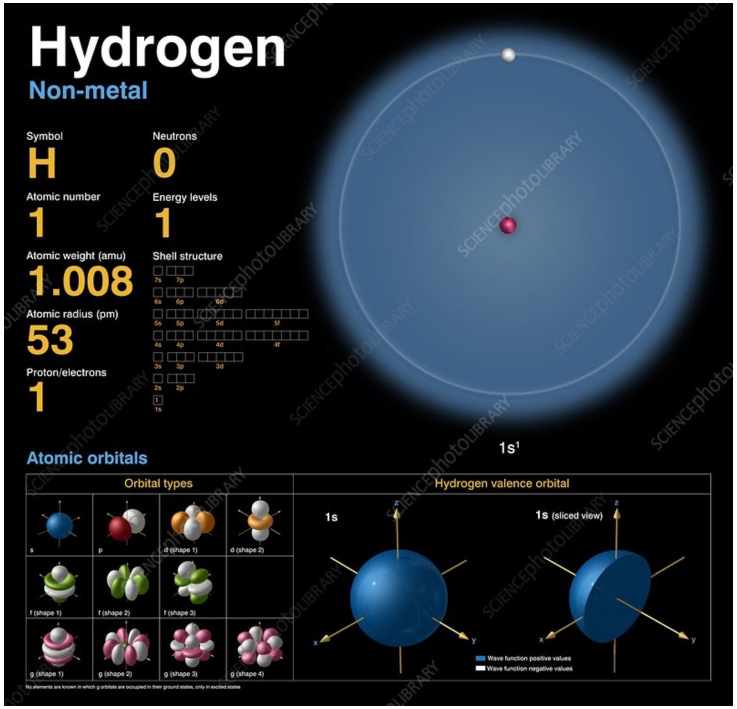
Bound states and dark matter

Camilo A. Garcia Cely
Alexander von Humboldt fellow

Materia Oscura in Colombia (MOCa)

Oct 7, 2020

Ordinary matter is in the form of bound states.



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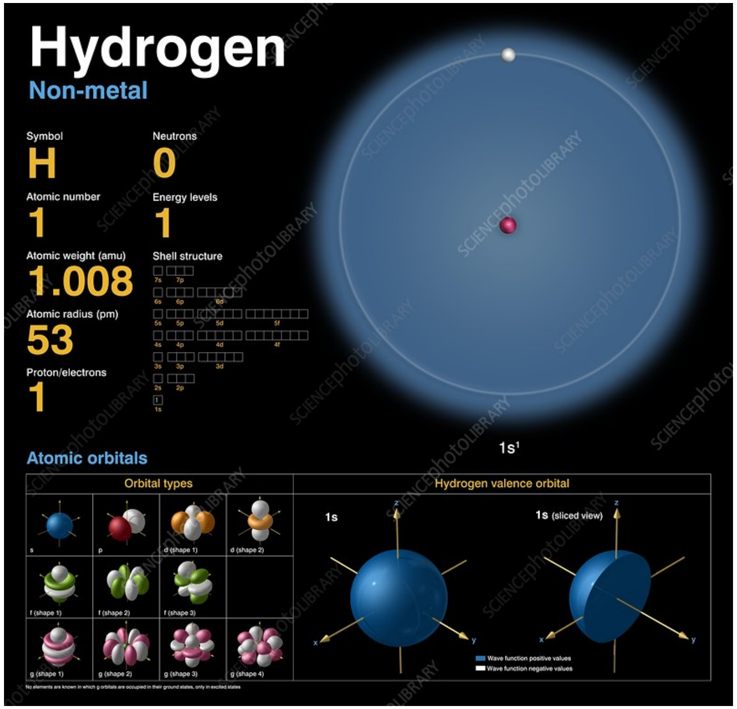

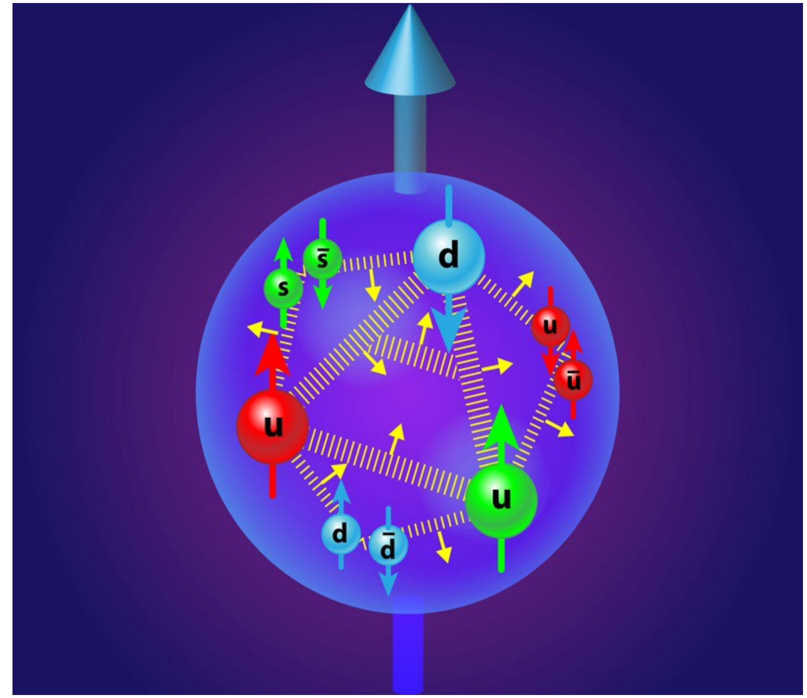

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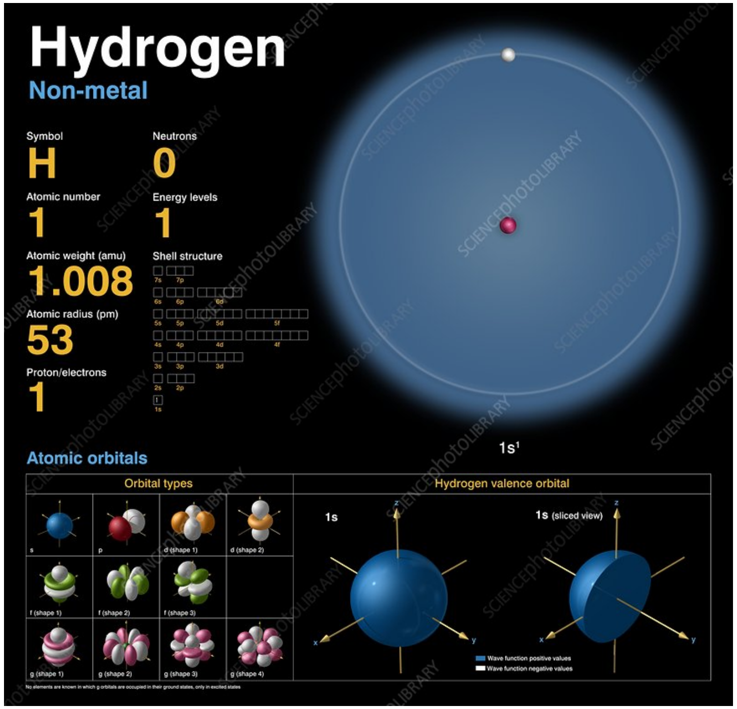

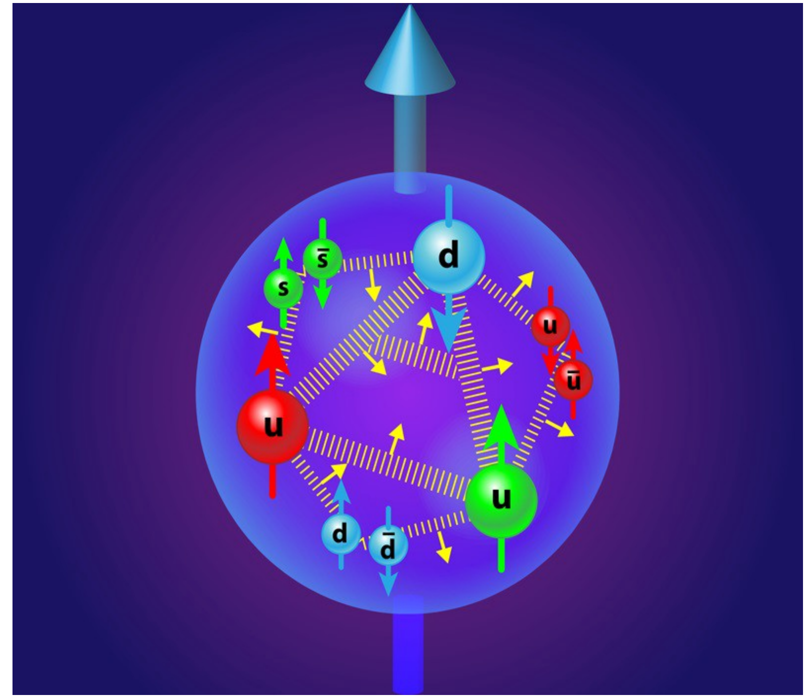

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It is natural to ask whether dark matter is made of bound states or if it is an elementary particle that can form them.

