Possible dark matter projects

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

*Conveners: Manoj Kaplinghat, Konstantin Matchev, Dan Hooper

DPF Meeting, UC Santa Cruz
August 14, 2013

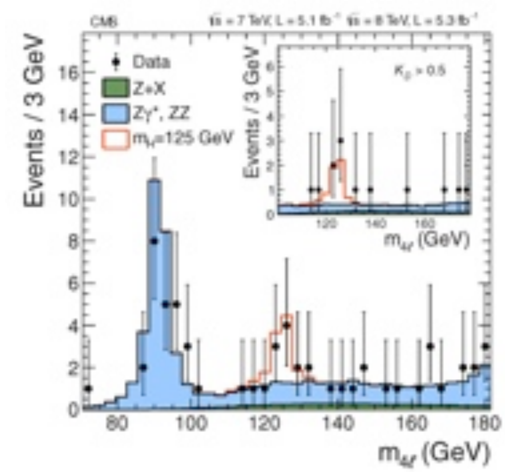
Looking for new particles

- Possible outcomes from new particle searches

Experiment says:	Nature says: The new particle X		
	is within reach of the experiment	is beyond reach of the experiment	does not exist
"we see a signal"	**GOOD**	**BAD**	
"we don't see it, will proceed to set a limit"	**NOT SO GOOD**	**GOOD**	

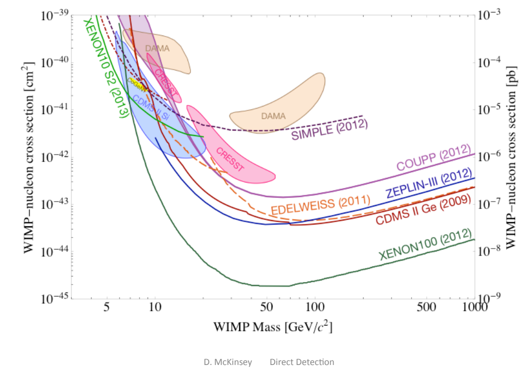
Two examples

- Higgs discovery at the LHC
  - signal is well defined, the rate is known in the SM
  - background is understood, measured very well
  - confirmation seen in several channels
  - confirmation seen in different experiments



- Direct and indirect WIMP searches
  - the signal strength is a priori unknown
  - backgrounds are not always well understood
  - cross-channel correlations very model-dependent
  - conflicting results from different experiments

Current limits



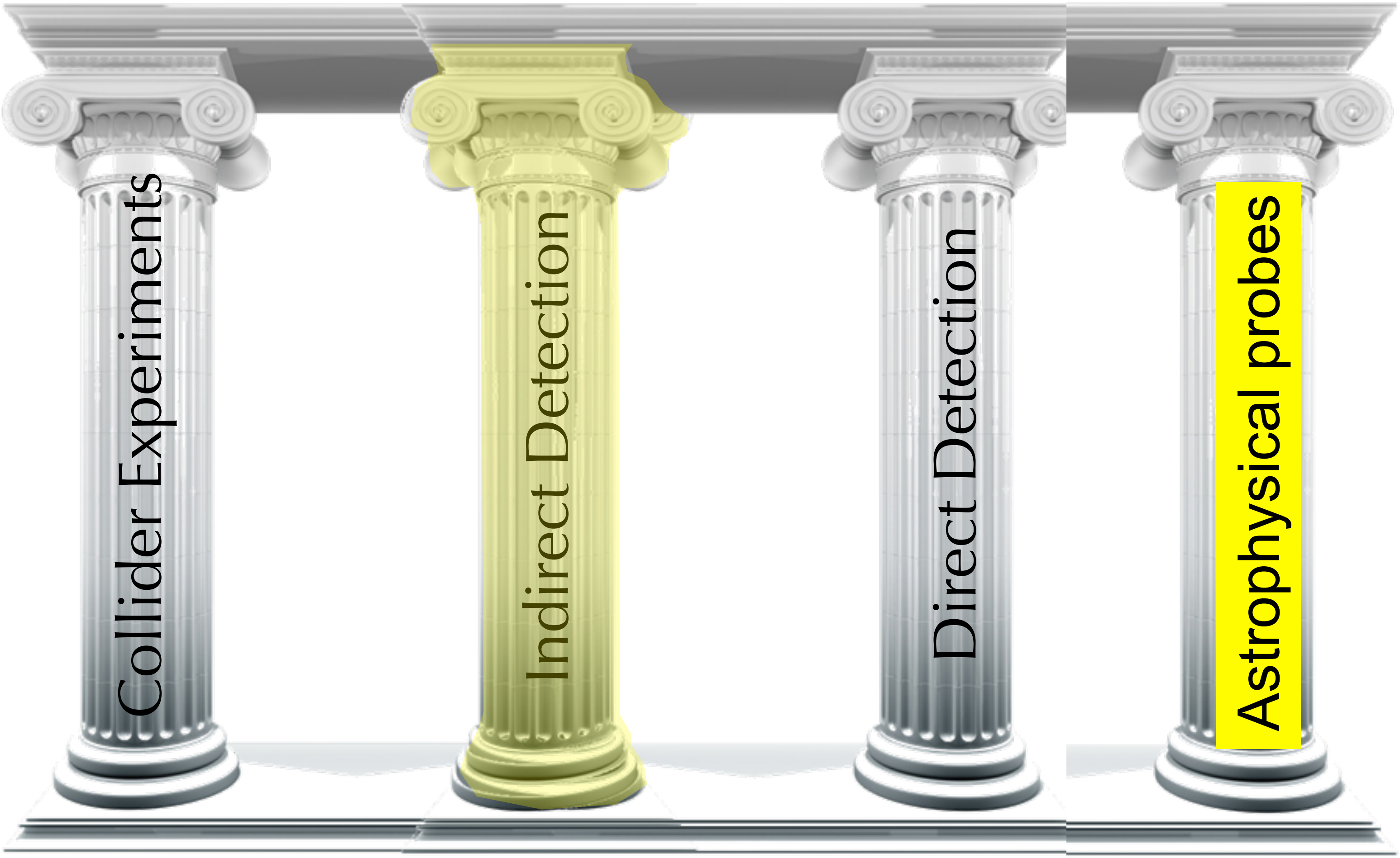
- What will be the gold standard for a dark matter discovery?

