Darker than dark:
Searching for hidden particles with tiny couplings

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PRISMA Colloquium
JGU Mainz
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Including results from
arXiv:1809.04849 with Saniya Heeba and Patrick Stöcker
arXiv:1908.09834 with Saniya Heeba
arXiv:1910.02091 with Matthias Geilhufe and Martin Winkler

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

TTK Institute for Theoretical Particle Physics and Cosmology
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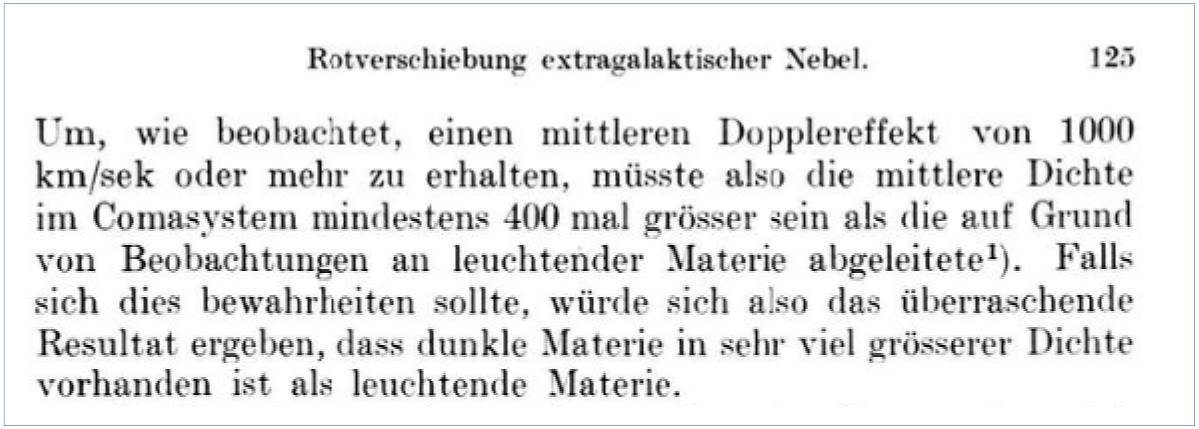
Outline

- The dark matter puzzle
- Dark matter in the early Universe
  - Weakly Interacting Massive Particles (WIMPs)
  - Feebly Interacting Massive Particles (FIMPs)
- Finding FIMPs
  - Part 1: Decaying dark matter
  - Part 2: New force carriers
  - Part 3: New detector concepts

How to find missing (dark) matter

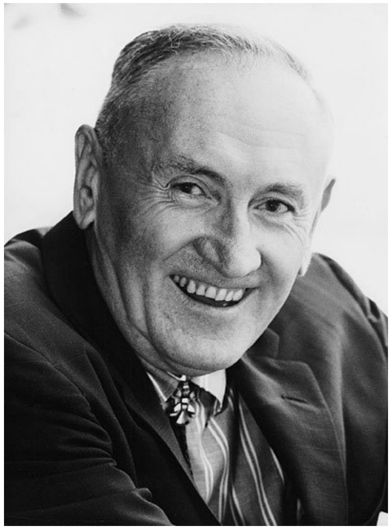
- Map out the **distribution of visible matter**
- Determine its **gravitational potential**
- Calculate the **motion of visible objects** in this potential
- Compare to **observations**

- First done in 1933 by Fritz Zwicky
  - Apply the virial theorem to the Coma cluster
  - Compare gravitational potential and velocity distribution



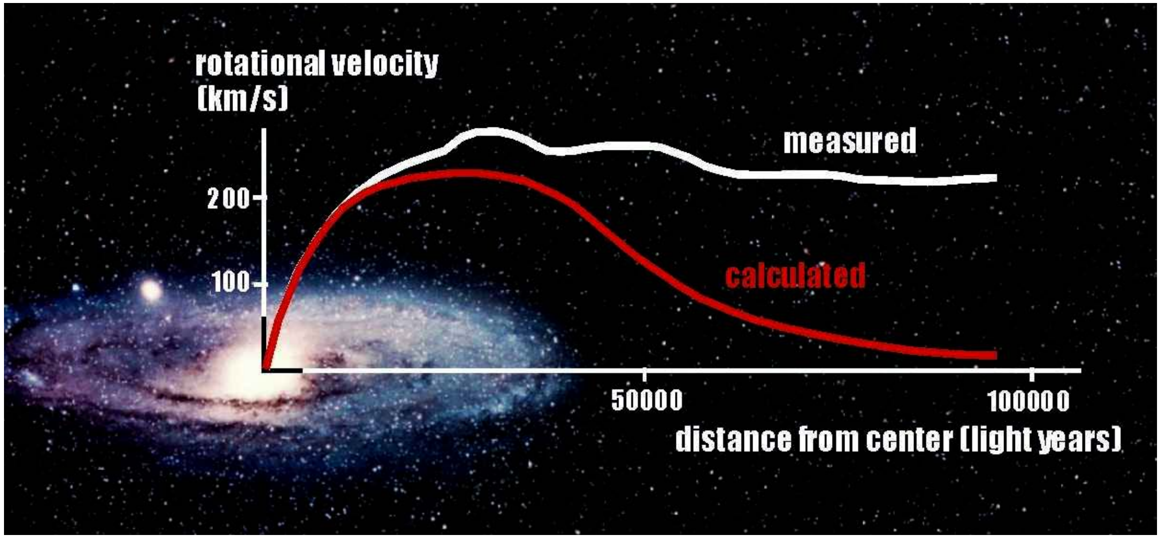
Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.



Galaxy scales: Rotation curves

- In the 1970s Vera Rubin applied a similar approach to galaxies
  - Measure the **rotational velocities** of stars and gas at different distances from the centre
  - Infer the **gravitational potential** needed to maintain these velocities



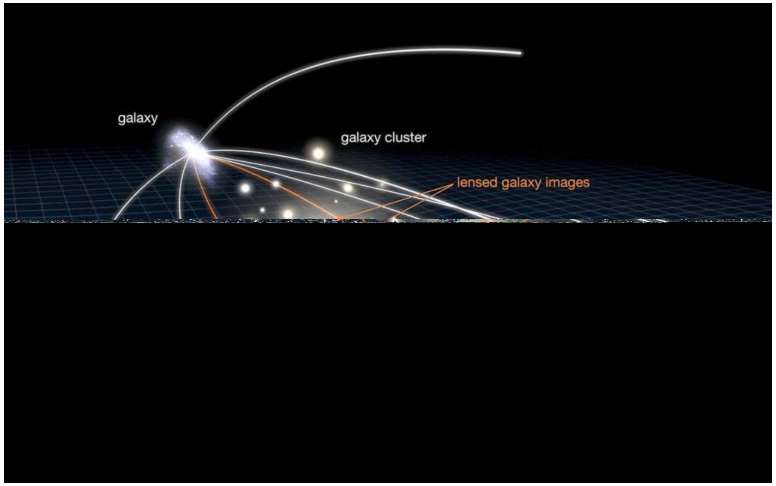
- Beyond the visible disk we expect velocities to decrease
- But velocities stay constant up to very large distances
- An **additional contribution from invisible matter** is necessary to keep these objects bound

Gravitational lensing & the Bullet Cluster

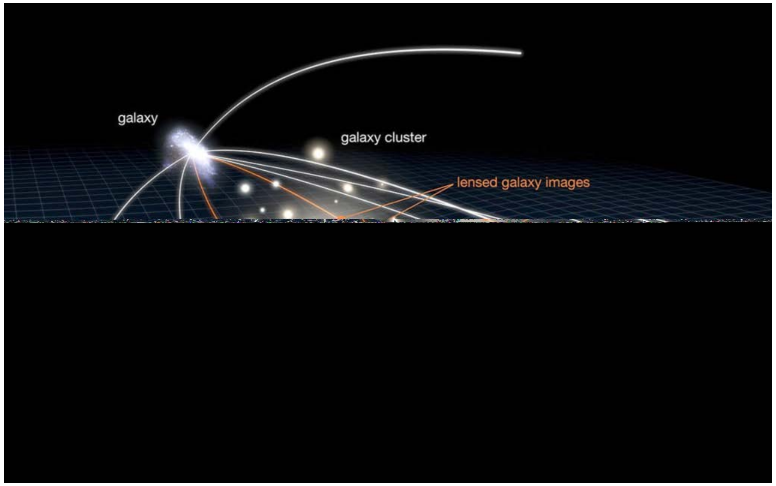
- To search for dark matter on even larger scales, we can make use of **gravitational lensing**

- Distortions of the shape of far-away objects allow to infer amount of matter along the way

- We can **map out the distribution** of dark matter!



Gravitational lensing & the Bullet Cluster



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- Distortions of the shape of far-away objects allow to infer amount of matter along the way
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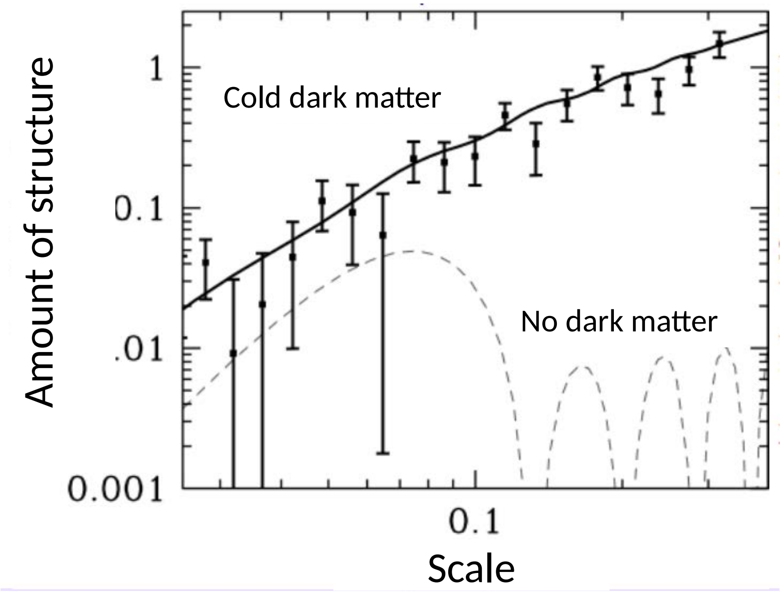
- The Bullet Cluster is a **collision of two galaxy clusters**
- The dominant contribution to gravitational lensing does not coincide with the light emission
- Explanation: **separation of dark and visible matter** due to the collision!

Cosmological scales: Structure formation



- We can even infer the presence of dark matter in the **very early Universe**
- Dark matter is not affected by the high density of energetic photons after the Big Bang
  - Gravitational collapse for dark matter is faster than for visible matter
  - Dark matter **forms structures much earlier** than visible matter
- Dark matter is necessary to explain observed **amounts of structure** in the present Universe

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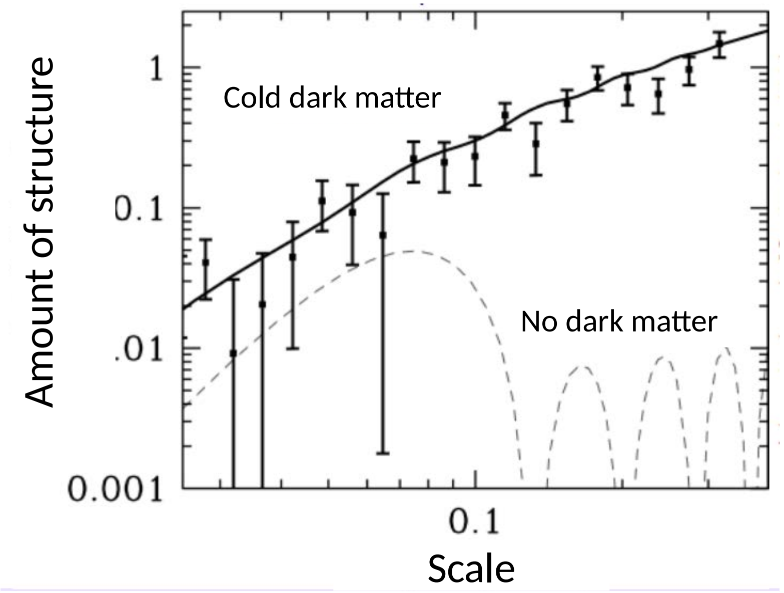

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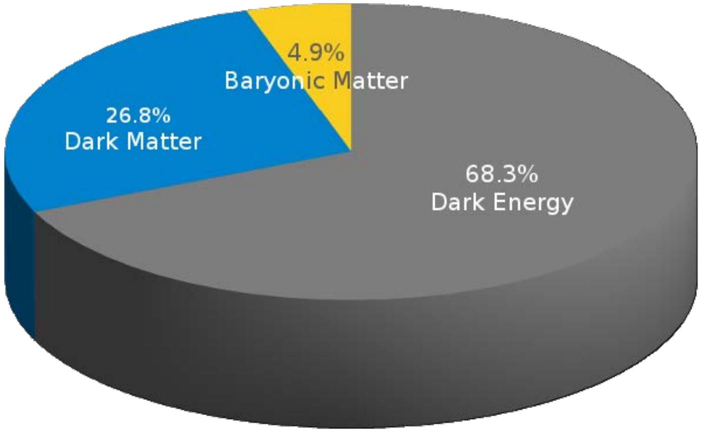
- Cosmological observations enable us to determine the dark matter contribution to the total energy density

Planck: $\boldsymbol{\Omega h^2 = 0.1199 \pm 0.0027}$

Impressive precision!