I. Dark matter forming bound states

This is rather common...

This is rather common...

Simple assumption: extend the SM with an electroweak multiplet

Quantum Numbers $SU(2)_L$	$U(1)_Y$	Spin	
2	1/2	0	Inert doublets 0.5-20 TeV
	1/2	1/2	Higgsino DM $\sim$ 1 TeV
3	0	0	
	0	1/2	Wino DM $\sim$ 2.9 TeV
	1	0	
	1	1/2	
4	1/2	0	
	1/2	1/2	
	3/2	0	
	3/2	1/2	
5	0	0	
	0	1/2	Fermionic 5-plet $\sim$ 10 TeV
7	0	0	Scalar 7-plet $\sim$ 25 TeV

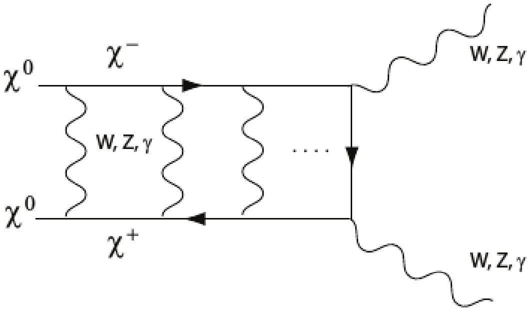
Cirelli, Fornengo, Strumia (2005)

Indirect detection of Winos

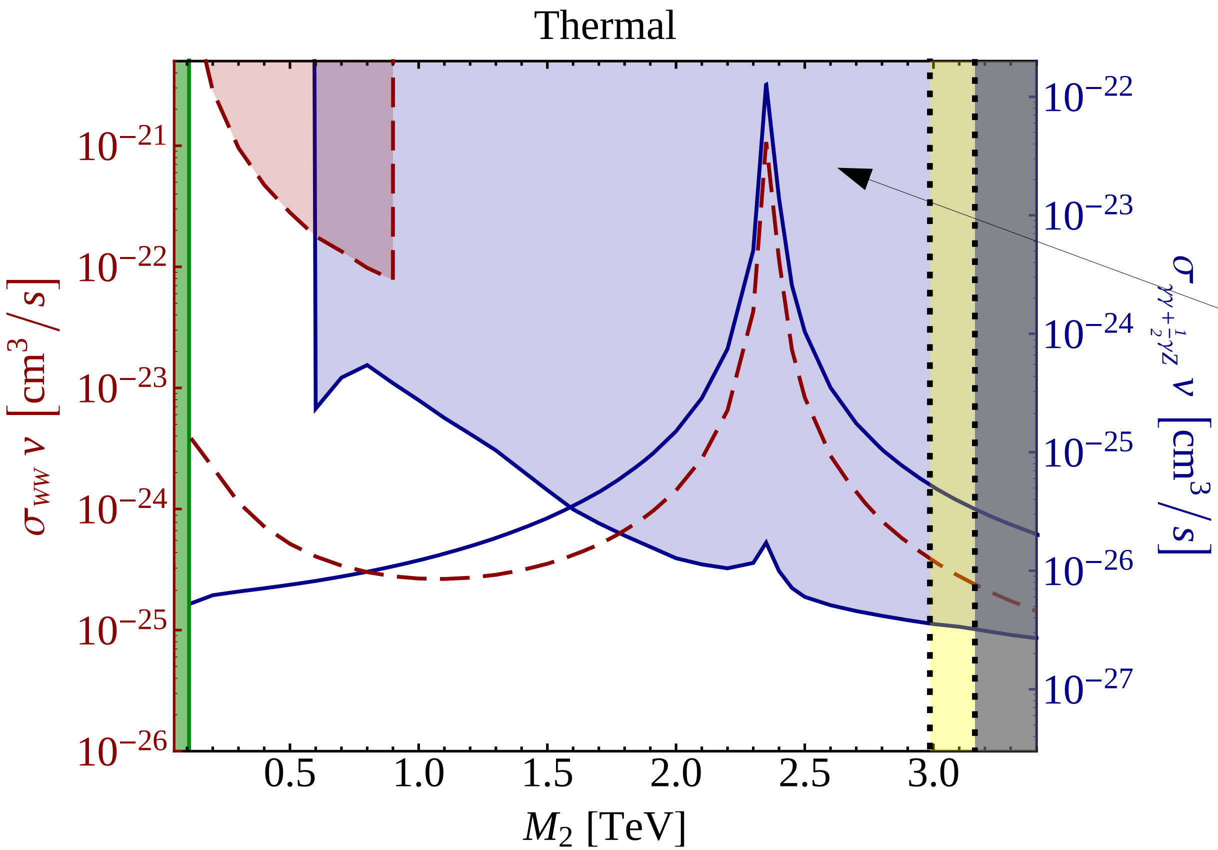
In the early Universe

$\sigma v \sim 1\,\mathrm{pb} \approx 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}.$

Sommerfeld Effect



Hisano et al (2004)



This signalizes the existence of a wino-wino bound state with a very small binding energy

Cohen et al (2013)

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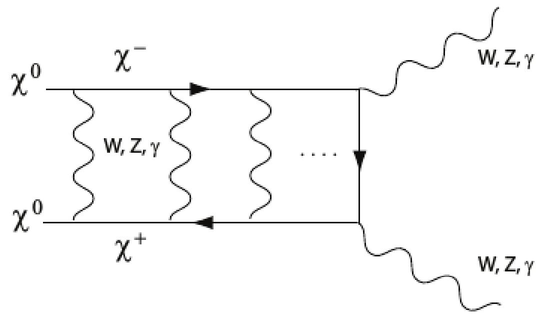
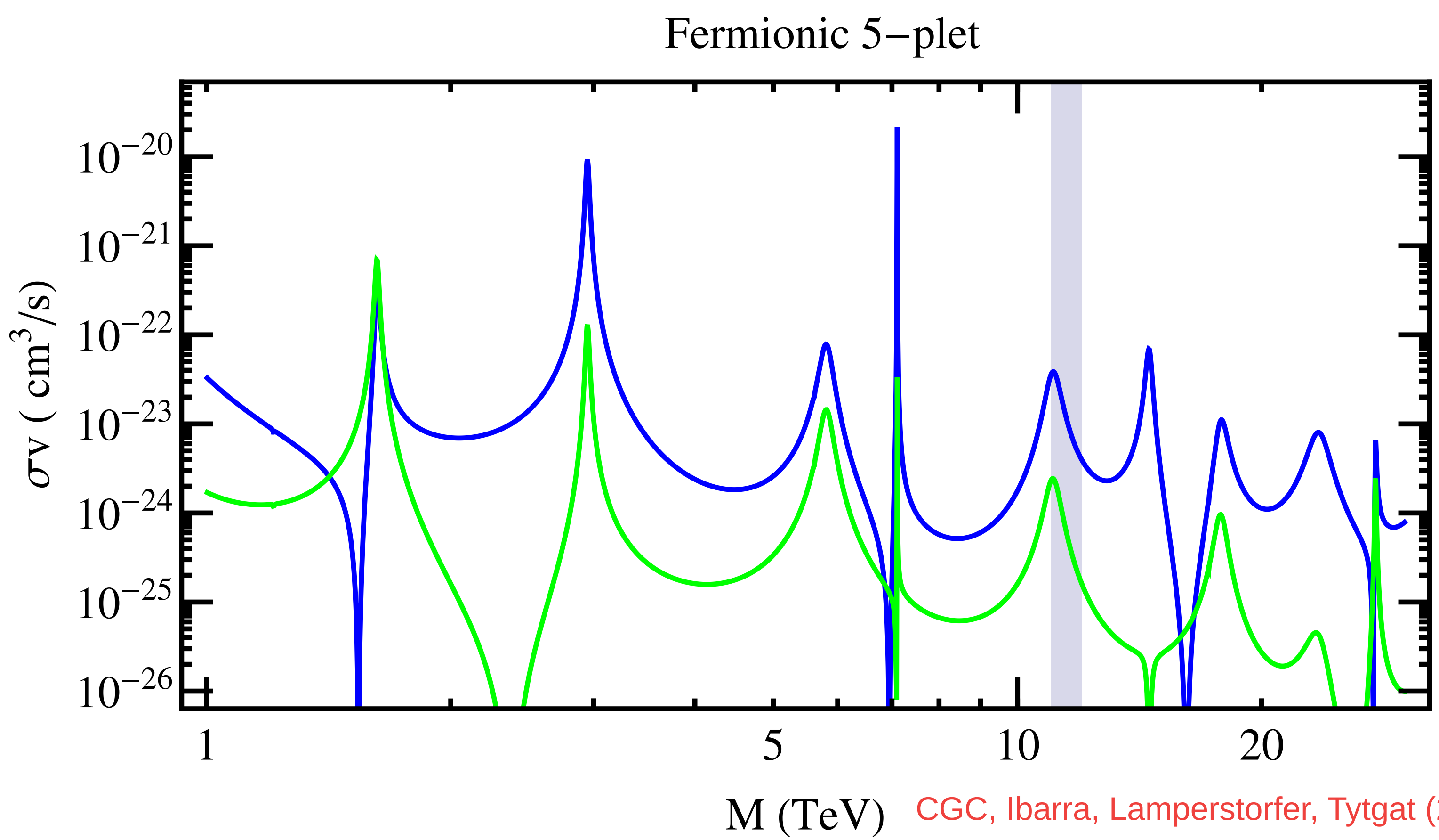


