Nikhef

Unconventional thermal(-ish) dark matter

Anastasiia Filimonova

DIS2022
Santiago de Compostela

DM particles: intriguing and confusing

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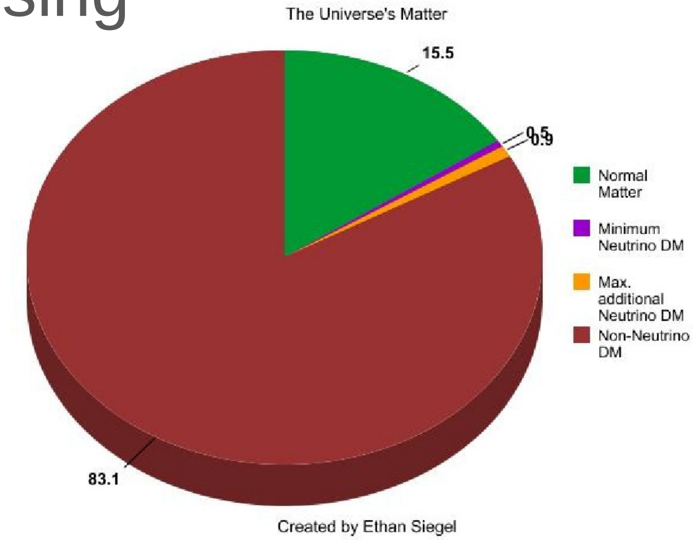

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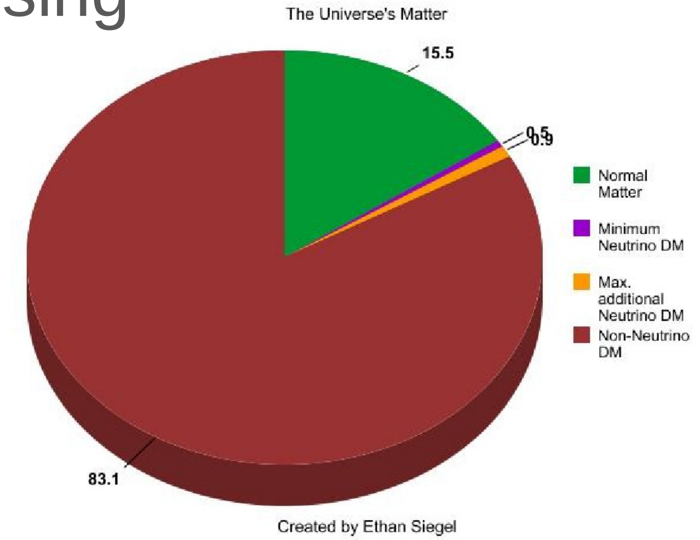
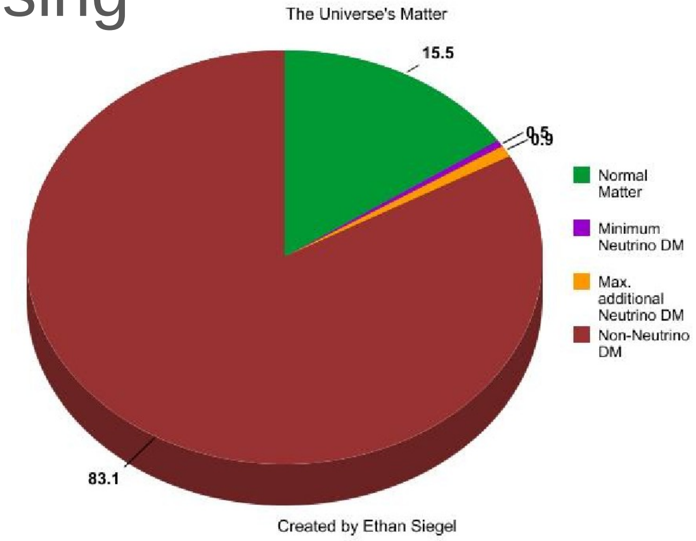


What we do know:

- Interact through gravity
- Massive (to cluster)
- If DM particles ever were relativistic – they should have slowed down early in the history of the Universe
- Electrically neutral (do not interact with photons)
- Stable on cosmological scales

DM particles: intriguing and confusing



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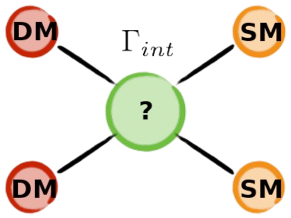
What we don’t know:

- Other interactions?
- Mass, spin….?
- Several species?

Why the electroweak scale?



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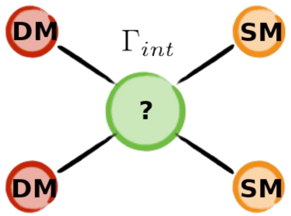

Assumption:

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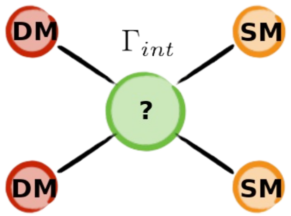

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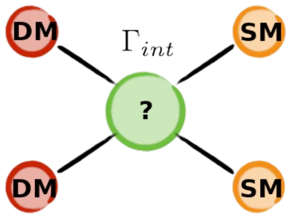

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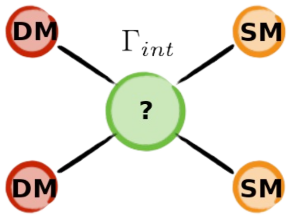

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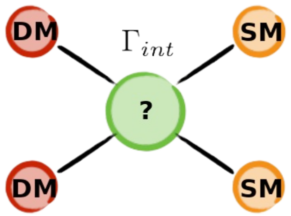

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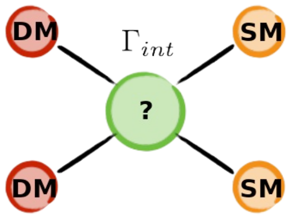

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Very simplified WIMPS

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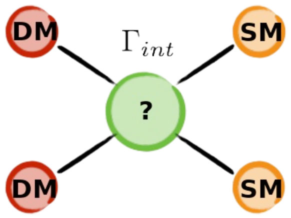

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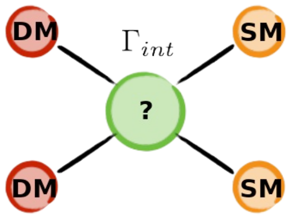

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Planck

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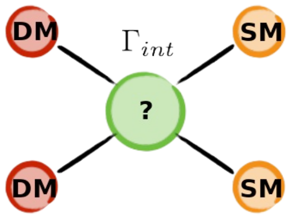

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"Natural" choice:

$\alpha \sim \alpha_{EW}$

$m_{DM} \sim O(100\text{GeV})$

And all these constraints...

