Dark matter in the coming decade:

Complementary paths to discovery and beyond

(CliffsNotes version)

Snowmass 2013 Cosmic Frontier Working Group 4:
Dark Matter Complementarity*

Cosmic Frontier Workshop, March 6, 2013

*Suggestions and corrections are most welcome and should be directed to one or more of the following contributors: Jim Buckley, Jonathan Feng, Manoj Kaplinghat, Konstantin Matchev, Dan McKinsey, and Tim Tait

Intro: part I

- Dark matter is six times as prevalent as normal matter in the Universe, but its identity is unknown. Dark matter is a grand challenge for fundamental physics and astronomy. Its mere existence implies that our inventory of the basic building blocks of nature is incomplete, and uncertainty about its properties clouds all attempts to understand how the universe evolved to its present state and how it will evolve in the future. At the same time, the field of dark matter will be transformed in the coming decade. This prospect has drawn many new researchers to the field, which is now characterized by an extraordinary diversity of approaches unified by the common goal of discovering the identity of dark matter.

Intro: part II

- As we will discuss, a compelling solution to the dark matter problem requires synergistic progress along many lines of inquiry. Our primary conclusion is that the diversity of possible dark matter candidates requires a balanced program based on four pillars: direct detection experiments that look for dark matter interacting in the lab, indirect detection experiments that connect lab signals to dark matter in the galactic halos, collider experiments that elucidate the particle properties of dark matter, and astrophysical probes that determine how dark matter has shaped the evolution of large-scale structures in the Universe.

Intro: part III

- In this Report we summarize the many dark matter searches currently being pursued in each of these four approaches. The essential features of broad classes of experiments are described, each with their own strengths and weaknesses. The goal of this Report is not to prioritize individual experiments, but rather to highlight the complementarity of the four general approaches that are required to sustain a vital dark matter research program. Complementarity also exists on many other levels,of course; in particular, complementarity *within* each approach is also important, but will be addressed by the Snowmass Cosmic Frontier subgroups that focus on each approach.

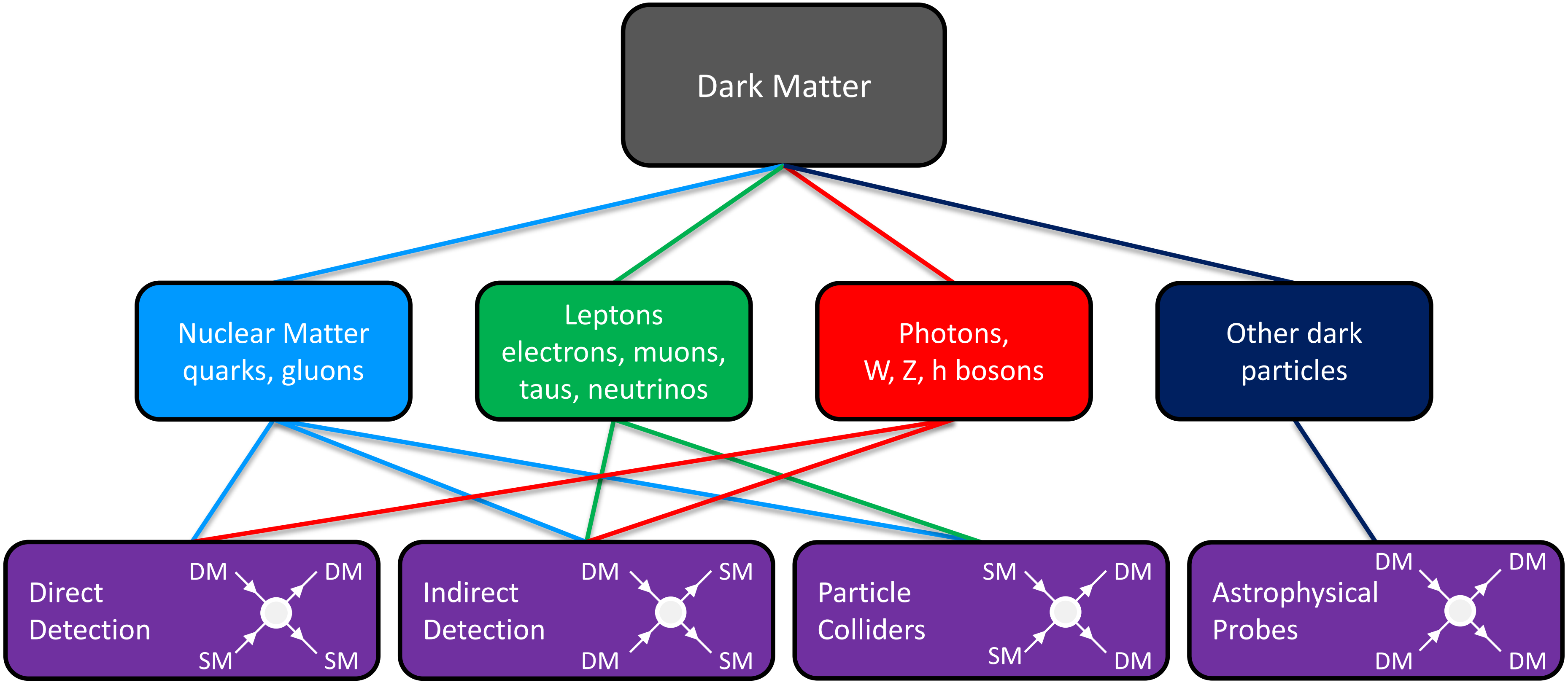
Table of Contents

What is dark matter?