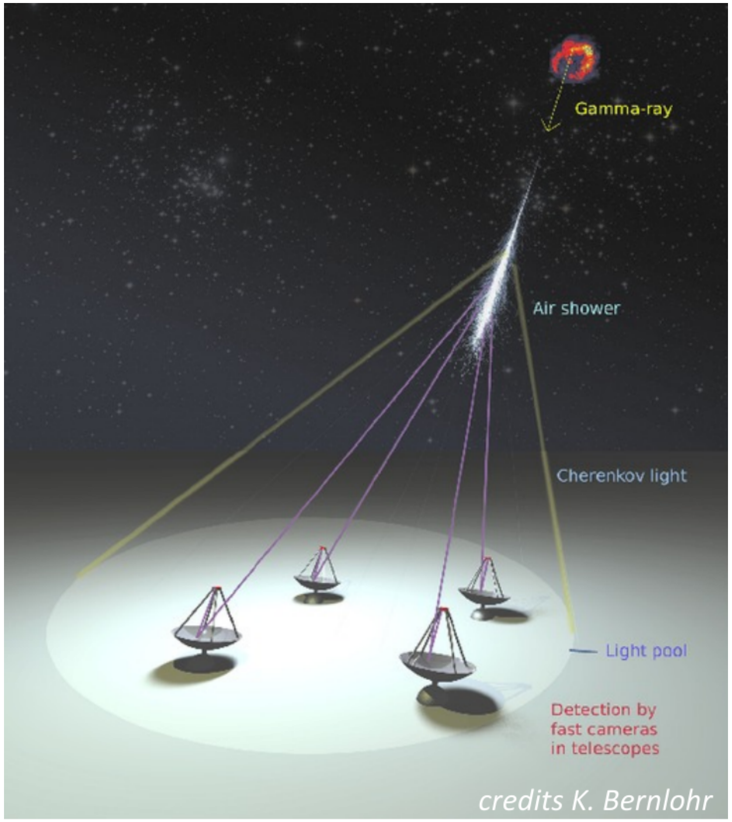


CGC, Ibarra, Lamperstorfer, Tytgat (2015)

How do we search for this?

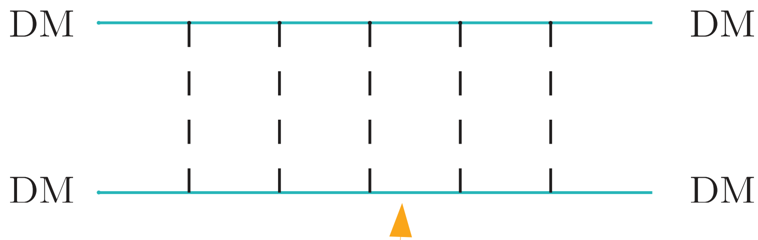
Indirect Searches with gamma-ray telescopes

H.E.S.S.



This is rather common...

$$V(r) = \pm\alpha \frac{e^{-m_\phi r}}{r}$$



$$\alpha m_{\mathrm{DM}} \gtrsim m_\phi$$

Any dark matter sector containing a light mediator

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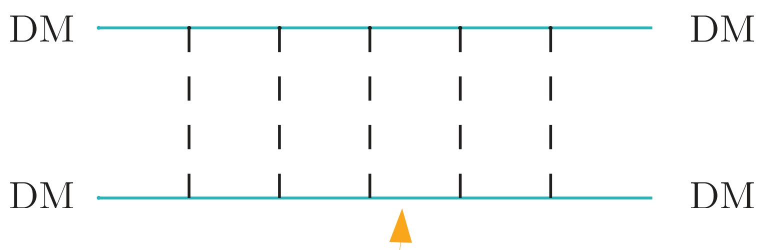

$$\alpha m_{\rm DM} \gtrsim m_\phi$$

Any dark matter sector containing a light mediator

For electroweak multiplets, the mediators are the electroweak bosons and the shallow bound states are formed for $m_{\rm DM} \gtrsim m_W/\alpha \sim$ TeV.

Searches at the intensity frontier

PRL **116,** 151801 (2016) PHYSICAL REVIEW LETTERS 15 APRIL 2016

Probing the Dark Sector with Dark Matter Bound States

Haipeng An,[1] Bertrand Echenard,[2] Maxim Pospelov,[3,4] and Yue Zhang[1]

Asymmetric dark matter interacting with a Stueckelberg field

Bound states

$1.68 m_V < \alpha_D m_\chi$

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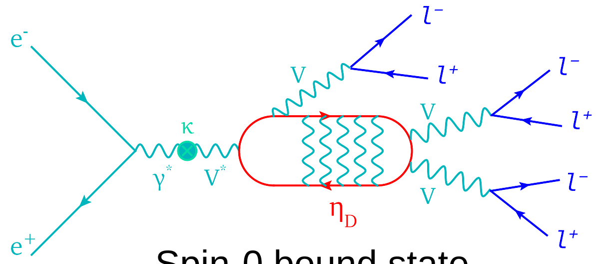

Spin-0 bound state

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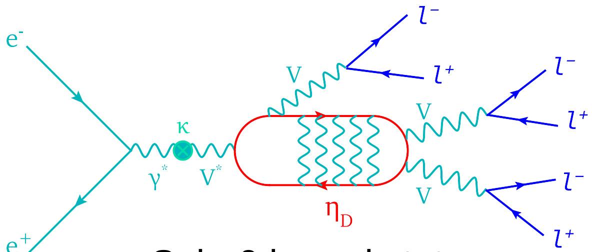

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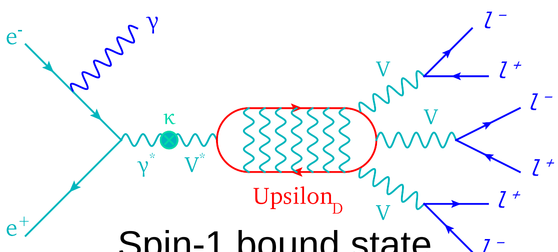

Spin-1 bound state

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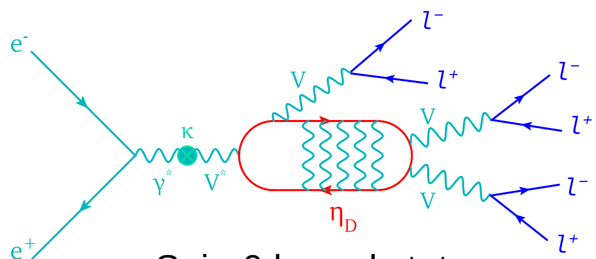
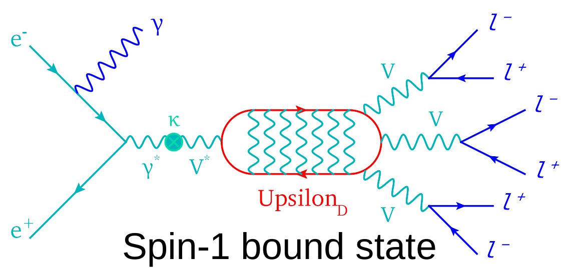
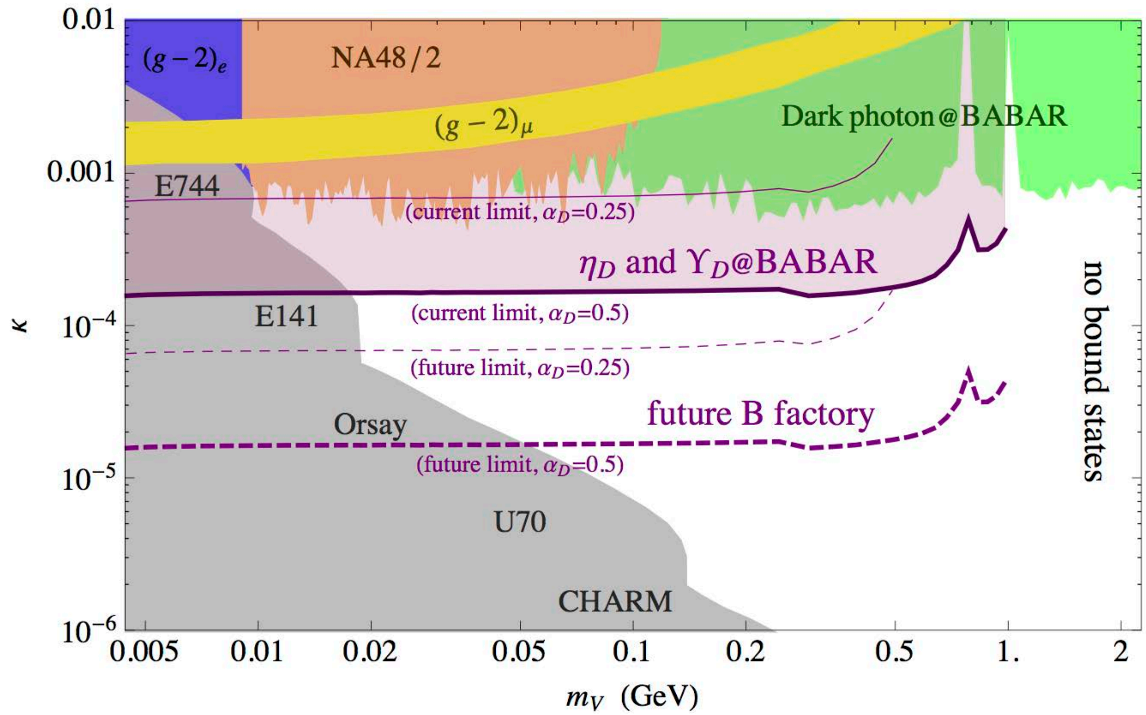