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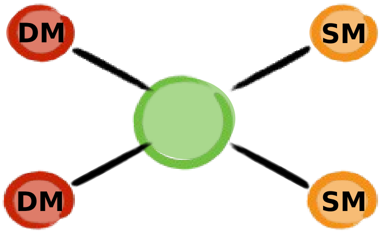

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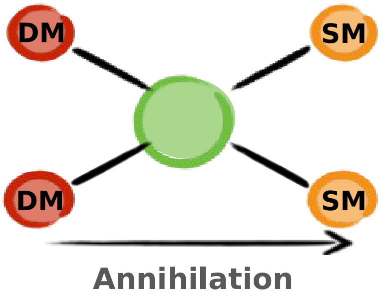

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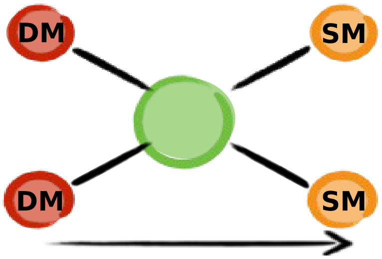

Annihilation (indirect detection)

Fermi satellite

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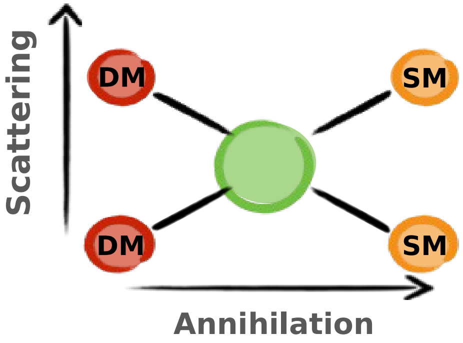

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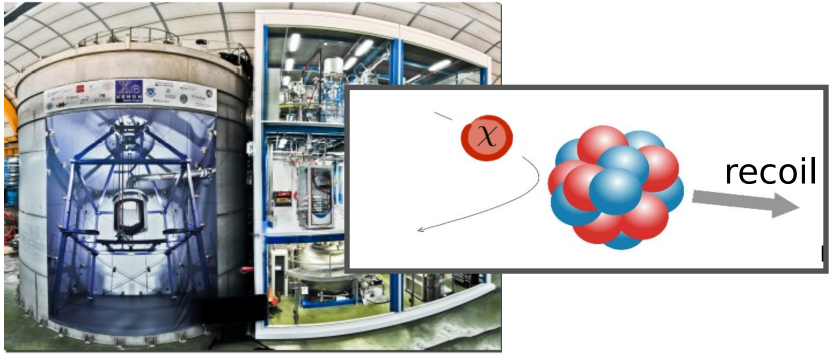
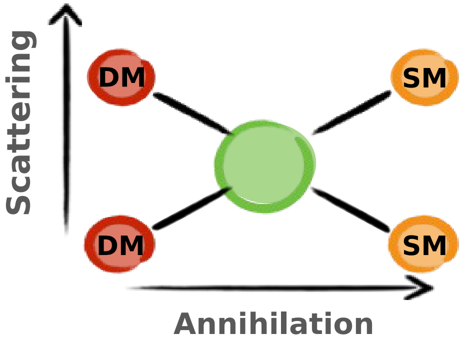
Scattering (direct detection)



Xenon experiment



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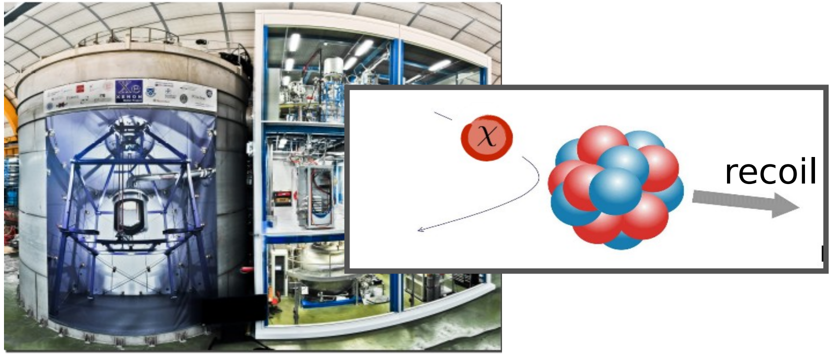

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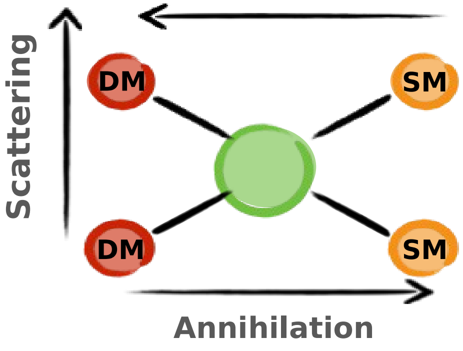

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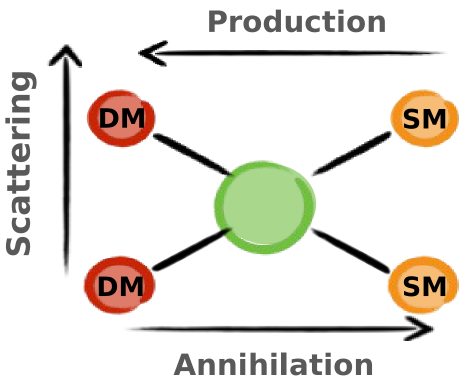

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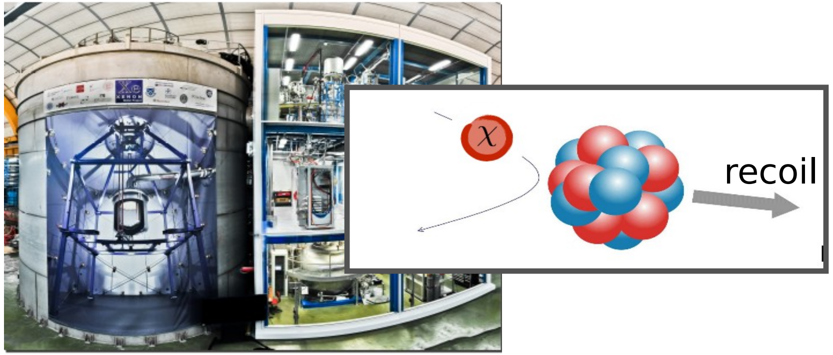

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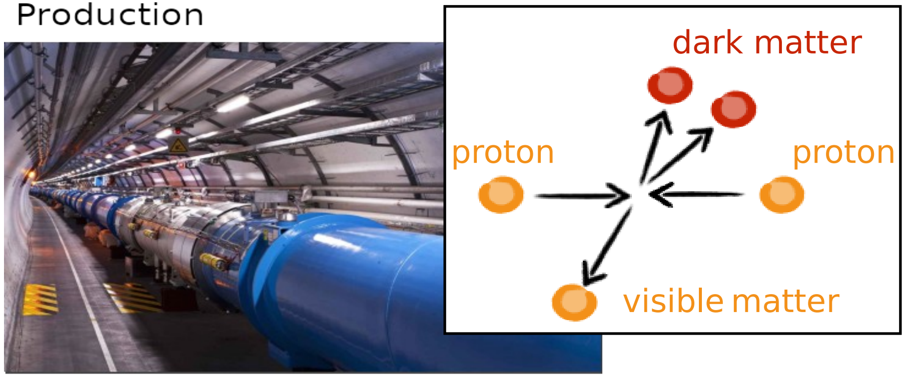
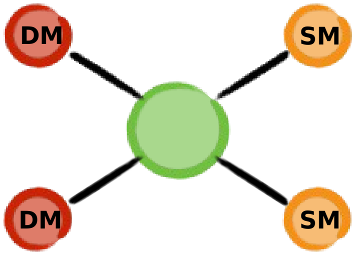
Production