- Overwhelming observational evidence for it
  - 6 times as prevalent as normal matter
- We are completely ignorant about its properties
  - mass, spin, lifetime, gauge quantum numbers
  - there could even be several DM species
- It could couple to any of the SM particles
  - including hidden sector particles
- There are many possibilities, including:
  - WIMPs (studied by CF1, CF2)
  - Asymmetric DM (CF1)
  - Axions (CF3)
  - Sterile neutrinos (CF3)
  - Hidden sector DM (CF4)

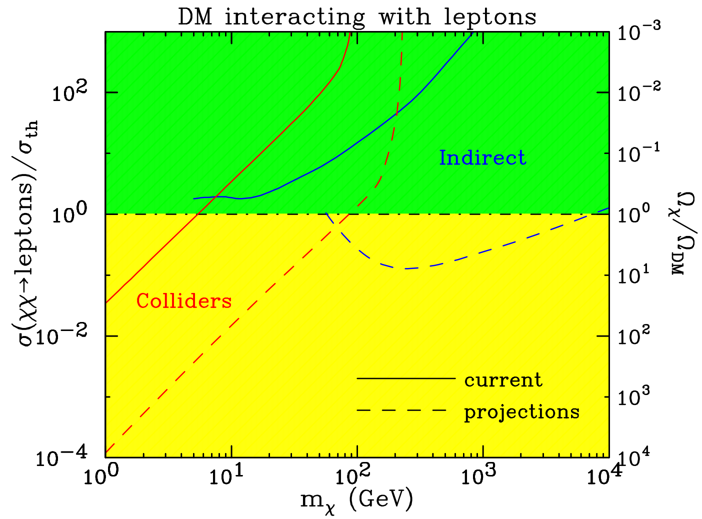
DM interactions vs. DM probes

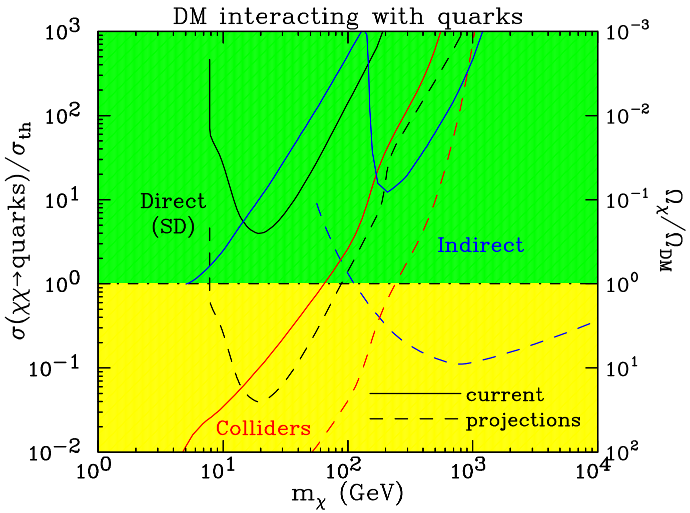
- For the purposes of this report, DM candidates are categorized according to their basic interactions

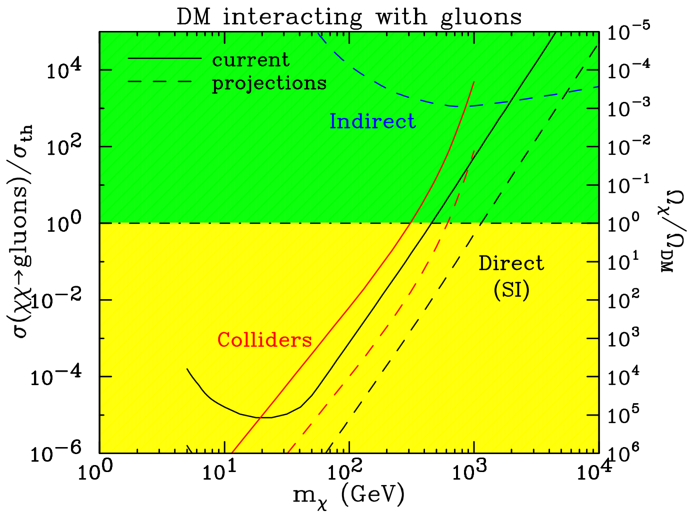


Concrete illustration of complementarity

- Different experimental probes fall in different regions
  - detailed explanation of these plots will follow shortly







Appendices: lists of experiments

DIRECT DETECTION

TABLE I: Current and planned direct detection experiments.