What is dark matter?

- Astrophysical observations clearly **confirm the existence** of dark matter (DM) in the Universe, but they give **almost no indications** concerning its nature
- No known particle (within the Standard Model of particle physics) has the **required properties** to be DM
- Need to postulate the **existence of a new particle** with unknown properties
- The only thing we know about it is **its abundance** in the Universe:

$$\Omega h^2 = 0.1199 \pm 0.0027$$

- Any model of dark matter must provide a mechanism to **explain this number**

by Saniya Heeba

Interaction rates in the early Universe

- To determine which **processes are important** in the early Universe, we calculate

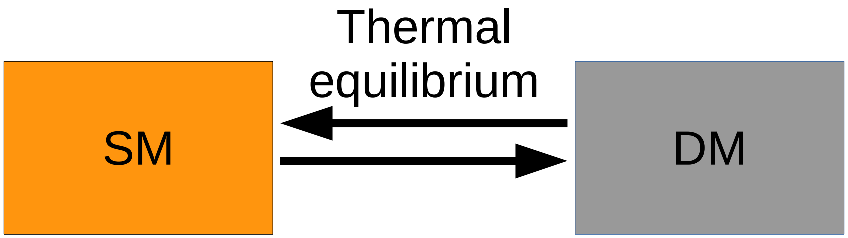
$$\Gamma \equiv \langle \sigma v \rangle \, n^{\mathrm{eq}}$$

with
σ : cross section for the process of interest
v : velocity of particles in the initial state
n^{eq} : number density of particles in the initial state
$\langle\,\rangle$: thermal average

- We then compare Γ to the **Hubble expansion rate** $H = a^{-1}\, \mathrm{d}a/\mathrm{d}t$
  - $\Gamma(T) > H(T)$: Interactions are fast ⟶
  - $\Gamma(T) < H(T)$: Interactions are slow ⇢

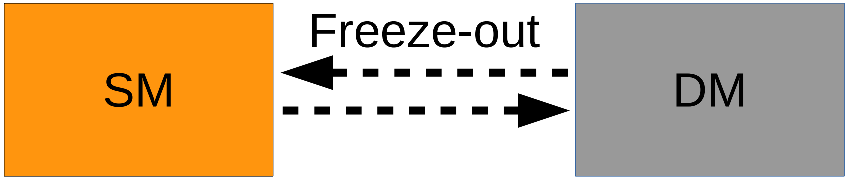
Thermal decoupling: The standard picture

- **High temperatures** (T >> m_{DM})
  - DM **annihilation and production** processes are in equilibrium



Universe expands and cools down

- **Low temperatures** (T << m_{DM})
  - **DM particles decouple** from equilibrium



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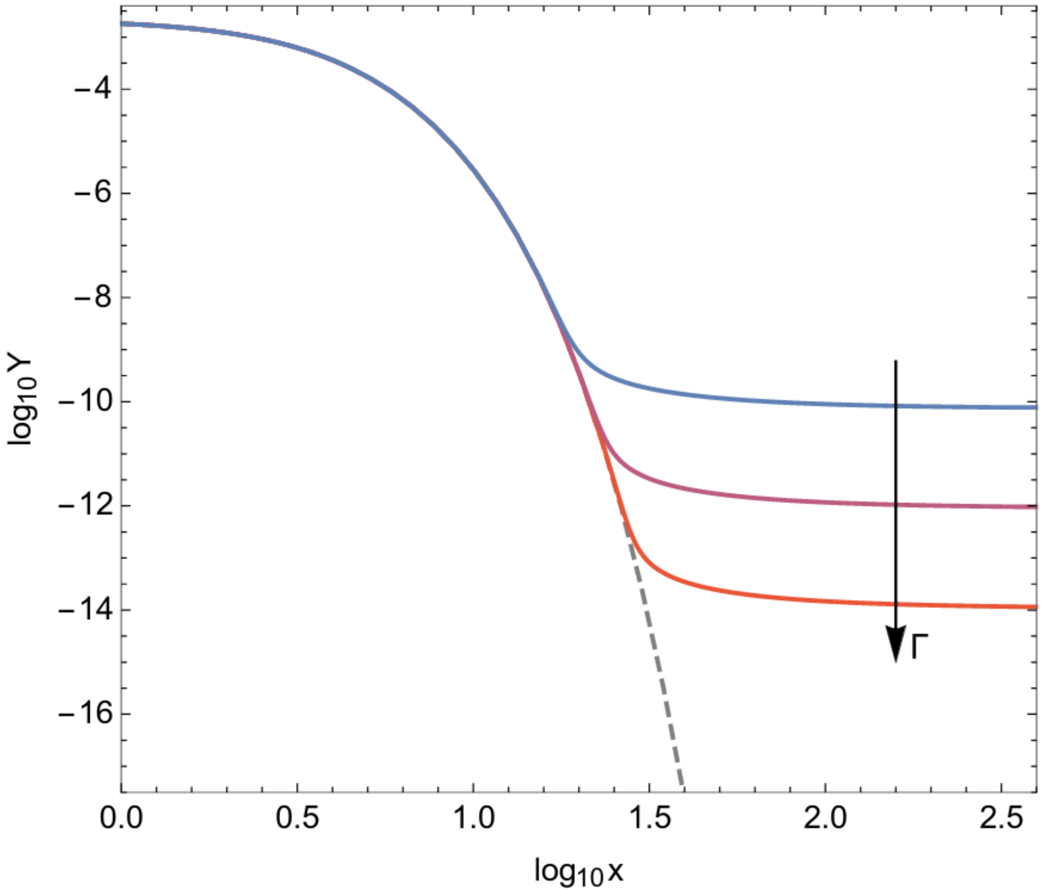
Bernal et al.: arXiv:1706.07442



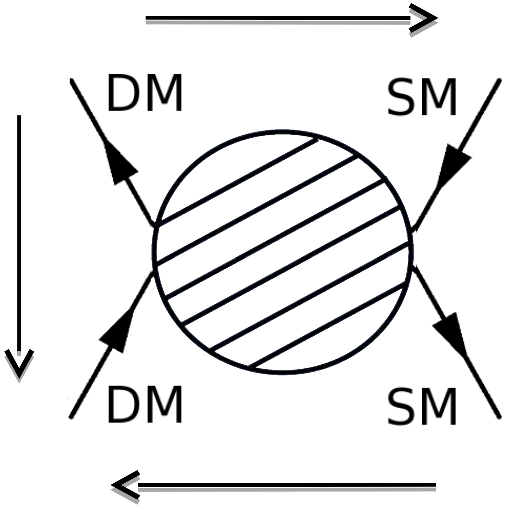
Qualitative solution: Stronger interactions ↔ smaller abundance

Weakly Interacting Massive Particles (WIMPs)

- Particles that obtain their relic abundance through **thermal freeze-out** are called WIMPs

- If these particles have similar interactions as known particles but are slightly heavier, thermal freeze-out leads to the **correct relic density**

- We can **hope to observe WIMPs** in the laboratory!



Search for particles produced in DM annihilation

Search for recoil energy from DM-nucleus scattering

Search for missing energy at colliders

Where Is My Particle?

- **Parameter space for WIMPs is getting tight!**
- **Most WIMP models are still viable**, but the non-observation of dark matter signals mounts **substantial pressure** on the WIMP idea
- Well-motivated to **question underlying assumptions** and consider alternative dark matter models

by Saniya Heeba

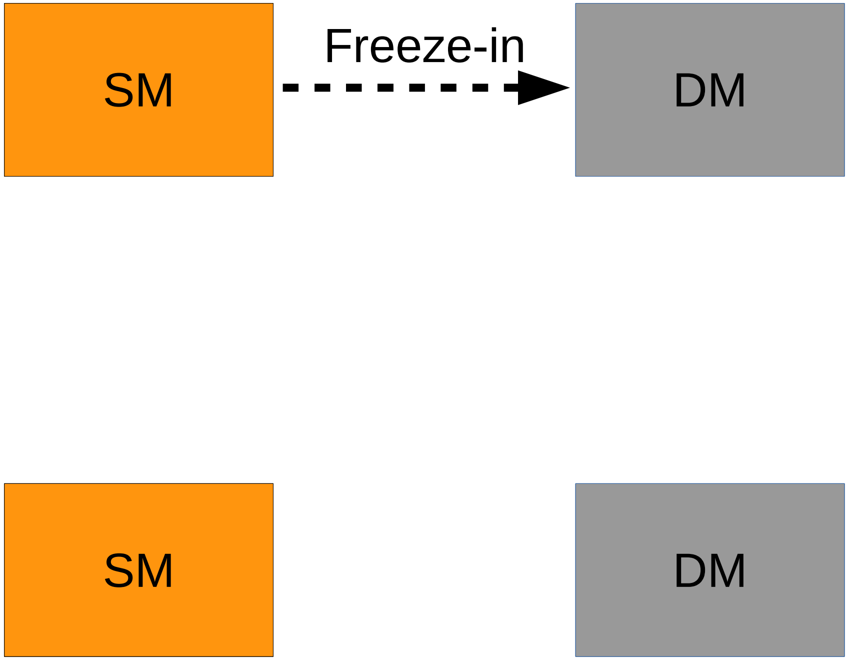
The freeze-in mechanism

- Assume that initial dark matter number density is negligible and that interactions between DM and the SM are extremely weak

- **High temperatures** (T >> m_{DM})
  - Particle production via **“energy leakage”** from the visible sector

Universe expands and cools down

- **Low temperatures** (T << m_{DM})
  - Interactions between the two sectors **completely negligible**