Large Hadron Collider

Conventional (WIMP) candidates under tension



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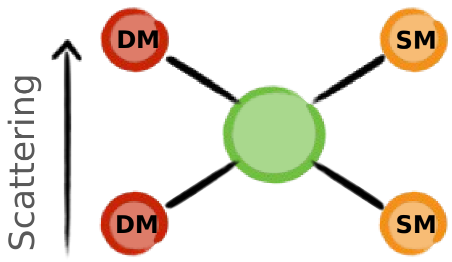
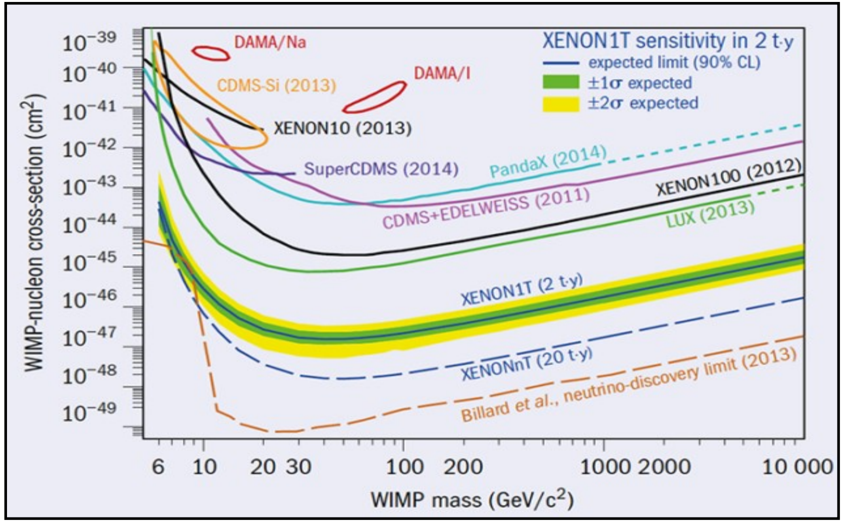


Image: XENON Collaboration



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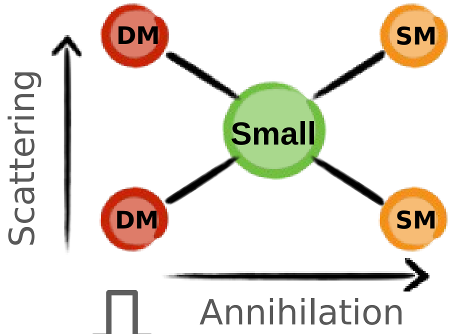

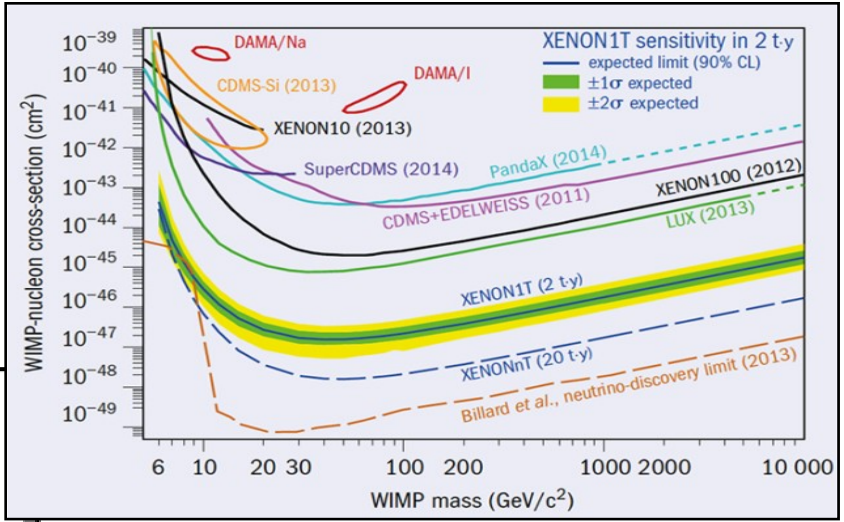

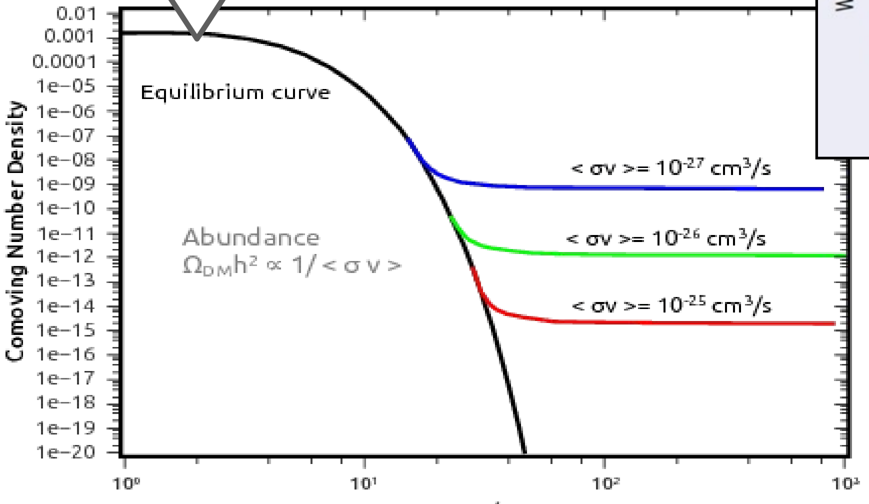

Arcadi et al. 1703.07364

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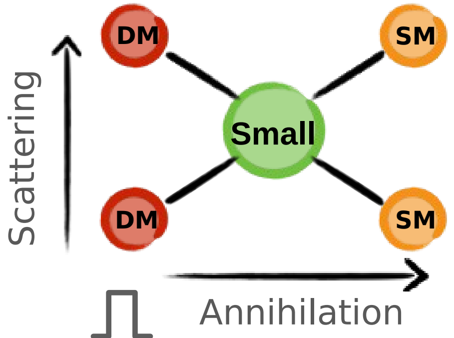