Status	Experiment	Target	Technique	Location	Major Support	Comments
Current	LUX	350 kg liquid Xe	Ion., Scint.	SURF	DOE, NSF, European	
Planned	LZ	7 ton liquid Xe	Ion., Scint.	SURF	DOE, NSF, European	
Current	Xenon100	62 kg liquid Xe	Ion., Scint.	LNGS	DOE, NSF, European	
Planned	Xenon1T	3 ton liquid Xe	Ion., Scint.	LNGS	DOE, NSF, European	
Planned	PandaX-1	1.2 ton liquid Xe	Ion., Scint.	Jinping	Chinese	
Planned	PandaX-2	3 ton liquid Xe	Ion., Scint.	Jinping	Chinese	
Current	XMASS-I	800 kg liquid Xe	Scint.	Kamioka	Japanese	
Planned	XMASS-1.5	5 ton liquid Xe	Scint.	Kamioka	Japanese	
Current	DarkSide-50	50 kg liquid Ar	Ion., Scint.	LNGS	DOE, NSF, European	
Planned	DarkSide-G2	5 ton liquid Ar	Ion., Scint.	LNGS	DOE, NSF, European	
Current	ArDM	1 ton liquid Ar	Ion., Scint.	Canfranc	European	
Current	MiniCLEAN	500 kg liquid Ar/Ne	Scint.	SNOLab	DOE	
Current	DEAP-3600	3.6 ton liquid Ar	Scint.	SNOLab	Canadian	
Planned	CLEAN	40 ton liquid Ar/Ne	Scint.	SNOLab	DOE	
Current	COUPP-60	CF_3I	Bubbles	SNOLab	DOE, NSF	
Planned	COUPP-1T	CF_3I	Bubbles	SNOLab	DOE, NSF	
Current	PICASSO		Bubbles	SNOLab	Canadian	
Current	SIMPLE		Bubbles	Canfranc	European	
Current	SuperCDMS	10 kg Ge	Ion., Phonons	Soudan	DOE, NSF	
Planned	SuperCDMS	100 kg Ge	Ion., Phonons	Soudan	DOE, NSF	
Current	Edelweiss	4 kg Ge	Ion., Phonons	Modane	European	
Current	CRESST	10 kg $CaWO_4$	Scint., Phonons	LNGS	European	
Planned	EURECA	Ge, $CaWO_4$				
Current	CoGeNT	Ge	Ion.	Soudan	DOE	
Current	TEXONO	Ge	Ion.		Chinese	
Current	DAMA/LIBRA	NaI			European	
Current	ELEGANT	NaI			Japanese	
Planned	DM-Ice	NaI				
Planned	CINDMS	NaI			Chinese	
Current	KIMS	CsI				
Current	DRIFT		Ion.			
Current	DMTPC	CF_4 gas	Ion.	WIPP		
Planned	NEXT	Xe gas	Ion., Scint.	Canfranc		
Planned	MIMAC		Ion.	Modane		
Planned	Superfluid He-4					
Planned	DNA	DNA				
TO BE CONTINUED						

INDIRECT DETECTION

TABLE II: Current and planned indirect detection experiments.

Status	Experiment	Target	Location	Major Support	Comments
Current	AMS	e^+/e^-, anti-nuclei	ISS	NASA	Magnet Spectrometer, Running
	Fermi	Photons, e^+/e^-	Satellite	NASA, DOE	Pair Telescope and Calorimeter, Running
	HESS	Photons, e^-	Namibia	German BMBF, Max Planck Society, French Ministry for Research, CNRS-IN2P3, UK PPARC, South Africa	Atmospheric Cherenkov Telescope (ACT), Running
	IceCube/ DeepCore	Neutrinos	Antarctica	NSF, DOE, International *Belgium, Germany, Japan, Sweden)	Ice Cherenkov, Running
	MAGIC	Photons, e^+/e^-	La Palma	German BMBF and MPG, INFN, WSwiss SNF, Spanish MICINN, CPAN, Bulgarian NSF, Academy of Finland, DFG, Polish MNiSzW	ACT, Running
	PAMELA	e^+/e^-	Satellite		
	VERITAS	Photons, e^+/e^-	Arizona, USA	DOE, NSF, SAO	ACT, Running
	ANTARES	Neutrinos	Mediterranean	France, Italy, Germany, Netherlands, Spain, Russia, and Morocco	Running
Planned	CALET	e^+/e^-	ISS	Japan JAXA, Italy ASI, NASA	Calorimeter
	CTA	Photons	ground-based (TBD)	International (MinCyT, CNEA, CONICET, CNRS-INSU, CNRS-IN2P3, Irfu-CEA, ANR, MPI, BMBF, DESY, Helmholtz Association, MIUR, NOVA, NWO, Poland, MICINN, CDTI, CPAN, Swedish Research Council, Royal Swedish Academy of Sciences, SNSF, Durham UK, NSF, DOE	ACT
	GAMMA-400	Photons	Satellite	Russian Space Agency, Russian Academy of Sciences, INFN	Pair Telescope
	GAPS	Anti-deuterons	Balloon (LDB)	NASA, JAXA	TOF, X-ray and Pion detection
	HAWC	Photons, e^+/e^-	Sierra Negra	NSF/DOE	Water Cherenkov, Air Shower Surface Array
	IceCube/ PINGU	Neutrinos	Antarctica	NSF, Germany, Sweden, Belgium	Ice Cherenkov
	KM3NeT	Neutrinos	Mediterranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov
	ORCA	Neutrinos	Mediterranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov
TO BE CONTINUED					

