Dark Matter: Overview, Models, & Motivation

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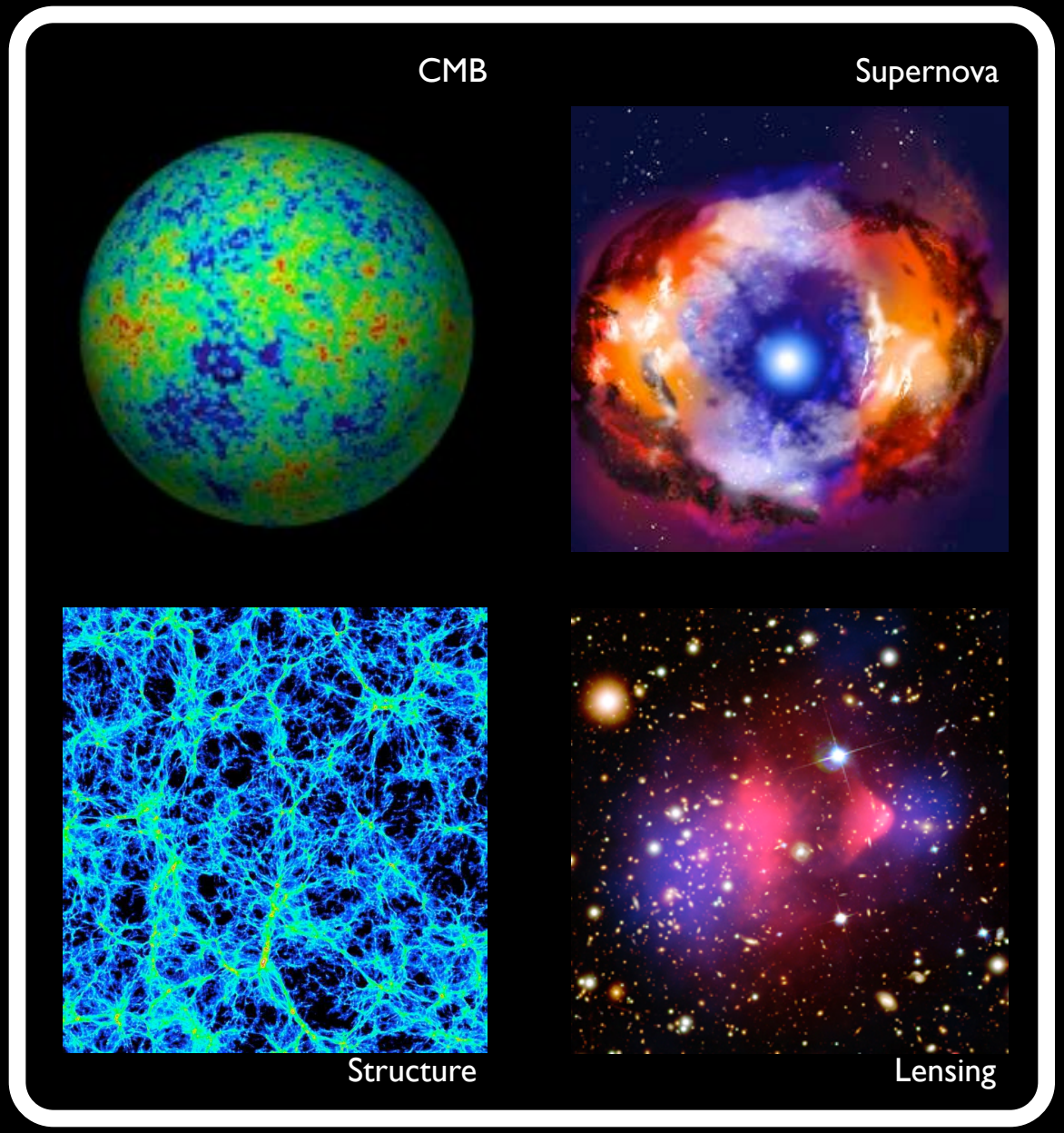
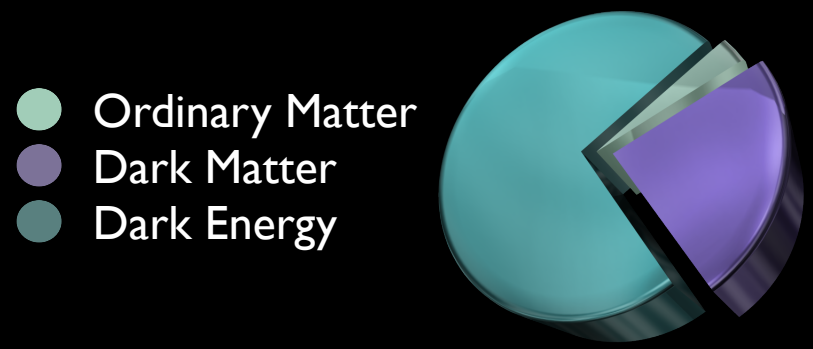
University of California, Irvine

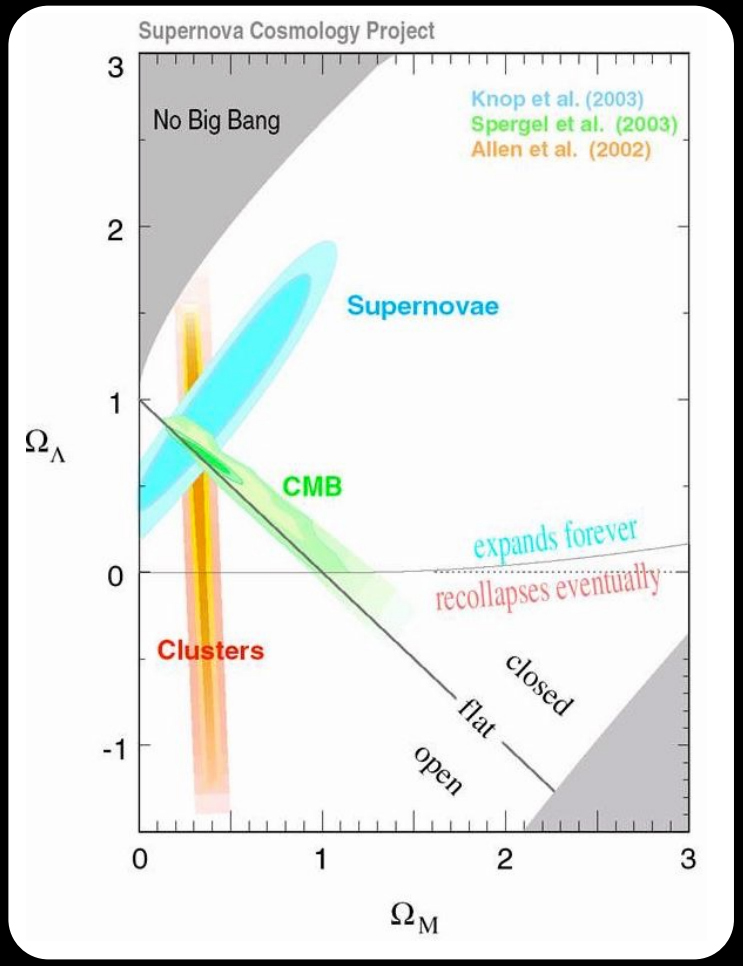
Snowmass Theory Frontier
KITP, February 23, 2022

Motivation

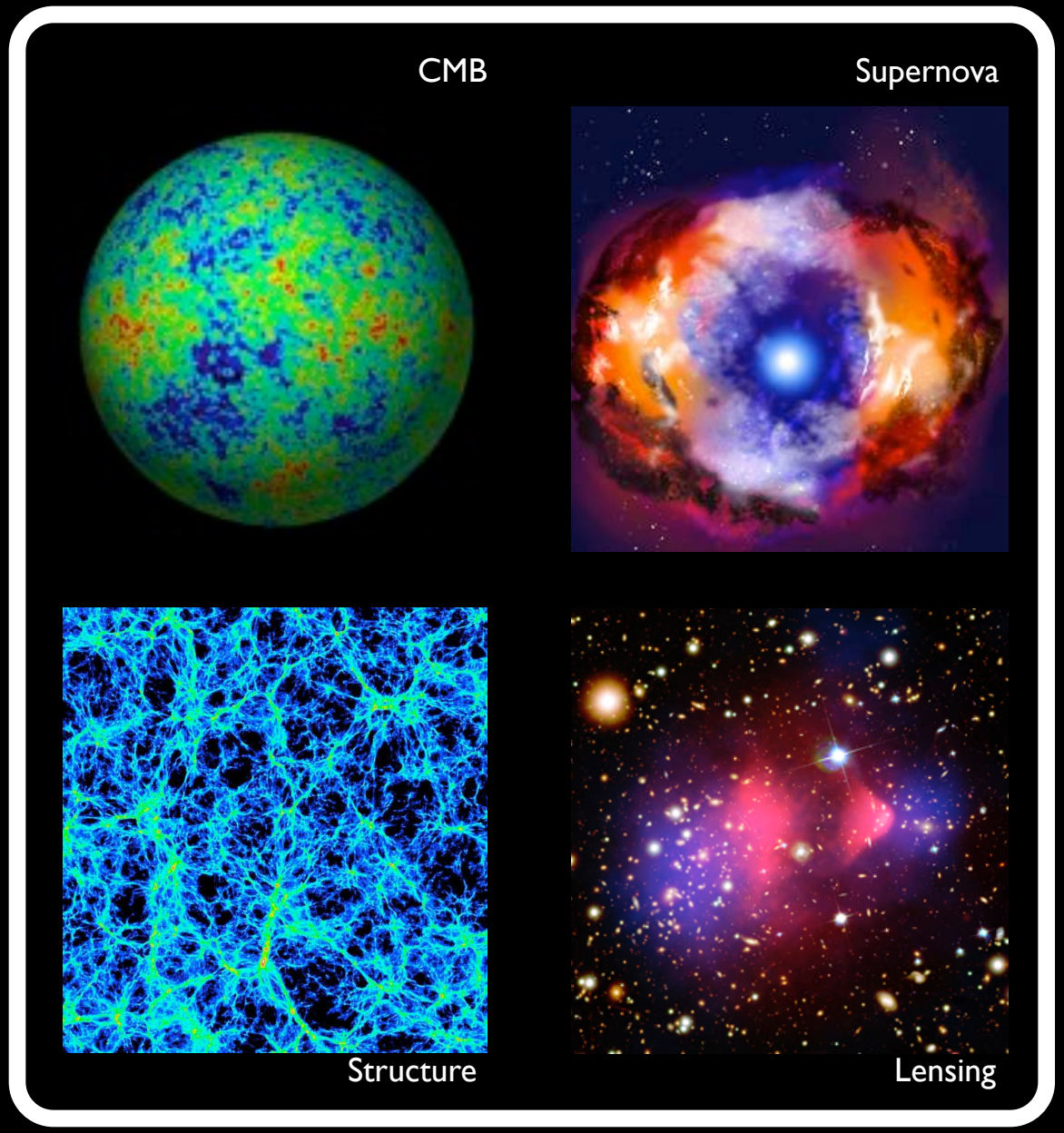
Dark Matter


CMB
Supernova
Structure
Lensing


Ordinary Matter
Dark Matter
Dark Energy


Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

Dark Matter


CMB
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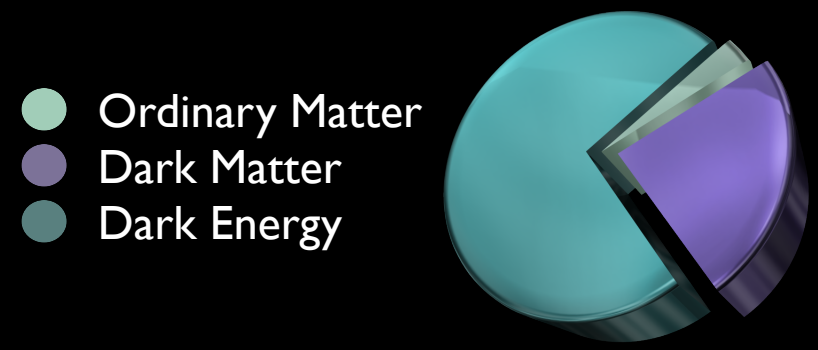
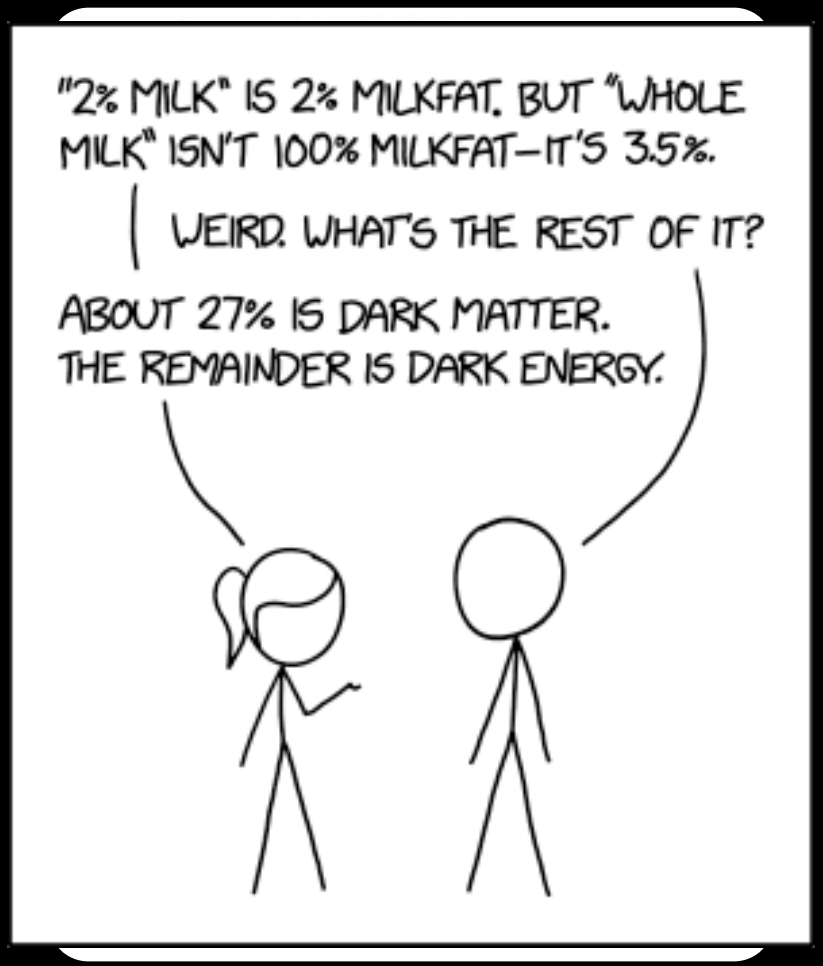
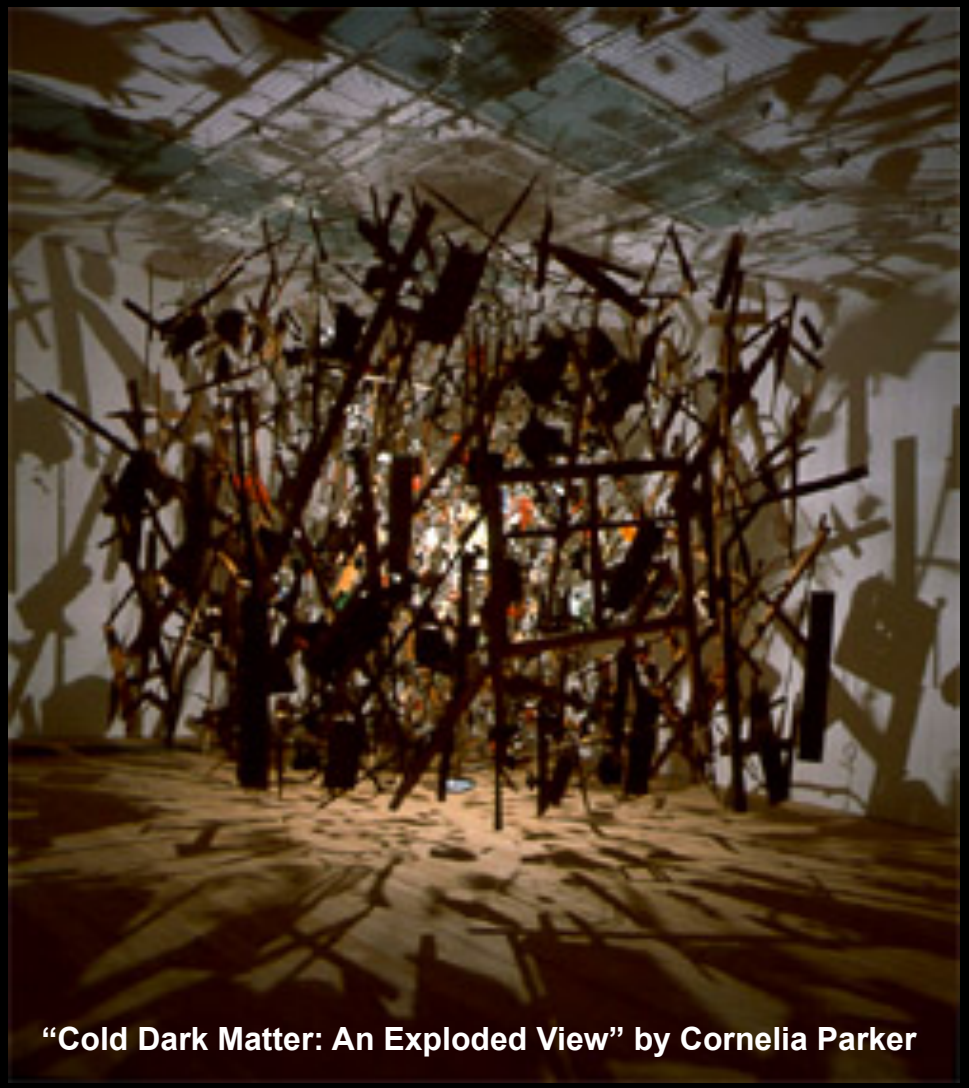
Lensing


Ordinary Matter
Dark Matter
Dark Energy


"2% MILK" IS 2% MILKFAT. BUT "WHOLE MILK" ISN'T 100% MILKFAT—IT'S 3.5%.
WEIRD. WHAT'S THE REST OF IT?
ABOUT 27% IS DARK MATTER. THE REMAINDER IS DARK ENERGY.

So what is Dark Matter?


"Cold Dark Matter: An Exploded View" by Cornelia Parker

- It's remarkable that measurements on very different scales all indicate a self-consistent picture of a Universe containing dark matter.
- Dark Matter is one of the few experimentally driven indications for Physics beyond the Standard Model.
- What do we know about it?
  - Dark (neutral)
  - Massive (non-relativistic)
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).