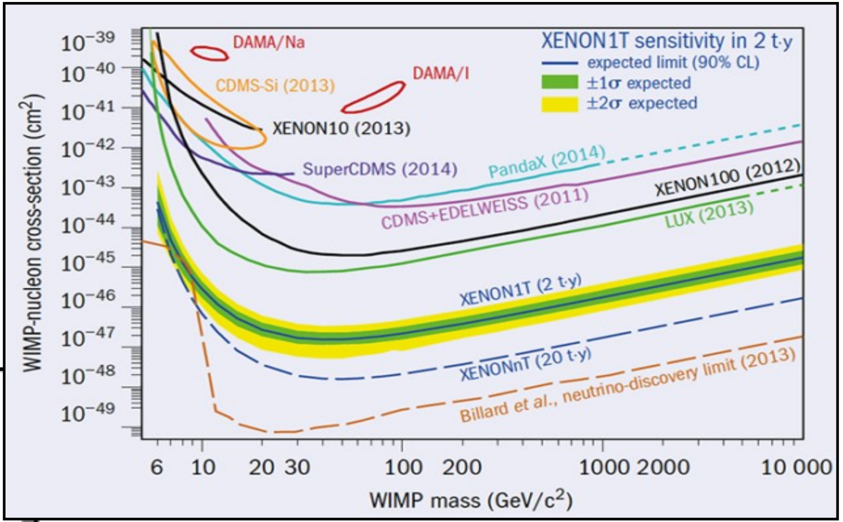

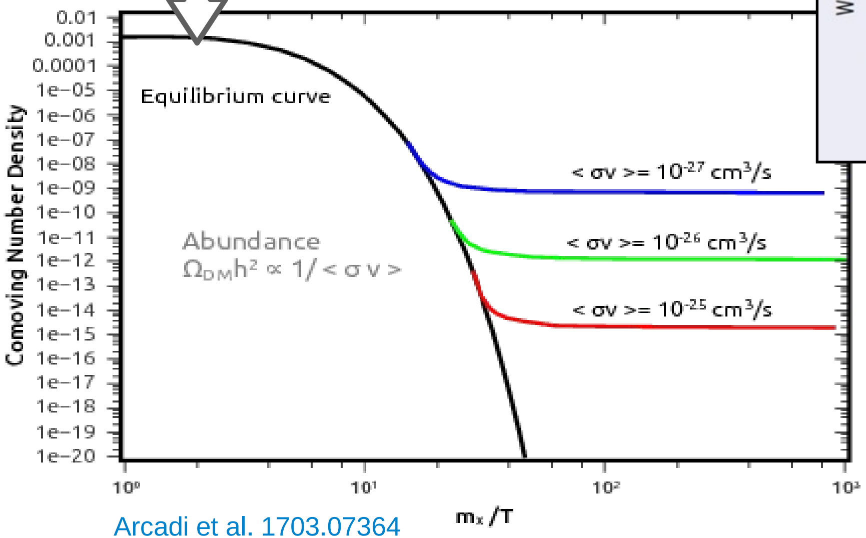

Arcadi et al. 1703.07364

Overabundance

Alternatives?

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Light: m < few GeV

Direct detection

e.g. Essig et al. [1509.01598], [1907.07682]

Colliders + beyond

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Physics Beyond Colliders at CERN [1901.09966]

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Heavy: m > few TeV

Telescopes

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Non-thermal

Freeze-in
e.g. Hall et al. [0911.1120], Bélanger et al. [1811.05478]

Early kinetic decoupling, **coscattering**

e.g Binder et al. [1706.07433], D'Agnolo et al. [1705.08450]

Different mass-coupling relation?

WIMPless miracle, coannihilation, forbidden dark matter

e.g Feng & Kumar [0905.3039], Griest & Seckel 1991, D'Agnolo & Ruderman [1505.07107]

From coannihilation to coscattering (inelastic scattering)

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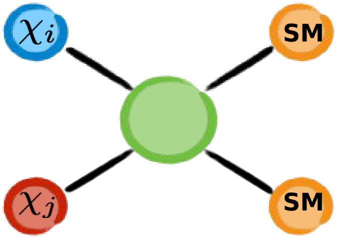
Coannihilation

Griest & Seckel 1991

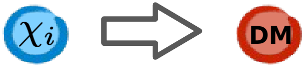
$$\sum_{ij}$$



$\langle \sigma v \rangle_{eff}$ ↑

at decoupling

But eventually



No Direct detection signal

From coannihilation to coscattering (inelastic scattering)

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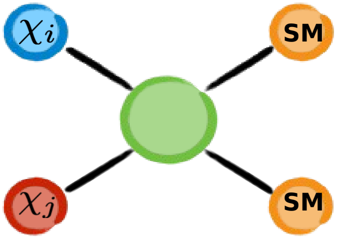

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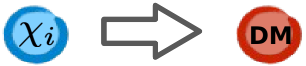

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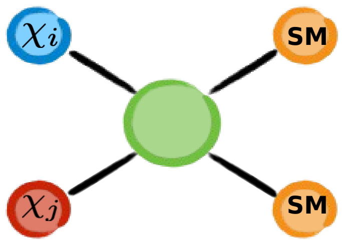

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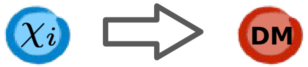

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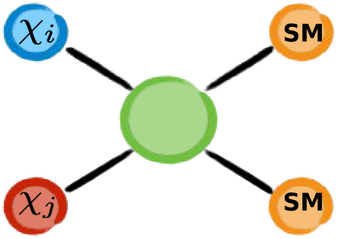

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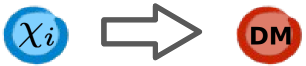

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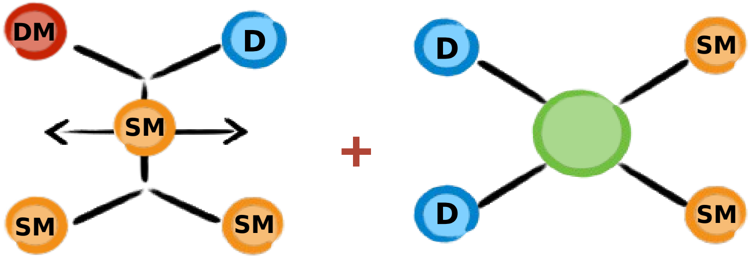
Coscattering

(inelastic scattering)

Not always thermal

(early kinetic decoupling)



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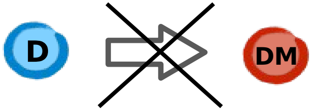
AF & S. Westhoff [1812.04628]
AF, S Junius, LL Honorez & S. Westhof [2201.08409]



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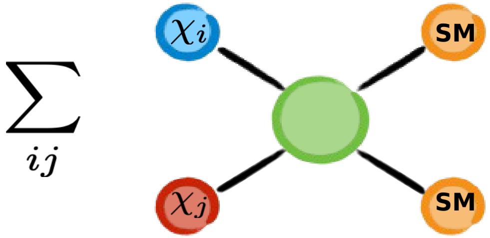

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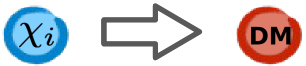

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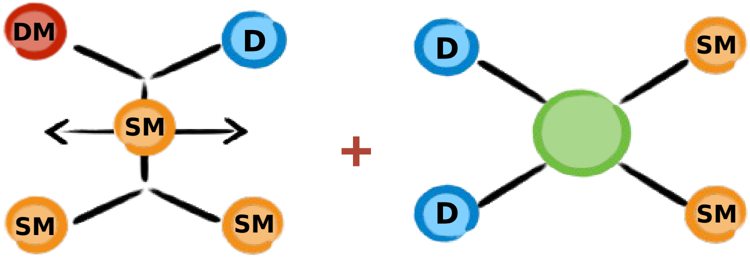

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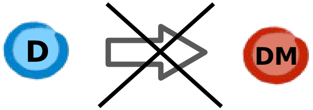

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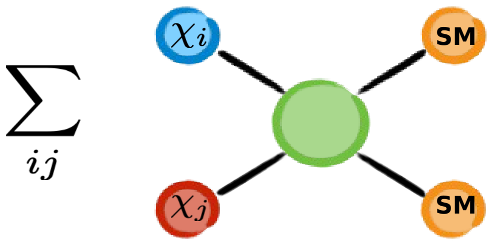

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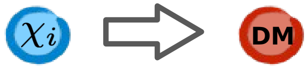

