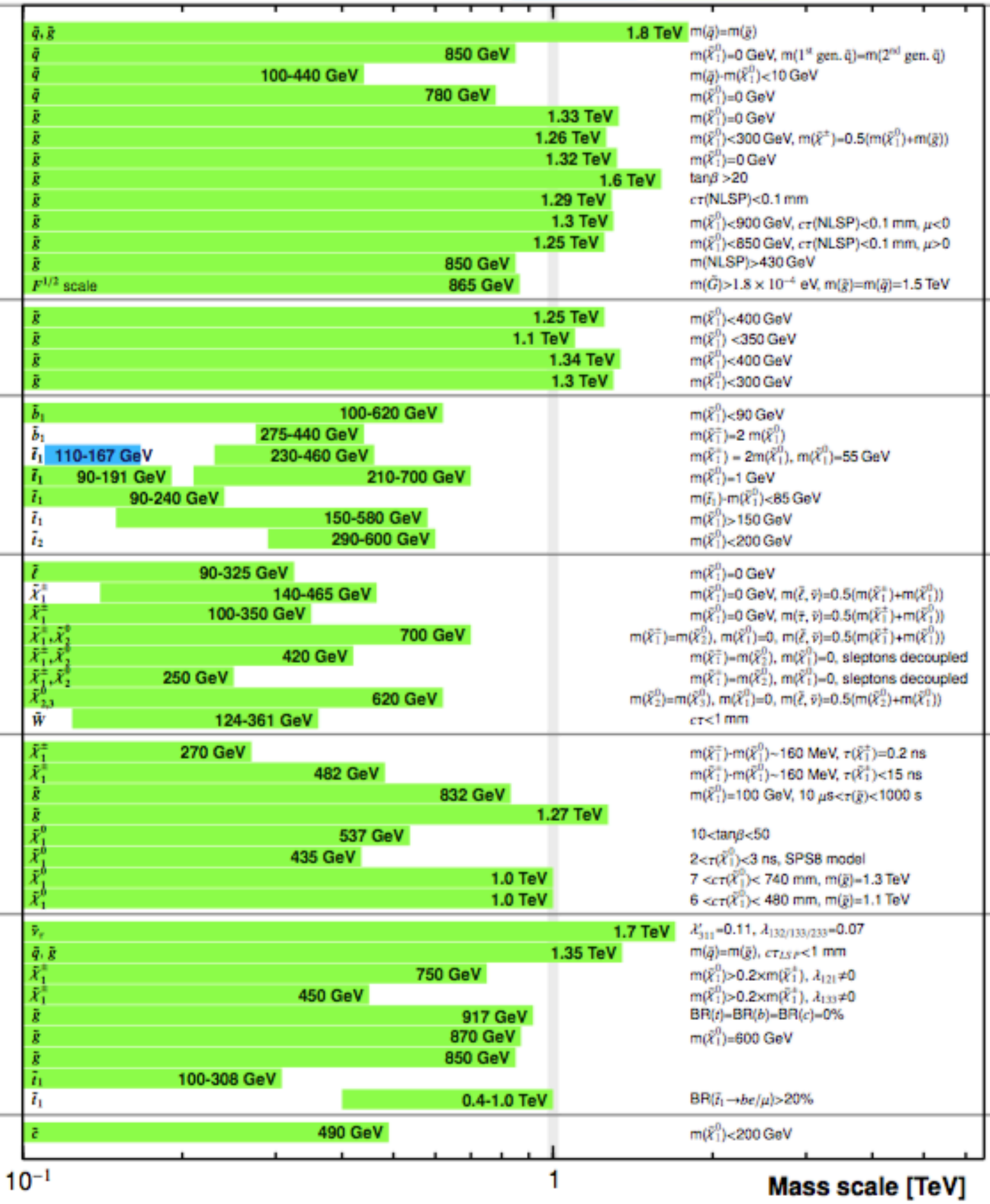
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

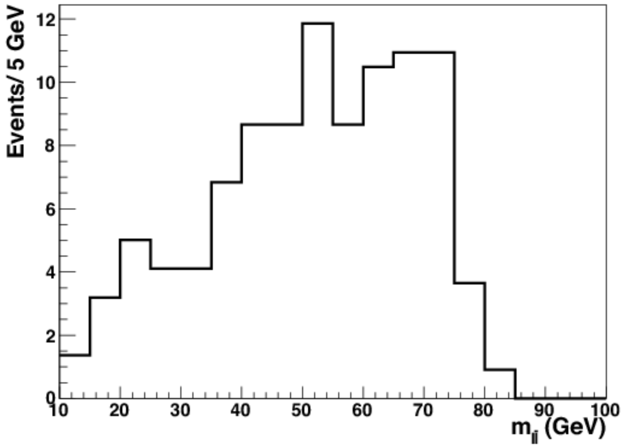


	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.8 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})$>1.8×10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 🟦 110-167 GeV 🟩 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 210-700 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 482 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	$m(\tilde{\chi}_1^0)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Particle properties can then be **reconstructed** using e.g. kinematic edges in invariant mass distributions:

$\tilde{\chi}_2^0 \to l\bar{l}\tilde{\chi}_1^0$ $m_{12} = \sqrt{p_1^2 + p_2^2}$ $m_{12} \leq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$



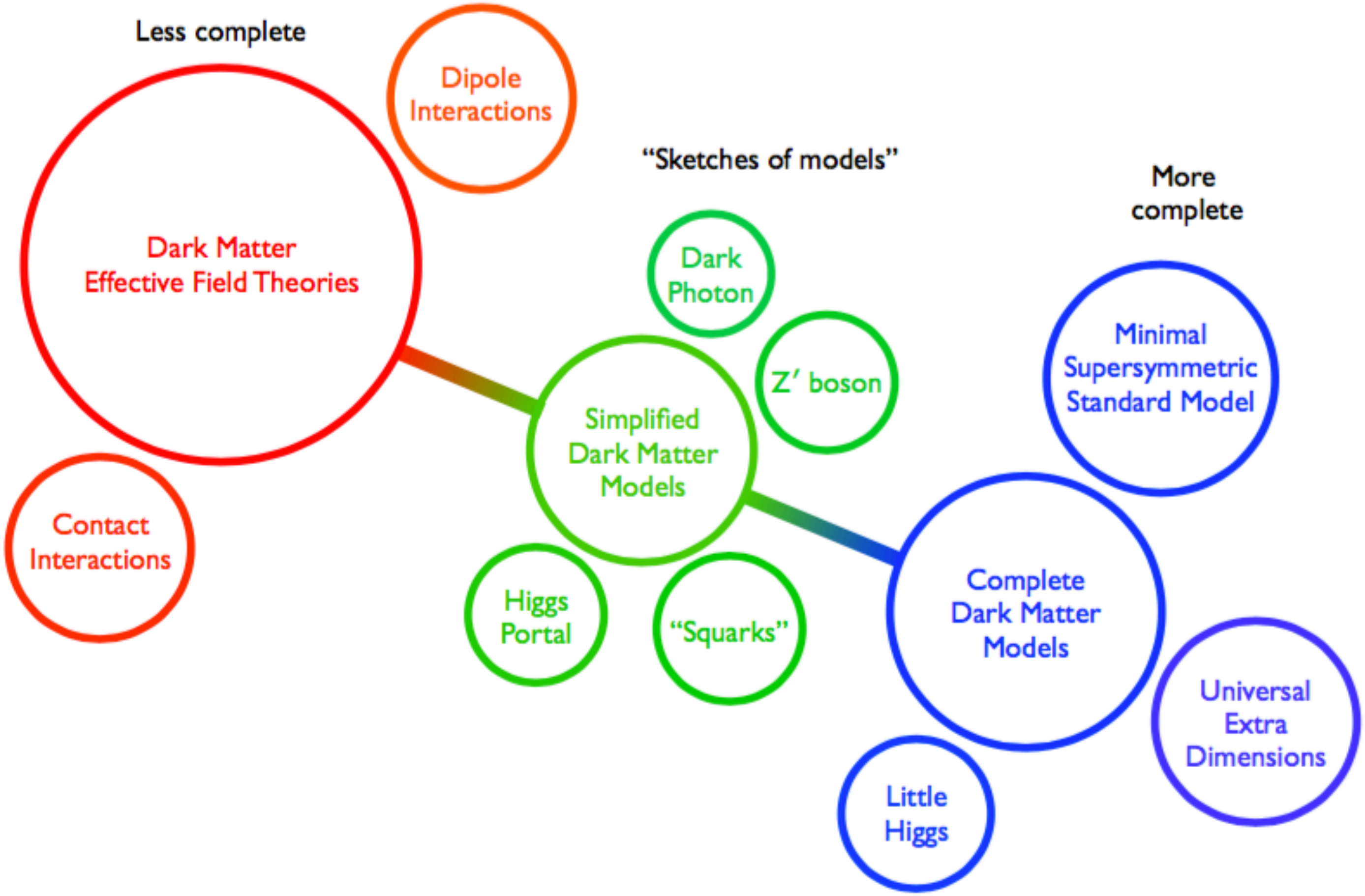
$\tilde{\chi}_2^0 \to \tilde{l}\,\bar{l} \to l\,\tilde{\chi}_1^0\,\bar{l}.$ $m_{12} < m_{\tilde{\chi}_1^0}\sqrt{1 - \frac{m_{\tilde{l}}}{m_{\tilde{\chi}_2^0}}}\sqrt{1 - \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{l}}}} \leq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