COLLIDERS

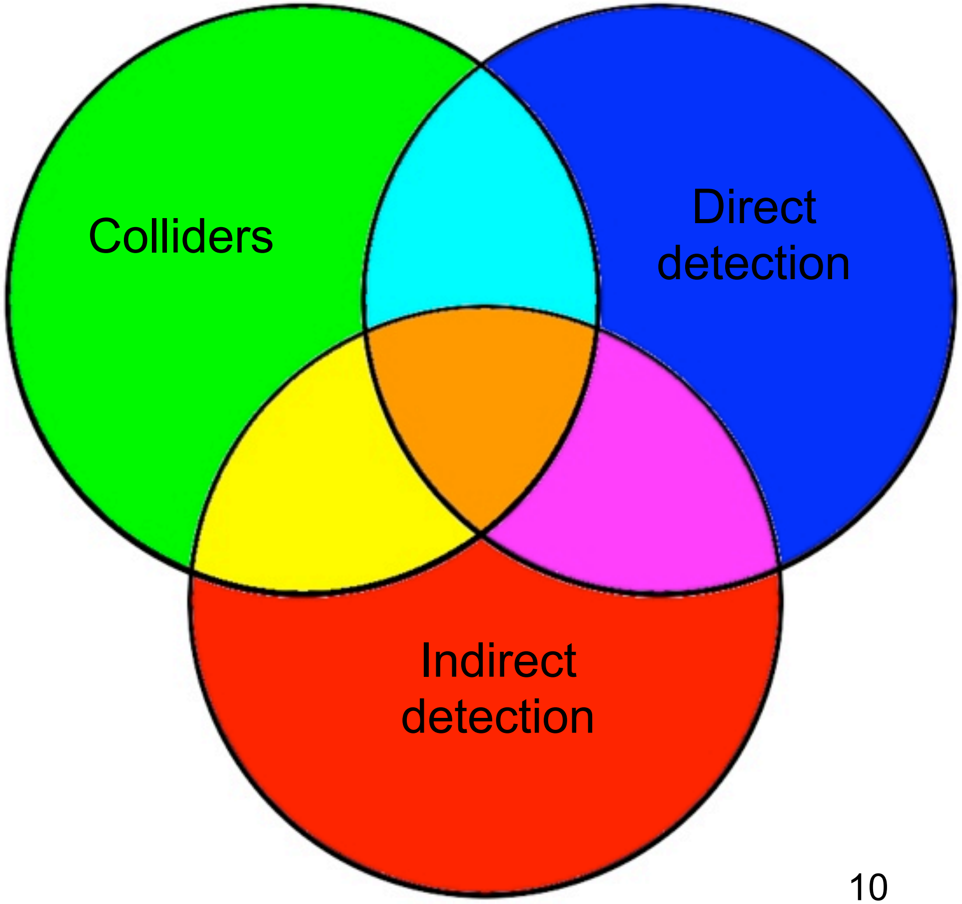
TABLE III: Current and proposed particle colliders.

Status	Collider	Type	E_{COM}, Luminosity	Major Support	Comments
Current	LHC	pp	8 TeV, 20 fb^{-1}	DOE, NSF	
Upcoming	LHC	pp	14 TeV, 300 fb^{-1}	DOE, NSF	
Proposed	HL LHC	pp	14 TeV, 3000 fb^{-1}		
Proposed	VLHC	pp	33-100 TeV		
Proposed	Higgs Factory	e^+e^-	250 GeV		
Proposed	ILC, CLIC	e^+e^-	0.5-3 TeV		
Proposed	Muon Collider	$\mu^+\mu^-$	6 TeV		
TO BE CONTINUED					

How to illustrate complementarity?

CPM Meeting, Fermilab 2012

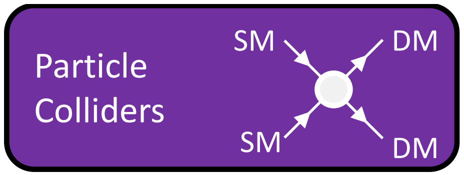
- Qualitatively: the presence of a signal in:

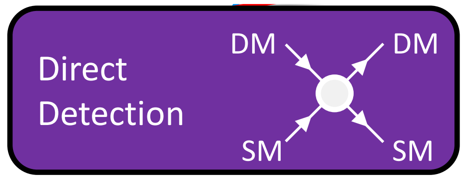


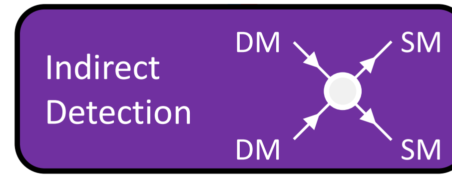
The point being this:

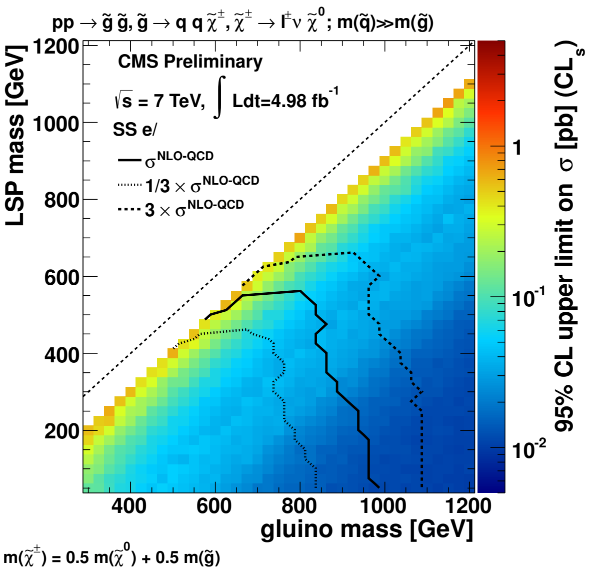
How to illustrate complementarity?