Spin-0 bound state



Spin-1 bound state



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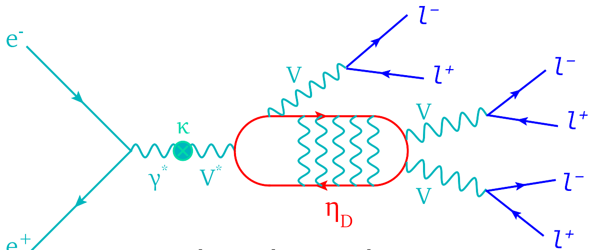
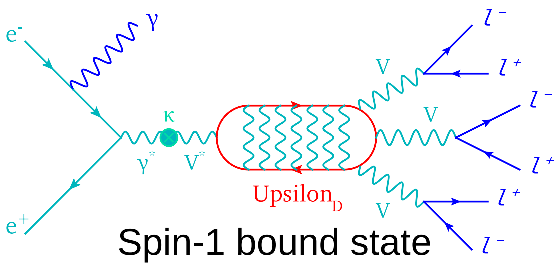


Spin-0 bound state



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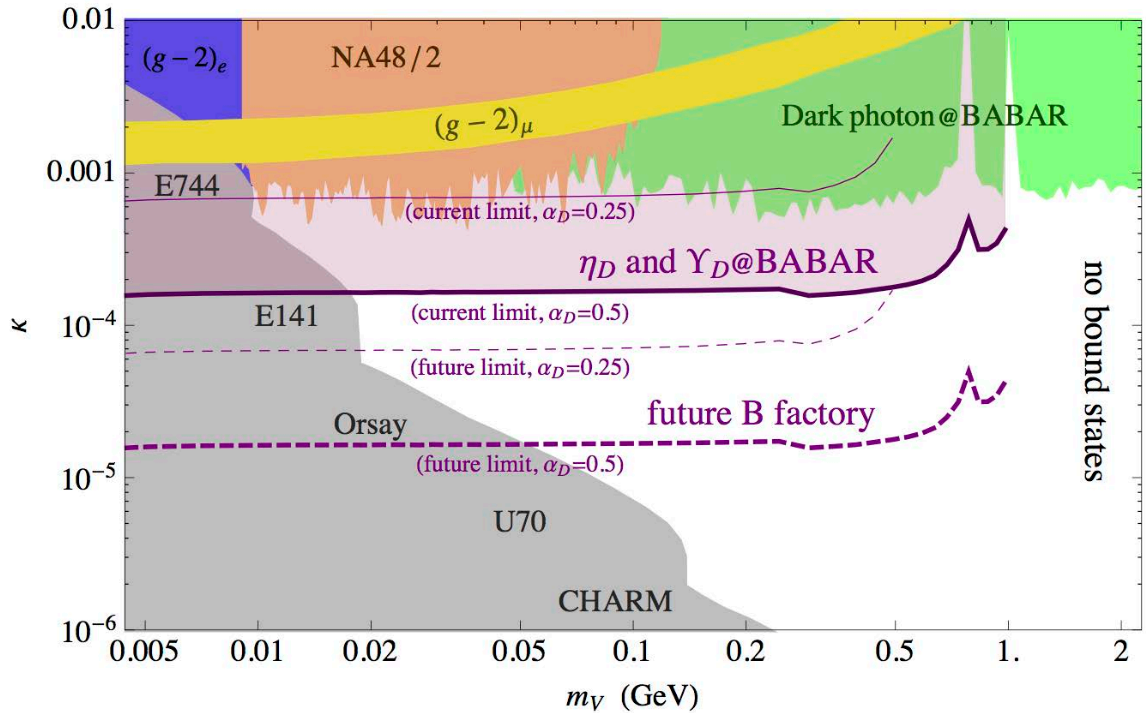


Some interesting aspects remain unexplored:

- Asymmetric vs. symmetric dark matter
- Realistc dark sector with the Higgs Mechanism giving mass to the light mediator
- Searches at Belle II

Duerr, CGC, Ferber, Schmidt-Hoberg (PRELIMINARY WORK)

II. Dark matter as a bound state

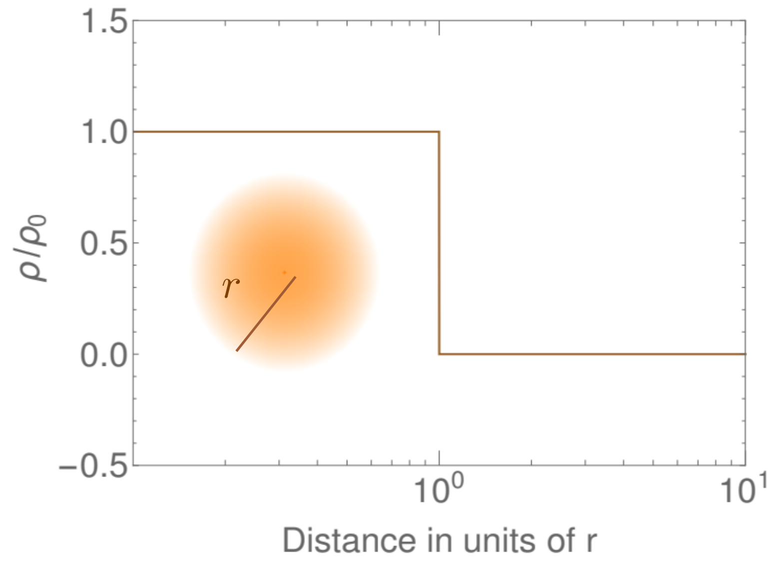
Based on

PHYSICAL REVIEW LETTERS **124,** 041101 (2020)

Finite-Size Dark Matter and its Effect on Small-Scale Structure

Xiaoyong Chu[1,*] Camilo Garcia-Cely[2,†] and Hitoshi Murayama[3,4,5,2,‡]

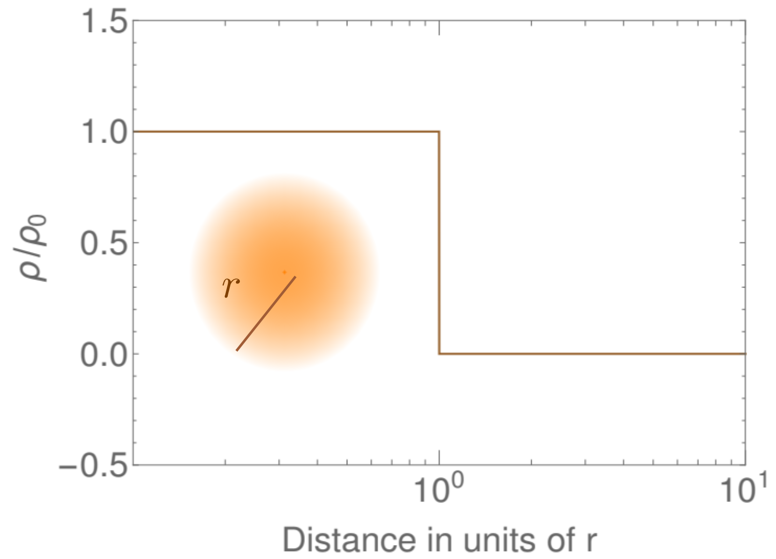
How do we know something has a finite size?