The Dark Matter Questionnaire

Circa 2013…

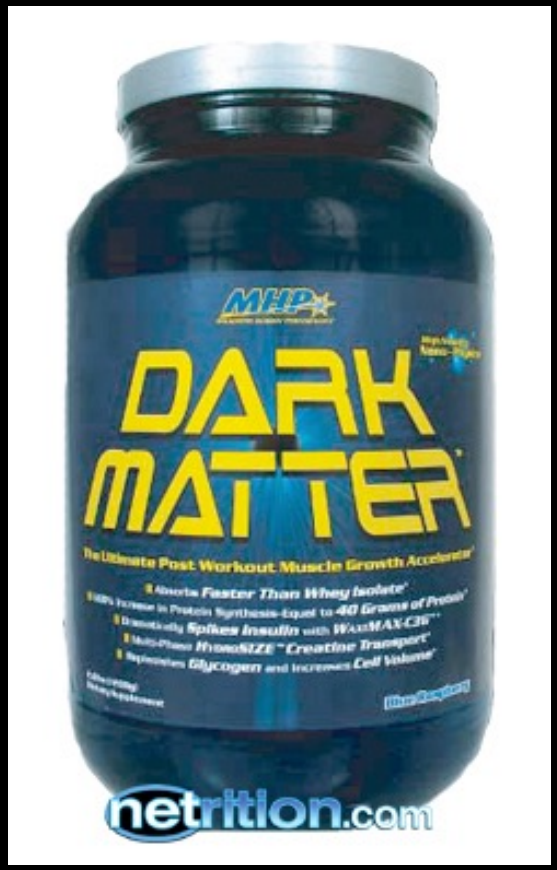
- ☐ Mass: _____
- ☐ Spin : _____
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

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

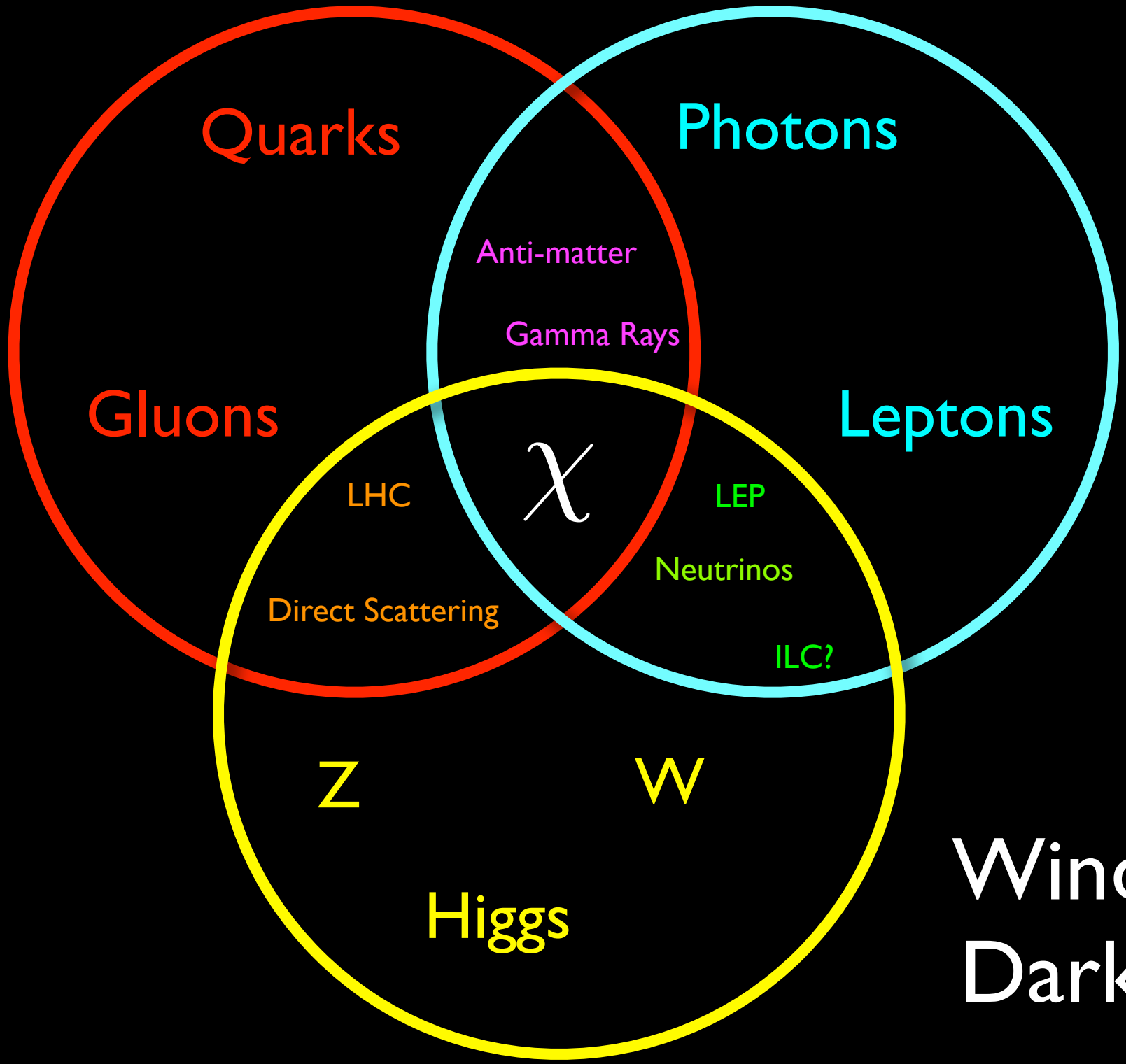
Thermal Relic?

- ☐ Yes ☐ No



$59.99 for 20 servings

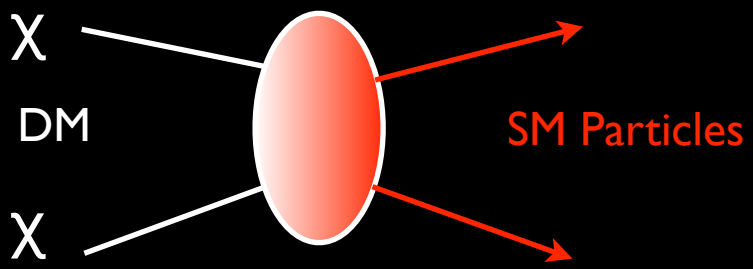
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

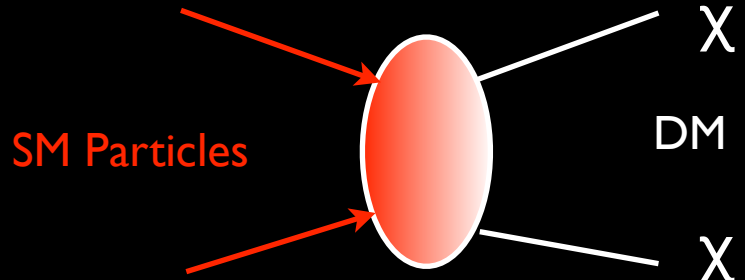


Windows on Dark Matter

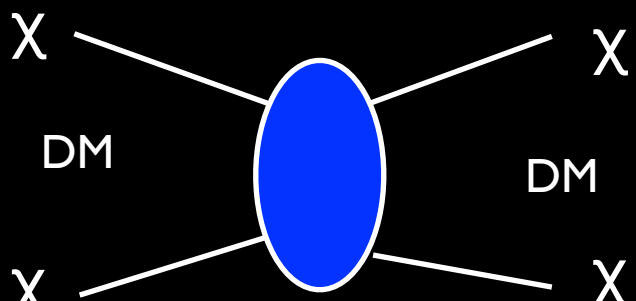
Probes of DM

Indirect Detection



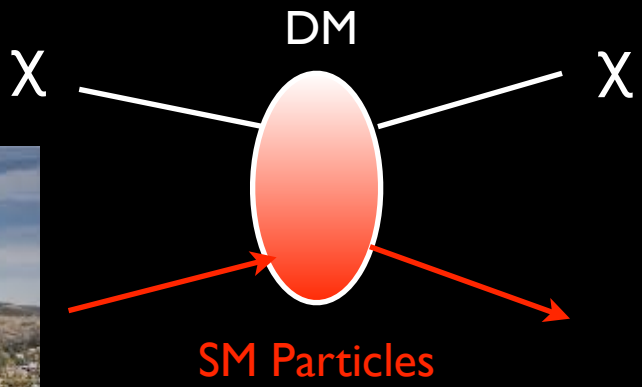


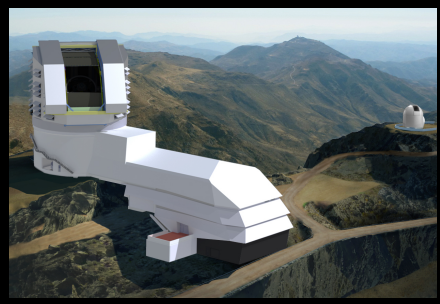
Collider Searches



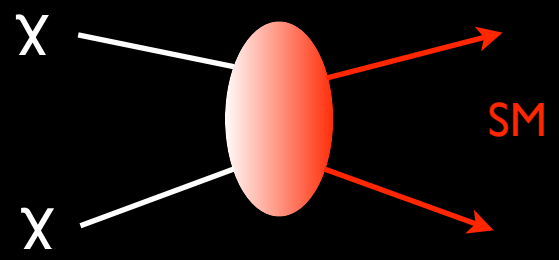
Self-Interactions

Direct Detection





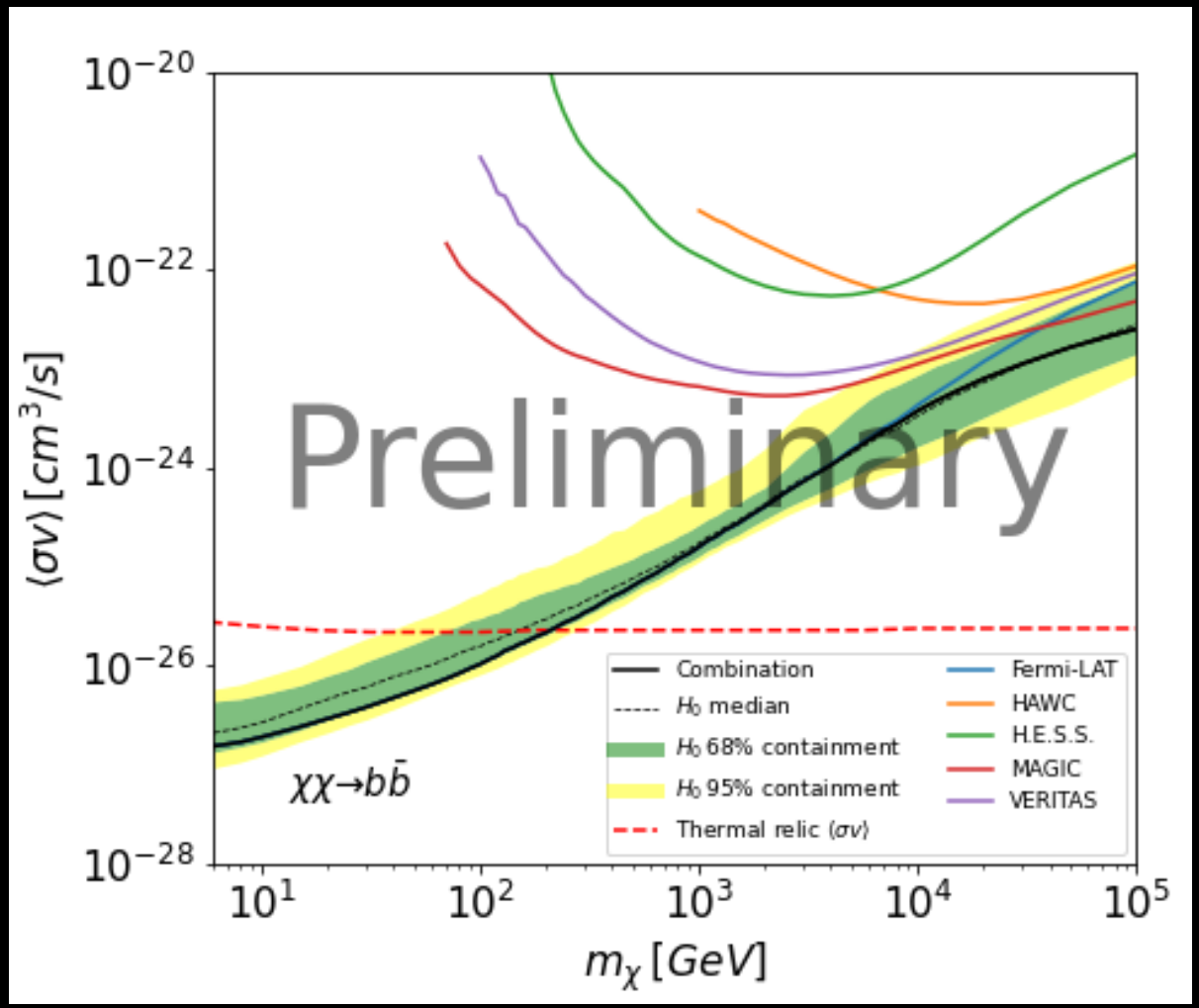
Indirect Detection

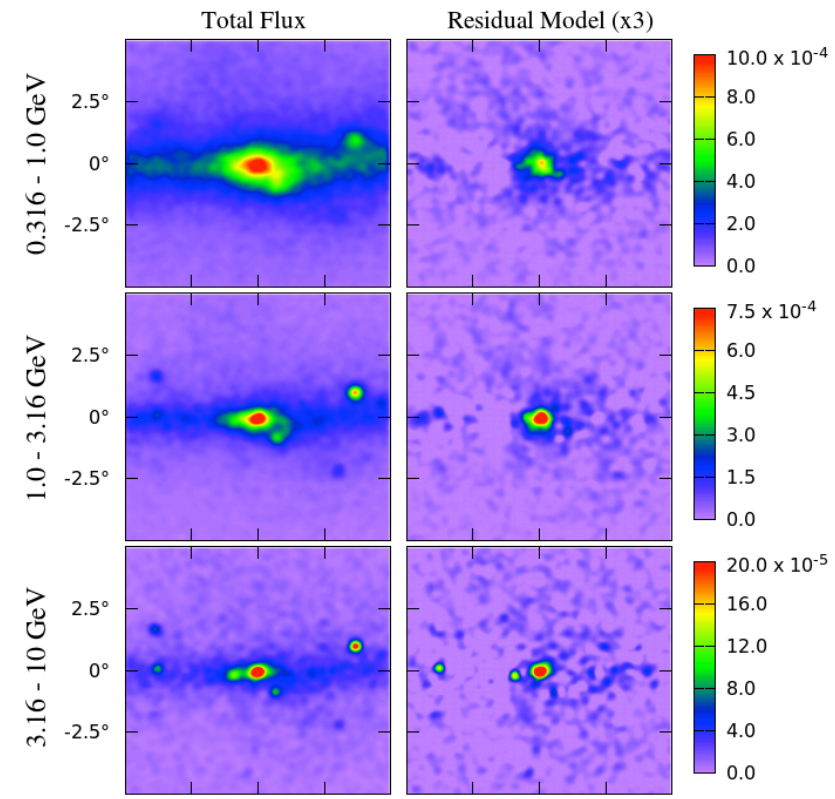


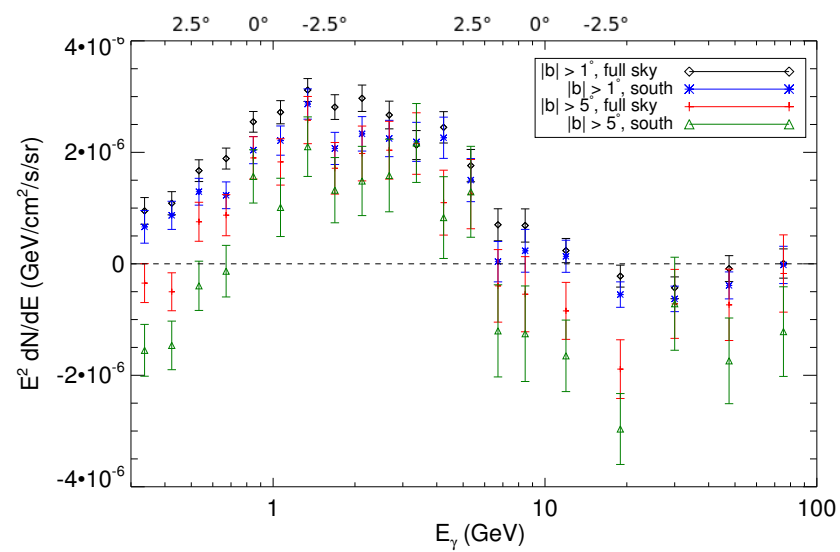
- Indirect detection tries to see dark matter annihilating.
- Dark Matter particles in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.
- In particular, photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth with directional information.
- Charged particles will generally be deflected on their way to us, but high energy anti-matter particles are rare enough that an excess of them could be noticeable.