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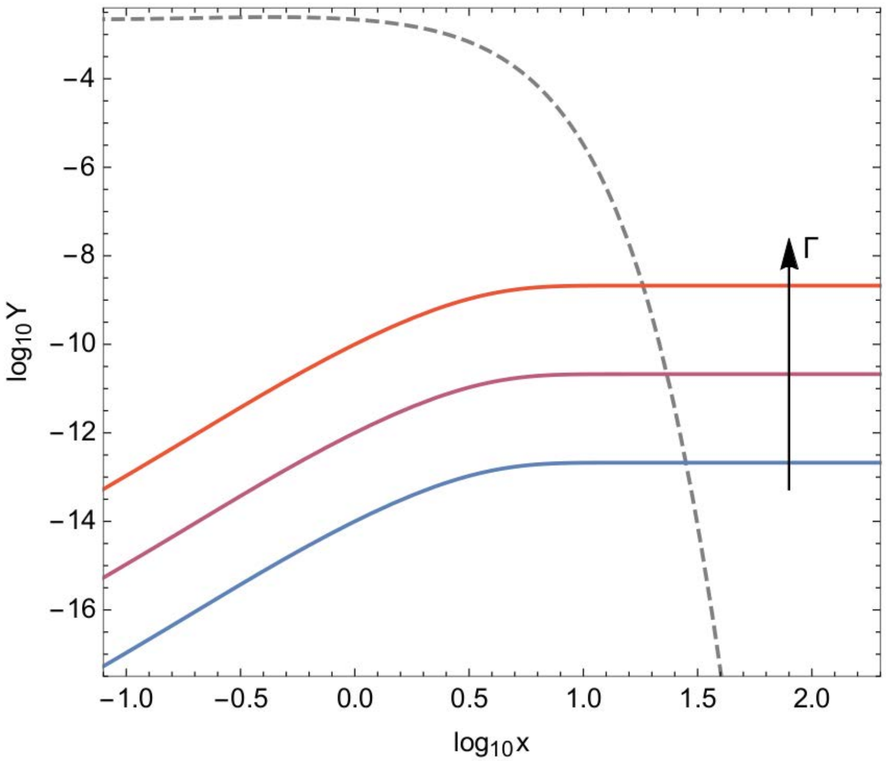


Qualitative solution: Stronger interactions ↔ larger abundance

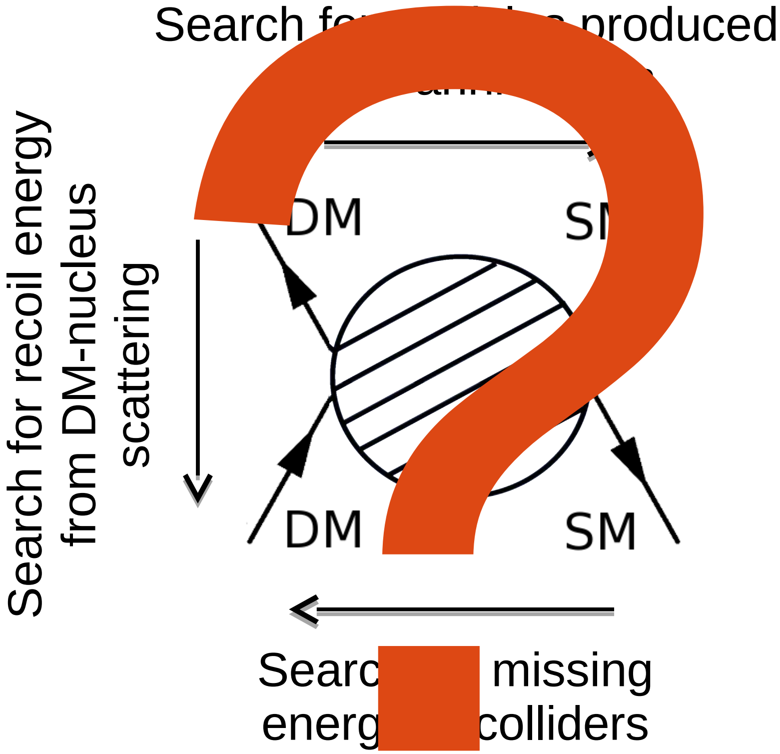
Feebly Interacting Massive Particles (FIMPs)

- Particles that obtain their relic abundance via the **freeze-in mechanism** are called FIMPs

- Write interaction rate as Γ = λ^2 T (with some effective coupling λ)

- The relic density requirement translates to to **$\lambda \sim 10^{-12}$**

- Such tiny couplings are **impossible to probe** with WIMP searches…



Feebly Interacting Massive Particles (FIMPs)

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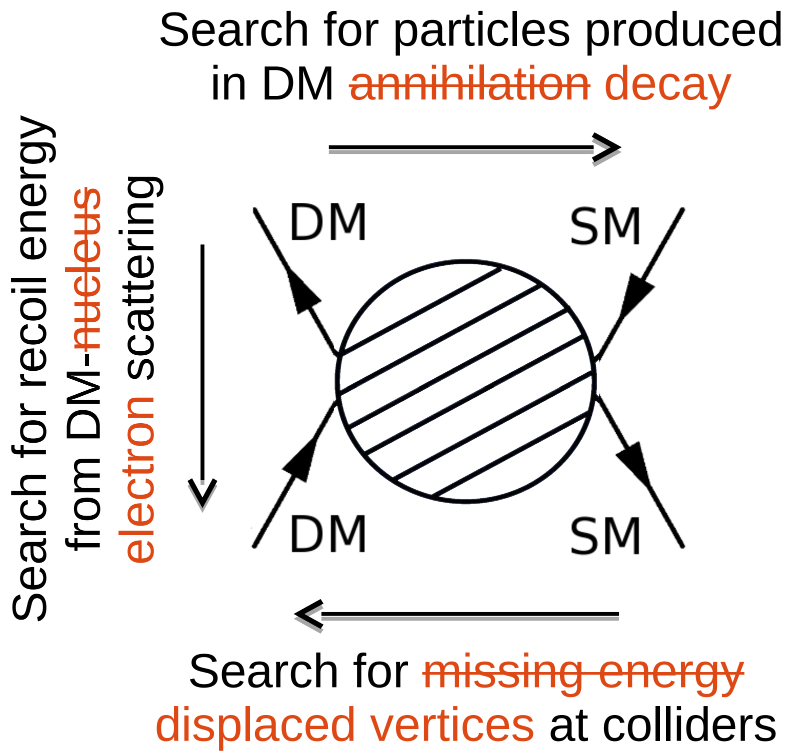
- The relic density requirement translates to to $\boldsymbol{\lambda \sim 10^{-12}}$
- Such tiny couplings are **impossible to probe** with WIMP searches…

…but they can be discovered with **dedicated search strategies**



Search for particles produced in DM ~~annihilation~~ decay

Search for recoil energy from DM-~~nucleus~~ electron scattering

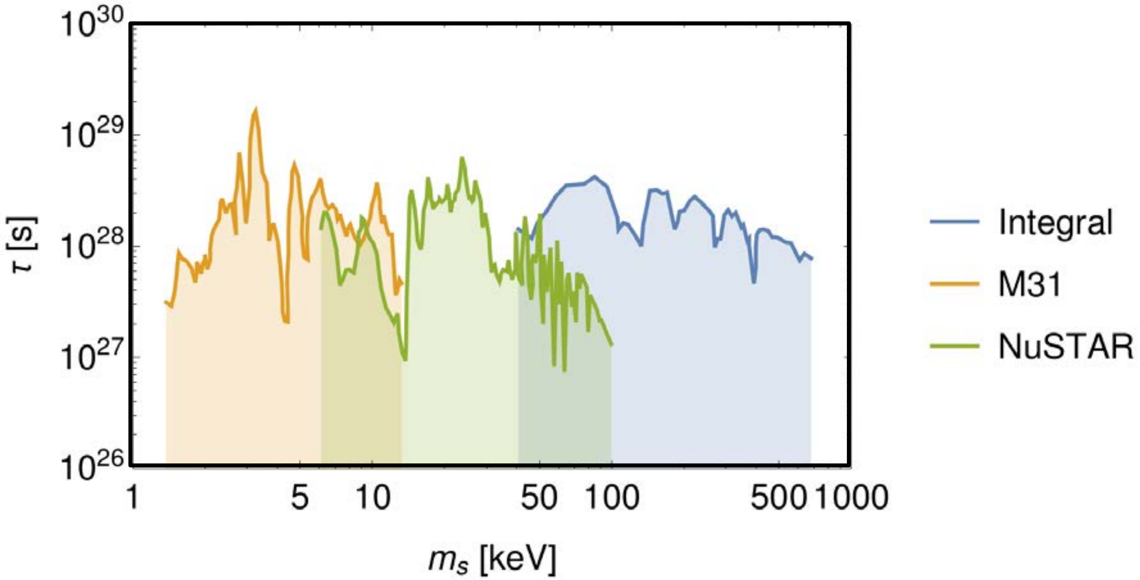
Search for ~~missing energy~~ displaced vertices at colliders

Part 1: Decaying dark matter

- Challenge the assumption that DM particles are perfectly stable

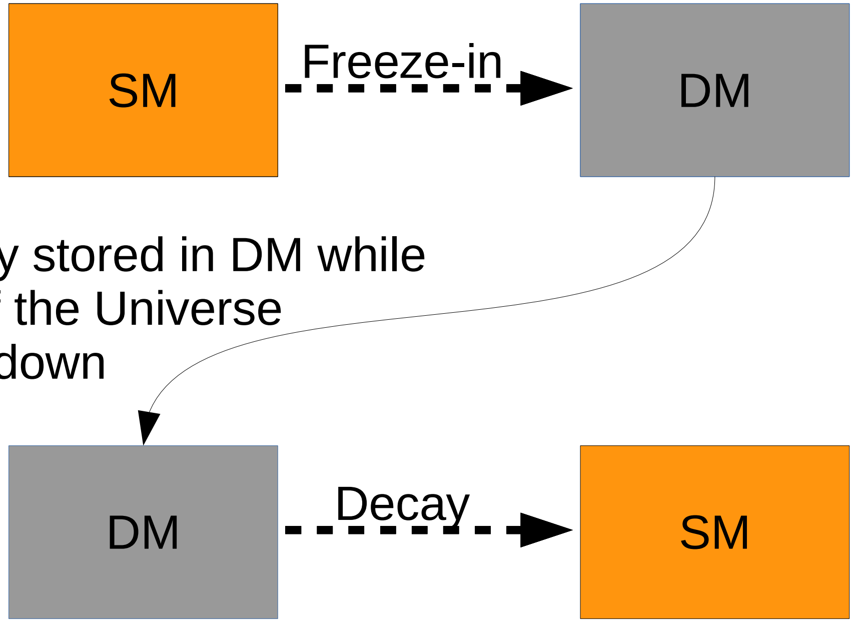
- Gravitational interactions only tell us that DM survives to the present day, i.e. the particles have a lifetime greater than the age of the Universe (~10^{17} s)

- However, if DM particles decay into SM particles (e.g. photons), observational constraints are much tighter and require $\tau > 10^{28}$ s (for keV-scale DM)



- For a DM particle to have such a long lifetime, it must have tiny couplings to SM particles → connection to freeze-in mechanism

Probing freeze-in with indirect detection



Early Universe:

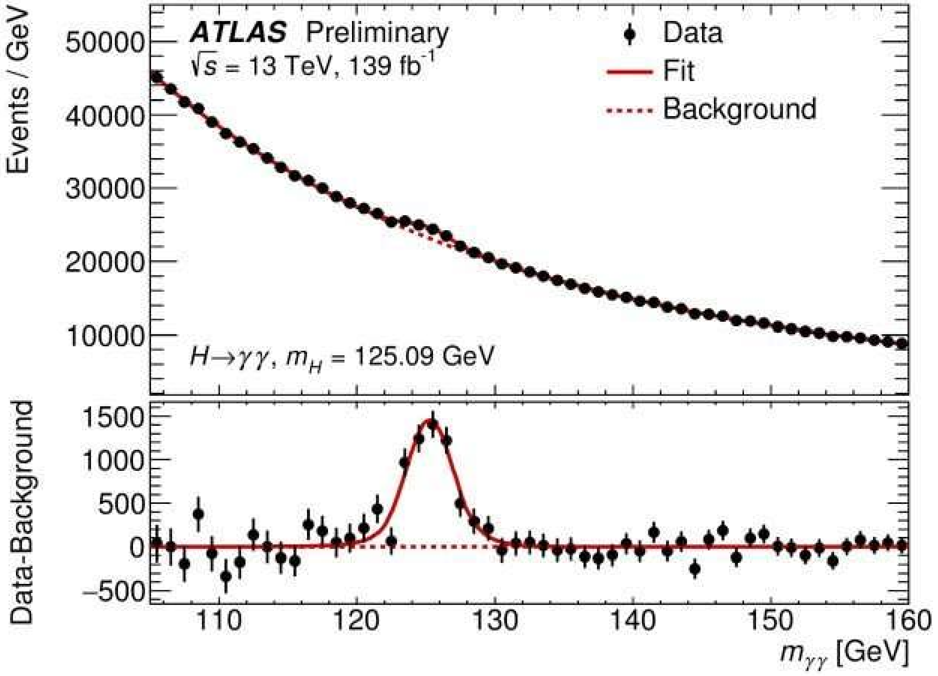
Energy stored in DM while rest of the Universe cools down

Present Universe:

If the same interaction is responsible for DM production and decay, we can probe the freeze-in mechanism by looking for the products of DM decay

Example: Higgs portal DM

- The Higgs boson *h*, which arises from the spontaneous breaking of electroweak symmetry, is the only known elementary particle with spin 0



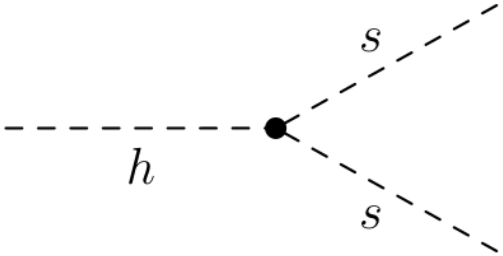
- What if the DM particle also has spin 0? What if it also arises from the spontaneous breaking of a new symmetry?