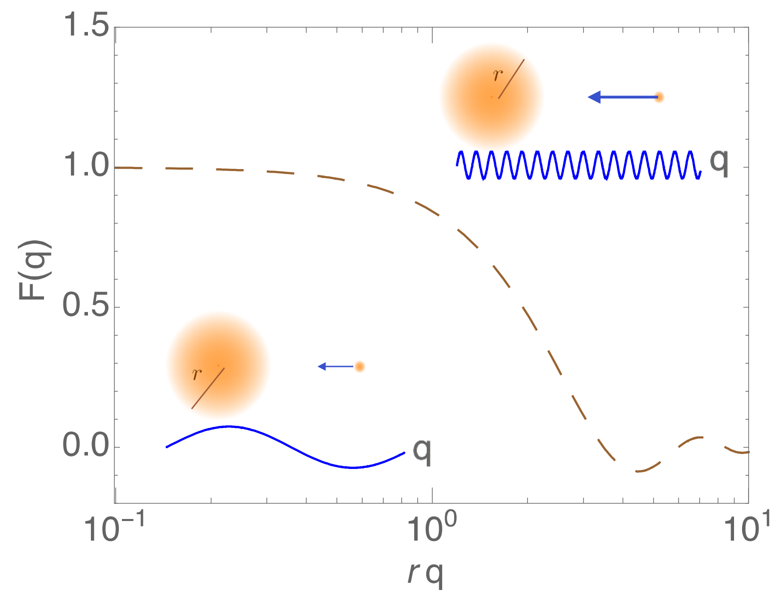


How do we know something has a finite size?

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\text{pointlike}} |F(q)|^2.$$

Fourier Transform
of the density





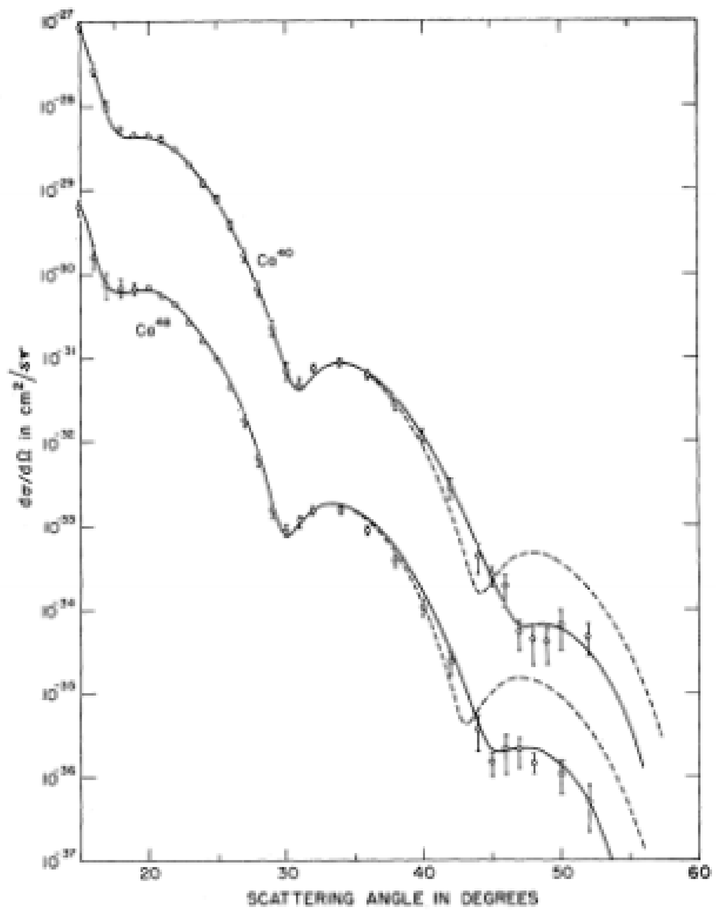
Camilo A. Garcia Cely (Alexander von Humboldt Fellow, DESY)

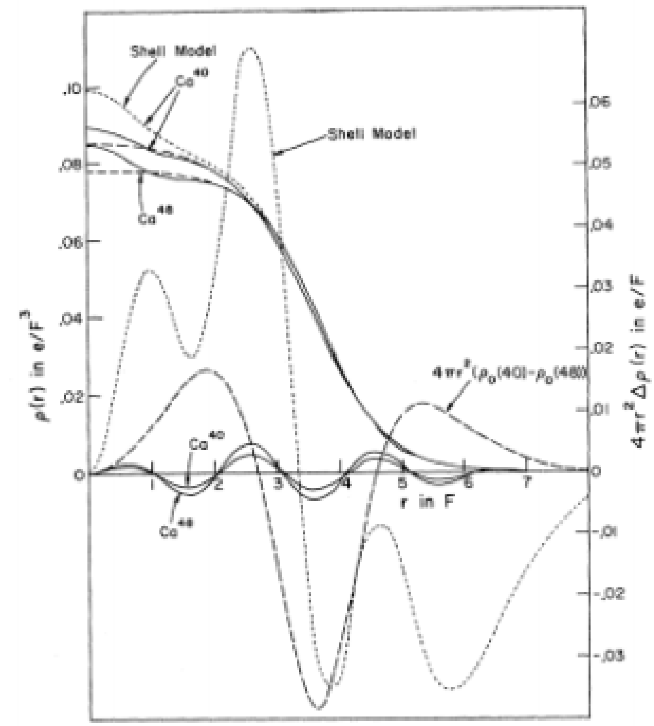
Realistic example

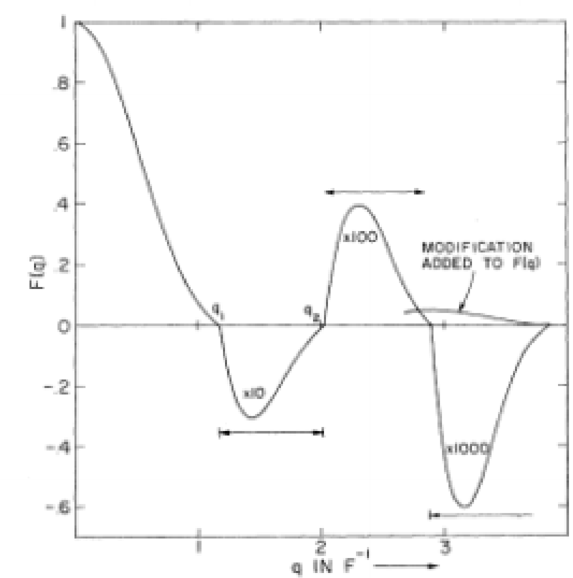
VOLUME 19, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1967

SCATTERING OF 750-MeV ELECTRONS BY CALCIUM ISOTOPES*

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\text{pointlike}} |F(q)|^2.$$



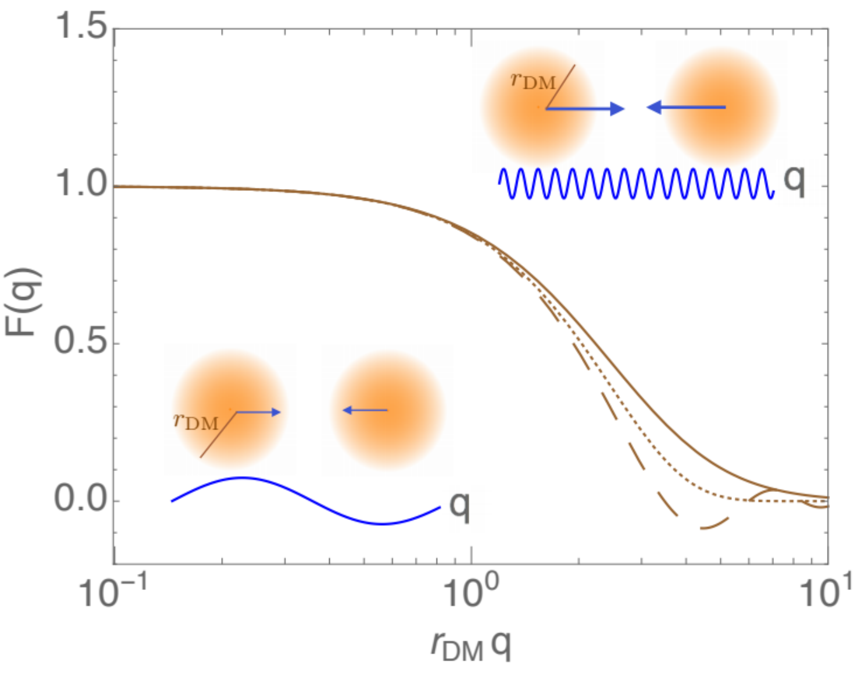




Dark Matter with a finite size

Suppose that dark matter has a finite size that is larger than its Compton wavelength: Puffy DM

Chu, CGC, Murayama (2019)