Indirect Detection

Fermi, HAWC, MAGIC, H.E.S.S., Veritas Combined
Armand et al, 2108.13646



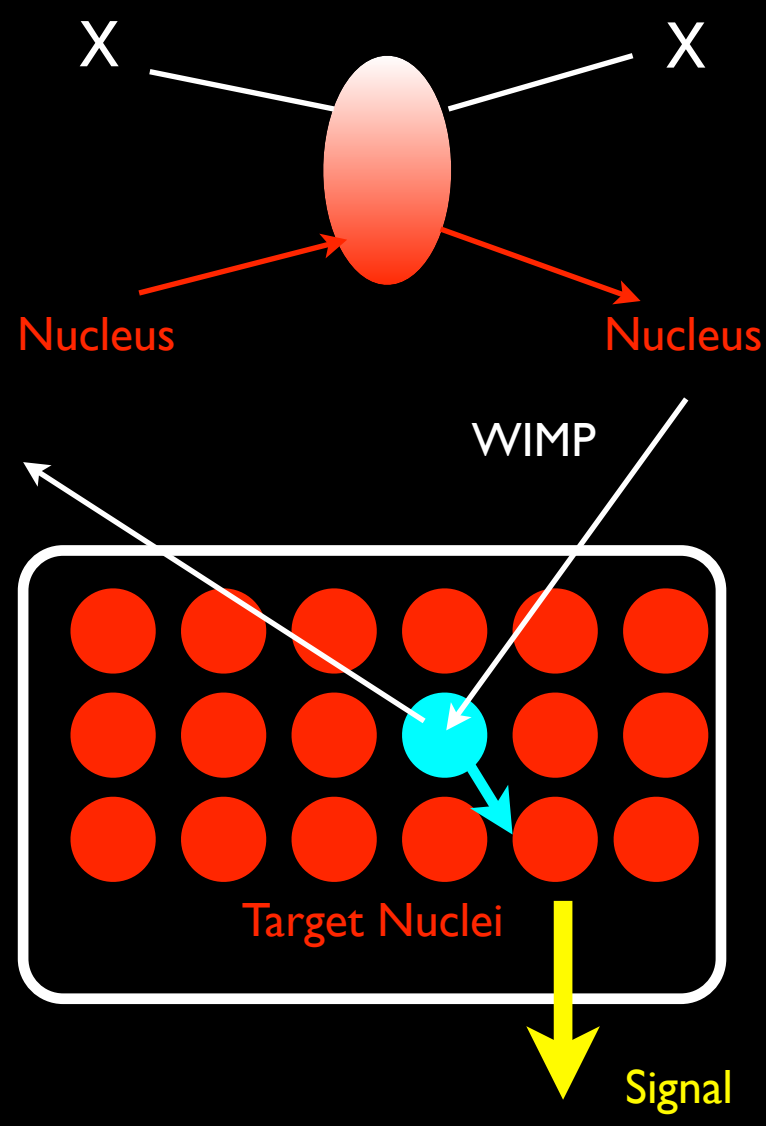


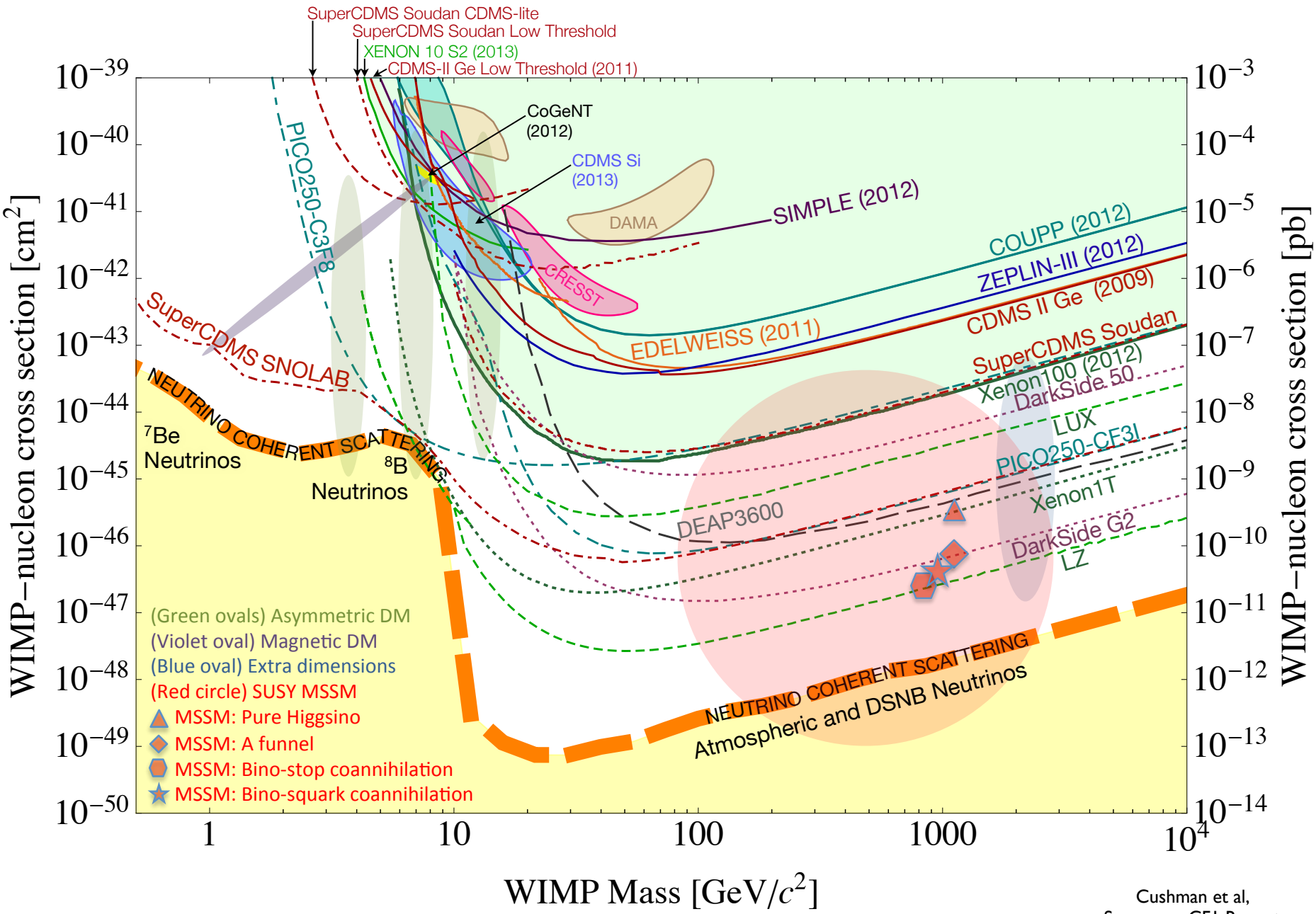


Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

Direct Detection

- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when dark matter brushes against it.
- Direct detection looks for the dark matter in our galaxy's halo, and a positive signal would be a direct observation.
- Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.
- The past decades have seen rapid advances, with orders of magnitude improvements in sensitivity every few years!

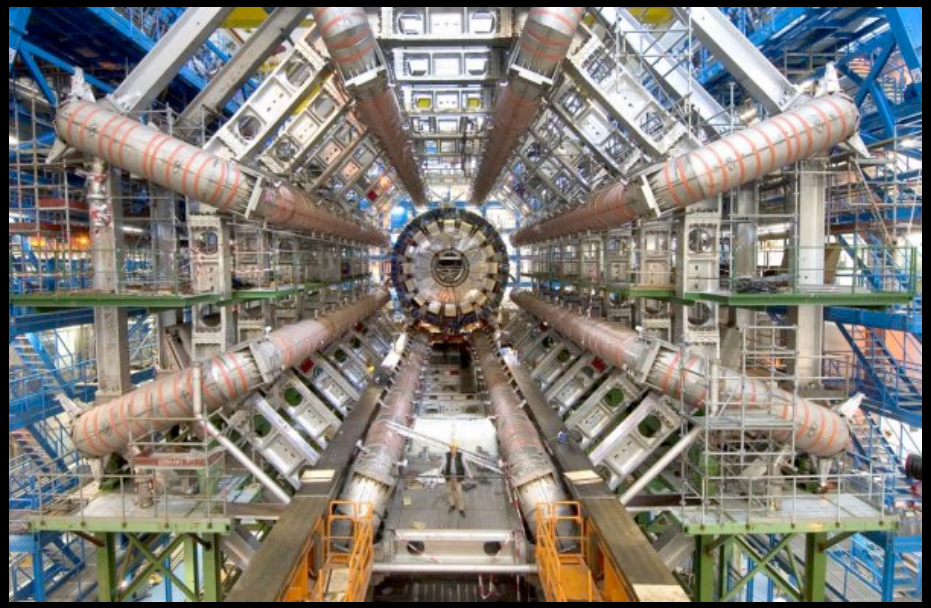




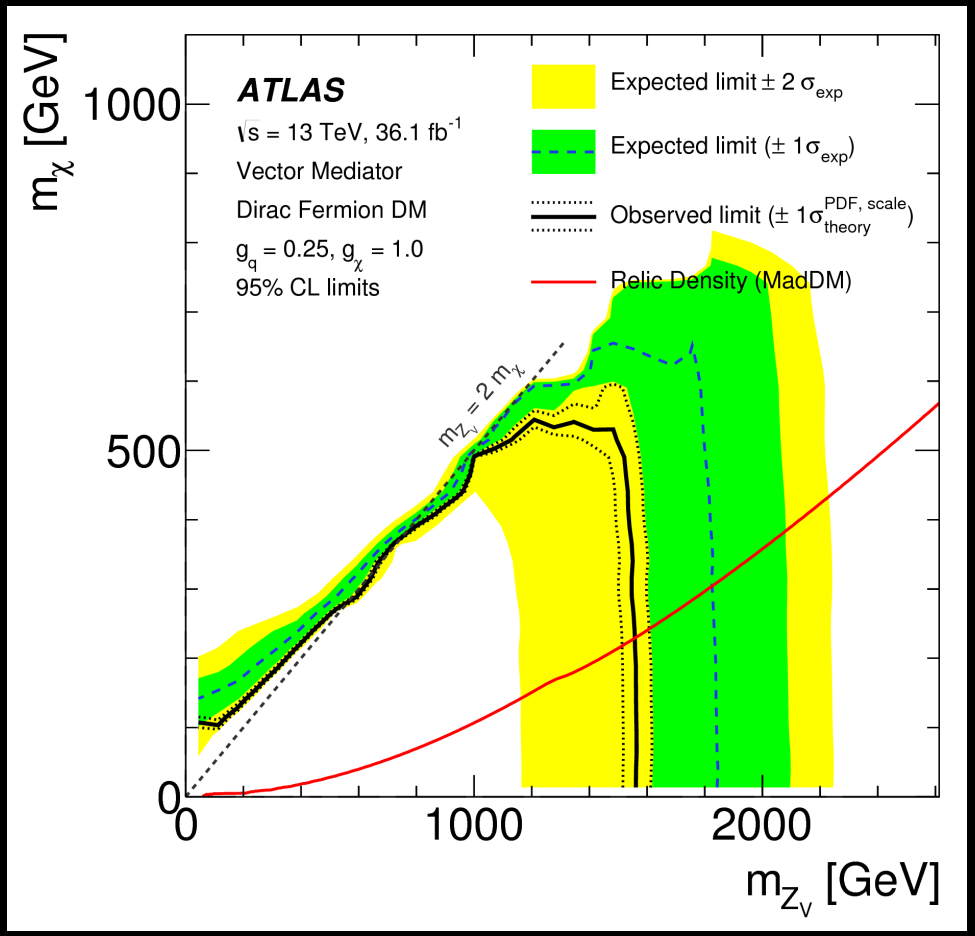
Cushman et al,
Snowmass CF1 Report

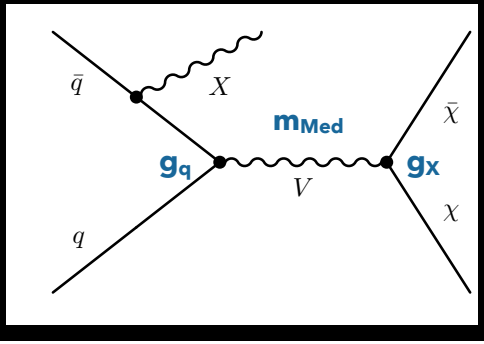
Collider Production

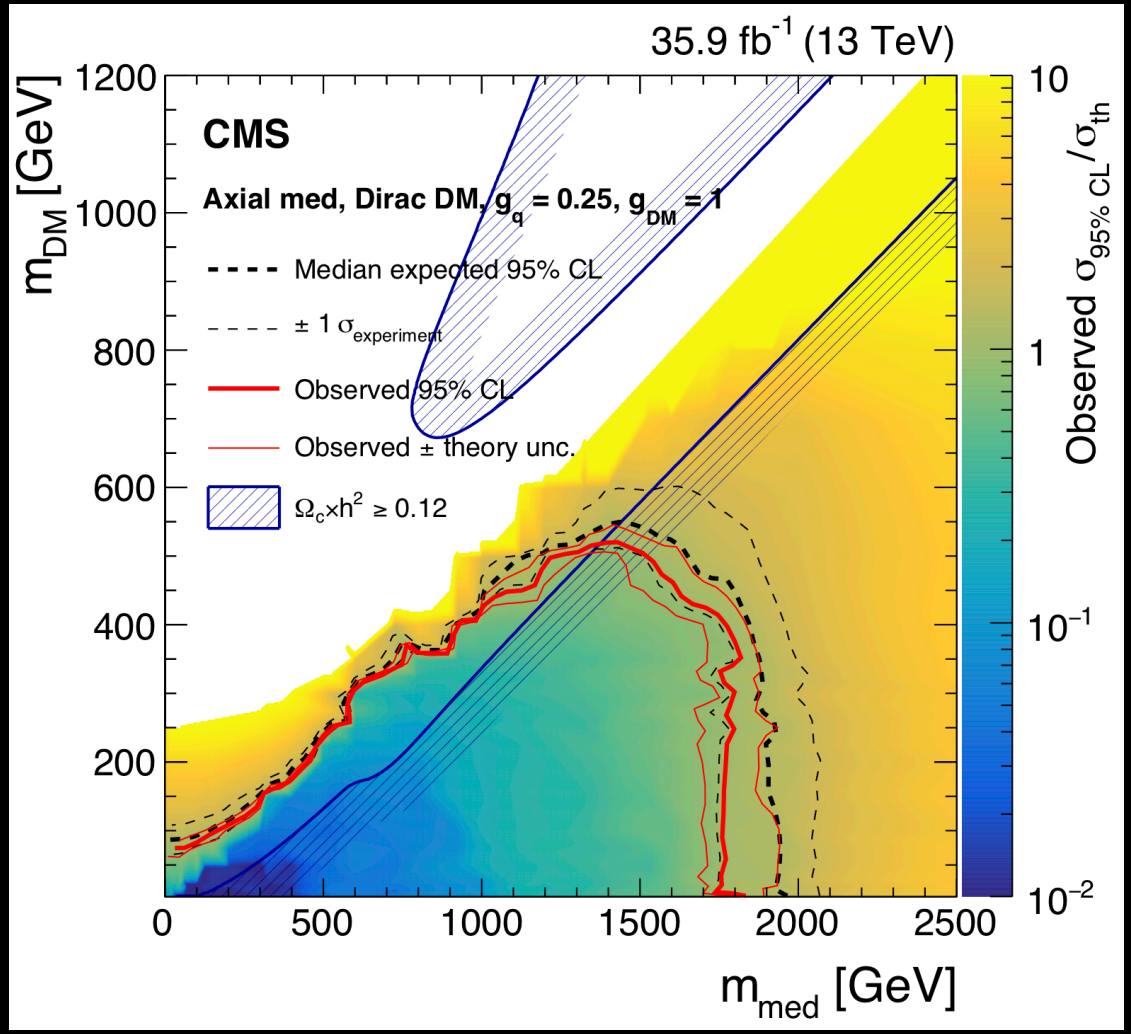
- If dark matter couples to quarks or gluons, we should also be able to produce them at high energy colliders.
- By studying the production of WIMPs in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- Collider detectors infer the presence of dark matter through momentum imbalance, which implies that it is most sensitive to cases where it can be produced relativistically.
-