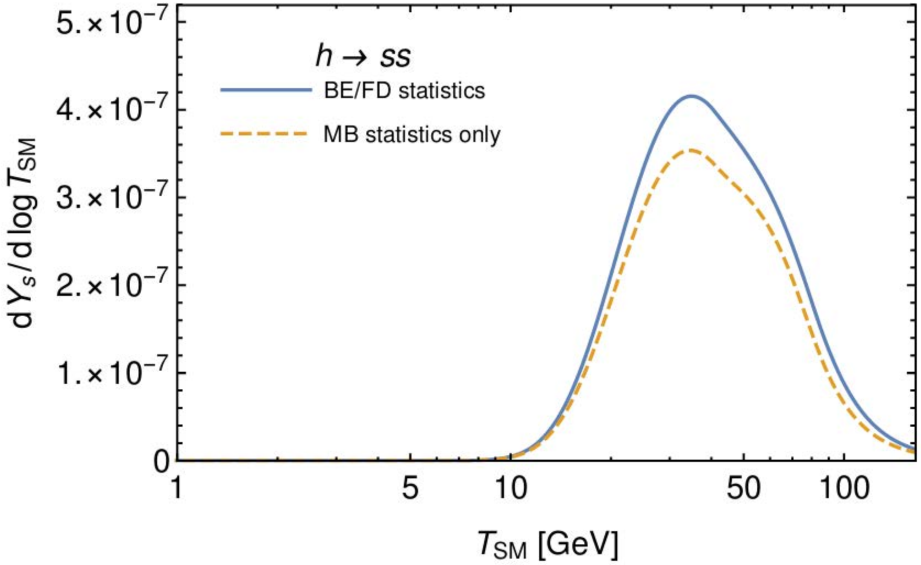
- If both particles have the same quantum numbers, they can mix with each other, such that mass eigenstates (*h* and *s*) are different from interaction eigenstates:

$$\begin{pmatrix} h_{\text{SM}} \\ h_s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

Consequences of Higgs mixing

- **Consequence 1:** Higgs decays produce DM particles





- For $T \sim m_h$ the early Universe is full of Higgs bosons
- Mixing of $\theta \sim 10^{-12}$ sufficient to match observed relic abundance

- **Consequence 2:** DM particles inherit Higgs decay modes
- Phenomenologically most interesting: decay into two photons

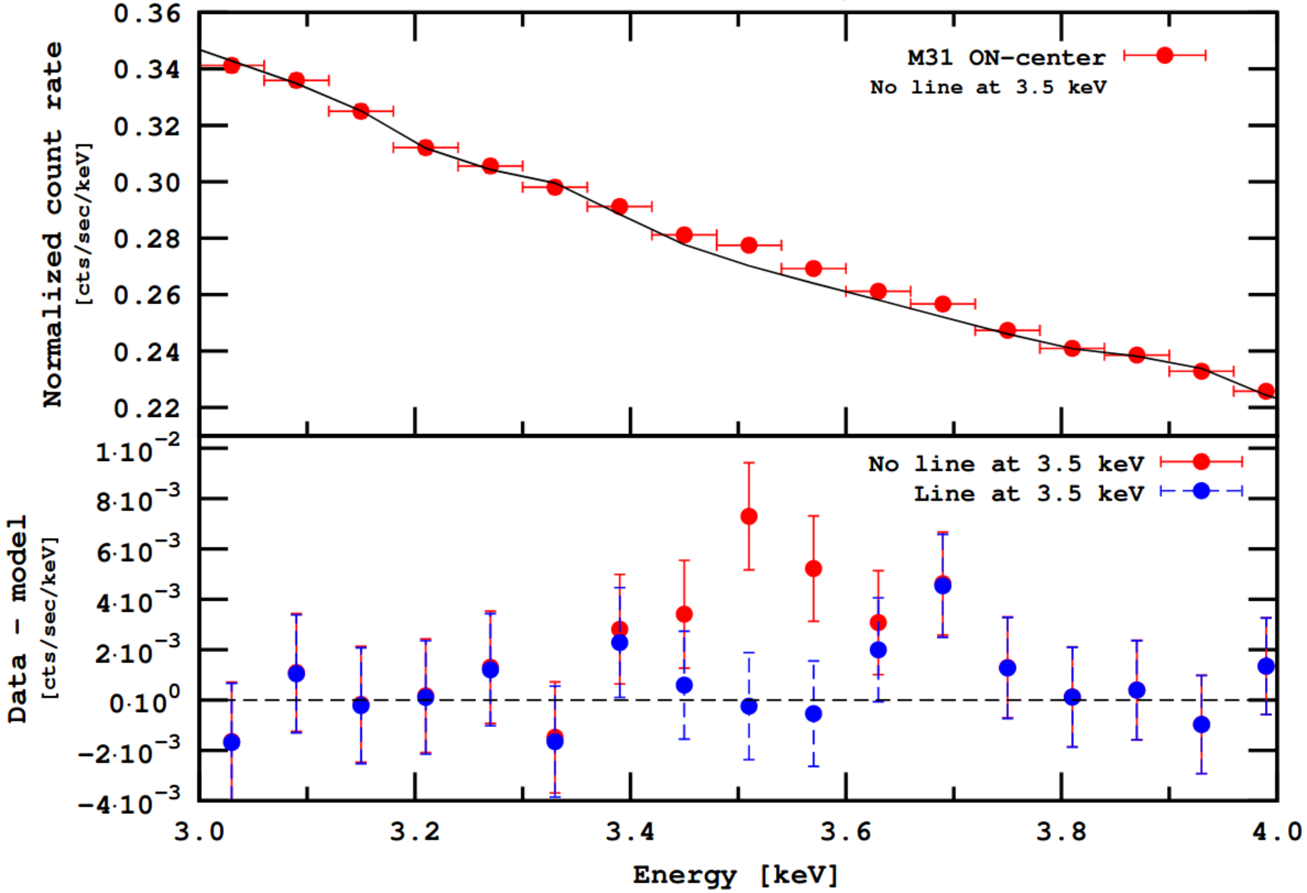
Intriguing coincidences

- For DM masses in the keV range, searches for DM decay products are sensitive to mixing angles $\theta \sim 10^{-12}$, as predicted from cosmological measurements

- Moreover, for several years a number of observations have provided hints for an unexplained x-ray line at 3.5 keV

- If not due to astrophysics, this could be evidence for decays of a spin-0 DM particle with $m_s \sim 7$ keV

Iakubovskyi et al.: arXiv:1510.00358

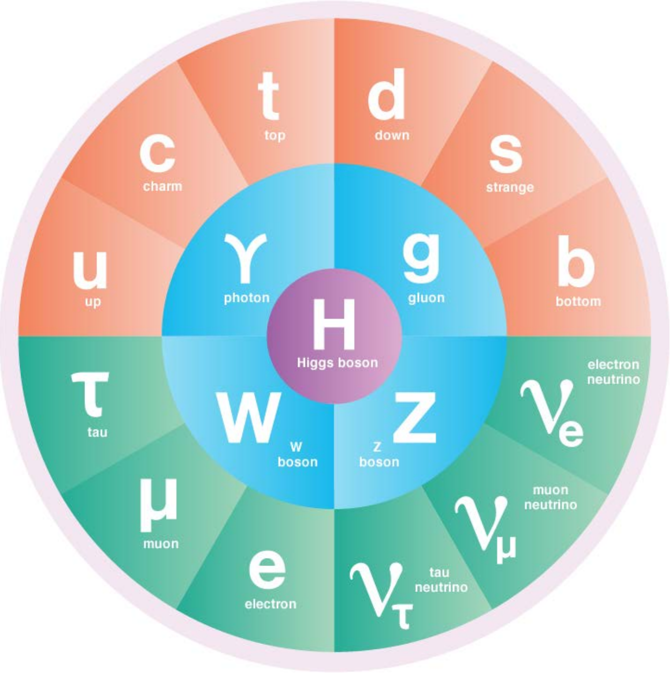


Part 2: New force carriers

- Challenge the assumption that DM particles couple directly to the SM

- Given the **complexity** of the visible sector (making up only 5% of the Universe), it is hardly plausible that the dark sector should be much simpler

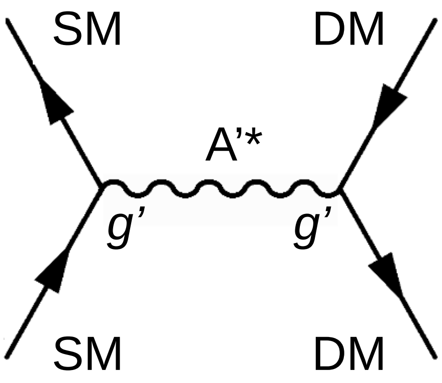
- In addition to new stable particles, there may also be **new force carriers**



- Simplest example: a dark fermion x coupled to a dark photon A' (like QED but with much smaller couplings)

Probing freeze-in with accelerator experiments

Early Universe:



- For 2 $m_{DM} > m_{A'}$ DM particles can only be produced from virtual dark photons (A'*)
- Cross section proportional to g'^4/m_{DM}^2
- Observed relic abundance requires $g' \sim 10^{-6}$

Probing freeze-in with accelerator experiments

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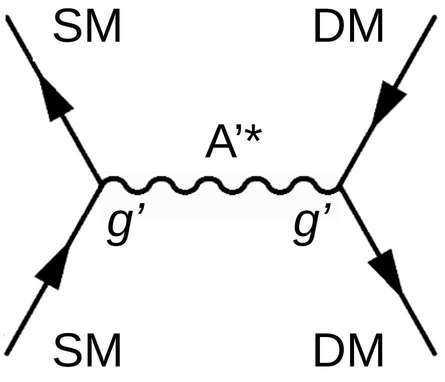
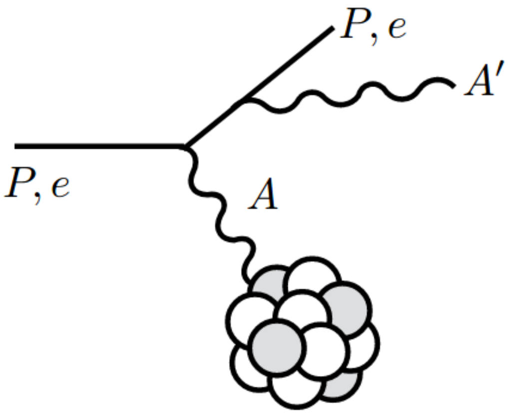


- For $m_{DM} > m_{A'}$ DM particles can only be produced from virtual dark photons (A'*)
- Cross section proportional to g'^4/m_{DM}^2
- Observed relic abundance requires g' ~ 10^{-6}