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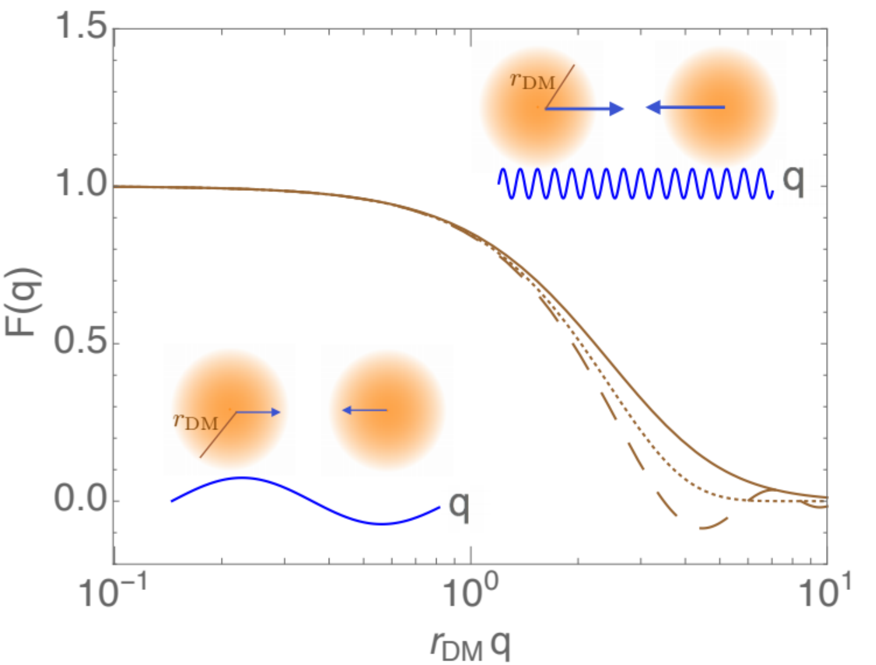
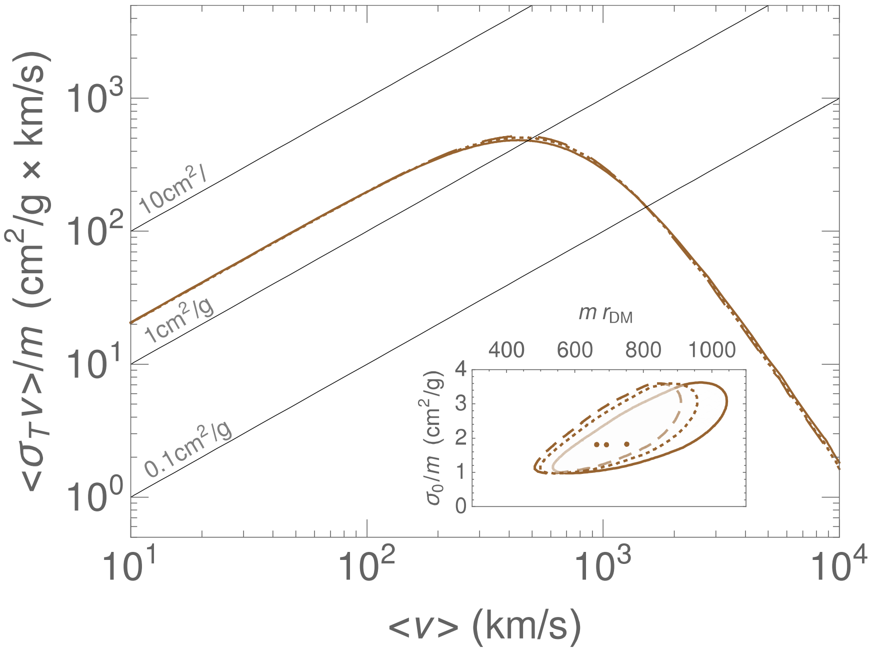


Shape	$\rho(r)$	r_{DM}	$F(q)$
tophat	$\frac{3}{4\pi r_0^3}\theta(r_0 - r)$	$2\sqrt{3}r_0$	$\frac{3(\sin(r_0 q) - r_0 q\cos(r_0 q))}{r_0^3 q^3}$
dipole	$\frac{e^{-r/r_0}}{8\pi r_0^3}$	$\sqrt{3/5}r_0$	$\frac{1}{(1+r_0^2 q^2)^2}$
Gaussian	$\frac{1}{8 r_0^3 \pi^{3/2}} e^{-r^2/(4r_0^2)}$	$\sqrt{6}r_0$	$e^{-r_0^2 q^2}$

Table I: Form factors for different density distributions.

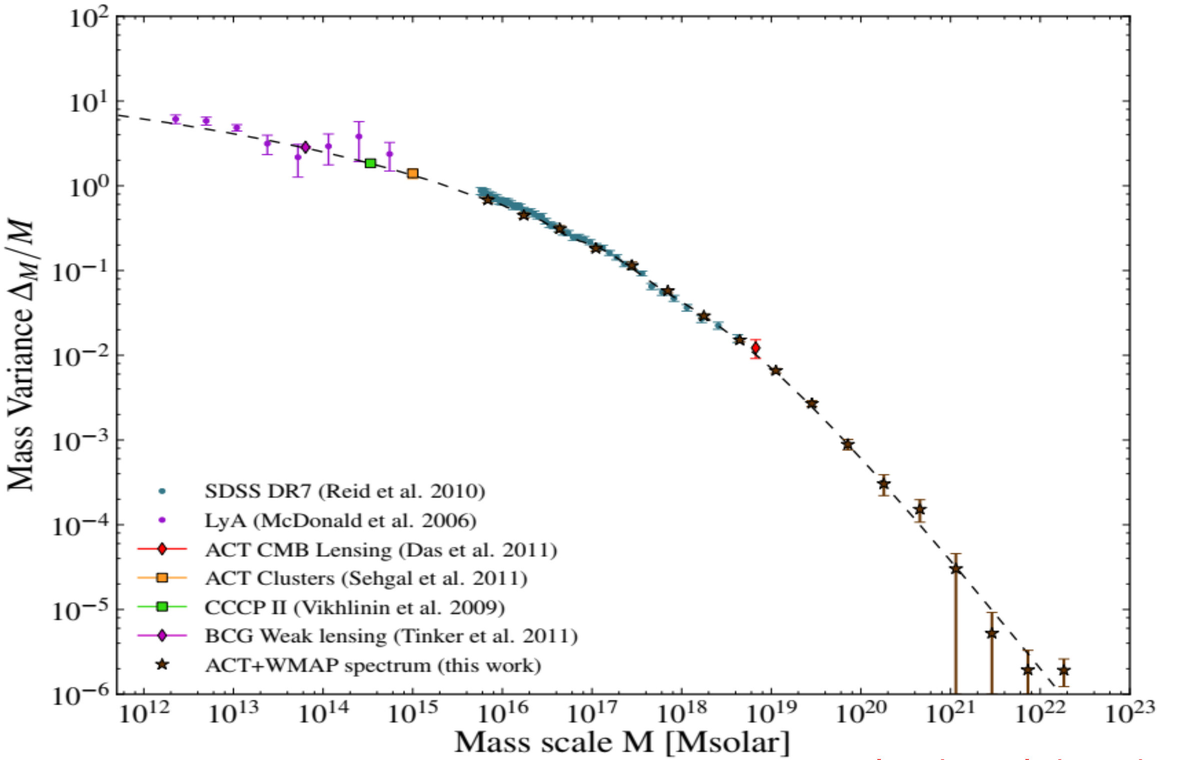
It is possible to obtain small cross section at cluster (v~ 1000 km/s) but small cross section in smaller objects (galaxies)



Is this useful?

Remarkably successful
at large scales

At low scales
N-body simulations
are needed



Hlozek et al. (2012)

Mass deficits at galactic scales

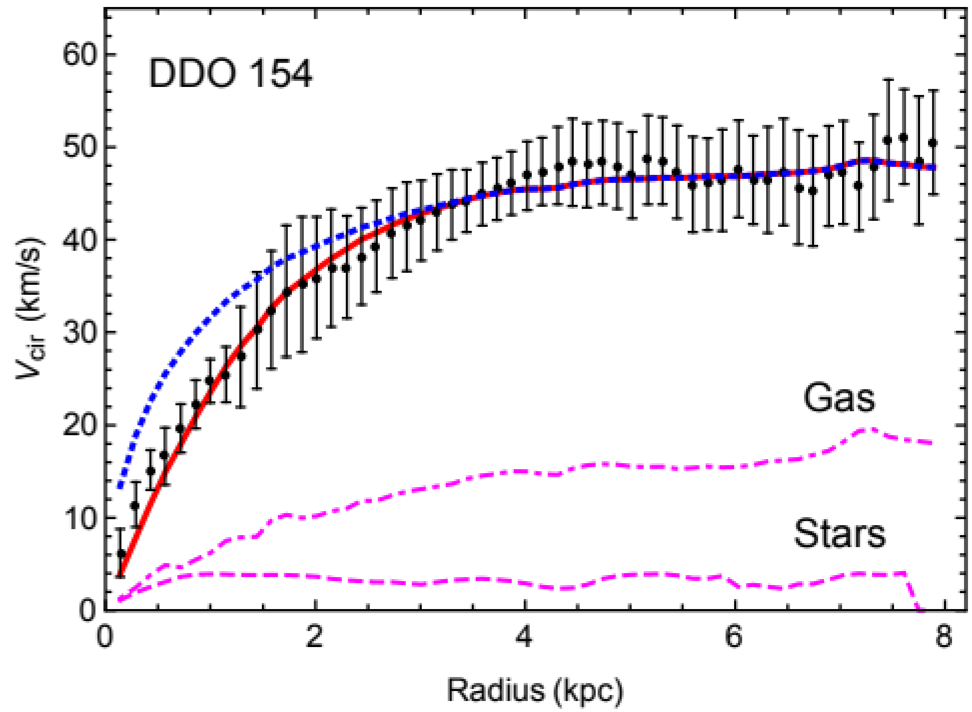
- Core vs. cusp problem
- Diversity problem
- Too-big-to-fail problem
- Missing satellites