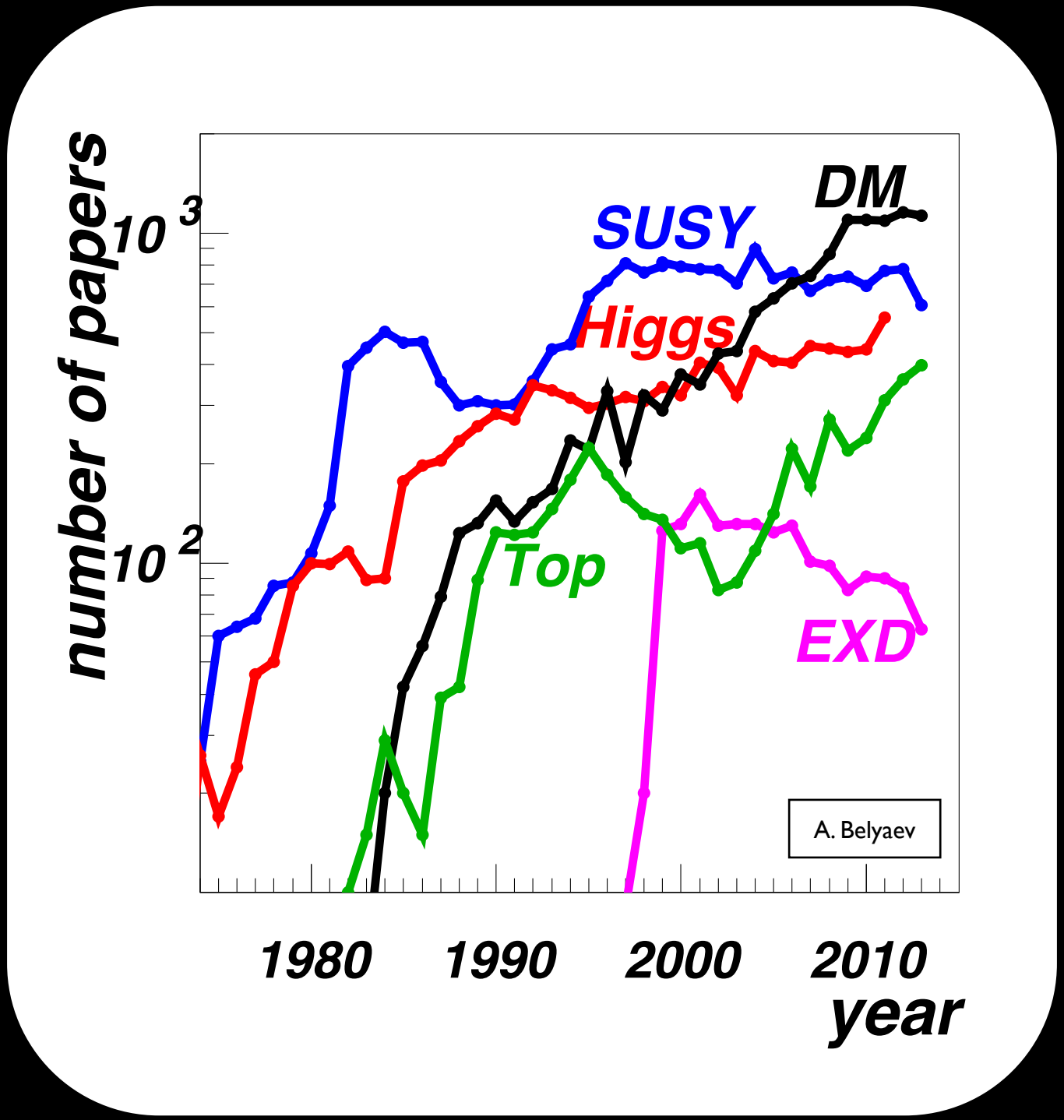
Mono-jet Searches





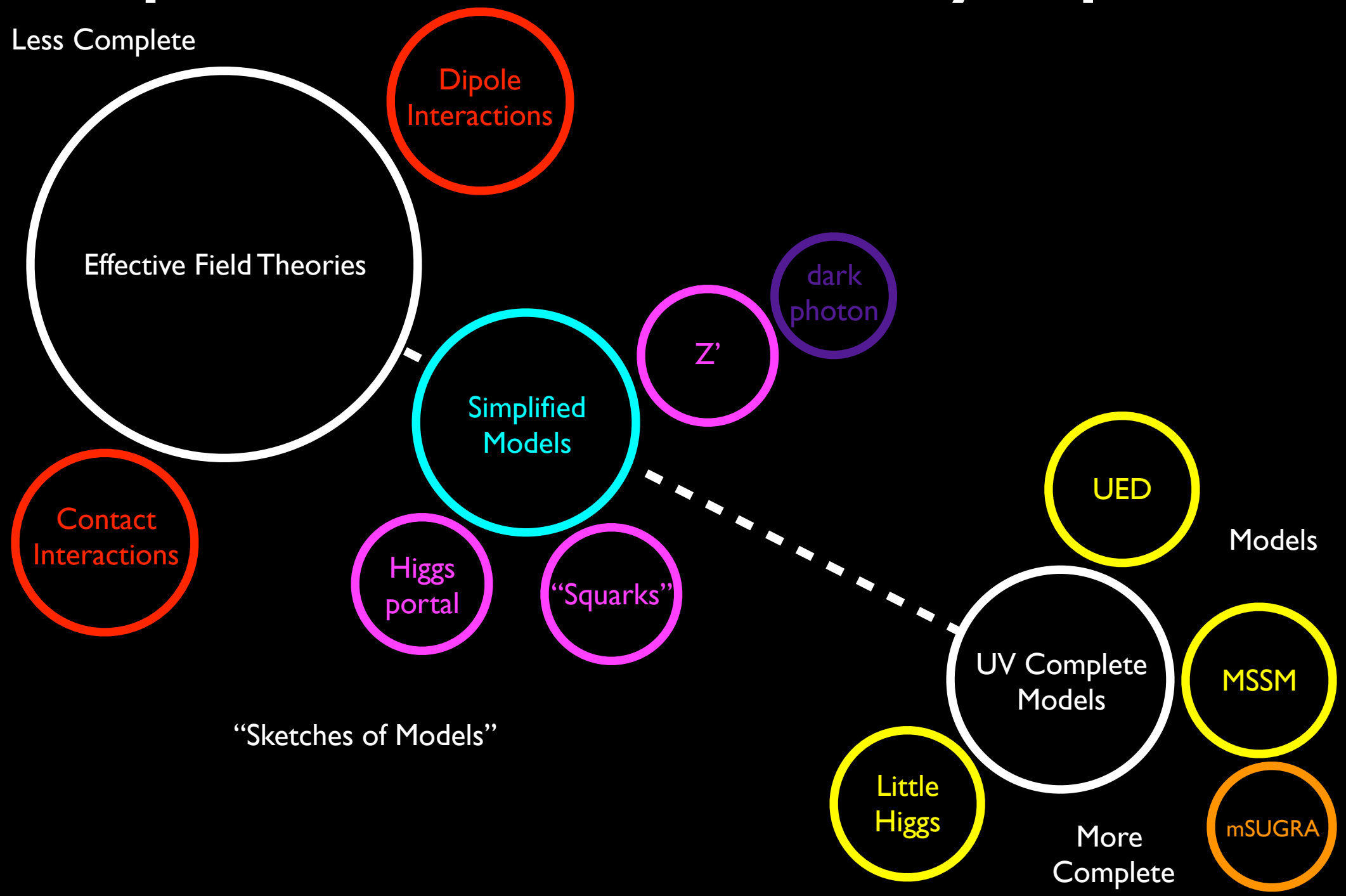


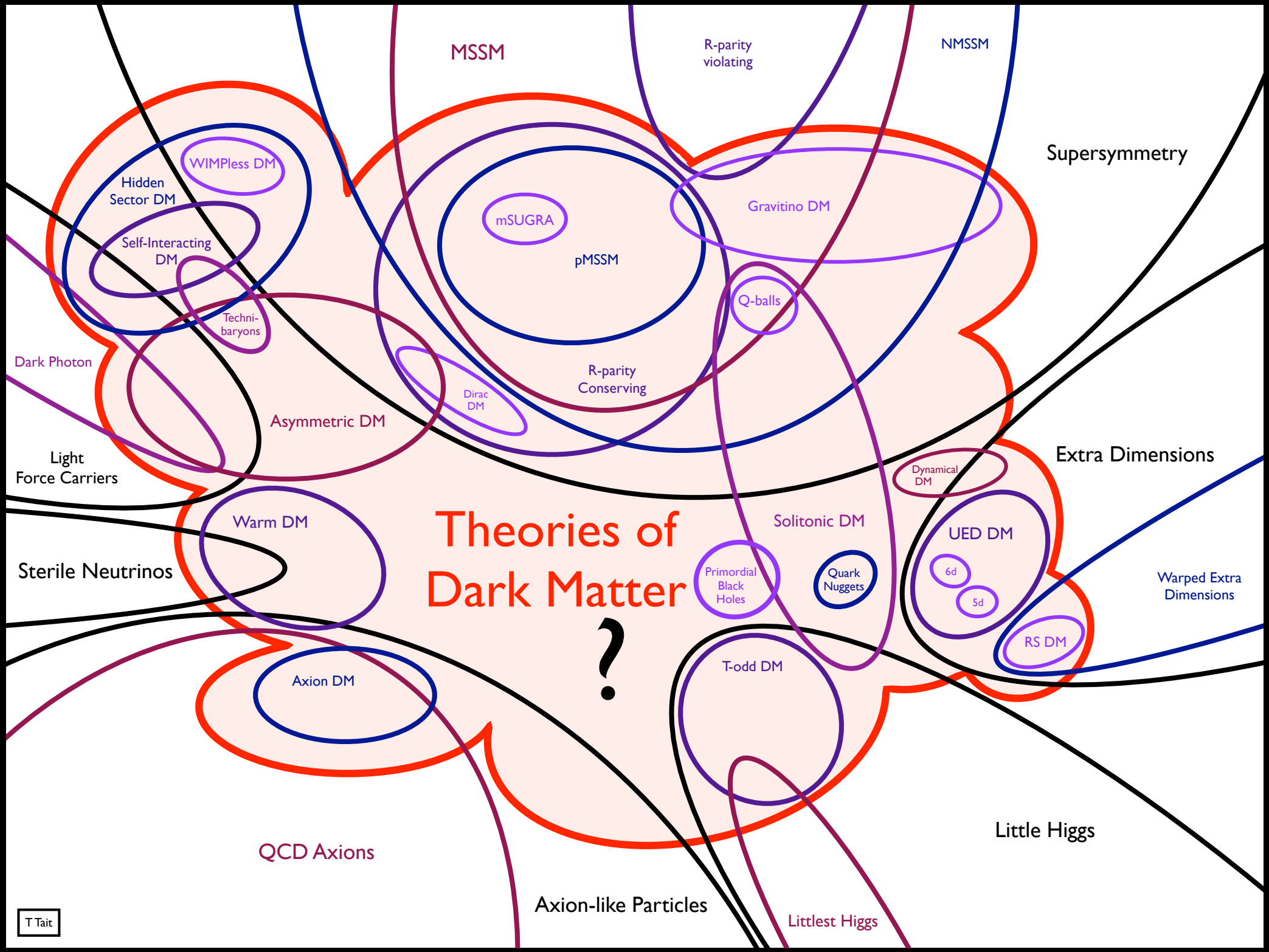
Searches for dark matter (missing momentum) plus a jet of hadrons places limits on the masses and couplings.


number of papers
10^3
10^2
SUSY
DM
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year

Models

Spectrum of Theory Space

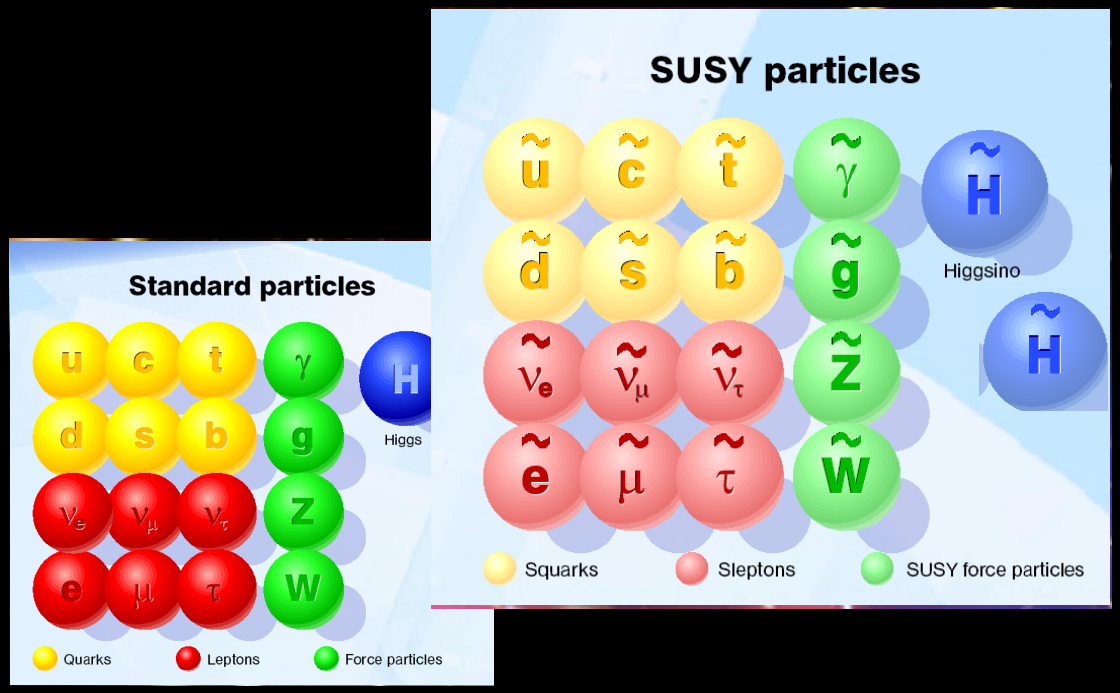



Theories of Dark Matter ?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Sterile Neutrinos
Solitonic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

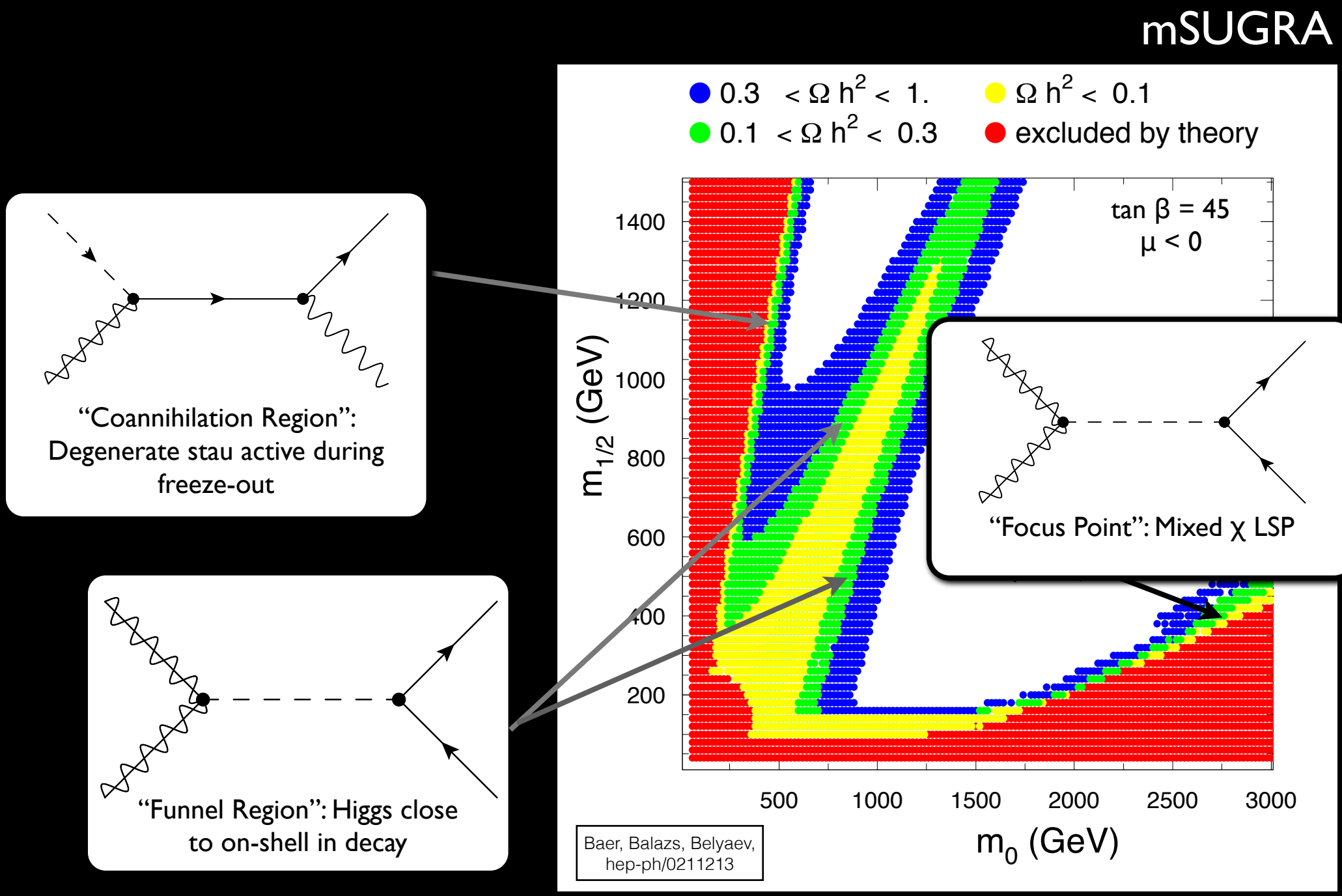
Where We Were

SUSY

- In the early days, dark matter was usually an afterthought that could be found in some of our favorite theories like SUSY extensions or the PQ solution to the strong CP problem.
- In particular, the Minimal Supersymmetric Standard Model contains a prototypical WIMP, lots of interesting associated phenomena, and (best of all) more than 100 quantities parameterizing supersymmetry breaking.
- mSUGRA reduced that to 4+1, which must never be referred to as five.

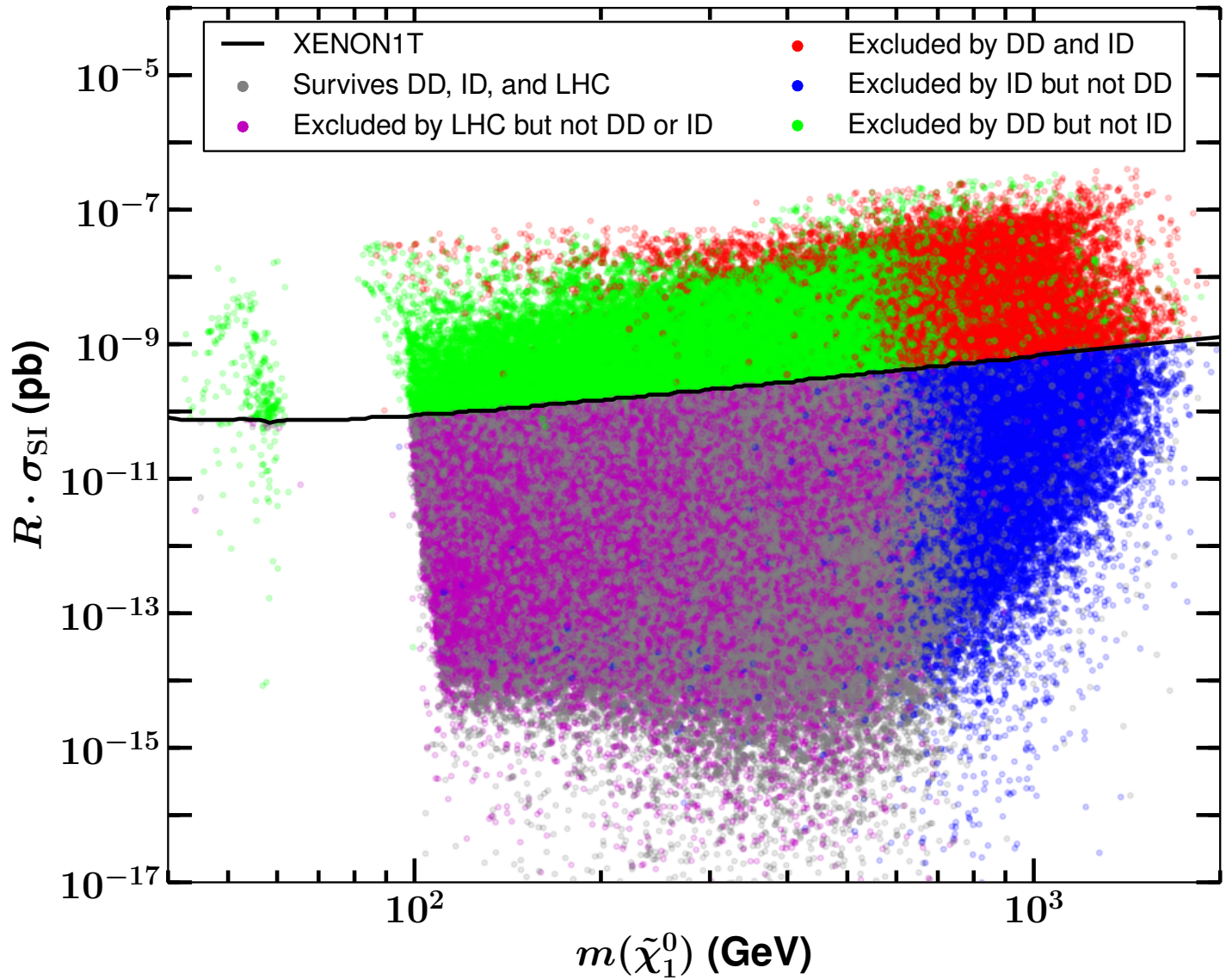


mSUGRA


mSUGRA
0.3 < Ω h² < 1.
Ω h² < 0.1
0.1 < Ω h² < 0.3
excluded by theory
tan β = 45
μ < 0
1400
1200
1000
800
600
400
200
m1/2 (GeV)
500
1000
1500
2000
2500
3000
m0 (GeV)
Baer, Balazs, Belyaev, hep-ph/0211213
"Coannihilation Region": Degenerate stau active during freeze-out
"Funnel Region": Higgs close to on-shell in decay
"Focus Point": Mixed χ LSP

pMSSM

Cahill-Rowley et al, 1305.6921



Contact Interactions

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

- E.g. leading interactions between quarks and gluons and a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and gauge invariance that describe WIMPs coupling to quarks or gluons.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.
- In principle, a realistic UV theory will turn on some combination of them, with related coefficients.

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

Other operators may be rewritten in this form by using Fierz transformations.

