Dark Matter

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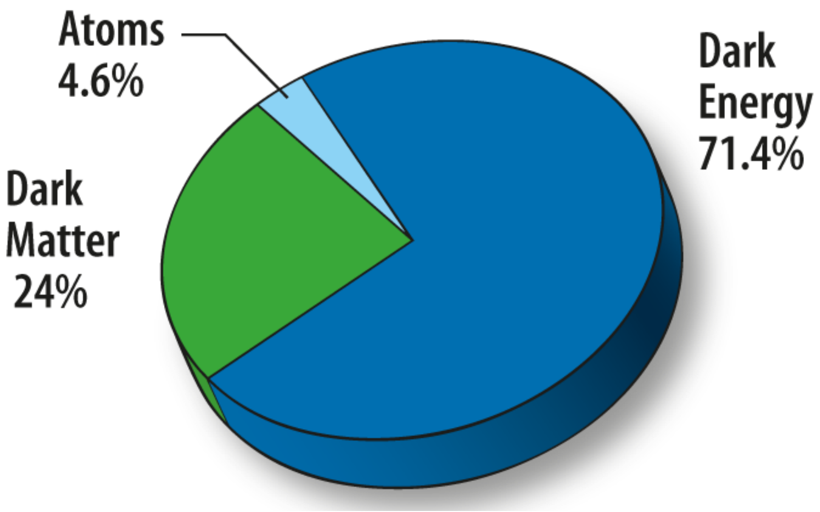
Outline for these lectures

- Evidence for dark matter
- Dark matter freezeout and relic density
- Dark matter candidates (WIMPs, asymmetric DM, sterile neutrinos, axions….)
- Indirect Detection
- Dark matter searches at colliders
- Direct Detection
- Dark matter in stars

Dark Matter Lecture #1

Dark matter properties



- 24% of the energy-density of the universe
  (about 84% of the total matter)

- Dark = does not radiate/absorb/scatter light
  → electrically neutral (at least to a good approximation)

- Cold = non-relativistic by he era of cosmological structure formation

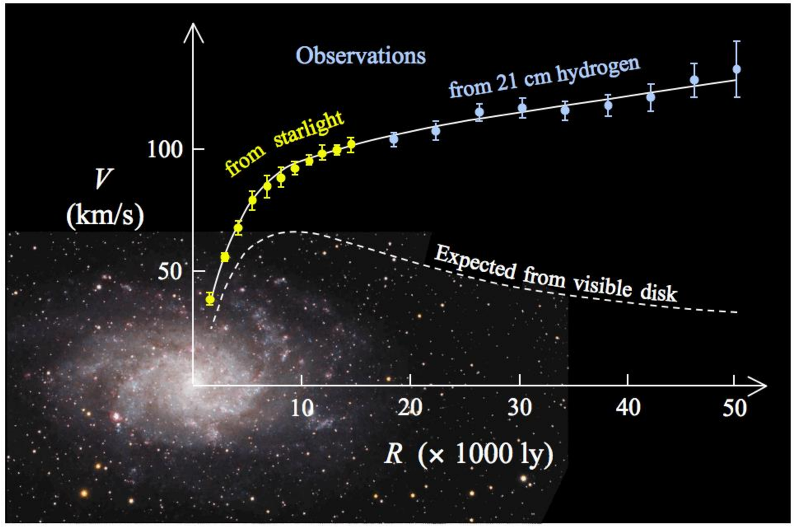
- Matter = gravitates/redshifts like matter. Behaves cosmologically like pressureless dust.

- Forms the scaffolding for the growth of structure in the universe. Present as halos around galaxies and clusters.

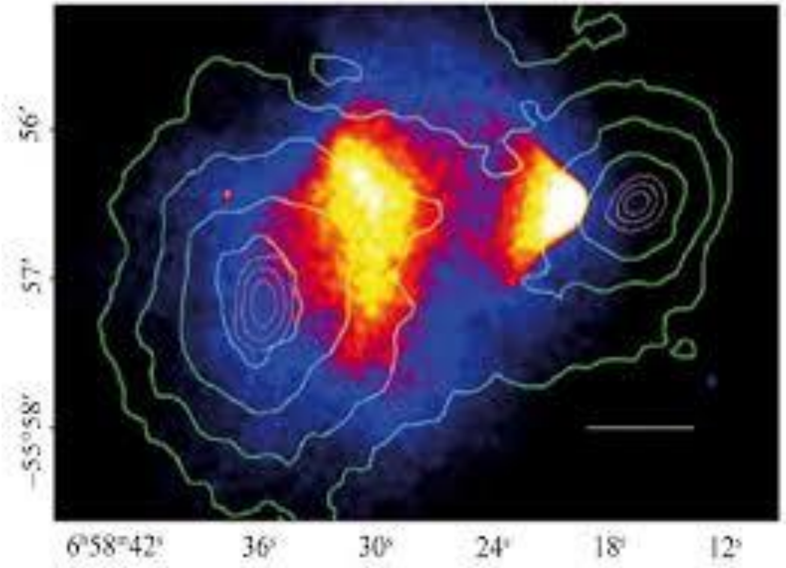
- Non-gravitational interactions are sufficiently weak that they have not yet been detected.

Evidence for dark matter

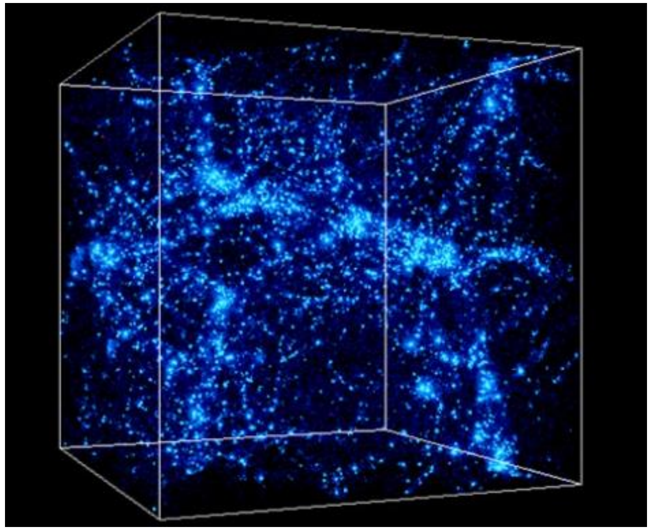
Astrophysical observations, on all scales, consistently point to the need for dark matter



Galaxy rotation curves



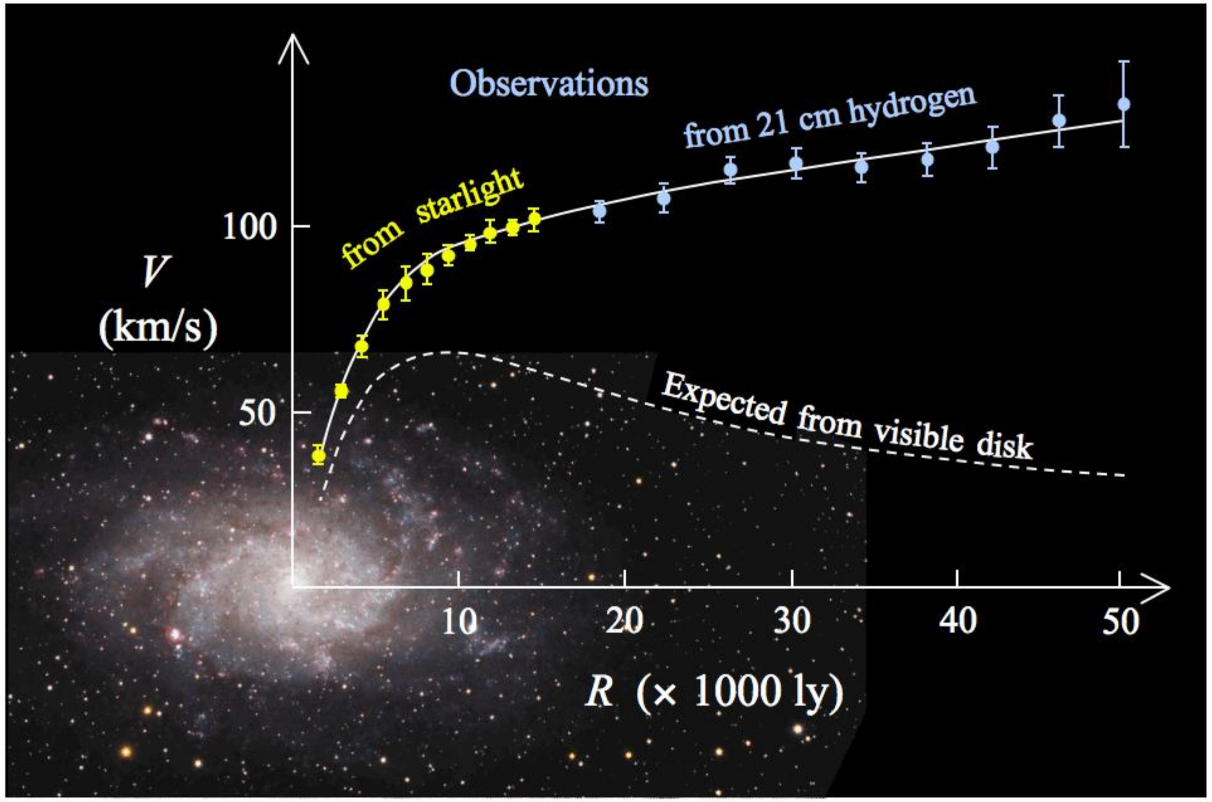
Clusters of galaxies

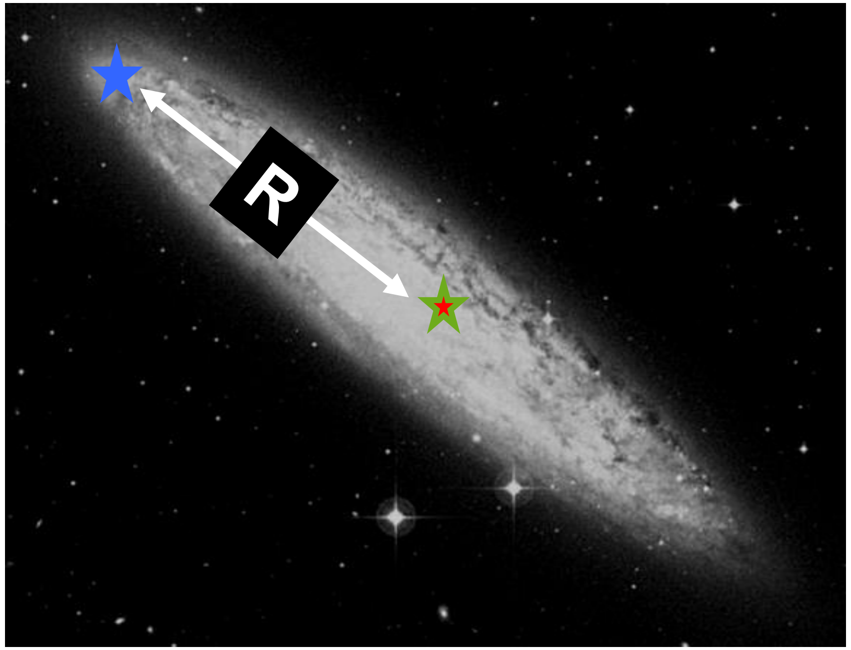


Large Scale Structure

Galaxy rotation curves

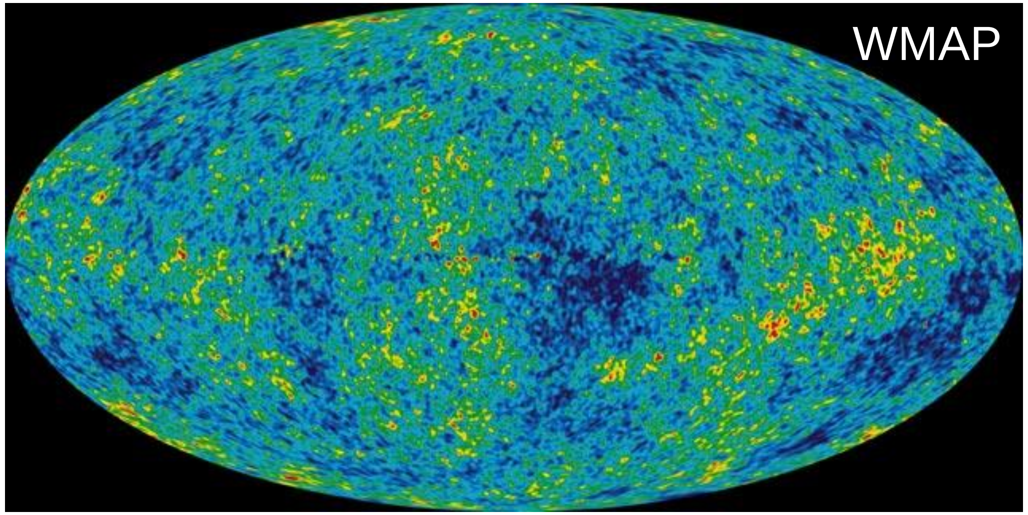
$$\frac{v^2}{R} = \frac{GM_{galaxy}}{R^2}$$

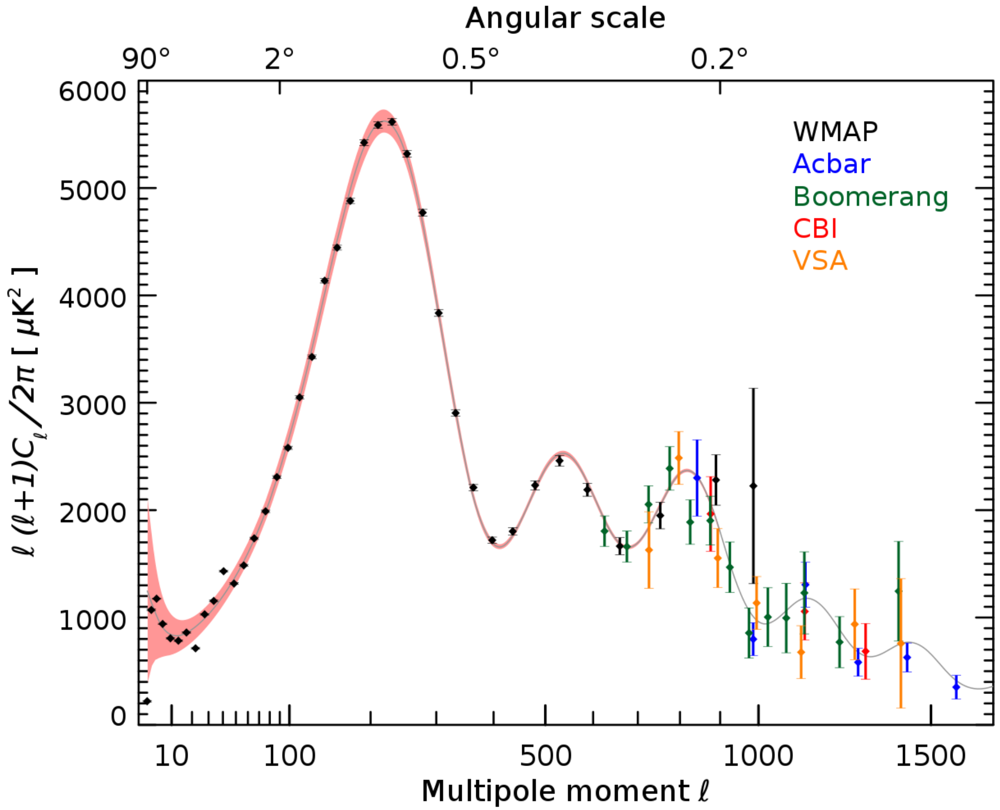




Galaxy rotation curves → there is more matter in galaxies than accounted for by stars/gas.

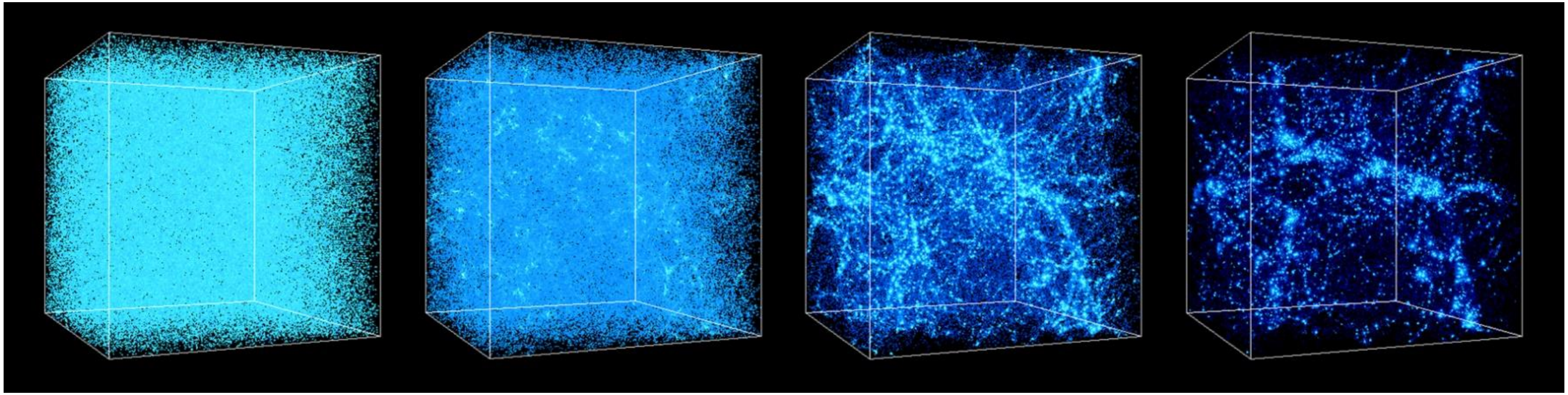
Cosmic microwave background





The CMB spectrum allow a precision determination of the baryonic matter and dark matter abundance of the universe.

Growth of Structure



Anatoly Klypin and Andrey Kravtsov, http://cosmicweb.uchicago.edu/filaments.html

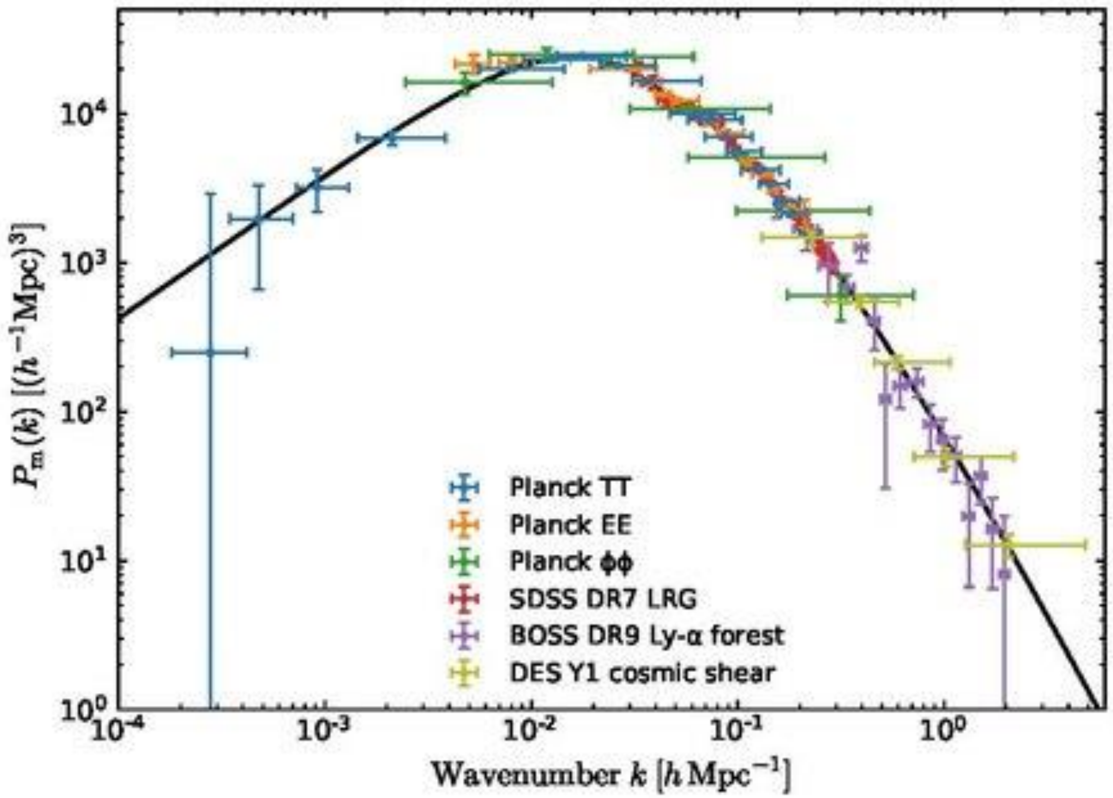
All viable model of structure formation are dominated by cold dark matter.

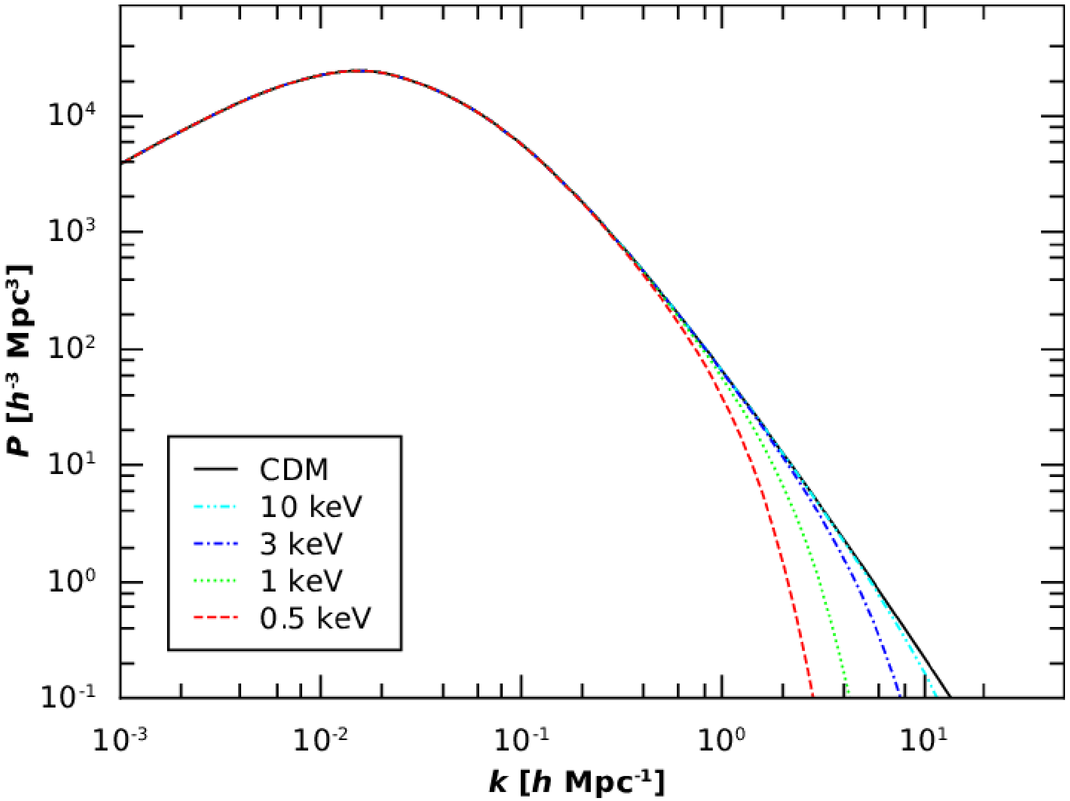
Structure formation begins with the formation of small structures, which merge to form larger structure.

Cold dark matter

Dark matter is (at least approximately) "cold" = non-rel. by the era of structure formation

→ *dark matter* ***cannot*** *be neutrinos (or other light relativistic particles) because they would "free-stream" from overdense regions, damping the growth of structure*





Gravitational Lensing

Galaxy cluster Abell 370

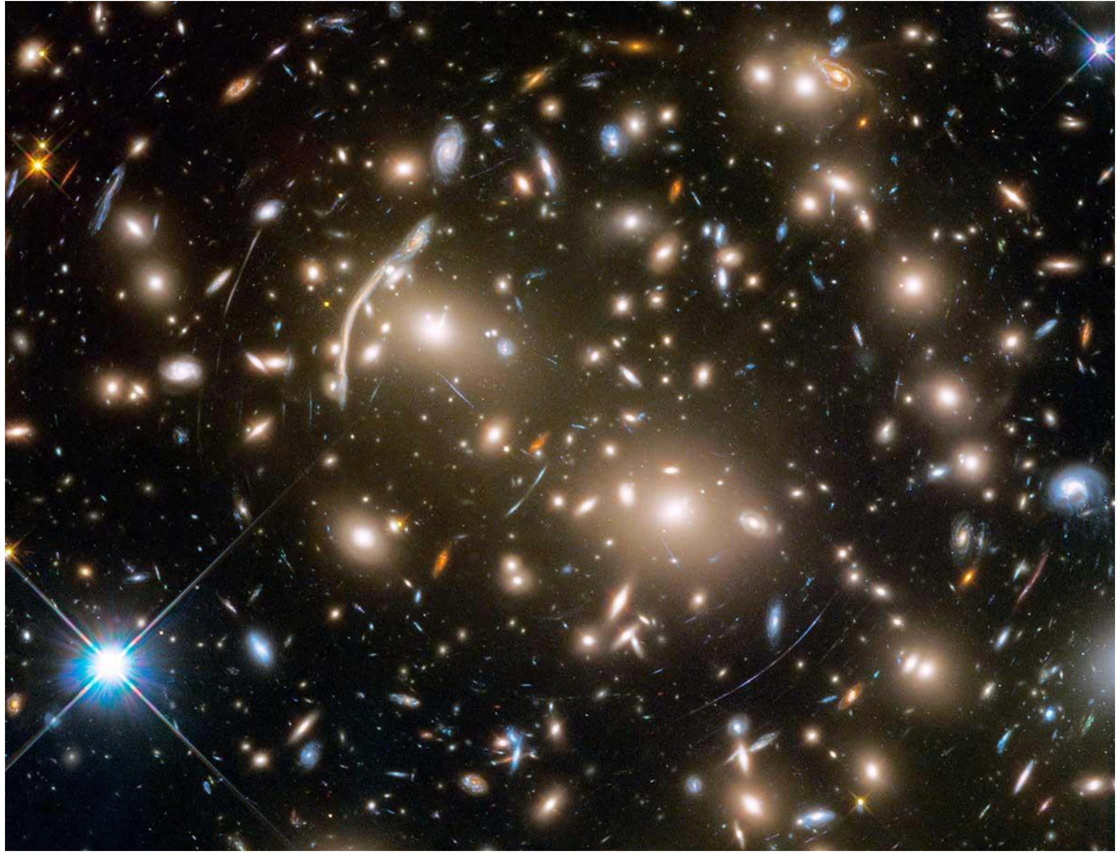
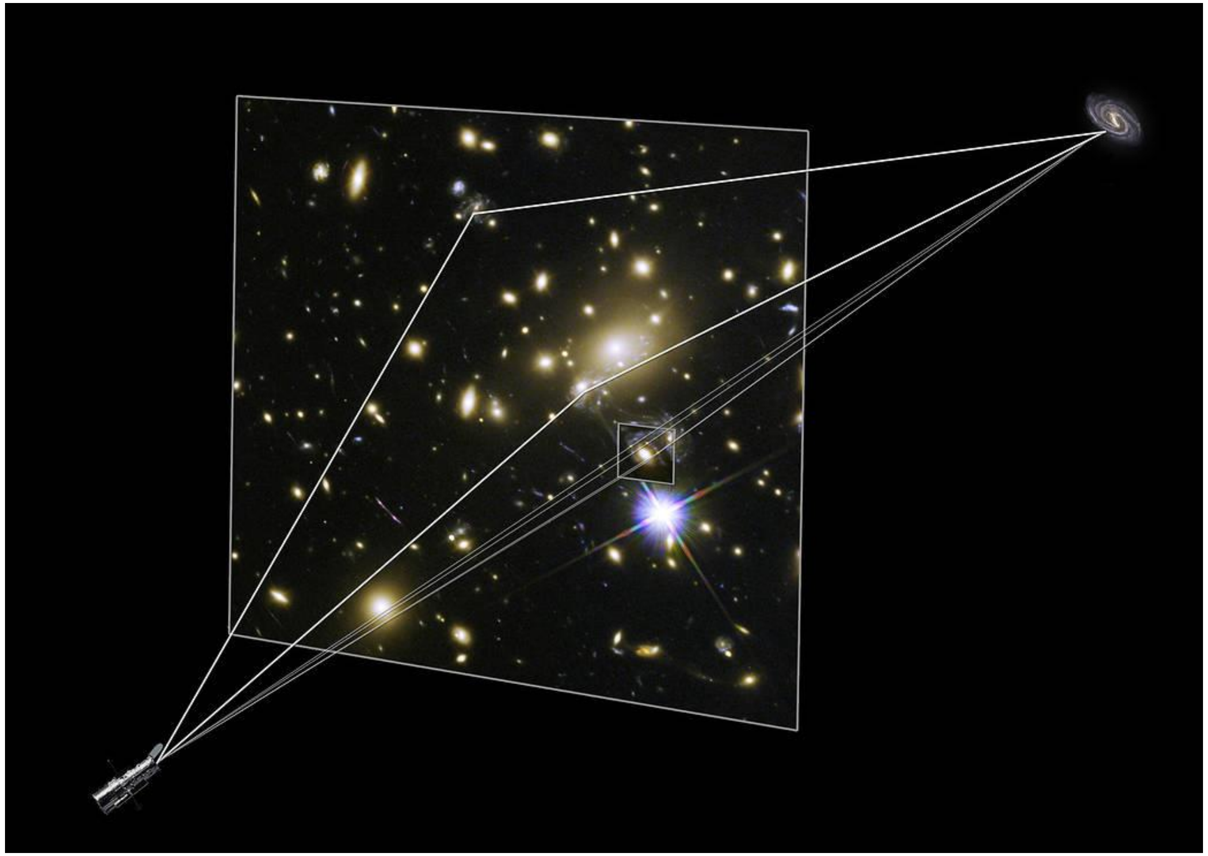


Image Credit: NASA/ESA



The lensed images act as probes of the matter distribution in the galaxy cluster

Bullet cluster

Red
→ X-rays trace the ordinary matter

Blue
→ inferred dark matter distribution

Implies that dark matter particles are non-interacting.

What is Dark Matter?

- Could it be dark clumps of ordinary (baryonic) matter? No, because:
  → BBN & CMB measure the baryonic matter abundance very well
  → MACHOs (Massive Compact Halo Objects) disfavoured by gravitational lensing

- Maybe we don't understand gravity very well?
  - Proposals such as MOND (Modified Newtonian Dynamics) fail to eliminate the need for dark matter on all astrophysical scales.

- Neutrinos or other known particles? →No

- Primordial black holes → possible over a narrow black hole mass range. But, difficult to obtain the right PBH abundance from models of inflation.

- **A new type of particle or particles** → the favoured explanation

Well motivated particle candidates:

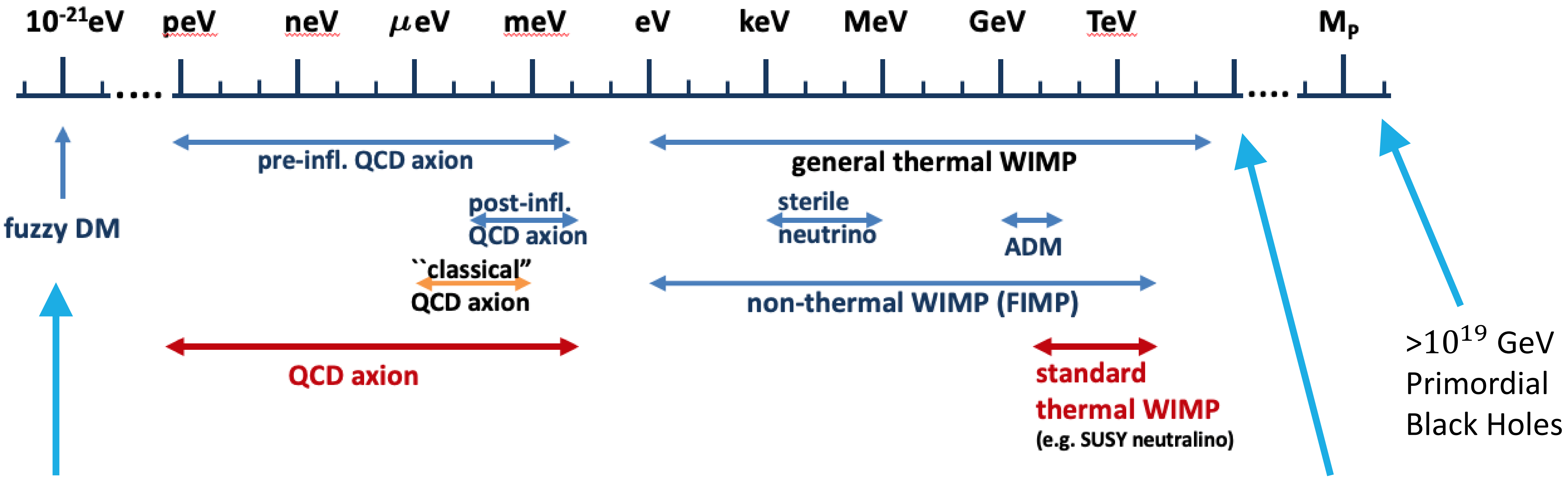
Dark matter density ~ 5 x ordinary matter density

Similar abundances seem highly unlikely, unless the dark and visible sectors were coupled in some way → prospects for detection of particle interactions.

Some of the most plausible particle models:

- WIMPs (Weakly Interacting Massive Particles) – connected to new GeV-TeV scale physics
- Axions – motivated by the Strong CP problem
- Sterile neutrinos – new physics is required in the neutrino sector
- Asymmetric dark matter – connection between dark matter and baryon asymmetry

Dark Matter mass



10^{-21}eV peV neV μeV meV eV keV MeV GeV TeV M_P

fuzzy DM

pre-infl. QCD axion

post-infl. QCD axion

``classical" QCD axion

QCD axion

general thermal WIMP

sterile neutrino

ADM

non-thermal WIMP (FIMP)

standard thermal WIMP

(e.g. SUSY neutralino)

$>10^{19}$ GeV
Primordial
Black Holes

"fuzzy":
de Broglie wavelength > galaxy

> 100 TeV
Composite DM
(non-pointlike)

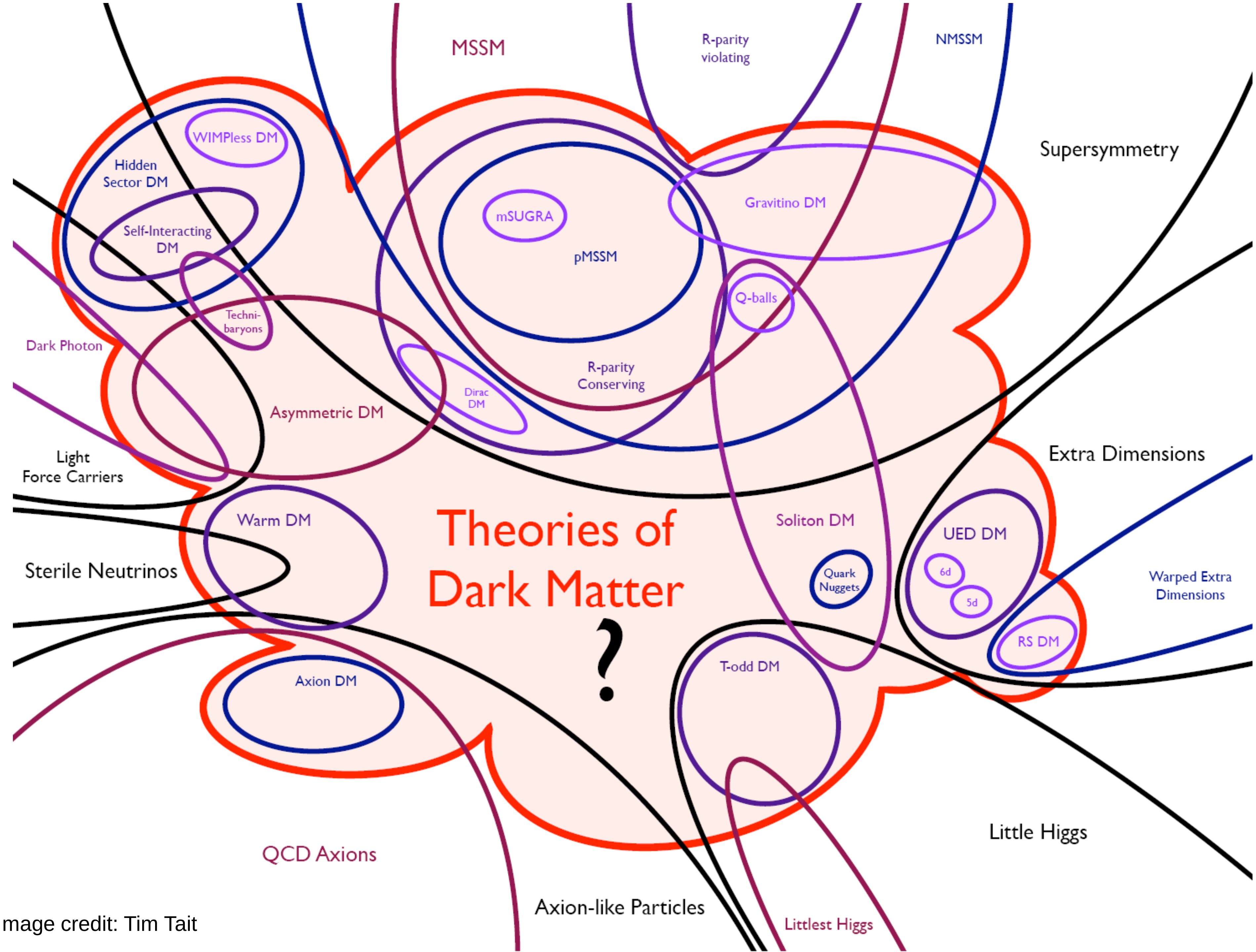


Image credit: Tim Tait

Weakly Interacting Massive Particles (WIMPs)

Dark matter freeze-out abundance:

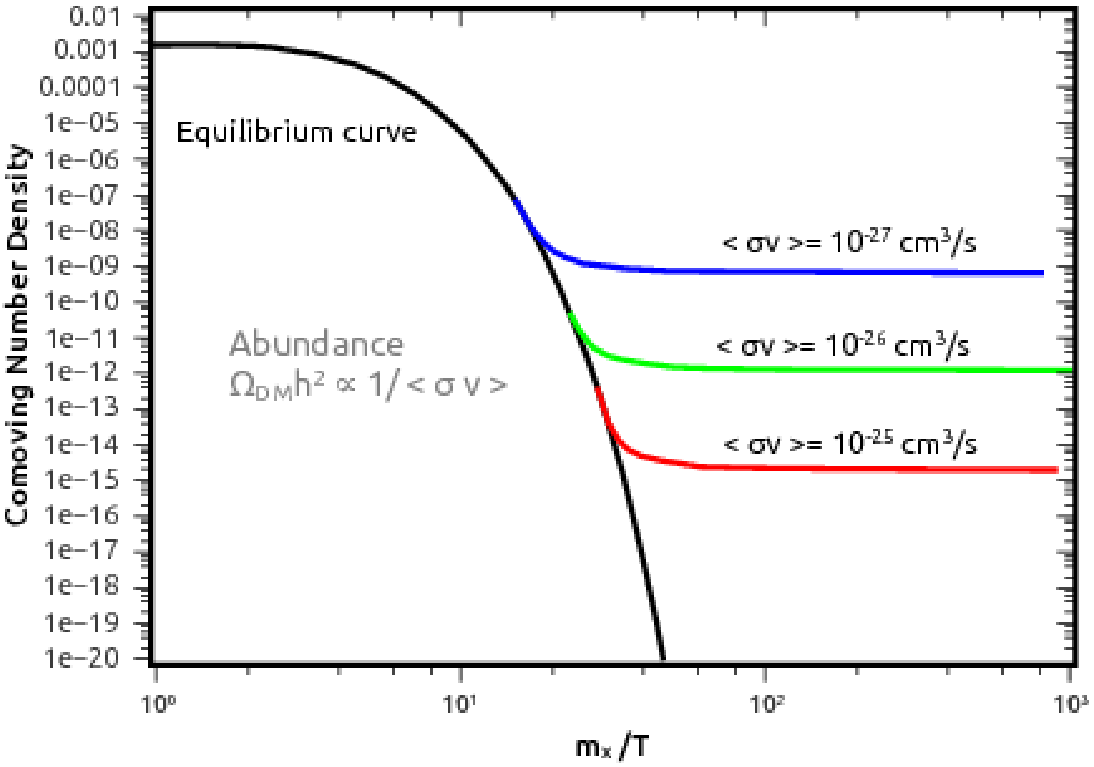
$$\Omega_\chi \propto \frac{1}{\langle \sigma_A v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$$

“WIMP Miracle”:

Correct relic density via thermal freezeout:

$g \sim g_{weak}$ and $m_\chi \sim$ GeV-TeV

$\chi + \chi \leftrightarrow$ regular matter



Freezeout and relic density

(1) Dark matter initially in thermal equilib:

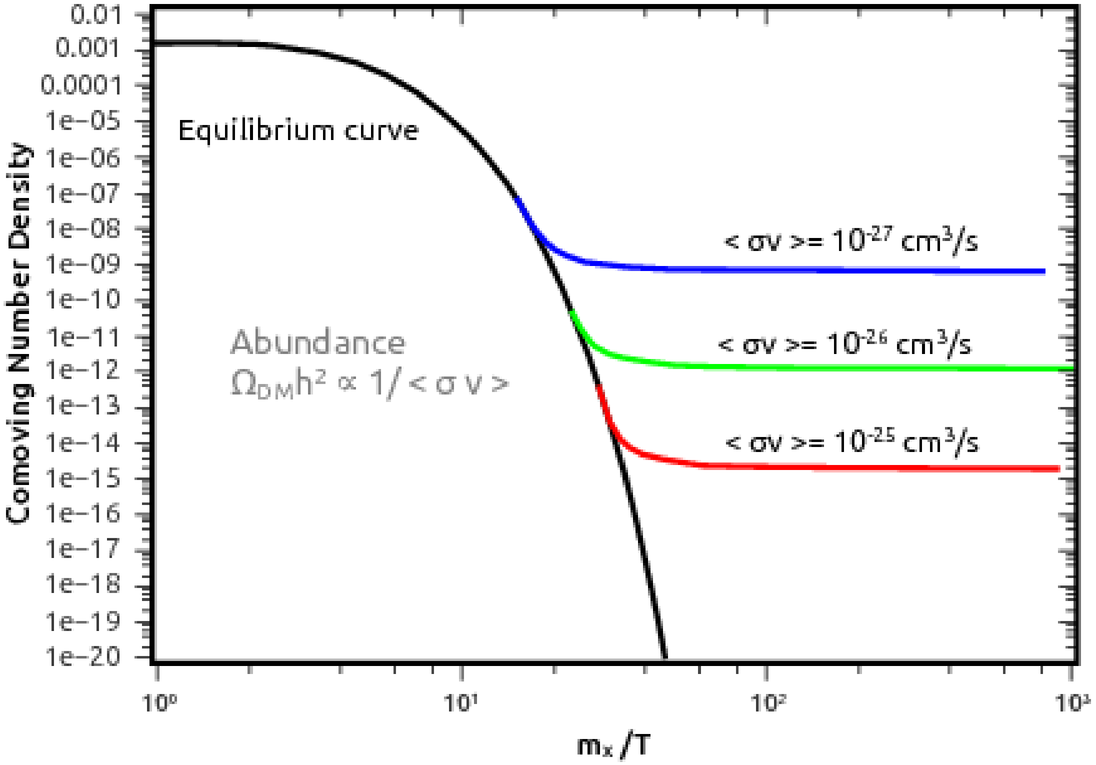
$$\chi + \chi \leftrightarrow \text{regular matter}$$

(2) Universe cools and the non-relativistic DM is Boltzmann suppressed:

$$N \sim (mT)^{3/2} e^{-m/T}$$

(3)“Freeze out” at m/T≈20.

$$N = constant \ \propto \frac{1}{\langle \sigma_A v \rangle}$$



→ Dark matter relic abundance proportional to inverse of the annihilation cross section.

Computing the DM relic density

Consider DM particles χ self annihilating with SM fermions as: $\chi\chi \leftrightarrow f\bar{f}$

(Up to factors of 2, the calculation is the same for $\chi\bar{\chi}$ particle-antiparticle annihilation, assuming particle-antiparticle asymmetry, $n_\chi = n_{\bar{\chi}} = \mathrm{n}$)

Boltzmann for the particle number density, n:

$$\frac{dn}{dt} = -3Hn\, \langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$

where H = Hubble expansion parameter $= \frac{\dot{a}}{a}$, where a = scale factor of the Universe

v = relative velocity of annihilating DM,

$\langle\sigma_A v\rangle$ = thermally averaged annihilation cross section

Computing the DM relic density

$$\frac{dn}{dt} = -3Hn\,\langle\sigma v\rangle(n^2 - n_{eq}^2)$$

where number density of DM particles is related to phase space distribution as:

$$n = g\int \frac{d^3p}{(2\pi)^3} f(p)$$

and the thermally averaged annihilation cross section is

$$<\sigma v> = \frac{g^2}{n_{eq}^2}\int \frac{d^3p_1}{(2\pi)^3}\int \frac{d^3p_2}{(2\pi)^3} v\sigma_{\chi\chi\to f\bar{f}} f_{eq}(p_1)\, f_{eq}(p_2)$$

Introduce new variable: $Y = \frac{n}{s}$ where s = entropy density = $\frac{p+\rho}{T} = \frac{2\pi^2}{45} g_{*s} T^3$

T = temperature, g_{*s} = entropy degrees of freedom

and change variables from t to $x = \frac{m}{T}$

The Boltzmann eqn now becomes:

$$\frac{x}{Y_{eq}} \frac{dY}{dx} = -\frac{<\sigma v> n_{eq}}{H} \left(\frac{Y^2}{Y_{eq}^2} - 1 \right)$$

Y becomes constant when $<\sigma v> n_{eq} = H$

i.e. when annihilation rate = expansion rate

Now integrate numerically (or do analytic approximation) to find:

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27}\ cm^3 s^{-1}}{<\sigma v>}$$

$\Omega_\chi h^2 \approx 0.1$ therefore $< \sigma v > \approx 3 \times 10^{-26} cm^3 s^{-1}$

WIMPs and WIMP-like miracles

Thermal freezeout suggests the electroweak-scale since: $\langle\sigma v\rangle \sim \frac{\alpha_{\mathrm{weak}}^2}{(100\ \mathrm{GeV})^2} \sim 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$

→A compelling benchmark, esp. given other motivation for new physics at the GeV-TeV scale.

But, in fact, any parameters that satisfy $\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_\chi^2}{g_\chi^4}$ would work ("WIMPless" miracle)

However, the mass range for WIMP-like DM is well-defined:

- < 100 TeV (to avoid the Unitarity limit)
- > 1 MeV (to avoid problems with big bang nucleosynthesis)

s-wave vs p-wave

It is useful to expand the annihilation cross section in terms of velocity, v:

$$<\sigma v> \; = \; a \; + \; bv^2 \; + \; O(v^4)$$

a term: s-wave (l=0) annihilation
b term: p-wave (l=1) annihilation

To obtain this result, expanding the cross section in terms of partial waves (l eigenstates).

- l^{th} partial wave contribution to the amplitude ~ k^l, where k is the CoM 3-momentum
- In the non-rel limit $k^2 = E^2 - m_\chi^2 = \frac{m_\chi^2 v^2}{(4-v^2)} \simeq \frac{m_\chi^2 v^2}{4}$

➢ v ≈ 10^{-3}c in the galaxy, so only the s-wave contribution is significant for indirect detection.
➢ In the early universe (at DM freezeout) v is bigger, so both terms important.

Unitarity limit – upper limit on thermal WIMP mass

Starting from the optical theorem: $\int d\beta (2\pi)^4 \delta^4(p_\alpha - p_\beta)\left|A_{\beta\alpha}\right| = 2Im\, A_{\alpha\alpha}$
(which follow from unitarity of the scattering matrix).