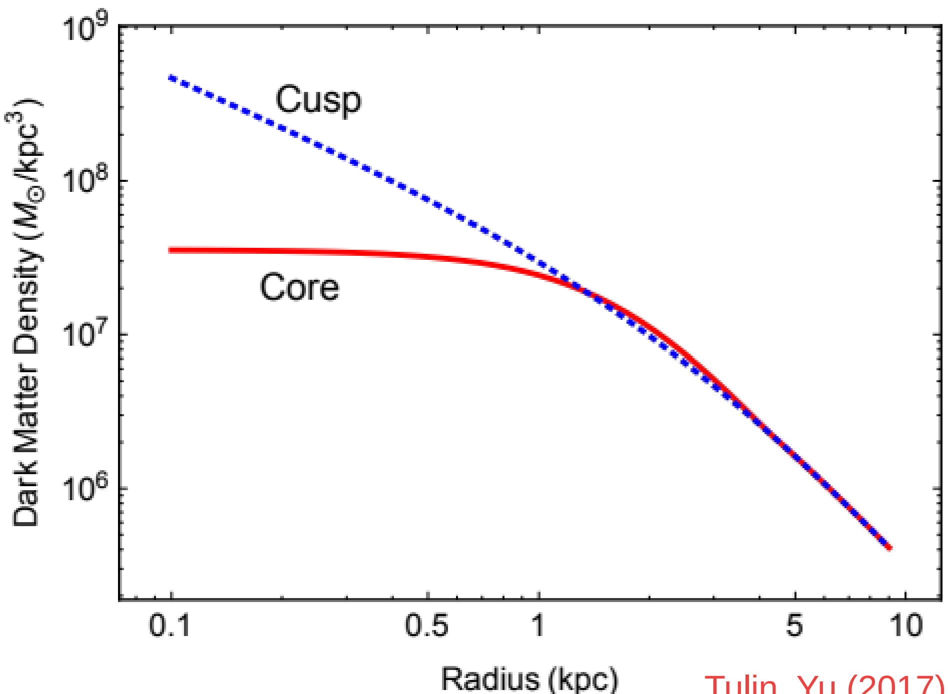
Heated debates!!!

Core vs. cusp problem
rotation curves again!

This is the seemingly mass deficit observed in objects such as dwarf galaxies when compared to the predictions of collisionless dark matter

Moore (1994)
Flores et al. (1994)
Naray et al. (2011)





Tulin, Yu (2017)

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2},$$

J. F. Navarro, C. S. Frenk, and S. D. M. White (1997)

Debate

Plausible explanations

- Baryonic effects (supernovae, star formation,...)
- Non-circular motions
- Systematic errors in the modelling of the internal dynamics of galaxies

Dark matter solution?

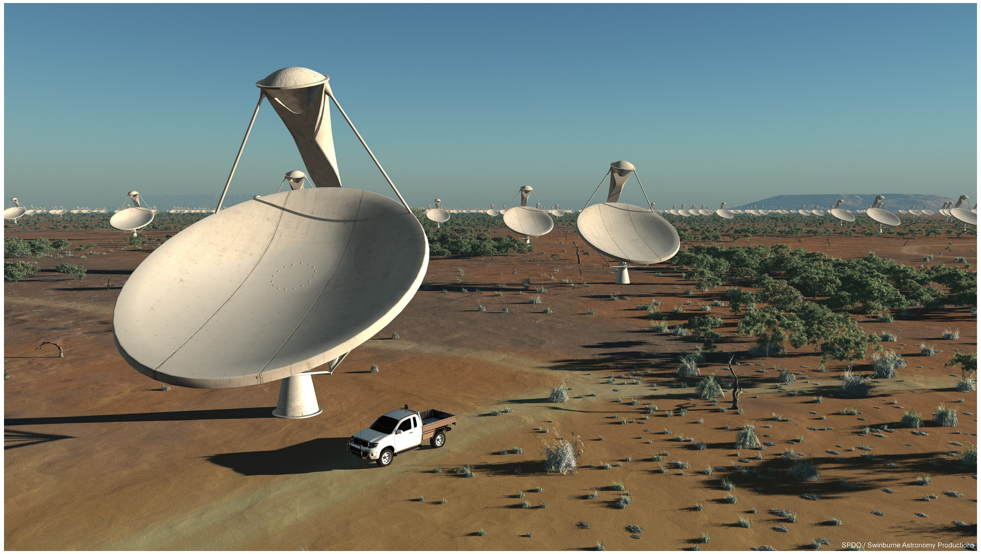
- postulate dark matter interactions that become relevant at small scales, without modifying the physics at large scales.

The future is data rich. For example...

The SKA will combine the signals received from thousands of small antennas spread over a distance of several thousand kilometres to simulate a single giant radio telescope

→ *extremely high sensitivity and angular resolution*

It has the potential to observe hundreds of nearby spiral galaxies at resolutions below 100 pc, providing a large and detailed sample of rotation curves.



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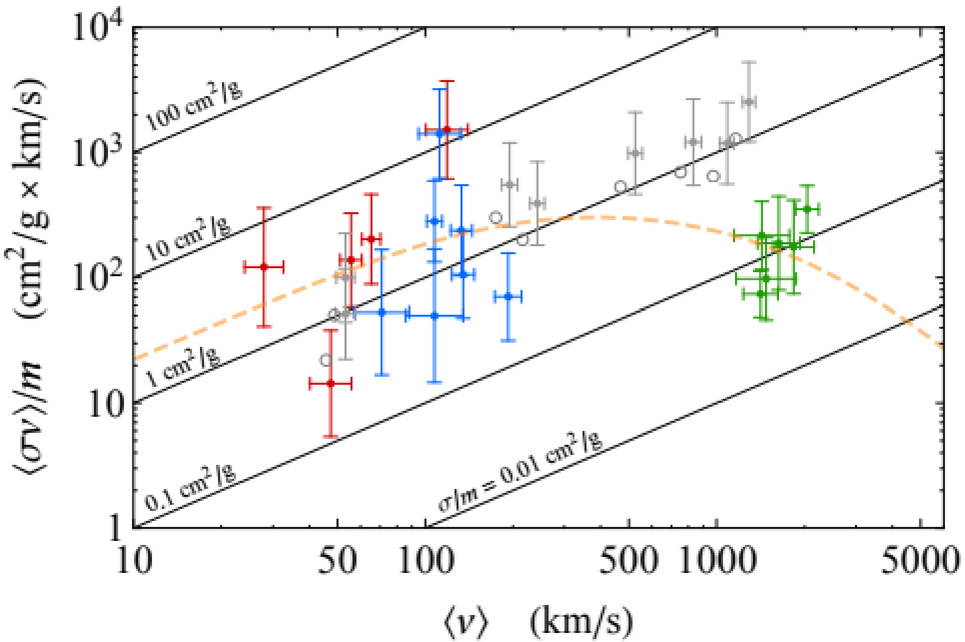
Dark matter halos as particle colliders

Kaplinghat ,Tulin, Yu (2017)



Maybe dark matter is a bound state

Suppose that dark matter has a finite size that is larger than its Compton wavelength: Puffy DM

Chu, CGC, Murayama (2019)

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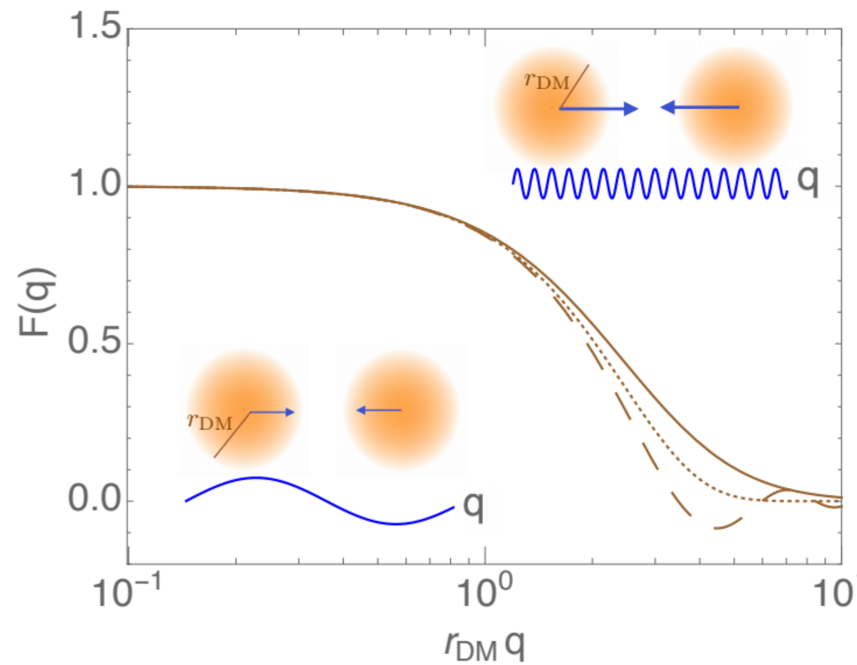