Complementarity

Dark Matter

Complementarity

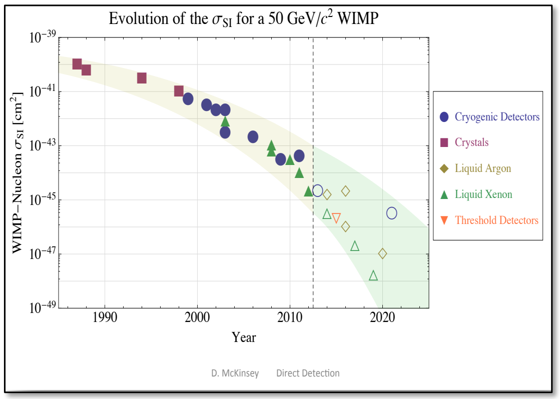
Dark Matter



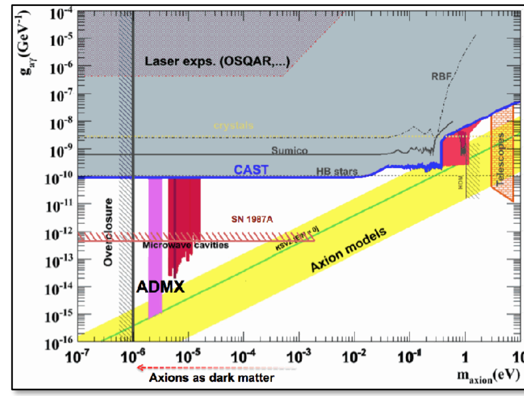
The different dark matter probes

- Direct detection see talk by Frank Calaprice

WIMPs

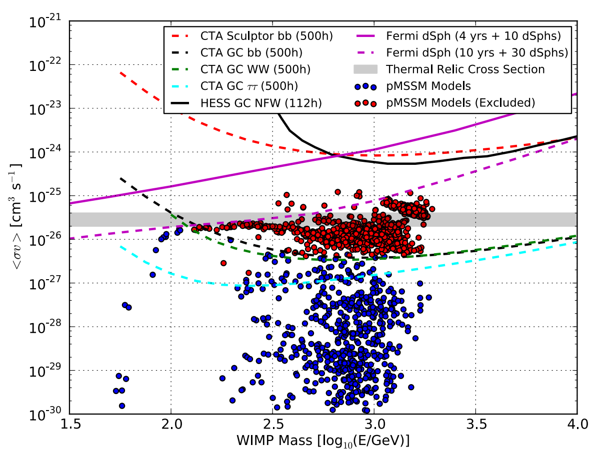


Axions

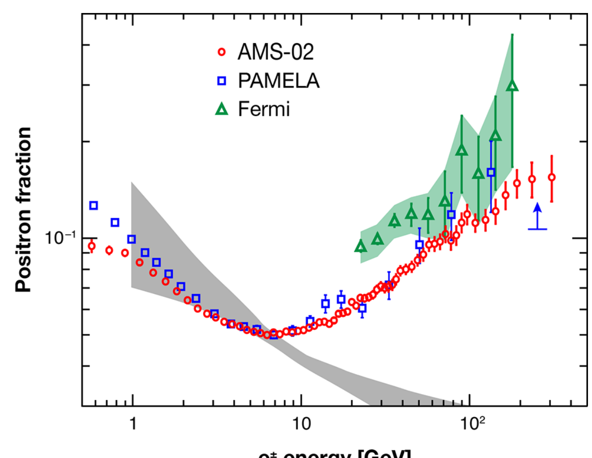


- Indirect detection see talk by Jim Buckley

Gammas



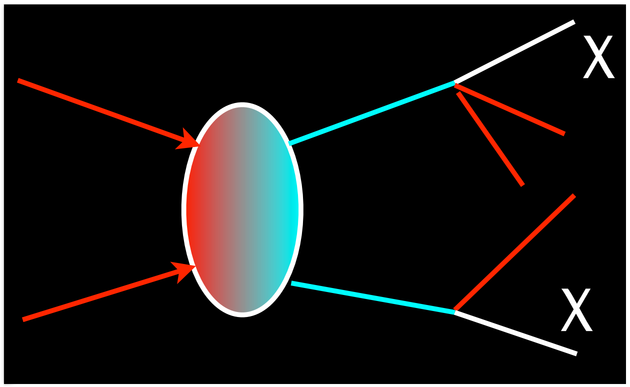
Positrons



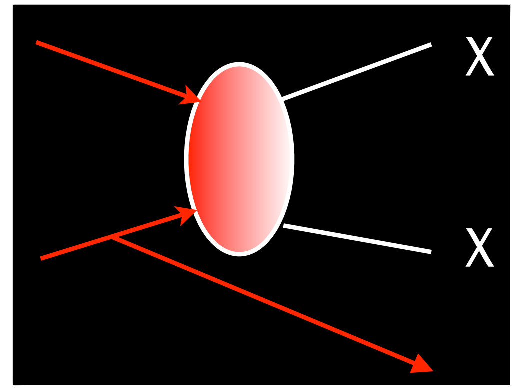
The different dark matter probes

- Colliders — see talks by Michael Peskin, Chris Hill, Paul Grannis

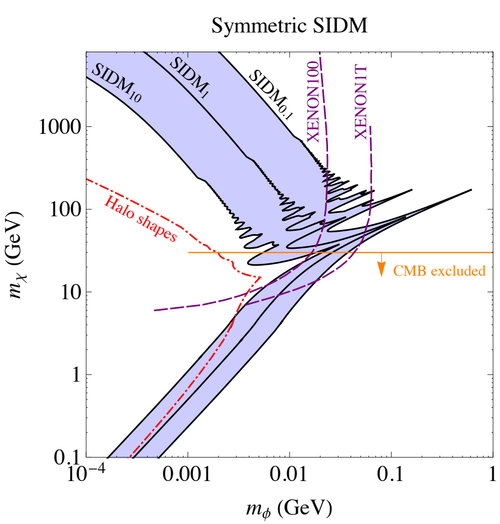
“SUSY-like”

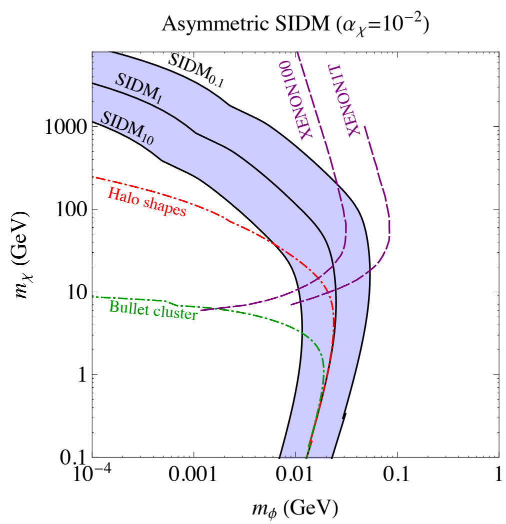


Monojets, Monophotons, ...



- Astrophysical probes — see talks by Scott Dodelson, Angela Olinto





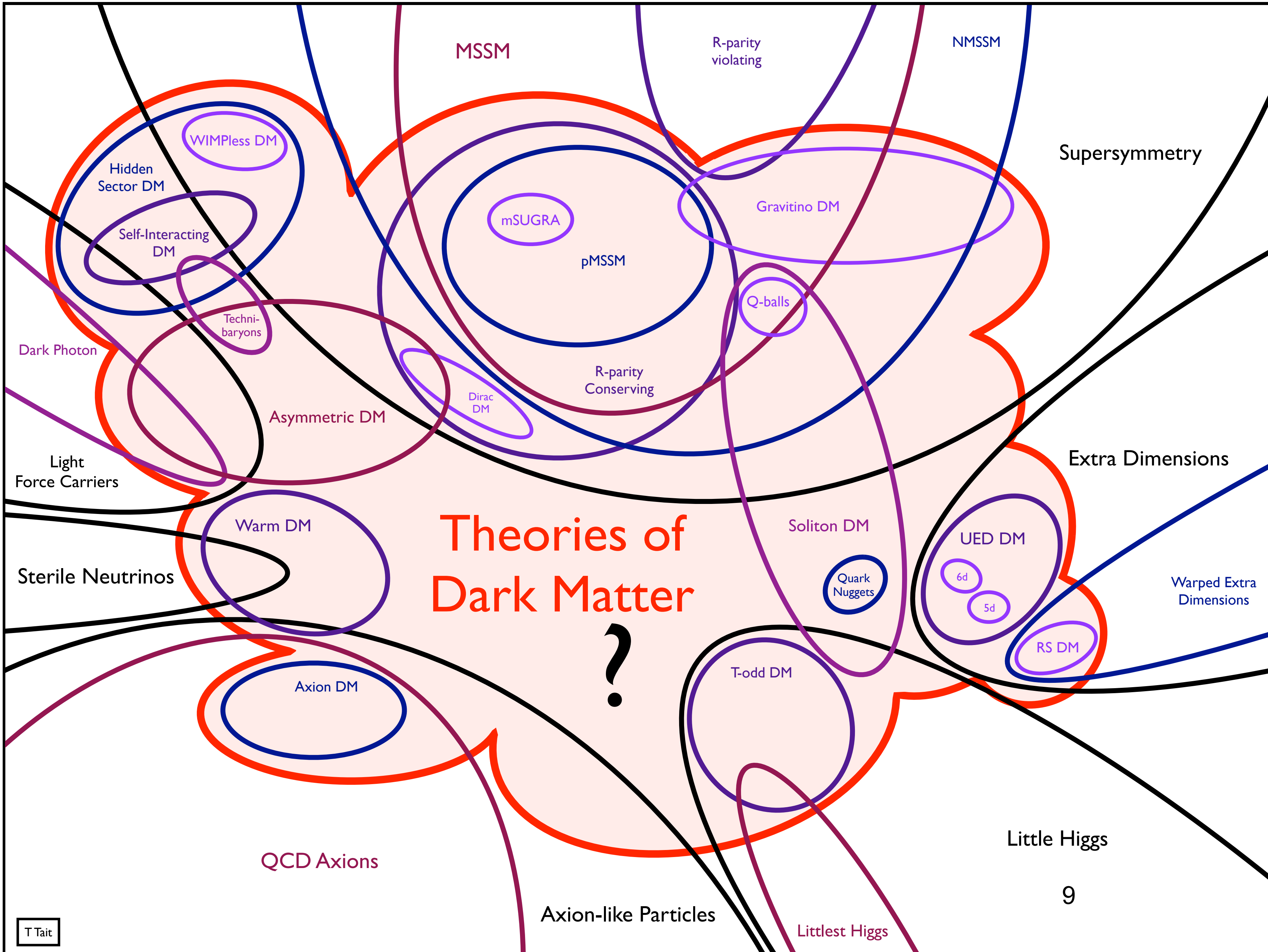
Kaplinghat, Tulin, Yu
arxiv:1308.0618

CF4 timeline

- Pre-SLAC workshop
  - Aspen workshop “Closing in on Dark matter” (Jan. 28 - Feb. 3 2013)
  - prepare draft of the short (10 pages) Complementarity Document
- SLAC workshop (March 6-8 2013)
  - open discussion of the Complementarity Document
  - three CF4 sessions with (mostly) theory talks
  - joint sessions with CF1 (direct), CF2 (indirect) and CF3 (non-WIMP)
- Pre-Snowmass
  - publish the short Complementarity Document arXiv:1305.1605
  - begin work on the long CF4 Summary Report
    - solicit white papers (six delivered)
- Snowmass (July 29 - August 6 2013)
  - In preparation:
    - long (30 pages) CF4 report
    - short (4 pages) summary

Why do we need (to fund) so many experiments?