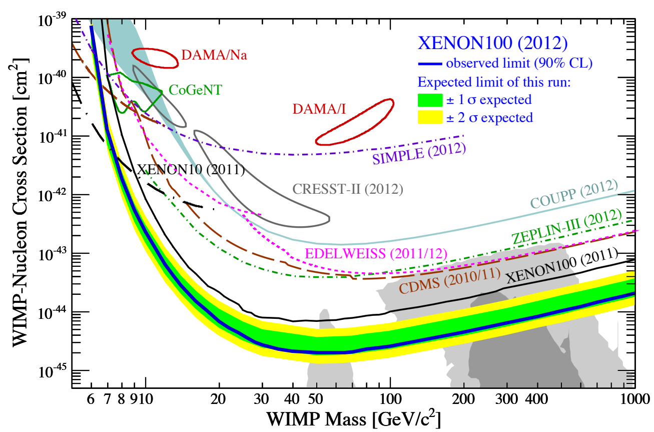
- Quantitatively: compare rates for the three probes
  - Problem: different quantities are being reported

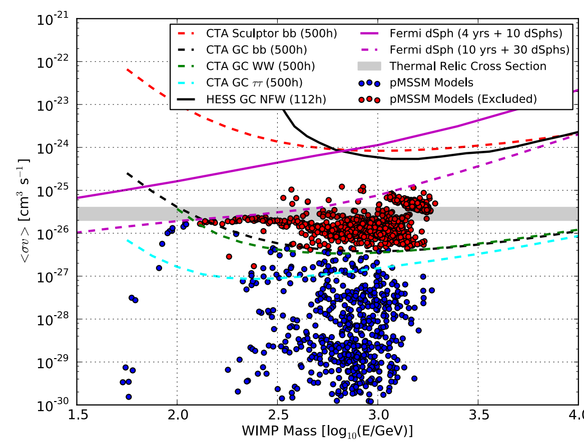












- How can we uniquely correlate those results?

I. Specific theory models

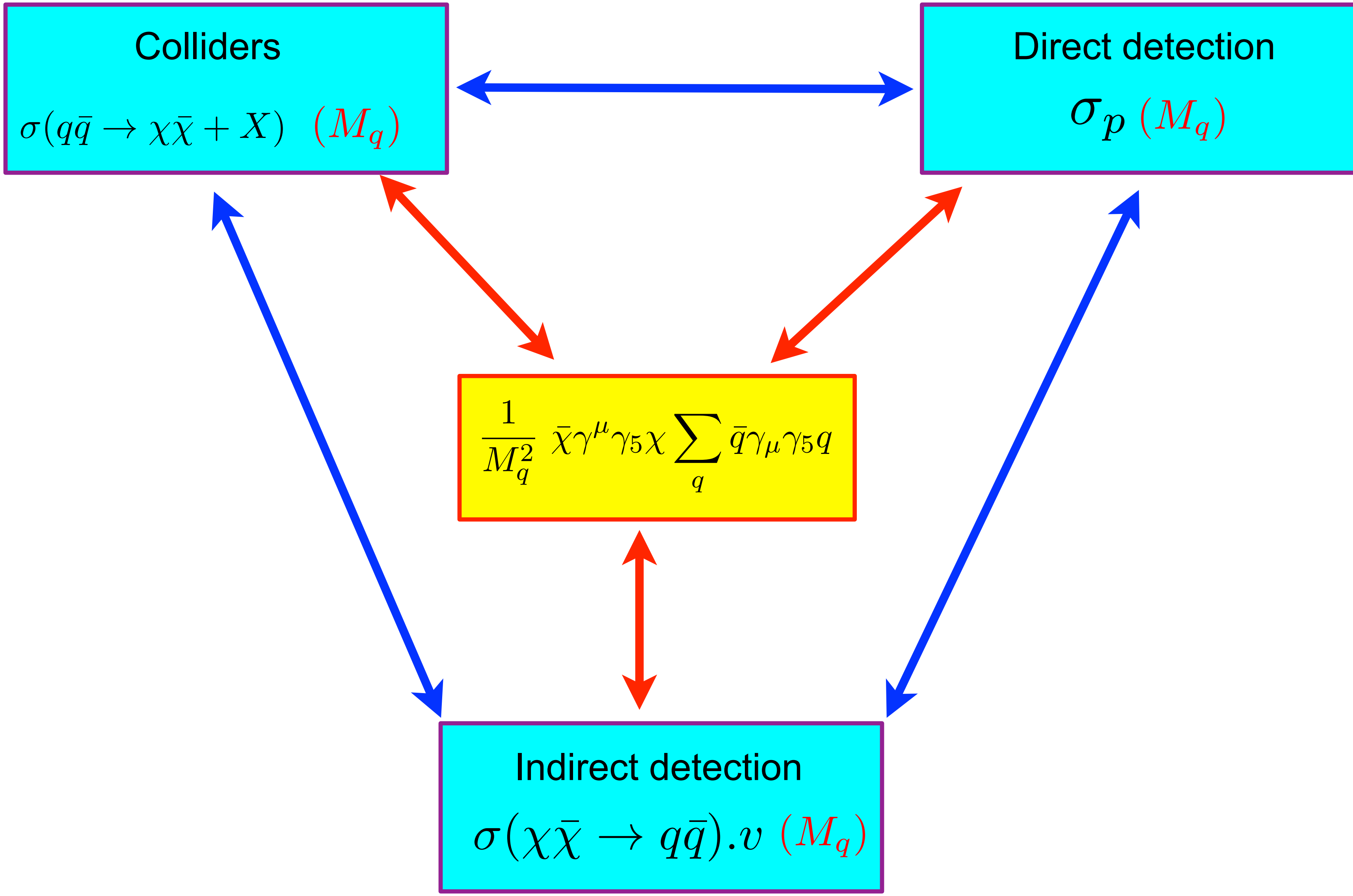
- Choose a complete new physics model with a dark matter candidate
  - See tomorrow afternoon’s CF4 sessions for talks on
    - MSSM (Baer)
    - MSUGRA (Sanford)
    - NMSSM (McCaskey)
    - UED (Kong)
    - Hidden charged DM (Yu)
- Compute the three types of signals as a function of the model parameters. Impose constraints.
- Problem: too many free input parameters
  - fewer parameters come at the cost of introducing model dependent assumptions