Example: Majorana WIMP

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

- The various types of interactions are accessible to different kinds of experiments.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation in the galactic halo
  - Collider Production

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

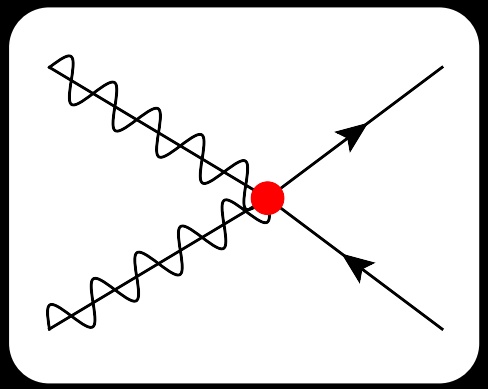
$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

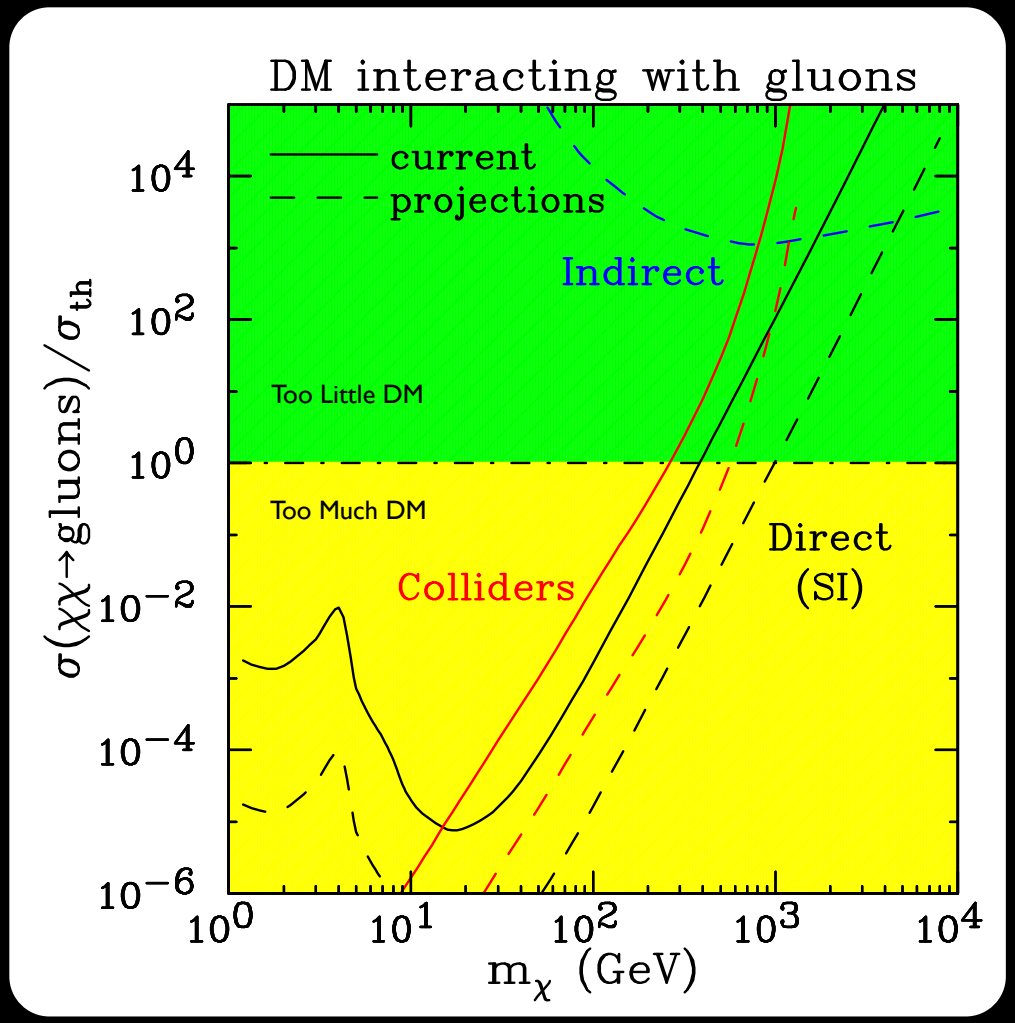
Other operators may be rewritten in this form by using Fierz transformations.

Complementarity

- We can map each interaction into a prediction for WIMPs annihilating.



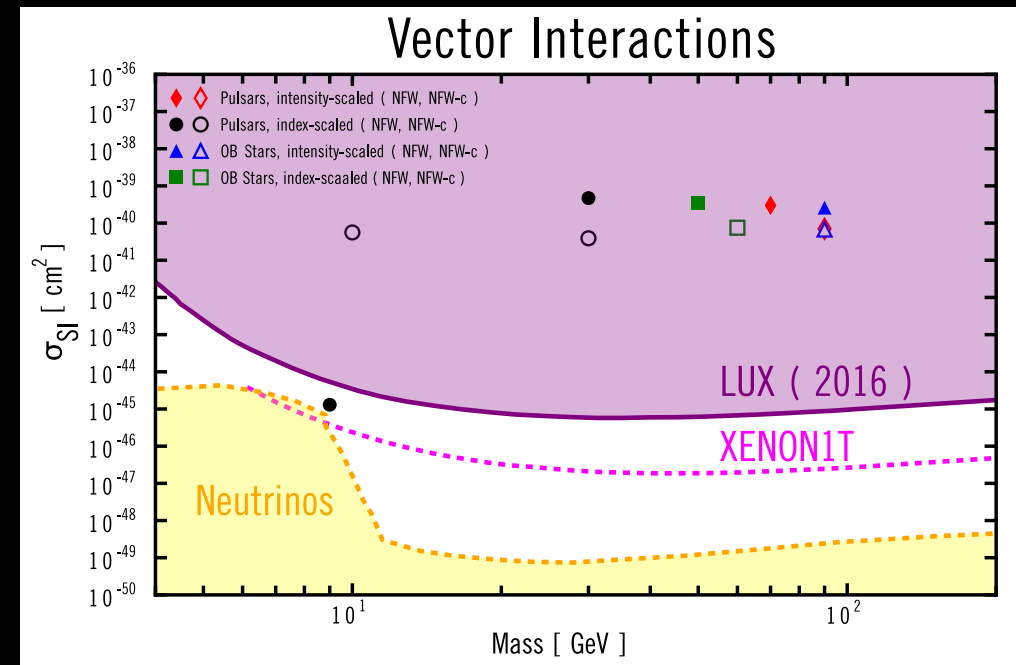
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.

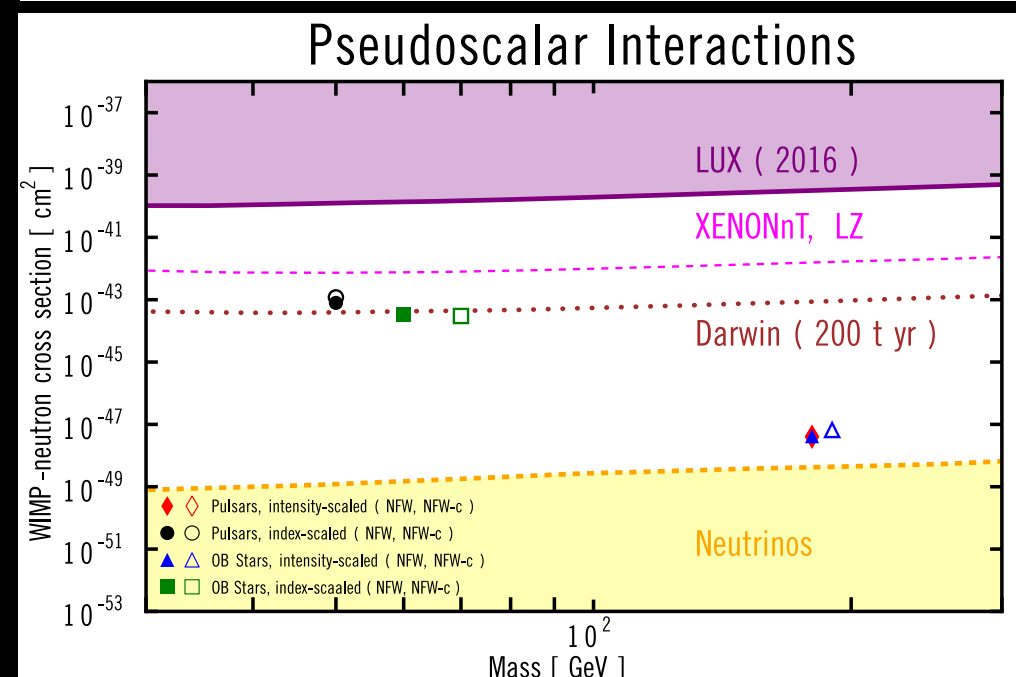


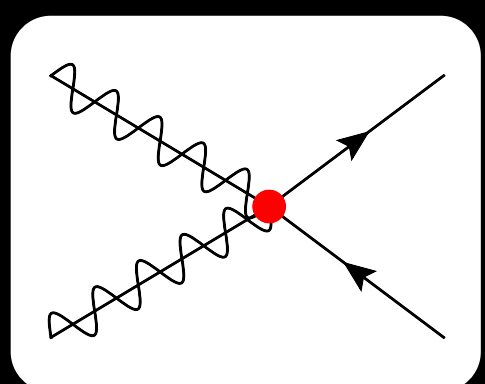
DM Complementarity, arXiv:1305.1605

Engineering

- This understanding also allows us to construct theories that realize experimental signals and/or evade experimental constraints.
- For example, we can saturate the Galactic Center Excess as a signal of dark matter annihilation while evading strong constraints from direct searches.







Karwin, Porter. Murgia, TMPT, Tanedo 1612.05867 & PRD

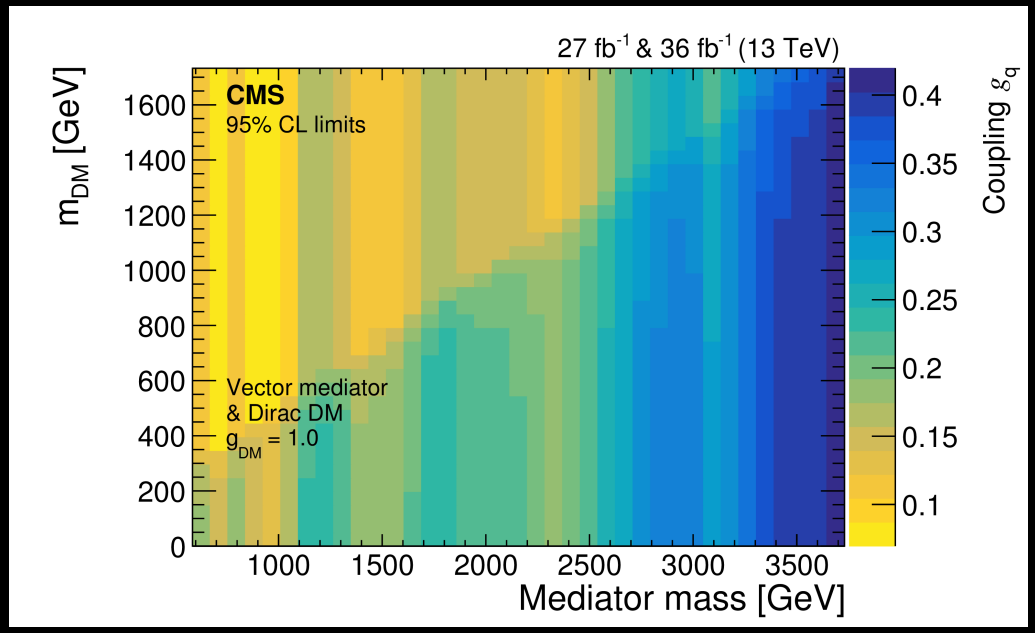
Where We Are

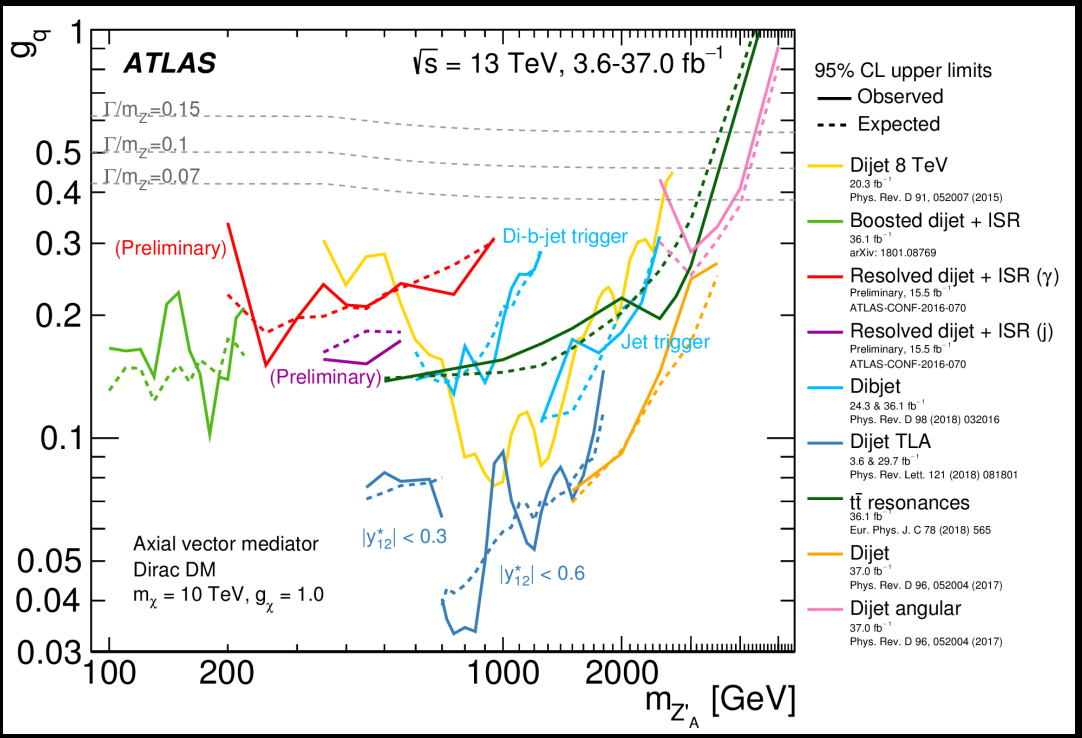
Simplified Models

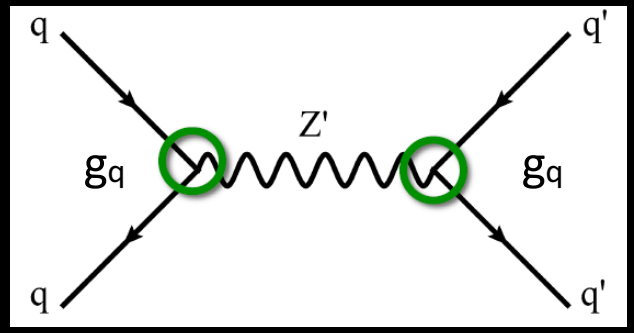
- A compromise is to include some of the important mediator particles as well as the dark matter.
- This allows one to discuss the mediators at colliders more robustly, and also to capture natural correlations that the EFT fails to describe.
- It also allows one to delve into theoretical considerations (such as a dark Higgs sector, more particles to cancel gauge anomalies, etc), which can be important for the phenomenology.

Mediator Searches

There are also searches purely for the mediator particles, by looking for cases in which it is produced and then decays back into ordinary particles such as electrons or jets of hadrons.



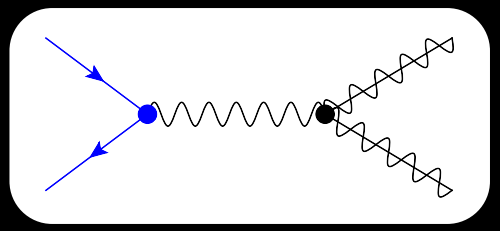


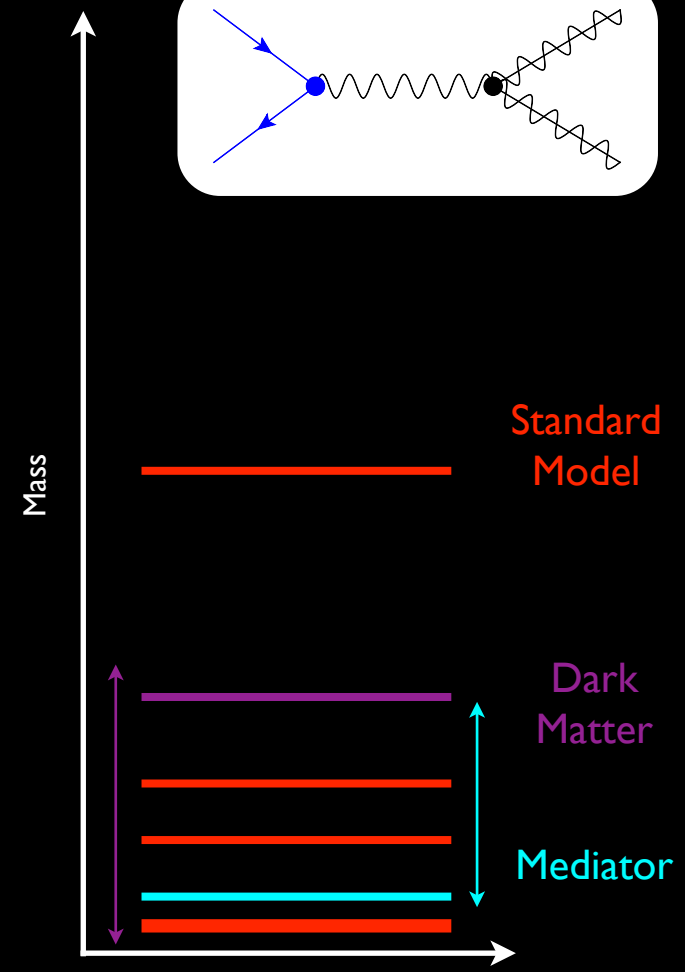


Where We're Going

Dark Photons

- An interesting part of the parameter space has light mediating particles
- This opens up a window where the relic density turns out correctly for light (~MeV) dark matter.
- In this limit, a natural explanation for the small couplings of the mediator to the standard model is that they come dominantly from kinetic mixing with $U(1)_Y$.
- In this limit, the couplings of the mediator to the SM look like photon couplings scaled down by ε. The mediator in this case is often referred to as a "dark photon".
- This regime motivates different kinds of searches, including for long-lived and/or low mass ultra weakly interacting particles.