Possible to construct **invariant mass** of multiple particles,

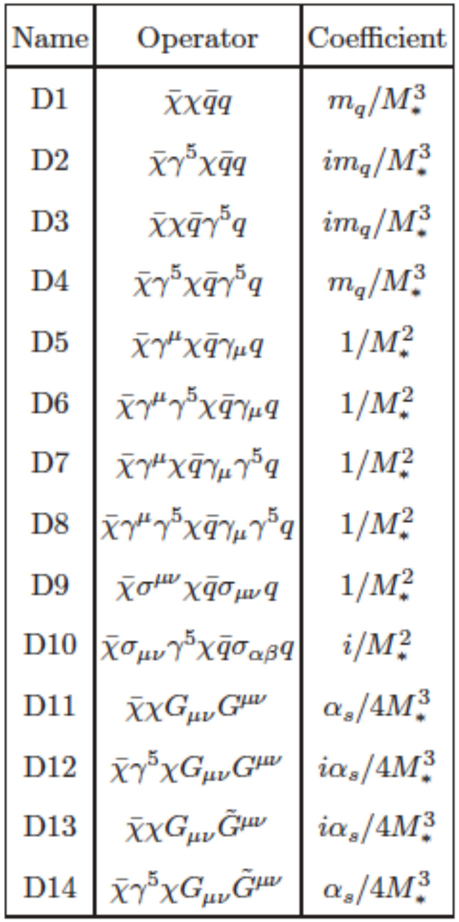
$$\tilde{q}_L \to q\tilde{\chi}^0_2 \to q\tilde{l}^{\pm}l^{\mp} \to q l^{\pm}l^{\mp}\tilde{\chi}^0_1$$

$$m(l\bar{l}q) \leq m_{\tilde{q}}\sqrt{1 - \frac{m_{\tilde{\chi}^0_2}}{m_{\tilde{q}}}}\sqrt{1 - \frac{m_{\tilde{\chi}^0_1}}{m_{\tilde{\chi}^0_2}}}.$$

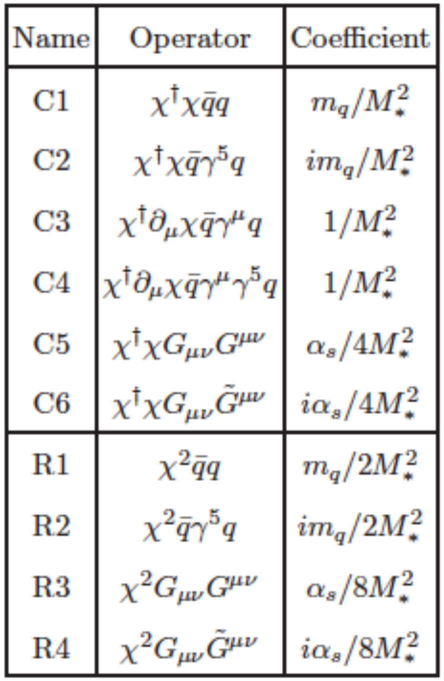
Name of the game: devise **cuts**
(missing energy, number of jets, OS, SS leptons etc)
that **maximize S/N**


Less complete
Dark Matter Effective Field Theories
Dipole Interactions
Contact Interactions
"Sketches of models"
Dark Photon
Z′ boson
Simplified Dark Matter Models
Higgs Portal
"Squarks"
More complete
Minimal Supersymmetric Standard Model
Complete Dark Matter Models
Universal Extra Dimensions
Little Higgs

EFT approach: assume some quantum numbers for DM (*m*,*J*), write down effective operators



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	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$



Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

arXiv:1008.1783 [hep-ph]

Algorithm is usual: calculate **production** cross section, **simulate** events, devise best possible set of **cuts**, compare **S/N**, set **limits** on effective operator scale

Issue: EFT has certain **range of validity**!
("cutoff") scale Λ corresponds to

$$\Lambda \sim M/\sqrt{g_1 g_2}.$$

Whether or not constraints make sense depends on whether the typical energy of the reaction (say momentum transfer P_{tr}) is smaller than, say, $\mathbf{4\pi\Lambda}$

Good example of a **test**:

$$R(\Lambda) = \frac{\sigma(P_{\rm tr} < 4\pi\Lambda)}{\sigma(\text{any } P_{\rm tr})}$$

In practice, scales probed by LHC very **borderline** for EFT to make sense... cutoff scale close to P_{tr},
one would expect to produce new physics **on-shell**...