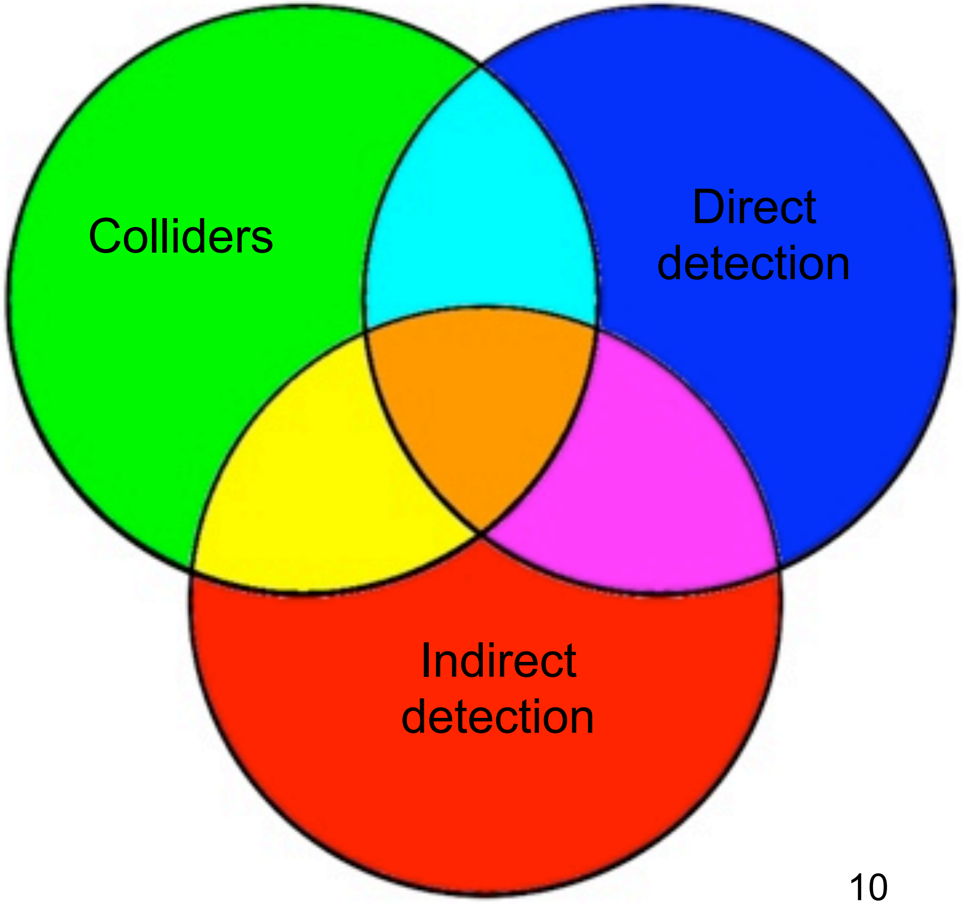
- No established theory of dark matter
  - many candidates: supersymmetry, extra dimensions, axions...
- Don’t know the best method to detect it
  - need all four probes in order to cover all bases
- The experiments are challenging
  - need independent confirmation
- There may be several dark matter species
  - a single experiment will not suffice
- Post-discovery complementarity
  - the need to measure precise properties:
    - mass, spin, couplings


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Soliton DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
Axion DM
T-odd DM
QCD Axions
Little Higgs
Axion-like Particles
Littlest Higgs
T Tait

How to illustrate complementarity?

CPM Meeting, Fermilab 2012

- Qualitatively: the presence of a signal in:



The point being this:

The importance of complementarity

com·ple·men·ta·ry
adj.
1. Forming or serving as a complement; completing.
2. Supplying mutual needs or offsetting mutual lacks.

- Observation of several signals will be needed to confirm a DM discovery
- All four probes are needed to get the full picture
- The limitations of one probe might be overcome by the strengths of the other probes
- A negative result from a given search also brings important complementary information
  - we need to find out not only what DM couples to, but also what it does <u>not</u> couple to.

Different levels of complementarity

- Between different types of probes
  - direct, indirect, colliders, astro

arXiv:1305.1605
+
long CF4 report

- Between different approaches within each probe
  - hadron colliders versus lepton colliders
  - indirect detection: neutrinos vs. gammas vs e^+
  - direct detection: techniques, targets, scale...

Summer
CF1, CF2, HE4
subgroup
reports

- Between different designs within each approach
  - e.g. D0 vs CDF, ATLAS vs CMS.
- Plots will be labelled simply as: “colliders”, “indirect detection”, “direct detection”. The limit comes from the best experiment at that point.

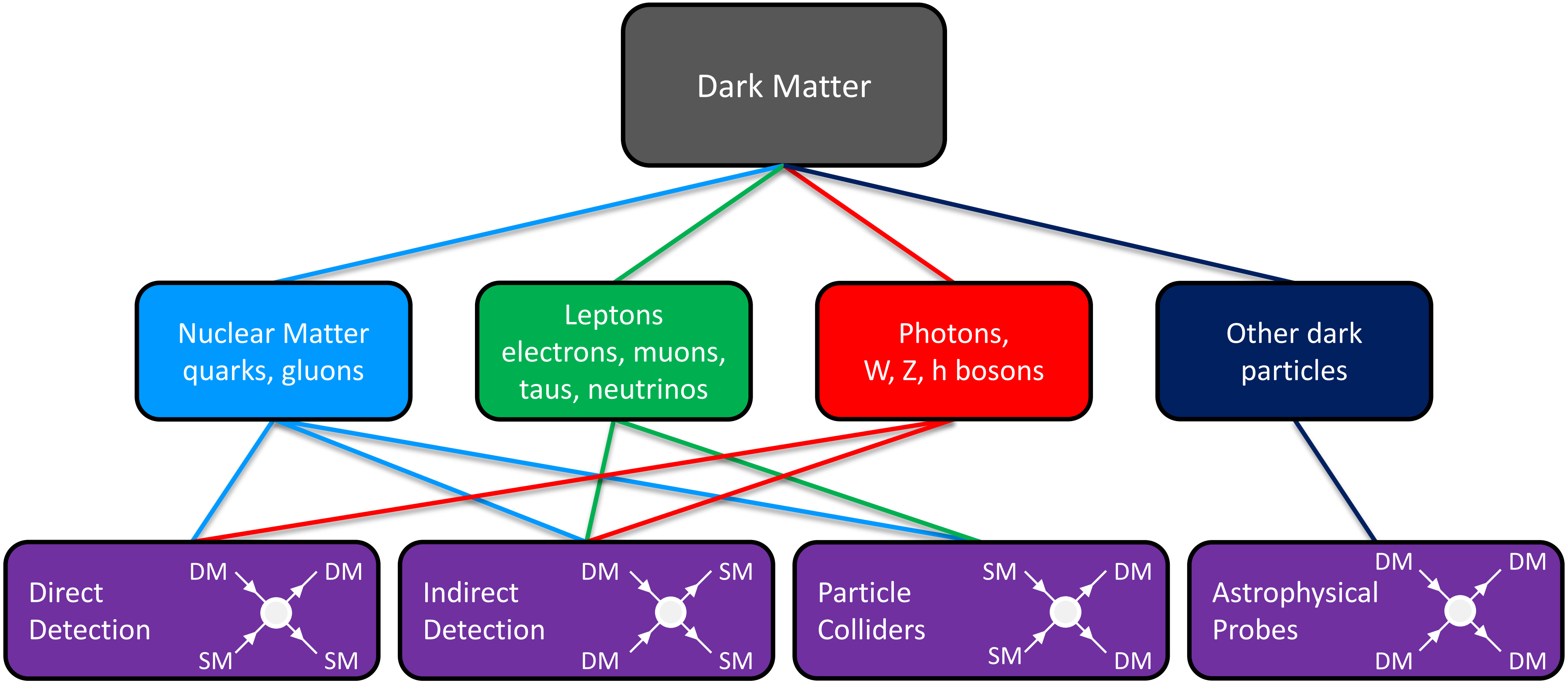
What is dark matter?

see Dark Matter colloquium at Snowmass

- 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 our purposes, DM candidates are categorized according to their basic interactions



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					

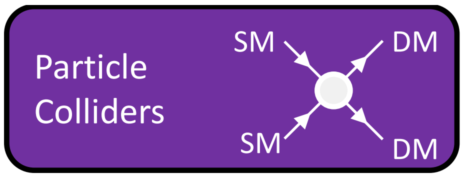
COLLIDERS

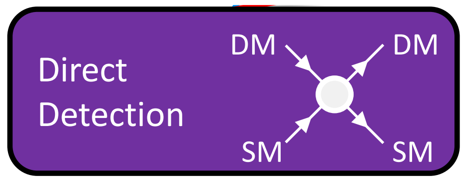
TABLE III: Current and proposed particle colliders.