One can derive an upper limit on the total inelastic cross section, for each partial wave contribution:

$$\langle \sigma v_{rel} \rangle^J_{total} < \langle \sigma v_{rel} \rangle^J_{max} = \frac{4\pi(2J+1)}{m_\chi^2 v_{rel}}$$

Griest &
Kamionkowski

Taking the s-wave term, and setting : $\langle \sigma v \rangle_{thermal} \sim 3 \times 10^{-26}\, cm^3/s < \langle \sigma v \rangle_{max}$

We obtain an upper limit on the mass of thermal relic DM: $m_\chi < 100\ \mathrm{TeV}$

BBN – lower limit on thermal WIMP mass

Big Bang Nucleosynthesis (BBN)production of light elements constrains the particle content of the Universe at a temperature of order keV-MeV.

Number of relativistic degrees of freedom usually parameterized in terms of an effective number of neutrino species:

$N_{\mathrm{eff}}^{\nu} = 3.046$ (in the Standard Model)

$N_{\mathrm{eff}}^{\nu} < 3.3$ - 4   from BBN

$$\rho = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\mathrm{eff}} \right]$$

For dark matter contribution to N_{eff}^{ν} to be consistent with BBN, need $m_{\mathrm{DM}} > O(\mathrm{MeV})$

Big Bang Nucleosynthesis

Temperature of Universe ~ MeV

The universe is radiation dominated (photons, neutrinos), plus electrons, positrons, and a small amount of baryons and dark matter.

Neutron to proton ratio set by weak interaction the processes like:

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n \leftrightarrow p + \bar{\nu}_e + e^- \qquad \Rightarrow \quad \frac{n}{p} \approx \exp\left(\frac{-(m_n - m_p)}{T}\right)$$

If there were extra radiation
→ The universe would expand faster
→ Weak interaction rates which convert neutrons to protons would freeze-out earlier
→ Larger neutron/proton ratio → more Helium

Chemical vs thermal decoupling

- The DM relic density ceases to track the equilibrium density when the number changing processes $(\chi\chi \leftrightarrow f\bar{f})$ become ineffective. This is *chemical decoupling*. The annihilation rate is proportional to $n_\chi^2 \sim \left(e^{-\frac{m}{T}}\right)^2$, i.e. doubly Boltzmann-suppressed.

  For a non-relativistic WIMP, we have: $x_{cd} = \frac{m_\chi}{T_{cd}} \approx 20$

- However, the WIMPs stay in thermal contact until much later, because scattering processes $(\chi f \leftrightarrow \chi f)$ are more frequent. This process has only a single Boltzman suppression.

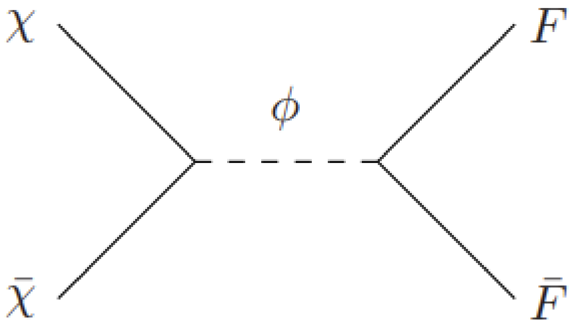
  Thermal or kinetic decoupling occurs at $x_{kd} = \frac{m}{T_{cd}} \simeq 200 - 10^5$ (large range)

Important exceptions to the standard freeze-out calc

1. Co-annihilation

2. Annihilation near a resonance

$$\sigma v = \left(\frac{g^2}{4\pi}\right)^2 \frac{s}{\left(M_\phi^2 - s\right)^2 - M_\phi^2\Gamma_\phi^2}$$



→ need to be careful with thermal average near the pole

3. Sub-threshold annihilation.

Annihilation $\chi\chi \leftrightarrow f\bar{f}$, with f heavier than χ.

(Possible for the higher energy componenet of the χ distribution, provided the mass splitting is not too large mass.

Including co-annihilations

If there are other dark-sector particles close in mass to the stable dark matter candidate, the standard calculation can fail.

Consider N particles, χ_i, with $i = 1, \ldots N$
Relic density controlled by (co)-annihilations of χ_i and χ_j

Write down a set of coupled Boltzmann eqns:

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j=1}^{N} <\sigma_{ij} v_{ij}> \left(n_i n_j - n_i^{eq} n_j^{eq} \right) \quad + i \leftrightarrow \text{j scattering terms}$$

$\sigma(\chi_i \chi_j \to X_{SM})$ is the total rate for $\chi_i \chi_j$ (co)-annihilation to SM particles

Ultimately, we will be interested in only the total number density:

$$n \equiv \sum_{i=1}^{N} n_i$$

because the heavier particles will eventually decay to the lightest.
$(i.e.\ \chi_{2,3,4\ldots.}$ all decay down to χ_1 with lifetime << age of universe)

The total number density satisfies the standard Boltzmann eqn:

$$\frac{dn}{dt} = -3Hn - <\sigma_{eff}v>(n^2 - n_{eq}^2)$$

with an effective annihilation rate given by:

$$\langle\sigma_{eff}v\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle \frac{n_i}{n^{eq}}\frac{n_j}{n^{eq}}$$

E.g., assume two dark particles, χ_1 and χ_2,

$m_1 < m_2$ and $\Delta = m_2 - m_2$

$$\sigma_{eff} = \sigma_{11} + e^{-\Delta m/T}\left(1 + \Delta m/m\right)^{3/2}\sigma_{12} + e^{-2\Delta m/T}(1 + \Delta m/m)^3\sigma_{22}$$

The processes involving the heavier particle are suppressed (larger Boltzmann suppression of number densities $N_i \sim (m_i T)^{3/2} e^{-m_i/T}$)

But, they are important if $\Delta = m_2 - m_2$ is small and/or the $\chi_1\chi_1$ self-annihilation happens to be suppressed.

Suppose the relic density is determined by the co-annihilation process $\chi_1\chi_2 \rightarrow X_{SM}$, with χ_1 self-annihilation cross section very small.

Indirect detection: very suppressed

- no χ_2 left in universe today to annihilate

Direct detection: very suppressed

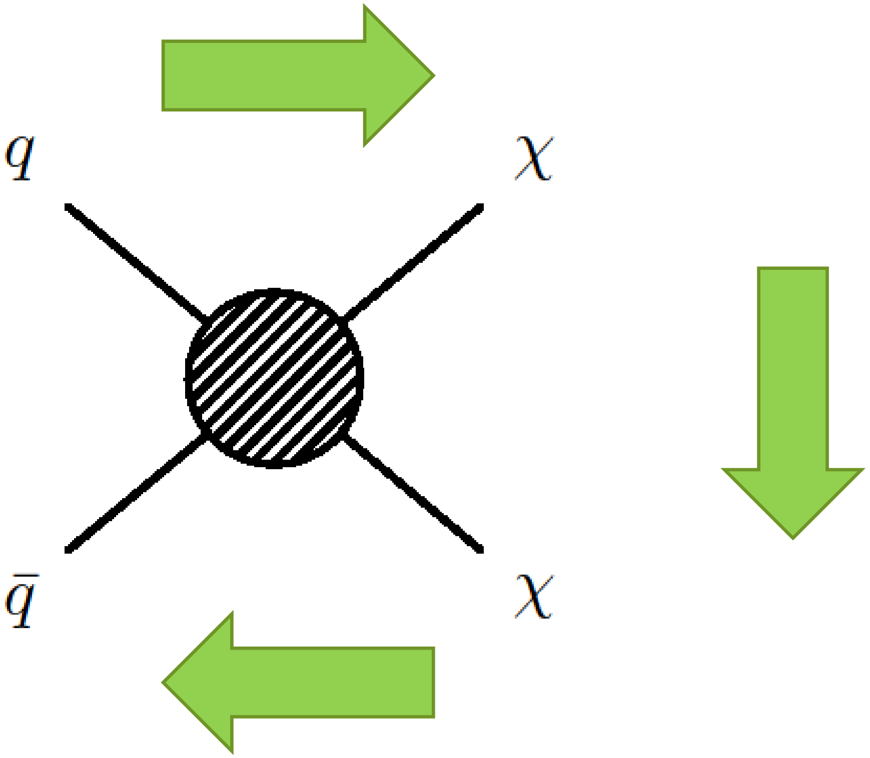
- $\chi_1 + N \rightarrow \chi_1 + N$ rate very small
- $\chi_1 + N \rightarrow \chi_2 + N$ kinematically forbidden unless $\chi_2 - \chi_1$ mass gap is tiny

Collider production

- unsuppressed

Dark Matter Lecture #2

Detecting WIMPs

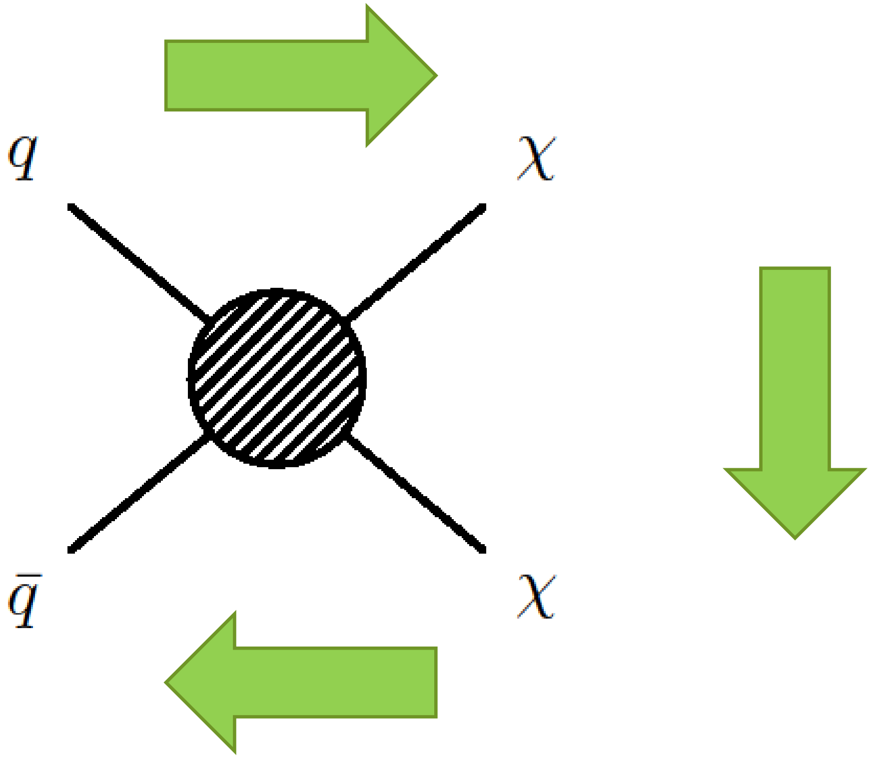


Collider searches (production)

direct detection
(scattering)

Indirect detection (annihilation)

Detecting WIMPs

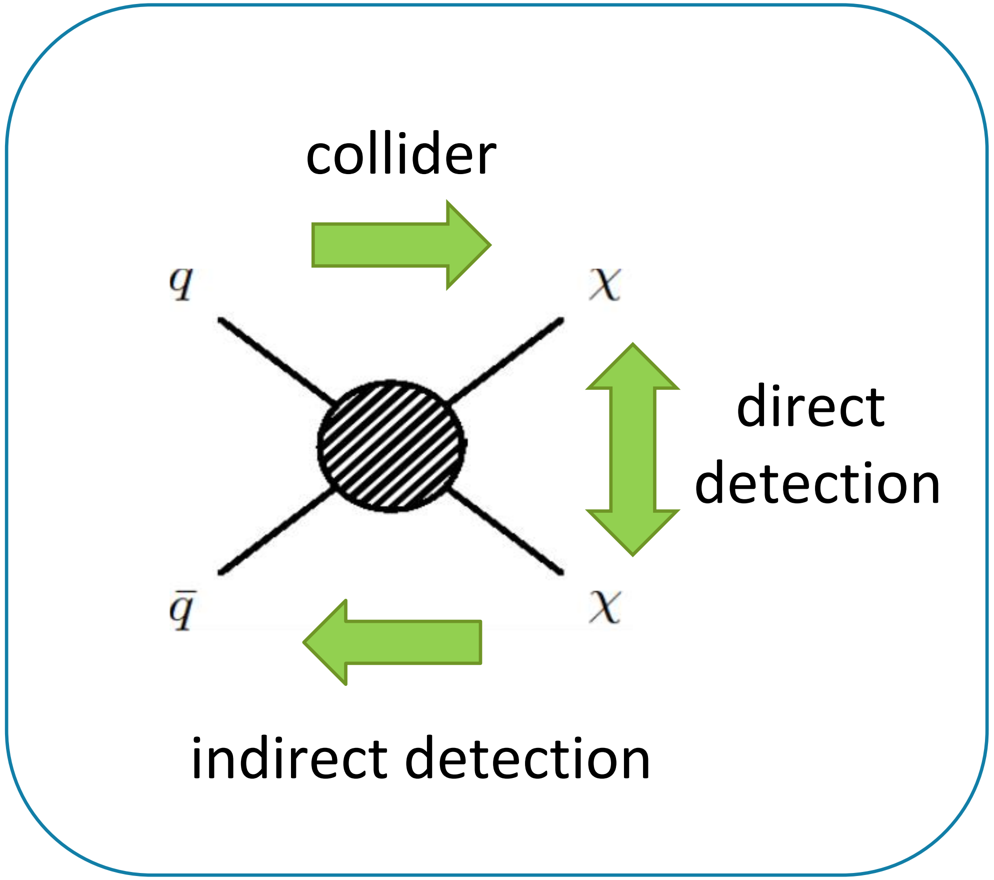


Collider searches (**make it**)

direct detection
(**shake it**)

Indirect detection (**break it**)

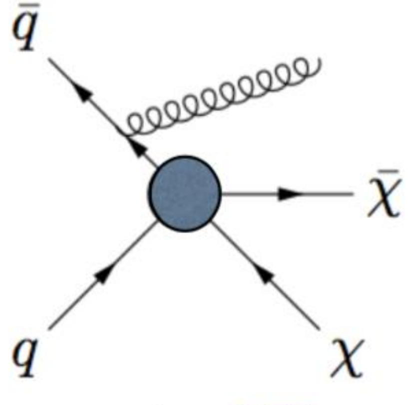
Detecting WIMPs



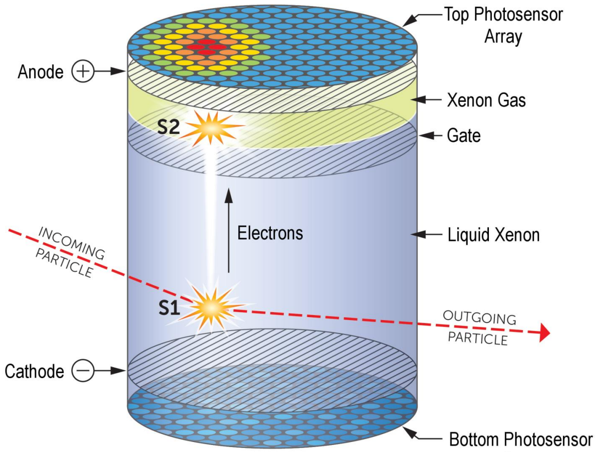
collider

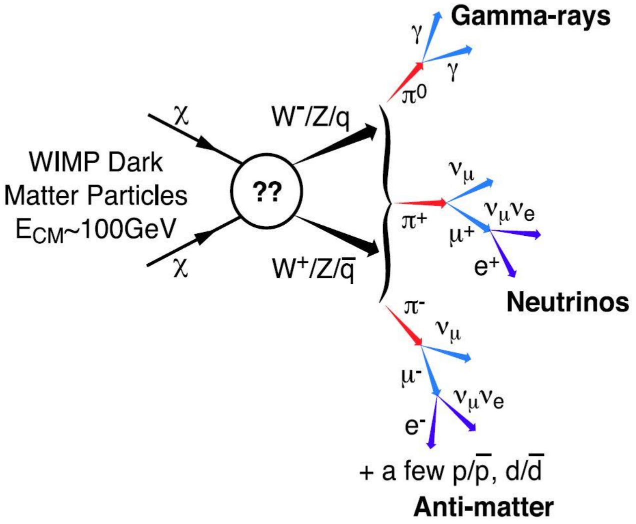
direct detection

indirect detection

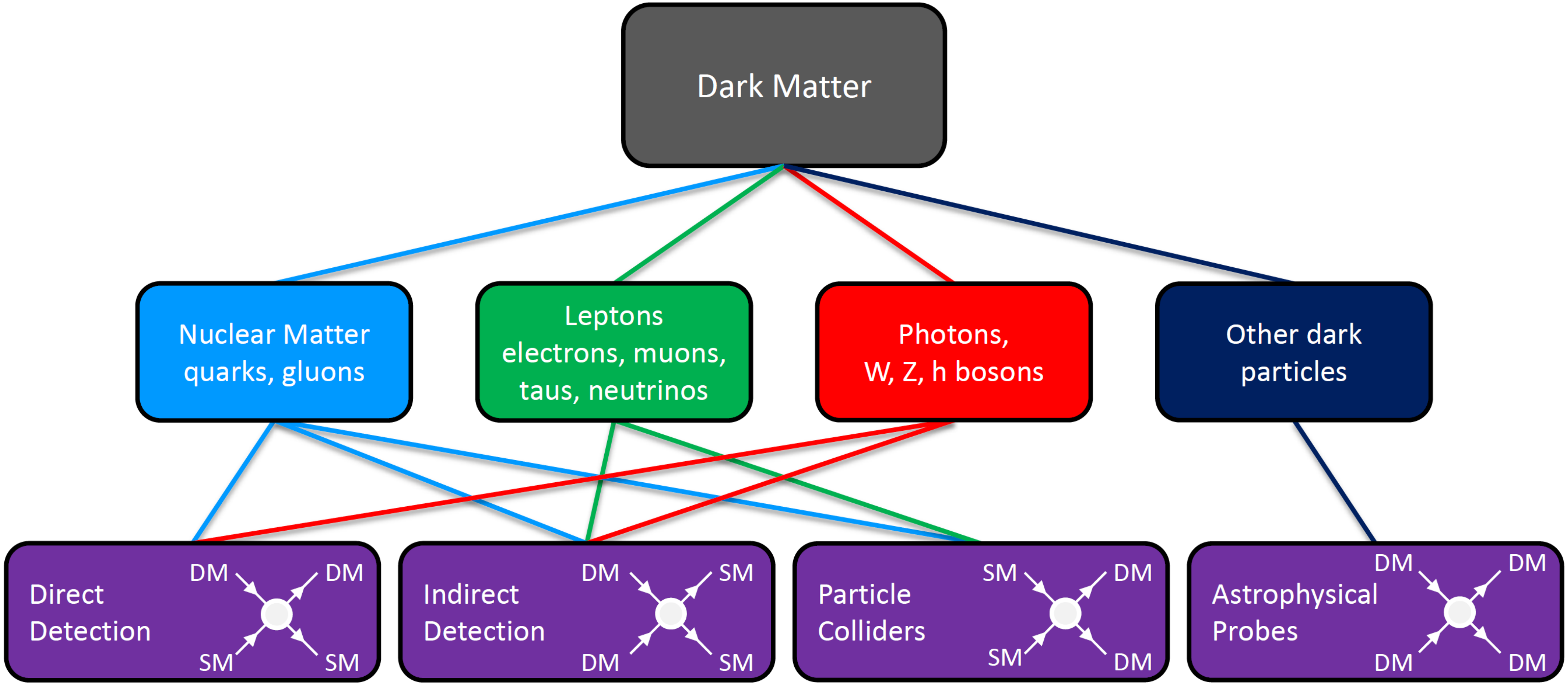


monojet +MET





Complementary probes of (non-gravitational) DM interactions



Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Direct
Detection

Indirect
Detection

Particle
Colliders

Astrophysical
Probes

Dark matter self interactions

❖ Dark matter should not strongly self interact.

- The Bullet Cluster
- Halo shapes (self interactions make galaxies too spherical)

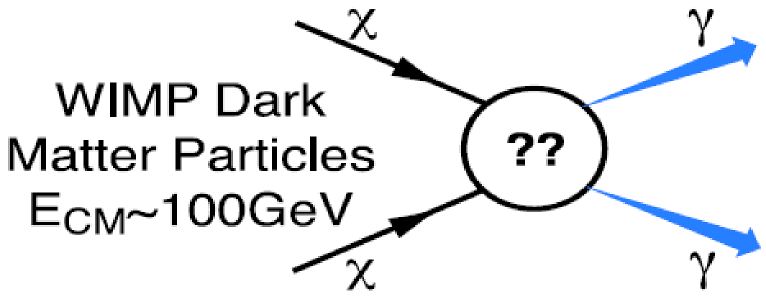
❖ But some amount of self interaction is usually expected. (Typically at tree-level, but certainly at loop level).

This is ok, and maybe even be desired:

→ helps to alleviate the CDM problem of too much structure on small scales.

However, there are other solutions to this problem, including warm dark matter, decaying dark matter, …

Dark Matter Indirect Detection

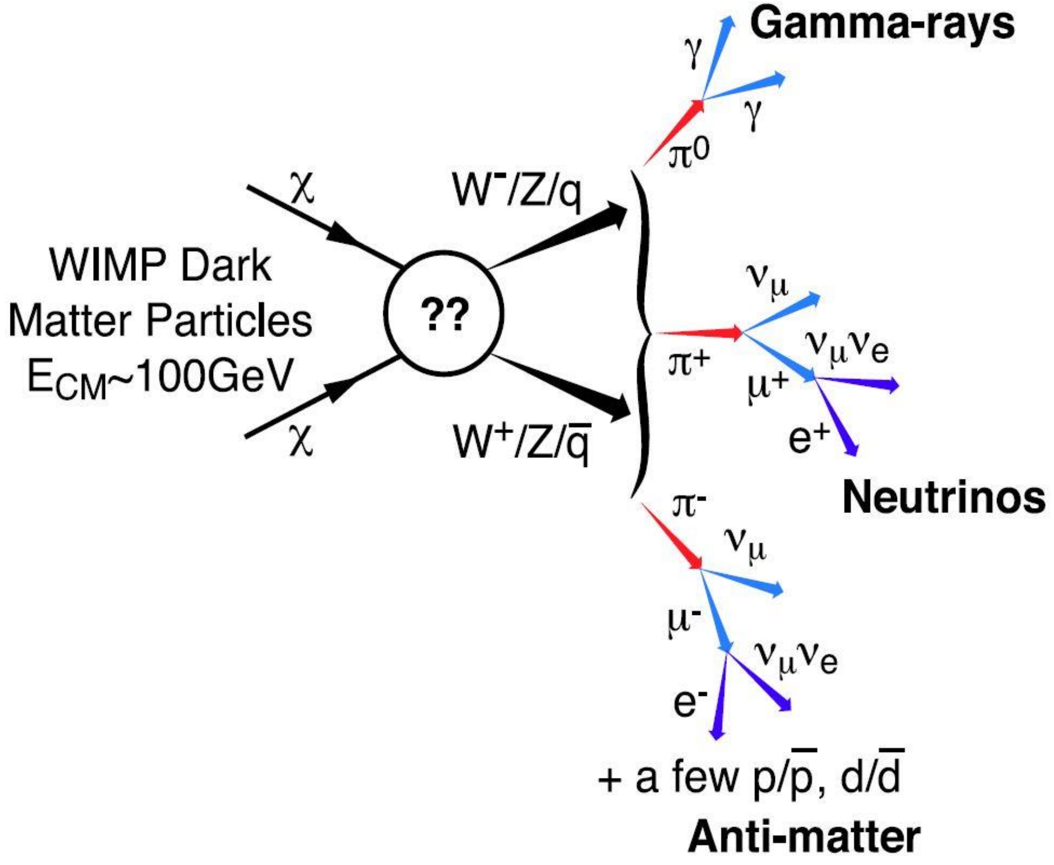


Search for DM annihilation or decay products from regions where the DM density is high and (ideally) astrophysical backgrounds are low.

Indirect detection – Detecting dark matter annihilation

Indirect detection probes the dark matter annihilation cross-section

→ The most direct detect test of the **thermal-relic WIMP paradigm**



Indirect detection – Detecting dark matter annihilation

Suitable sources for indirect detection signals:

- The galactic centre (of our Milky Way galaxy)
- Dwarf galaxies
- Clusters

Also:
- Diffuse extra-galactic flux
- Dark matter annihilation in the Sun/Earth/planets

s-wave vs p-wave

It is useful to expand the annihilation cross section in terms of velocity, v:

$$\langle \sigma v \rangle = a + b v^2 + O(v^4)$$

a term: s-wave (l=0) annihilation
b term: p-wave (l=1) annihilation

- v ≈ 10^{-3}c in the galaxy, so only the s-wave contribution is significant for indirect detection.
- In the early universe (at DM freezeout) v is bigger, so both terms important.

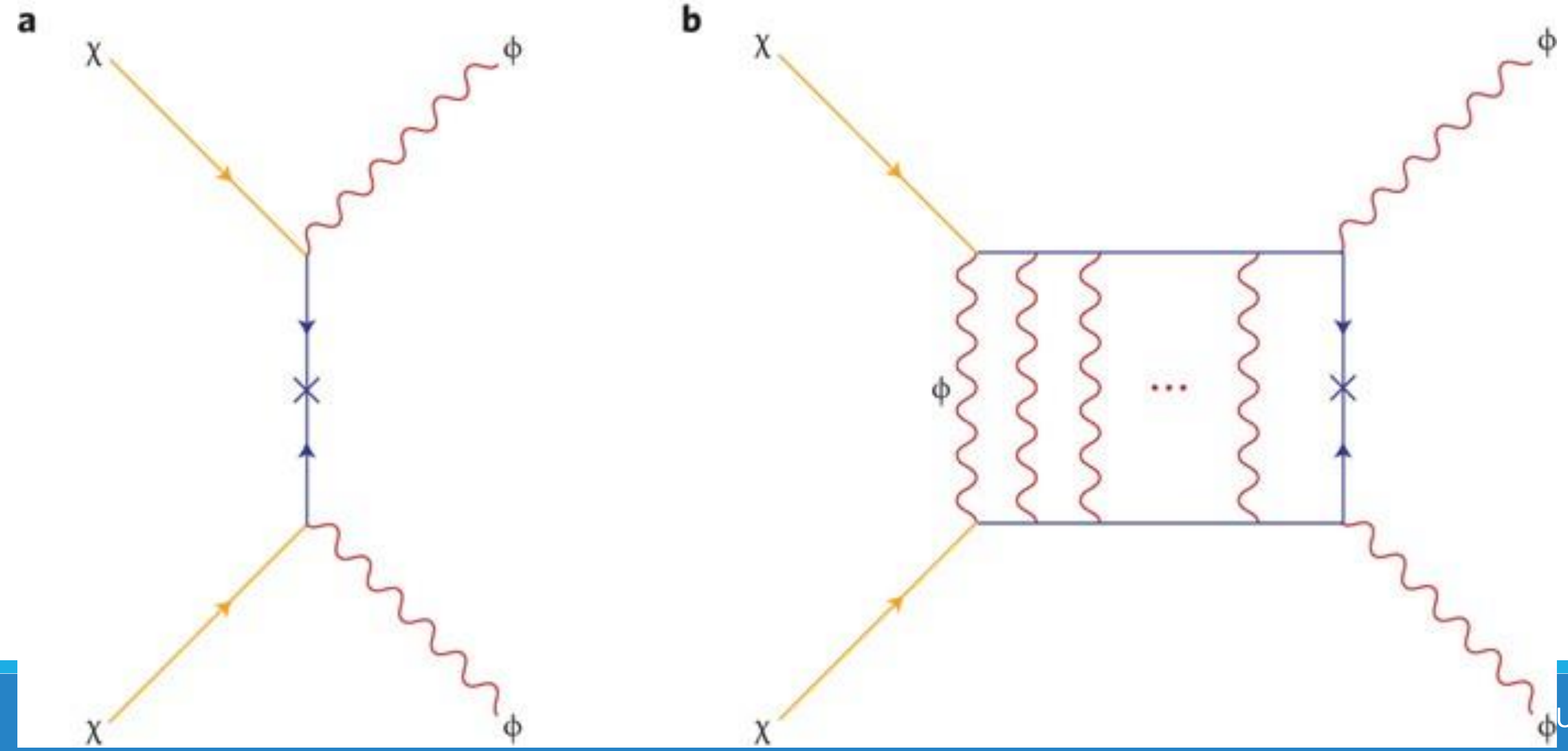
→ s-wave typically assumed when comparing indirect detection and freezeout.
→ p-wave would give very suppressed indirect signal.

Sommerfeld enhanced annihilation

We usually calculate cross section using perturbation theory.

But, this approach breaks down in the presence of long range forces and low velocity.

In this limit, Born approximation breaks down, as the particle wavefunctions are not well approximated by plane waves. Deformation of wavefunction for coulomb-like potential.



Equivalent to formation of short-lived bound states

Sommerfeld enhanced annihilation

Assume DM interacts with a light force carrier ϕ with fine structure constant: $\alpha_\chi = \frac{\lambda^2}{4\pi}$

For $m_\phi = 0$, annihilation cross section is enhanced by the “Sommerfeld factor”:

$$S = \frac{\pi\alpha_\chi / v_{rel}}{1 - e^{-\pi\alpha_\chi / v_{rel}}}$$

For $m_\phi \neq 0$, the enhancement typically cut off at a value $\propto = \alpha_\chi m_\chi / m_\phi$.
(There are also resonance regions for particular (tuned) values of α_χ, m_χ & m_ϕ.)

Note the $1/v$ dependence of the Sommerfeld enhanced cross section.

DM at freezeout: $v \sim 1/3$ DM in the galaxy now: $v \sim 10^{-3}$

→ Mechanism for boosting present day annihilation w.r.t. freezeout cross section

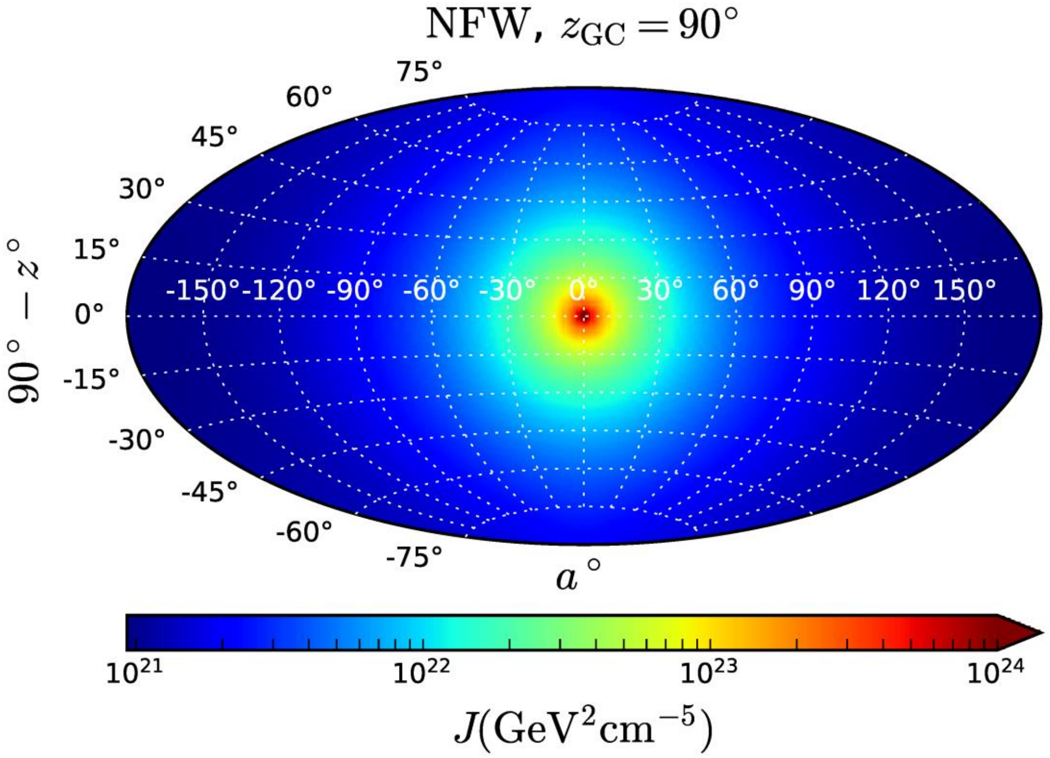
Dark matter annihilation signal

$$\frac{d\Phi_{\Delta\Omega}}{dE} = \langle \sigma v \rangle \frac{J_{\Delta\Omega}}{8\pi m_{DM}^2} \frac{dN}{dE}$$

Annihilation cross section

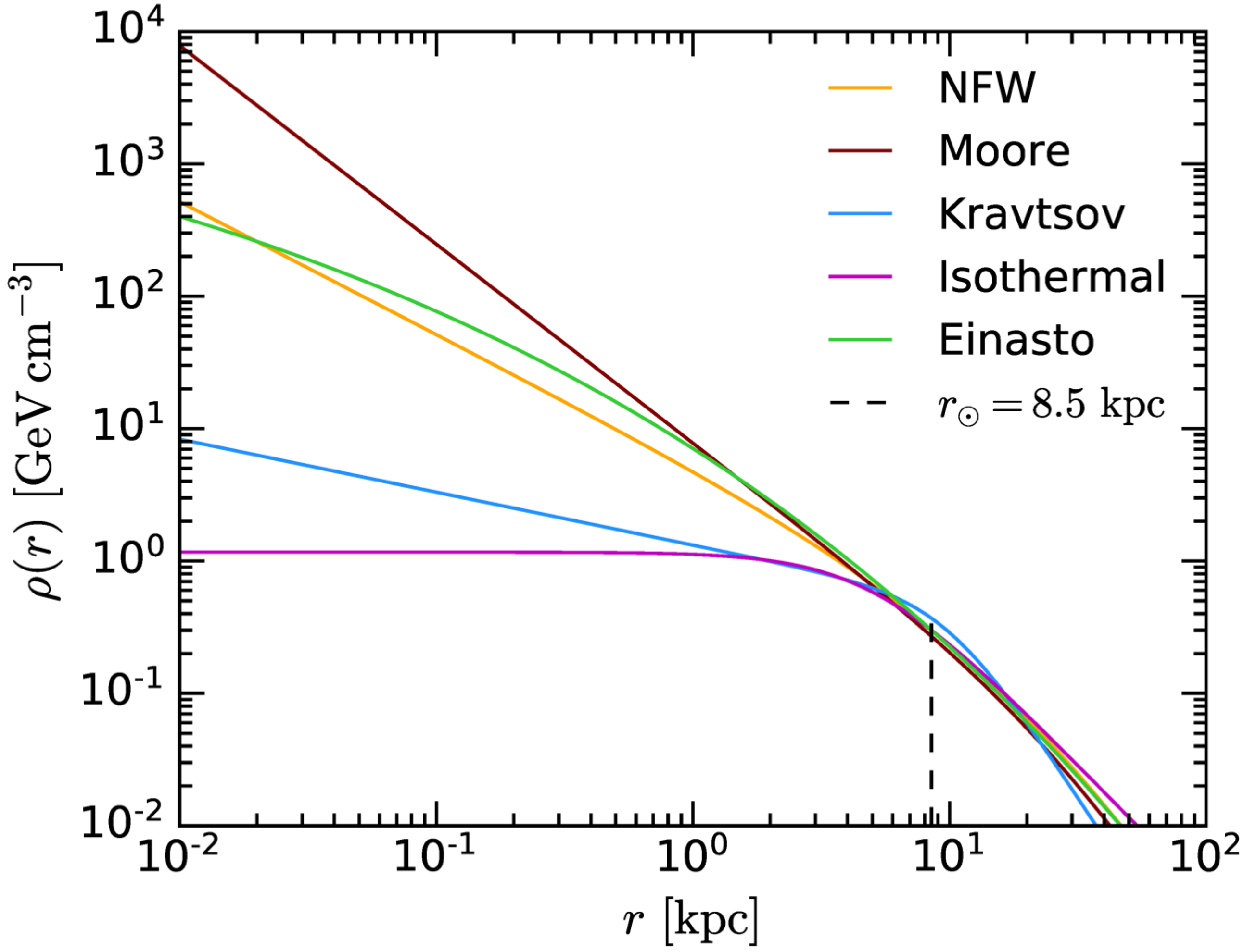
Integral of (density)^2 along line of sight

Spectrum per annihilation



e.g. For χχ→γγ, we have $\frac{dN_\gamma}{dE_\gamma} = 2\delta(m_\chi - E_\gamma)$

Galactic density profile



(Relatively) small uncertainty in DM density near the Earth.

DM density in the galactic centre highly dependent on the halo profile assumed.

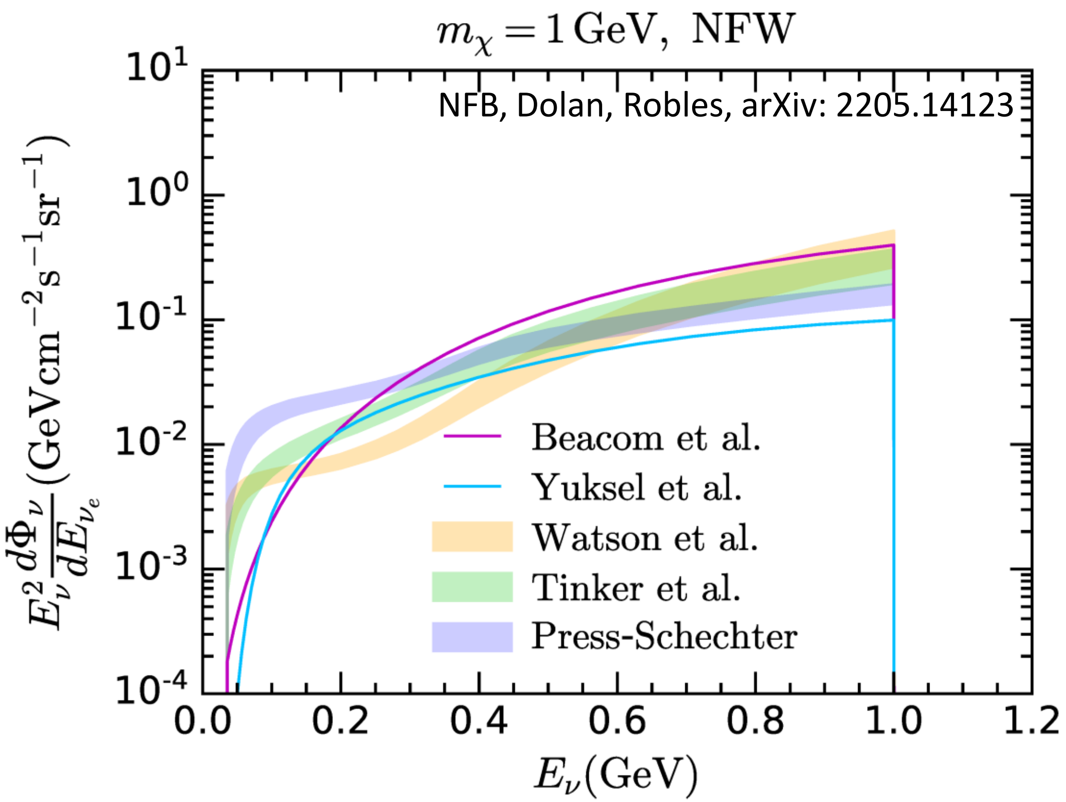
Indirect detection – extra galactic flux

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{2}\frac{c}{4\pi H_0}\frac{\Omega_{DM}^2\rho_c^2}{m_{DM}^2}\int_0^{z_{up}} dz\,\frac{\Delta^2}{h(z)}\frac{dN_\nu(E_\nu')}{dE_\nu{}'}$$

Flux produced at energy E' redshifted to $E = \frac{E'}{1+z}$:

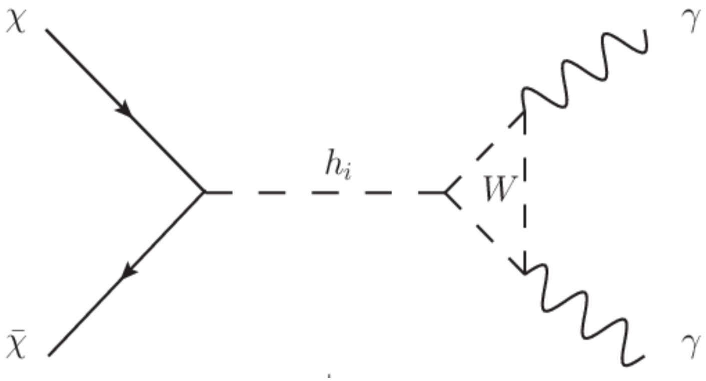
$$h(z) = \sqrt{\Omega_{m,0}(1+z) + \Omega_{\Lambda,0}}$$

Δ^2 parametrises dependence on the choice of the Halo clustering factor.



NFB, Dolan, Robles, arXiv: 2205.14123

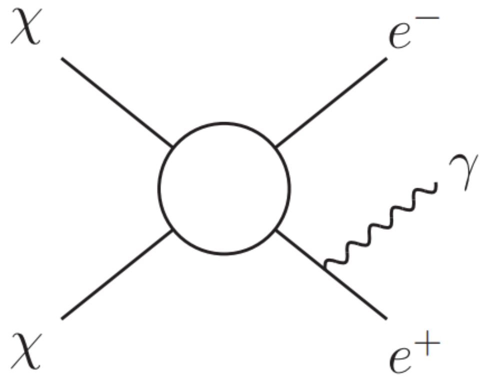
Annihilation modes:



- $\chi\chi \rightarrow \gamma\gamma$ → should be loop suppressed

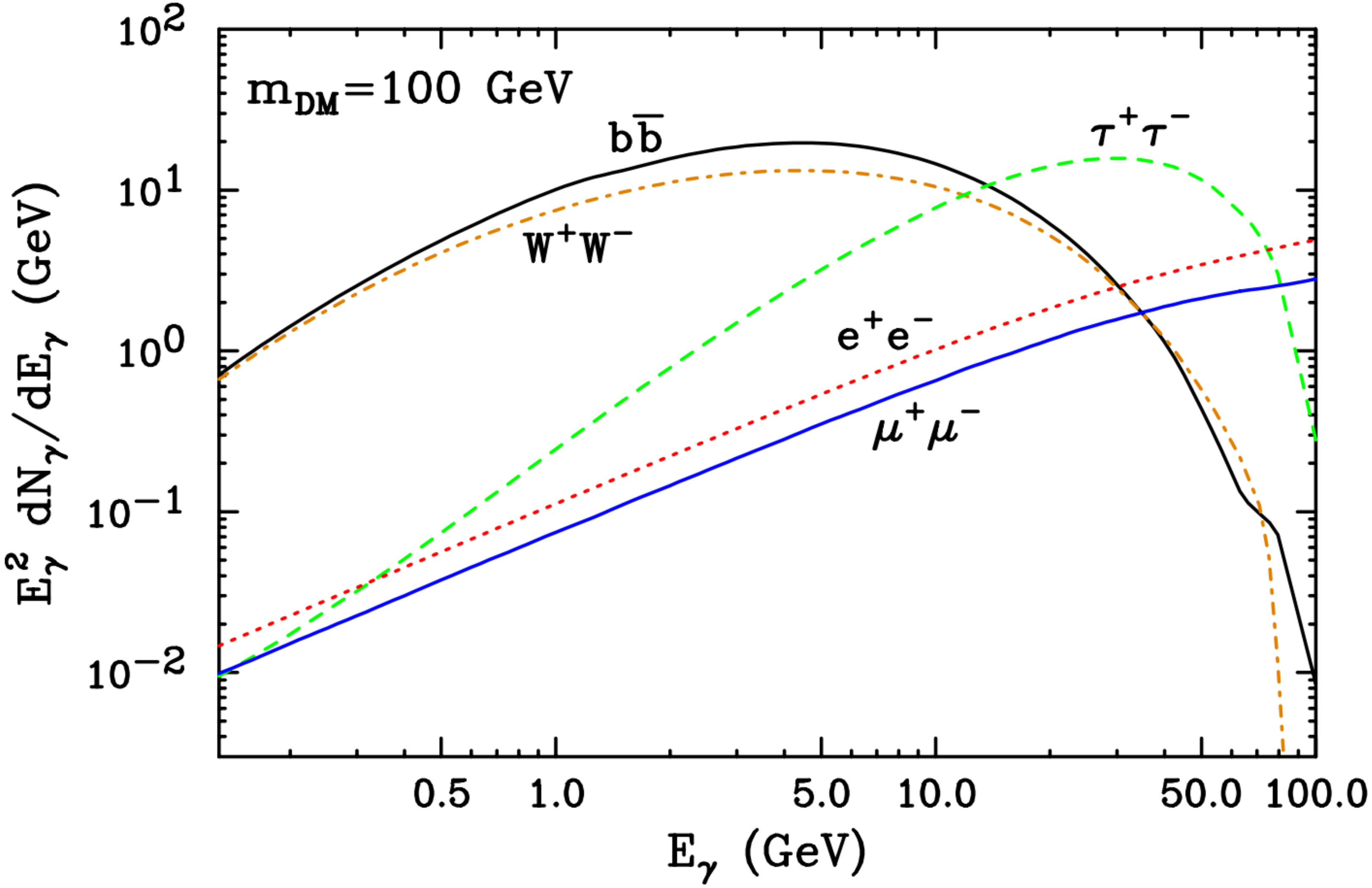
- $\chi\chi \rightarrow e^+e^-$ → detect electrons/positrons or, gamma rays from bremsstrahlung & inverse Compton scattering

Note: $\chi\chi \rightarrow e^+e^-$ necessarily accompanied by $\chi\chi \rightarrow e^+e^-\gamma$ "internal bremsstrahling"



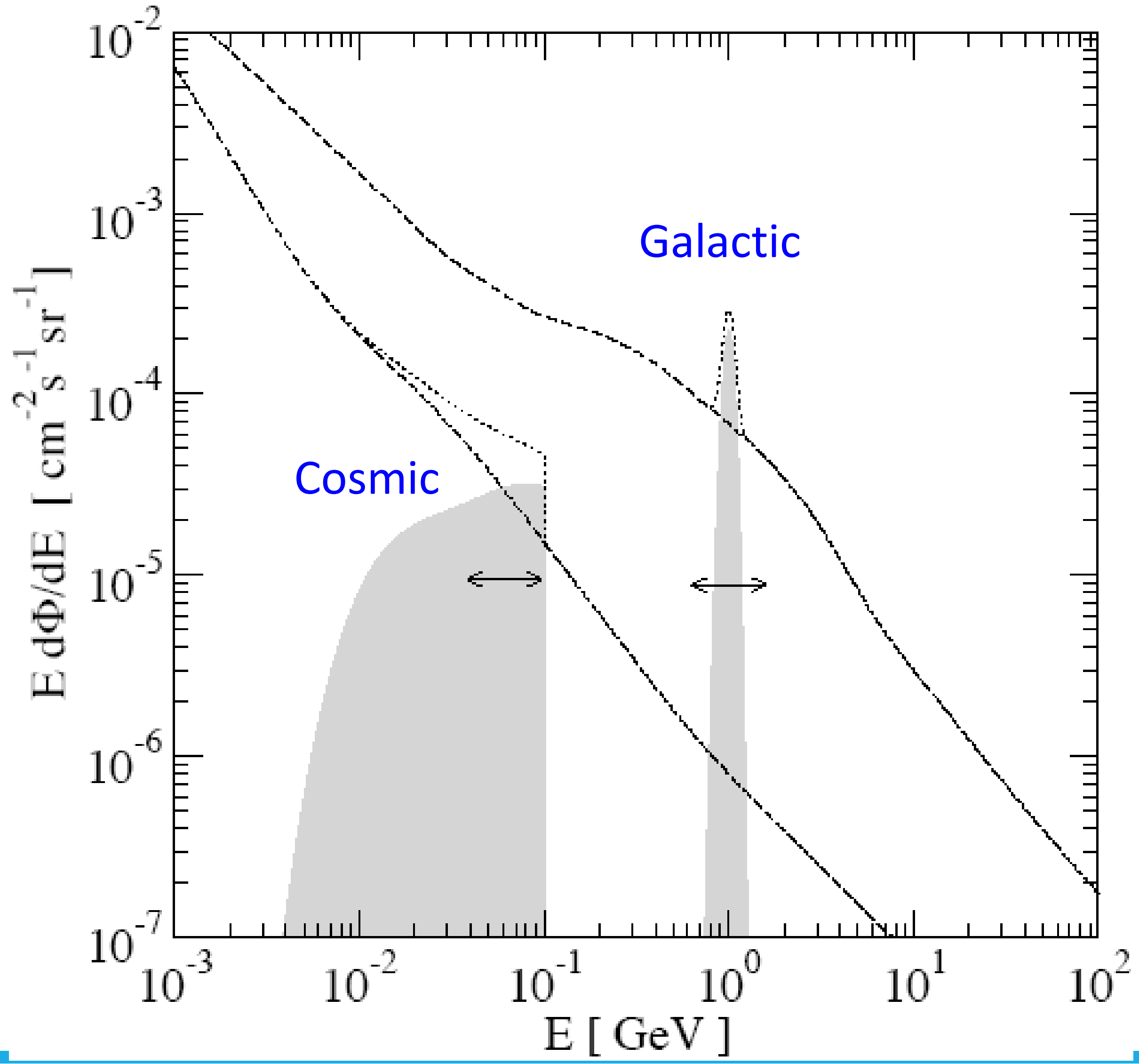
- $\chi\chi \rightarrow \mu^+\mu^-$ → less internal brem than electrons (lighter particles radiate more)
- $\chi\chi \rightarrow \tau^+\tau^-$ → hadronic decays modes produce broad spectrum of photons
- $\chi\chi \rightarrow \bar{b}b$ → hadronic decays modes produce broad spectrum of photons