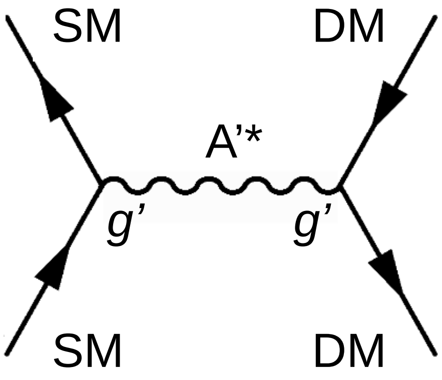
Laboratory:

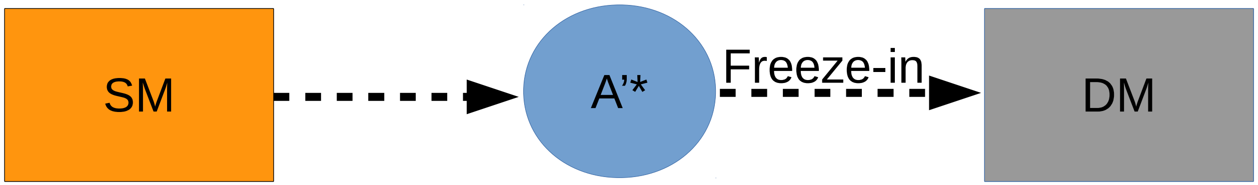


- In the laboratory one can produce real (i.e. on-shell) dark photons by shooting charged particles at a fixed target → dark Bremsstrahlung
- Cross section proportional to g'^2/m_A^2

Probing freeze-in with accelerator experiments

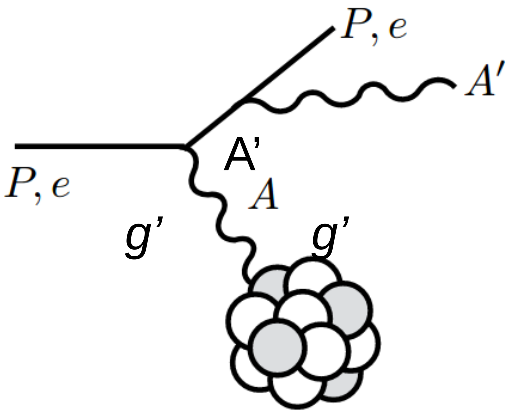
Early Universe:

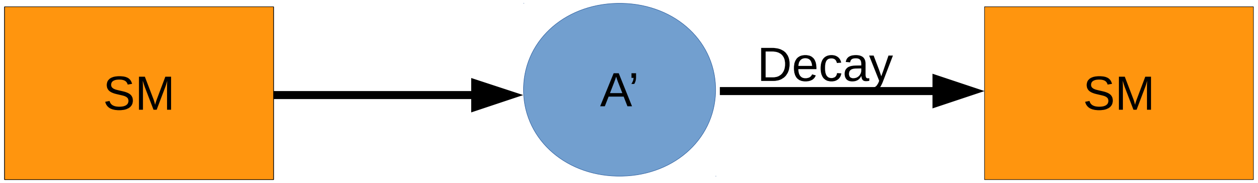




SM → A'* → Freeze-in → DM

Laboratory:

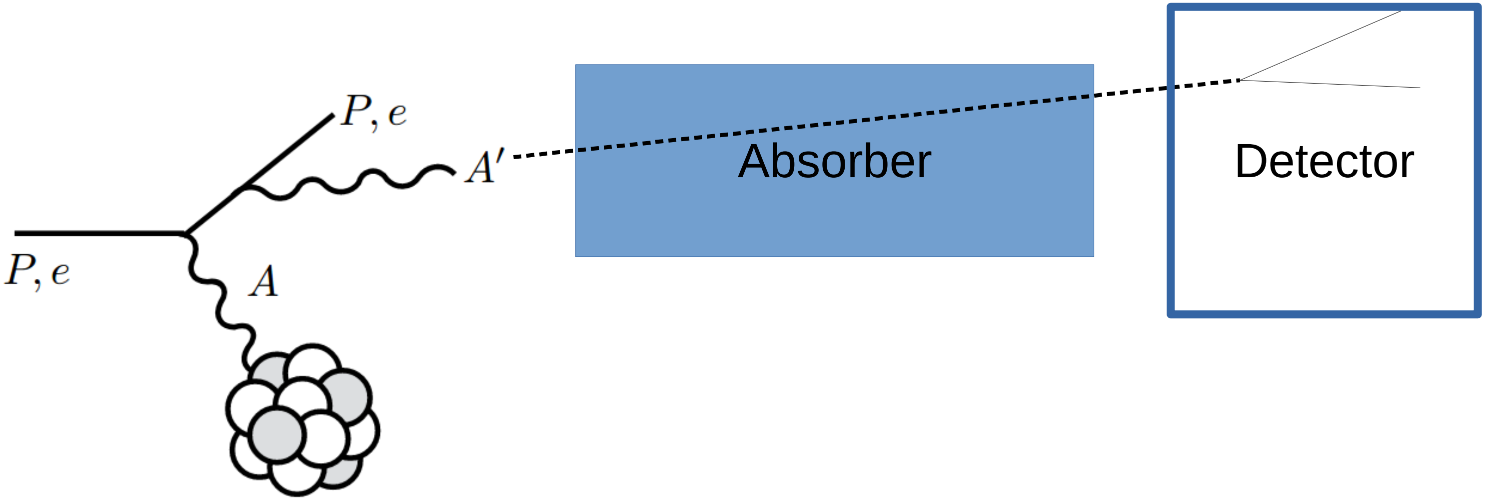




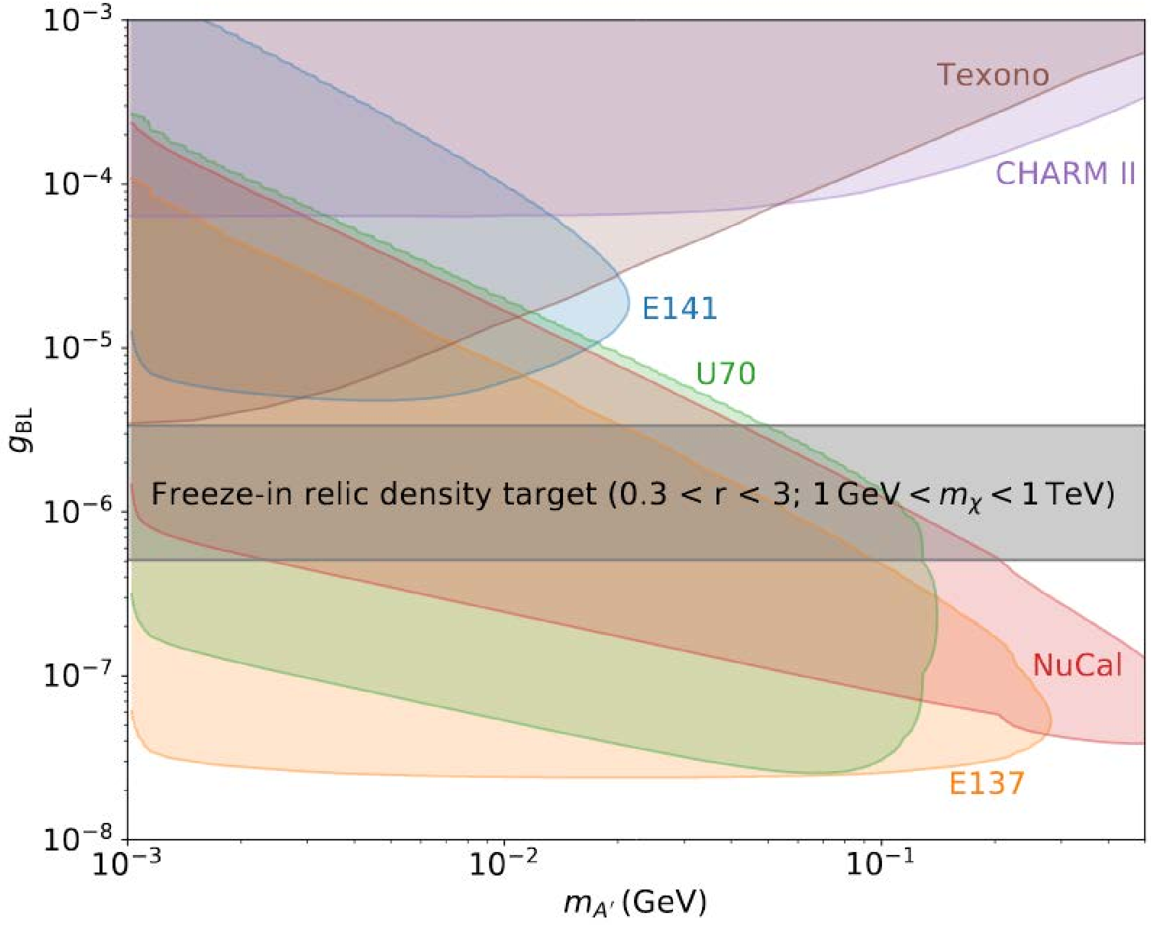
SM → A' → Decay → SM

Probing freeze-in with accelerator experiments

- Dark photons are so weakly coupled that they **easily travel through the target and absorber**
- For $m_{A'} > 2\ m_e$ they are however **unstable** against the decay into two electrons
- Example: $m_{A'} \sim 10$ MeV and $g' \sim 10^{-6}$ → decay length ~ 1m
- We can search for dark photon decays in a **decay volume** behind the absorber