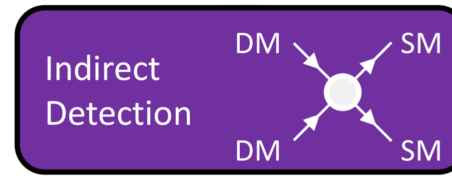
Status	Collider	Type	E_{COM}, Luminosity	Major Support	Comments
Current	LHC	pp	8 TeV, 20 fb^{-1}	DOE, NSF	
Upcoming	LHC	pp	14 TeV, 300 fb^{-1}	DOE, NSF	
Proposed	HL LHC	pp	14 TeV, 3000 fb^{-1}		
Proposed	VLHC	pp	33-100 TeV		
Proposed	Higgs Factory	e^+e^-	250 GeV		
Proposed	ILC, CLIC	e^+e^-	0.5-3 TeV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

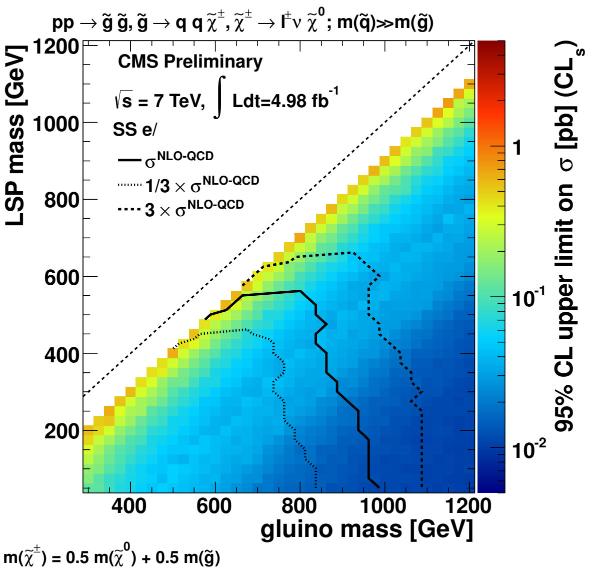
How to illustrate complementarity?

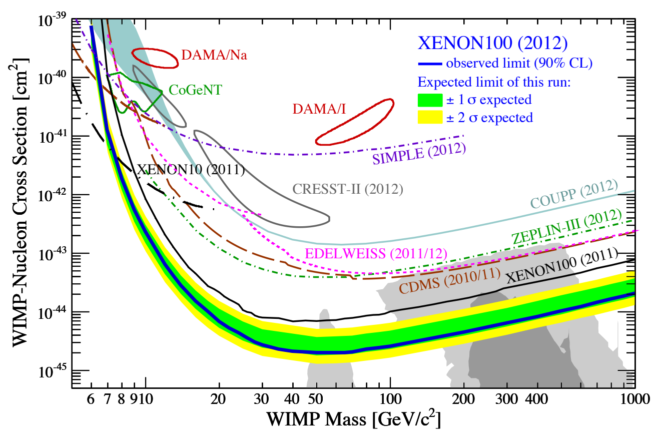
- Quantitatively: compare rates for the three probes
  - Problem: different quantities are being reported

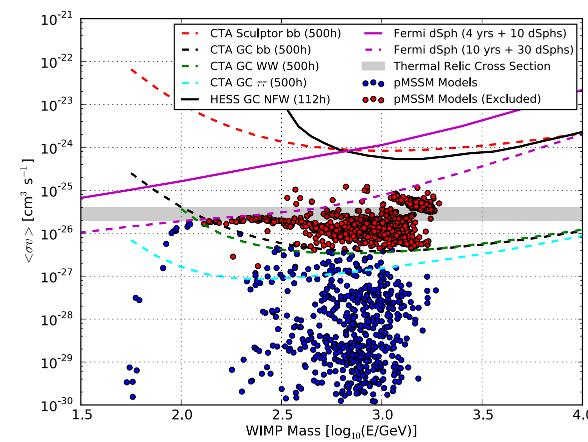












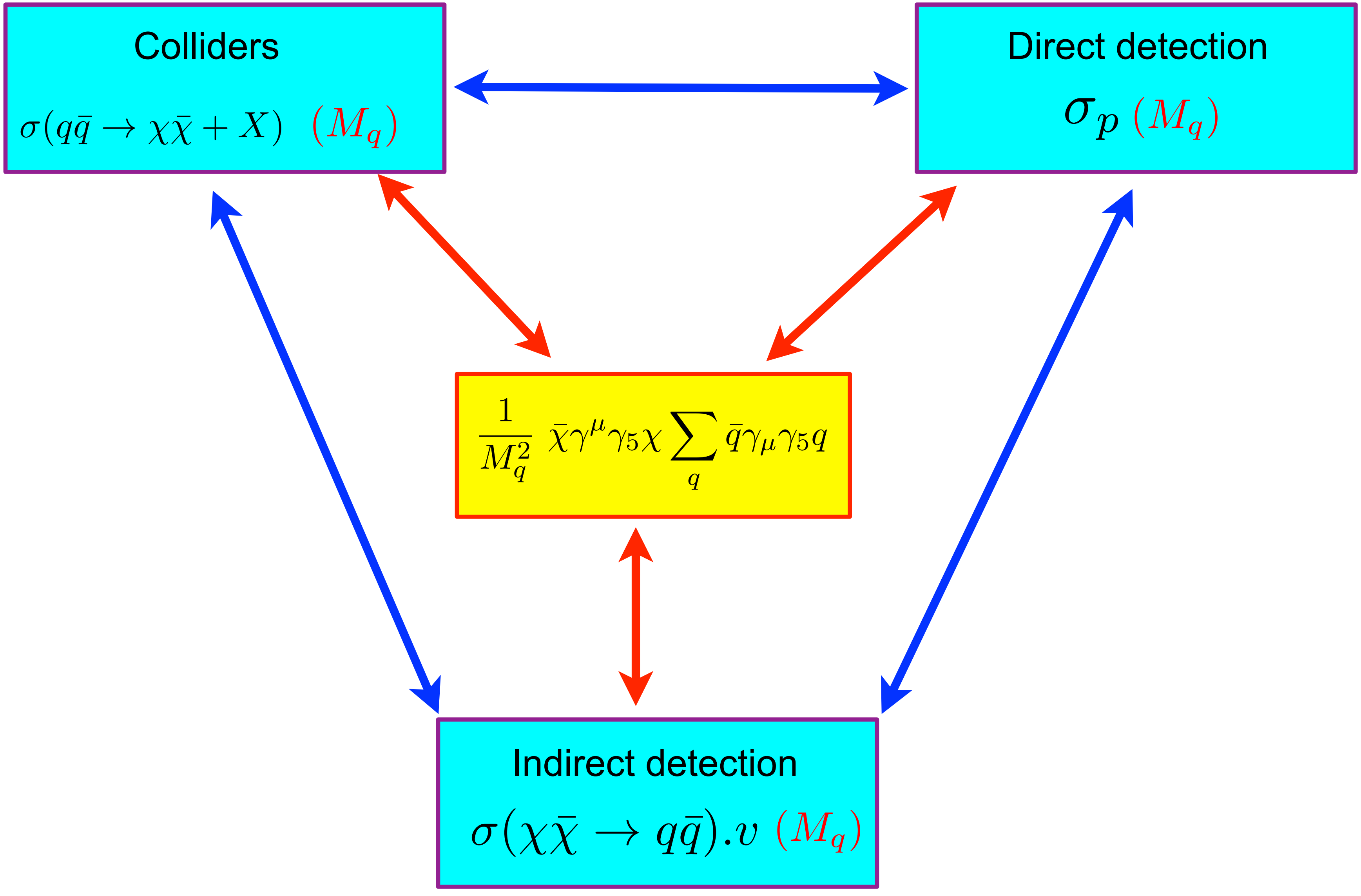
- How can we uniquely correlate those results?