Annihilation spectra (γ-rays):



Buckley & Hooper
arXiv:1004.1644

Dark matter annihilation to γ-rays - signal & background



Mack, Jacques, Beacom, NFB, Yuksel, arXiv:0803.0157

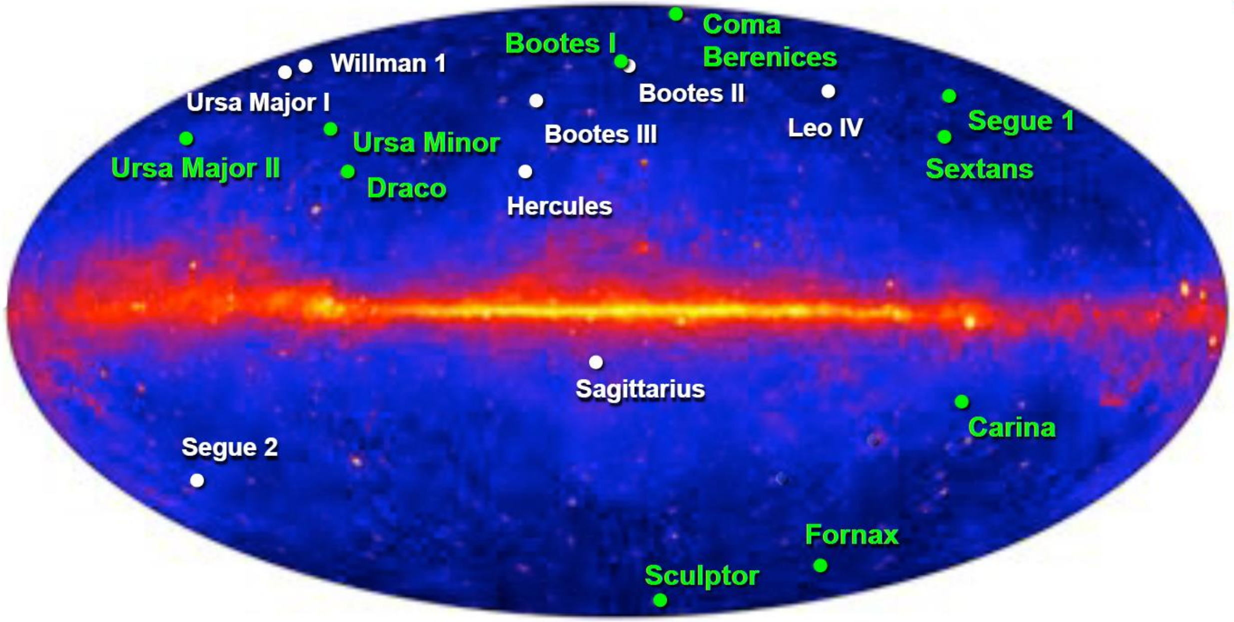
Indirect detection with Milky Way dwarfs

Fermi
Gamma-ray
Space Telescope

Dwarf spheroidal galaxies

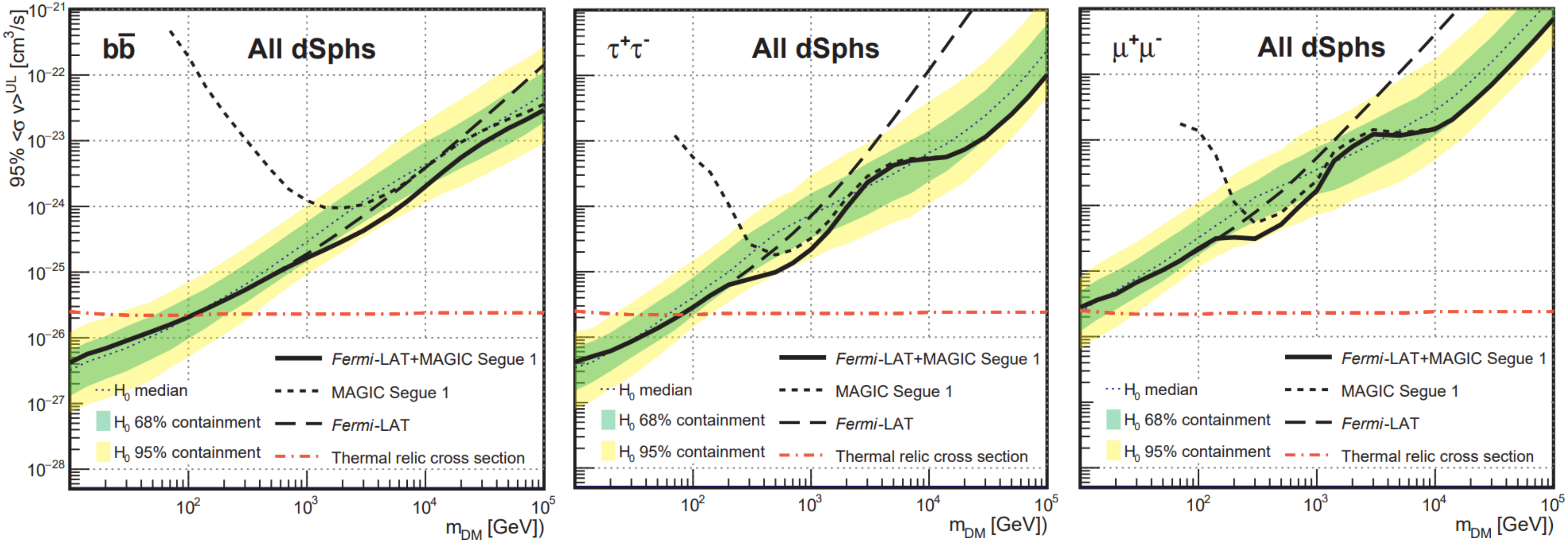
- ✓ dSphs are DM dominated systems (they have very high M/L ratios).
- ✓ Many dSphs are closer than 100 kpc to the Galactic Centre.
- ✓ Low background

Negligible astrophysical backgrounds
→ robust limits



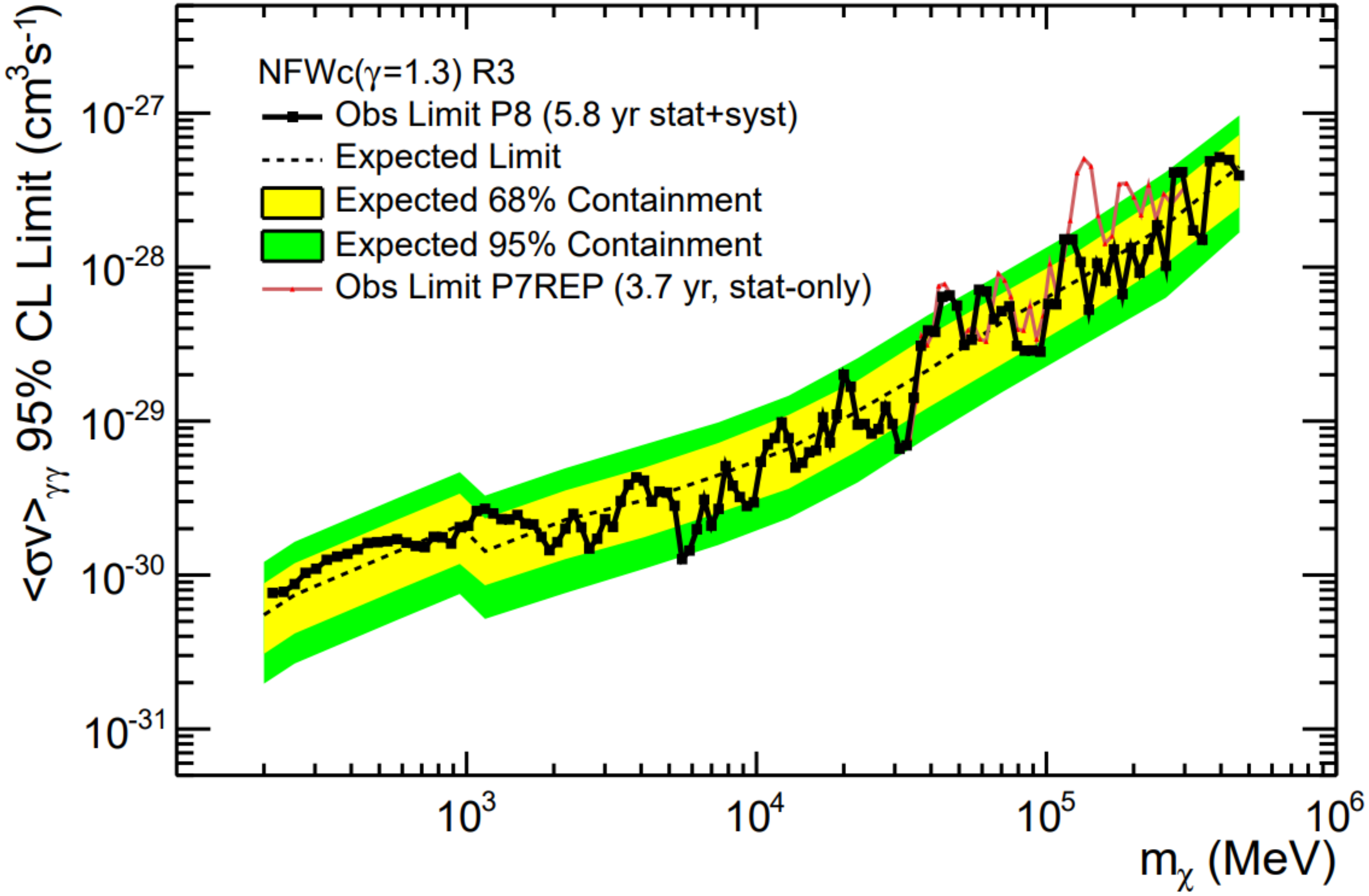
Indirect detection with Milky Way dwarfs

arXiv:1601.06590



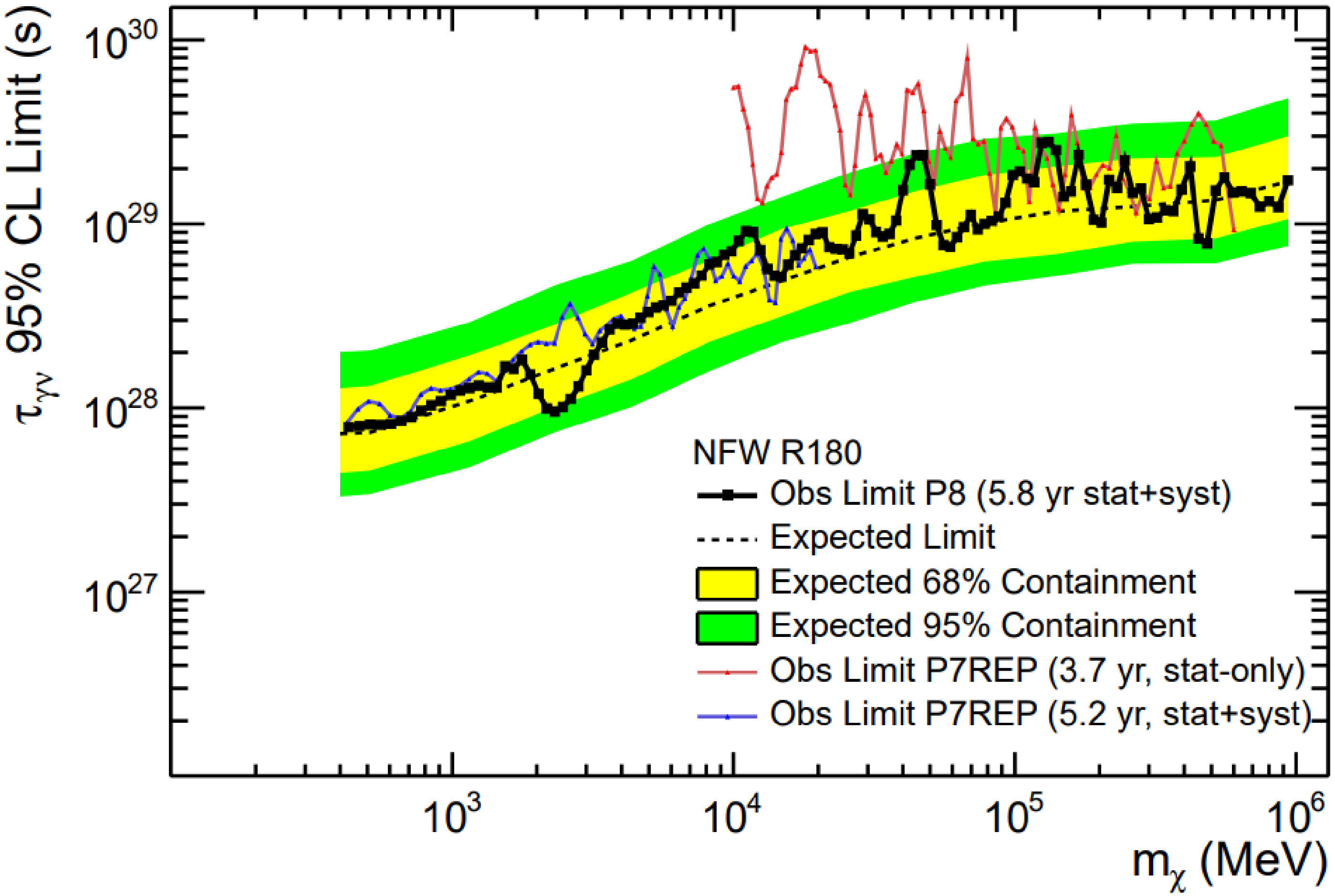
Gamma ray lines – the smoking gun…

Fermi Gamma ray line search from 200 MeV – 500 GeV
No globally significant line signal. arXiv:1506.00013



Note: gamma ray lines should be loop suppressed, thus subdominant to continuum gammas.

Gamma ray lines – DM decay



$\tau \gg$ age of Universe $\sim 10^{17}$ s

CMB limits on DM annihilation

Recombination history of the universe could be modified if DM annihilations inject energy into the photon-baryon plasma.

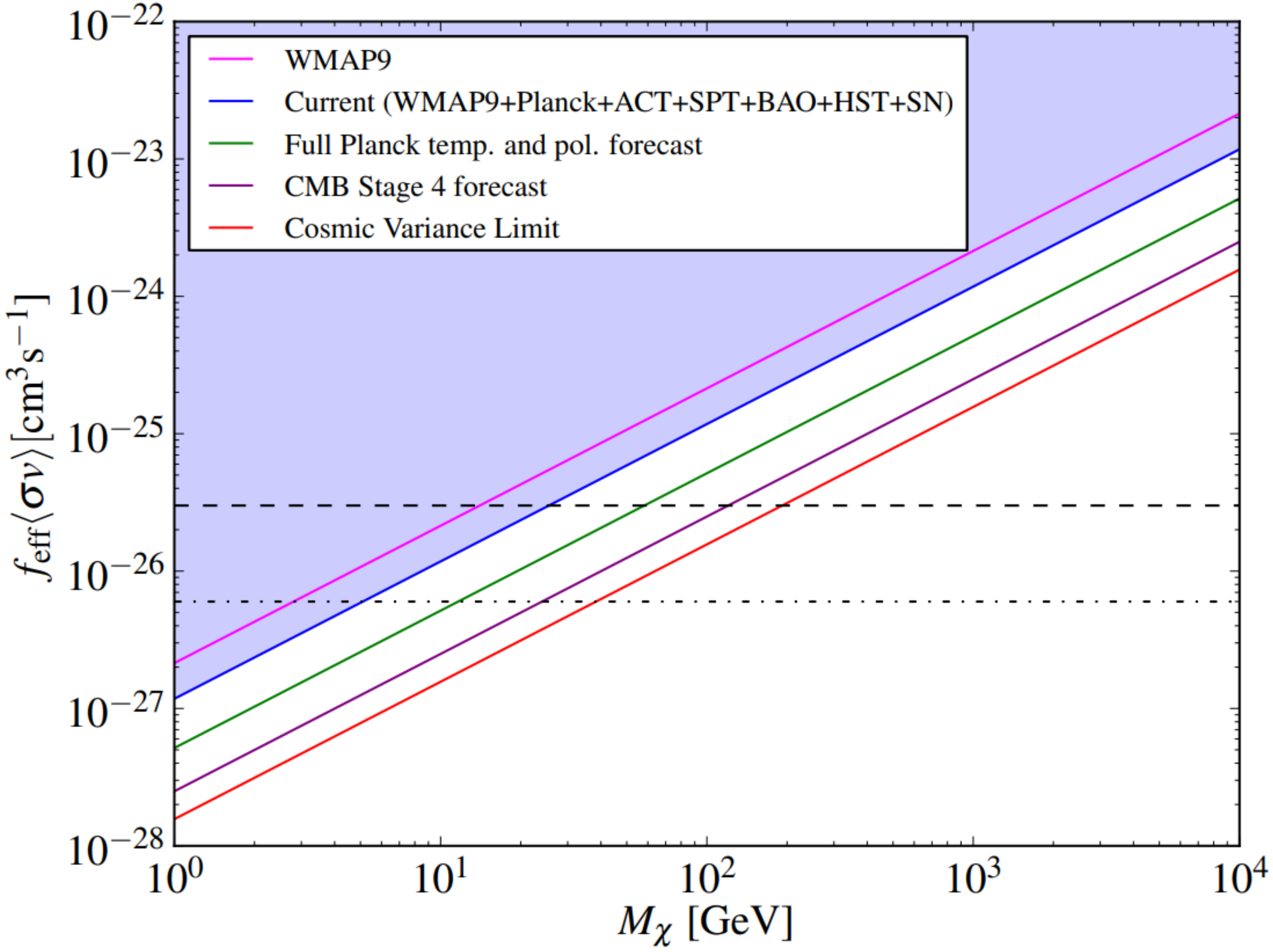
Limits depend on:

- the fraction of the DM energy absorbed by the plasma
  →typical value f=0.2 (larger for annihilation to electrons)

- Velocity dependence of the cross section
  →If p-wave suppressed, annihilation rate is very small

Currently exclude thermal relics with m <5 GeV

CMB limits on DM annihilation



$f_{\rm eff}$ = fraction of energy absorbed by the CMB plasma

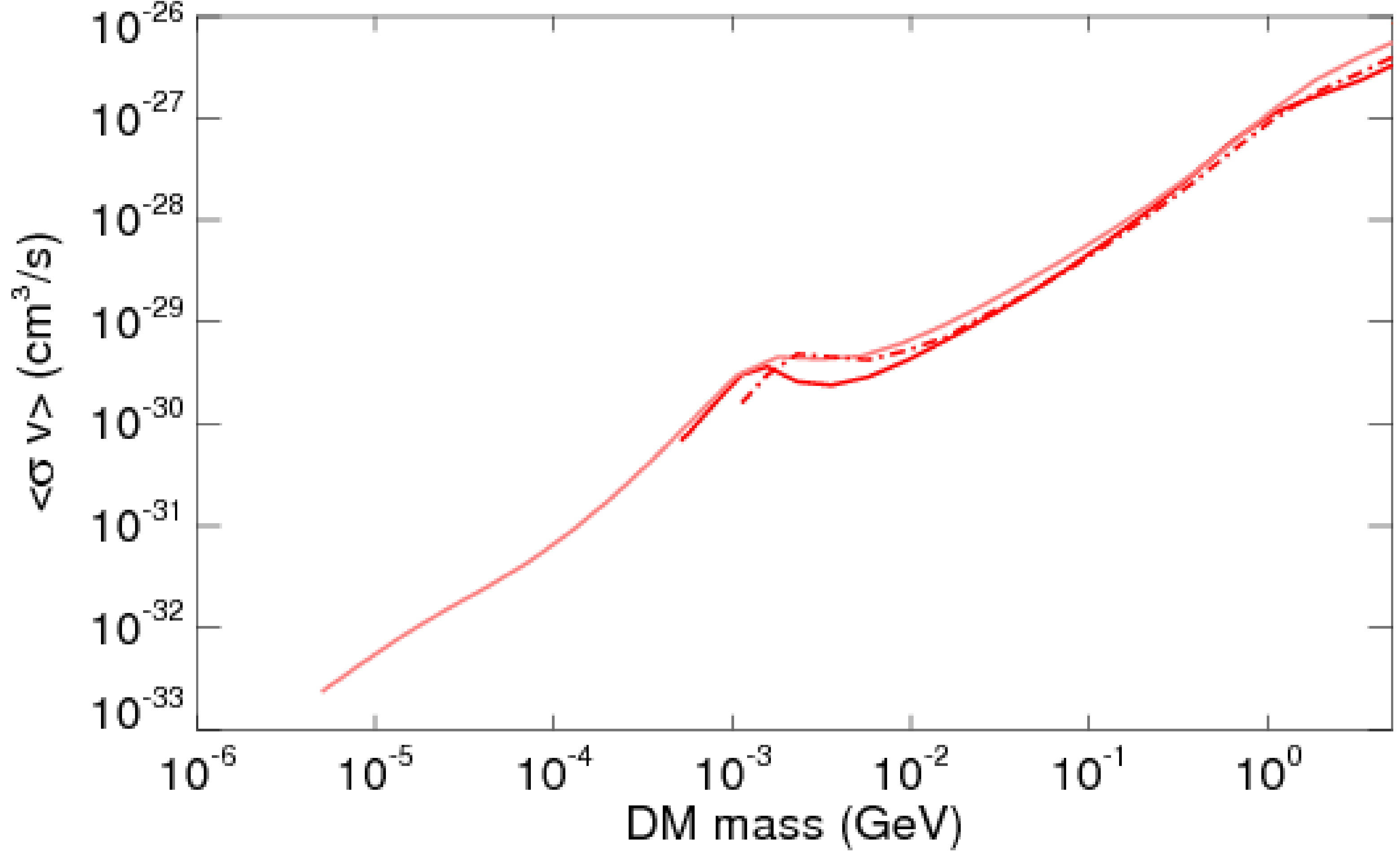
$f_{\rm eff} \sim 0.2$ for most annihilation channels (larger for annihilation to e+e-)

Madhavacheril, Sehgal & Slatyer, arXiv:1310.3815

CMB limits on DM annihilation

Very strong limits on annihilation of light dark matter to electrons or photons

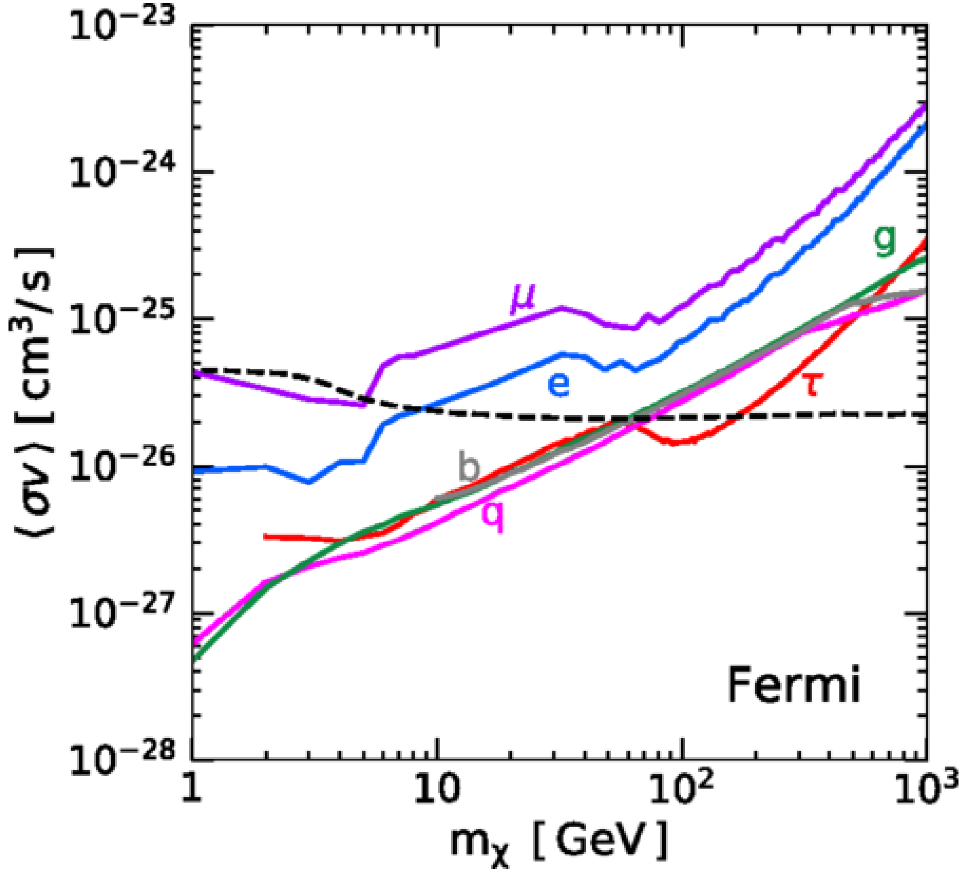
T. Slatyer, arXiv: 1506.03811



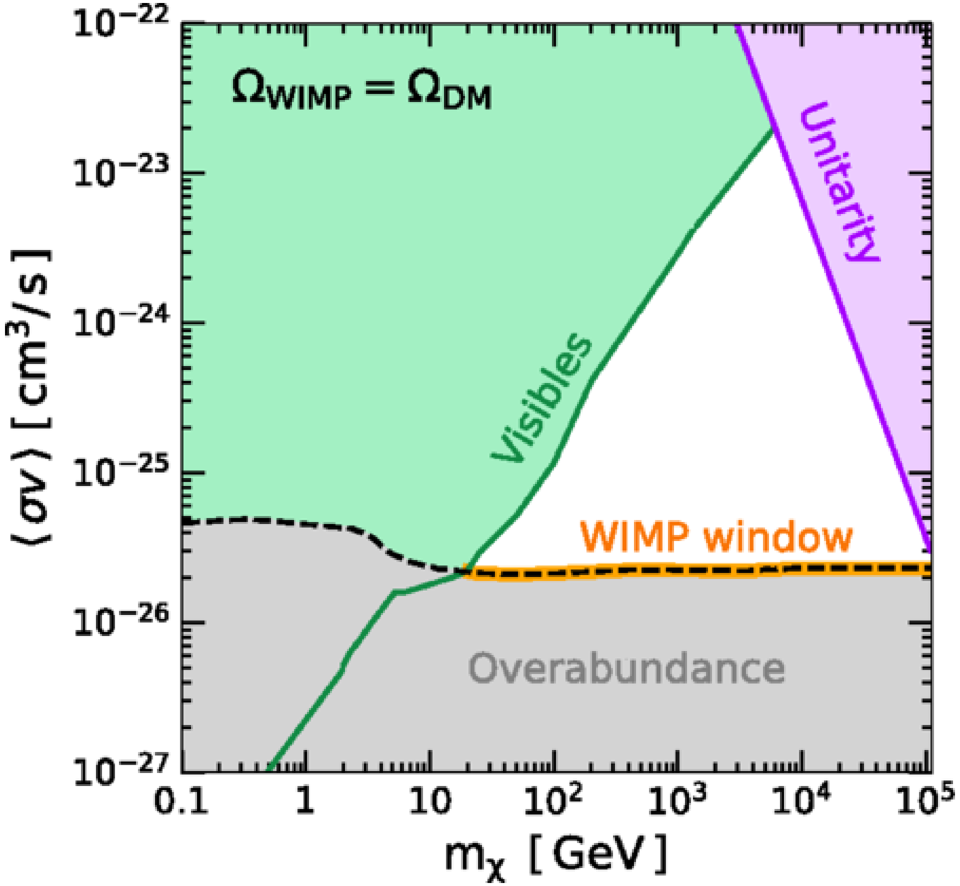
Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

Fermi dSph limits

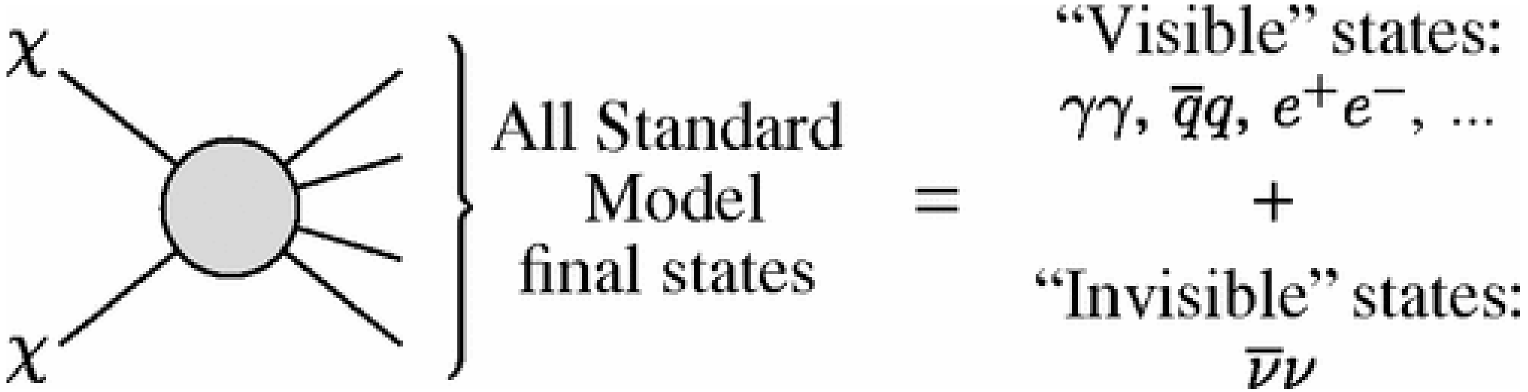


Annihilation to "visible" SM states



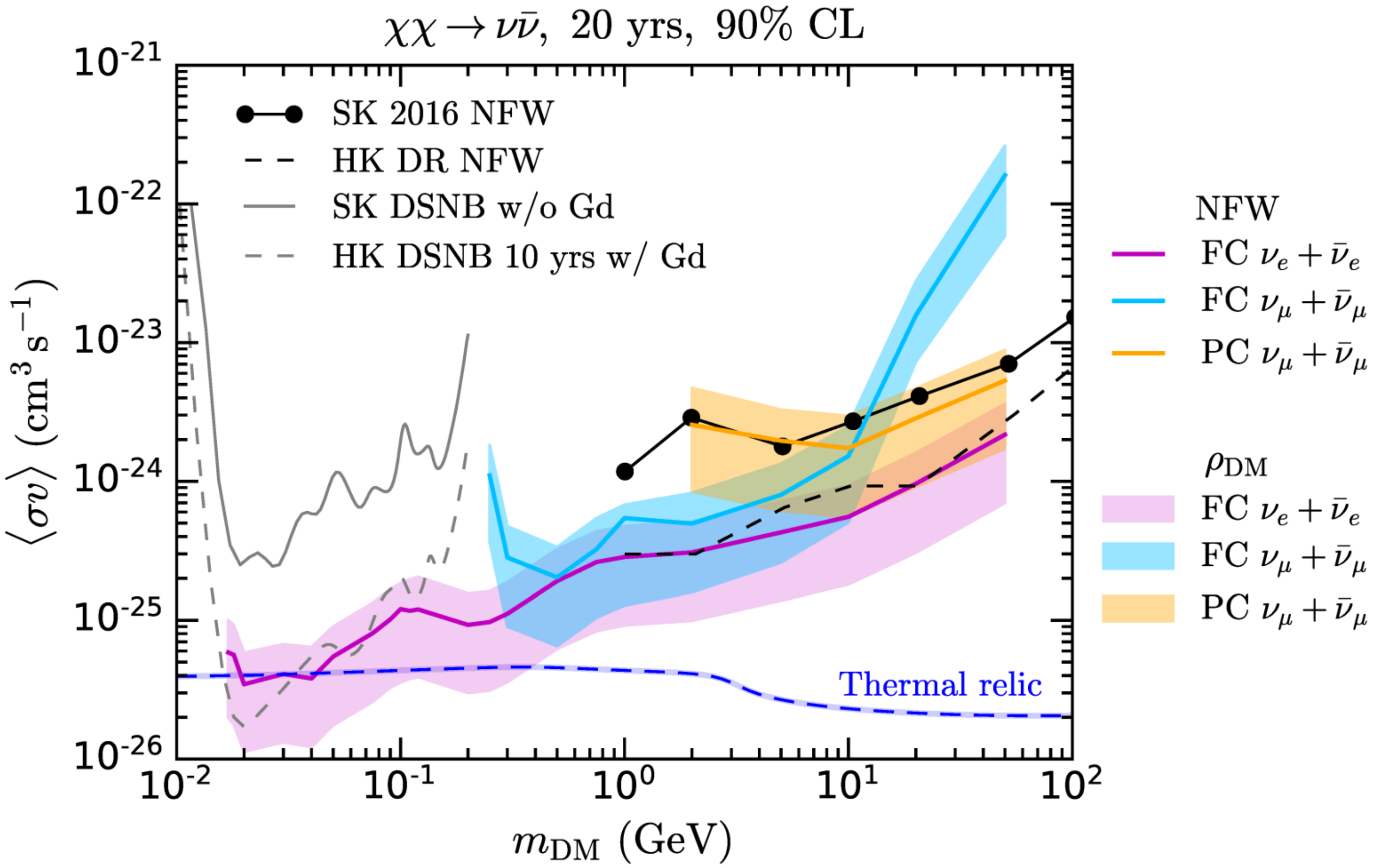
Annihilation to neutrinos

- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to “invisible” or hard-to-detect final states.



- Can DM annihilate to neutrinos without producing charged fermions?
  - Yes, e.g., “neutrino portal” models
- **Annihilation to neutrinos – can we probe thermal-relic cross sections**?

Annihilation cross section limits: $\chi\chi \rightarrow \nu\bar{\nu}$

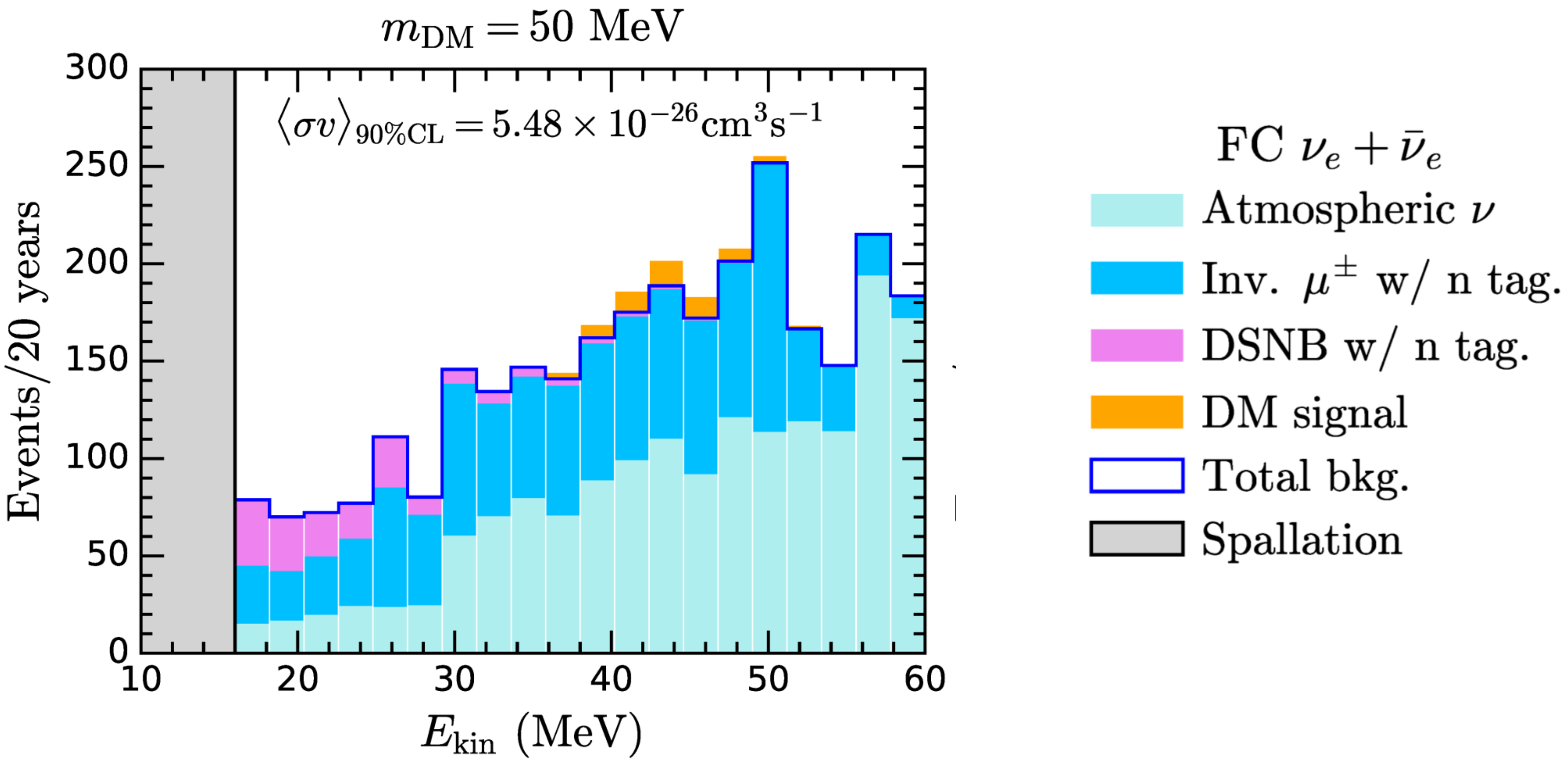


Thermal relic sensitivity for DM mass of ~ 30 MeV

NFW – central lines
Isothermal – upper
Moore - lower

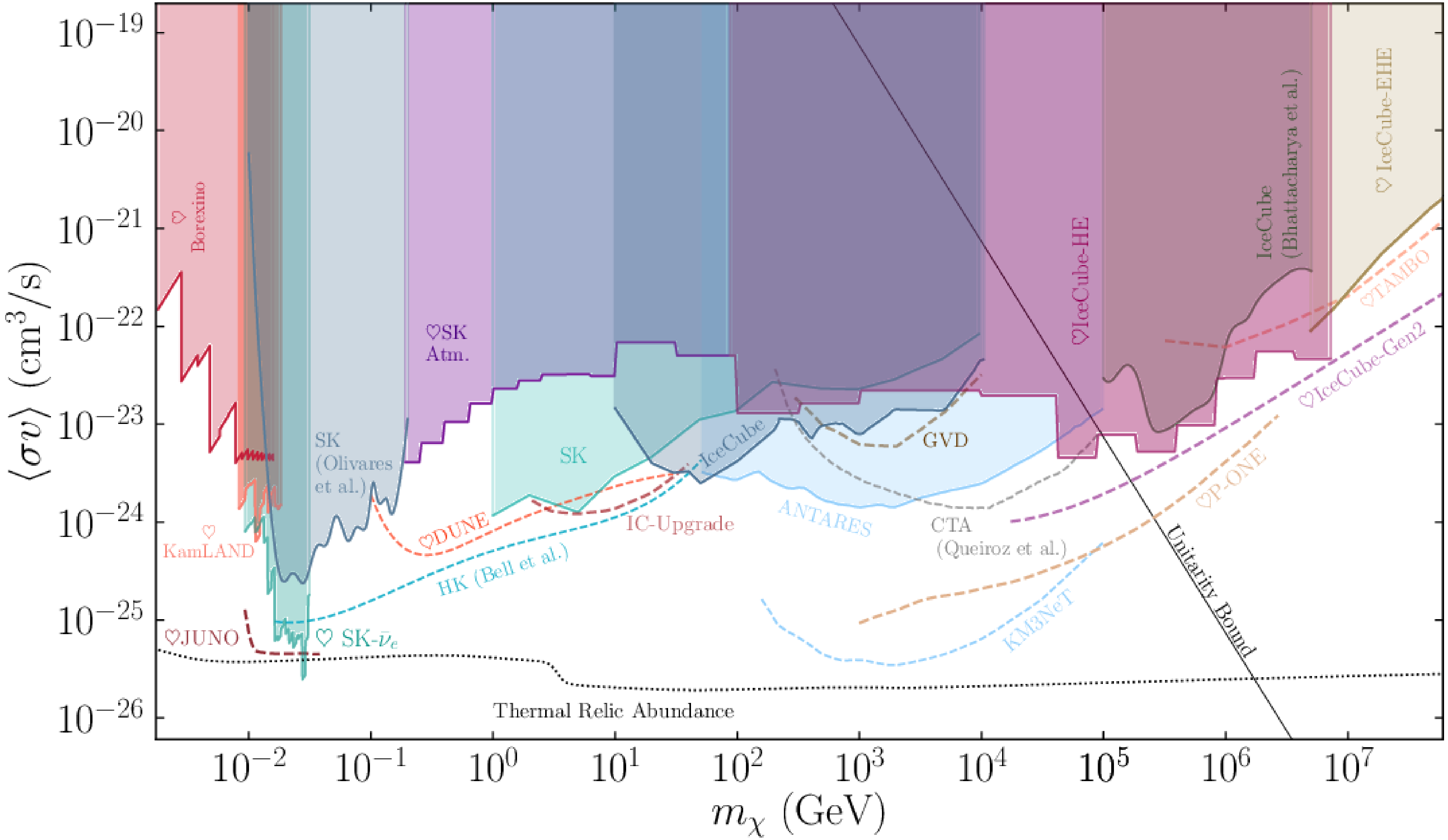
NFB, Dolan, Robles, arXiv: 2005.01950

DM annihilation to neutrinos - signal & backgrounds



NFB, Dolan, Robles, arXiv: 2005.01950

Annihilation cross section limits: $\chi\chi \rightarrow \nu\bar{\nu}$

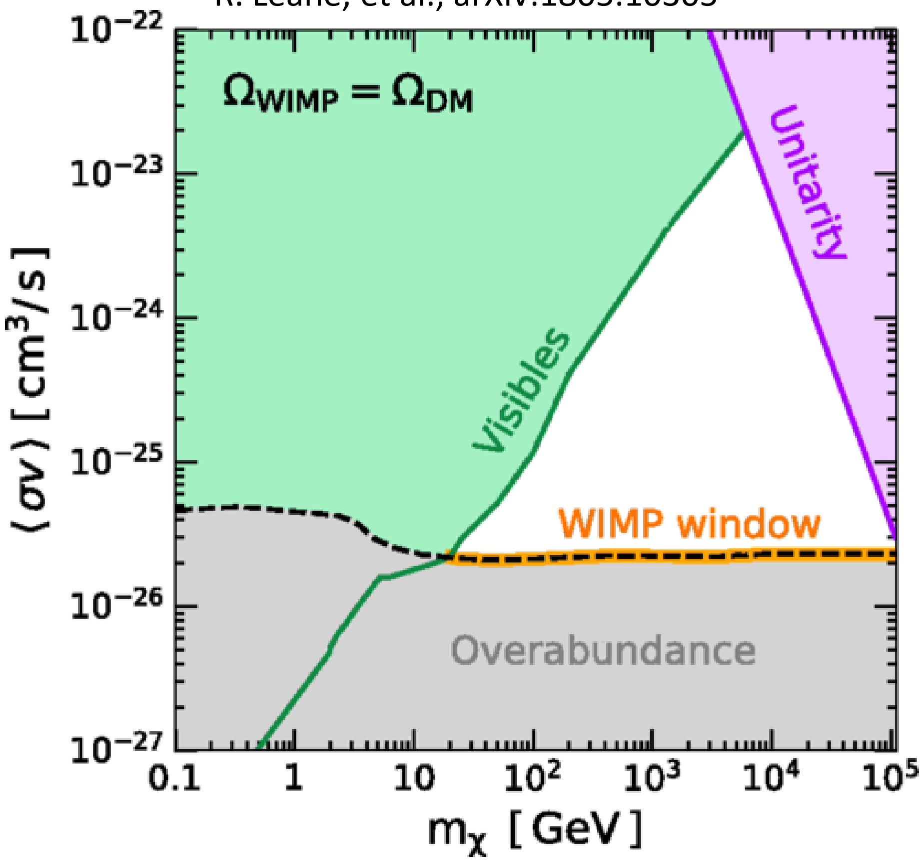


Arguelles
arXiv: 2005.01950

Indirect detection → much of the WIMP window yet to be tested

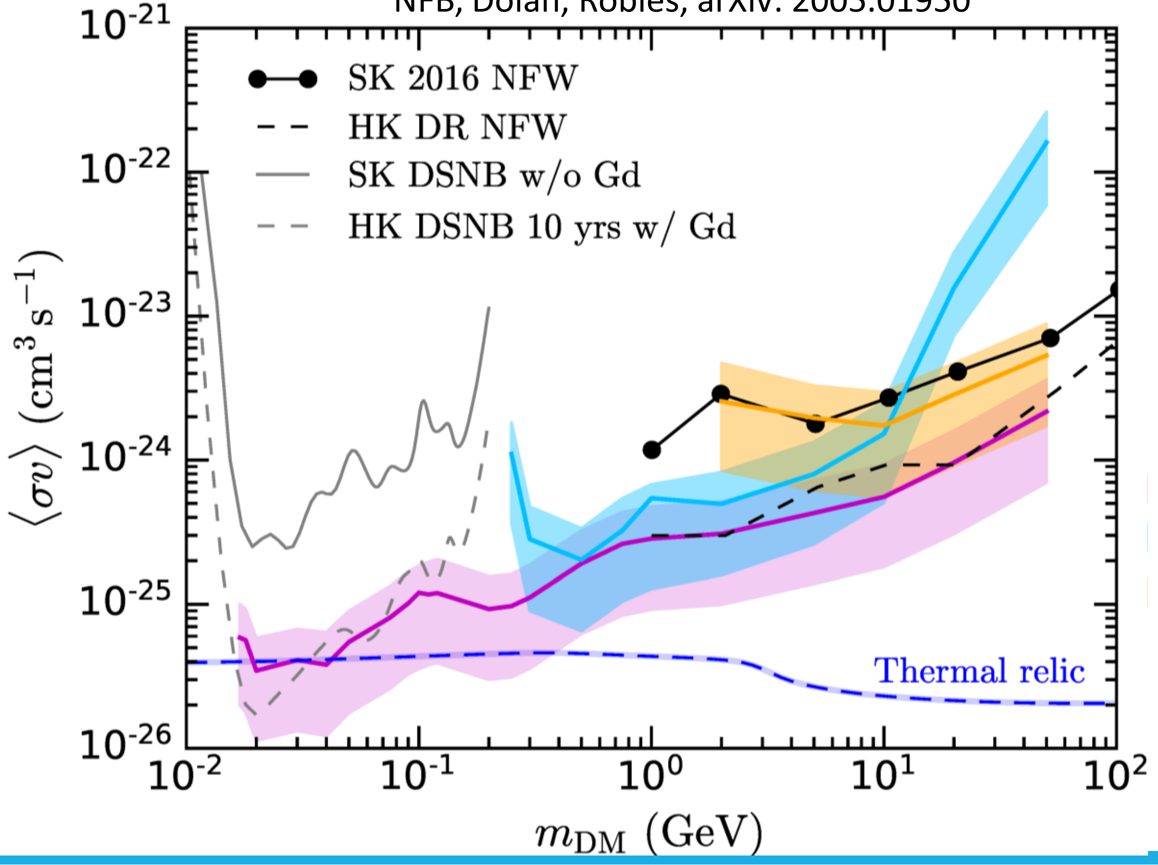
Annihilation to “visible” SM states

R. Leane, et al., arXiv:1805.10305



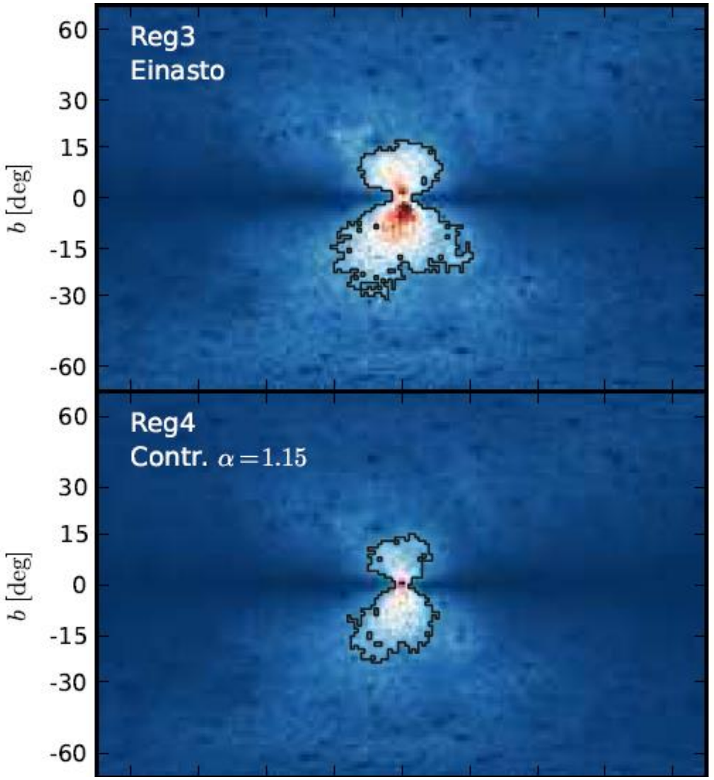
Annihilation to “invisible” SM states

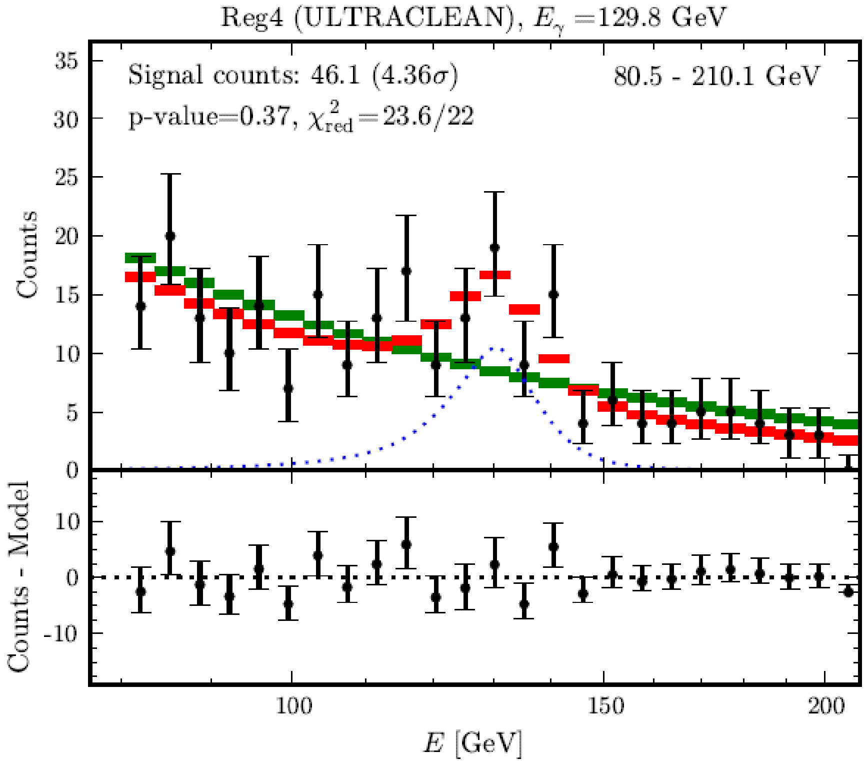
NFB, Dolan, Robles, arXiv: 2005.01950



Claimed indirect detection signals:

Fermi gamma ray line at ~ 130 GeV?