II. Model-independent approaches

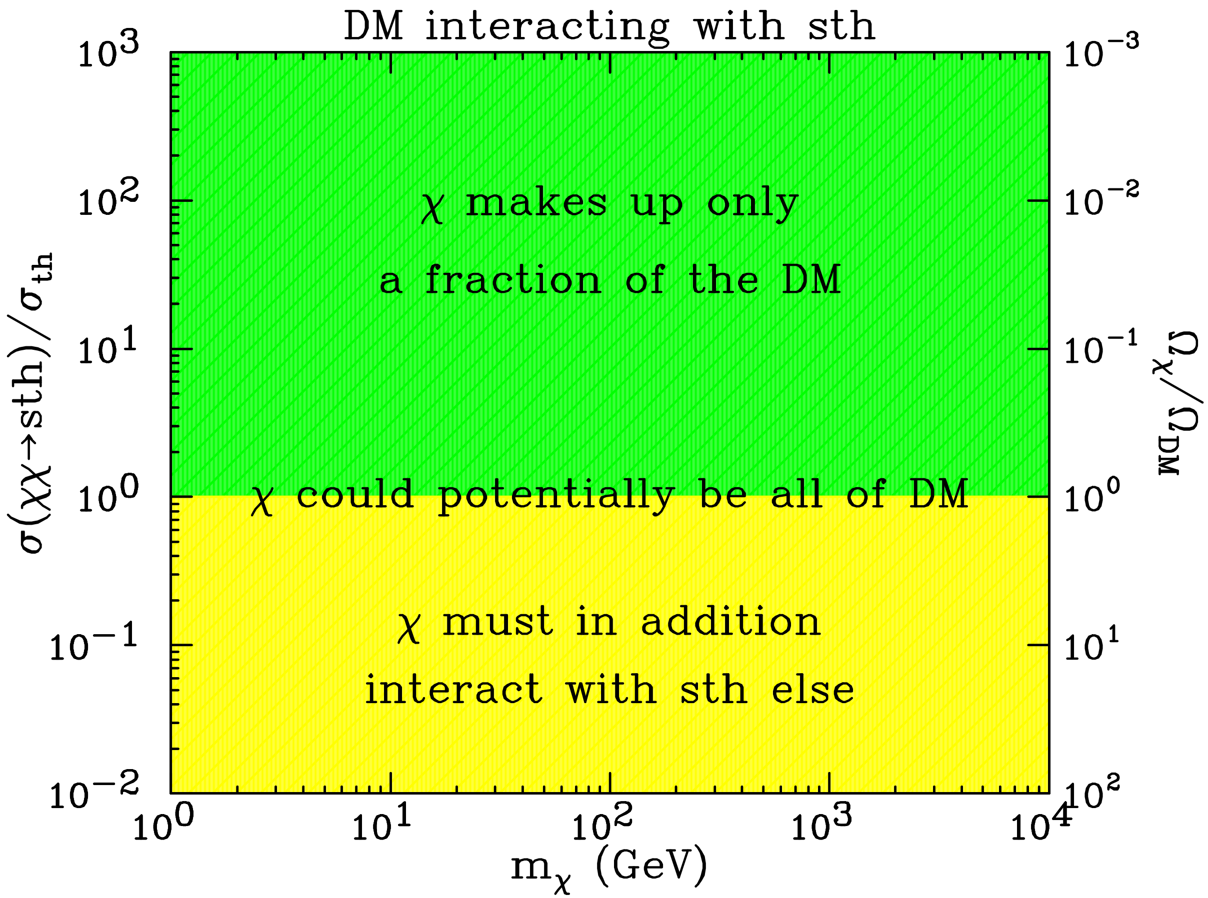
- Alternatively, be agnostic about the underlying theory model
- Parameterize our ignorance about
  - the origin of SUSY breaking
    - pMSSM talks (Ismail, Cotta, Cahill-Rowley, Drlica-Wagner)
  - the type of DM-SM interactions and their mediators
    - effective operators (Shepherd)
- Effective Lagrangian considered in the complementarity document:

$$\frac{1}{M_q^2}\ \bar{\chi}\gamma^\mu\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q + \frac{\alpha_S}{M_g^3}\ \bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu} + \frac{1}{M_\ell^2}\ \bar{\chi}\gamma^\mu\chi\sum_\ell \bar{\ell}\gamma_\mu\ell$$