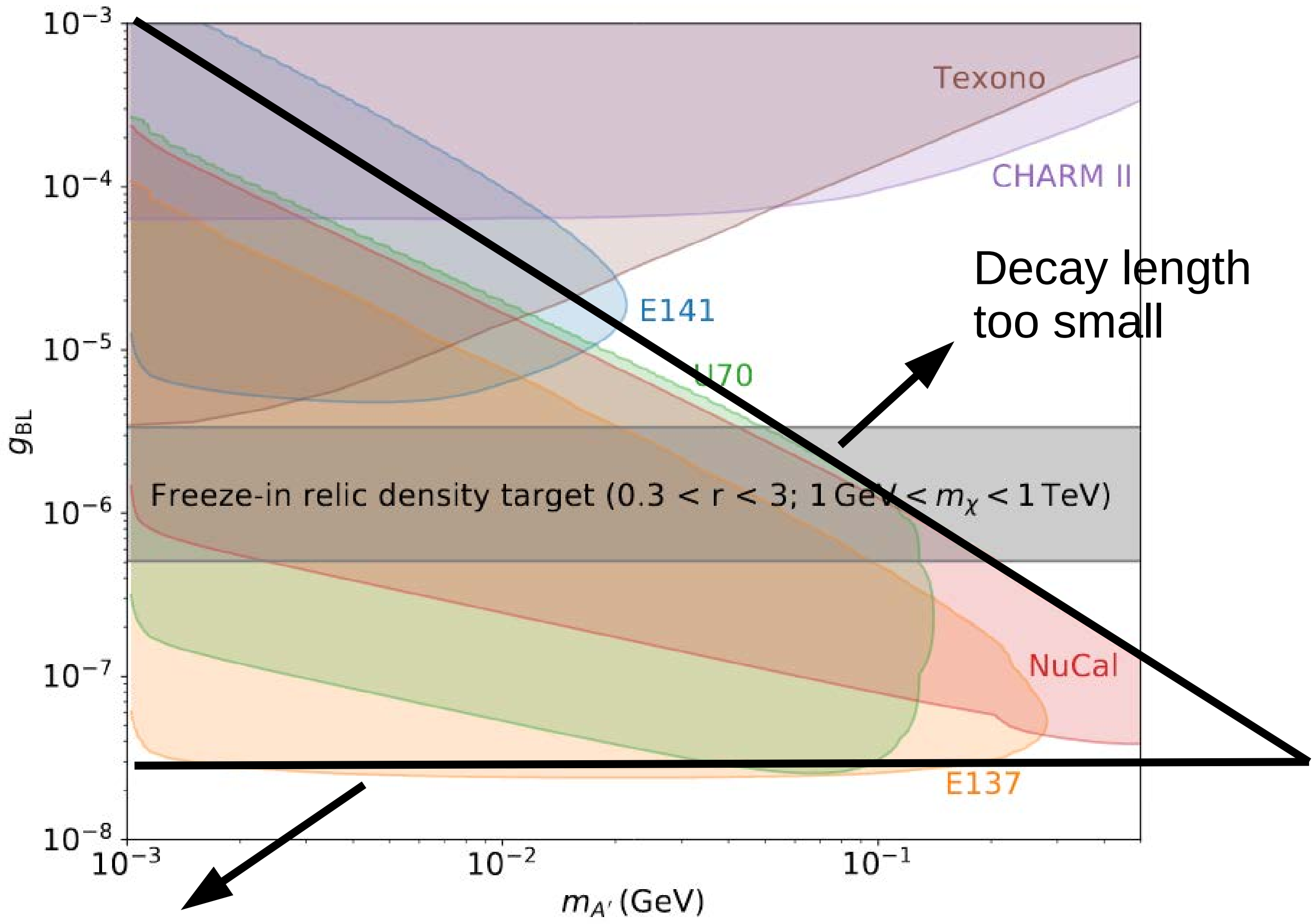
Results



Freeze-in target band for different DM masses and couplings

Constraints from fixed-target experiments

Results

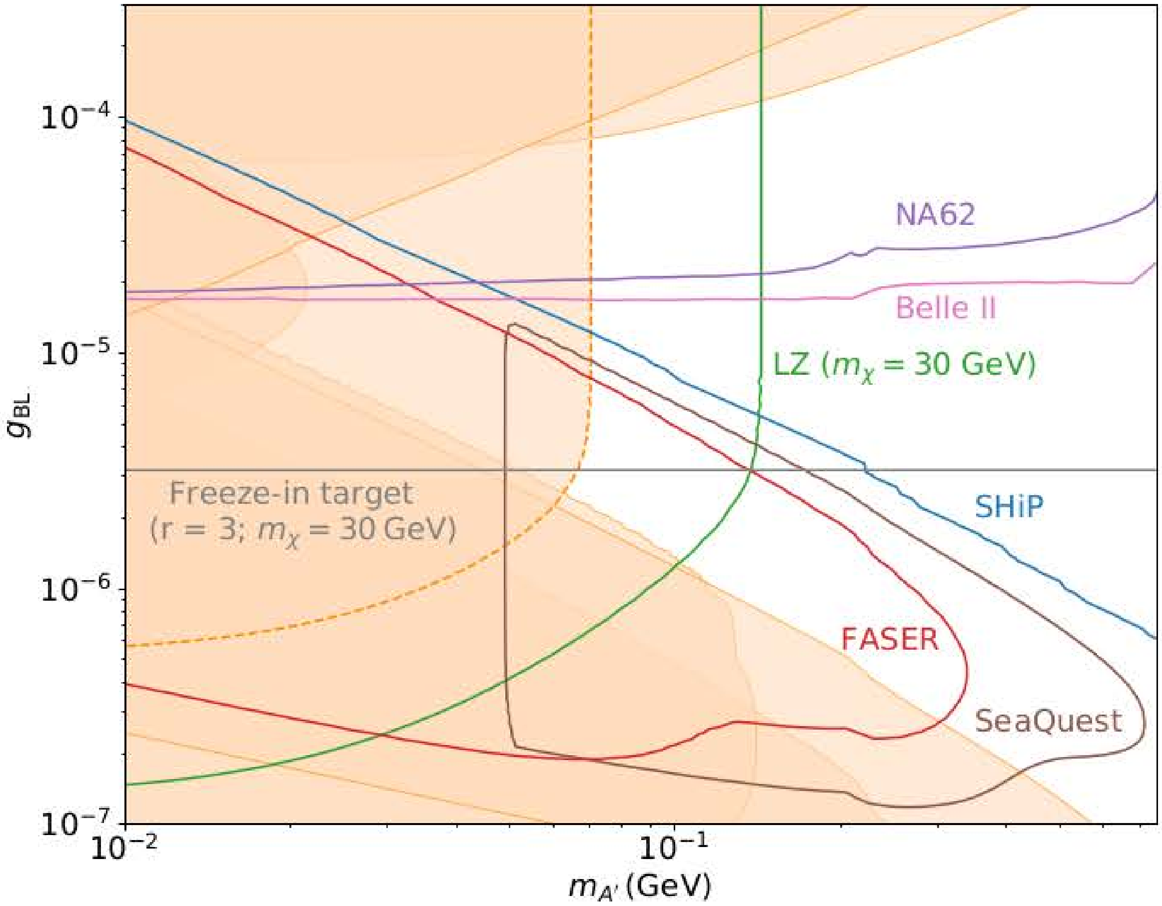


Decay length too small

Production rate too small

Strong constraints, but also plenty of unexplored parameter space!

Projections

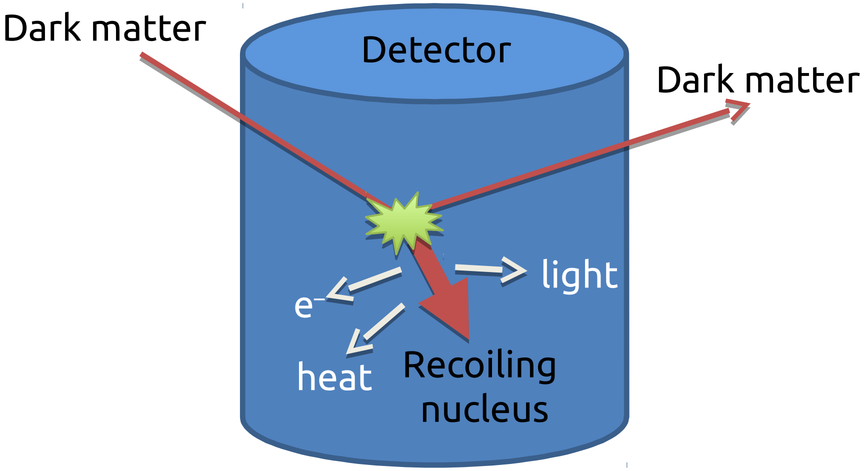


Many plans to improve sensitivity with fixed-target experiments and e^+e^- colliders!

Part 3: New detector concepts

- Challenge the existing design of dark matter detectors and **explore new approaches**

- Direct detection experiments looking for the scattering of GeV-scale WIMPs typically have an energy threshold of order keV



- DM particles in the Milky Way halo have $v \sim 10^{-3}$ and therefore $E_{\mathrm{kin}} \sim 10^{-6}\, m_{\mathrm{DM}}$

- When scattering on a heavy nucleus, only a fraction of this energy can be deposited

- Conventional direct detection experiments are **insensitive to keV-scale DM**

- Solution: Search for **DM-electron scattering** in crystals with **small band gap**

Dirac materials

- Materials in which elementary excitations can be described by **Dirac equation**

- Energy-momentum relation: $E_{\mathbf{k}}^{\pm} = \pm\sqrt{v_{\mathrm{F}}^{2}\,\mathbf{k}^{2} + \Delta^{2}}$

k: lattice momentum

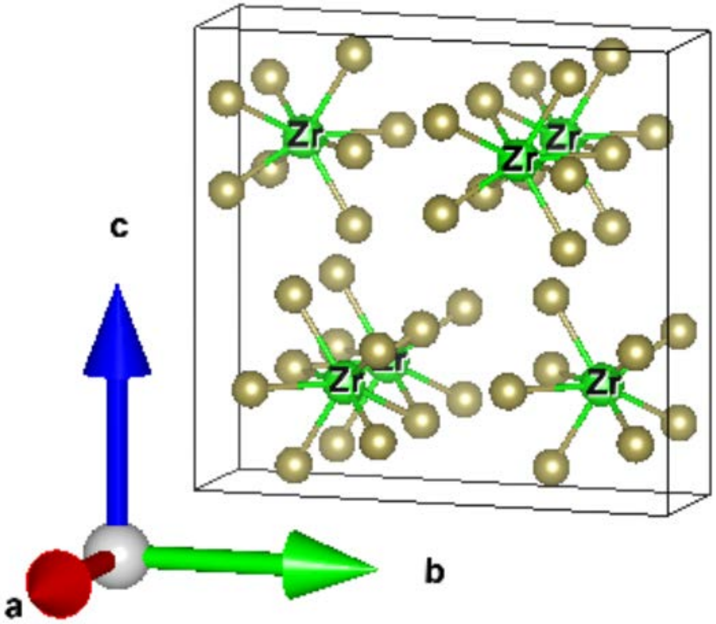
v_F: Fermi velocity (replacing speed of light)

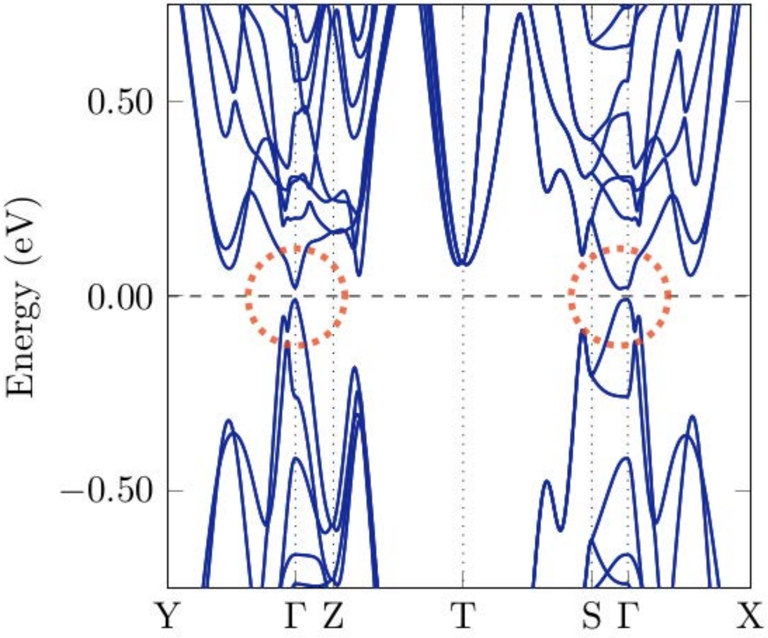
2Δ: Band gap (replacing rest mass)

- For k >> Δ dispersion relation becomes linear → electrons behave like free relativistic fermions

- **Crucial advantage:** Δ can be as small as 10 meV

Example: $ZrTe_5$



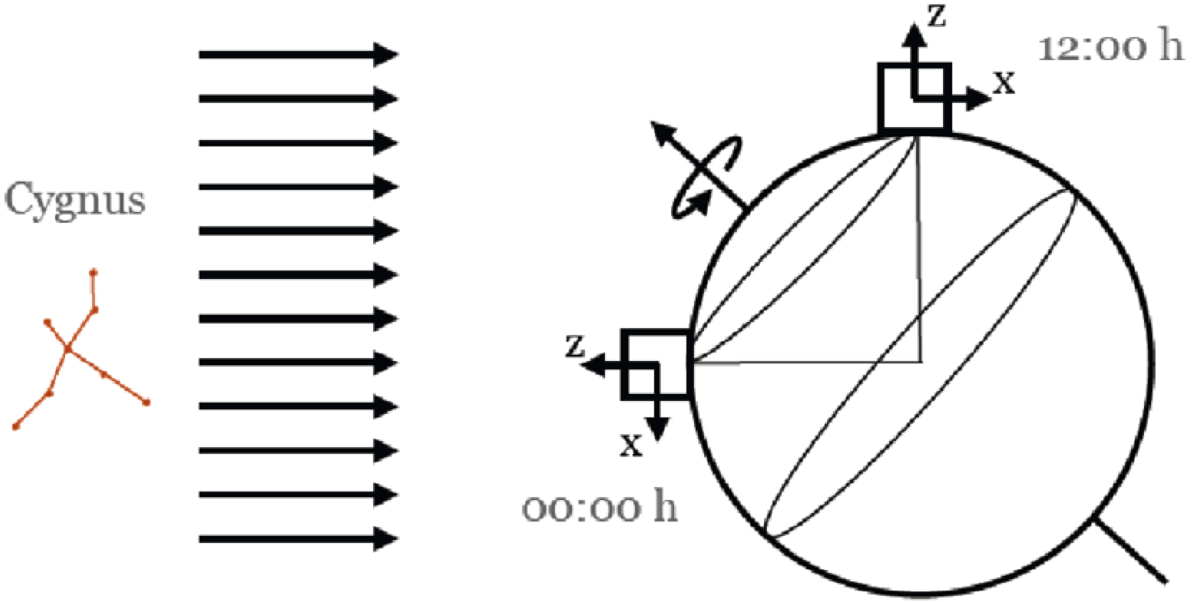


- Band structure calculated with density functional theory + structural optimisation

	v_{Fx}	v_{Fy}	v_{Fz}	Δ [meV]
Theory	1.1e-3	9.1e-4	4.4e-4	15.6
Experiment	1.3e-3	1.6e-3	6.5e-4	11.75

Identifying a dark matter signal

- **Problem:** background from thermal excitations of electrons
- Need to look for **characteristic properties** of DM signal
- Crucial observation: DM flux is **not isotropic** in the laboratory frame (“WIMP wind”)



- Direction of the WIMP wind **changes by almost 90 degrees** over the course of 12 hours

Directional detection from anisotropies

- Dirac materials can have significant anisotropies!