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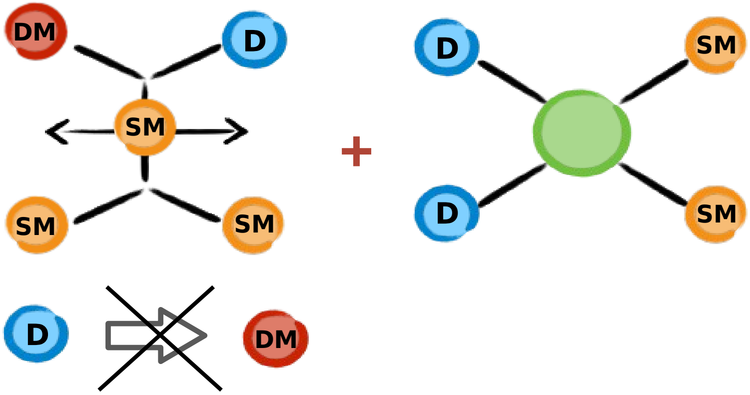

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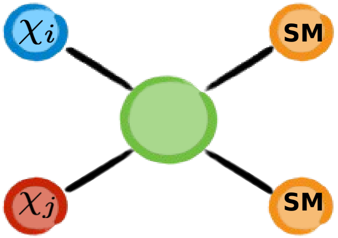

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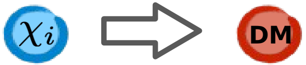
But eventually



No Direct detection signal

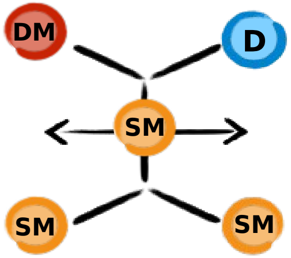
Coscattering

(inelastic scattering)

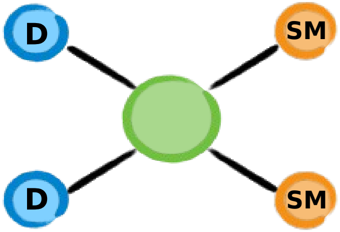
Not always thermal

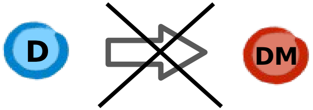
(early kinetic decoupling)

D'Agnolo et al. [1705.08450]
AF & S. Westhoff [1812.04628]
AF, S Junius, LL Honorez & S. Westhof [2201.08409]



+





$$n_{SM} \langle \sigma v \rangle_{DM \to M} \sim H$$

Very high

Correct relic abundance

for much smaller couplings

So just continue searching?

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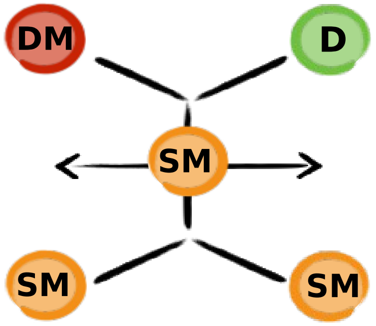

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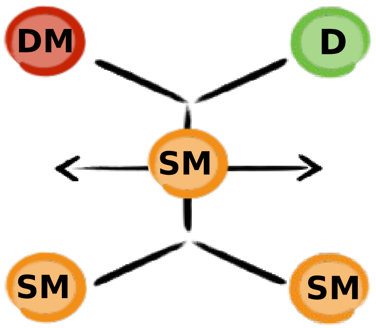

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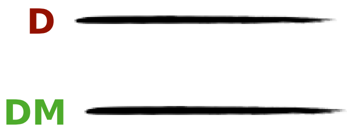

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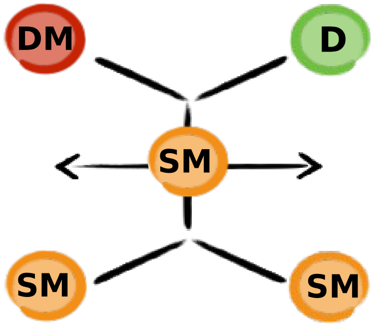

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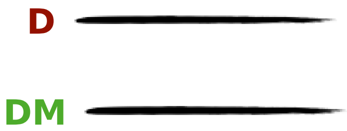

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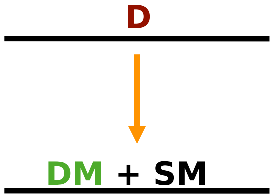

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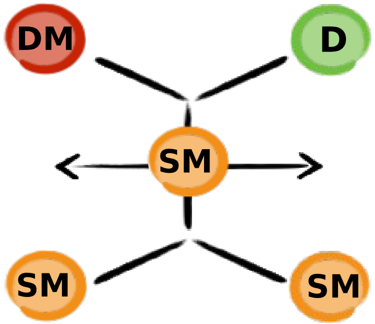

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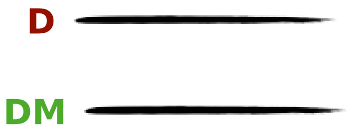

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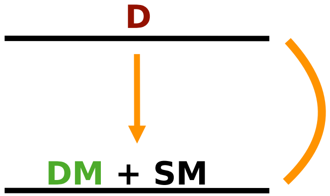

Defines p_T of SM

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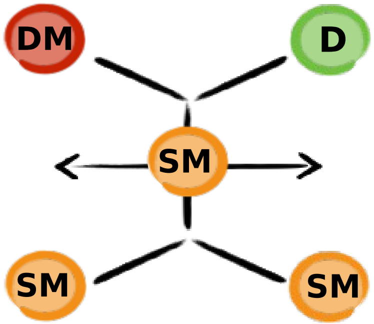

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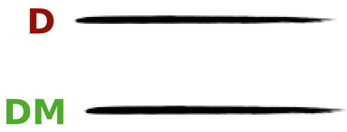

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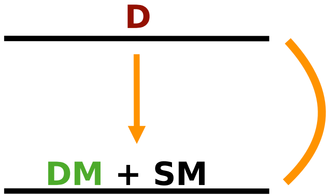

Defines p_T of SM

Particles are soft

LLPs @ colliders: heavy vs. light

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~Electroweak scale

pp-experiments: LHC

Soft products

⇩

High backgrounds

⇩

New experimental developments

(e.g. cross-triggers)

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MeV-GeV scale

Also at ee-experiments: Belle II

Very clean signatures

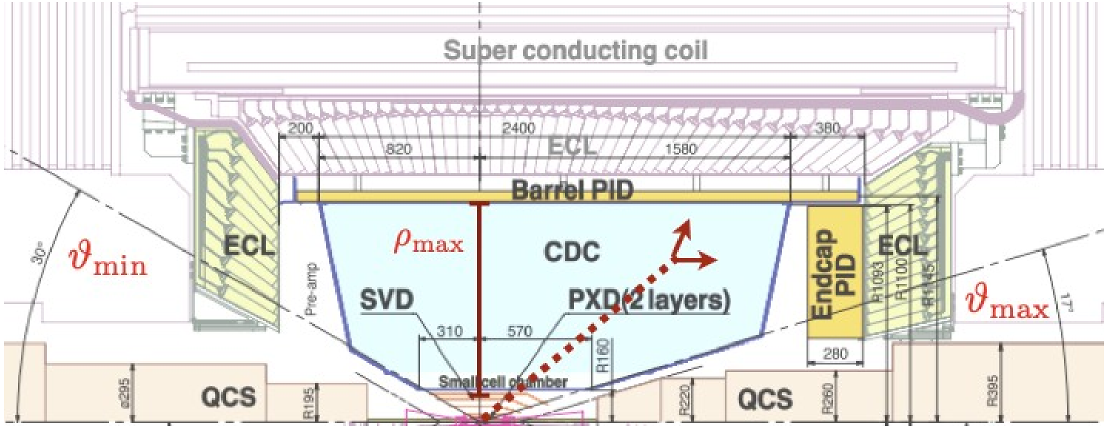
Bonus:

B-mesons are produced almost at rest

⇩

Large lifetimes can be probed

LLP and missing energy searches at Belle II



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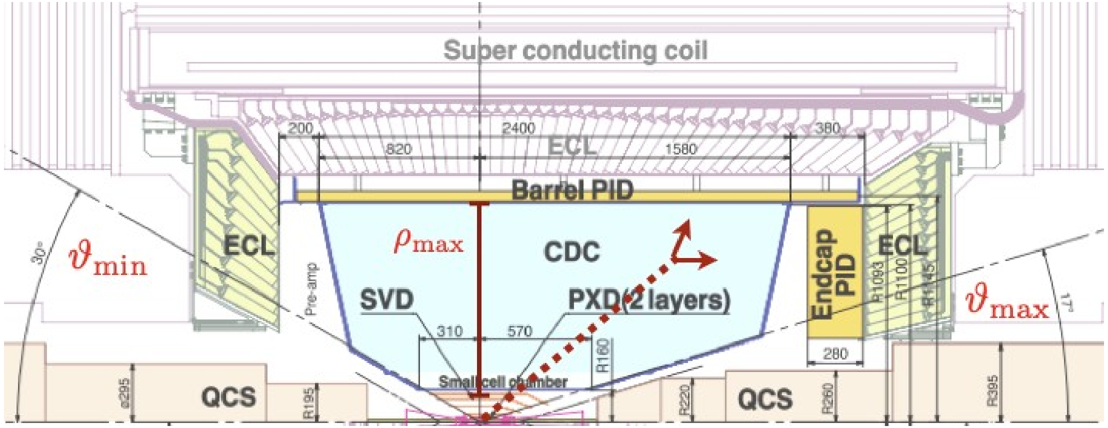
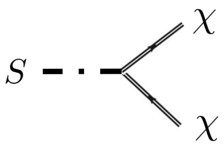
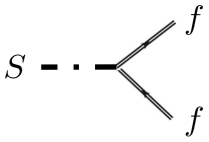


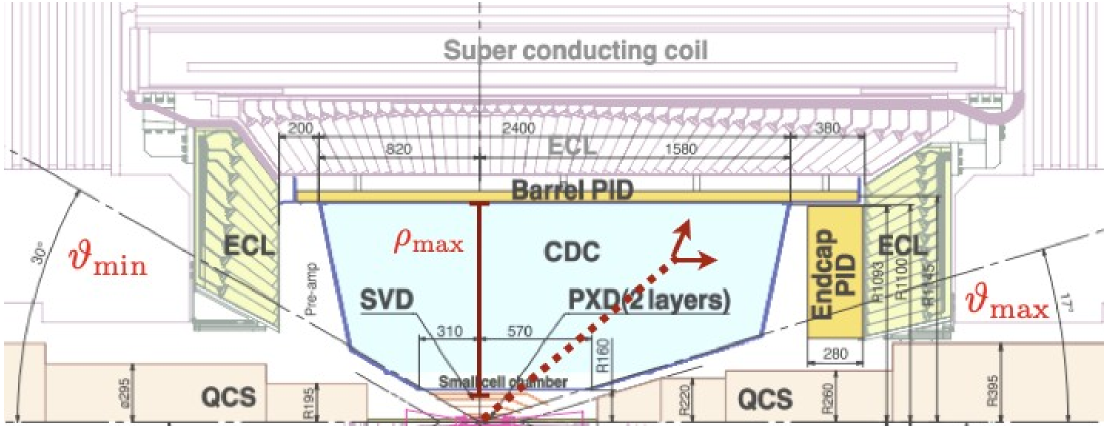


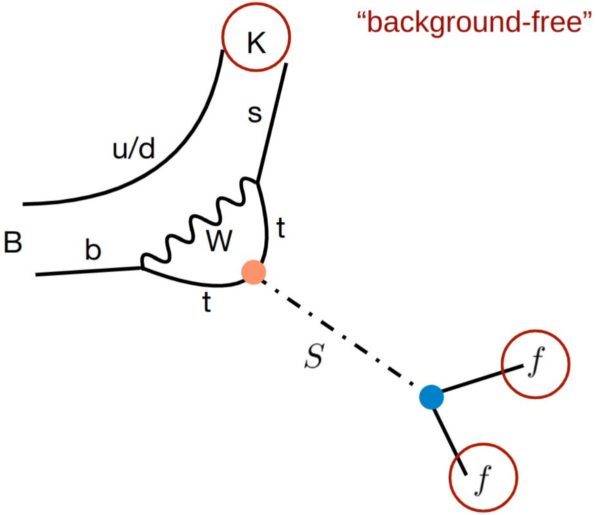
Missing energy

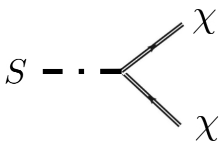


Displaced searches

LLP and missing energy searches at Belle II







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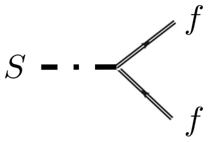


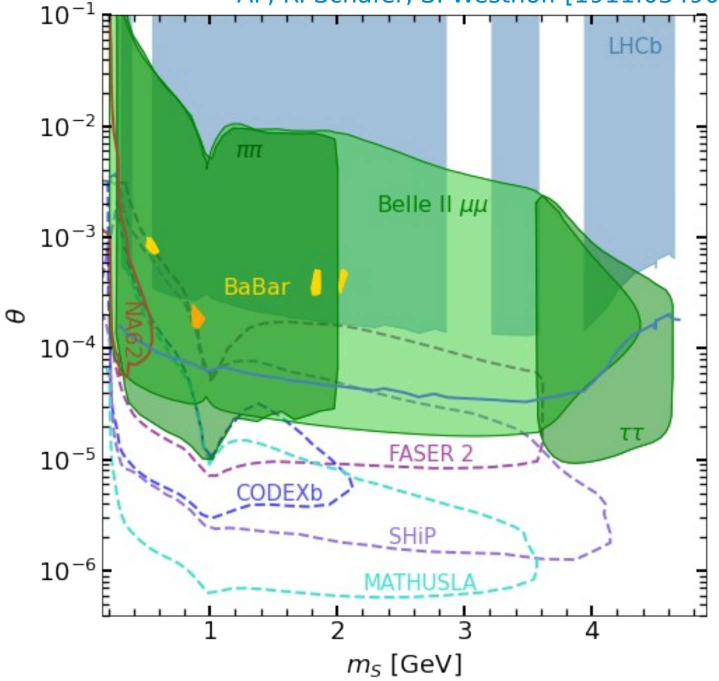
Displaced searches

LLP and missing energy searches at Belle II are very promising!