Weniger 1204.2797, and several other groups.

A surprise! Remember, gamma ray lines are loop suppressed.

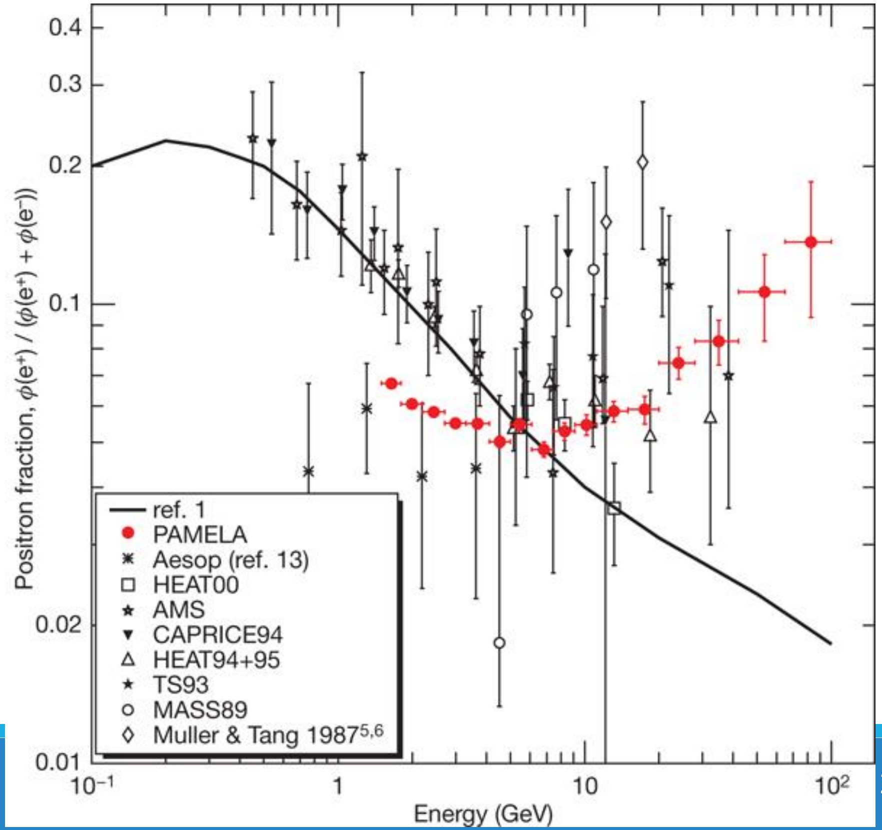
Official Fermi-LAT analysis with more data found a lower significance.

Claimed indirect detection signals: *Positrons*

DM annihilation signal? Or maybe pulsars?

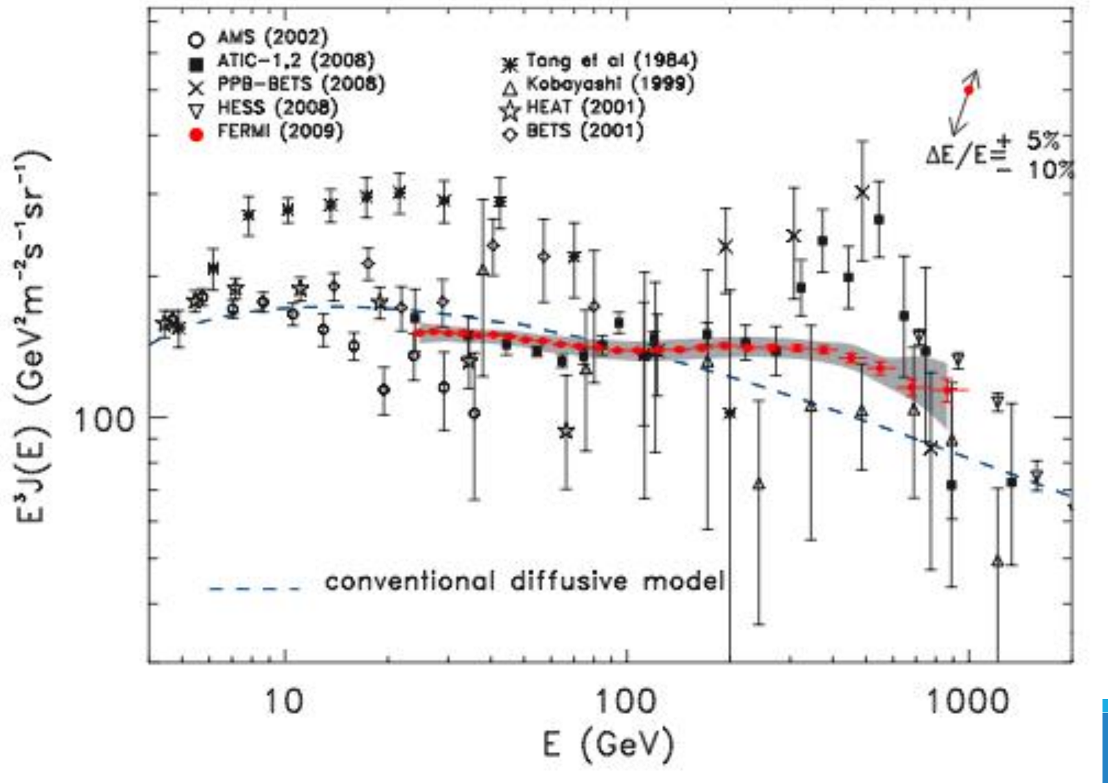
PAMELA e+ excess

Nature 458, 607-609



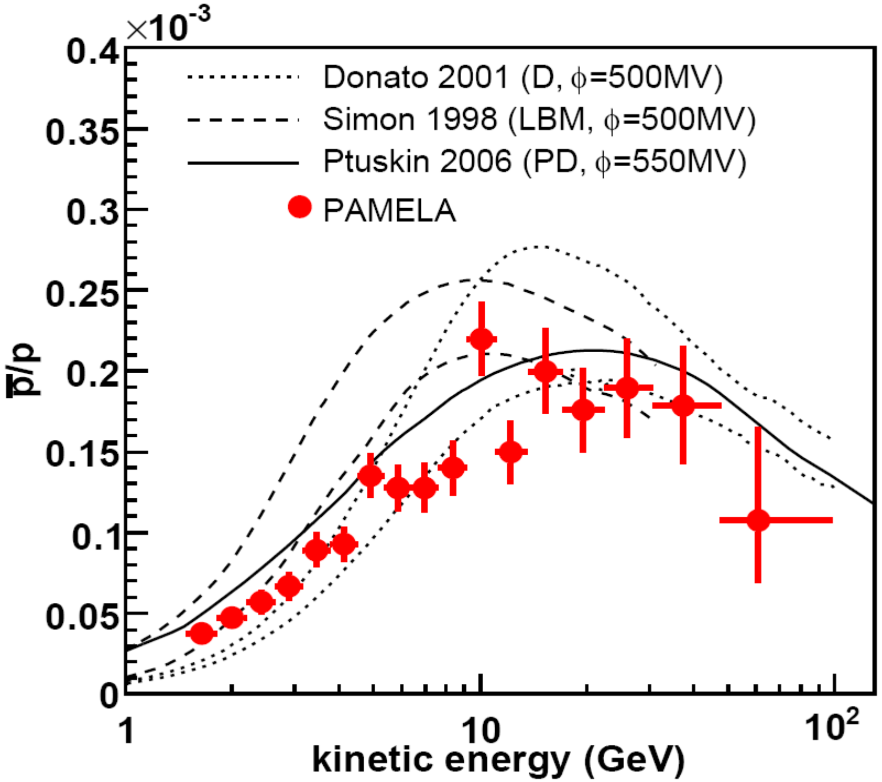
Fermi e^{+}+e^{-} excess

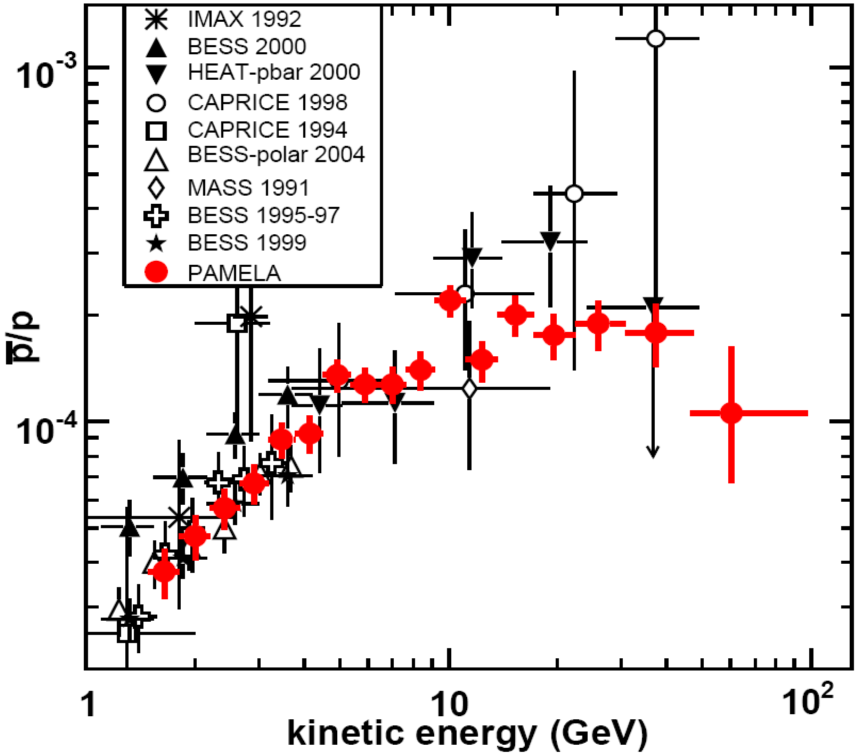
Phys. Rev. Lett. 102, 181101 (2009)



Antiprotons

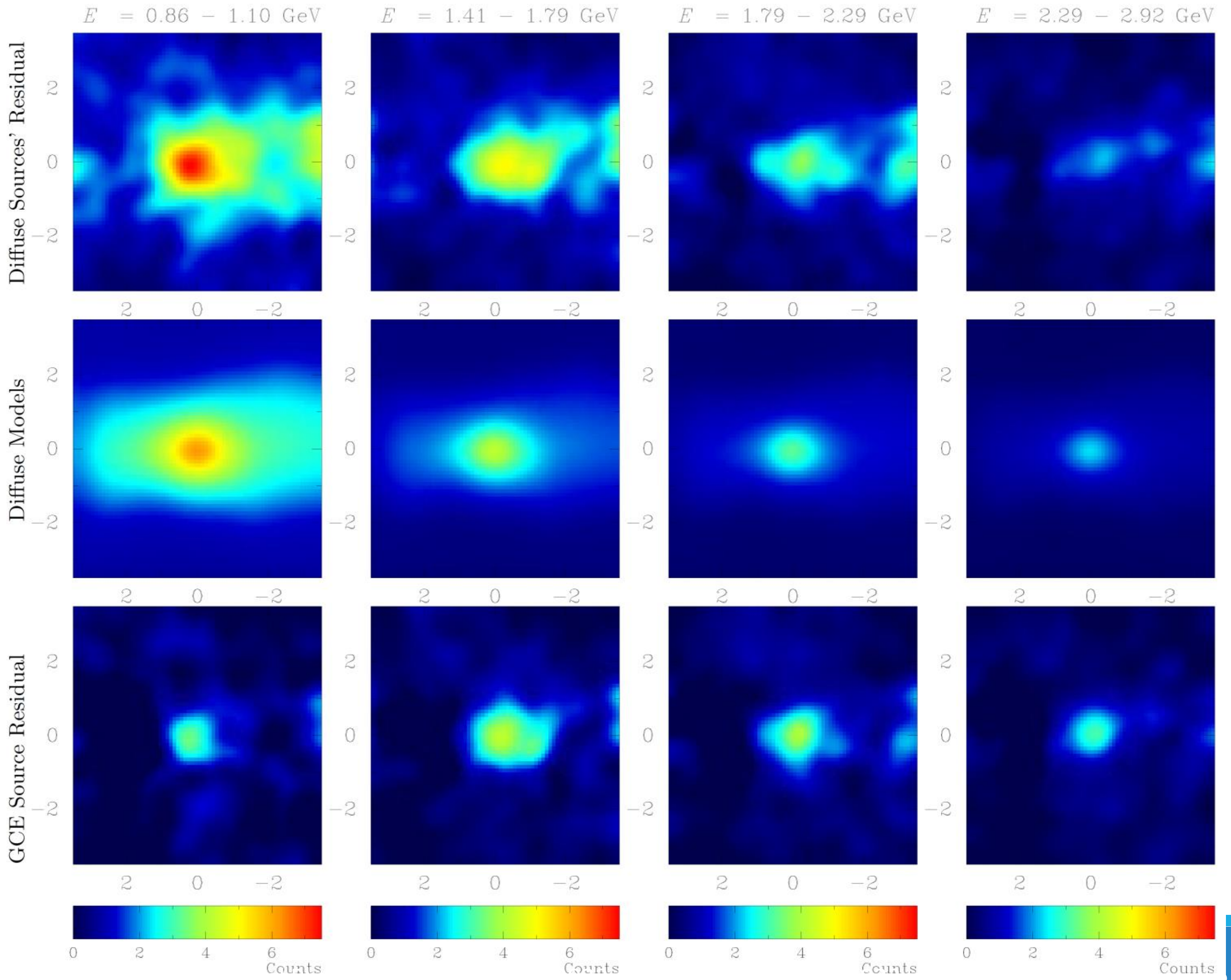
(In principle, annihilation to antiparticles is a good indirect detection channel, given the low antimatter abundance in local universe.)





Antiproton data consistent with theory expectation (for secondary production of antiprotons via cosmic ray propagation in the Galaxy).

Claimed indirect detection signal: *Galactic Centre Excess*



Abazajian et al, arXiv:1402.4090

Galactic Centre Excess

Extended source of 1-3 GeV gamma ray emission within ~ 1.5kpc of the Galactic Centre, seen in Fermi-LAT data.
Spatial distribution consistent with DM distribution

Can be fit by annihilation to (for example):

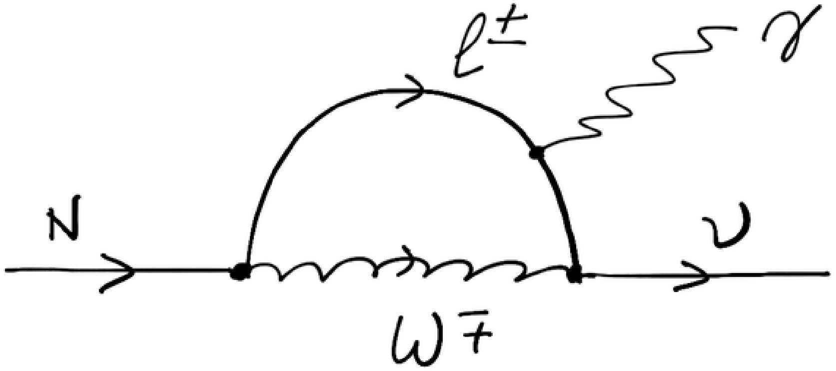
- bbar with 40 GeV DM mass
- tau+tau- with 10 GeV DM mass

with a cross section roughly consistent with a thermal relic.

BUT, unresolved point sources (e.g. millisecond pulsars) can mimic this signal.

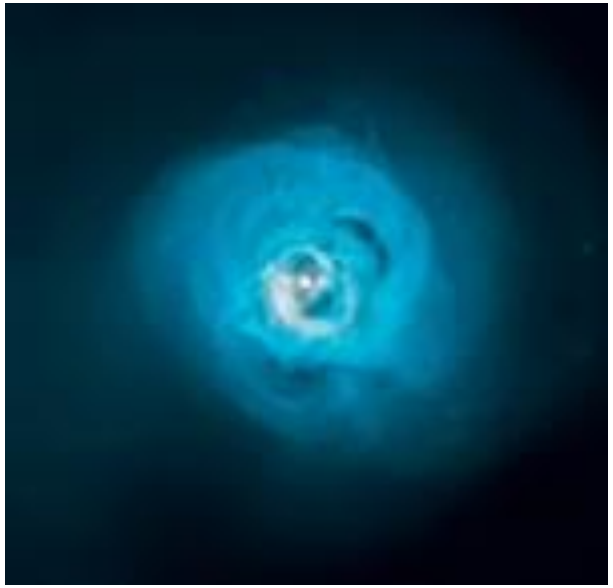
Sterile neutrino dark matter

- “Sterile” (right handed) neutrinos are a viable DM candidate.
- Produced in early universe via active-sterile oscillations
- Pauli exclusion principle prevents arbitrary high number density
  → dense galaxies set lower limit on mass (Tremaine–Gunn bound)
- Heavy neutrinos can decay radiatively via a loop diagram, to produce a photon line:



$$\Gamma_\gamma(m_s,\theta) = 1.38\times 10^{-29}\ \mathrm{s}^{-1}\ \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

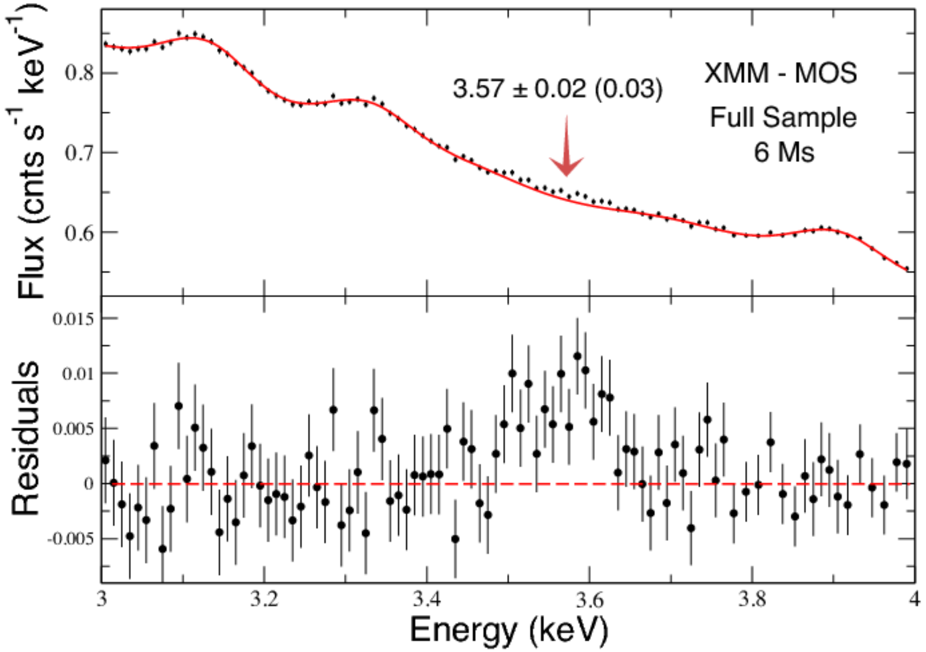
3.5 keV Xray line - decay of sterile neutrino DM?



Excess of 3.5 keV Xrays seen in Perseus, Andromeda and other nearby clusters (*Caution* many nearby atomic transition lines…)

E = 3.57 keV $\Rightarrow$ m = 7 eV

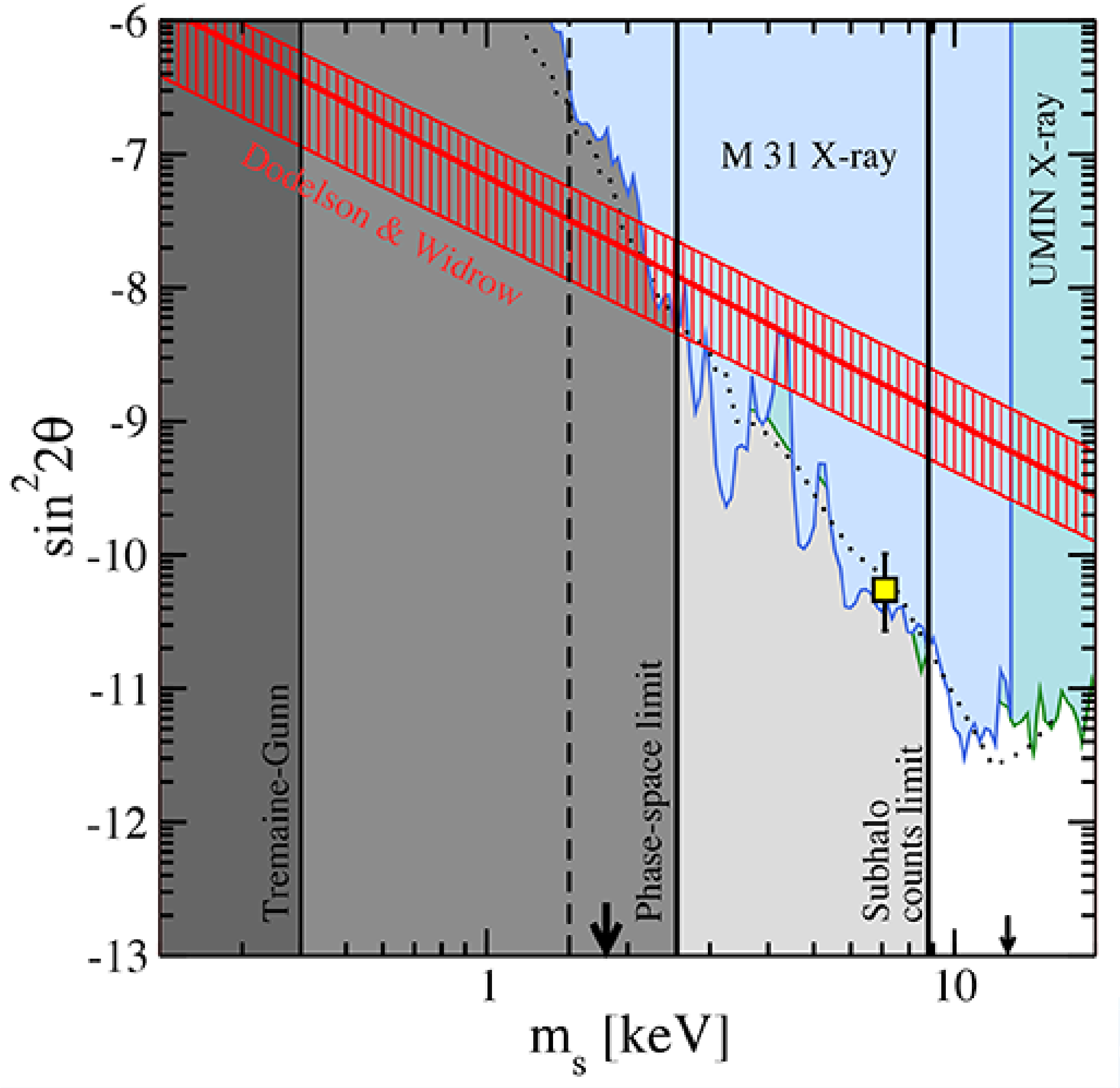
Bulbul et al 1402.2301, ApJ



However, no signal seen in Milky Way.

Note 7 keV dark matter would be "warm"
→ impact on small scale structure.

Sterile neutrino dark matter parameter space



Horiuchi et al, 1311.0282

Dark Matter Lecture #3

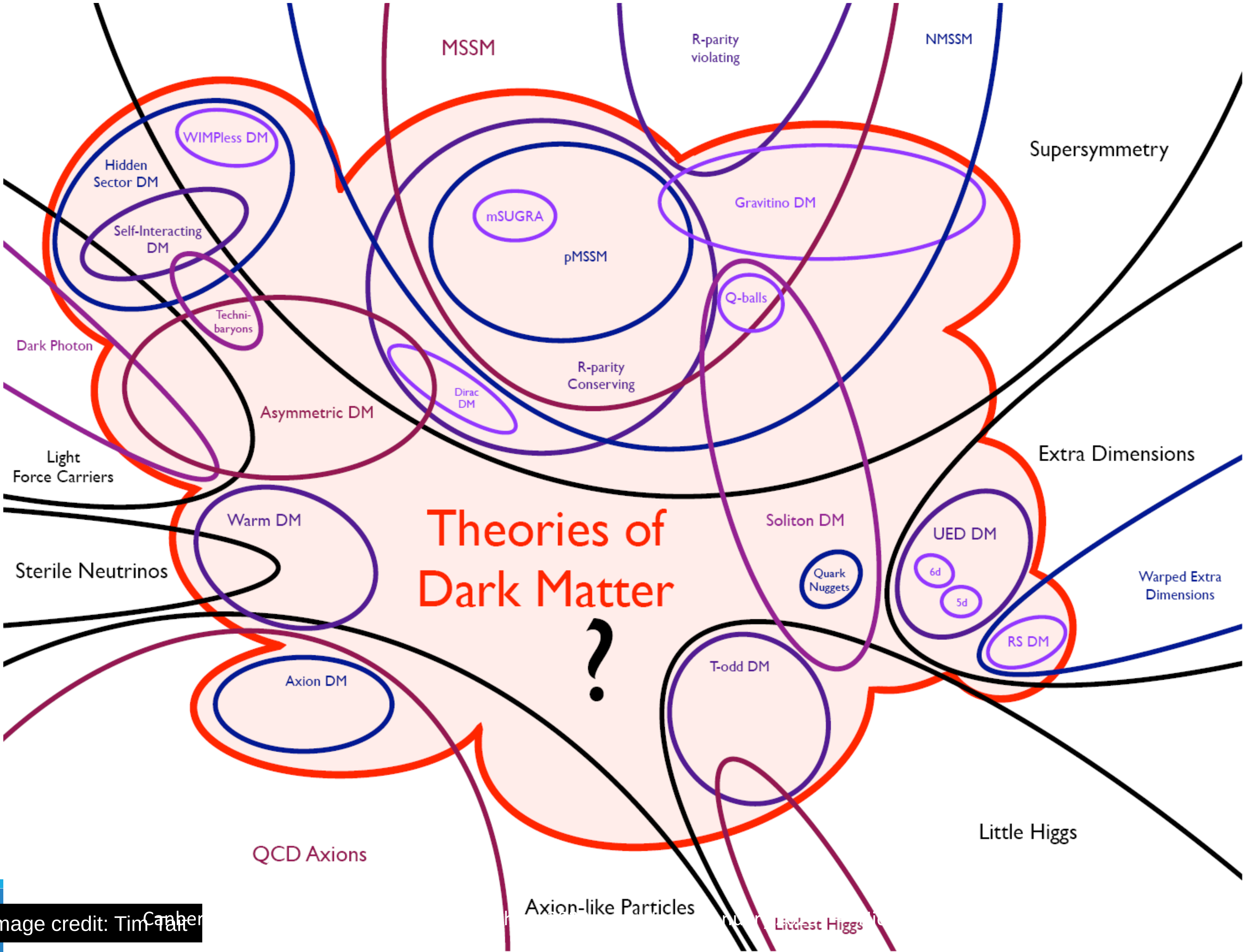


Image credit: Tim Tait

Asymmetric dark matter

The density of ordinary matter and dark matter are similar: $\boldsymbol{\Omega_{dark} \simeq 5\Omega_{baryon}}$
Is the same physics responsible for both?

- Ω_{baryon} is determined by the size of the matter-antimatter asymmetry;

$$\eta = \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

- Suppose there were a DM-antiDM asymmetry of similar size.

→Then we need $\mathrm{m}_{dark} \simeq 5\mathrm{m}_{proton} \simeq 5\ \mathrm{GeV}$ (→ a "dark QCD"??)

- (Have replaced the question of "why similar density?" with "why similar mass?")

Asymmetric dark matter

Requirements:

- Mechanism to simultaneously create B(visible) and B(dark) asymmetries, or create an asymmetry in one sector and communicate it to the other.
- Sufficiently large DM annihilation cross section to annihilate the symmetric part (to leave only particles and no antiparticles).

Implications:

- Light DM.
- Suppressed indirect detection (nothing to annihilate with)
- The physics that connects the dark and visible sectors may or may not be at an experimentally accessible energy scale.
- Large annihilation cross section means either sizeable couplings with SM particles, or else new light (dark) degrees of freedom.

Define: B_V = baryon number
B_D = dark baryon number

Asymmetric dark matter realized by :

- breaking B in one sector, creating an asymmetry (requires the Sakharov conditions to be fulfilled), communicating the asymmetry to the other sector.

or

- Breaking some linear combination of B_V and B_D:

$$B_{broken} = B_V - B_D$$
$$B_{conserved} = B_V + B_D$$

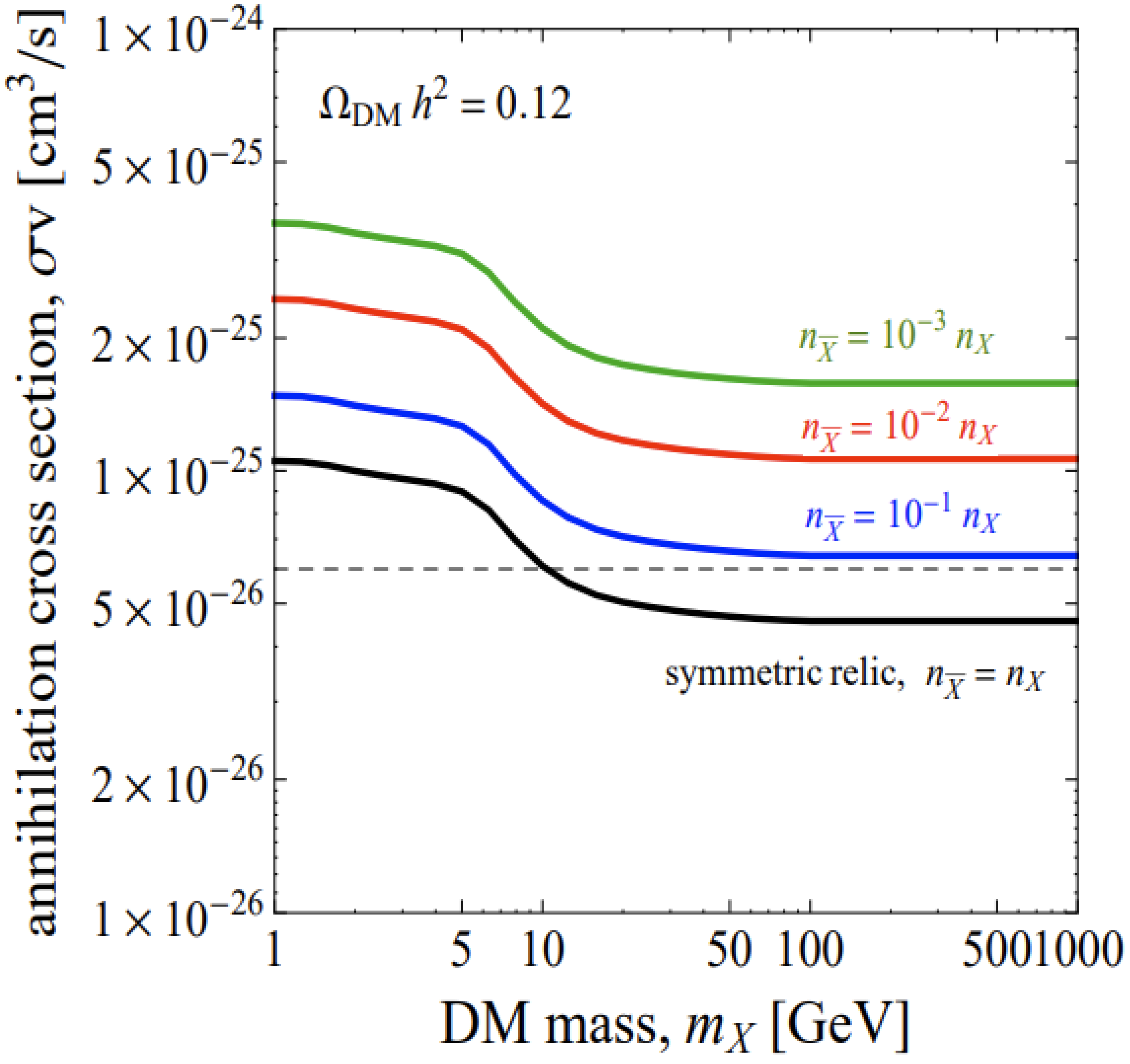
→ creation of equal and opposite asymmetries in the dark and visible sectors.
Perhaps the most elegant version of this scenario.

In the visible sector, all the baryons annihilate with all the antibaryons, leaving only the small asymmetric component.

Similarly, asymmetric dark matter require a sufficiently big dark matter annihilation cross sector to annihilate away the symmetric component, leaving the small asymmetry.

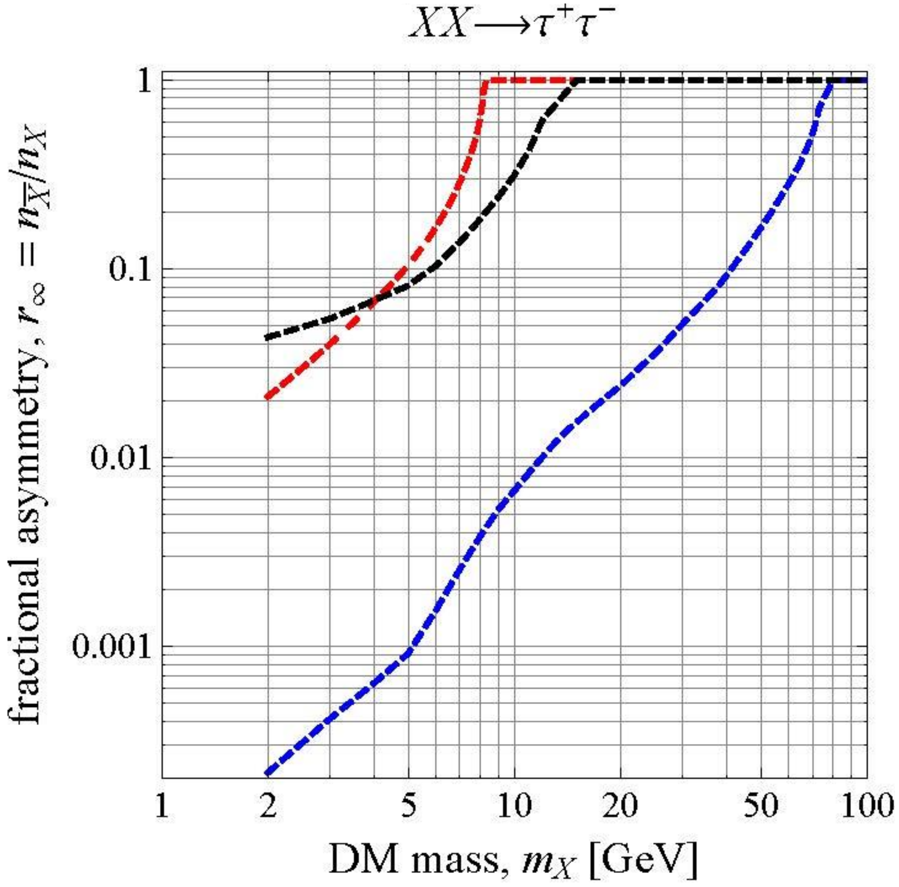
→ Need an annihilation cross section larger than those for standard WIMPs

→ Hence large interaction rates → detection prospects.

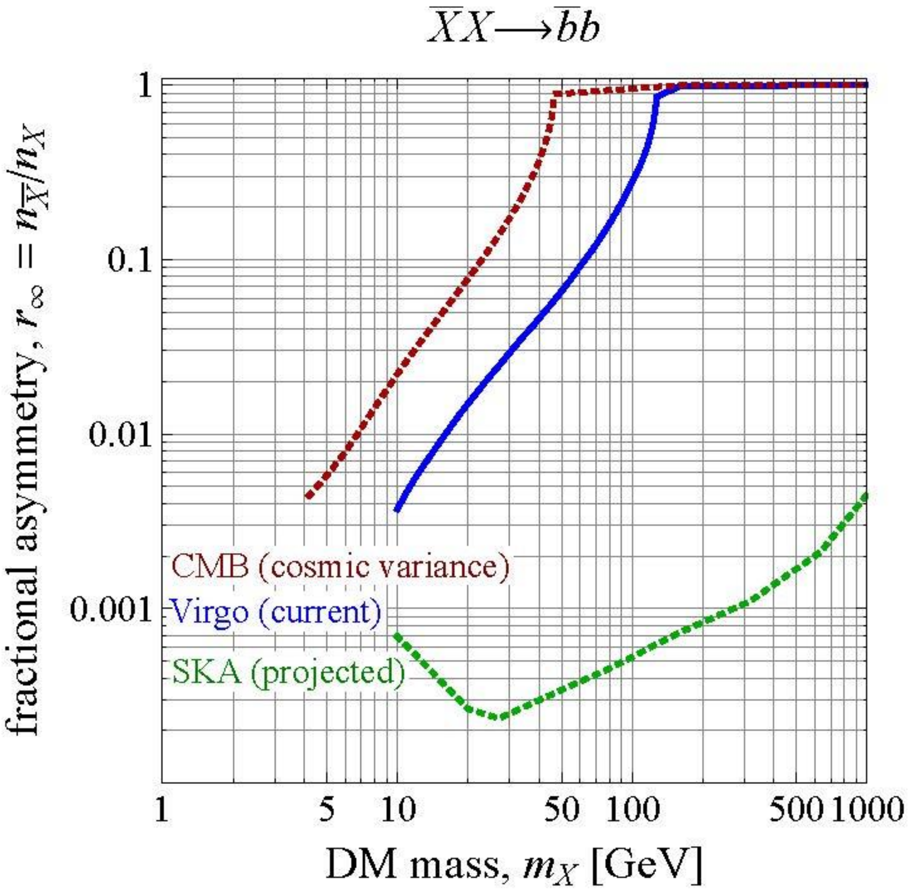


ADM – indirect detection limits

Current limits,

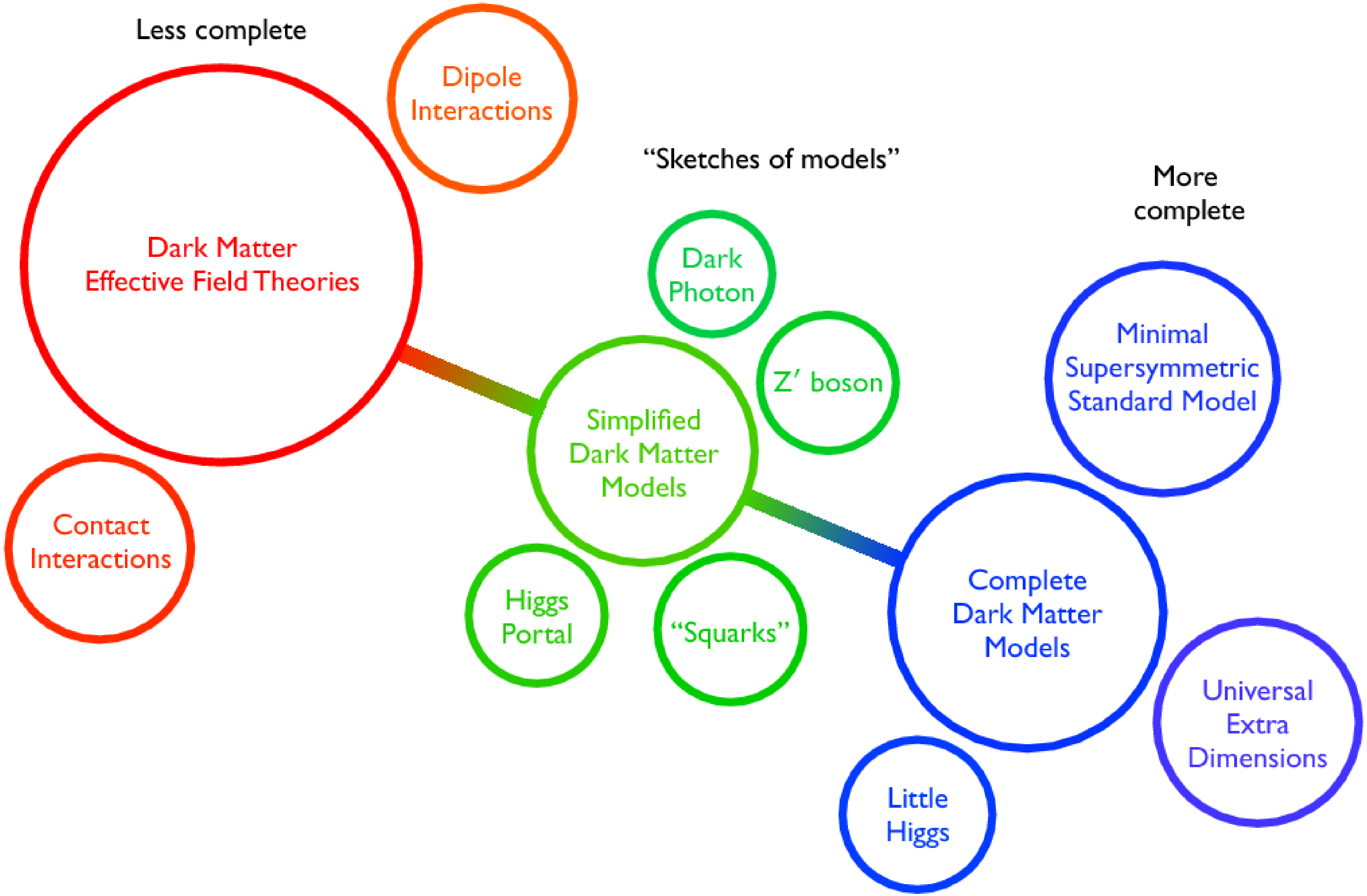


Future limits

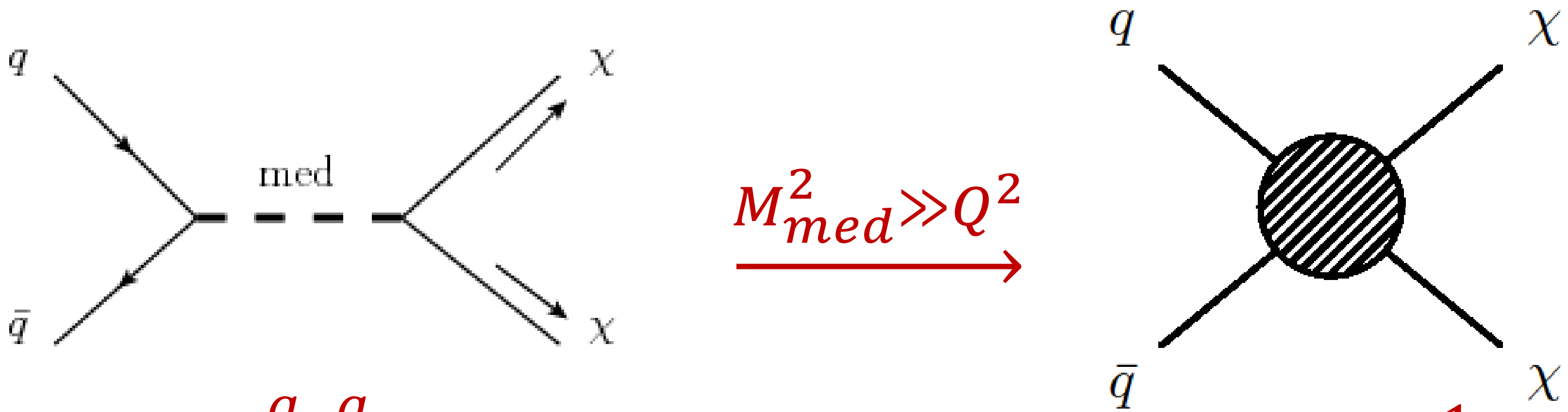


NFB, Horiuchi & Shoemaker, arXiv:1408.5142

Dark matter models



Effective Field Theory (EFT) operators



$$\xrightarrow{M_{med}^2 \gg Q^2}$$

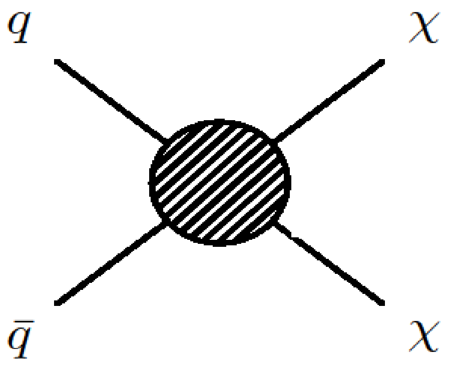
$$\frac{g_\chi g_q}{Q^2 - M_{med}^2}$$

$$\frac{g_\chi g_q}{M_{med}^2} = -\frac{1}{\Lambda^2}$$

So we have a contact interaction: $\mathrm{L}_{\mathrm{EFT}} = \frac{1}{\Lambda_{\mathrm{eff}}^2}\, \bar{q} q \bar{\chi} \chi$