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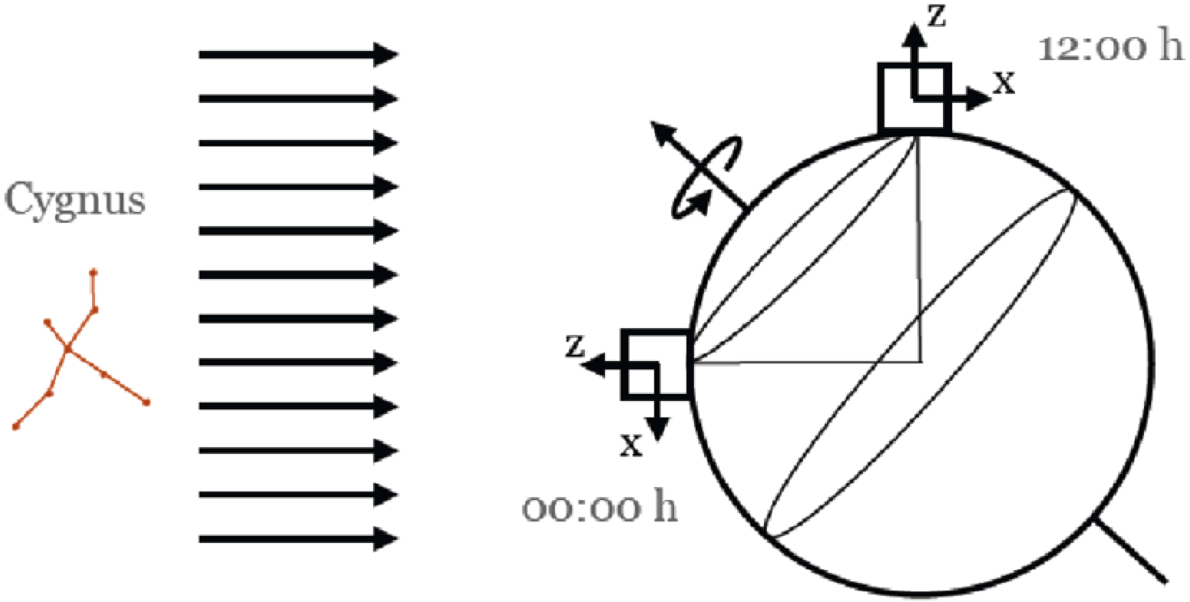
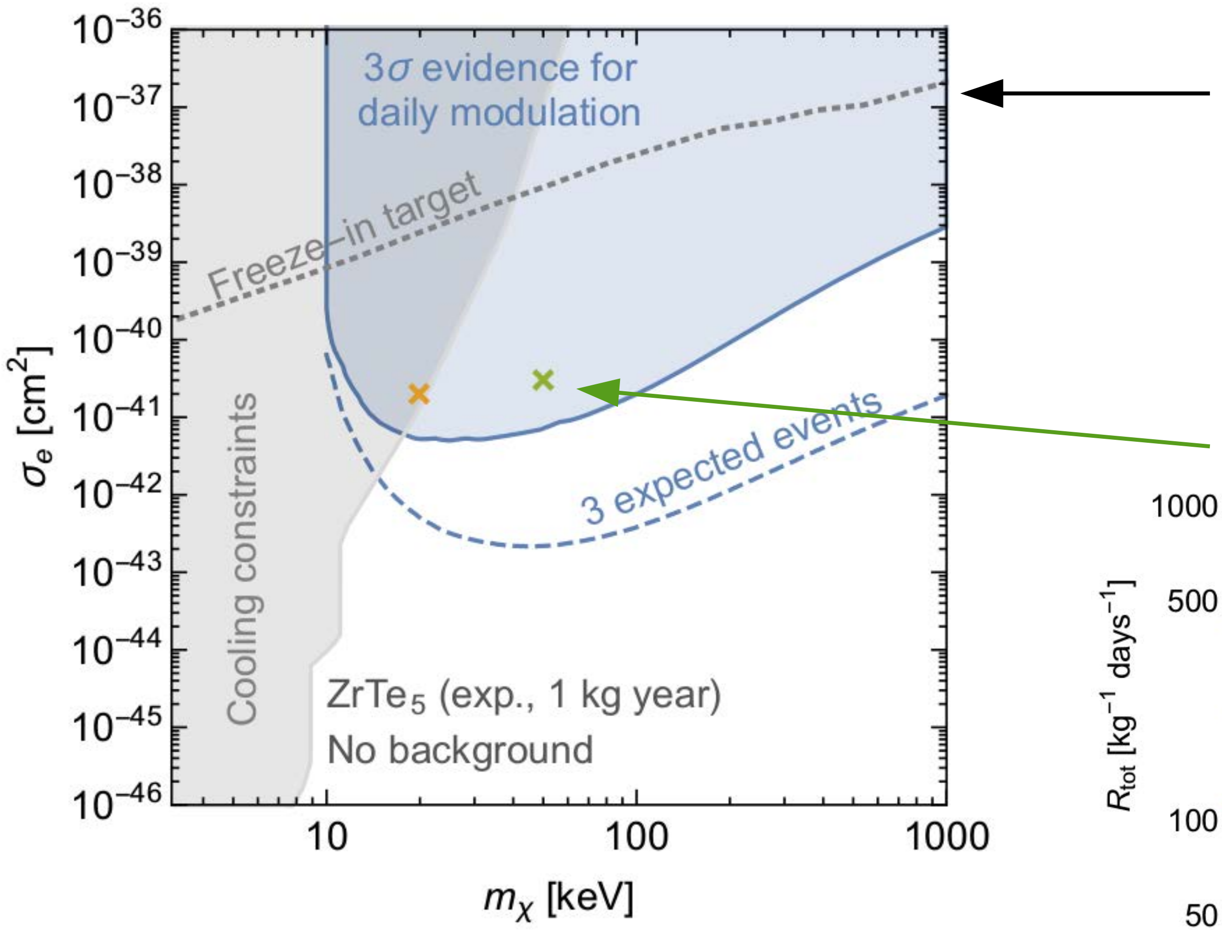
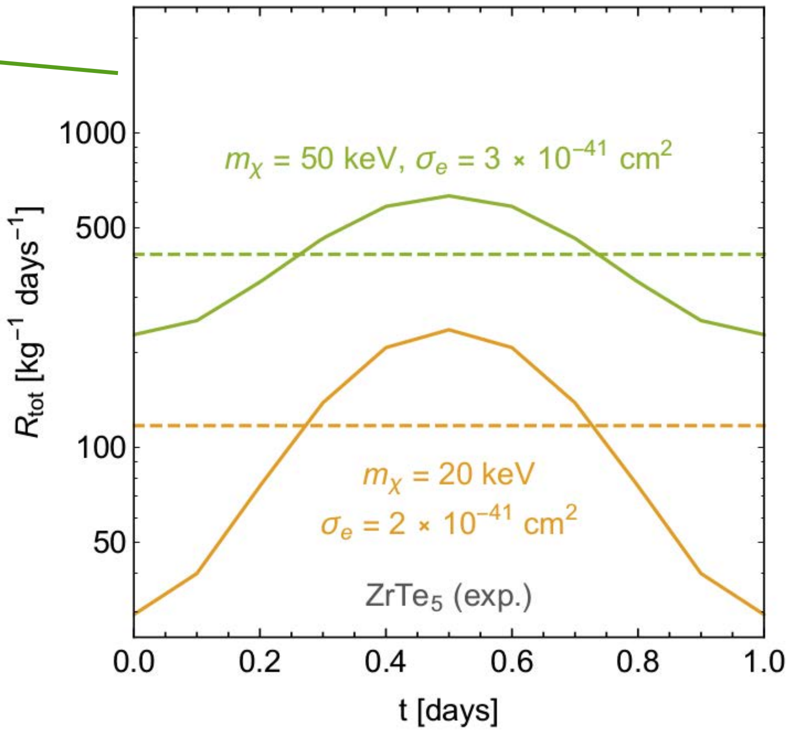


- Scattering is **suppressed** when the Fermi velocity pointing towards the WIMP wind is large

Sensitivity estimates



Dirac materials have **enormous potential** for testing the freeze-in mechanism for keV-scale DM



- Also promising: Organic Dirac materials like BNQ-TTF

Conclusions

- We have **convincing evidence** for the existence of dark matter, but **no experimental information** revealing its nature

- The **non-observation of evidence for WIMPs** suggests that dark matter particles may have never been in thermal equilibrium in the early Universe (so-called **FIMPs**)

- In spite of their **tiny couplings**, FIMPs can be probed in a number of different ways
  - If the same interaction is responsible for dark matter **production and decay**, we can connect the relic abundance to **observable x-ray signals**
  - If a **new force carrier** (e.g. a dark photon) is responsible for dark matter production, we can search for it at **accelerator experiments**
  - If we develop new dark matter detectors based on **quantum materials with tiny energy threshold**, we can probe otherwise inaccessible regions of parameter space

- Let's find FIMPs!