Dark scalar:

Displaced starches can compete with proposed long-baseline experiments

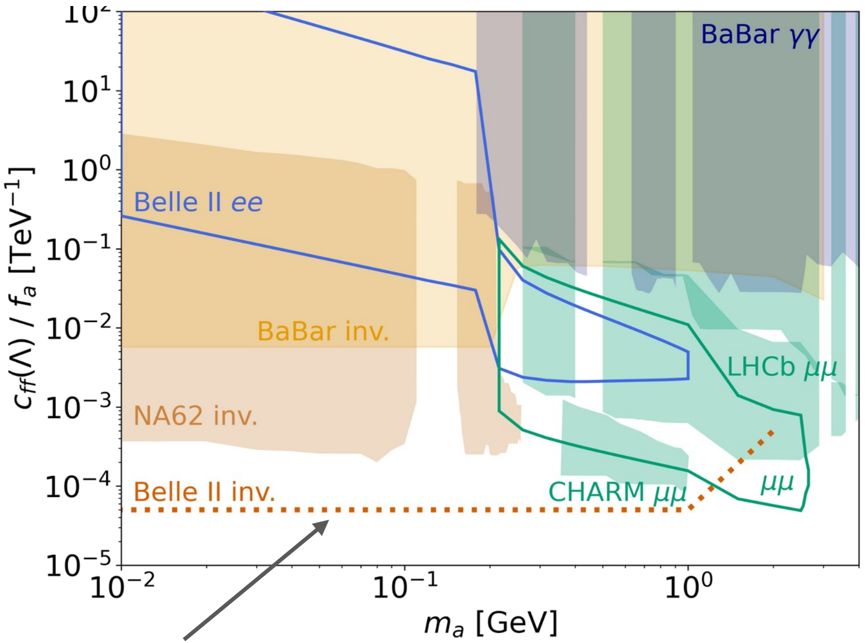
AF, R. Schäfer, S. Westhoff [1911.03490]



ALPs (fermion coupling only):

Complementarity of invisible and displaced searches.

T. Ferber, AF, R. Schäfer, S. Westhoff [2201.06580]



A new search strategy for two-body invisible decays

Alternative dark matter candidates?

Light: m < few GeV

Direct detection

e.g. Essig et al. [1509.01598], [1907.07682]

Colliders + beyond

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Heavy: m > few TeV

Telescopes

e.g. Antares: [1912.05296],
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Non-thermal

Freeze-in

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BSM (heavy) DM + SM mediator

+ let's keep DM thermal (we like it)

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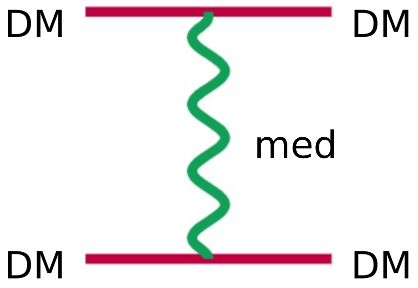

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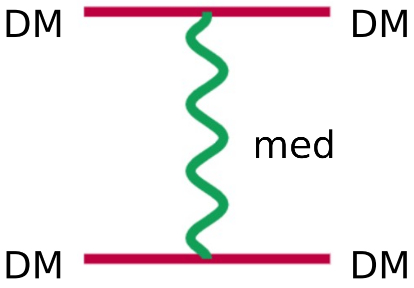
Interaction length $\sim \frac{1}{m_{med}} > \frac{1}{\mu\alpha}, \frac{1}{\mu v_{rel}}$



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for bound states

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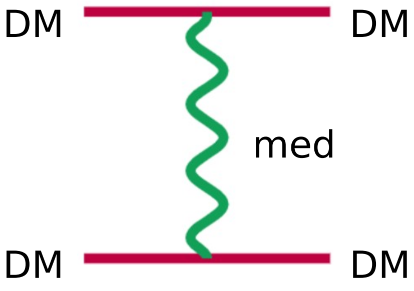

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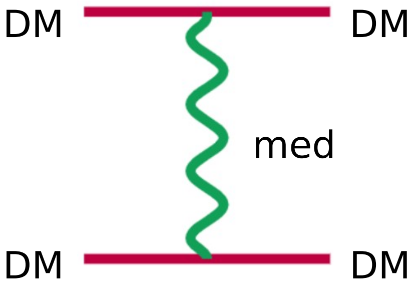

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Typically, viable scenarios have dark matter at multi-GeV or TeV scale

Long-range interactions and their implications

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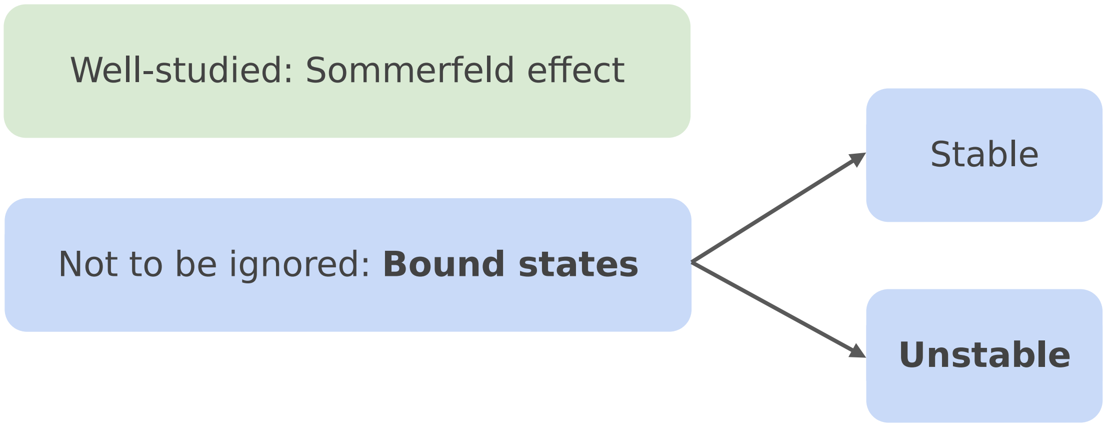

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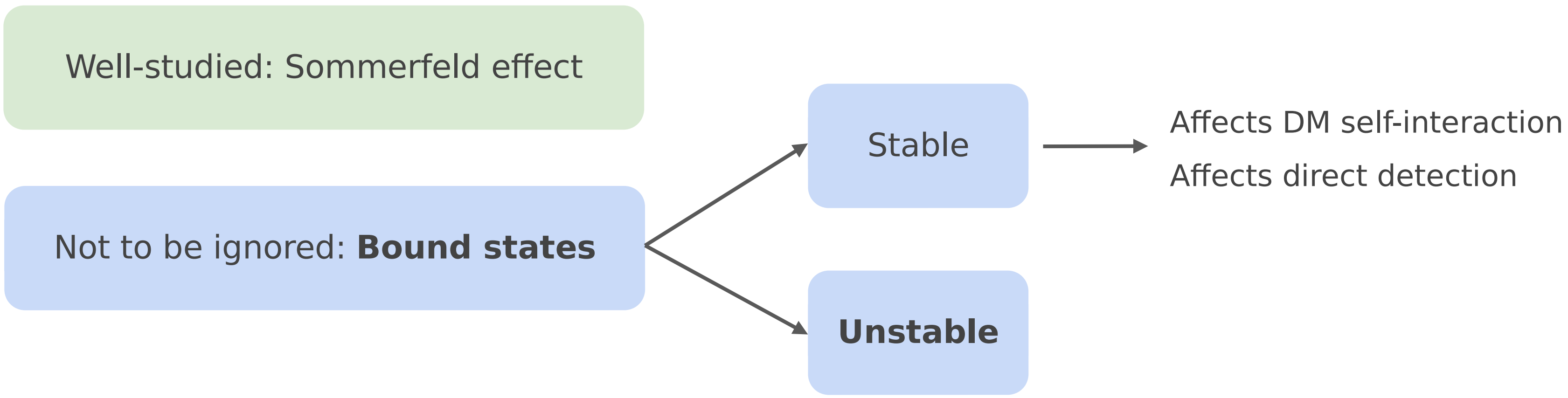