Advantages:	- simple, model-independent description
Disadvantages:	- breaks down if Q^2 is large or mediator is light; - a given UV-complete model might lead to multiple EFT operators

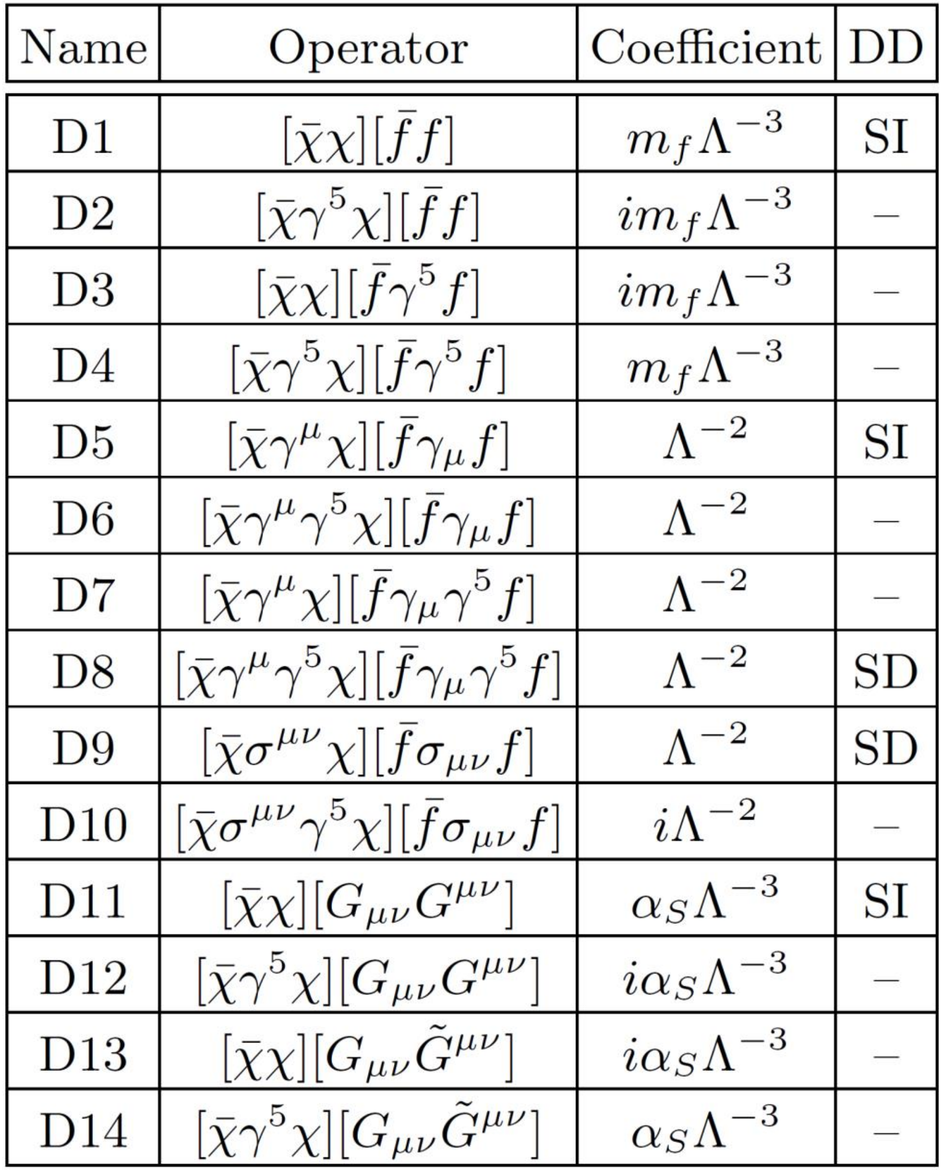
Effective operators for fermionic dark matter



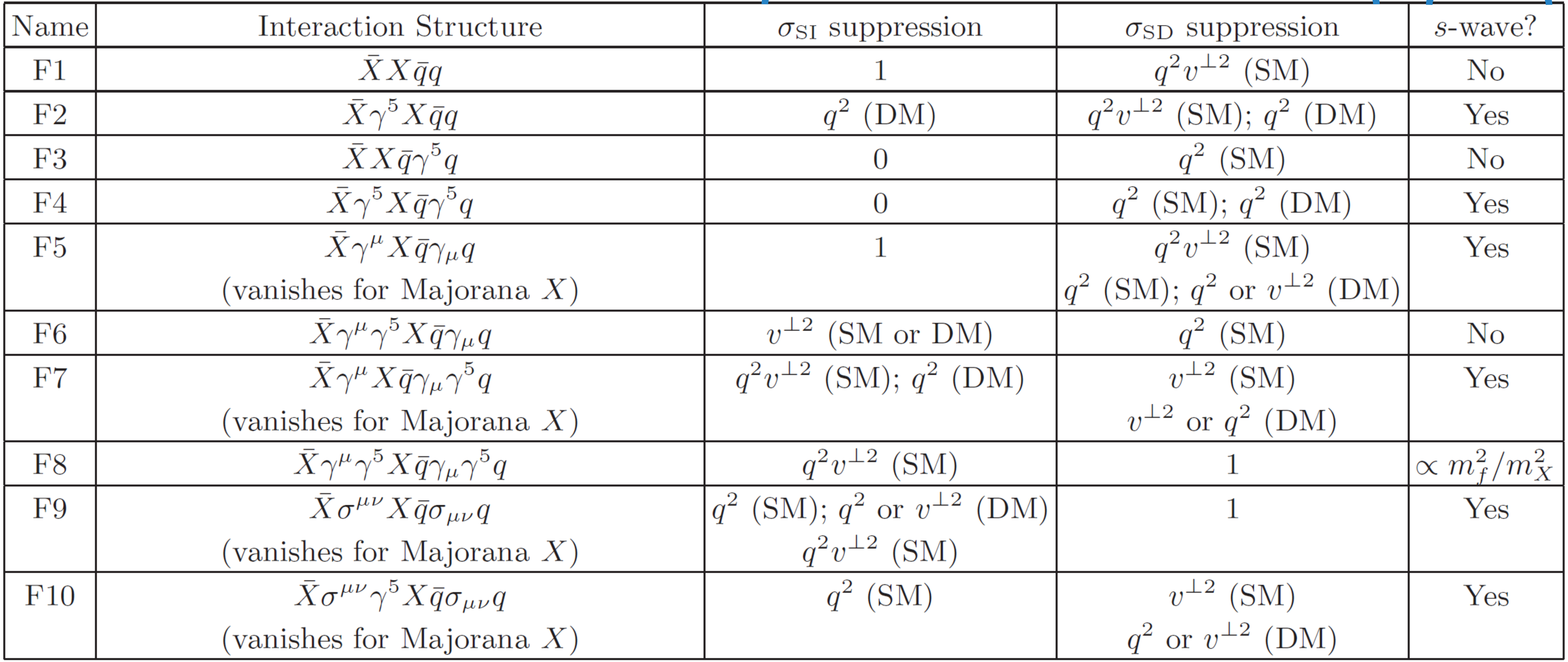
Contact interaction of fermionic DM with SM quarks or leptons:

$$L_{\mathrm{eff}} = \frac{1}{\Lambda_{\mathrm{eff}}^2}\left(\bar{\chi}\,\Gamma_\chi \chi\right)\left(\bar{\mathrm{f}}\,\Gamma_f \mathrm{f}\right)$$

$$\Gamma_{\chi,f} \in \{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$



Name	Operator	Coefficient	DD
D1	$[\bar{\chi}\chi][\bar{f}f]$	$m_f\Lambda^{-3}$	SI
D2	$[\bar{\chi}\gamma^5\chi][\bar{f}f]$	$im_f\Lambda^{-3}$	–
D3	$[\bar{\chi}\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-3}$	–
D4	$[\bar{\chi}\gamma^5\chi][\bar{f}\gamma^5 f]$	$m_f\Lambda^{-3}$	–
D5	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	SI
D6	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	–
D7	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	–
D8	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	SD
D9	$[\bar{\chi}\sigma^{\mu\nu}\chi][\bar{f}\sigma_{\mu\nu} f]$	Λ^{-2}	SD
D10	$[\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi][\bar{f}\sigma_{\mu\nu} f]$	$i\Lambda^{-2}$	–
D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–



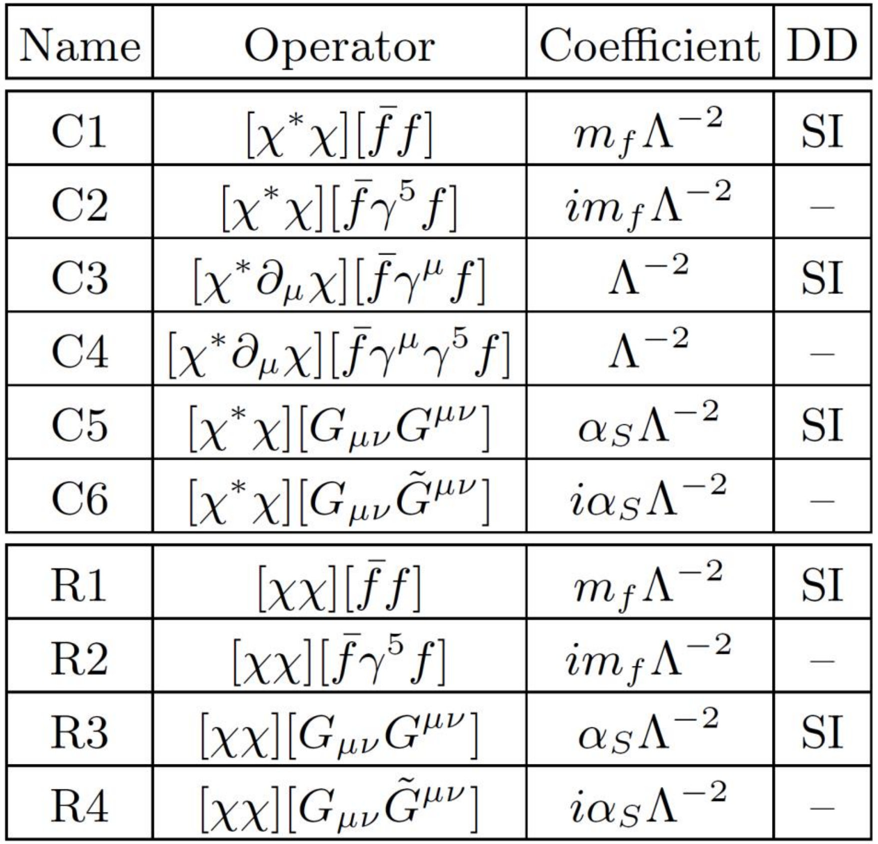
		scattering cross section		annihilation cross section
Name	Interaction Structure	$\sigma_{\rm SI}$ suppression	$\sigma_{\rm SD}$ suppression	s-wave?
F1	$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	q^2 (SM); q^2 (DM)	Yes
F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
F9	$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	1	Yes
F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes

Kumar & Marfatia, arXiv:1305.0601

Effective operators for scalar dark matter

Complex scalar DM

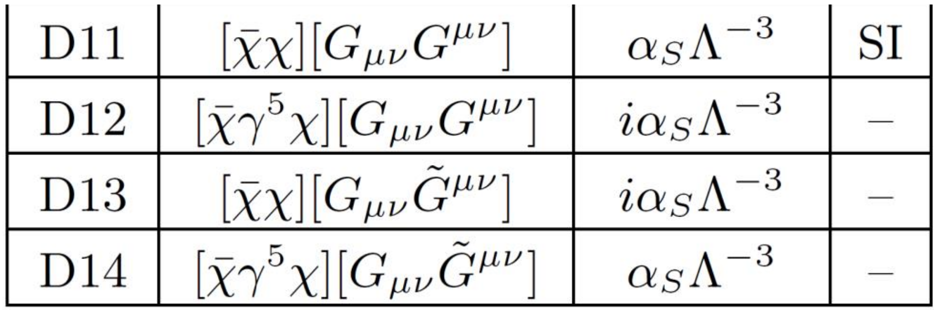
Real scalar DM



Name	Operator	Coefficient	DD
C1	$[\chi^*\chi][\bar{f}f]$	$m_f\Lambda^{-2}$	SI
C2	$[\chi^*\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-2}$	–
C3	$[\chi^*\partial_\mu\chi][\bar{f}\gamma^\mu f]$	Λ^{-2}	SI
C4	$[\chi^*\partial_\mu\chi][\bar{f}\gamma^\mu\gamma^5 f]$	Λ^{-2}	–
C5	$[\chi^*\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-2}$	SI
C6	$[\chi^*\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-2}$	–
R1	$[\chi\chi][\bar{f}f]$	$m_f\Lambda^{-2}$	SI
R2	$[\chi\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-2}$	–
R3	$[\chi\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-2}$	SI
R4	$[\chi\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-2}$	–

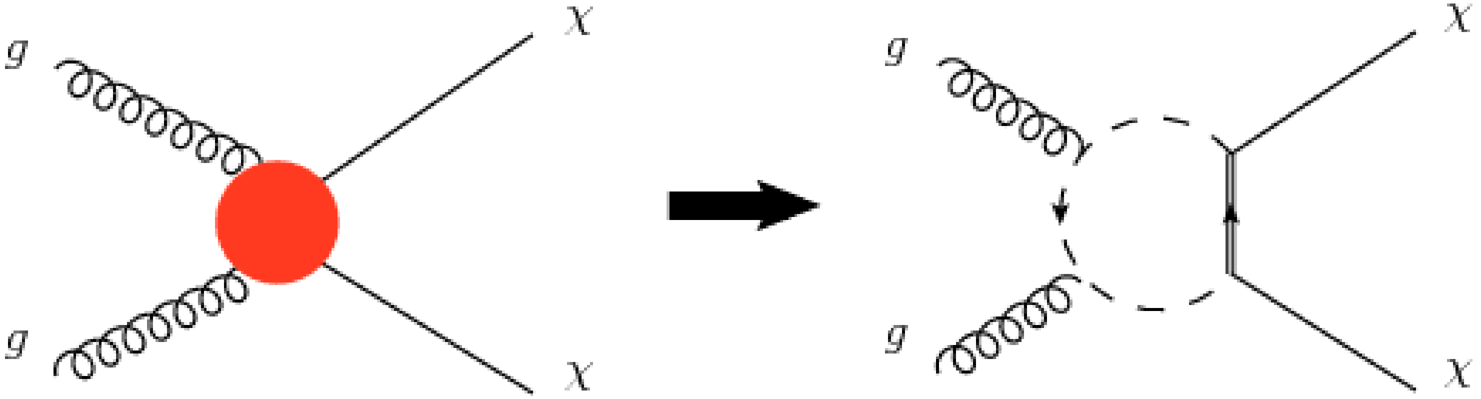
Can also write down EFTs to describe DM interactions with SM gauge bosons or the Higgs boson

Models with gluon couplings



D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–

- ❑ Mono-jets place strong limits
- ❑ No tree-level UV completion is possible



Abdallah et al
1409.2893

Constraining WIMP models

- ❖Relic density

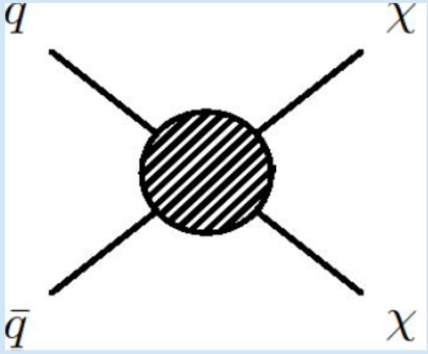
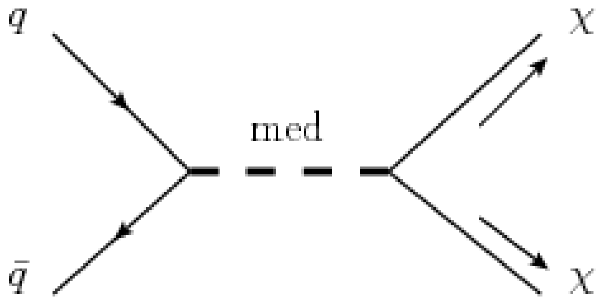
  →lower limit on $\frac{g_\chi^4}{m_\chi^2}$ (upper limit on Λ_{eff}) to prevent over-closure

- ❖Direct detection, collider, and indirect detection

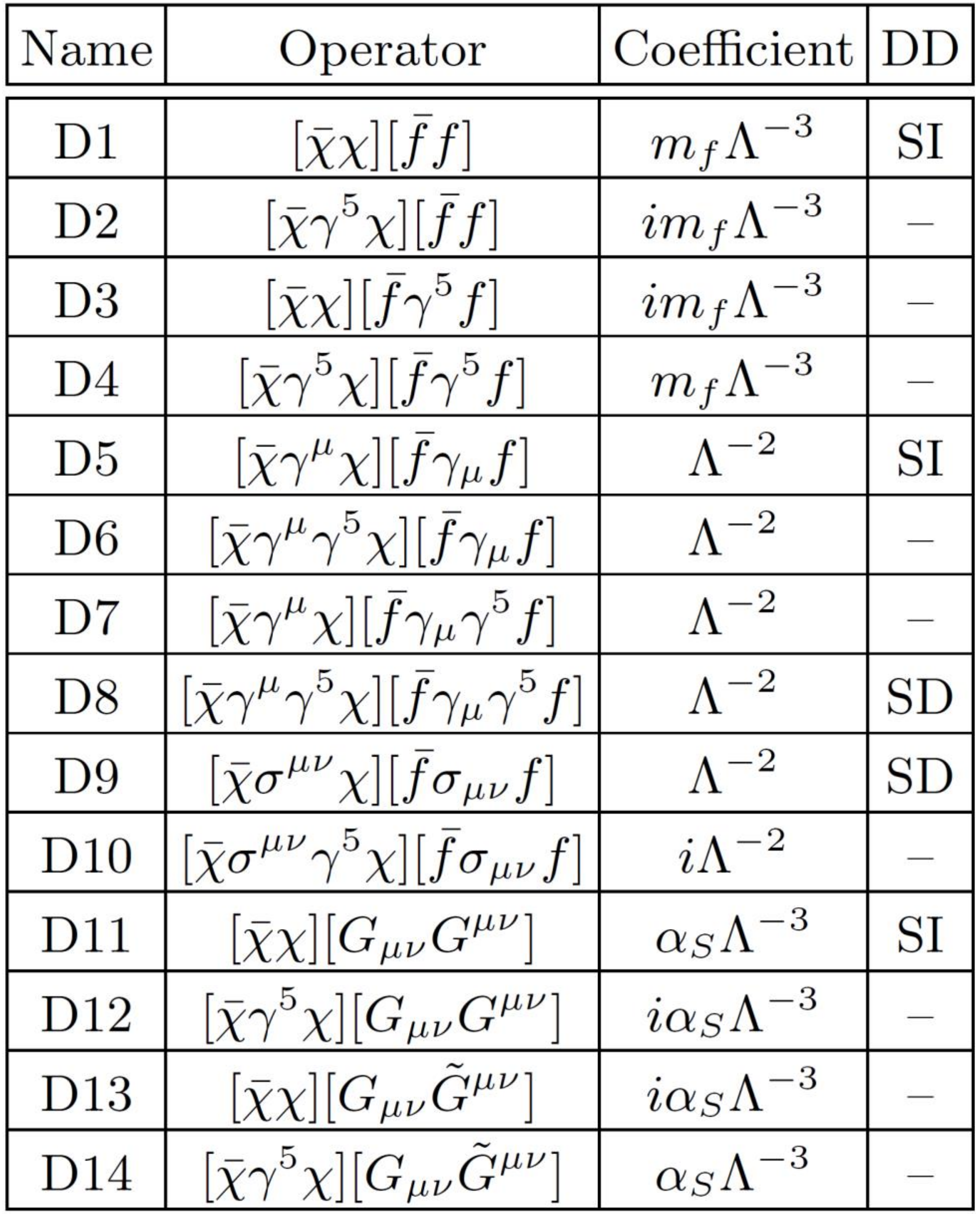
  → upper limits on $\frac{g_\chi^4}{m_\chi^2}$ (lower limit on Λ_{eff}) to be consistent with null observations

In some cases, these limits are approaching. But, it is easy for a WIMP to hide:
Velocity suppressed cross sections, annihilation to dark states; light mediators; non-trivial flavour structure of DM couplings; leptophilic DM; multiple thermal relics, non-standard expansion history, etc.

There is much work to do to fully test the WIMP parameter space.

<table>
<tr><td>Effective Field Theories (EFTs)</td><td>
$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M_{med}^2}$</td><td>• Simple
• EFTs break down if momentum transfer is $\geq M_{med}$</td></tr>
<tr><td>Simplified Models</td><td>
• Explicit introduction of a mediator</td><td>• Unitarity issues if they break gauge invariance in the standard model or dark sector.</td></tr>
<tr><td>Self-consistent Simplified Models</td><td colspan="2">• May require multiple mediators
→Physics not adequately captured by a single EFT operator or a single-mediator simplified model.</td></tr>
</table>

Effective Operators for DM interactions



Name	Operator	Coefficient	DD
D1	$[\bar{\chi}\chi][\bar{f}f]$	$m_f\Lambda^{-3}$	SI
D2	$[\bar{\chi}\gamma^5\chi][\bar{f}f]$	$im_f\Lambda^{-3}$	–
D3	$[\bar{\chi}\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-3}$	–
D4	$[\bar{\chi}\gamma^5\chi][\bar{f}\gamma^5 f]$	$m_f\Lambda^{-3}$	–
D5	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	SI
D6	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	–
D7	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	–
D8	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	SD
D9	$[\bar{\chi}\sigma^{\mu\nu}\chi][\bar{f}\sigma_{\mu\nu} f]$	Λ^{-2}	SD
D10	$[\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi][\bar{f}\sigma_{\mu\nu} f]$	$i\Lambda^{-2}$	–
D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–

Violate $SU(2)_L$

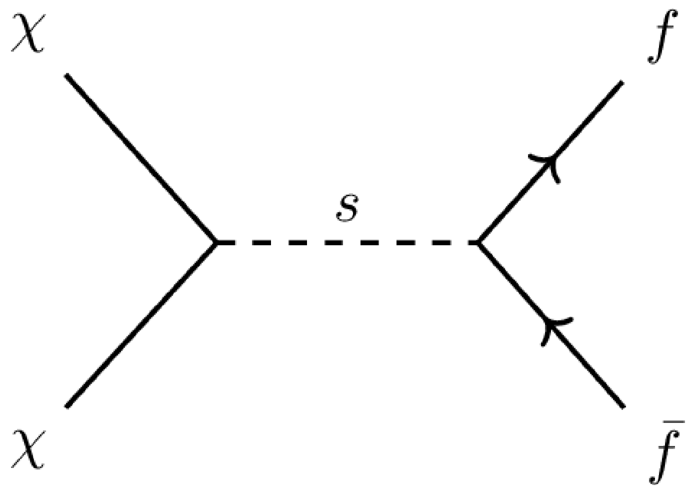
Don't necessarily violate $SU(2)_L$
(but can be chosen to do so)

Violate $SU(2)_L$

Be careful using this framework at energy larger or comparable to the electroweak scale!

Unitarity and Simplified Models – scalar interaction

Consider a scalar (or pseudo scalar) mediator:



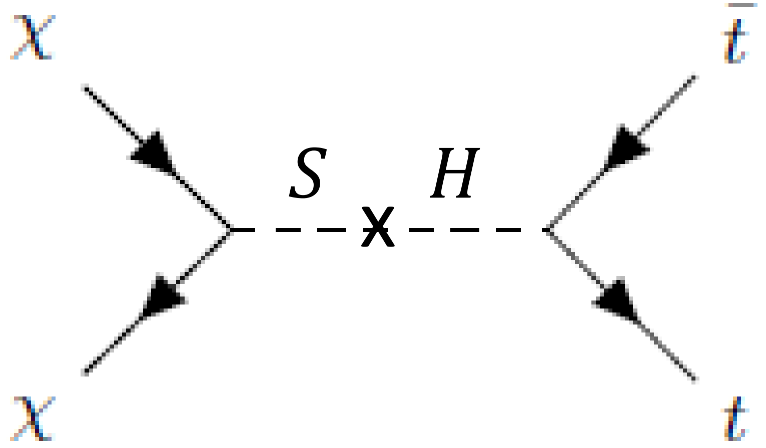
This model is clearly ***not*** gauge invariant under $SU(2)_L$ because:

- dark matter can couple only to a singlet scalar
- quarks couple only to SM Higgs (or other scalar with the same quantum numbers as the Higgs)

Scalar mediator must mix with the Higgs

Higgs portal: $\frac{1}{2}\lambda_{HS}\mathrm{H}^{\dagger}\mathrm{H}S^2$

- SM Higgs field H couples to quarks
- Singlet scalar S couples to DM



After symmetry breaking, we have mixing of the two mass eigenstate scalars, $\boldsymbol{h}$ and $\boldsymbol{s}$, which both mediate quark-DM interactions

$$L = -\sum_{f}\frac{m_i}{v}\bar{f}_i f_i(\boldsymbol{h}\cos\epsilon - \boldsymbol{s}\sin\epsilon) - y_{DM}\bar{\chi}\chi(\boldsymbol{s}\cos\epsilon + \boldsymbol{h}\sin\epsilon)$$

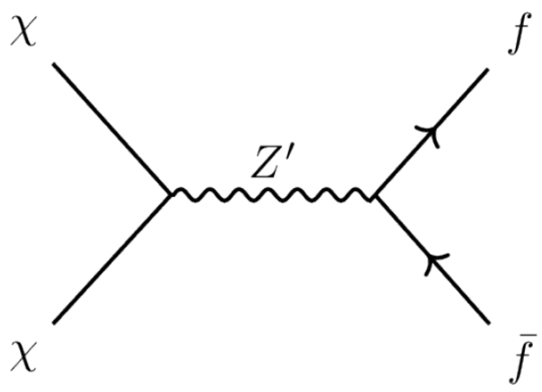
→ ***Interference effects***

→ **Destructive interference of h and s occurs when $m_s \sim m_h$ → Blind spot for direct detection**

Unitarity and Simplified Models – axialvector interaction

Consider a model where DM couples to SM fermions via a spin-1 mediator, *Z’*

where Z’ is the gauge boson of a new U(1) symmetry



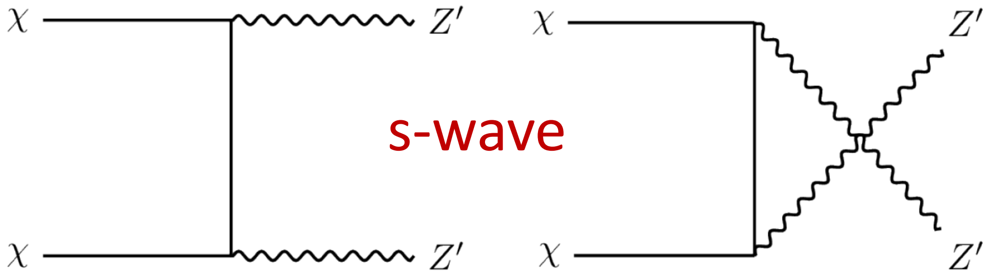
Axial vector couplings → unitarity is violated at high energy

The problem is that the masses break dark-sector gauge invariance.

→**Need a Higgs mechanism in the dark sector!**
→ Introduction of further dark sector particles (beyond the DM candidate and mediator)

Annihilation to individual mediators

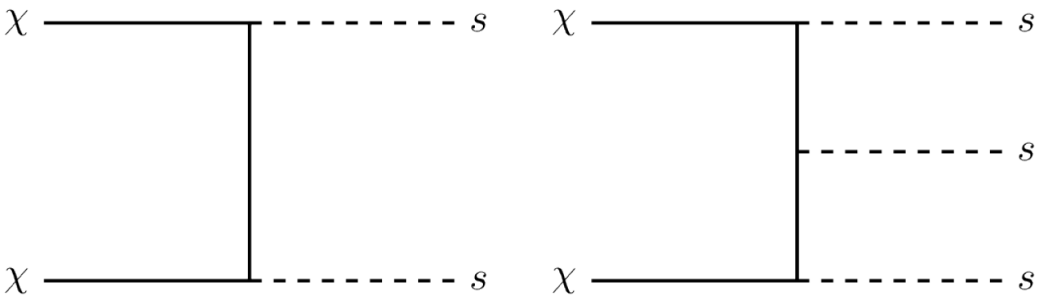
Simplified Model
with vector mediator



s-wave

Badly behaved at high energy

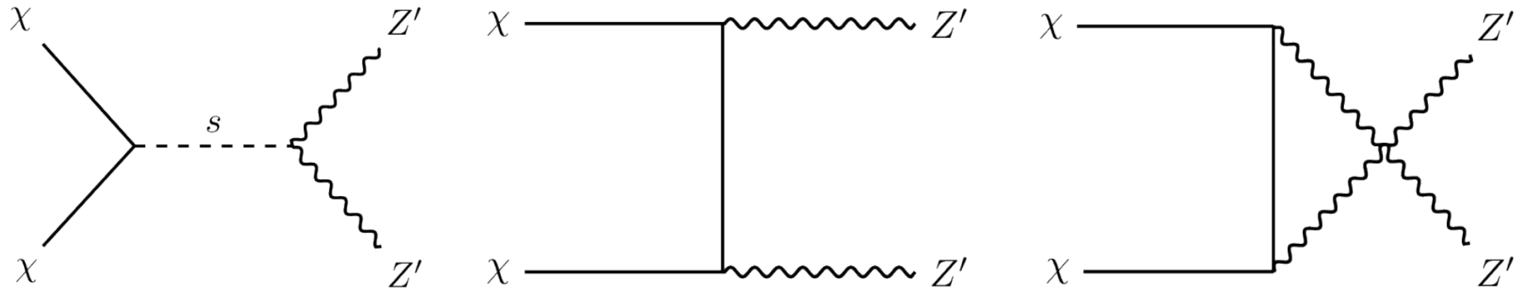
Simplified Model
with scalar mediator



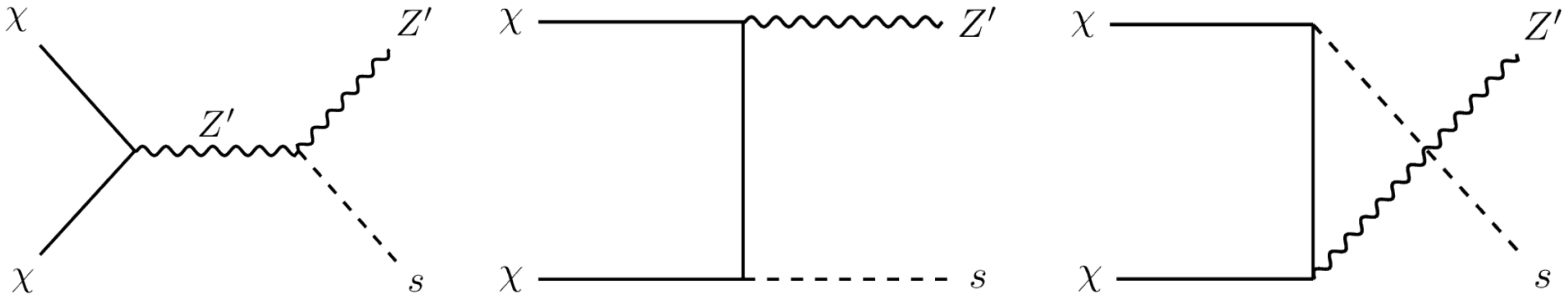
p-wave
suppressed

s-wave,
phase space suppressed

Including both mediators



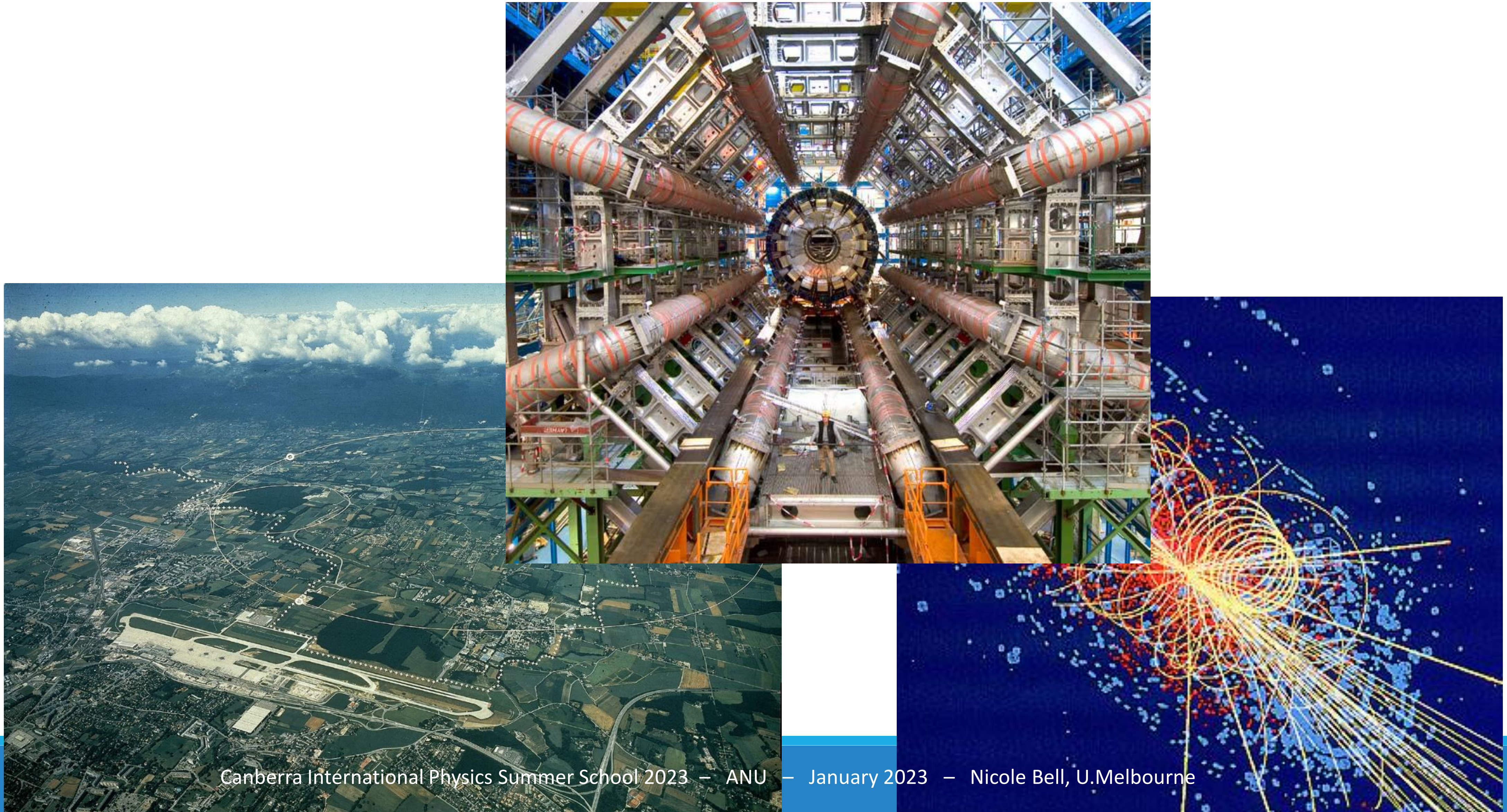
New contribution to $\chi\chi \to Z'Z'$ (prevents unphysical high energy behaviour



New, dominant, s-wave annihilation process $\chi\chi \to sZ'$

NFB, Cai & Leane, arXiv:1605.09382

Dark Matter at the collider experiments



Mono-X signal at colliders

- ☐ The dominant DM production process is <u>invisible</u> (DM stable, weakly interacting) :

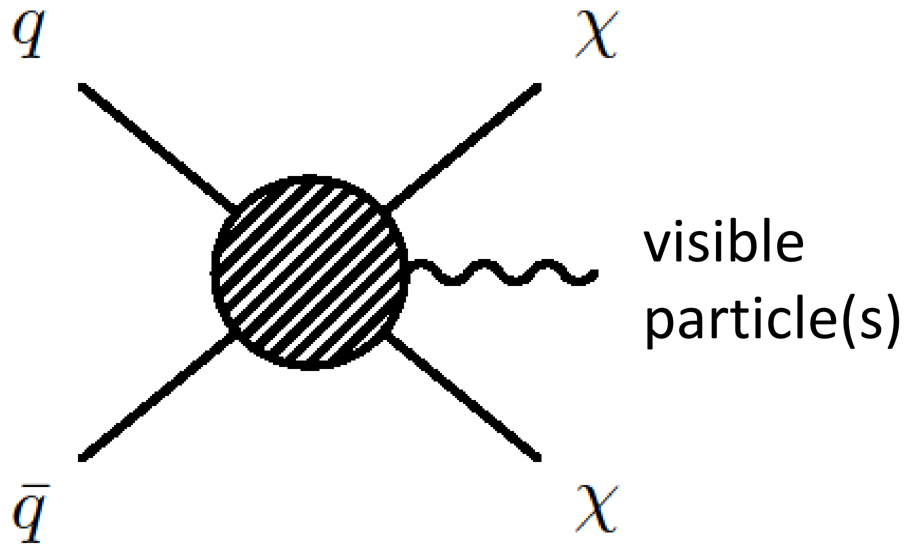
$$\bar{q}q \rightarrow \chi\chi$$

- ☐ Need visible particles in the final state, to recoil against missing transverse energy

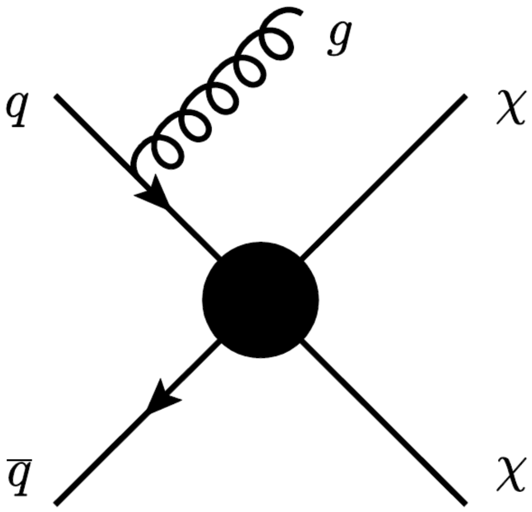
$$\bar{q}q \rightarrow \chi\chi + \text{ SM particle}$$

Mono-X process in which DM is visible as a high p_T state + missing E_T

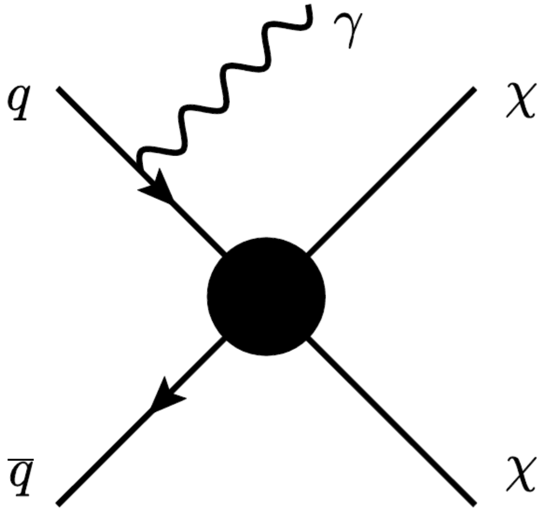
→ Mono-jet, mono-photon, mono-Z, mono-W, mono-Higgs



Mono-jet

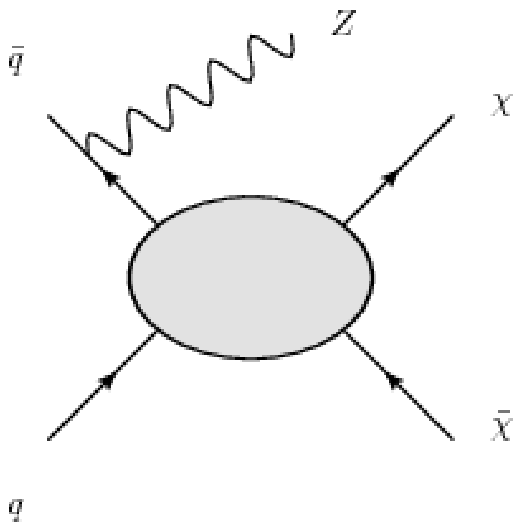


Mono-photon

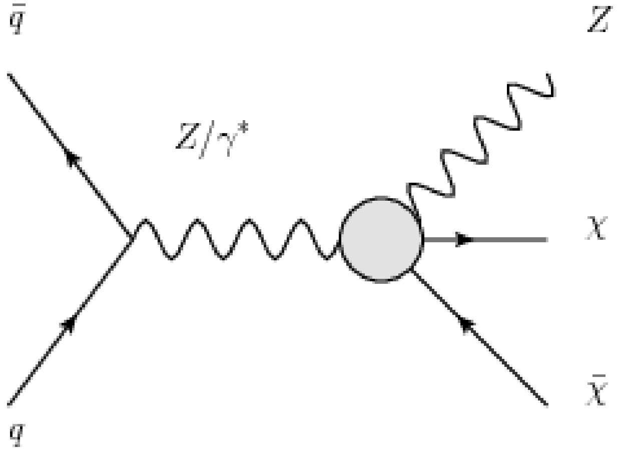


Other mono-X processes

Mono-Z , initial state radiation

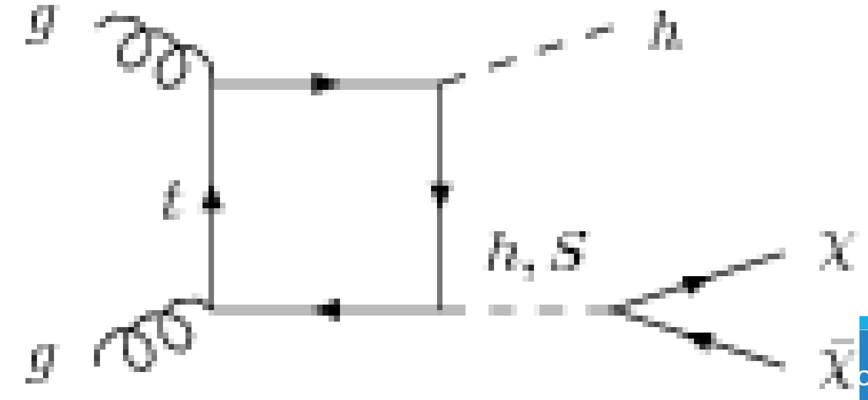


Mono-Z from DM interacting directly with Z bosons



L. Carpenter et al

Mono-Higgs



Higgs Portal DM

Take the EFT approach and consider interactions of the form:

$$\frac{1}{\Lambda^n} O_{DM} O_{SM}$$

where O_{DM} = dark matter operator
O_{SM} = standard model operator

and with O_{DM} & O_{SM} both singlets under the SM gauge group

The lowest dimension SM operator is the Higgs bilinear: $H^\dagger H$

→ Form "Higgs portal" operators of the form: $\frac{1}{\Lambda^n} O_{DM}(H^\dagger H)$

Types of Higgs portals

- Scalar Higgs portal: $\lambda_s S^2 (H^\dagger H)$
- Vector Higgs portal: $\lambda_V V^\mu V_\mu \, (H^\dagger H)$
- Fermionic Higgs portal: $\frac{1}{\Lambda}(\bar{\chi}\chi)(H^\dagger H)$

Higgs Portal & Higgs invisible width

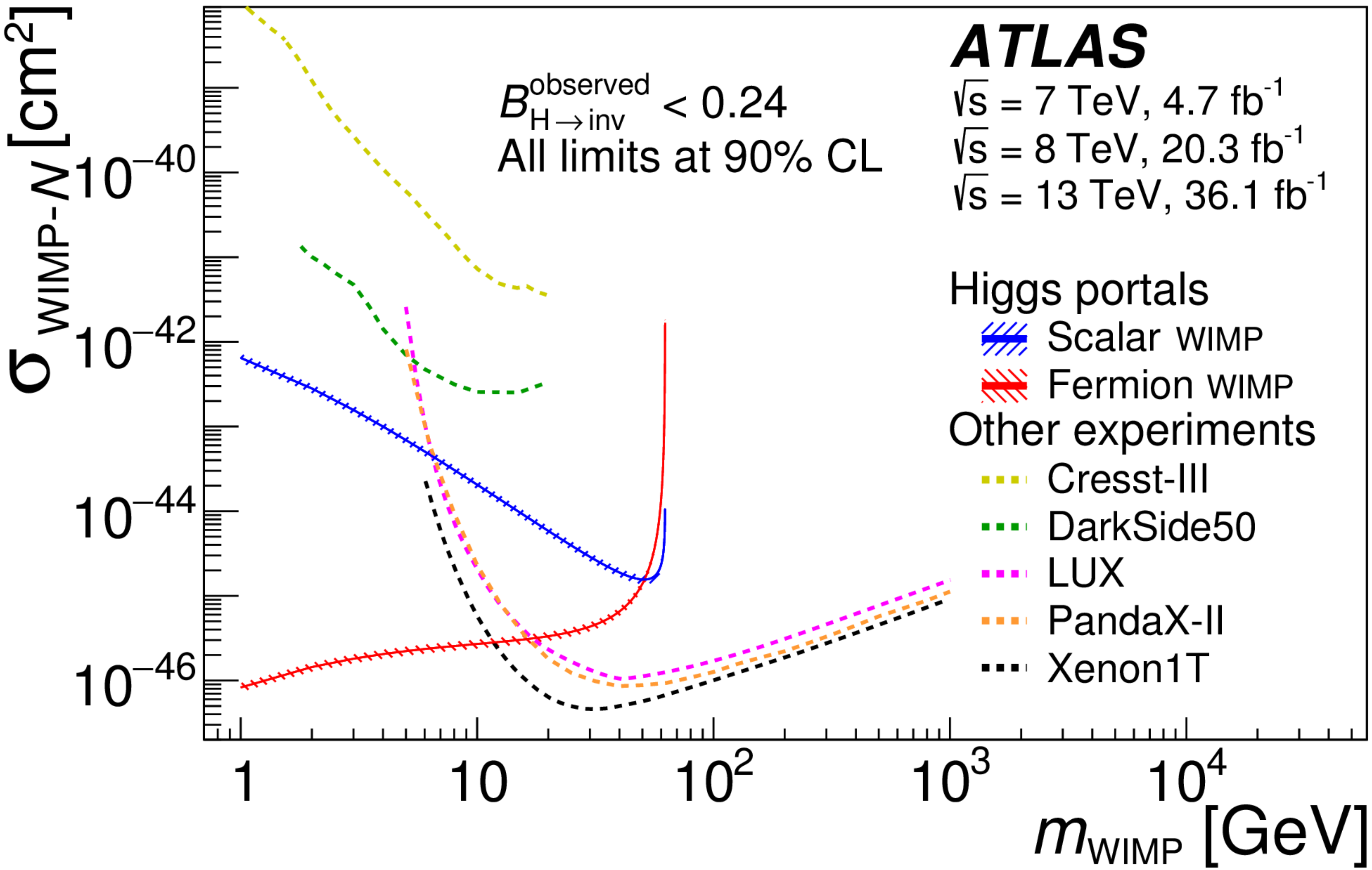
If $m_{DM} < \frac{m_{\text{higgs}}}{2}$

→ Higgs width increased by decay to dark matter, $H \to \bar{\chi}\chi$
→ Constraints from LHC determinations of Higgs invisible width