D8 D11 D5


Colliders
$\sigma(q\bar{q} \to \chi\bar{\chi} + X) \quad (M_q)$
Direct detection
$\sigma_p \ (M_q)$
$\frac{1}{M_q^2} \ \bar{\chi}\gamma^\mu\gamma_5\chi \sum_q \bar{q}\gamma_\mu\gamma_5 q$
Indirect detection
$\sigma(\chi\bar{\chi} \to q\bar{q}).v \ (M_q)$

Complementarity parameter space

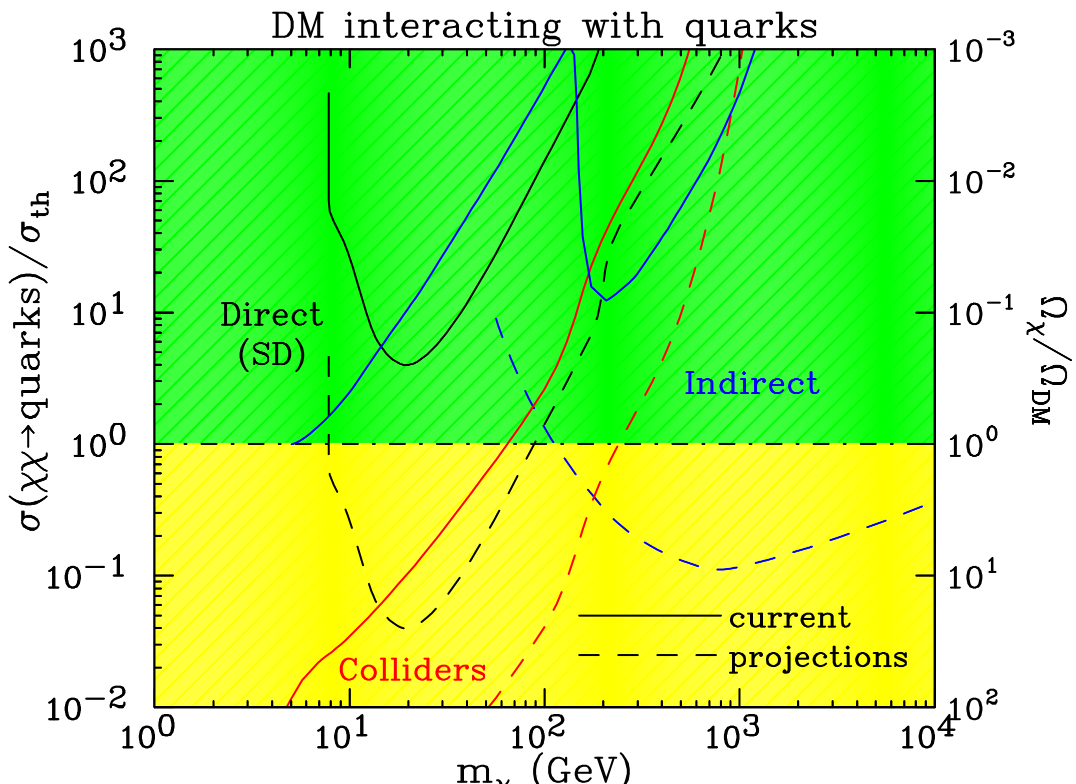


$$\frac{\Omega_\chi}{\Omega_{DM}} \sim \frac{\sigma_{thermal}}{\sigma(\chi\bar{\chi} \to qq) + \sigma(\chi\bar{\chi} \to other)}$$

DM coupling exclusively to quarks

- Flavor universal axial vector coupling (D8 operator)