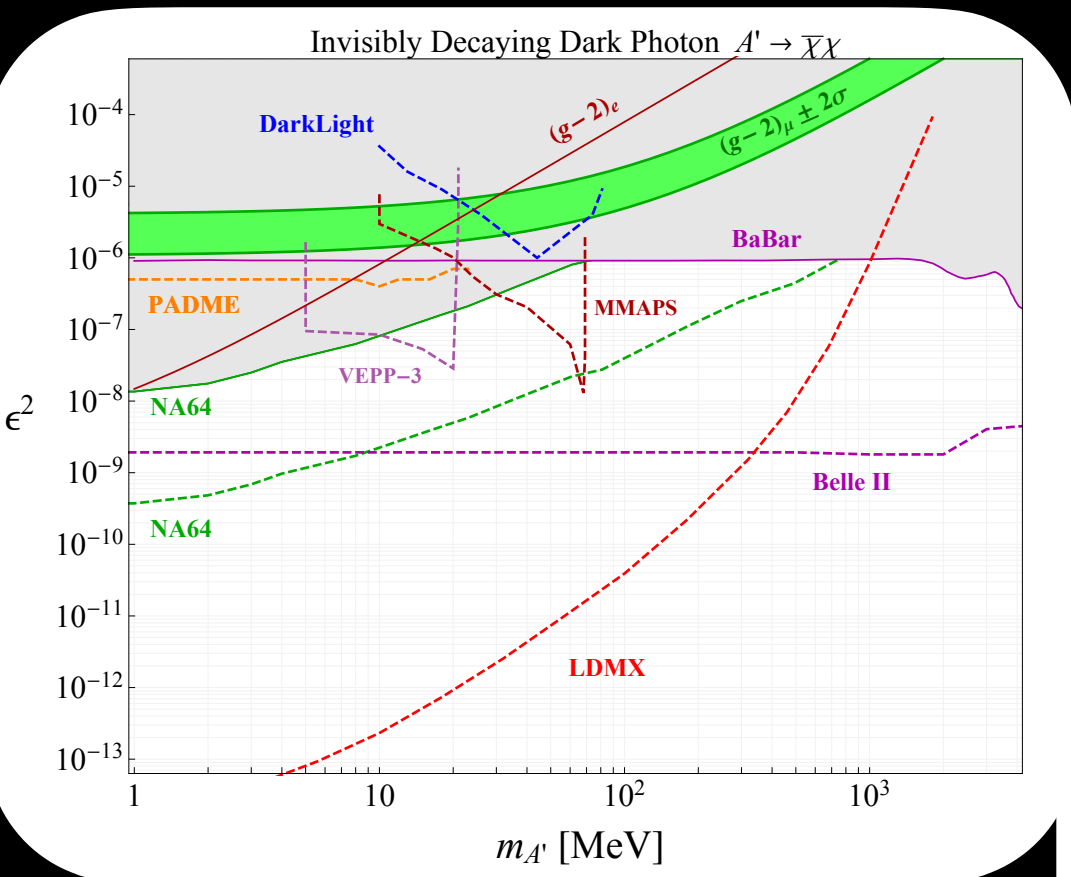




γ_D Parameters:

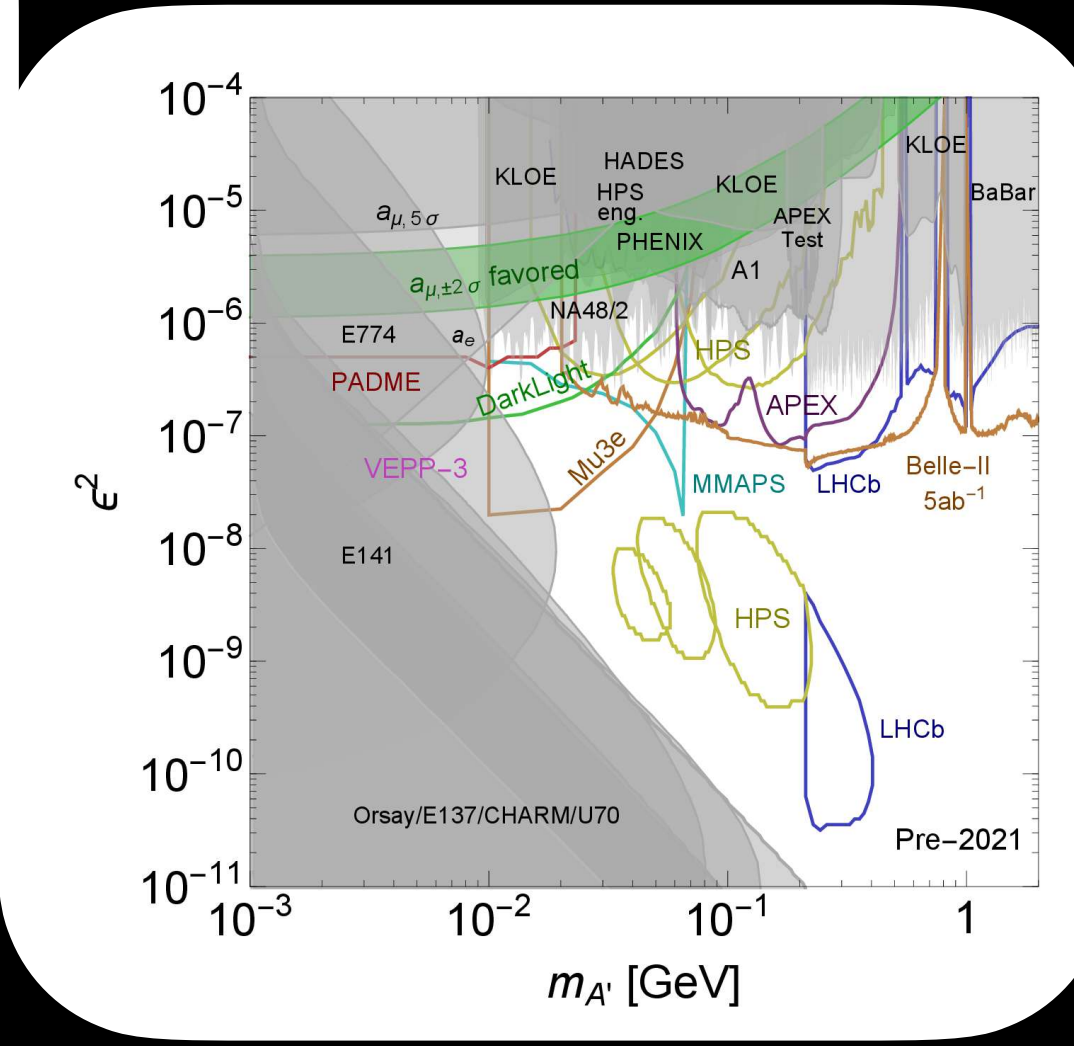
$$\{m_\chi, m_{A'}, \alpha_D, \epsilon\}$$

New Experiments



~100% BR into invisible channels.

~100% BR into visible channels.

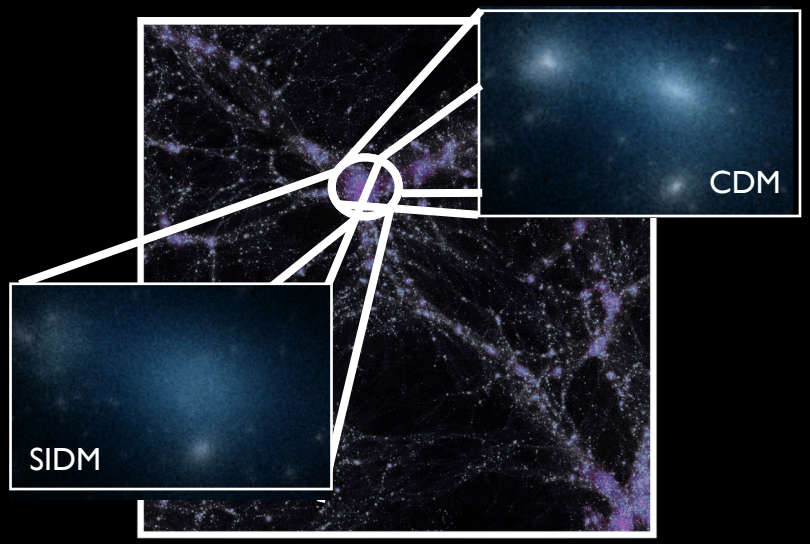


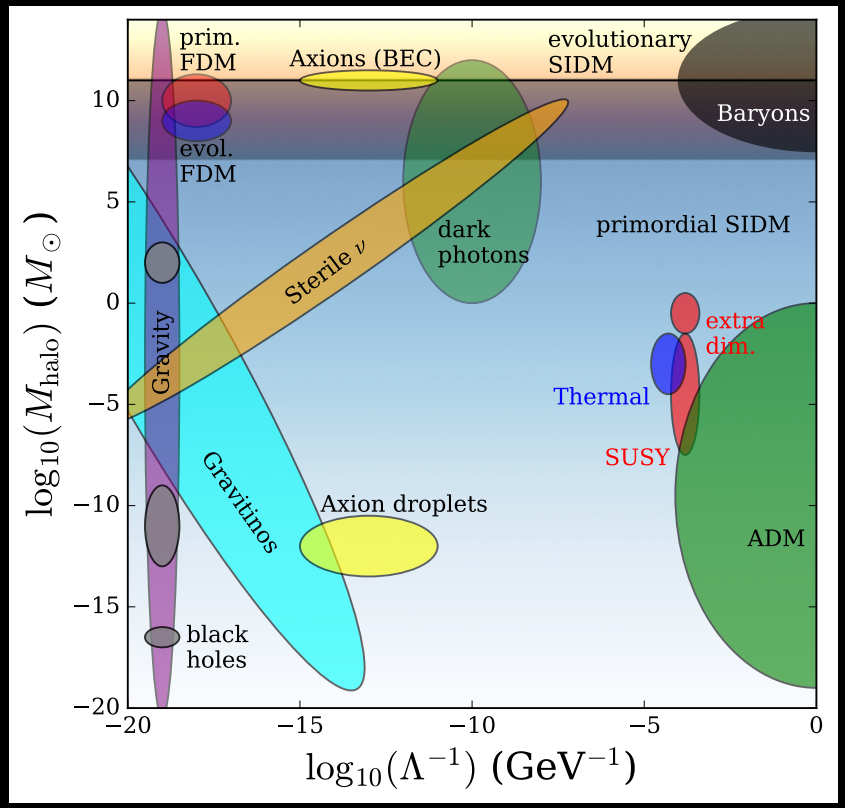
US Cosmic Visions Report
arXiv:1707.04591

Many projects both underway and proposed can search for light mediators decaying (dominantly) invisibly.

Astronomical Probes

- Dark matter with interesting dynamics on large scales could leave an imprint in the structure of the Universe.
- E.g. Dark matter with large enough self-interactions could retain the successes describing large scale structure, but show measurable differences at the smallest scales.
- Observations have driven attention to how we simulate the impact of baryonic matter, leading to better and
- Astronomy provides a unique perspective on properties that particle searches cannot probe.

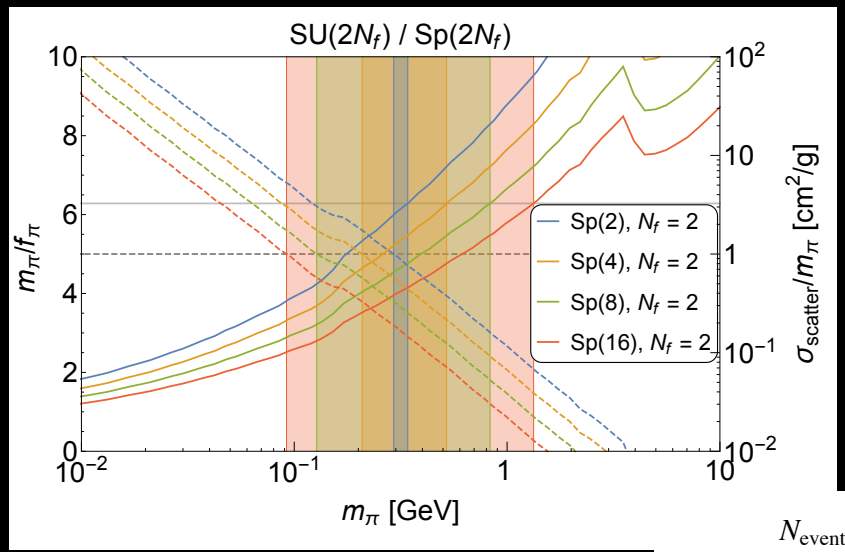




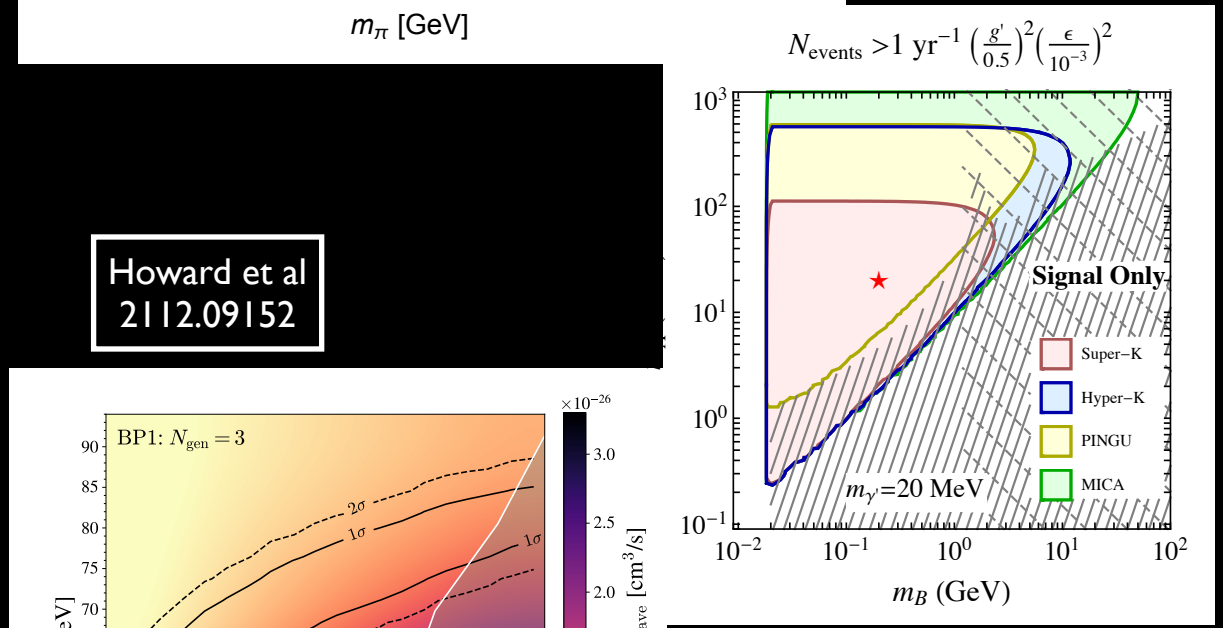
Buckley, Peter
Physics Reports 2018

New Directions

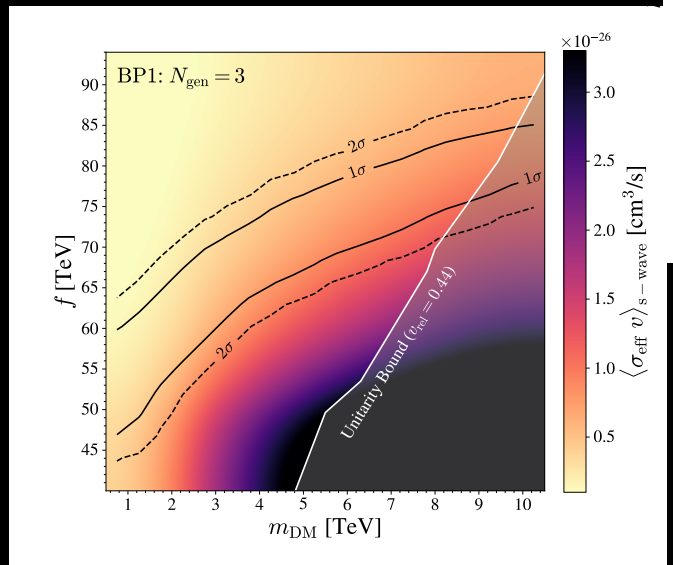
- Models of dark matter have ceased to be about finding it in 'our favorite theories of other things' and is now more about exploring a wide range of phenomena and trying to cover as wide a net as possible…
- Given how little we know, this feels like a healthy and reasonable approach.
- Dark matter production is a probe of the conditions in the early Universe.
- It's impossible to do justice to the volume of work here!



Hochberg et al 1411.3727



Howard et al 2112.09152



Agashe et al 1405.7370

New Descriptions

Nuclear (NR) EFT

1. P-even, S_χ-independent

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (v^\perp)^2, \qquad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp),$$

2. P-even, S_χ-dependent

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}),$$

3. P-odd, S_χ-independent

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

4. P-odd, S_χ-dependent

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

5. P-odd, S_χ-independent:

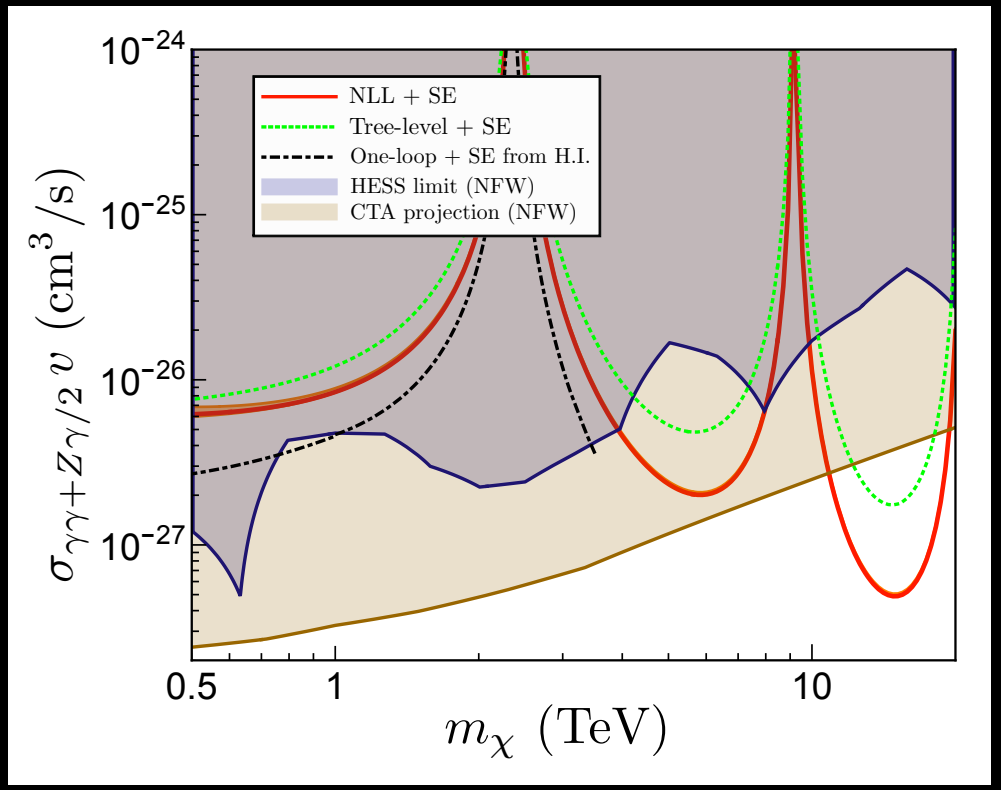
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q},$$

6. P-odd, S_χ-dependent

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}.$$

Fitzpatrick et al, 1203.3542

Gamma Rays from Winos



Ovanesyan, Slatyer, Stewart
1409.8294 & PRL

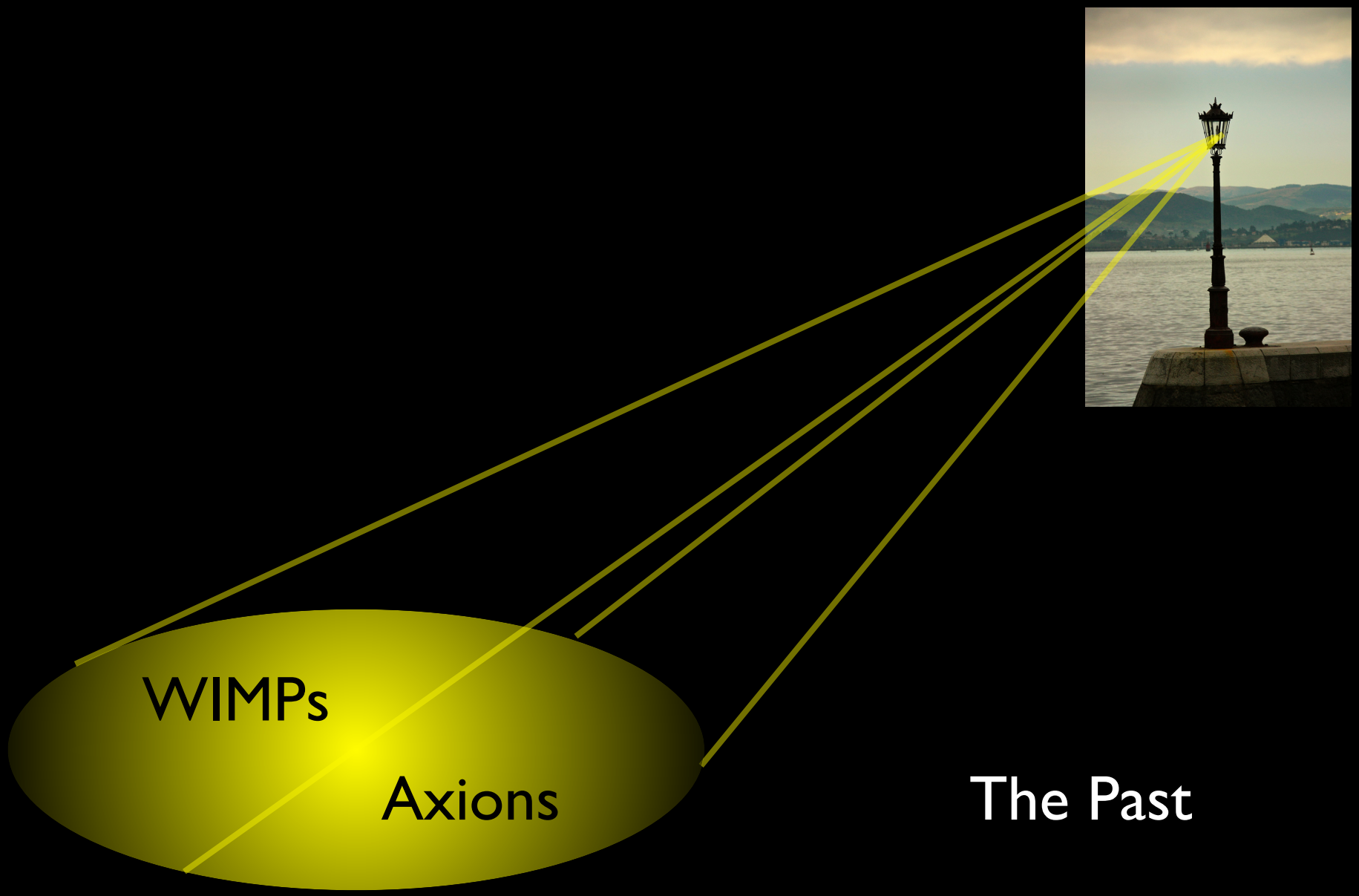
Outlook

- It is impossible to do justice to the theoretical activity related to dark matter in 20 minutes…
- Nevertheless, dark matter remains a vigorous area of research, ranging from exploring new models, to investigating novel uses of existing data, to proposing new experiments.
  - All of these advances, including the experimental ones, are the result of a vigorous theory program.
- Dark matter is one of the few tangible manifestations of physics beyond the Standard Model that it is impossible to imagine could go away. Understanding its properties is likely to provide deep information as to how to amend the Standard Model.
- The important thing is to keep looking for new ways to look for it!