Part 1: Technical points

- For a precise prediction of the expected signal strength, we need accurate calculations of the DM relic abundance:
  - Thermal masses of SM particles in the initial state
  - Quantum statistics for relativistic particles in the plasma
  - Accurate treatment of electroweak phase transition
  - Inclusion of all possible processes

- Although DM particles couple very weakly to the SM, they may still couple strongly to each other
  - Number-changing processes in the Early Universe
  - DM self-interactions in astrophysical systems

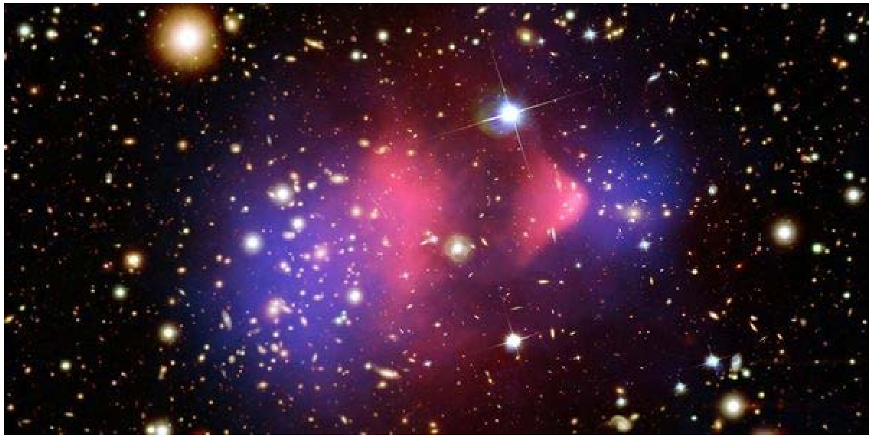
$W^+, b \to t, \rho$
$Z, W^+ \to W^+, \rho$
$g, t \to t, \rho$
$W^-, t \to b, \rho$
$W^-, c \to s, \rho$
$W^-, u \to d, \rho$
$W^+, d \to u, \rho$
$W^+, s \to c, \rho$
$W^-, W^+ \to Z, \rho$
$\bar{u}, d \to W^-, \rho$
$\bar{c}, s \to W^-, \rho$
$\bar{t}, t \to g, \rho$
$Z, b \to b, \rho$
$Z, d \to d, \rho$
$Z, s \to s, \rho$
$Z, c \to c, \rho$
$Z, u \to u, \rho$
$W^+, \tau^- \to \nu_t, \rho$
$W^+, \mu^- \to \nu_m, \rho$
$\mu^-, h \to \mu^-, \rho$
$\bar{d}, d \to h, \rho$
$e^+, e^- \to \rho, \rho$
$\bar{u}, u \to h, \rho$
$d, h \to d, \rho$
$u, h \to u, \rho$
$e^+, e^- \to h, \rho$
$e^-, h \to e^-, \rho$

$\tau^+, \tau^- \to \gamma, \rho$
$\bar{c}, c \to \gamma, \rho$
$\gamma, b \to b, \rho$
$\bar{b}, b \to \gamma, \rho$
$\gamma, \mu^- \to \mu^-, \rho$
$W^-, W^+ \to \rho, \rho$
$\mu^+, \mu^- \to \gamma, \rho$
$\bar{c}, c \to h, \rho$
$\gamma, s \to s, \rho$
$Z, Z \to \rho, \rho$
$h, h \to \rho, \rho$
$\bar{s}, s \to \gamma, \rho$
$\bar{s}, s \to \rho, \rho$
$\tau^+, \tau^- \to h, \rho$
$b, h \to b, \rho$
$\bar{u}, u \to \gamma, \rho$
$\gamma, u \to u, \rho$
$\mu^+, \mu^- \to \rho, \rho$
$\gamma, d \to d, \rho$
$\bar{d}, d \to \gamma, \rho$
$\bar{t}, t \to \rho, \rho$
$e^+, e^- \to \gamma, \rho$
$c, h \to c, \rho$
$\gamma, e^- \to e^-, \rho$
$\tau^-, h \to \tau^-, \rho$
$\bar{s}, s \to h, \rho$
$\mu^+, \mu^- \to h, \rho$
$\bar{d}, d \to \rho, \rho$
$\bar{u}, u \to \rho, \rho$
$s, h \to s, \rho$

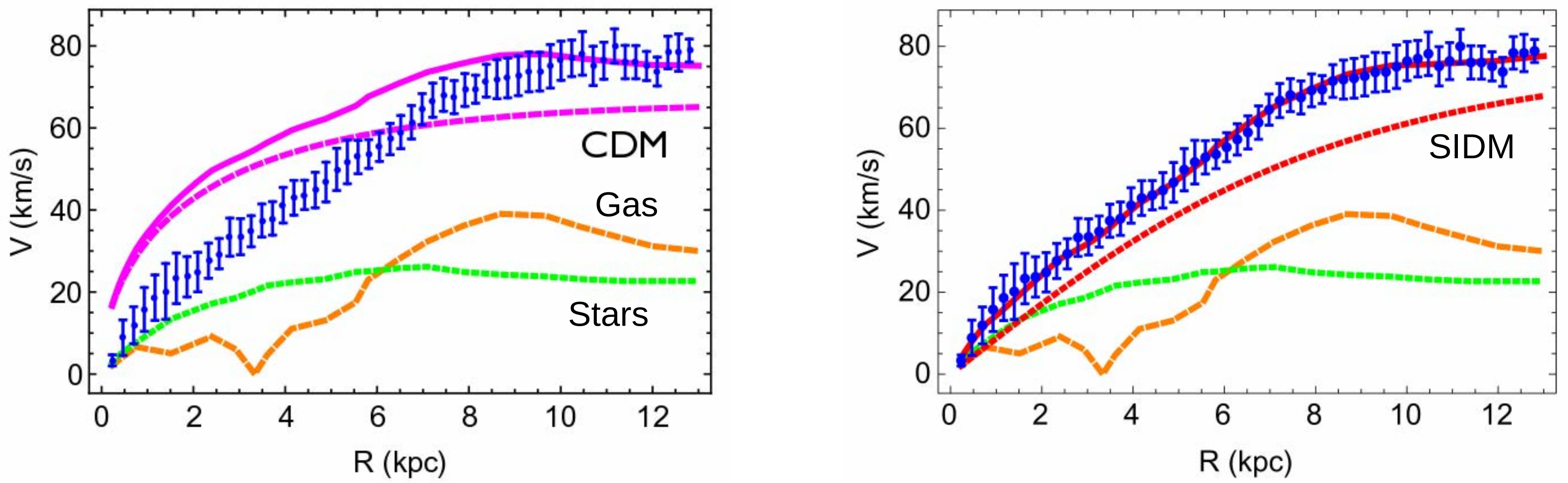
$W^-, W^+ \to h, \rho$
$\bar{\nu}_e, \nu_e \to Z, \rho$
$\bar{\nu}_m, \nu_m \to Z, \rho$
$\bar{\nu}_t, \nu_t \to Z, \rho$
$Z, \tau^- \to \tau^-, \rho$
$Z, e^- \to e^-, \rho$
$Z, \mu^- \to \mu^-, \rho$
$\bar{d}, d \to g, \rho$
$\bar{t}, t \to h, \rho$
$Z, h \to Z, \rho$
$Z, Z \to h, \rho$
$g, u \to u, \rho$
$\bar{u}, u \to g, \rho$
$e^+, e^- \to Z, \rho$
$\mu^+, \mu^- \to Z, \rho$
$\tau^+, \tau^- \to Z, \rho$
$W^-, c \to d, \rho$
$W^+, s \to u, \rho$
$W^-, u \to s, \rho$
$W^+, d \to c, \rho$
$\bar{u}, s \to W^-, \rho$
$\bar{c}, d \to W^-, \rho$
$\gamma, t \to t, \rho$
$\bar{c}, c \to \rho, \rho$
$\bar{t}, t \to \gamma, \rho$
$\tau^+, \tau^- \to \rho, \rho$
$h, h \to h, \rho$
$\bar{b}, b \to h, \rho$
$\gamma, c \to c, \rho$
$\gamma, \tau^- \to \tau^-, \rho$

$W^+, e^- \to \nu_e, \rho$
$W^-, \nu_e \to e^-, \rho$
$W^-, \nu_m \to \mu^-, \rho$
$W^-, \nu_t \to \tau^-, \rho$
$Z, t \to t, \rho$
$g, b \to b, \rho$
$W^-, W^+ \to \gamma, \rho$
$\bar{b}, b \to \rho, \rho$
$\bar{\nu}_e, e^- \to W^-, \rho$
$\bar{\nu}_m, \mu^- \to W^-, \rho$
$\bar{\nu}_t, \tau^- \to W^-, \rho$
$\bar{t}, b \to W^-, \rho$
$g, s \to s, \rho$
$\bar{b}, b \to g, \rho$
$\gamma, W^+ \to W^+, \rho$
$\bar{d}, d \to Z, \rho$
$\bar{s}, s \to Z, \rho$
$\bar{b}, b \to Z, \rho$
$Z, \nu_e \to \nu_e, \rho$
$Z, \nu_m \to \nu_m, \rho$
$Z, \nu_t \to \nu_t, \rho$
$\bar{u}, u \to Z, \rho$
$\bar{c}, c \to Z, \rho$
$\bar{s}, s \to g, \rho$
$W^+, h \to W^+, \rho$
$t, h \to t, \rho$
$g, c \to c, \rho$
$\bar{t}, t \to Z, \rho$
$\bar{c}, c \to g, \rho$
$g, d \to d, \rho$

Quick detour: Dark matter self-interactions



- Bullet Cluster: The dominant form of matter in galaxy clusters behaves very **differently from baryonic gas**
- Observations require $\sigma / m_x \lesssim 1.5\ \mathrm{cm}^2/\mathrm{g}$ (= 3 barn/GeV)
- A self-interaction cross section close to this bound may give a **better fit to observations** than cold DM (cusp-core problem)

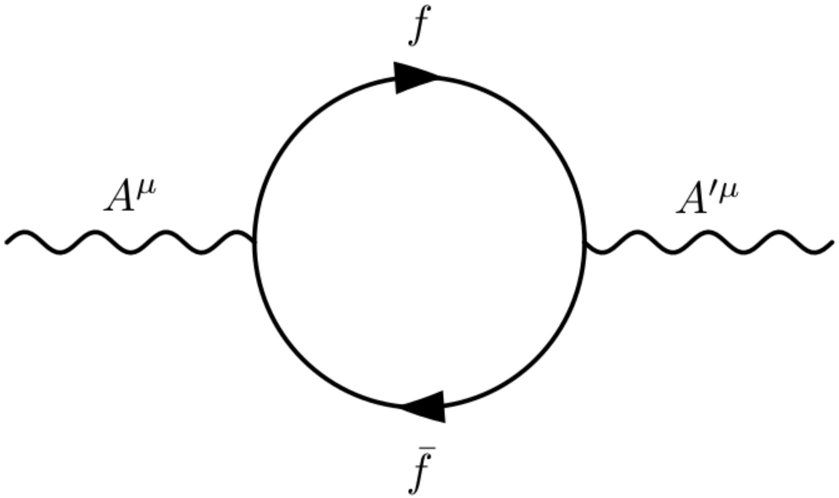


Tulin & Yu: arXiv:1705.02358

Part 2: Technical points

- Freeze-in production and laboratory constraints depend on the **specific coupling structure** of the dark photon
- Interesting example: Equal but opposite coupling to **baryons and leptons** ($g' = g_{\text{B-L}}$)
- DM charge is a **free parameter**, but should be similar in size to the other couplings

- **Important subtlety:** At finite temperatures the SM photon acquires a **plasma mass**, leading to mixing between the dark and the visible photon
- **Plasmon decays** give important contribution to DM relic density



Part 3: Technical points

- Various ingredients are necessary to calculate scattering rate

$$R_{\mathbf{k}\to\mathbf{k}'} = \frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{8\pi\mu_{\chi e}^2}\int d^3q\,|F_{\mathrm{DM}}(q)|^2|\mathcal{F}_{\mathrm{med}}(q)|^2|f_{\mathbf{k}\to\mathbf{k}'}(q)|^2\,\frac{\tilde{g}(v_{\mathrm{min}},\psi)}{|\mathbf{q}|}$$

Part 3: Technical points

- Various ingredients are necessary to calculate scattering rate

In-medium effects

Astrophysics

$$R_{\mathbf{k}\to\mathbf{k}'} = \frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{8\pi\mu_{\chi e}^2}\int d^3q\,\boxed{|F_{\mathrm{DM}}(q)|^2}\boxed{|\mathcal{F}_{\mathrm{med}}(q)|^2}\boxed{|f_{\mathbf{k}\to\mathbf{k}'}(q)|^2}\boxed{\frac{\tilde{g}(v_{\mathrm{min}},\psi)}{|\mathbf{q}|}}$$

Particle physics

Transition probability

Requires knowledge of dielectric tensor and polarisation tensor

$$\mathcal{F}_{\mathrm{med}}(q) = \frac{1}{1+\left(q_x^2\frac{v_{\mathrm{F},z}^2}{\kappa_{xx}}+q_y^2\frac{v_{\mathrm{F},y}^2}{\kappa_{yy}}+q_z^2\frac{v_{\mathrm{F},z}^2}{\kappa_{zz}}\right)\frac{\pi(\tilde{q}^2)}{q^2}}$$

$$\pi(\tilde{q}^2) = -\frac{g\,e^2}{24\pi^2\,v_{\mathrm{F},x}v_{\mathrm{F},y}v_{\mathrm{F},z}}\left(\log\left|\frac{4\tilde{\Lambda}^2}{\tilde{q}^2}\right|+i\pi\Theta\left(\tilde{q}^2\right)\right)$$