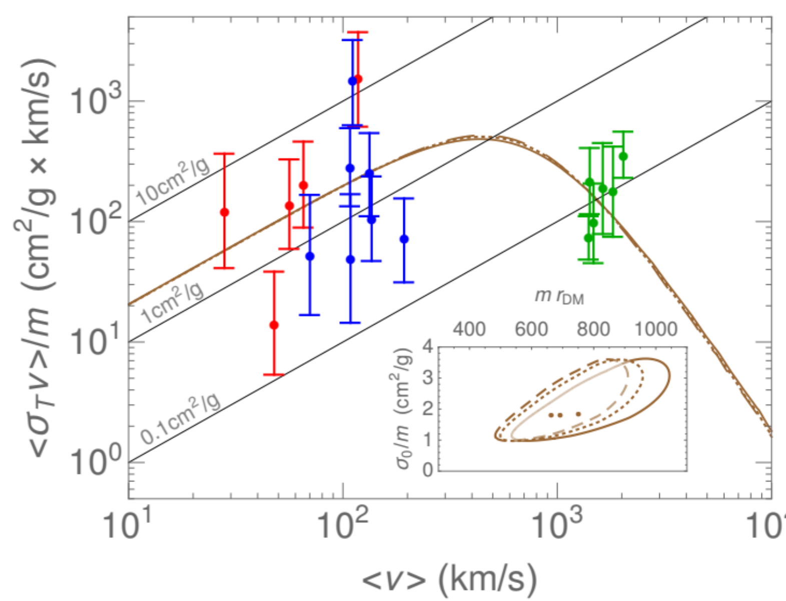

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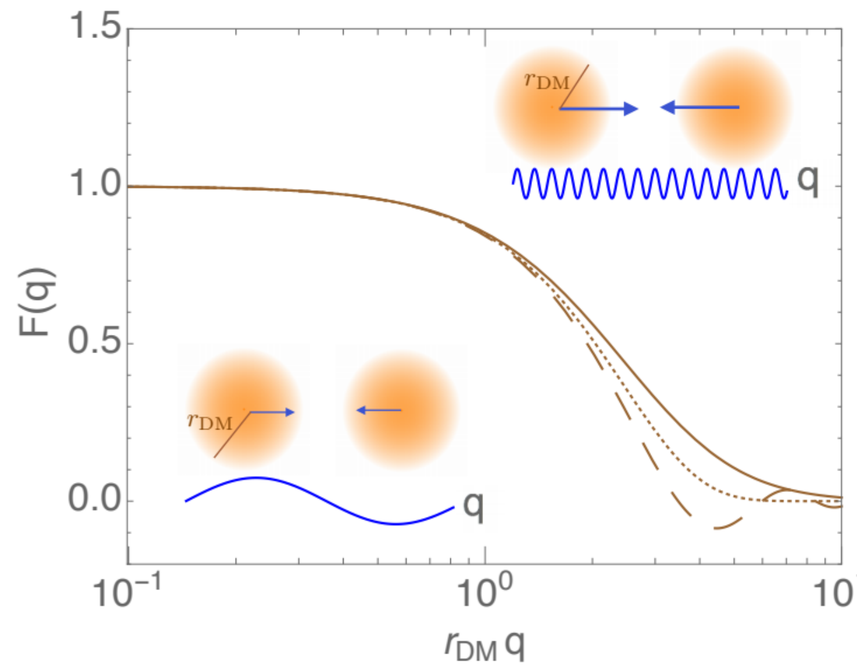

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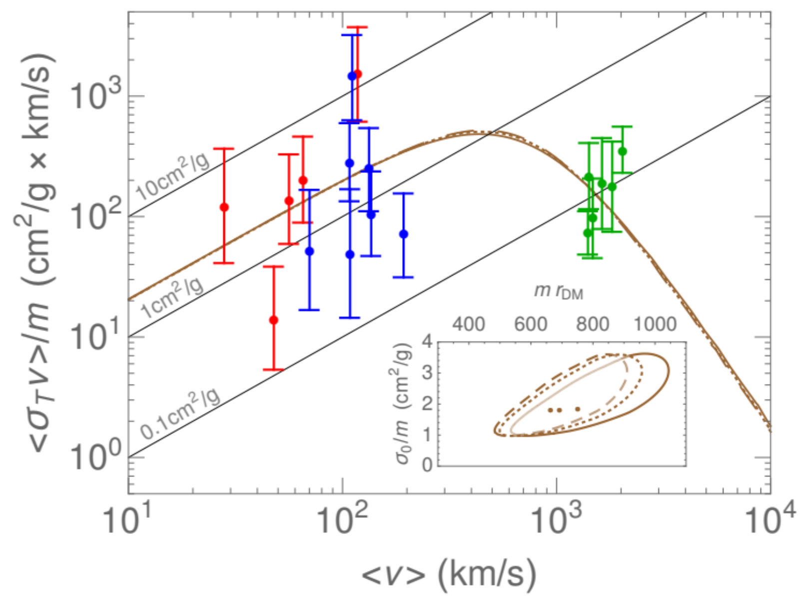

The way the non-relativistic cross section varies with the velocity is largely independent of the dark matter internal structure when the range of the mediating force is short.

A model of puffy dark matter

a QCD-like theory of dark matter

Particle	$SU(3)_D$	$U(1)_D$	Description
c	$\mathbf{3}$	2/3	Dark charm quark
d	$\mathbf{3}$	-1/3	Dark down quark
γ_D	$\mathbf{1}$	0	Dark photon
η	$\mathbf{1}$	0	Pseudoscalar meson $d\bar{d}$
D^+	$\mathbf{1}$	1	Pseudoscalar meson $c\bar{d}$
ρ	$\mathbf{1}$	0	Vector meson $d\bar{d}$
Σ_c	$\mathbf{1}$	0	Dark baryon cdd
Δ^-	$\mathbf{1}$	-1	Dark baryon ddd
DM	$\mathbf{1}$	0	Bound state of A Σ_c baryons

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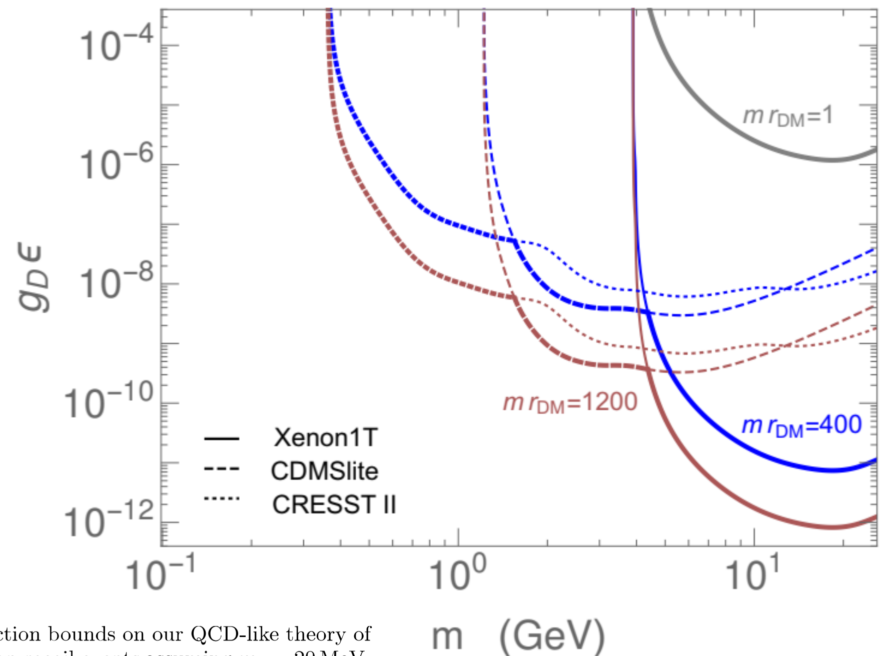
DM	**1**	0	Bound state of A Σ_c baryons

Chu, CGC, Murayama (2019)

low-threshold direct detection experiments have the potential to probe Puffy Dark Matter.



Direct detection bounds on our QCD-like theory of Puffy DM from nucleon recoil events assuming $m_{\gamma_D} = 20$ MeV. For a heavier dark photon, this bound scales with $m^2_{\gamma_D}$.

Conclusions

- *Bound states are generally predicted in dark matter sectors with light mediators.*
- *They play an important role for indirect detection. Particuarly for multi-TeV dark matter (searches with gamma-ray telescopes).*
- *They are also important for studying the collision of dark matter particles in dark matter halos.*

Thanks for your attention