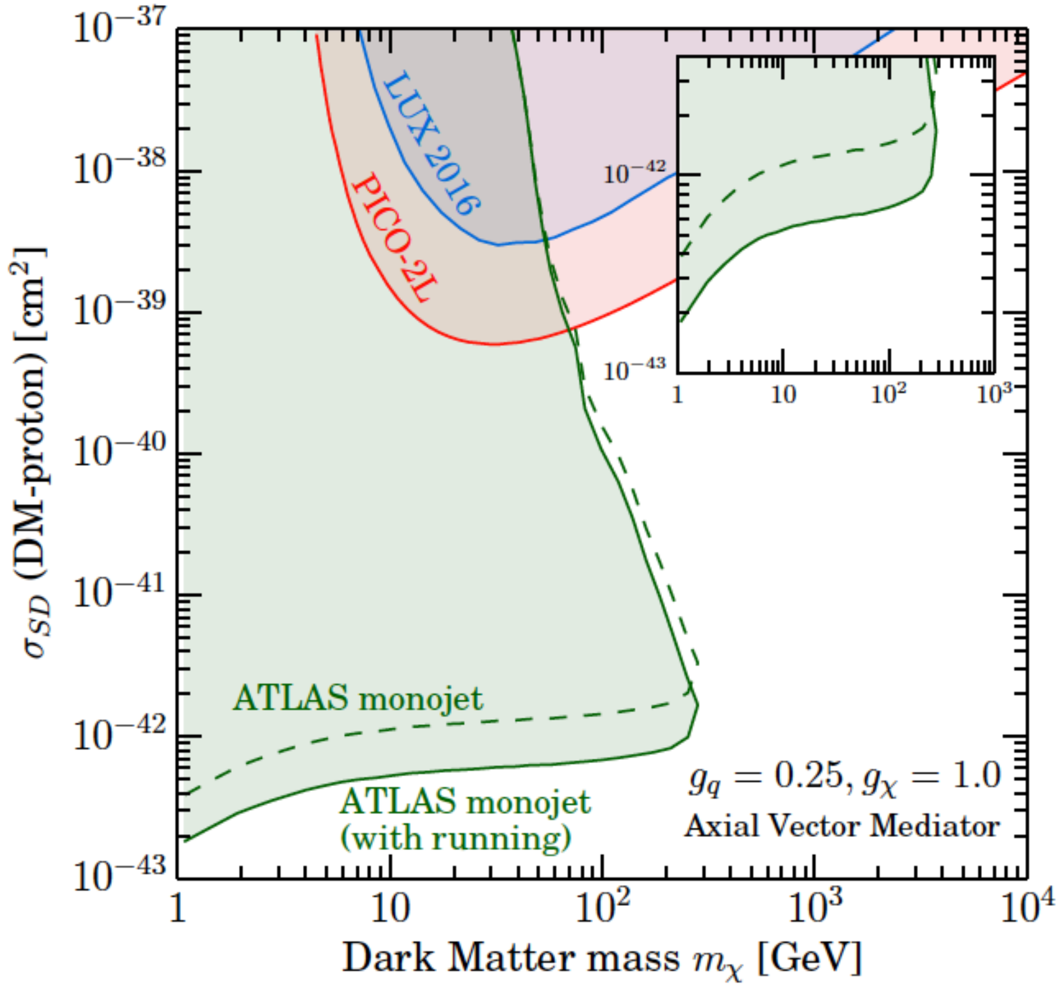
Alternate approach of **simplified models**, e.g.

$$\mathcal{L}_S \supset -\frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j \ + \ \text{h.c.}$$

$$\mathcal{L}_V \supset -\frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu \bar{\chi}\gamma^\mu \chi - g_q^{ij} V_\mu \bar{q}_i \gamma^\mu q_j \ + \ \text{h.c.}.$$

Set (meaningful) constraints on combinations of **mediator mass** and **couplings**, for given DM masses

Can **compare** with **direct detection** results, but beware of RG effects in **matching scales**!!



σ_{SD} (DM-proton) [cm^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10
10^2
10^3
10^4
Dark Matter mass m_χ [GeV]
LUX 2016
PICO-2L
ATLAS monojet
ATLAS monojet (with running)
$g_q = 0.25, g_\chi = 1.0$
Axial Vector Mediator
10^{-42}
10^{-43}
1
10
10^2
10^3

Additional probe: invisible **Higgs decay** to DM!

$$\lambda_{H\chi\chi}\,\bar{\chi}\chi|H|^2$$

$$\Gamma_H^{\rm inv} = \frac{{\rm BR}(H \to {\rm invisible})}{1 - {\rm BR}(H \to {\rm invisible})} \times \Gamma_H$$