I. Effective theory approach

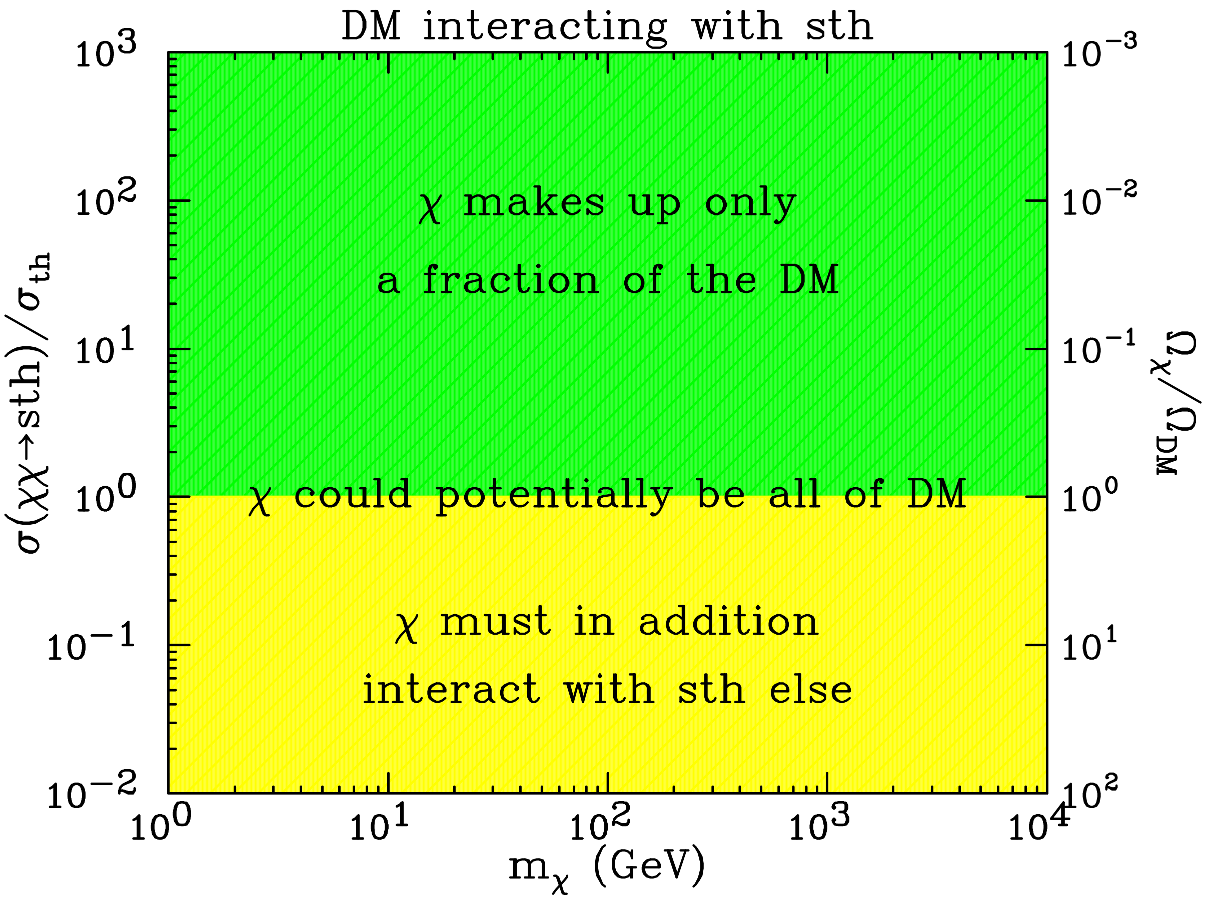
- Be completely agnostic about the underlying theory model, consider 4-point effective operators
  - this approach is being applied to Higgs couplings
- Parameterize our ignorance about their origin
  - introduce one mass scale for each type of operator
- Effective Lagrangian considered in the complementarity 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

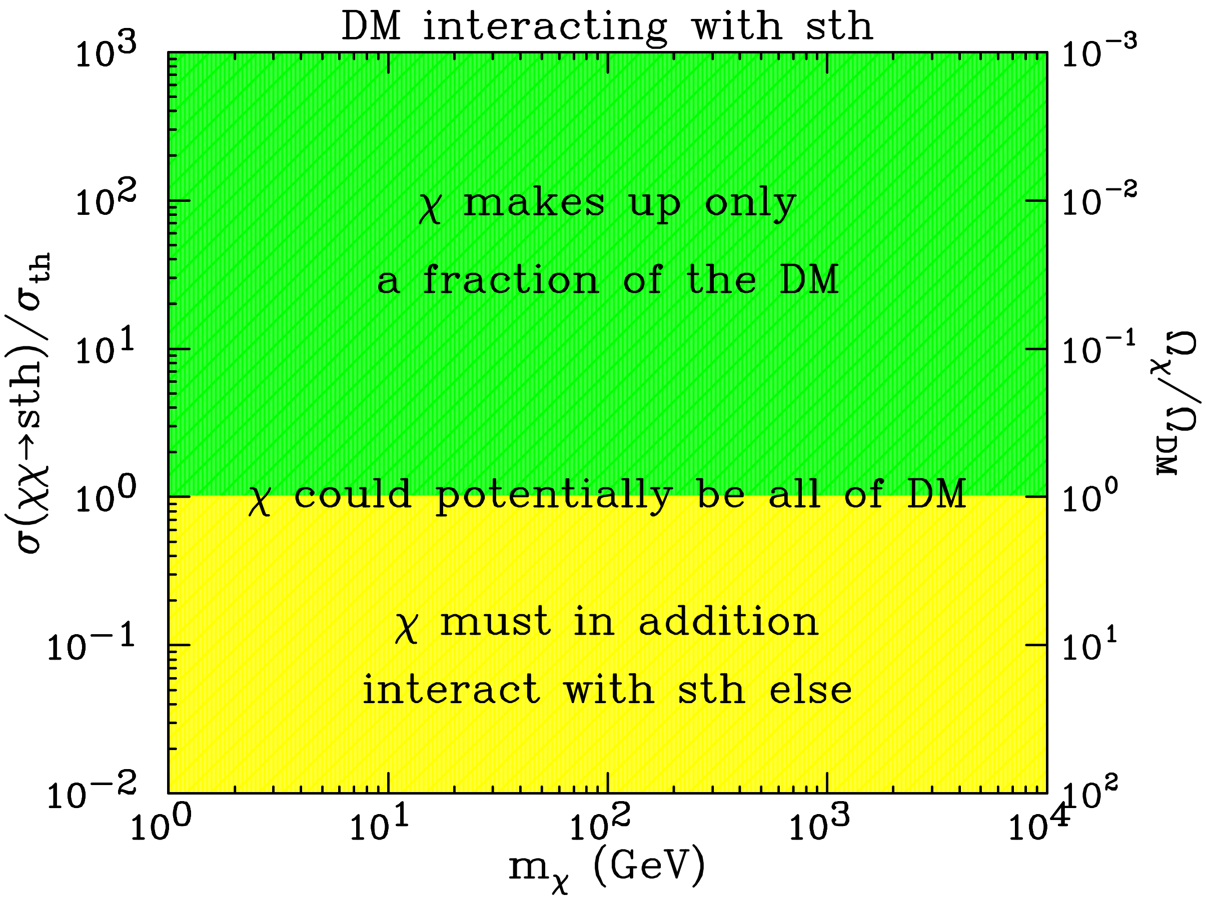

Colliders
$\sigma(q\bar{q} \to \chi\bar{\chi} + X)$ (M_q)
Direct detection
σ_p (M_q)
$\frac{1}{M_q^2} \bar{\chi}\gamma^\mu\gamma_5\chi \sum_q \bar{q}\gamma_\mu\gamma_5 q$
Indirect detection
$\sigma(\chi\bar{\chi} \to q\bar{q}).v$ (M_q)