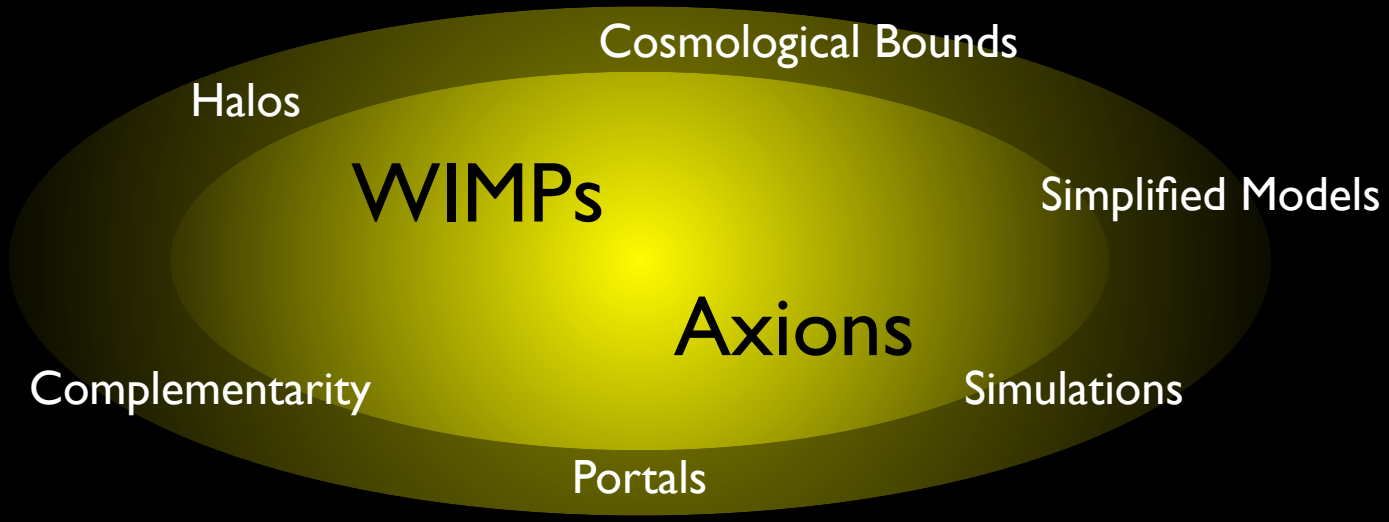
Outlook

The Lamppost

Outlook



Outlook



The Present

Outlook

Boosted DM

Dark Shower

Dark Sectors

Black Holes

Dark Blobs

SIMPs

Self-Interacting

Fuzzy DM

Multi-messenger

Low Mass Searches

Astrophysical Probes

Nonstandard Cosmologies

Cosmological Bounds

Halos

New Experiments

WIMPs

Simplified Models

Da

Axions

The Future

Complementarity

Simulations

Portals

New Observables

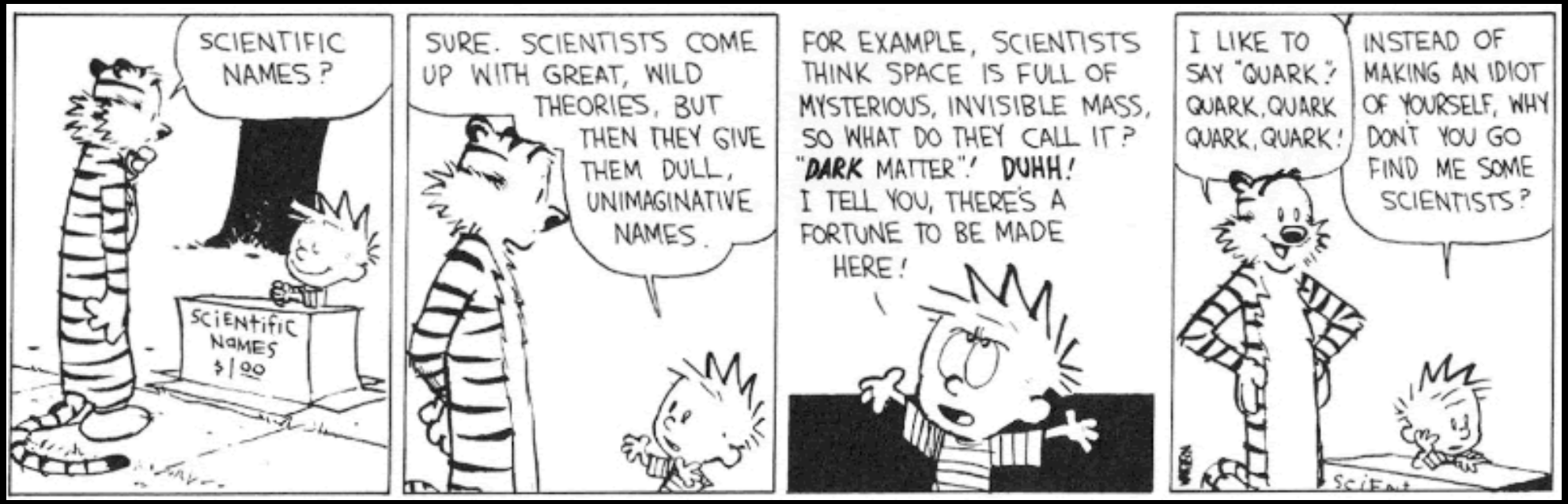
New Models

LLP's

Thank You!

Bertone, TMPT 1810.01668 & Nature

Sketches of ....


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
I LIKE TO SAY "QUARK"? QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?

Direct Detection

- The rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

$$\frac{dN}{dE} = \sigma_0 \frac{\rho}{m} \int dv f(v) F(E)$$

DM density

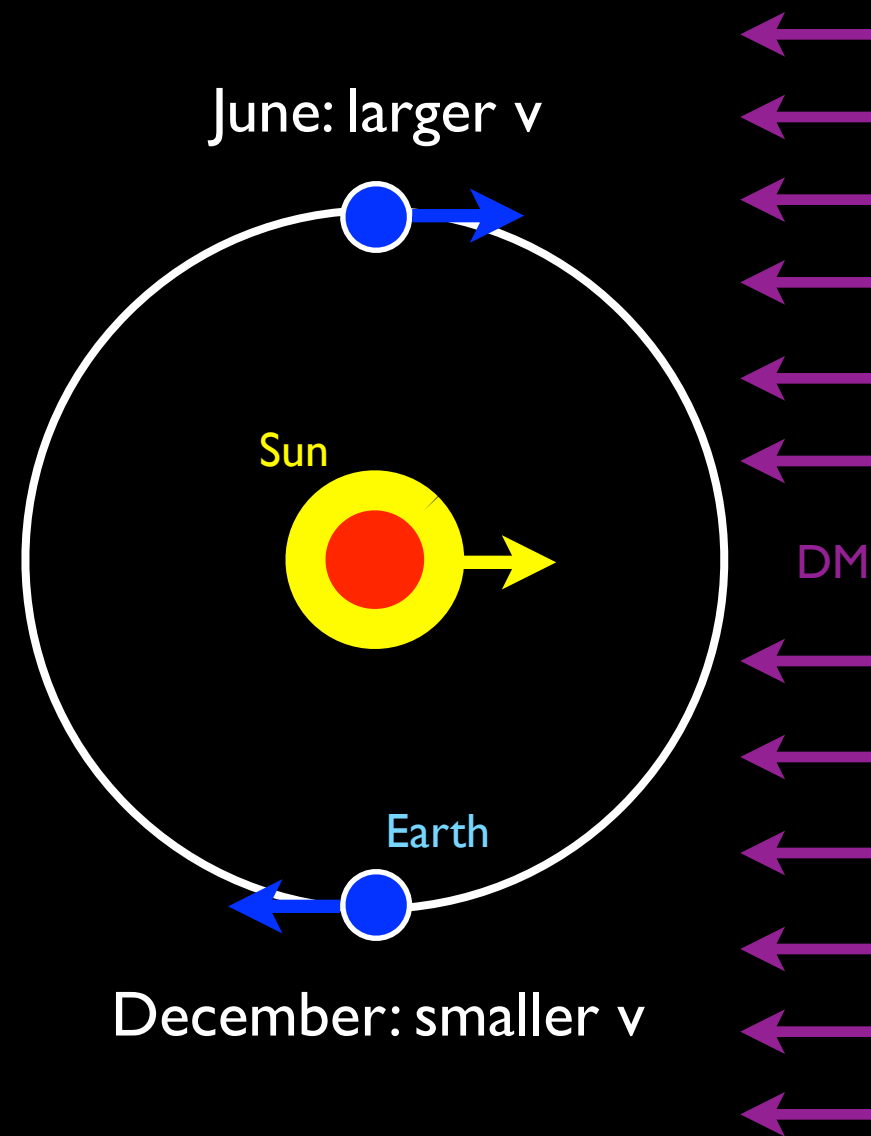
Nuclear Physics

DM velocity distribution

- The energy spectrum of the recoiling nucleus depends on the WIMP mass, its coupling to quarks, and nuclear physics.

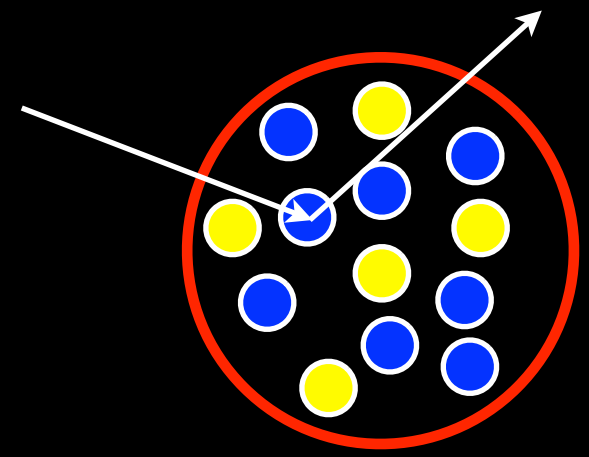
- The cross section is dominated by the effective WIMP interactions with quarks and gluons.

- An interesting handle on the signal is an expected annual modulation.

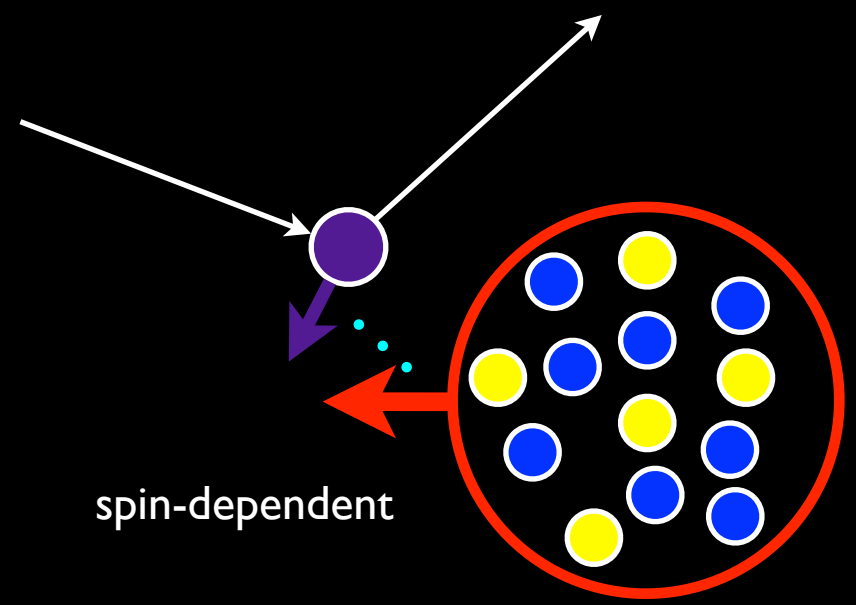


Direct Detection

- There are two distinct classes of direct detection searches:
  - Spin-independent (SI) scattering looks for direct scattering of the WIMP from the nucleons in the nucleus.
  - Spin-dependent (SD) scattering looks for interactions coupling the WIMP's spin to the nuclear spin.
- Because of the low momentum transfer, the dark matter typically probes the entire nucleus.
  - The SI scattering receives a coherent enhancement for large nuclei.
  - The strongest limits are currently on SI cross sections for Xenon targets.



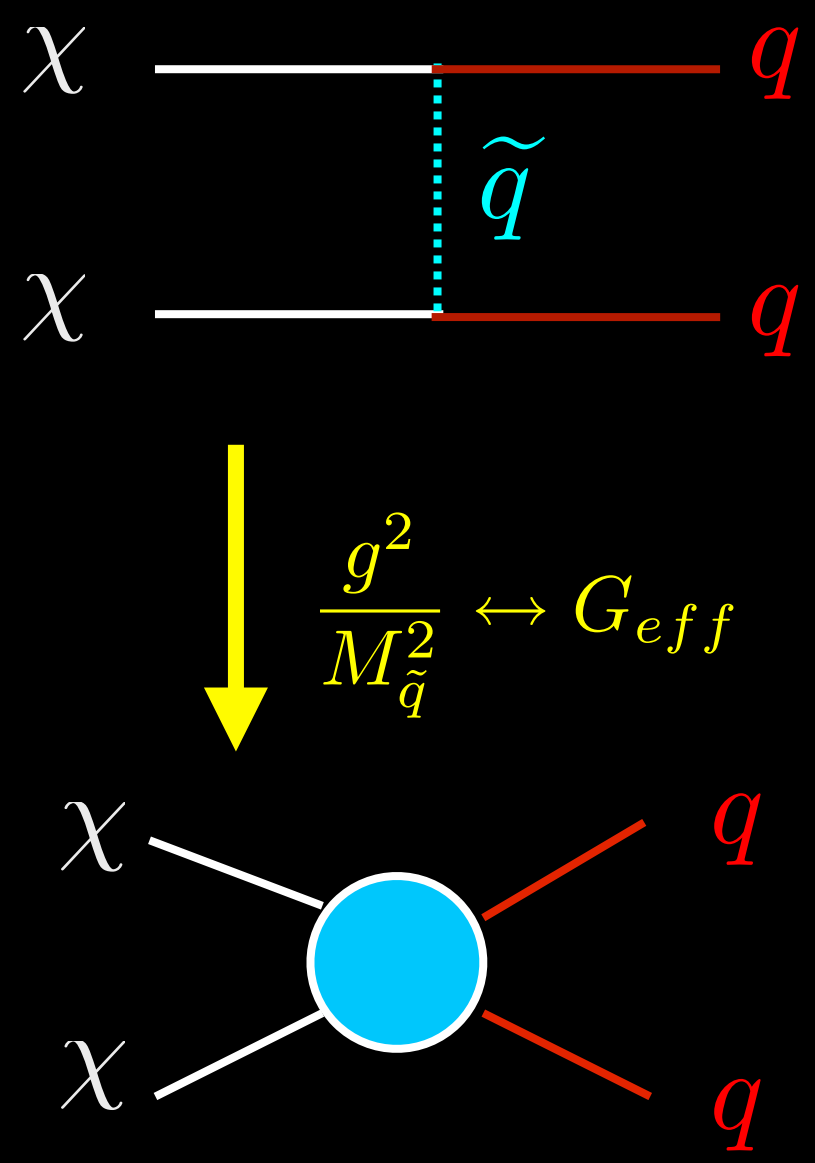
spin-independent



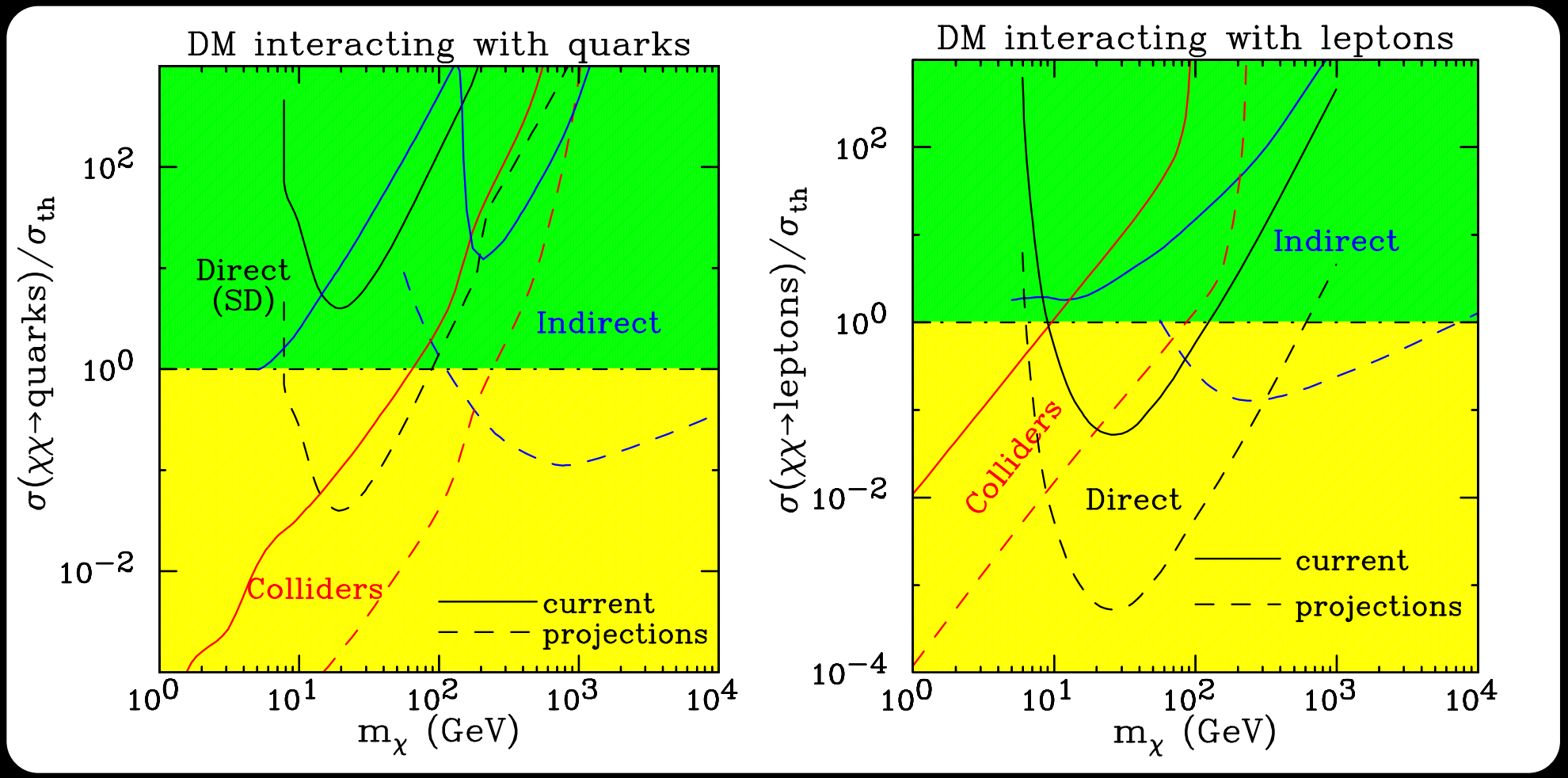
spin-dependent

Contact Interactions

- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved.
- The drawback to a less complete theory is such a simplified description will undoubtably miss out on correlations between quantities which are obvious in a complete theory.
- And it will break down at high energies, where one can produce more of the new particles directly.