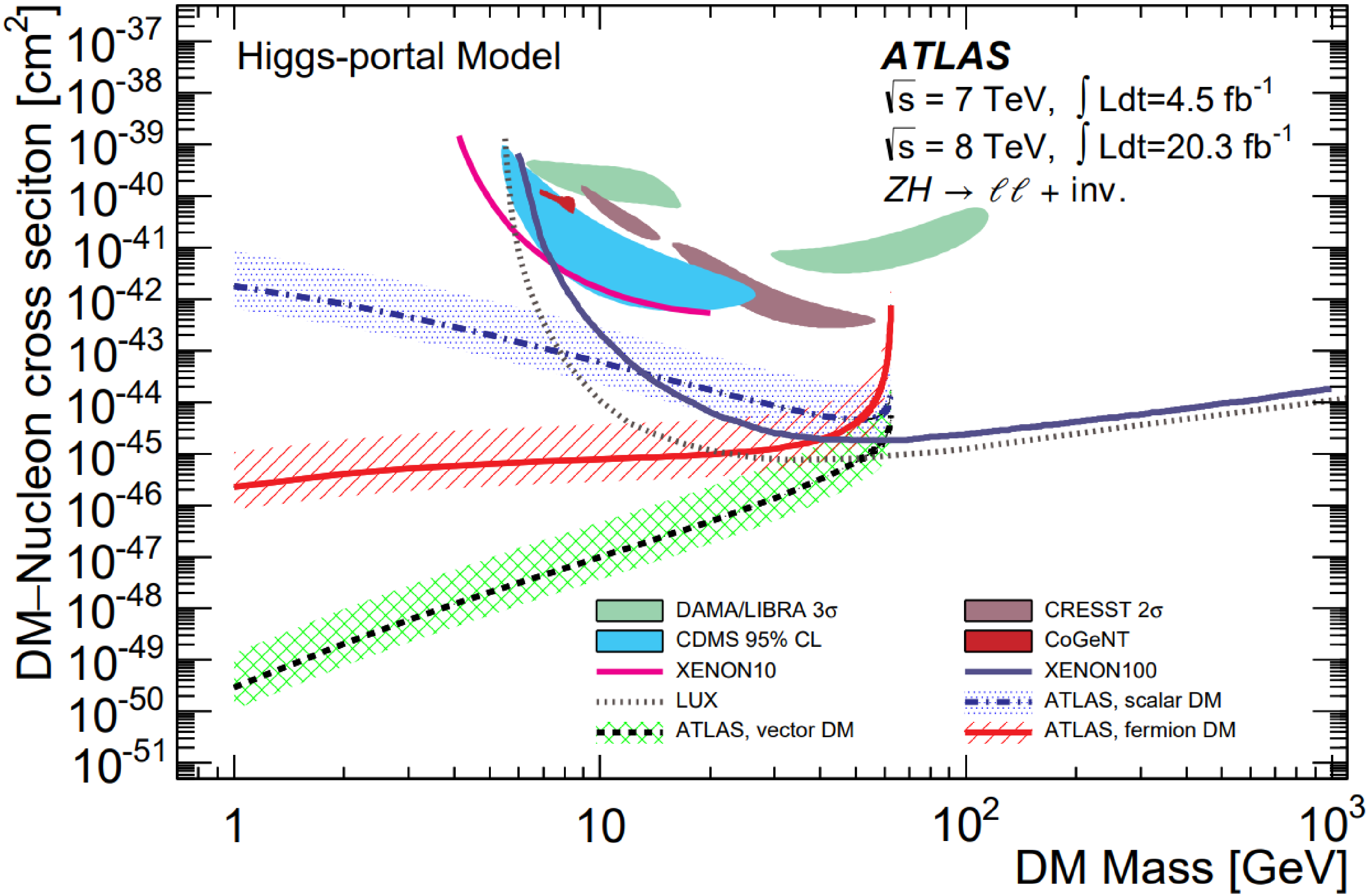
Br(inv) < 0.24 ATLAS, arXiv:1904.05105

Because the SM Higgs width is so small (about 4 MeV), even modest limits on B(inv) place strong limits on Higgs portal models.

arXiv: 1904.05105



arXiv:1402.3244



EFT: Useful, but have limitations

- ❑ For an EFT description to be valid, need: $\Lambda = \frac{M_{med}}{\sqrt{g_q g_\chi}} > \frac{m_{dm}}{4\pi}$

This does NOT hold for all the parameter space relevant for LHC searches (G.Busoni et al)

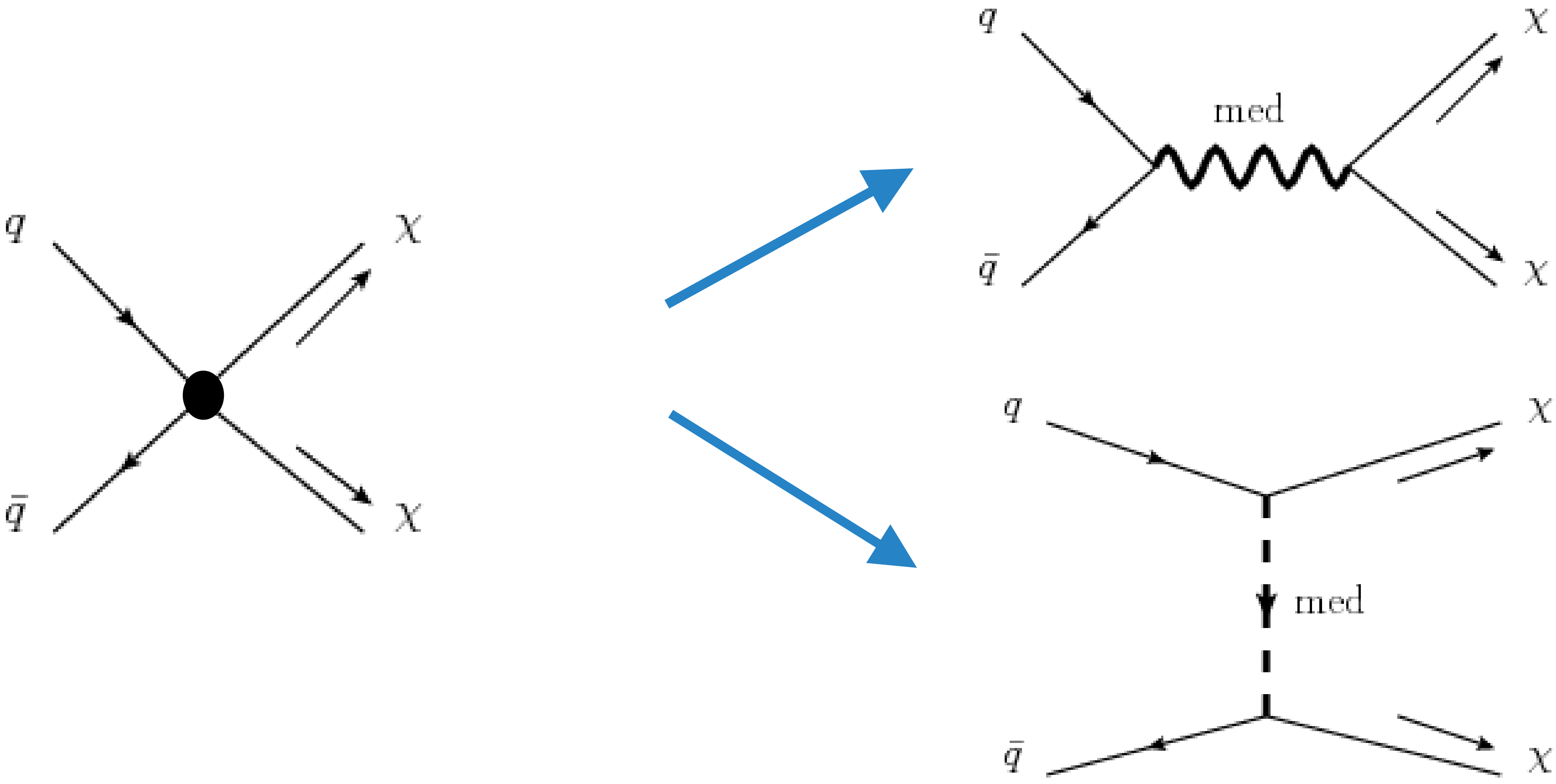
- ❑ EFT bounds can over-estimate or under-estimate constraints on a given model

- ❑ Unitarity issues due to lack of gauge invariance …

- ❑ Importantly: in many UV complete theories, there exist other dark sector particles at energy scales accessible to the LHC.

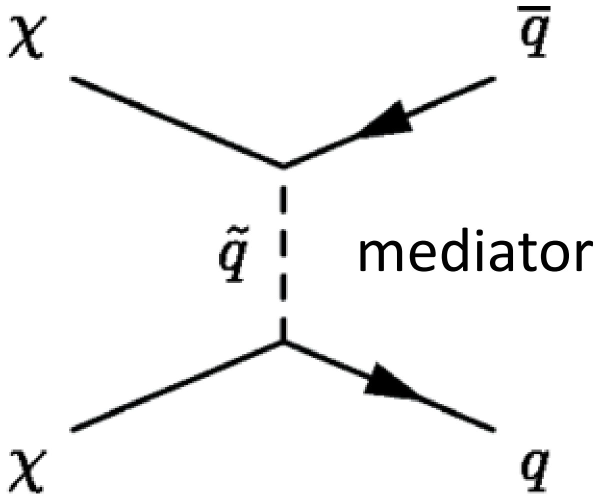
Particles with SM quantum numbers, or a Z’ gauge boson, … etc.

Beyond an EFT → Simplified Models



A given EFT maps to multiple simplified models

t-channel mediator



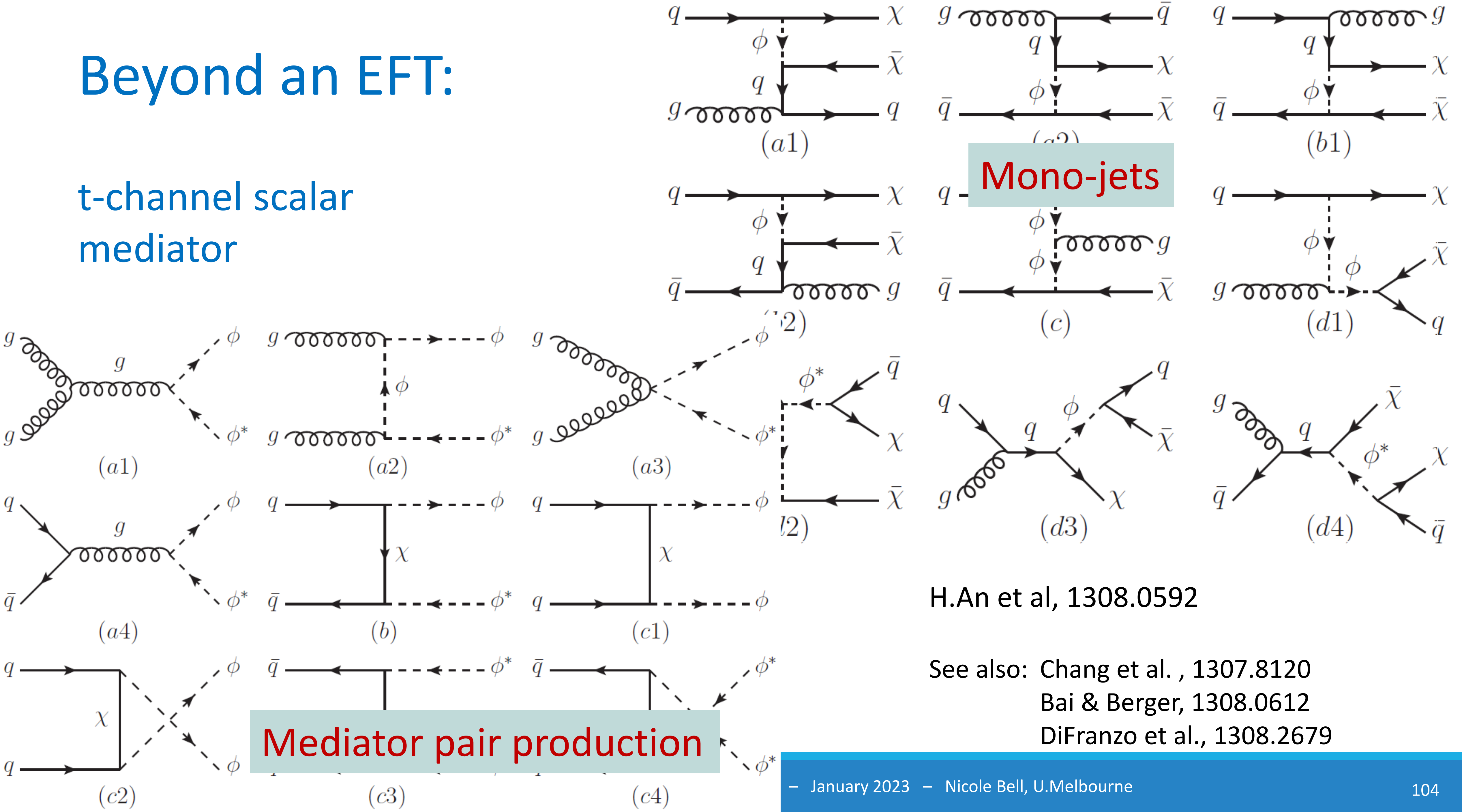
The mediator:

- If χ stabilized by a symmetry → the mediator also carries this symmetry.
- Carries SM quantum numbers → can be pair produced at colliders
- Is heavier than the DM (so the DM does not decay to the mediator)

e.g. mediator = squark (DM = neutralino of SUSY models)

Beyond an EFT:

t-channel scalar mediator



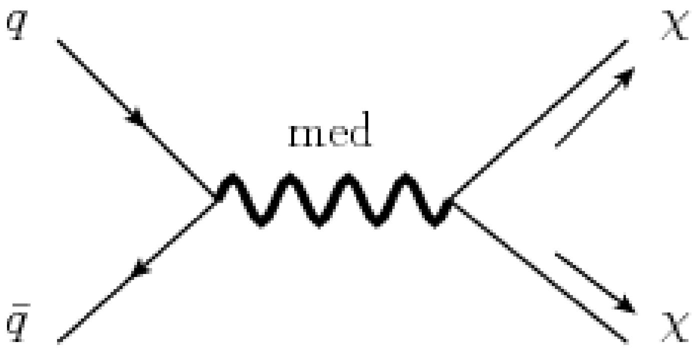
Mono-jets

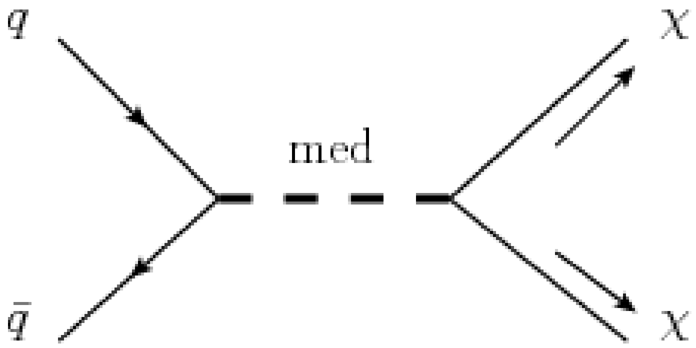
Mediator pair production

H.An et al, 1308.0592

See also: Chang et al. , 1307.8120
Bai & Berger, 1308.0612
DiFranzo et al., 1308.2679

s-channel mediator





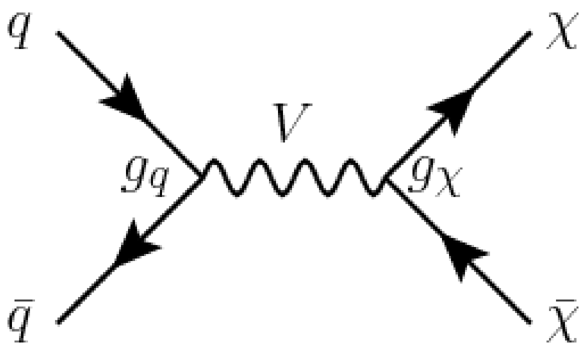
The mediator:

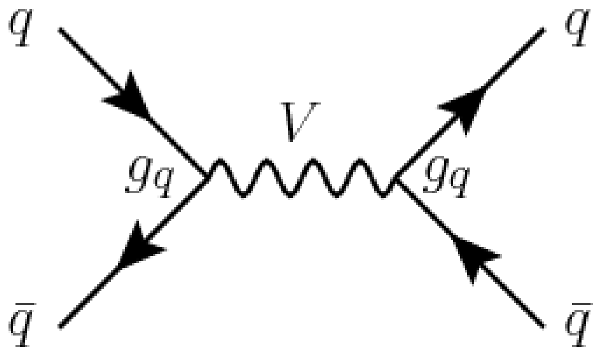
- Directly couples to the SM → can produce mediator at colliders
- Can be lighter or heavier than the DM
- Mass and width are important

s-channel vector mediator

$$\mathcal{L} = V_\mu \bar{\chi} \gamma^\mu (g_\chi^V - g_\chi^A \gamma_5) \chi + \sum_{f=q,l,\nu} V_\mu \bar{f} \gamma^\mu (g_f^V - g_f^A \gamma_5) f$$

V_μ = new dark-sector mediator, such as a Z', with vector and/or axialvector couplings



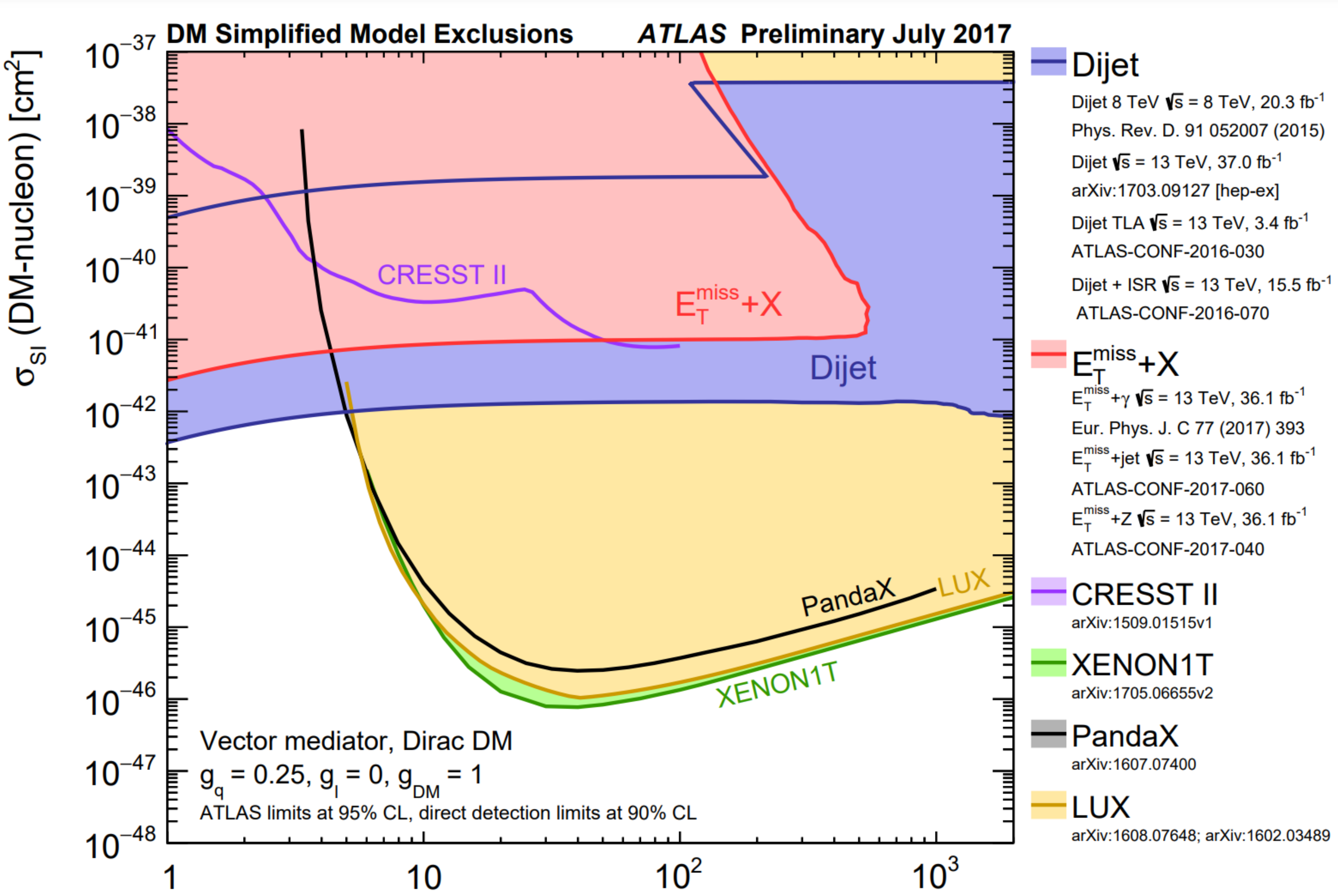


Search for:

- Dark matter production → Mono-jets + missing ET
- Mediator resonances → Dijet resonance (“bump hunting for an on-shell mediator
- Non-standard contributions to $\bar{q}q\bar{q}q$ contact interactions (at very high mediator mass)

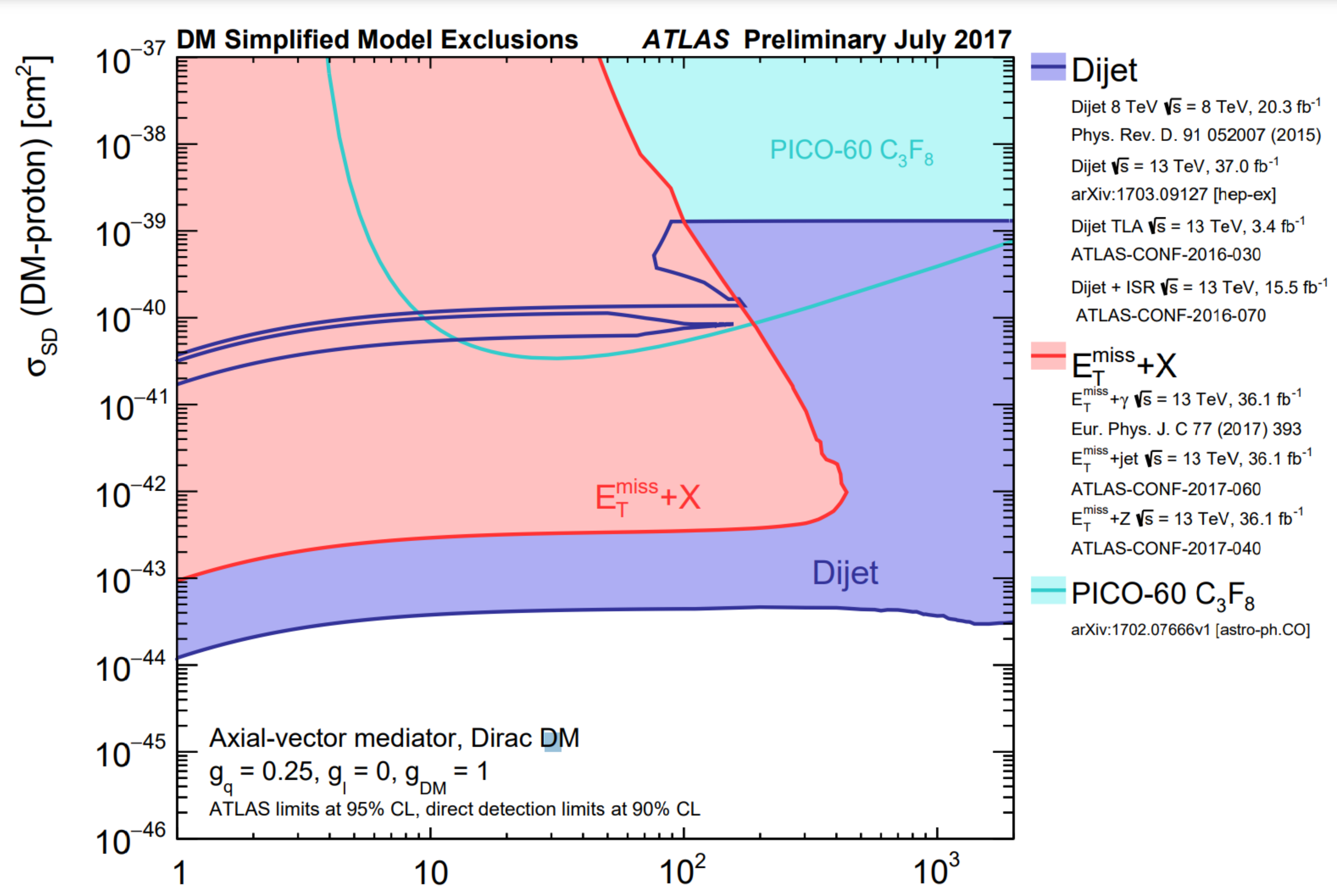
s-channel vector mediator

Collider vs direct detection (spin-independent)



s-channel vector mediator

Collider vs direct detection (spin-dependent)



Complementarity of collider/direct/indirect

If we see a missing E_T (DM candidate) signal at a collider, we won’t know if it’s really the dark matter without other information.

❖ Is it stable?

→DM must be stable on a timescale of order **10 Gyr**. Colliders will tell us about stability on only **nanosecond** timescales (long enough to escape the detector).

❖ Does it contribute all the relic density?

→ Need to measure couplings to *all* SM particles to infer the total annihilation rate.

❖ Indirect detection

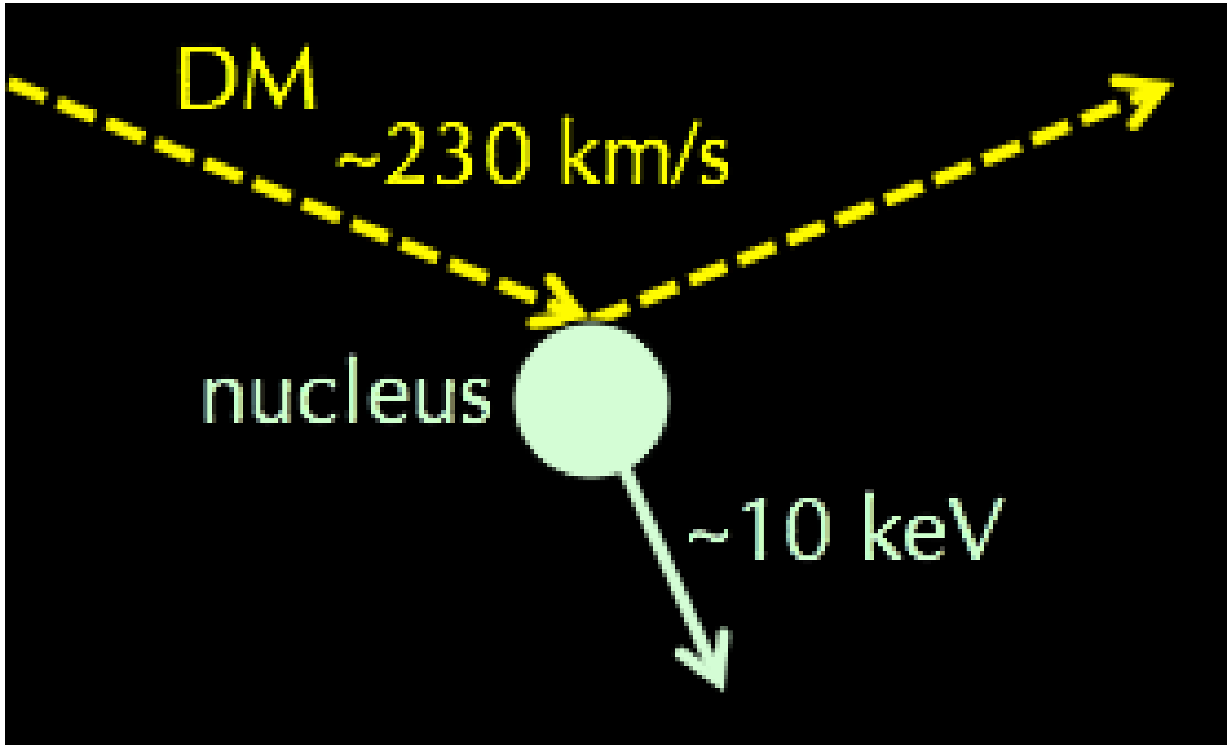
→ Most direct test of the annihilation cross section and hence the WIMP paradigm.

❖ Direct detection.

→ Detection of actual relic particles.

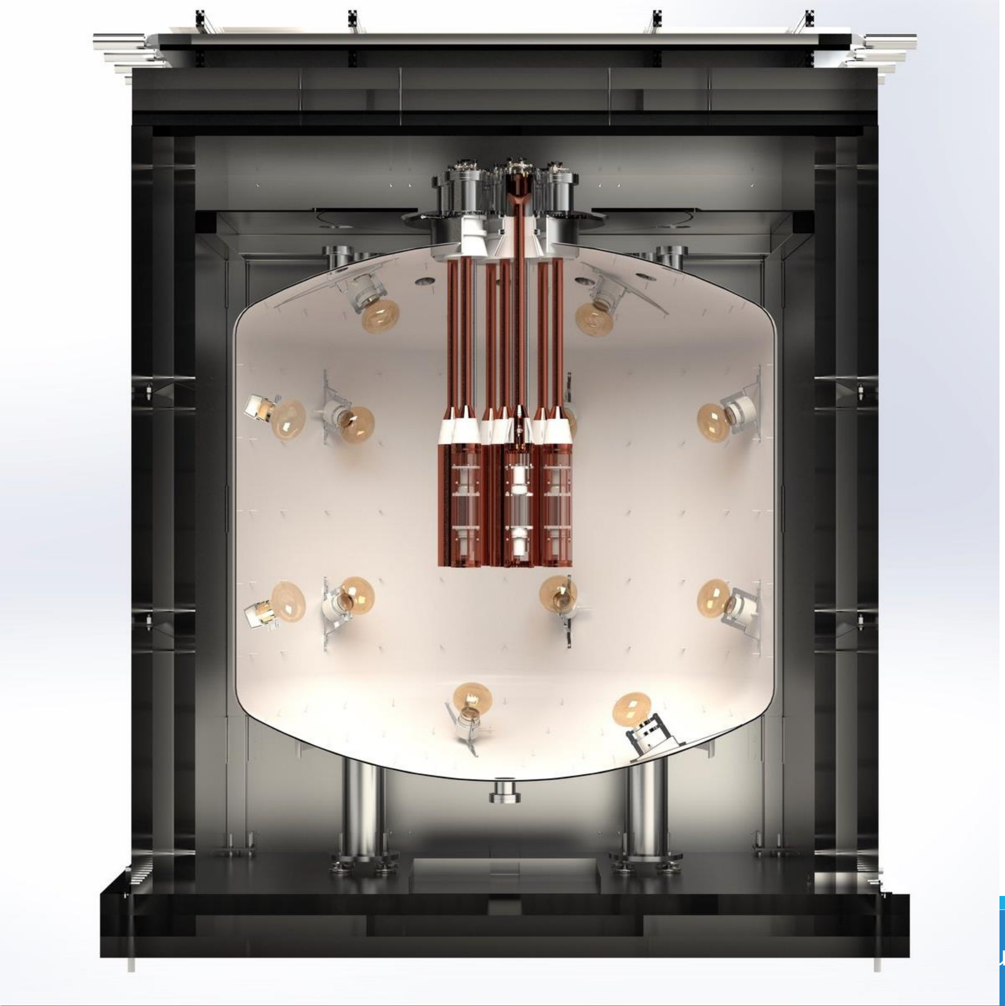
Dark Matter Lecture #4

Dark Matter Direct Detection



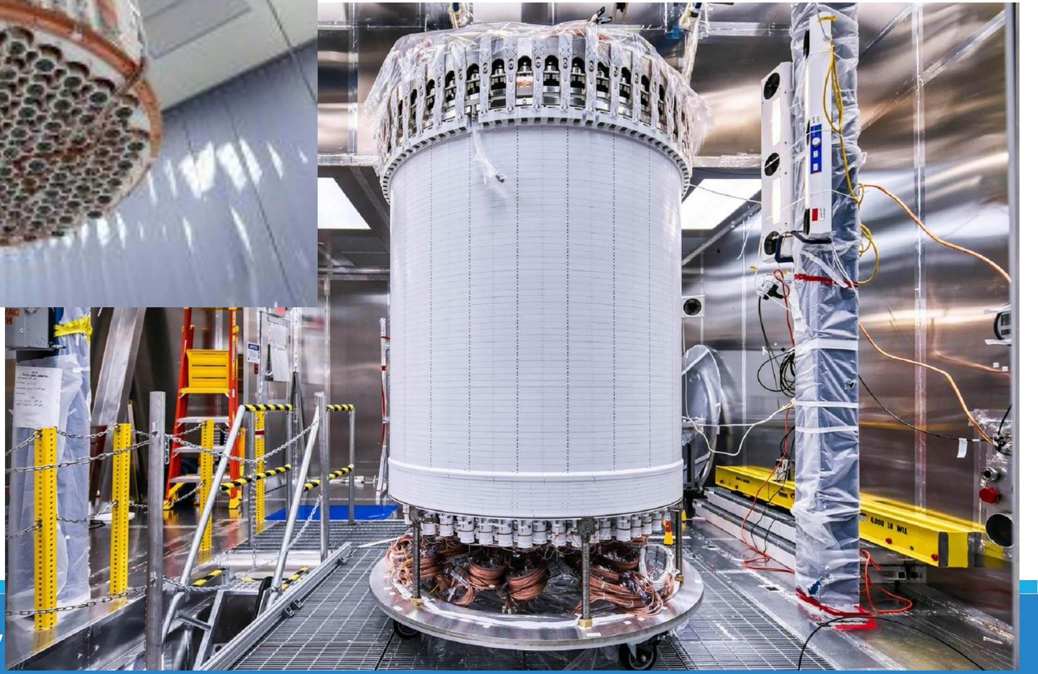
Dark Matter Direct Detection

SABRE experiment
(to go to SUPL lab in Australia)



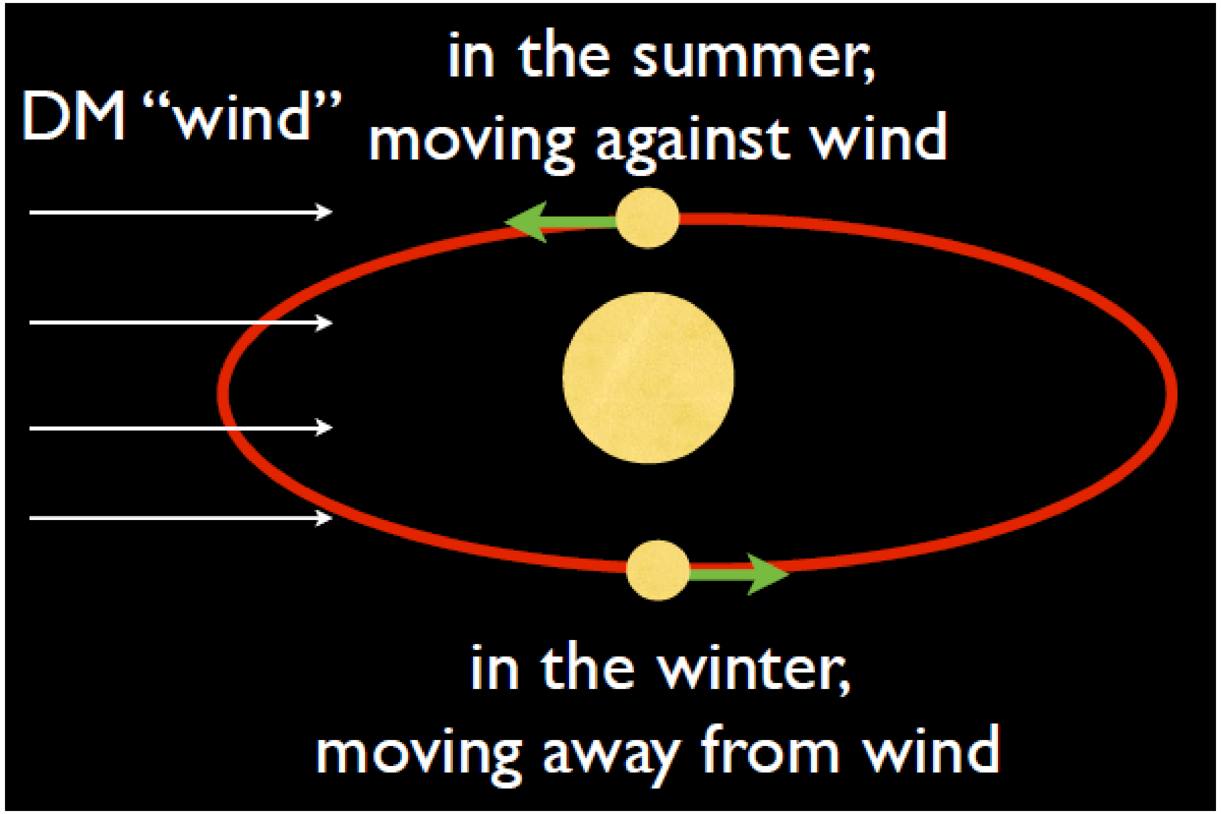
XENON1T

LUX-ZEPLIN (LZ)



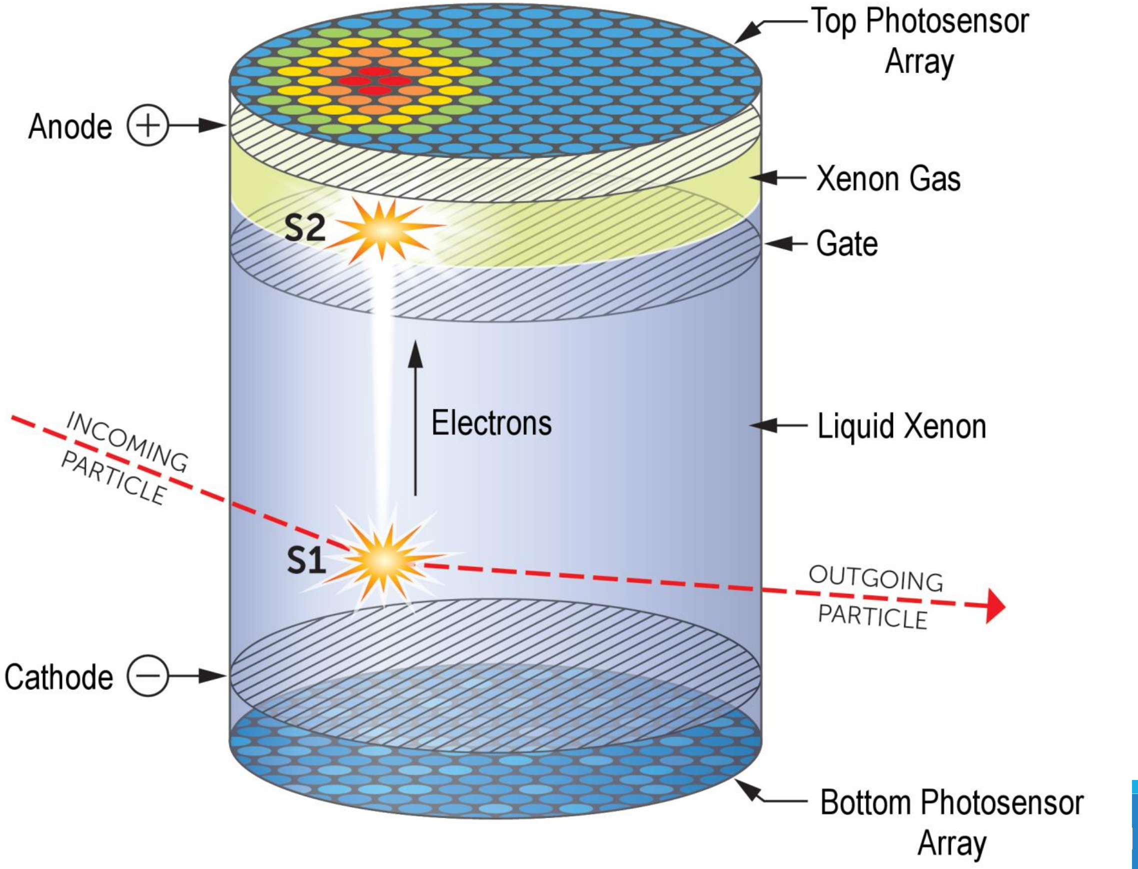
Direct Detection

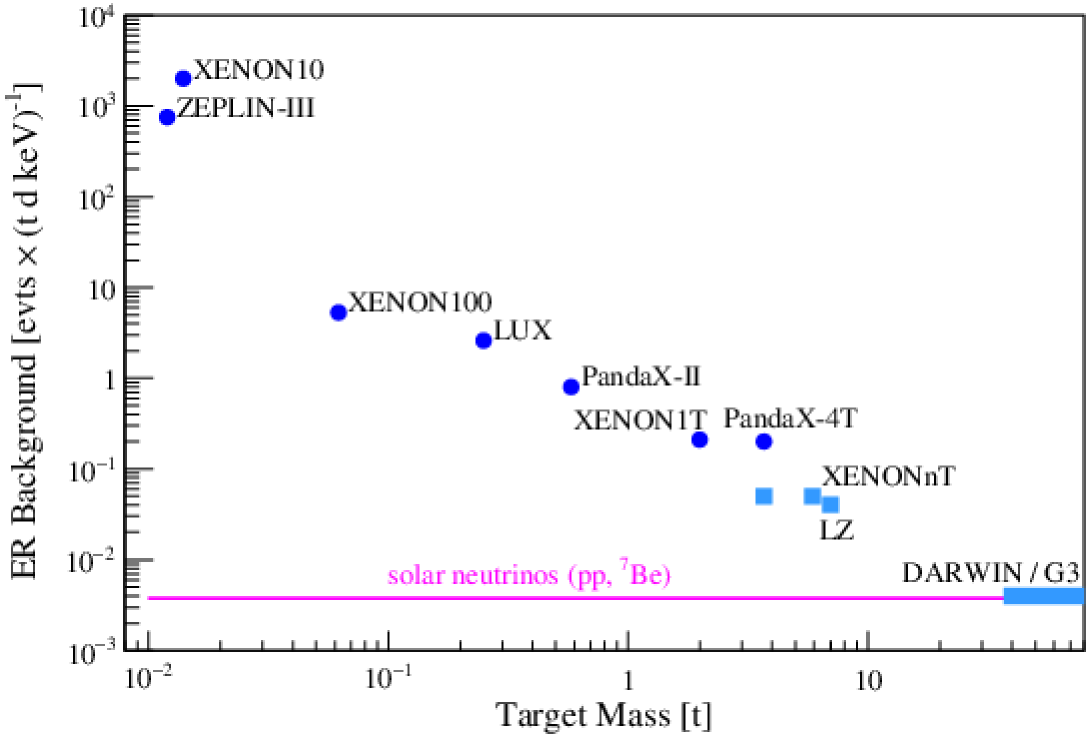
Search for nuclear recoil (or electron recoil) arising from the scattering of dark matter particles with nuclei (electrons).



Direct Detection Experiments

Nuclear recoil experiments search for the occasional collision of dark matter particles with nuclei in a detector





Images from: arXiv:2203.02309

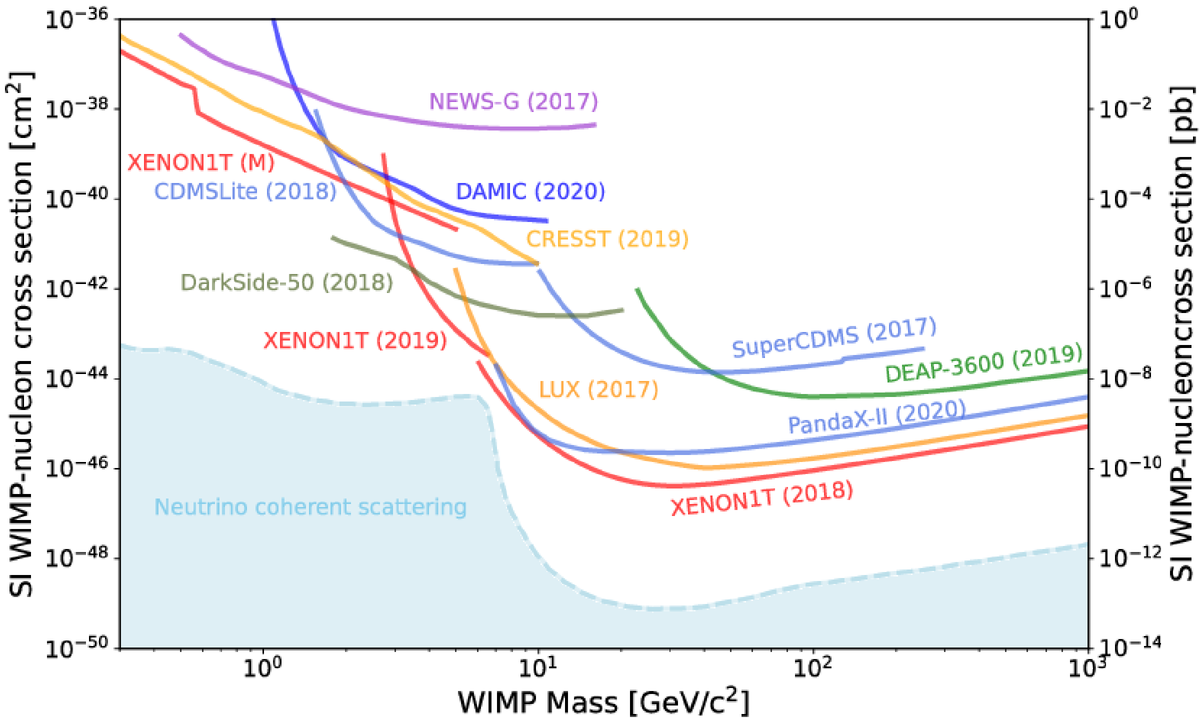
Direct Detection limits

Spin-independent (SI) interactions

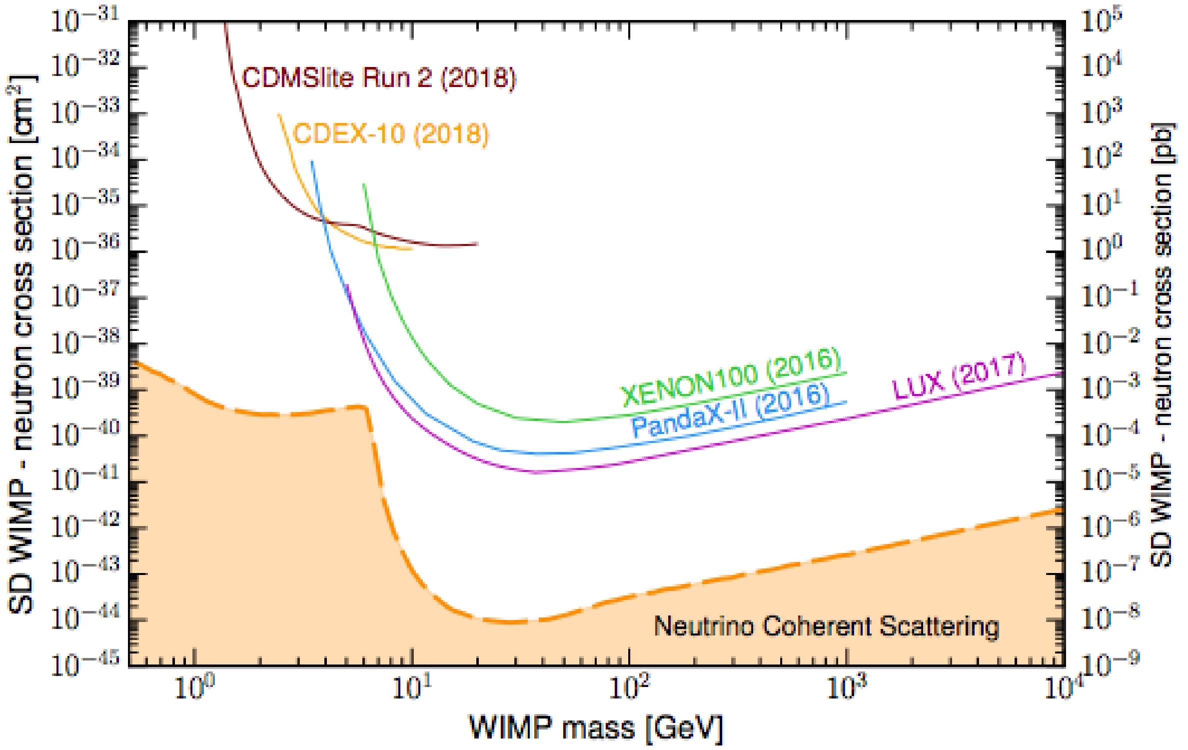
→ strong bounds due to coherent enhancement

Spin-dependent (SD) interactions

→ weaker bounds



J. Aalbers et al. arXiv:2203.02309



S. Robles

Spin-independent vs Spin-dependent

- **Spin dependent** - DM interacts coherently with whole nucleus, with A^2 enhancement
- **Spin dependent** – DM couples to spin of nucleus.
- In addition, some interactions are suppressed by velocity or momentum transfer.