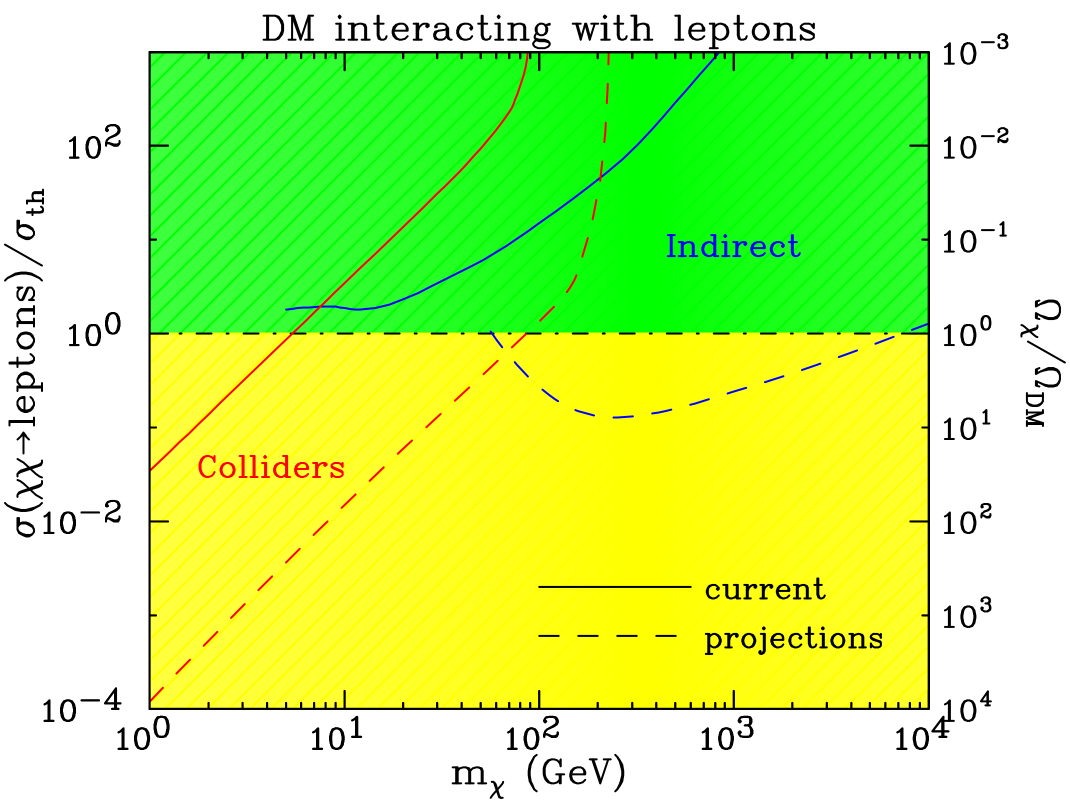
$$\frac{1}{M_q^2}\ \bar{\chi}\gamma^\mu\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q$$



DM coupling exclusively to leptons

- Flavor universal vector coupling (D5 operator)

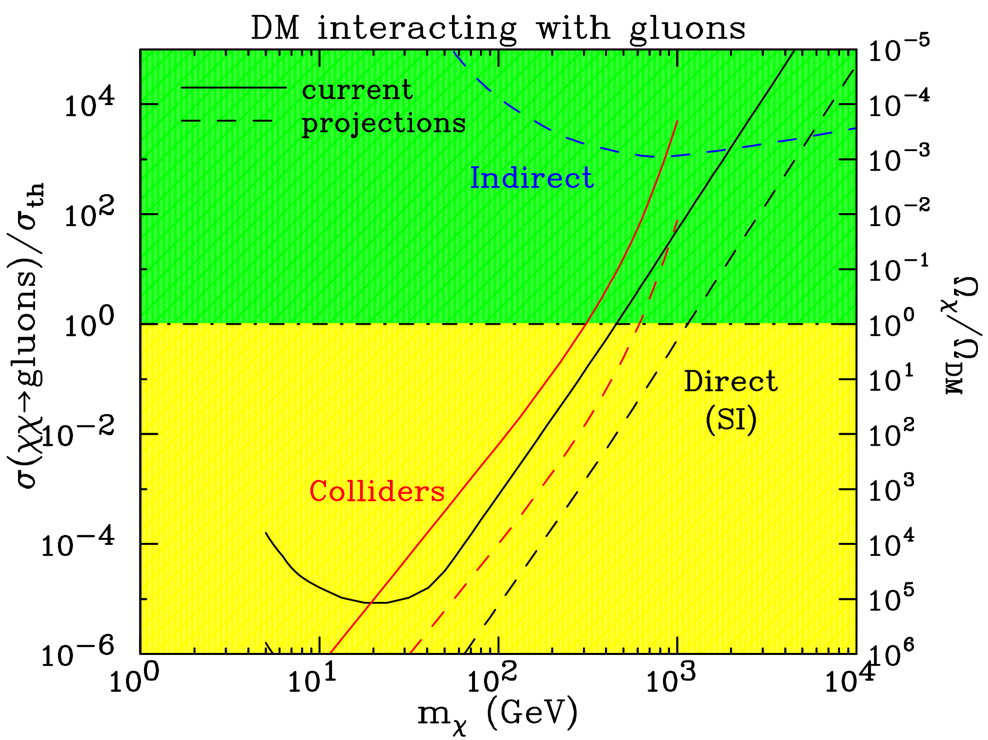
$$\frac{1}{M_\ell^2}\ \bar{\chi}\gamma^\mu\chi\sum_\ell\bar{\ell}\gamma_\mu\ell$$



DM coupling exclusively to gluons

- 4-point interaction (D11 operator)

$$\frac{\alpha_S}{M_g^3}\ \bar{\chi}\chi\ G^{a\mu\nu}G^a_{\mu\nu}$$



Action items

- Collect feedback at the CF workshop
  - suggestions are already coming in
  - are there any major points missing?
- Finish writing
  - Write conclusions section
    - Venn diagram?
  - References: more or fewer?
  - Complete the tables with DM experiments
  - Authorship?
- Draft an executive summary document
- Anything else?