Complementarity parameter space



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

Complementarity parameter space



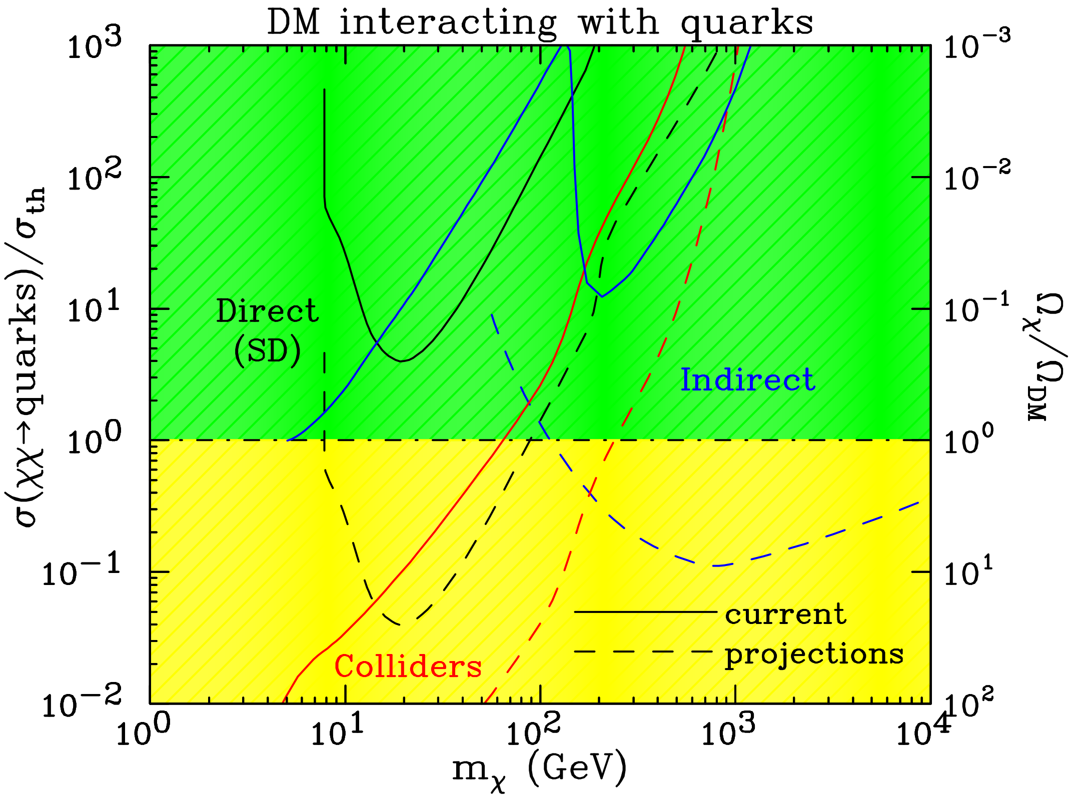
$$\frac{\Omega_\chi}{\Omega_{DM}} \sim \frac{\sigma_{thermal}}{\sigma(\chi\bar{\chi}\to qq) + \sigma(\chi\bar{\chi}\to other)}$$

assuming no other interactions

DM coupling exclusively to quarks

- Flavor universal axial vector coupling (D8 operator)

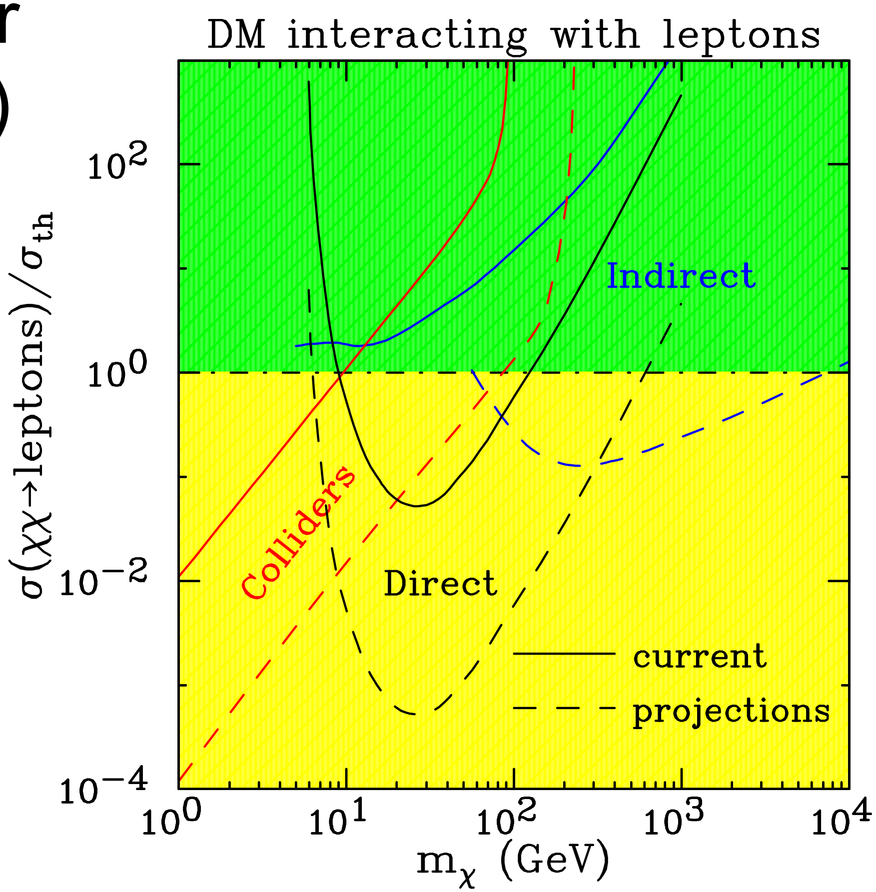
$$\frac{1}{M_q^2}\ \bar{\chi}\gamma^{\mu}\gamma_5\chi \sum_q \bar{q}\gamma_\mu\gamma_5 q$$



DM coupling exclusively to leptons

- Flavor universal vector coupling (D5 operator)

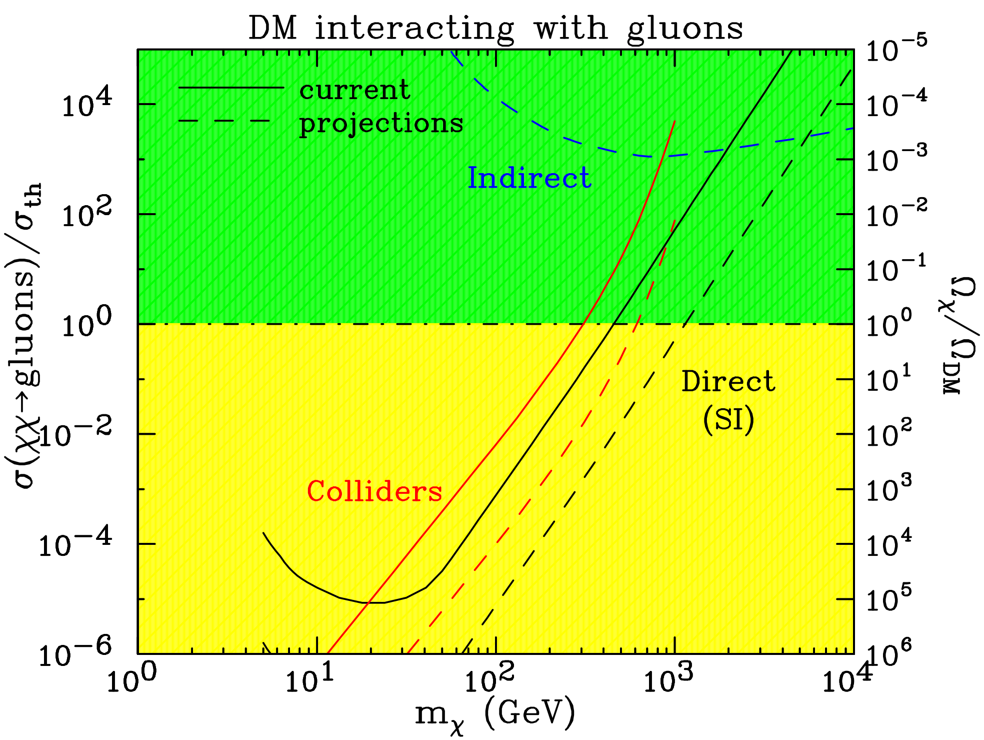
$$\frac{1}{M_\ell^2}\ \bar{\chi}\gamma^\mu\chi\sum_\ell\bar{\ell}\gamma_\mu\ell$$



DM coupling exclusively to gluons

- 4-point interaction (D11 operator)