Name	Interaction Structure	σ_{SI} suppression	σ_{SD} suppression	s-wave?
F1	$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	q^2 (SM); q^2 (DM)	Yes
F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
F9	$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	1	Yes
F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes

Direct Detection rates

Differential rate for WIMP scattering: $$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{max}} v f(v) \frac{d\sigma}{E_R} d^3 v$$

where: m_N = nucleus mass
v_{min} minimum DM velocity to produce detectable event at energy *E*
v_{max} is galactic escape velocity

$$v_{min} = \sqrt{m_N E/(2\mu^2)}$$

where $\mu = m_\chi m_\mathrm{N}/(m_\chi + m_N)$ = reduced mass

Direct detection experiments most sensitive for $m_\chi \sim m_N$

Cross section

Differential cross section:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left(\sigma_0^{SI} F_{SI}^2(q) + \sigma_0^{SD} F_{SD}^2(q)\right)$$

where $F_{SI}^2(q)$ and where $F_{SD}^2(q)$ are form factors.

For spin-independent scattering:

$$\sigma_0^{\mathrm{SI}} = \sigma_p \cdot \frac{\mu_A^2}{\mu_p^2} \cdot [Z \cdot f^p + (A - Z) \cdot f^n]^2$$

Usually $f_n = f_p$ is assumed (i.e. DM couples with same strength to neutrons and protons)

Then we have: $\sigma_0^{SI} \propto A^2$ where A is the nucleon number.

Direct Detection rates

Ball-park numbers:

$$R \sim 0.13 \; \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

$$E_R = \frac{p^2}{2m_N} = \frac{m_\text{r}^2 v^2}{m_N}(1 - \cos\theta) \quad \sim 30\ \text{keV}$$

Approaches to Direct Detection

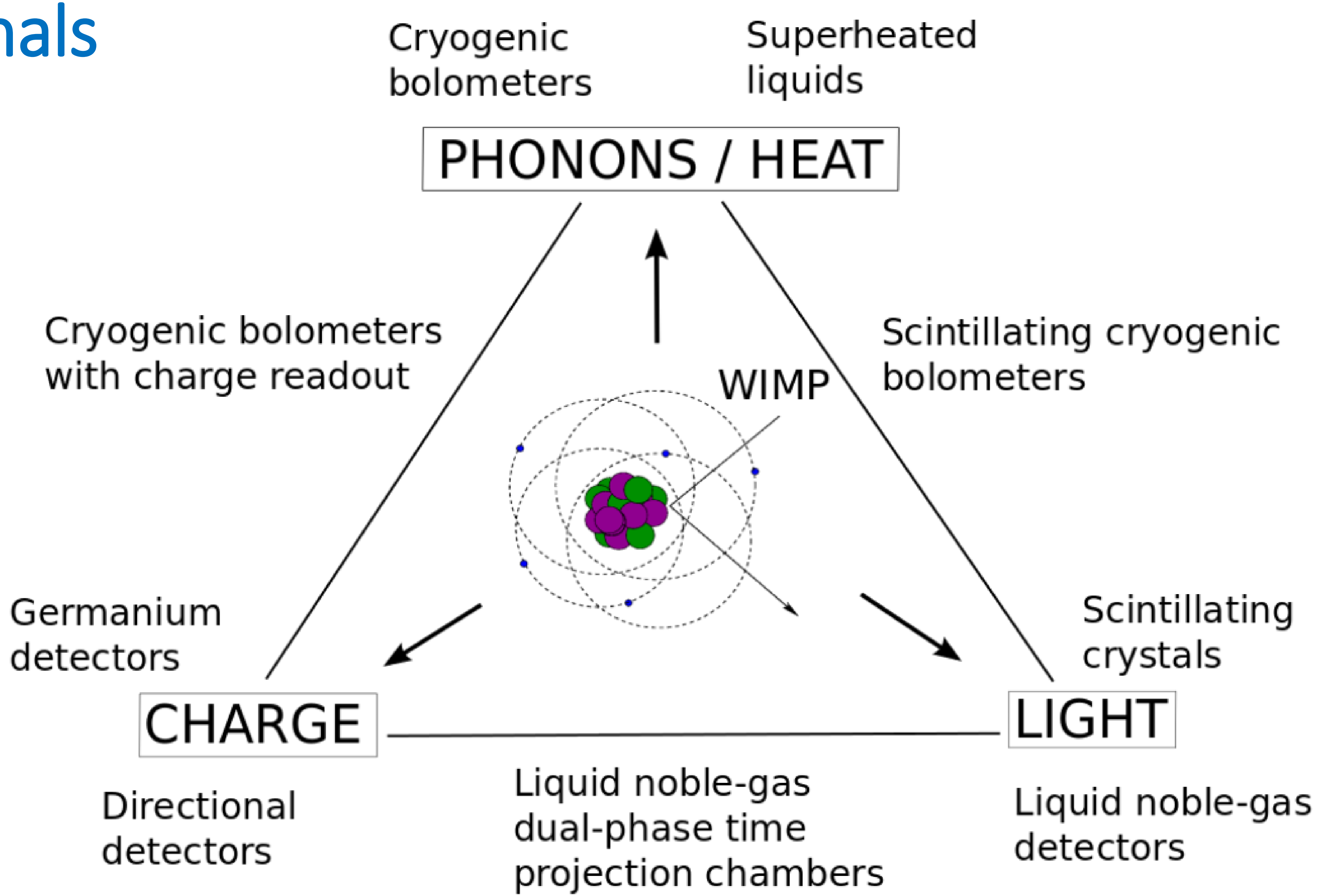
All experiments located underground to shield against backgrounds.

Two approaches:

☐ Very low background experiment
→ where you aim to select only DM events (LZ, Xenon, etc)

☐ Annual modulation signal
→ look for annual modulation on top of a large background (DAMA/Libra)

Types of signals



Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

WIMP

Scintillating cryogenic bolometers

Germanium detectors

Scintillating crystals

CHARGE

LIGHT

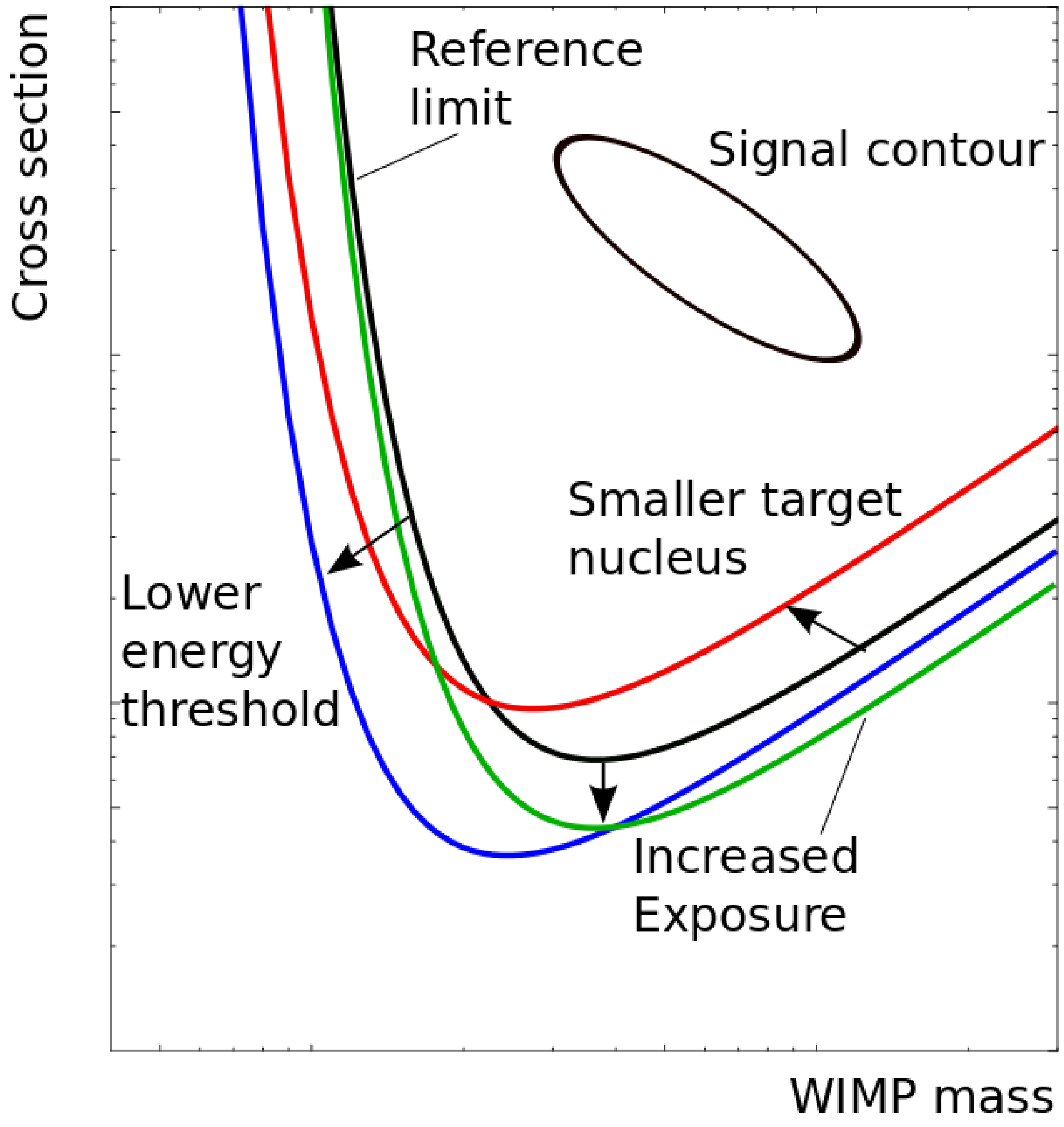
Directional detectors

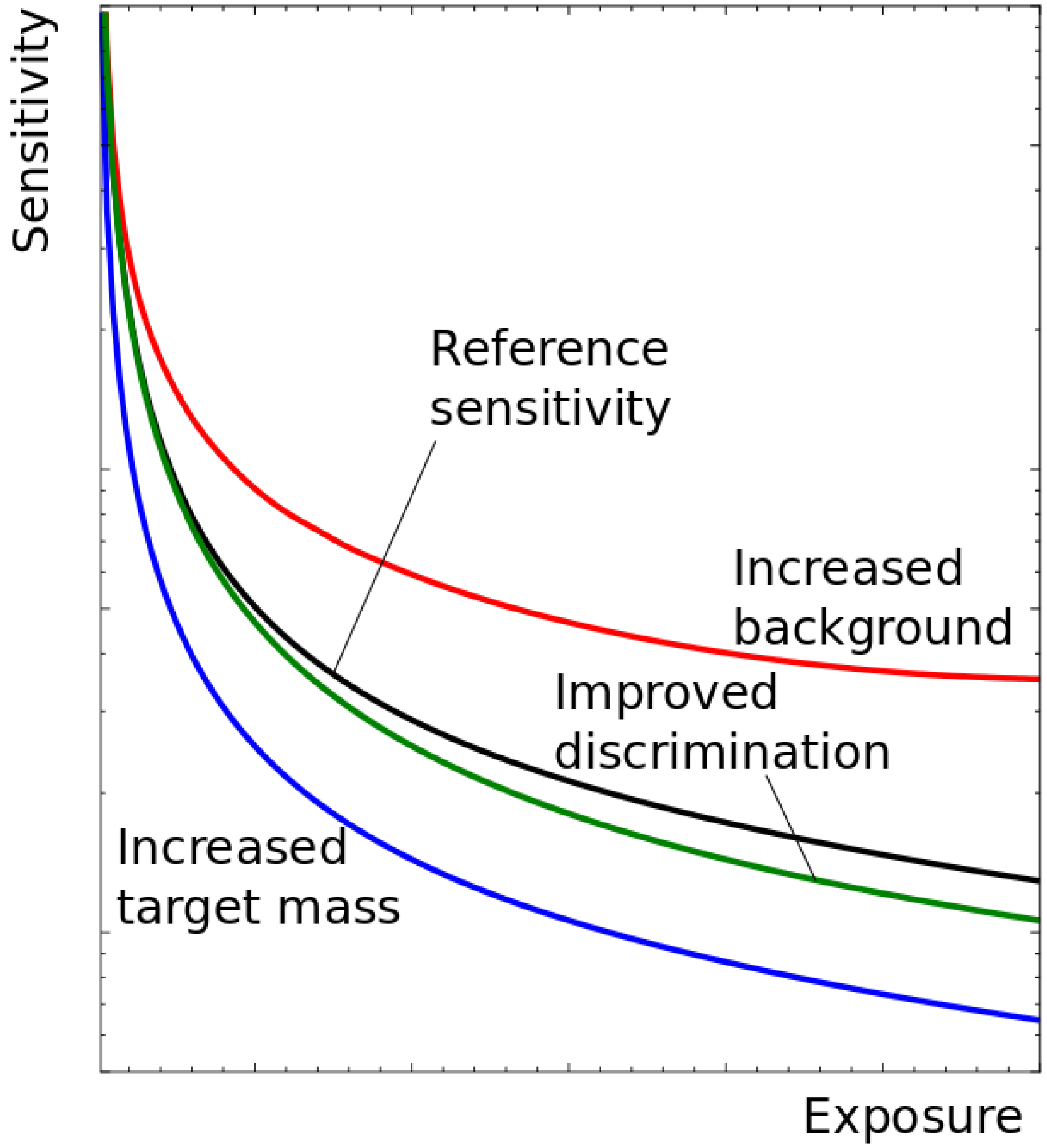
Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

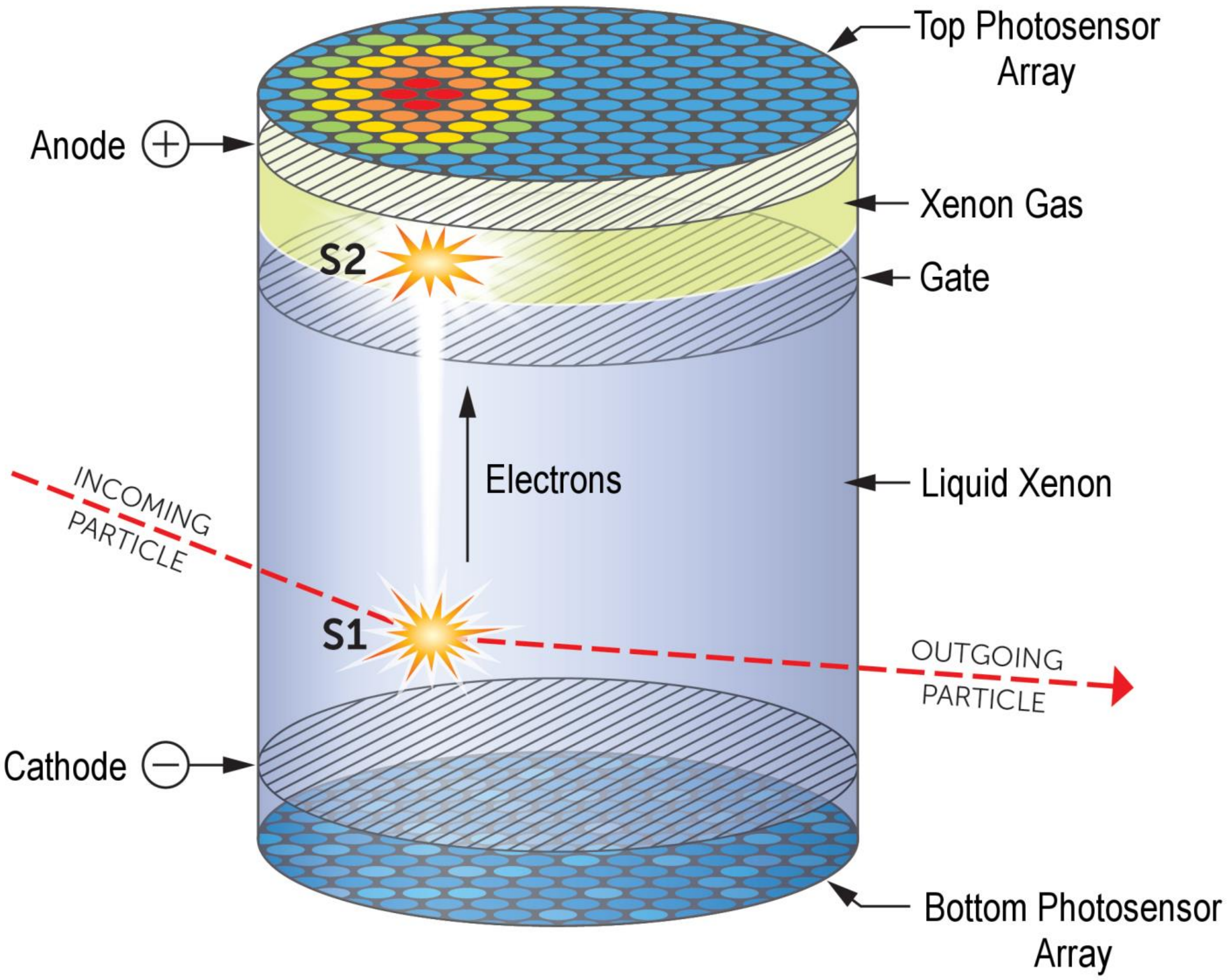
arXiv:1509.08767

arXiv:1509.08767





Dual-phase liquid noble gas TPCs

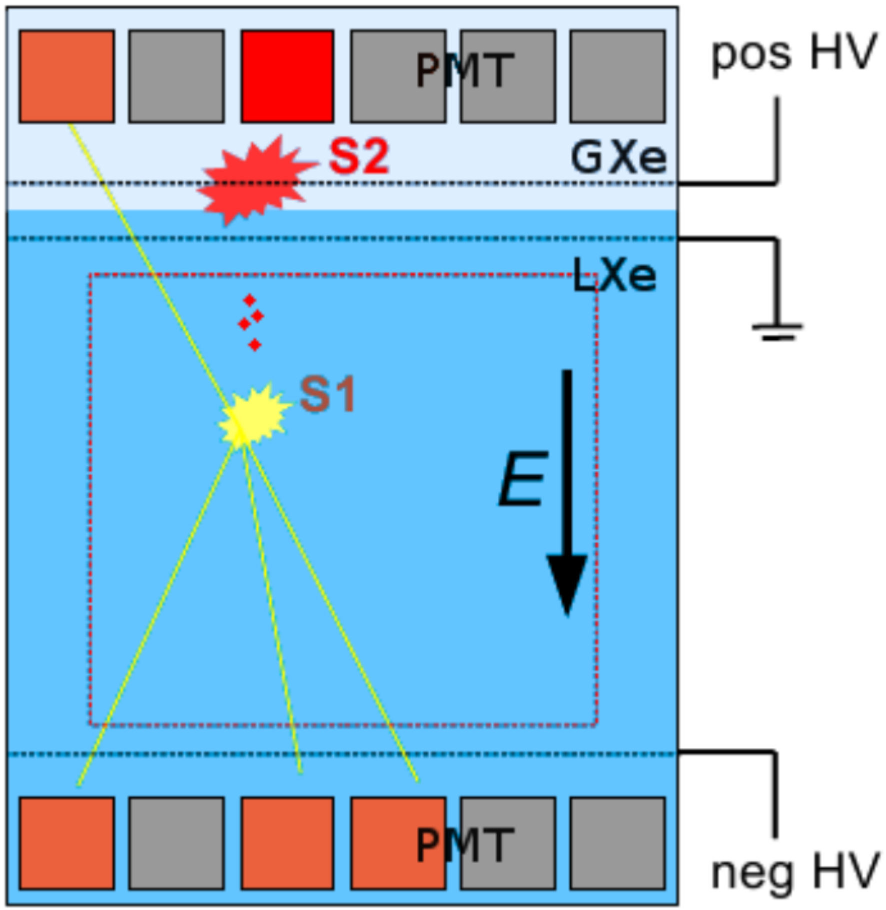


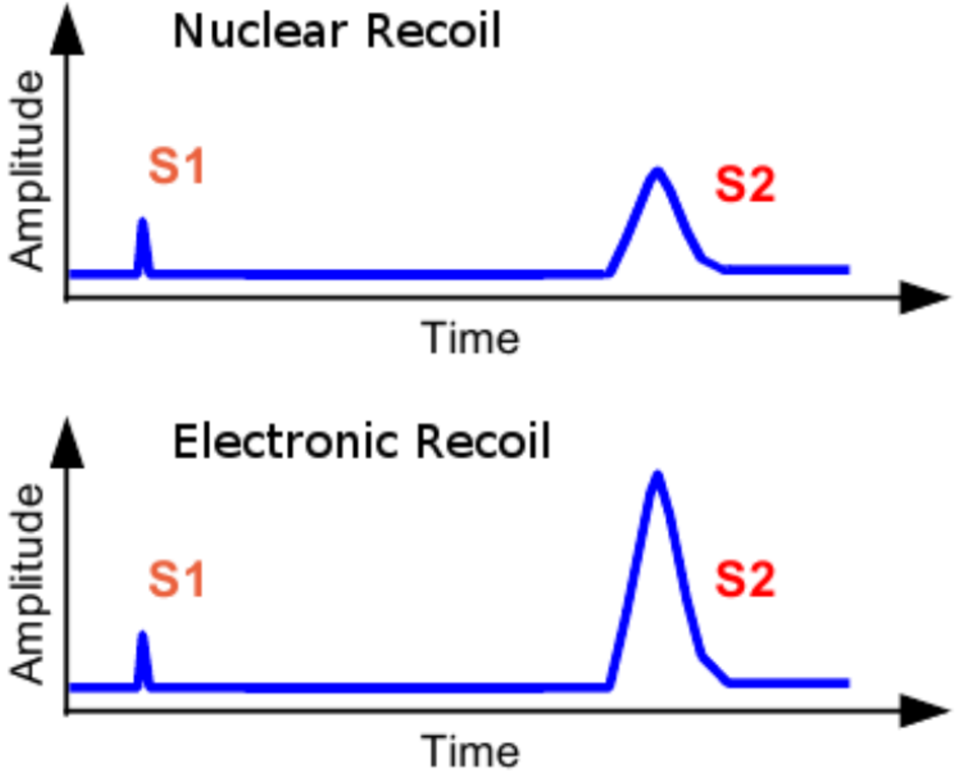
- Electrons drifted upward in electric field→ secondary scintillation signal in the gas phase (S2)

- Excitation→scintillation light (S1)
- Ionisation

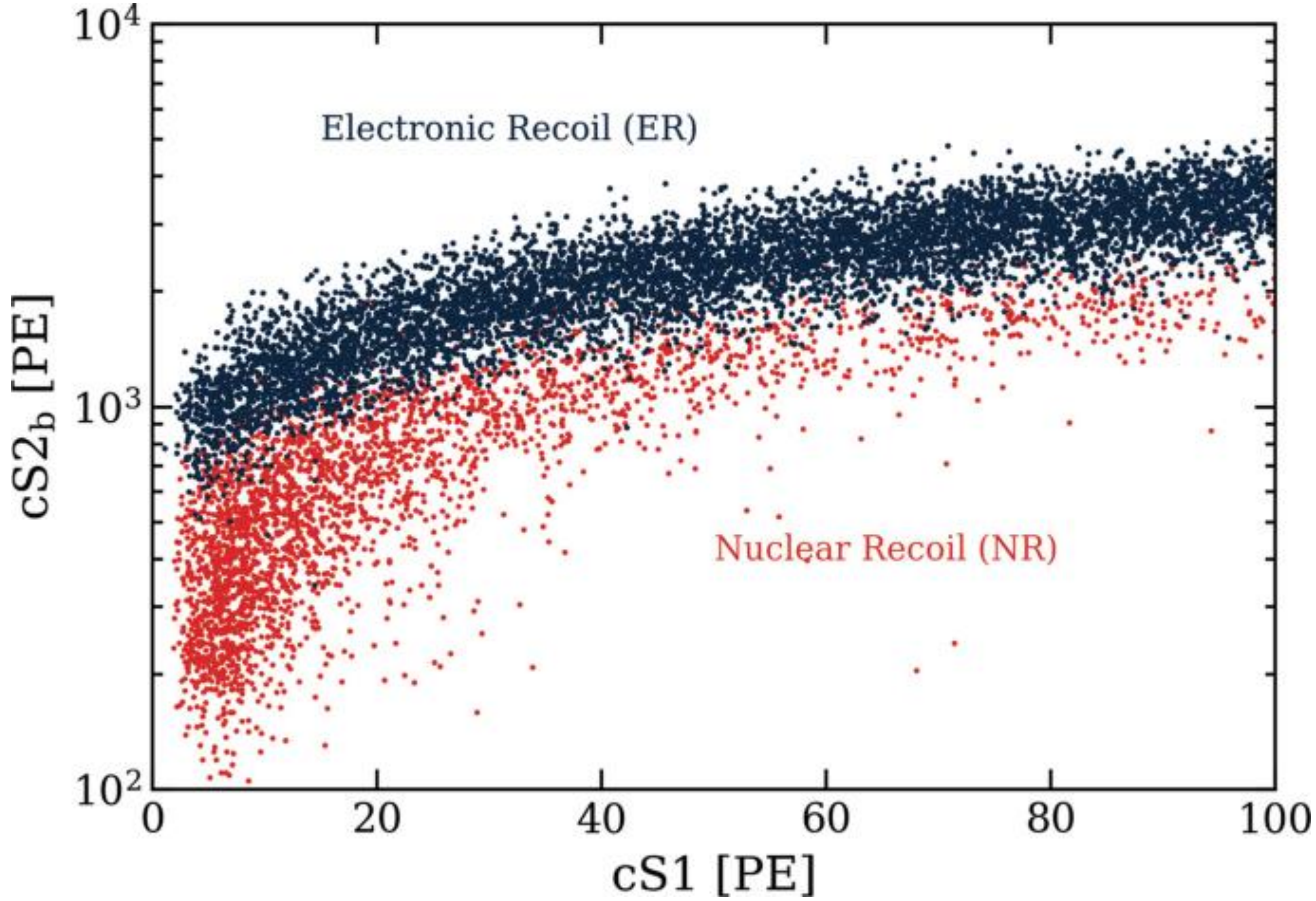
Nuclear vs electron recoil discrimination:

arXiv:1405.7600





Nuclear vs electron recoil discrimination:



Annual modulation signal

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) \cdot \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

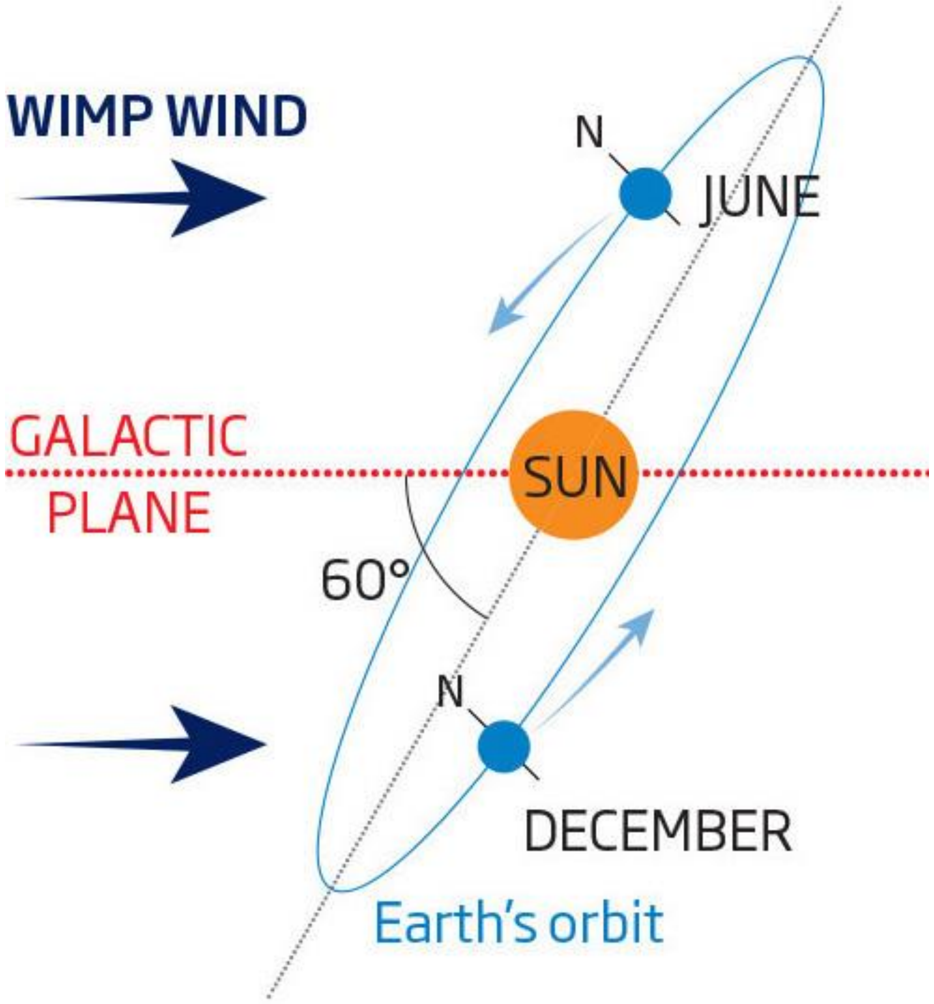
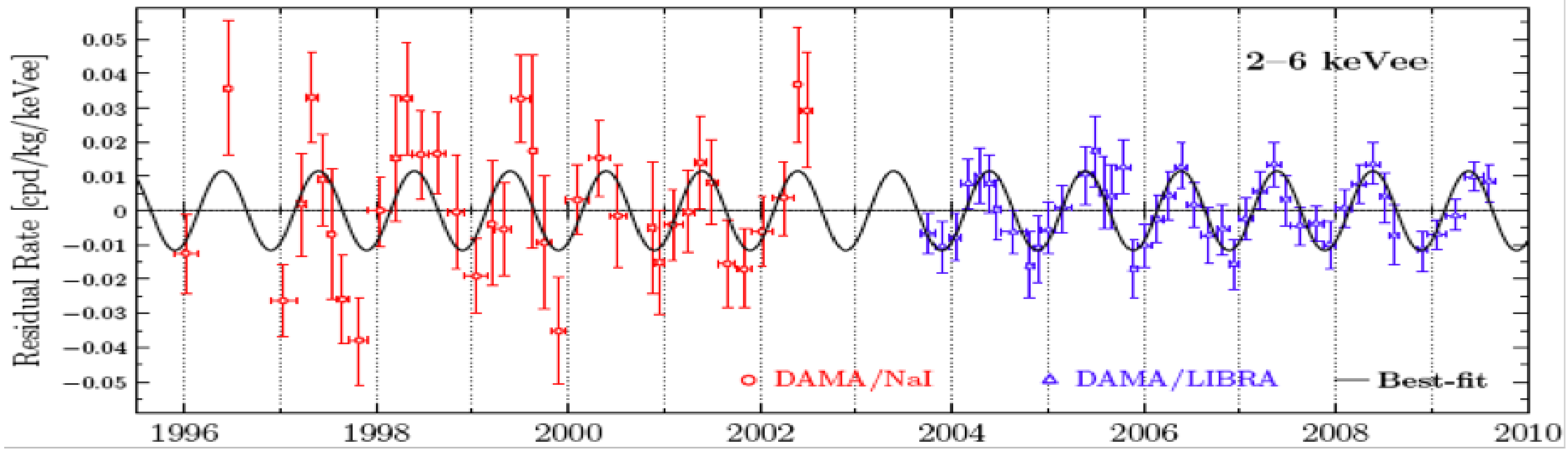


Image credit: New Scientist

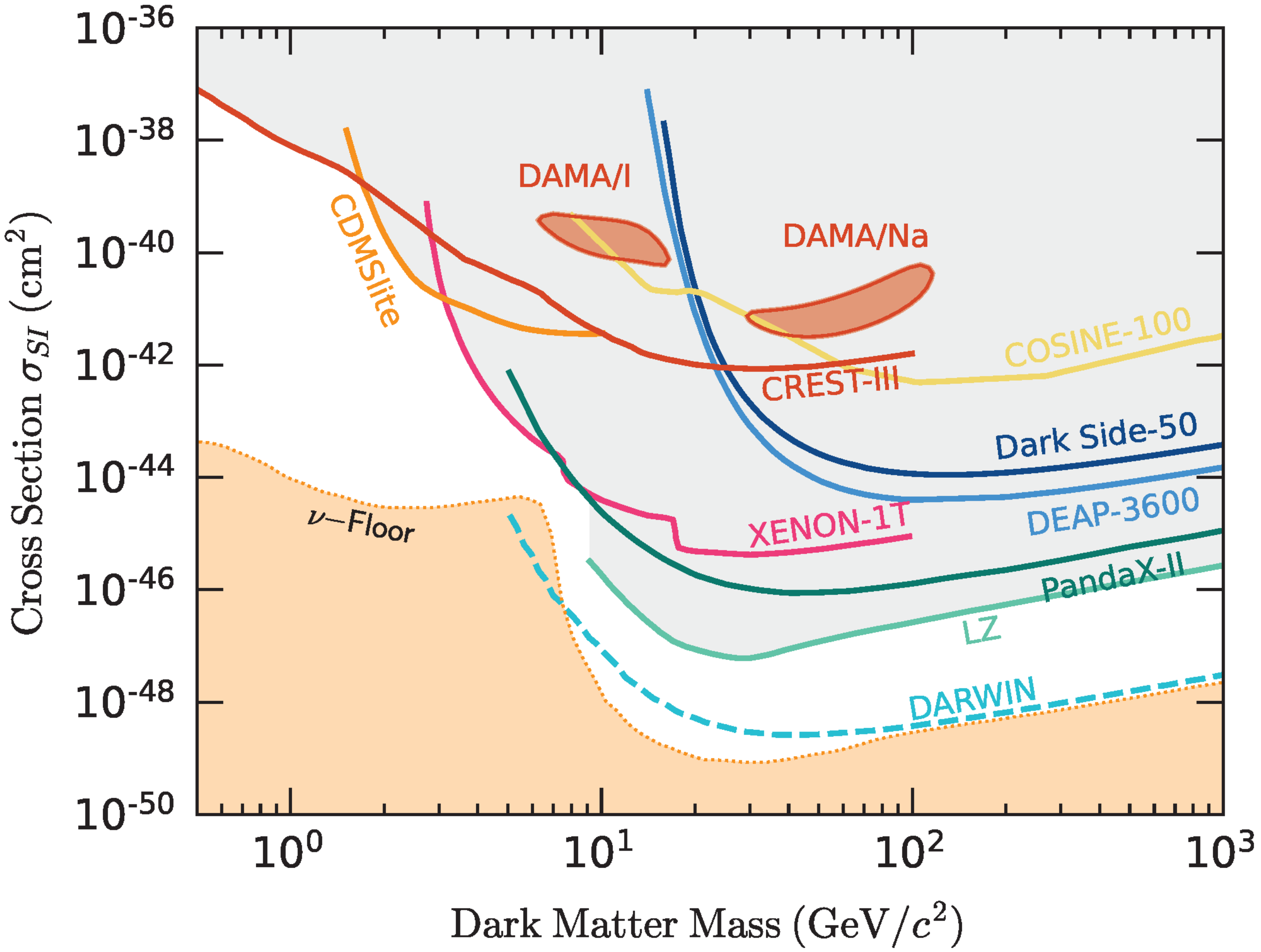
DAMA/LIBRA annual modulation

R. Bernabei et al. (DAMA-LIBRA), EPJ C (2013) 73:2648



Now over 13σ confidence level

Comparison of DAMA signal with exclusion limits from other experiments



→ repeat the experiment in Southern Hemisphere!

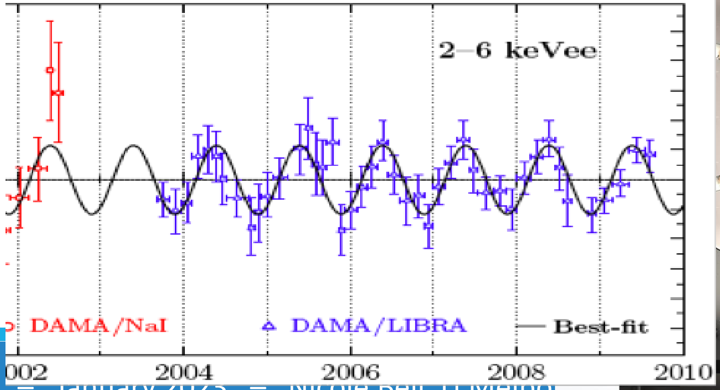
Dark matter, or a non-understood background?

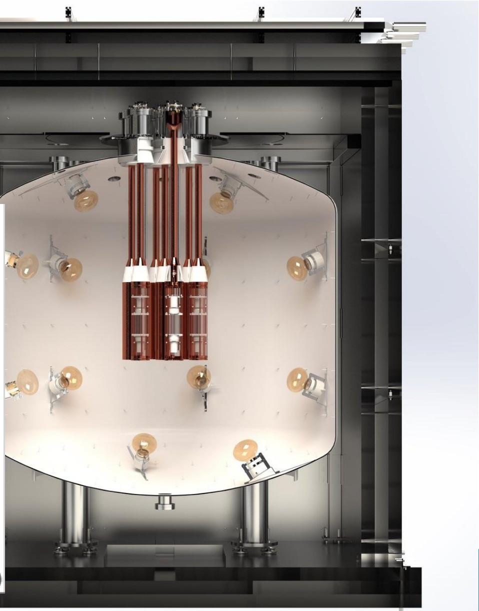
Something is modulated. Strong motivation to check the systematics with an experiment in the southern hemisphere.

→ The phase of a background modulation could be expected to change with location (sessional variation of atmosphere, etc).

→ A genuine dark matter signal will look the same anywhere on Earth.

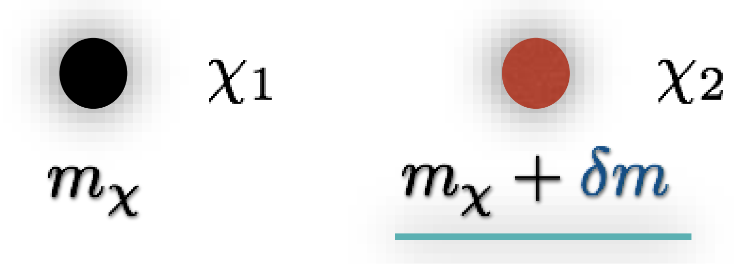
→ SABRE experiment in the SUPL lab in Australia will test/resolve this question





Inelastic dark matter

Two *almost degenerate* dark matter states:



Called inelastic because the $\chi_1\chi_1$ coupling is absent and hence the dominant interaction is

$$\boldsymbol{\chi_1}\, n \rightarrow \boldsymbol{\chi_2}\, n$$

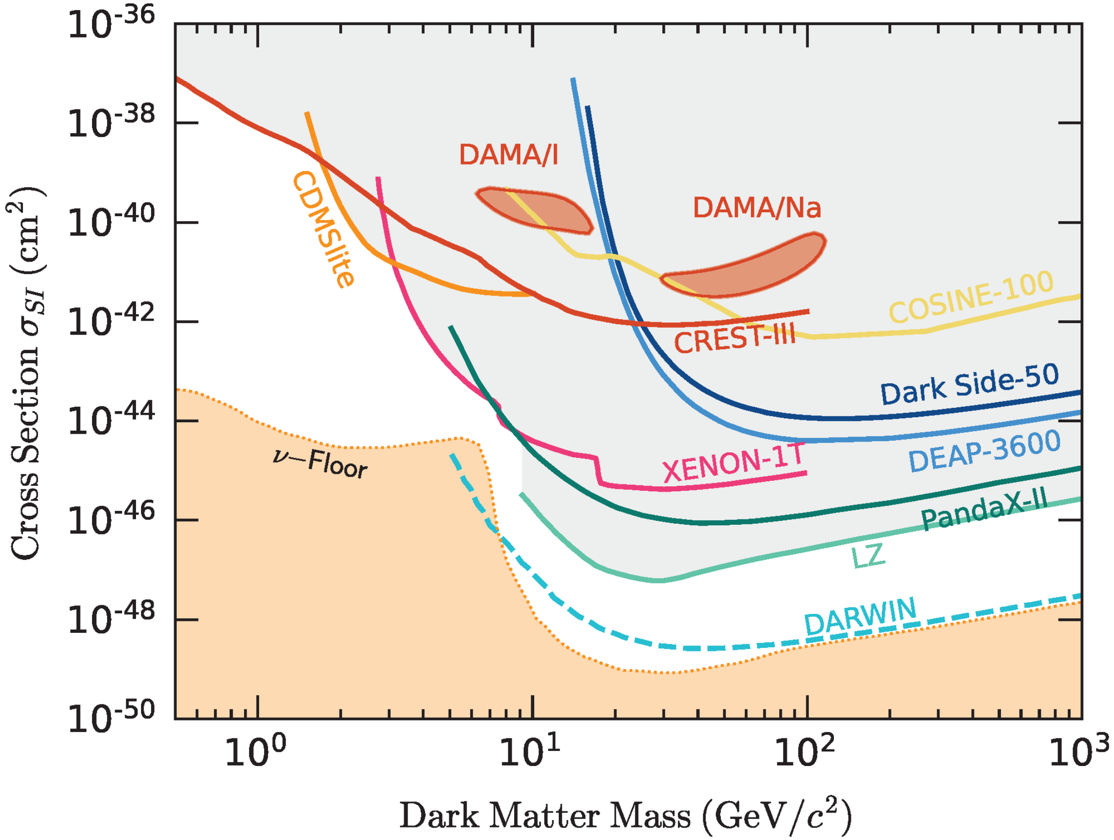
Kinematically forbidden unless mass splitting is small, $\delta m \ll m$

- Direct detection experiments restricted to keV mass splittings, e.g., δ < 180 keV for Xenon
- Bigger mass splittings accessible if DM is quasi-relativistic (some astrophysics scenarios)

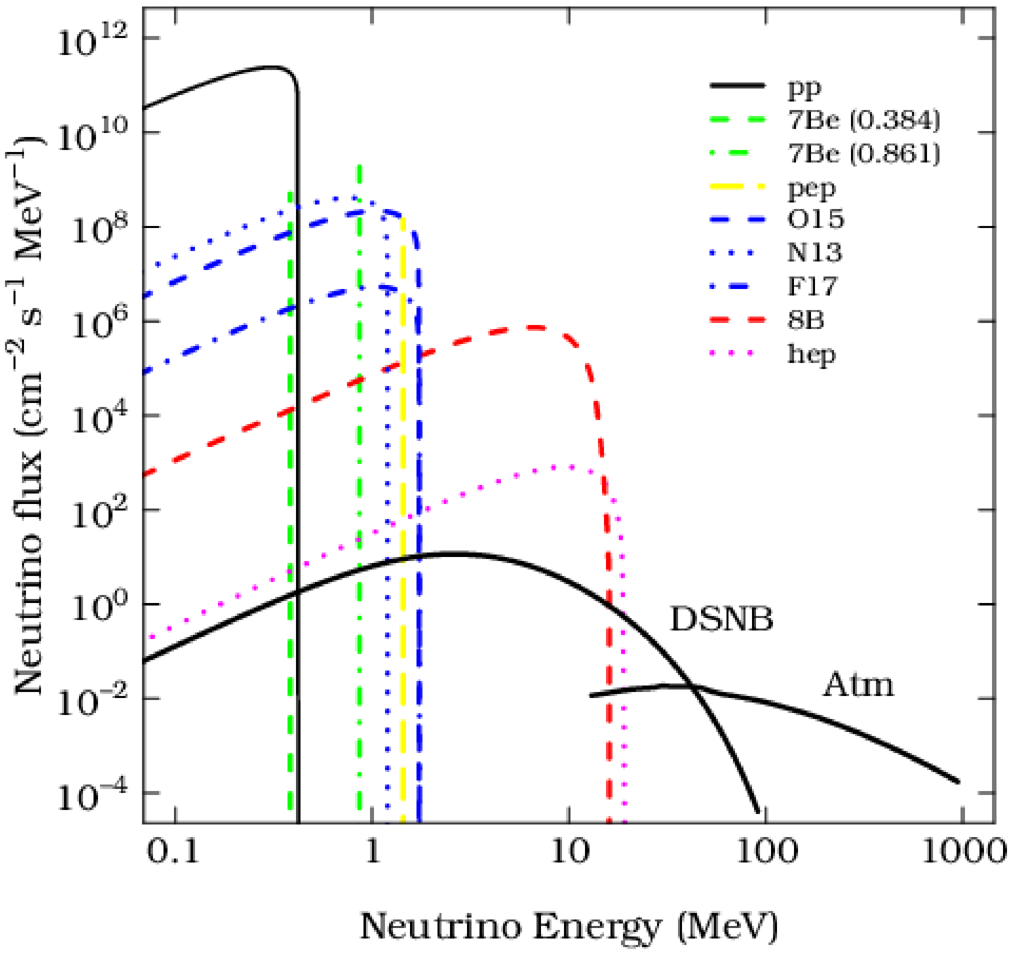
Direct detection challenges: neutrino floor

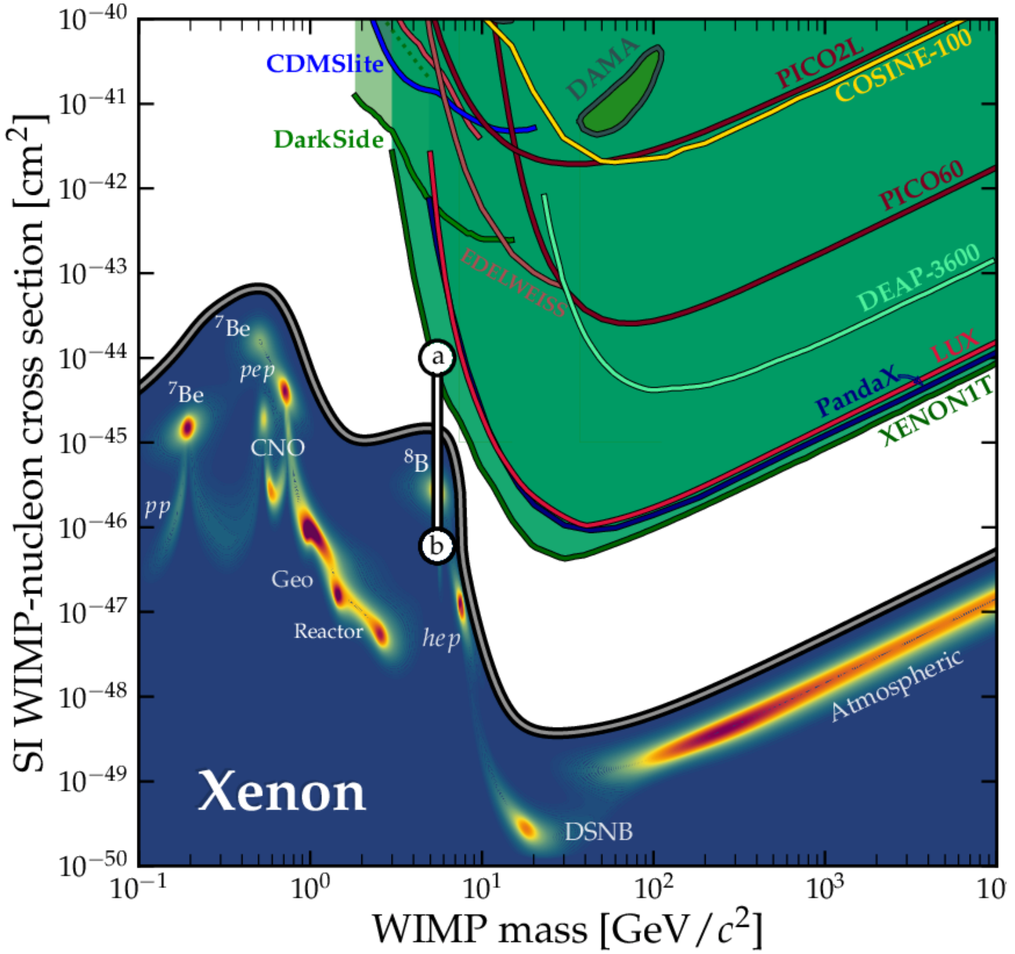
- Next generation experiments will approach the “neutrino floor”, where solar, atmospheric and relic supernova neutrinos become an important background

- Development of directional detection
- *Australian involvement in CYGNUS, a directional detection experiment*



Direct detection challenges: neutrino floor

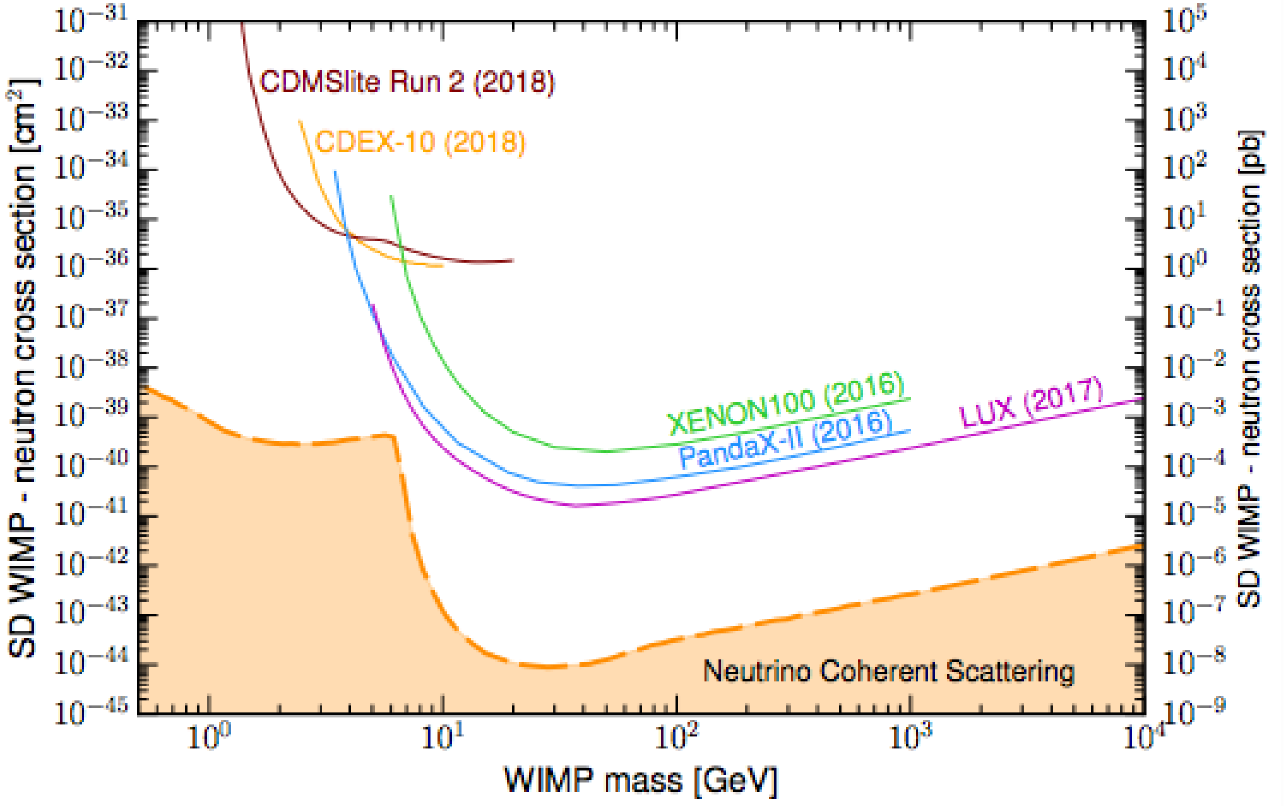




Ciaran O’Hare

Direct detection challenges: low-mass dark matter

- Low-mass dark matter gives very low-energy recoil signals
  -- below experimental thresholds
  - New detection technologies, to achieve lower thresholds
  - New analyses to probe lower mass dark matter using existing detectors



Migdal effect

The ionization of an atom following a nuclear recoil

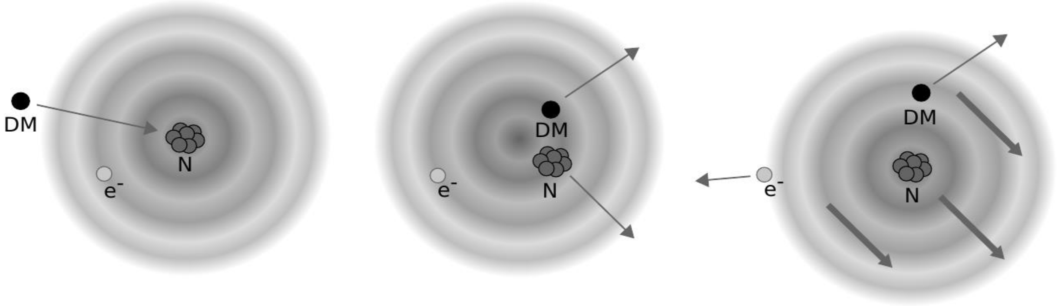


Image: M. Dolan et al.