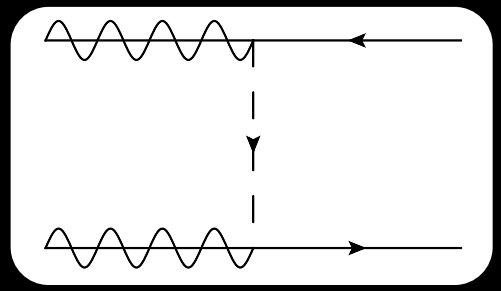


Quarks & Leptons

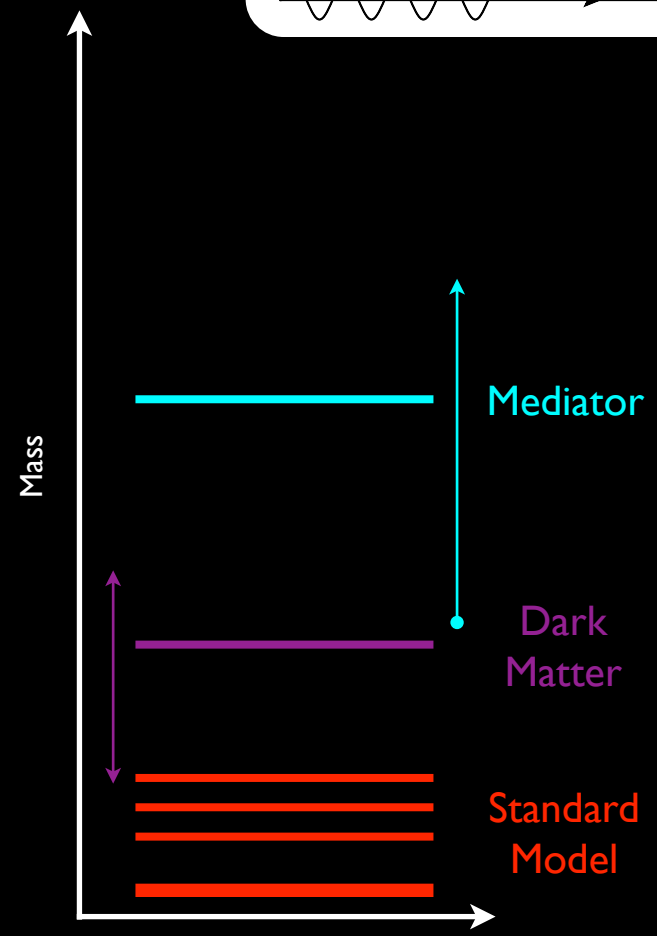


- Within this theory framework, there is a lot of complementarity in coverage of the parameter space.
- Covering the space is not enough. If we see conflicting information from two types of searches, it really means that we are seeing a break-down of our theoretical assumptions, which in this case means more light particles.

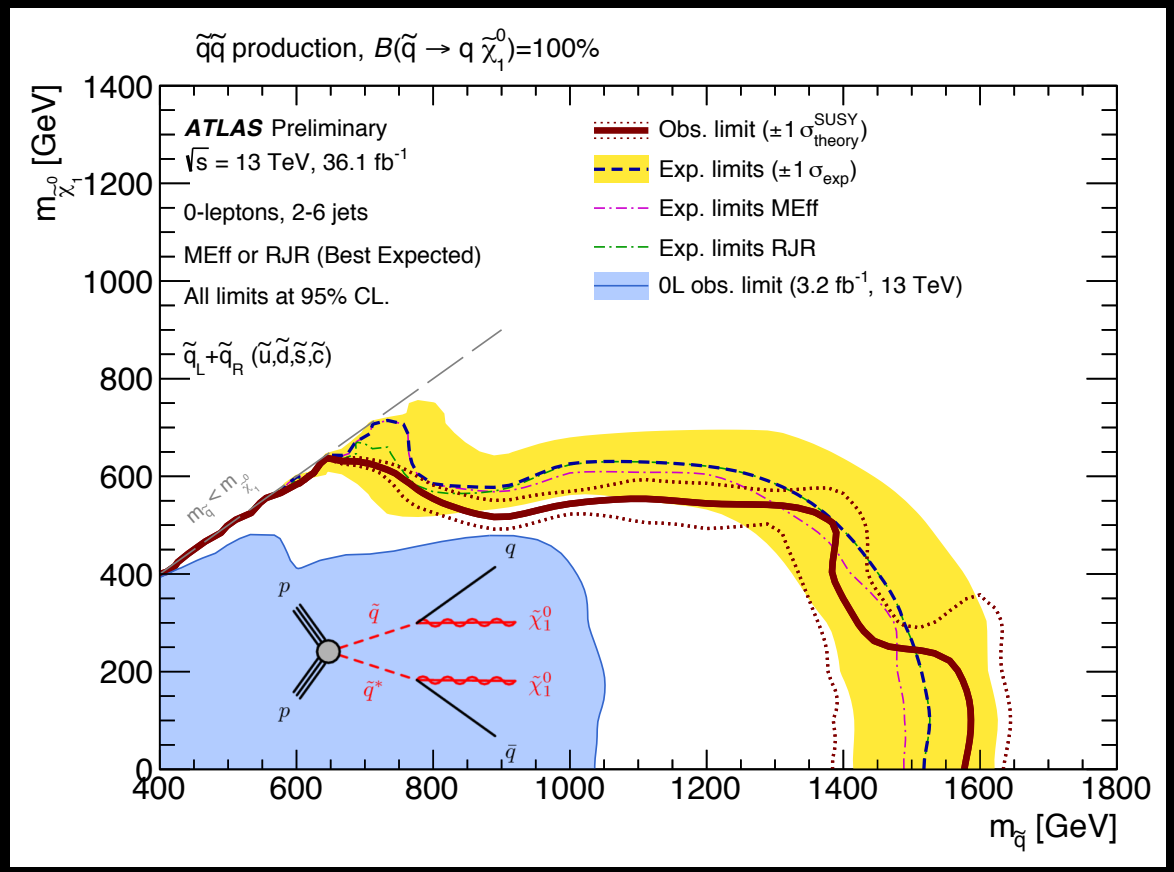
QCD-Charged Mediator

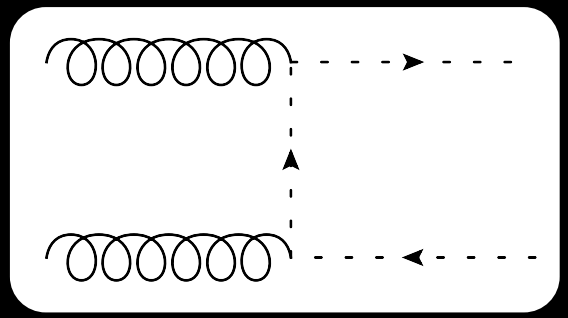


- Another common structure has dark matter interacting with quarks via a colored scalar mediator.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, etc.
- If we assume that the quark couplings are family-universal, there are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

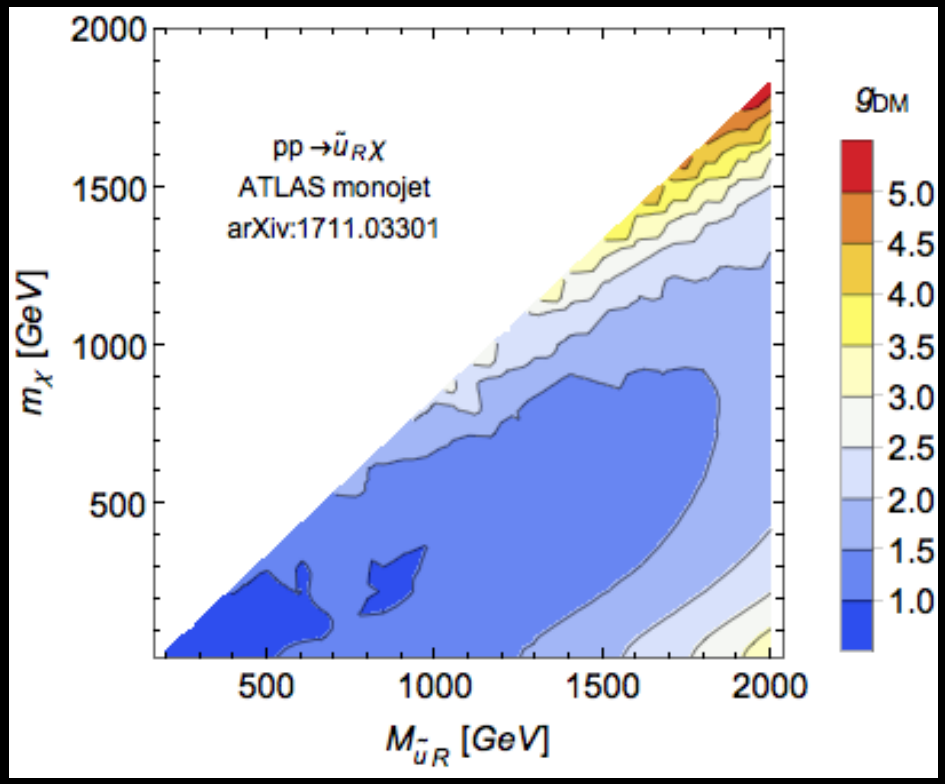


Mediator Production

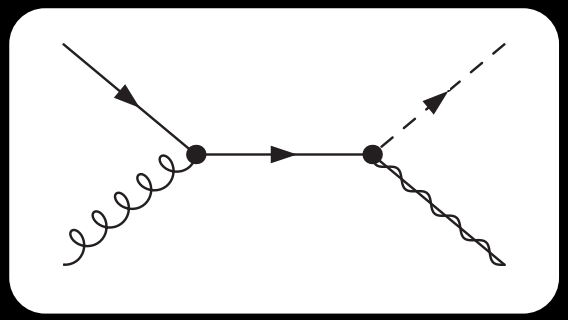




Pair Production

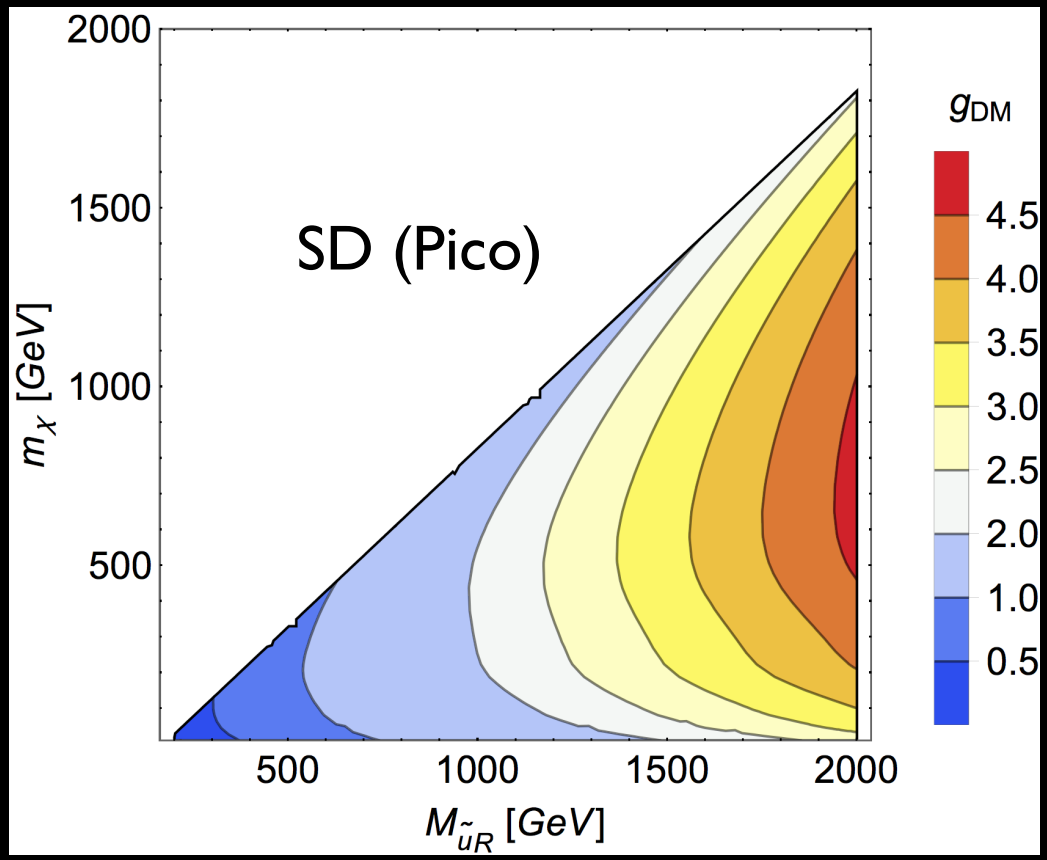


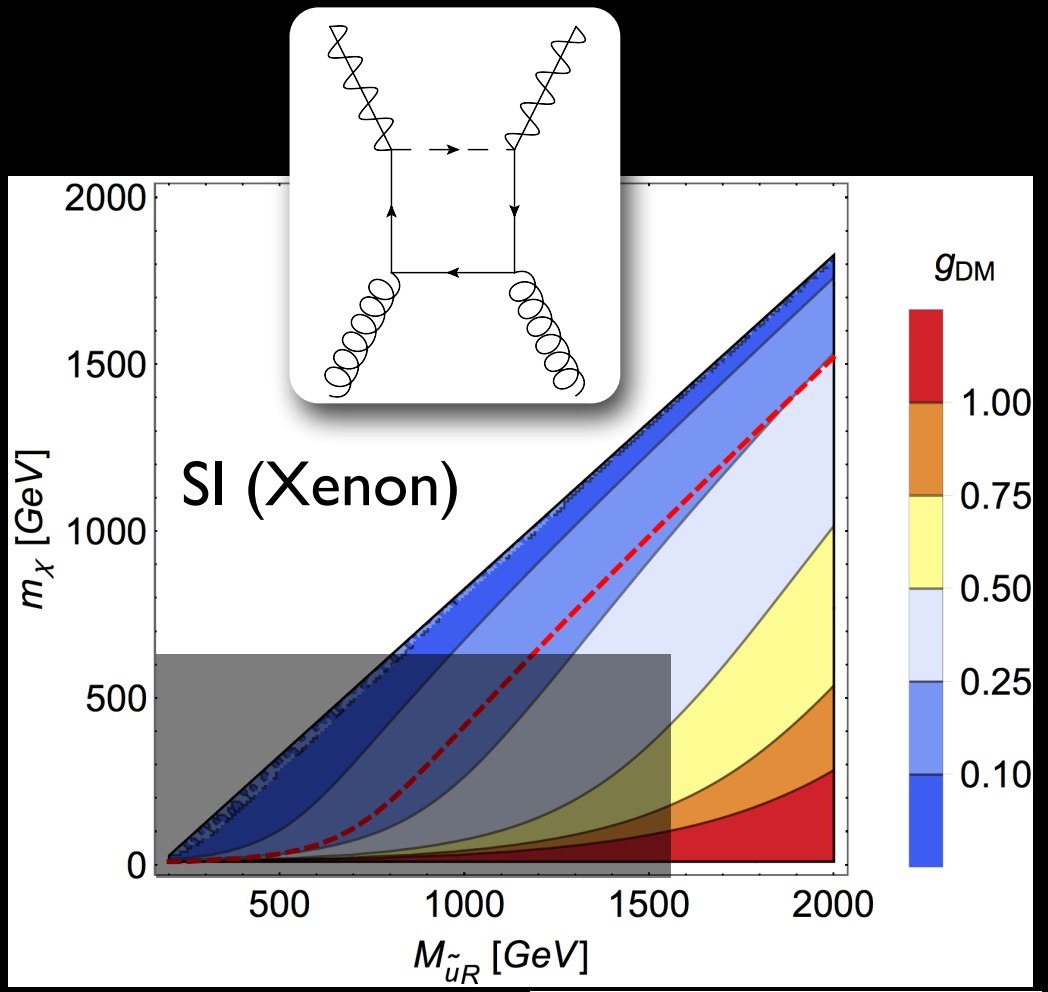
"Monojet"



Mohan, Sengupta, TMPT, Yan, Yuan 2019

Direct Detection





Mohan, Sengupta, TMPT, Yan, Yuan 2019

- At tree level, the fact that Majorana particles have vanishing vector current implies that the scattering with nuclei is spin-dependent..
- But at one loop, the scattering is spin-independent, and these are the dominant constraint- the smaller rate is compensated by the stronger experimental bounds.