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



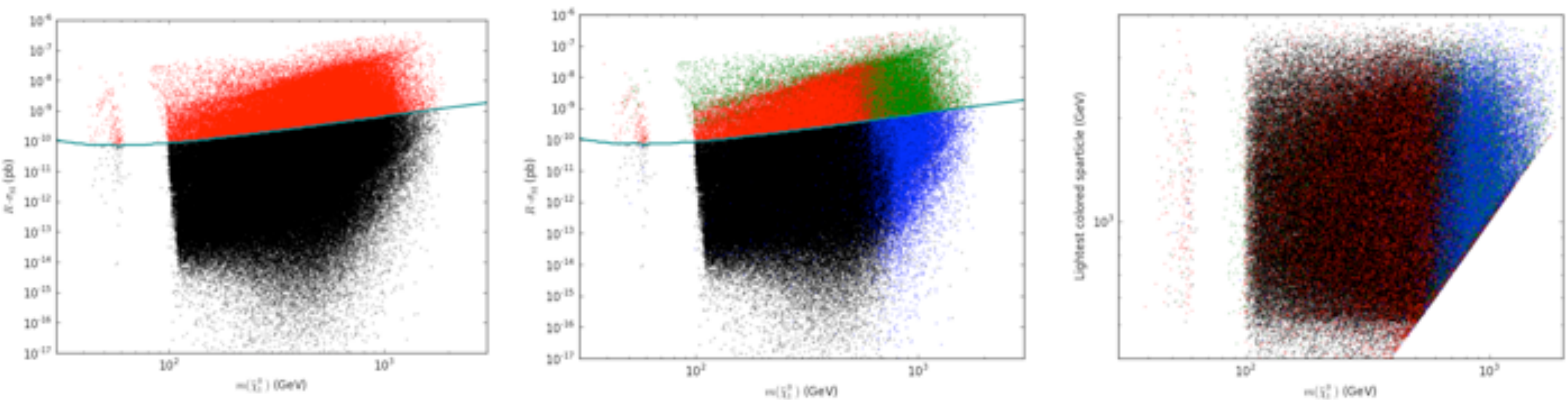
II. Specific theory models

- Choose a complete new physics model with a dark matter candidate
  - Minimal supersymmetry
    - model-independent parametrization, aka pMSSM
    - MSUGRA (focus point scenario)
    - non-minimal SUGRA with light higgsino
  - Non-minimal supersymmetry
    - NMSSM
  - Extra dimensions
    - minimal UED
- Compute the three types of signals as a function of the model parameters. Impose constraints.

The pMSSM approach
(SUSY without prejudice)

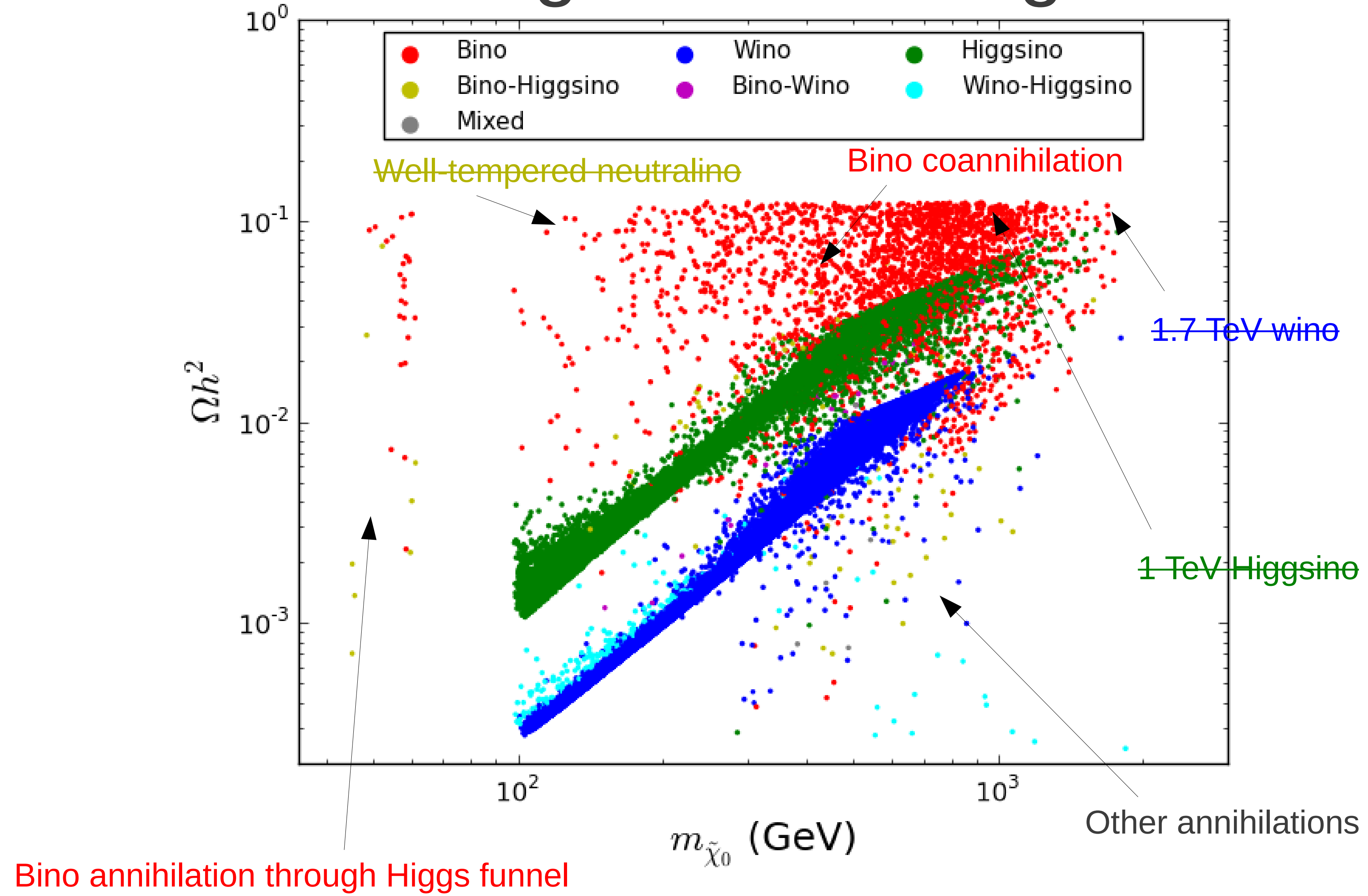
Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett, Ismail, Rizzo, M. Wood
arXiv:1305.6921

- Sequentially apply projected constraints from
  - direct detection (red versus black)
  - indirect detection (red->green; black->blue)
  - LHC



talk by A. Ismail “Complementarity in the pMSSM”