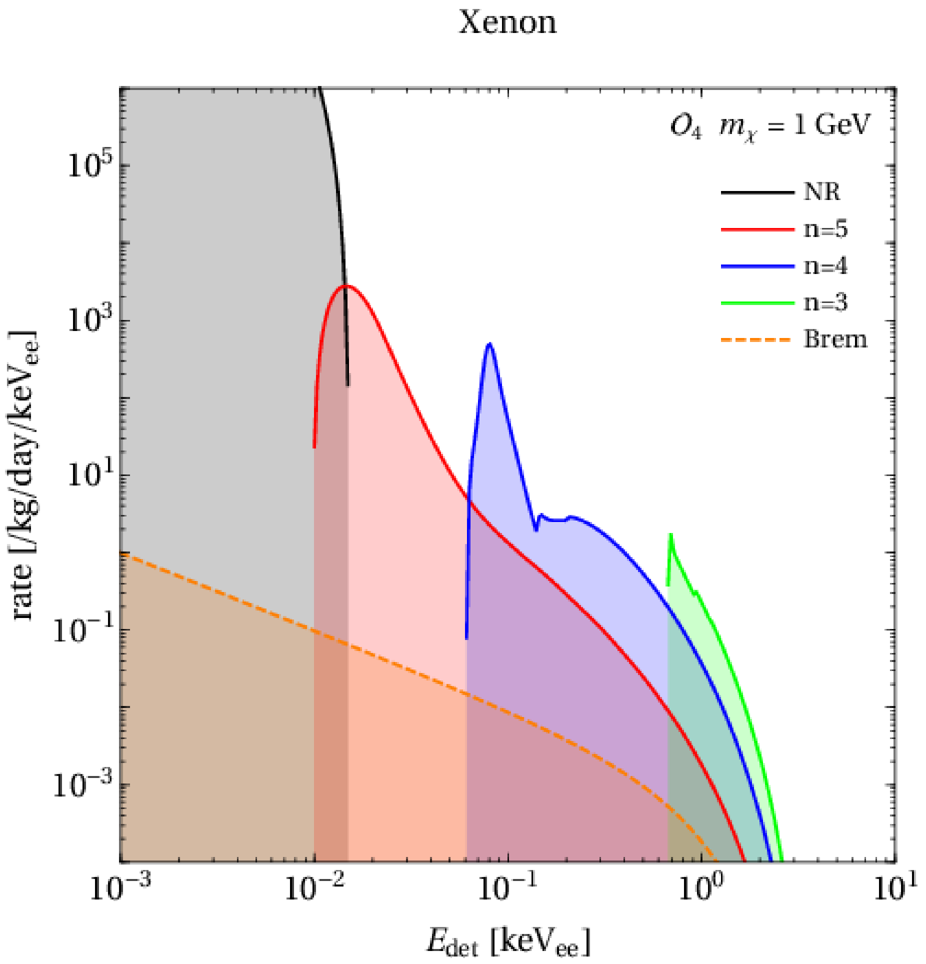
→ Useful in cases where the nuclear recoil is below threshold (i.e., low mass dark matter) and we can instead detect the ionization signal

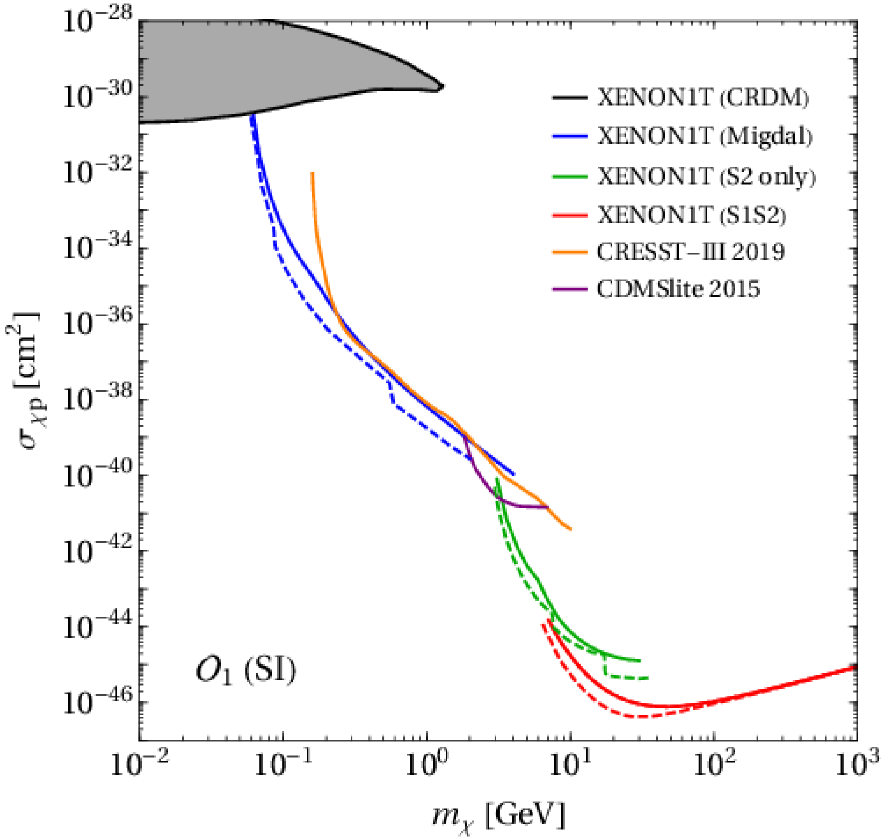
Nuclear recoil: $E_{R,max} = \frac{2\mu_T^2}{m_T} v_{max}^2$

Migdal electrons: $E_{EM,max} = \frac{\mu_T}{2} v_{max}^2$

m_T = Target mass
μ_T = DM-nucleon reduced mass

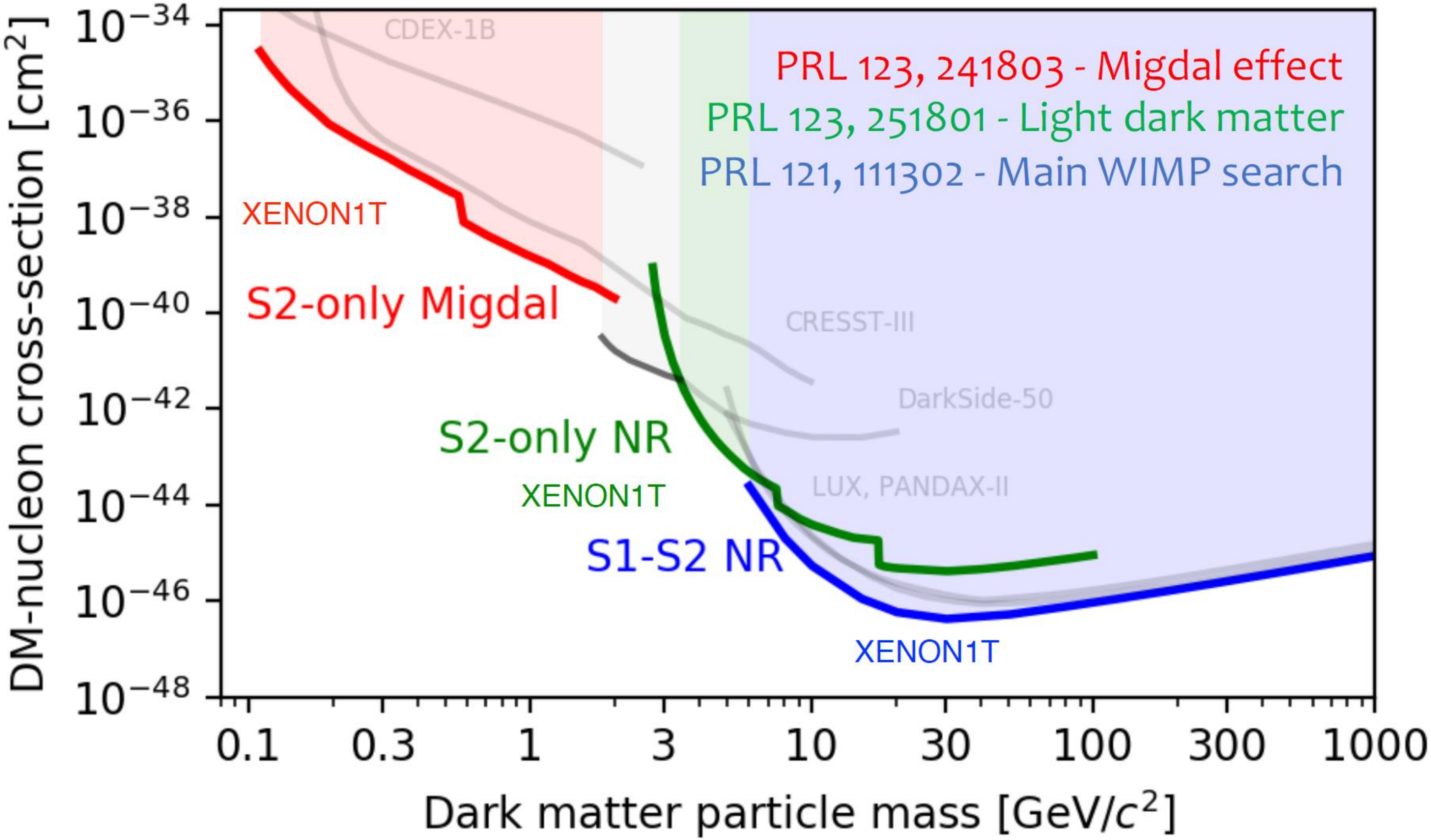
Migdal effect





NFB, Dent, Newstead, Sabharwal & Weiler, PRD, arXiv:1905.00046

Xenon1T limits



PRL 123, 241803 - Migdal effect

PRL 123, 251801 - Light dark matter

PRL 121, 111302 - Main WIMP search

Boosted Dark Matter

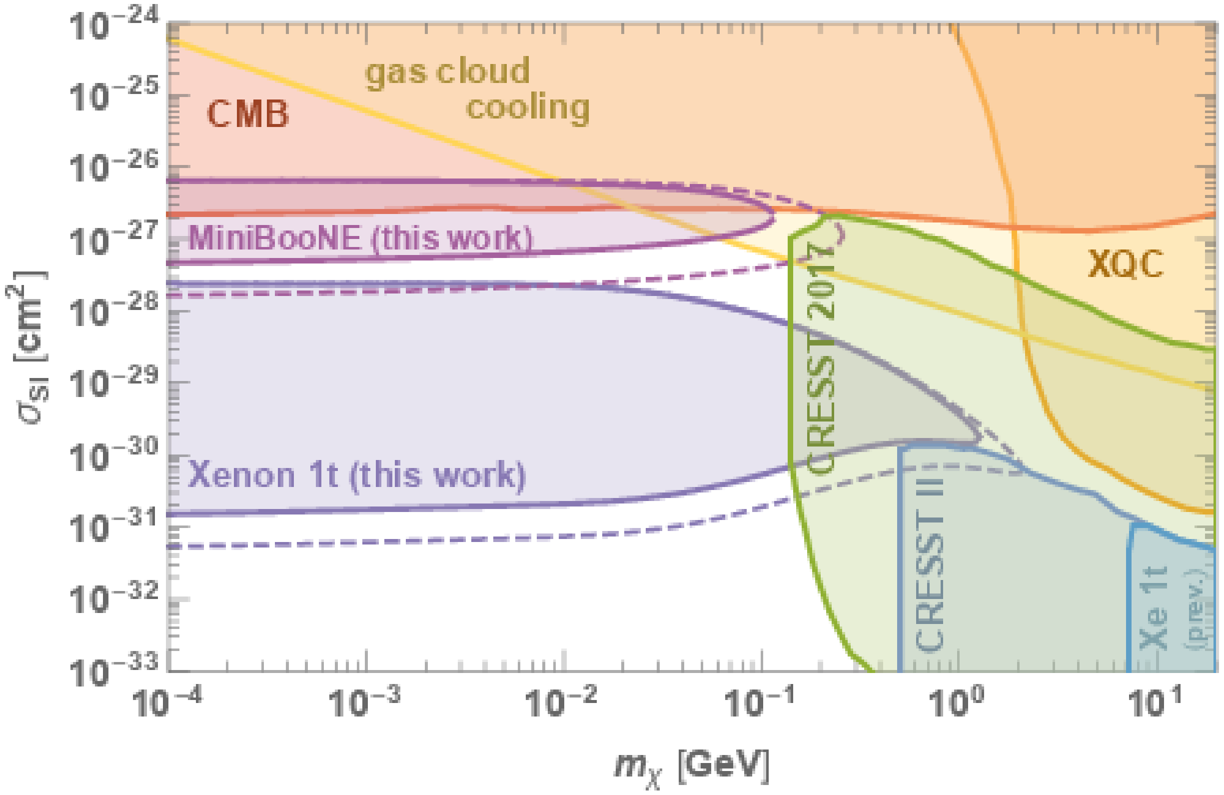
Halo dark matter
  → highly nonrelativistic
    → low energy nuclear recoils in direct detection experiments

Could there be a population of higher-energy dark matter?

- ○ Boosted DM produced from decay/annihilation of heavier dark states
- ○ Cosmic-ray upscattered dark matter ("inverse direct detection")
- ○ DM produced in cosmic ray interactions in the atmosphere ("CR beam dump")
- ○ Solar reflected dark matter
- ○ Supernova dark matter (light dark matter produced in galactic supernova)

Cosmic ray up-scattered dark mater

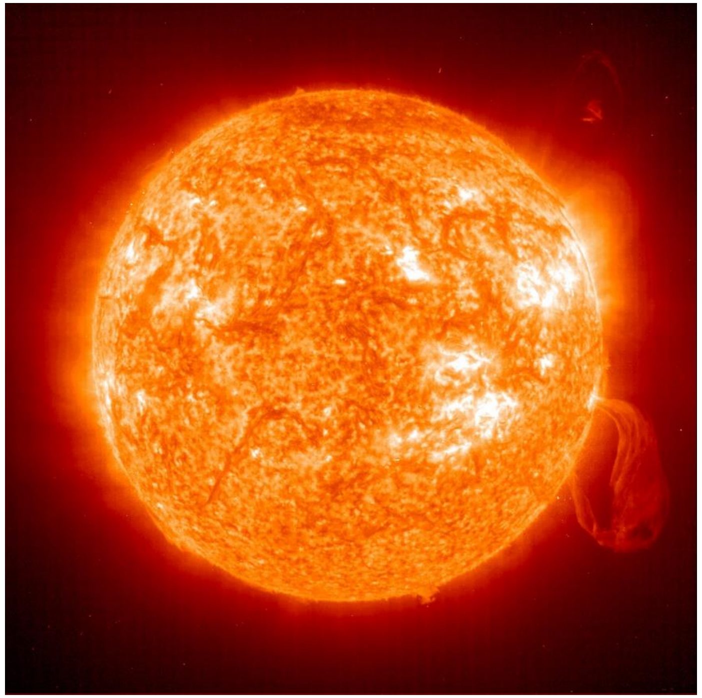
Bringmann & Pospelov, PRL 2019



Allows light dark to be constrained using existing experiments.

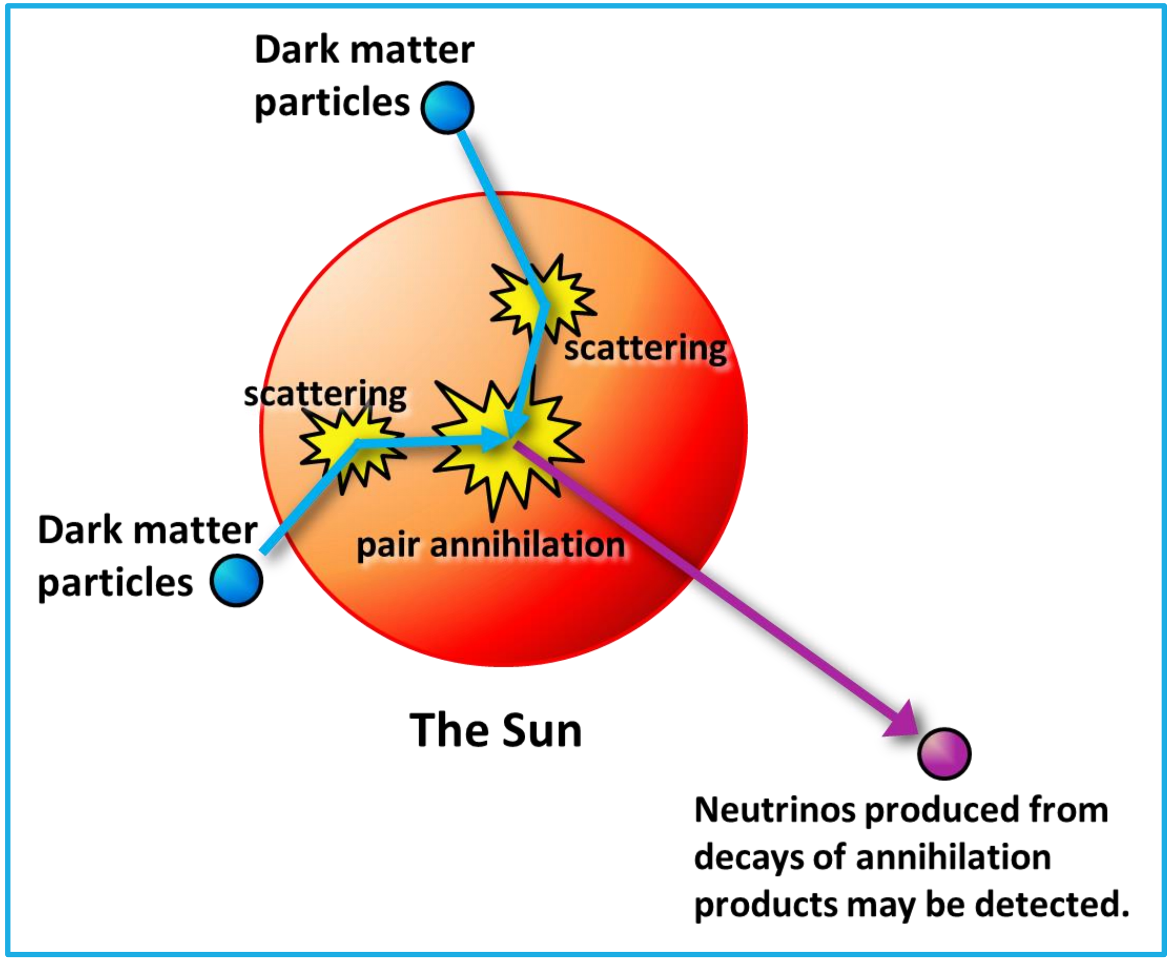
Note that dark matter absorption in the earth imposes upper limit on the cross sections that can be constrained.

Dark Matter Capture in Stars



Dark Matter Capture in Stars

→ an alternative approach to Dark Matter Direct Detection experiments



- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of the star → neutrinos escape

In equilibrium:

Annihilation rate = Capture rate

→ controlled by DM-nucleon scattering cross section

→ probes the same quantity as dark matter direct detection experiments

Capture, annihilation, evaporation

DM number density depends on Capture, Annihilation & Evaporation rates:

$$\frac{dN_\chi}{dt} = C - AN_\chi^2 - EN_\chi$$

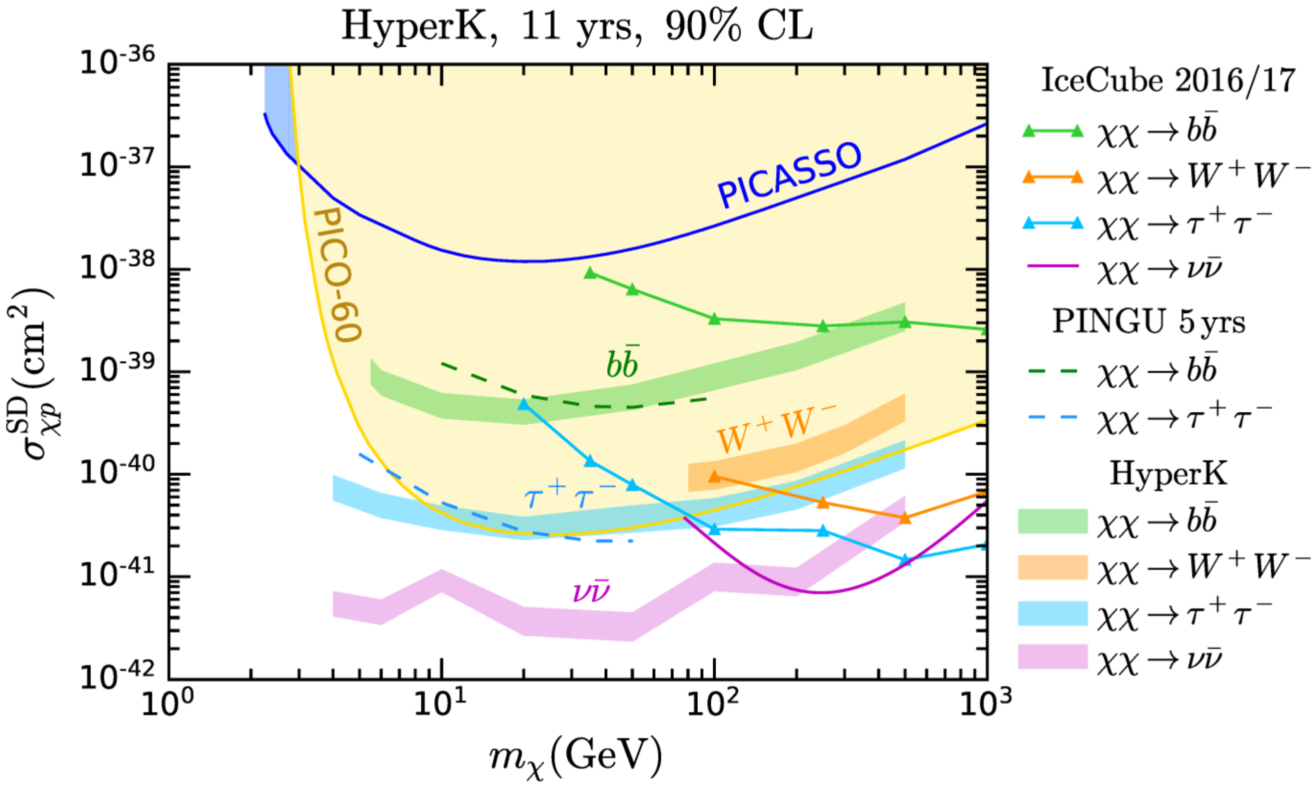
Neglecting evaporation (negligible in the Sun for $m_\chi > 4$ GeV) we have

→ $N_\chi(t) = \sqrt{\frac{C}{A}} \tanh\left(\frac{t}{\tau_{eq}}\right)$ where $\tau_{eq} = 1/\sqrt{CA}$

Capture-annihilation equilibrium when $t \gg \tau_{eq}$: $\Gamma_{ann} = \frac{1}{2} AN_\chi^2 = \frac{1}{2} C$

Dark matter annihilation in the Sun

Spin-Dependent (SD)



NFB, Dolan & Robles, arXiv:2107.04216

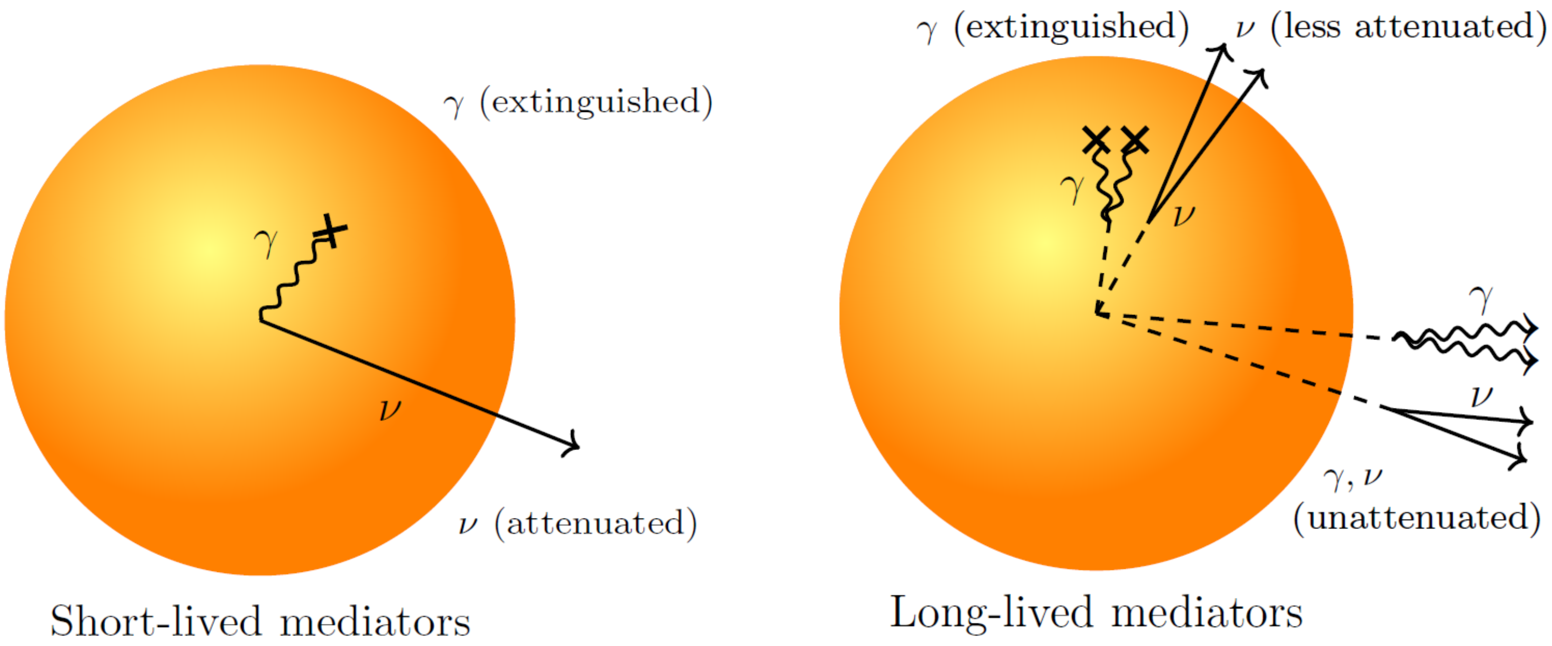
Spin-dependent (SD) interactions:
- solar DM searches competitive or better than direct detection experiments

Spin-independent (SI) interactions:
- direct detection experiments win.

Gamma Rays from the Sun → long lived dark-sector particles

If captured DM annihilates to a light, long-lived mediator (e.g. a dark photon):

- Annihilation products can escape the Sun
- Decay beyond solar core → less attenuation of neutrino signal (NFB & Petraki, JCAP 2011)
- Decay between Sun and Earth → solar gamma rays or cosmic rays



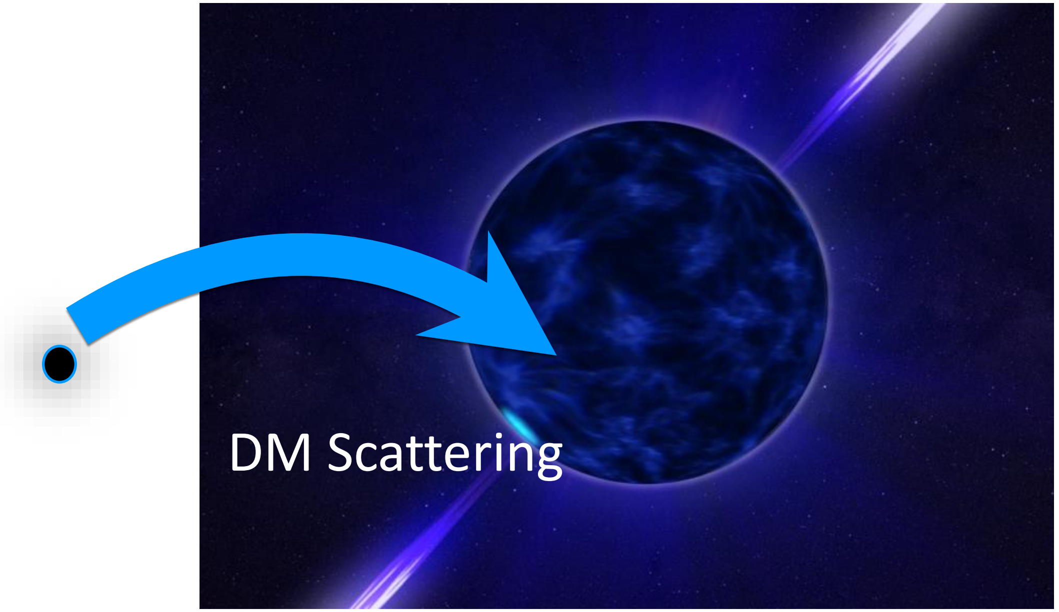
Leane, Ng & Beacom, arXiv:1703.04629

Neutron Stars

Due to their extreme density, ***neutron stars*** capture dark matter ***very*** efficiently.

Capture probability saturates at order unity when the cross section satisfies the **geometric limit**

$$\sigma_{th} \sim \pi R^2 \frac{m_n}{M_*} \sim 10^{-45}\mathrm{cm}^2$$



Dark Matter in Neutron Stars → Black holes?

Kouvaris; Kouvaris & Tinyakov; McDermott, Yu & Zurek; Bramante, Fukushima & Kumar; NFB, Petraki & Melatos; Bertone, Nelson & Reddy; and others.

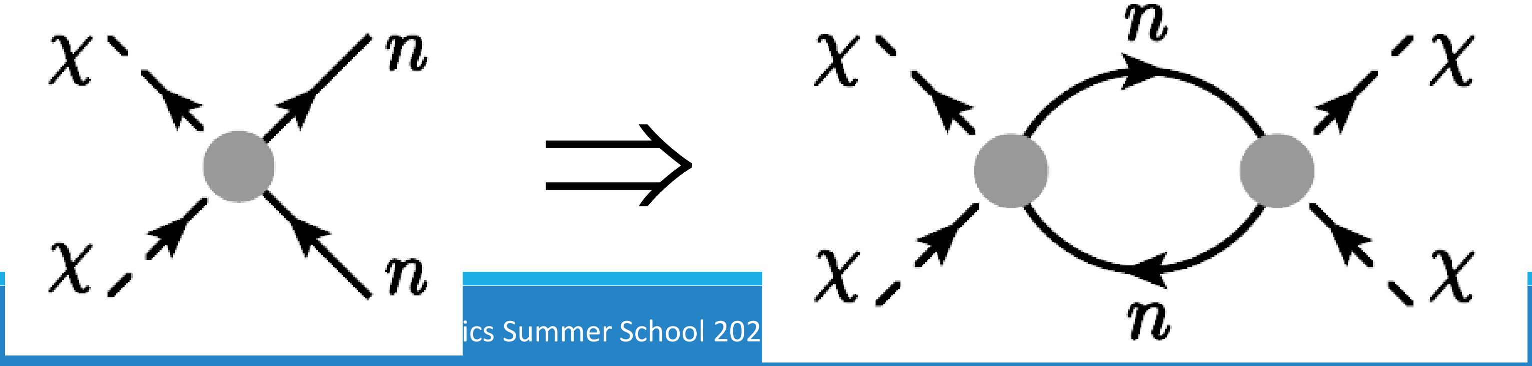
- Due to their density, neutron stars capture dark matter very efficiently

- Can neutron stars accumulate so much dark matter that they would collapse to back holes? Yes, but typically only if:
  - No annihilation (e.g. asymmetric DM)
  - DM is bosonic (and condenses to a small self gravitating BEC), or
  - DM is fermionic with attractive self-interactions, and
  - No repulsive-self interactions that prevent collapse (even very very tiny self-interaction is enough) **NFB, Petraki & Melatos, PRD 2013**

→ **Black hole formation possible but quite unlikely for *typical* WIMP-like dark matter**

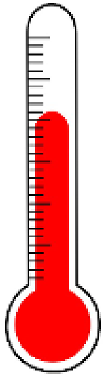
Evolution of DM in a neutron star

- Capture - DM-nucleus scattering
- Thermalisation – scattering, energy loss, DM accumulates in a small thermal sphere.
- Self gravitation (and possible BEC formation) – occurs when enough DM has accumulated to overwhelm the NS gravity (in the small thermal sphere).
- Collapse ? – if self gravitating DM exceeds the Chandrasekhar limit.
  – black hole grows by accretion or evaporates
- Self-interactions prevent collapse. Not that if DM scatters from nucleons, a self-interaction term must be present, at least at loop level.



Neutron star heating

→ from dark matter scattering plus annihilation



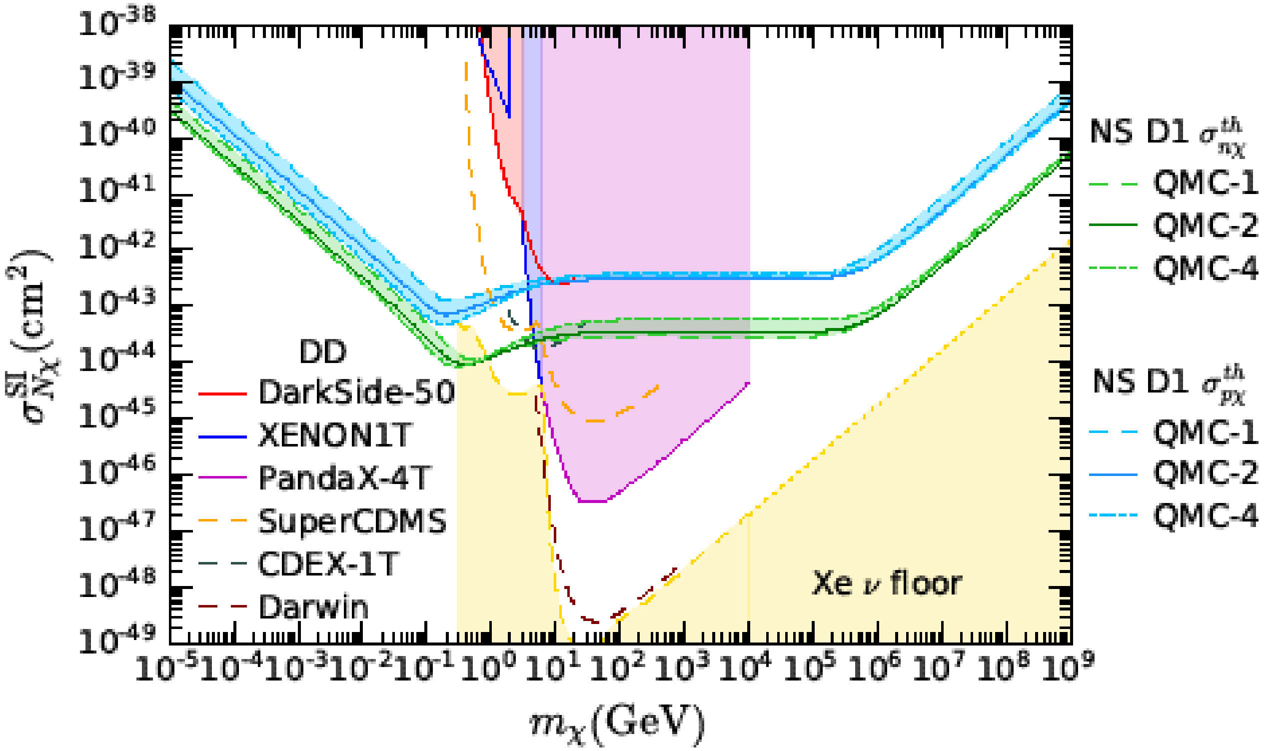
- **Capture** (plus subsequent energy loss)
  → DM ***kinetic energy*** heats neutron star ~ **1700K** (Baryakhtar et al)
- **Annihilation** of thermalised dark matter
  → DM ***rest mass energy*** heats neutron star ~ **additional 700K**

Coolest known neutron star (PSR J2144-3933) has a temperature of ~ 4.2 x 10^4 K.

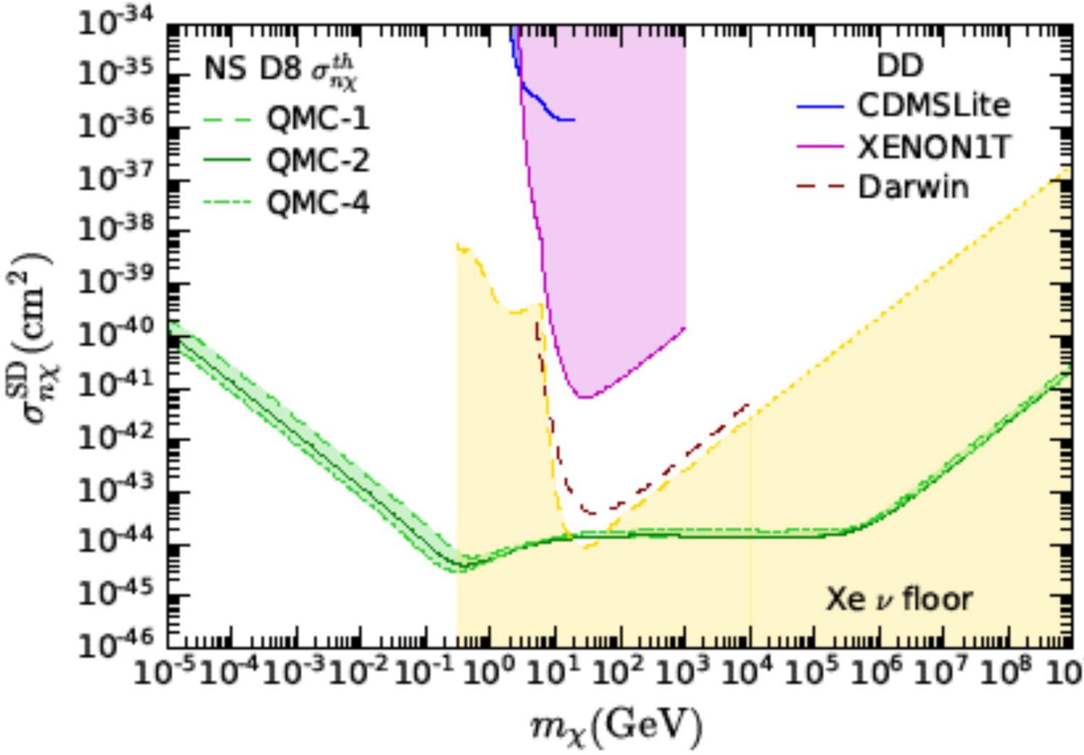
Old isolated neutron stars should cool to: 1000 K after ~ 10 Myr
100 K after ~ 1 Gyr

Kinetic Heating Sensitivity: nucleon scattering

Spin-Independent (SI)

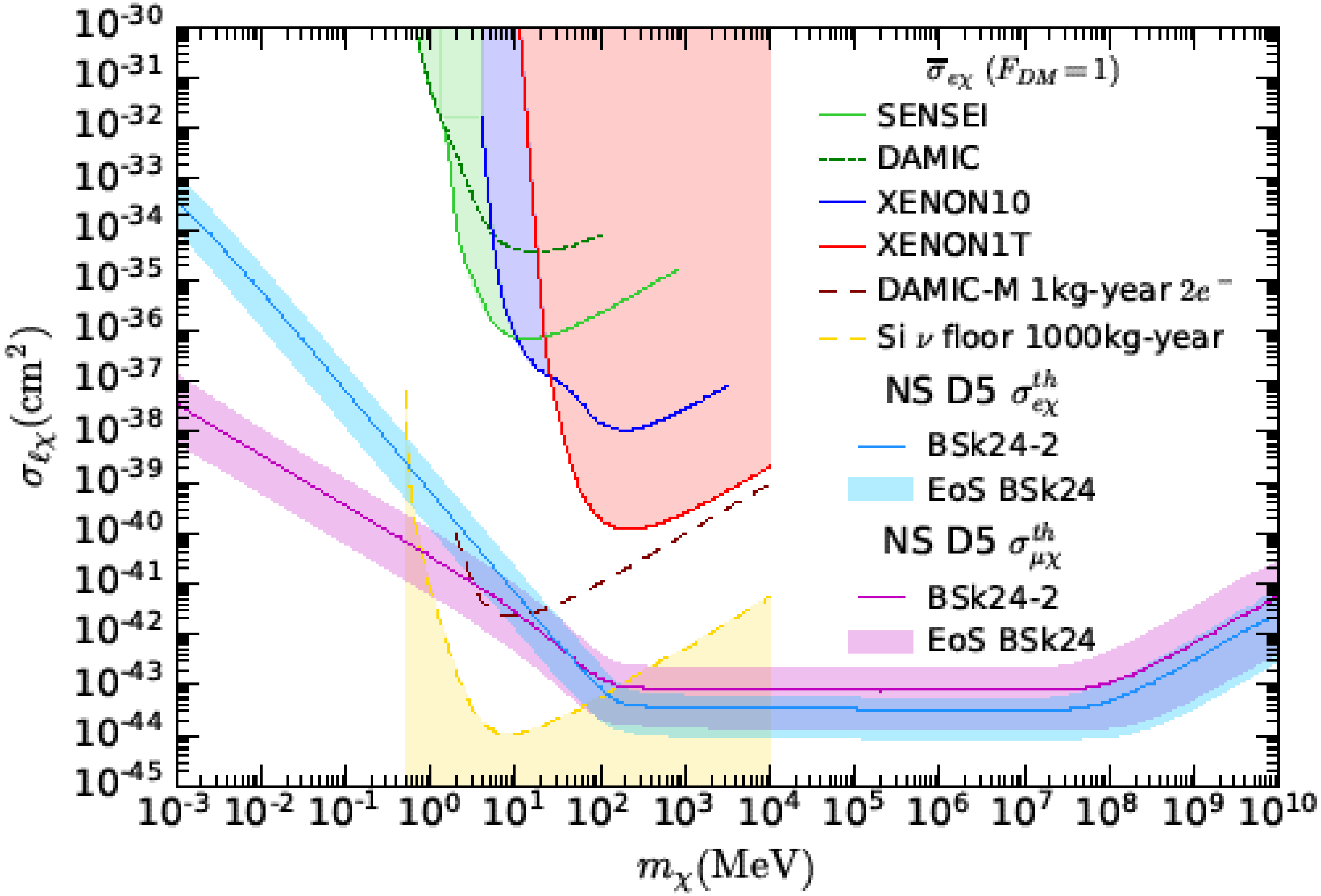


Spin-Dependent (SD)



Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, arXiv:2108.02525

Kinetic Heating Sensitivity: lepton scattering



NFB, Busoni, Robles & Virgato arXiv:2010.13257

Muon scattering

Electron scattering

Useful references

Freezeout:

- Kolb and Turner, “The Early Universe”

Review papers:

- Bertone, Hooper, Silk, Physics Reports 405, 279, 2005 [arXiv:hep-ph/040417]
- Feng, Ann. Rev. Astron. Astrophys. 48: 495, 2010 [arXiv:1003.0904]

Direct detection:

- Undagoitia and Rauch, J. Phys. G43, 1, 013001, 2016 [arXiv:1509.08767]
- Aalbers et al, J.Phys.G 50, 1, 013001 2023 [arXiv:2203.02309]