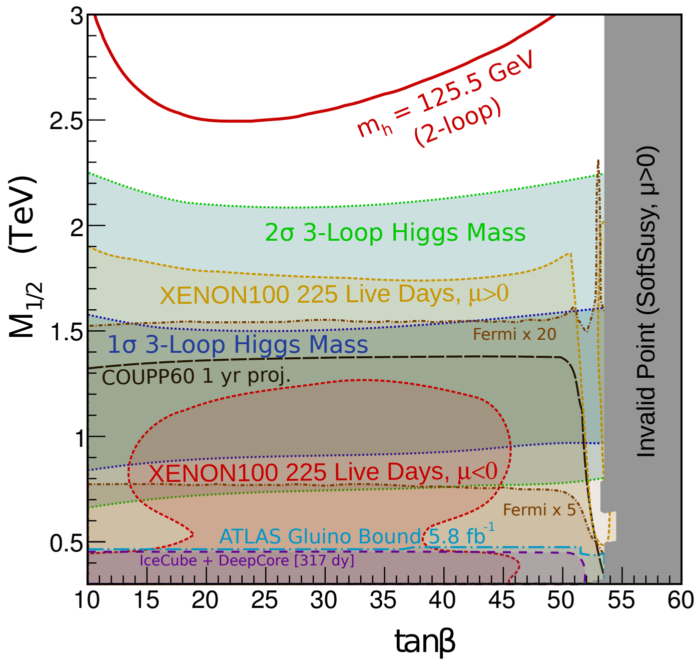
Most surviving LSPs are eigenstates



Supergravity - mediated SUSY

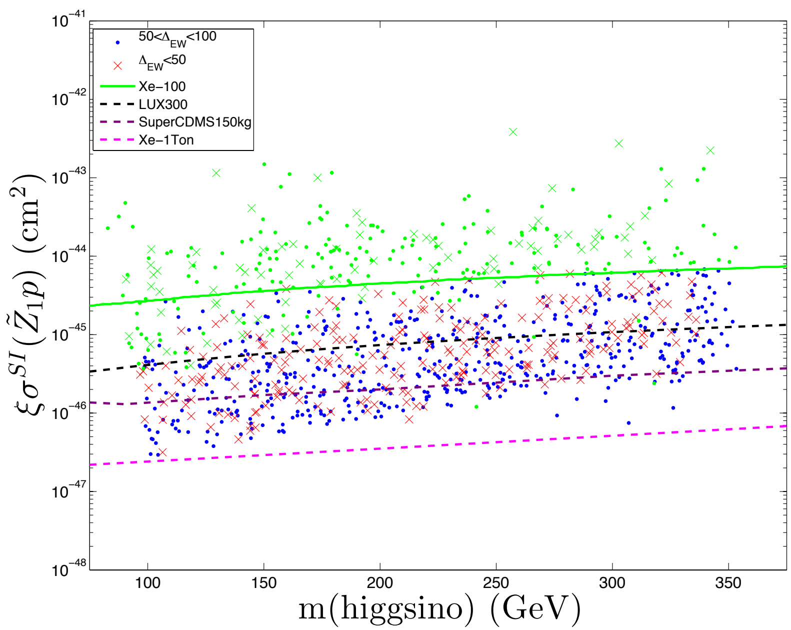
- Focus point SUSY

D. Sanford
1306.4961



- Natural SUSY

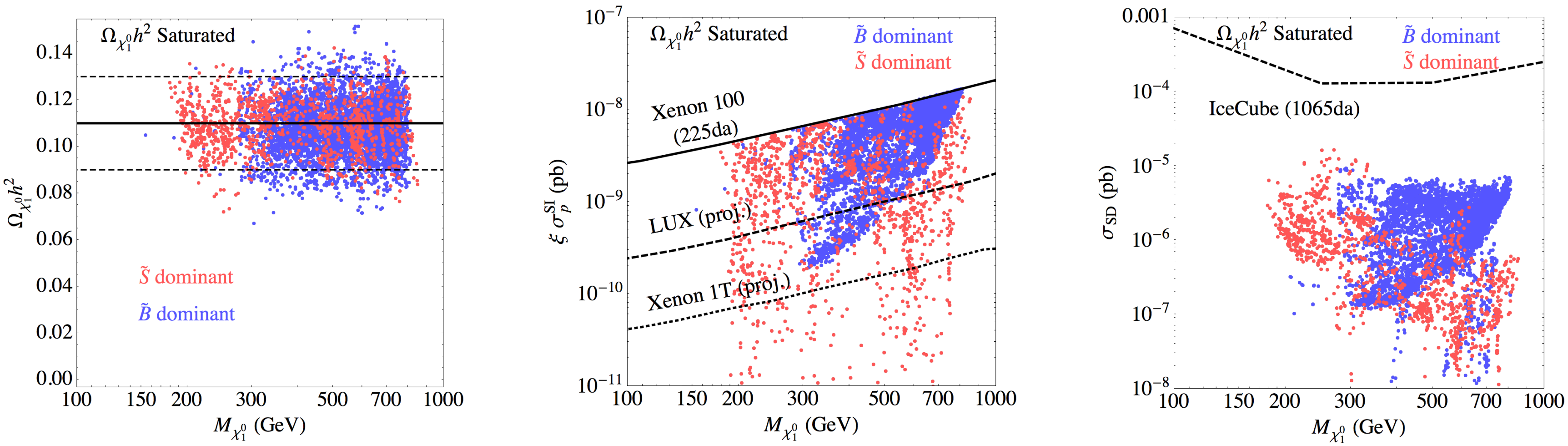
Baer,Barger,Michelson,Tata
1306.4183



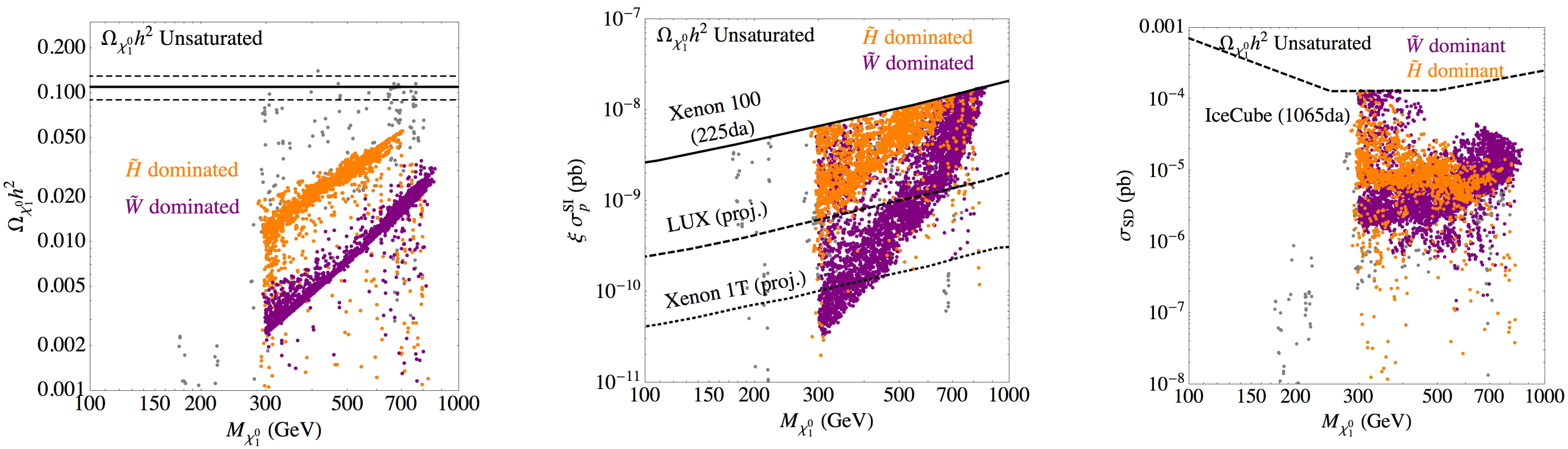
Non-minimal SUSY: NMSSM

McCaskey,Shaughnessy 1307.0851

SATURATED



UNSATURATED

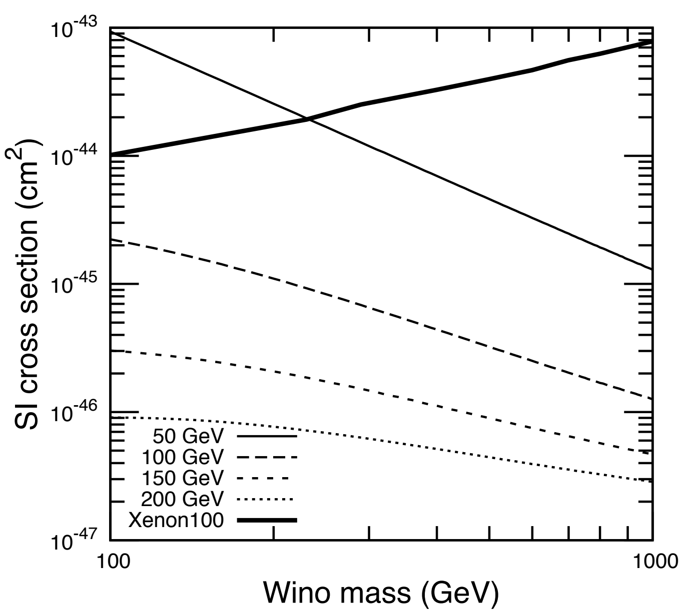


Complementarity: mass degeneracy

- If the NLSP is degenerate with the DM
  - collider signals are degraded (soft jets, etc.)
  - direct detection signals are enhanced

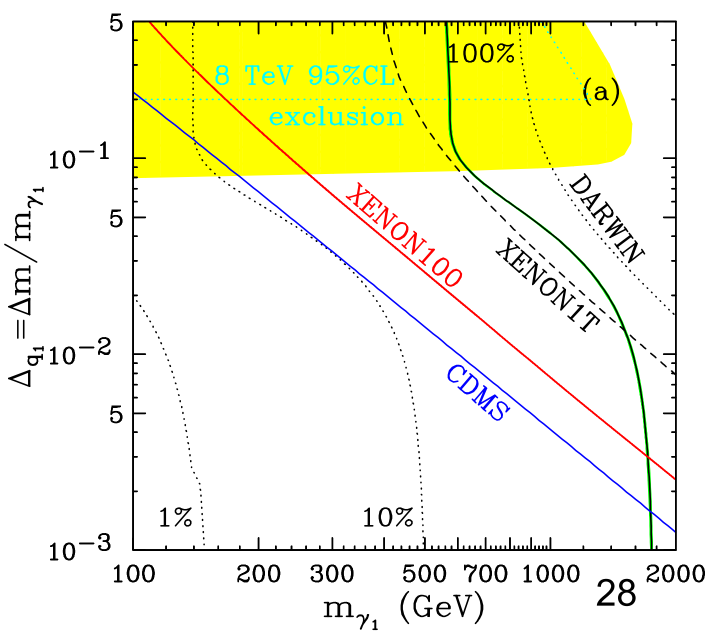
- SUSY (squarks)

Hisano,Ishiwata,Nagata 1110.3719



- UED (KK quarks)

Arrenberg,Baudis,Kong,KM,Yoo 1307.6581



The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

Thermal Relic?

- ☐ Yes ☐ No

Credit: T. Tait