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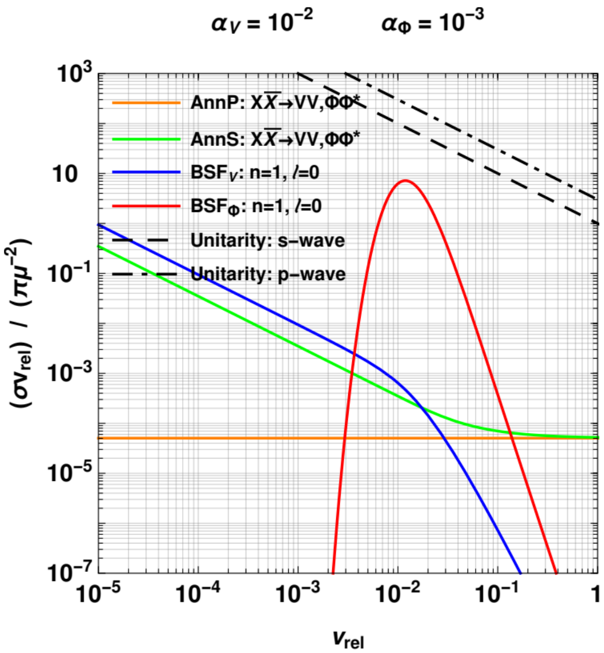
Affect Indirect detection

Dramatic example: scalar mediator



Huge enhancement from BSF_Φ

Oncala, Petraki [1911.02605]

+ Higgs portal models,
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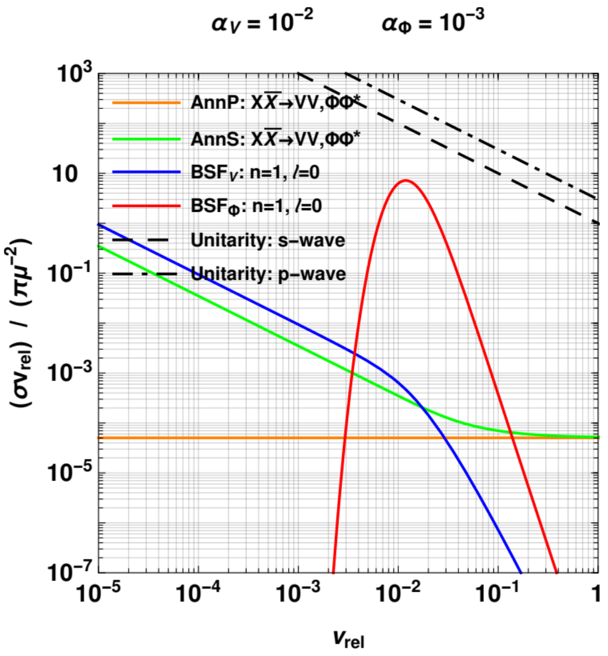

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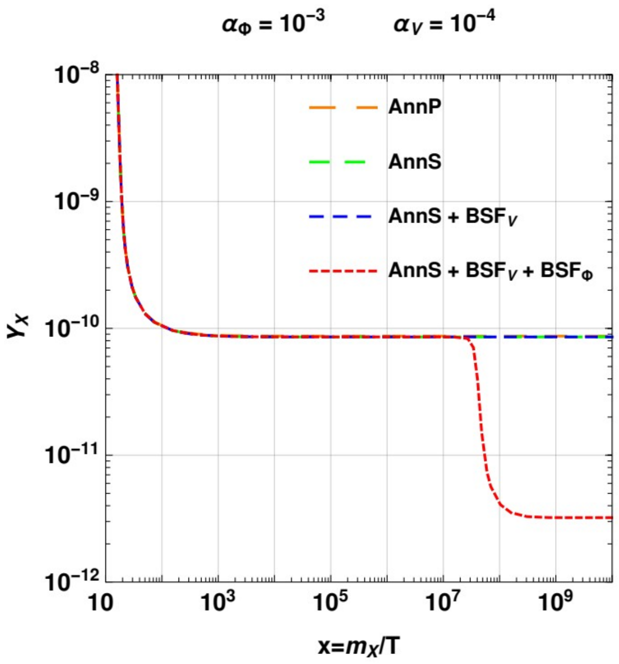
Relic density predictions change by orders of magnitude!



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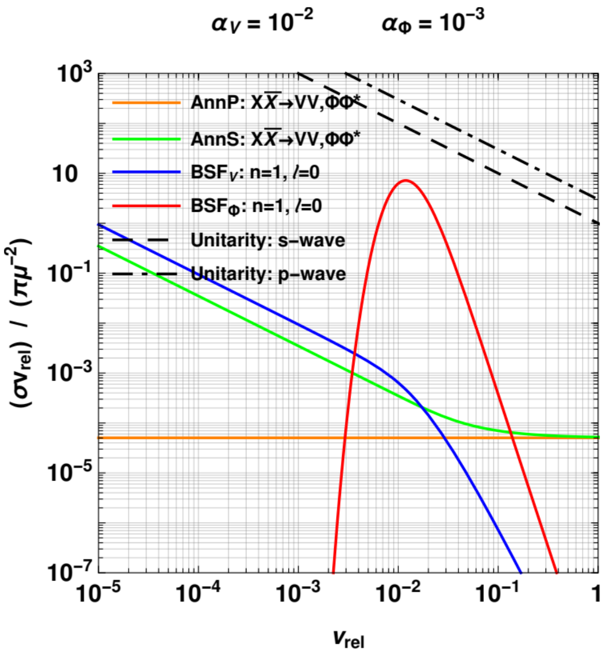

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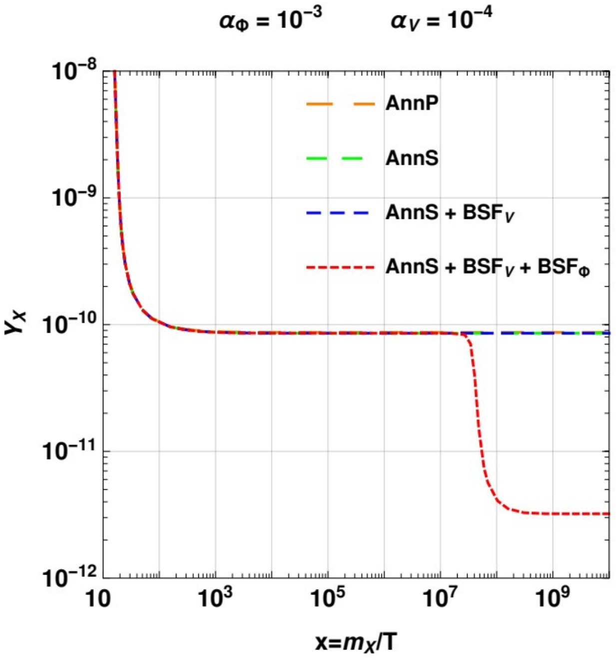

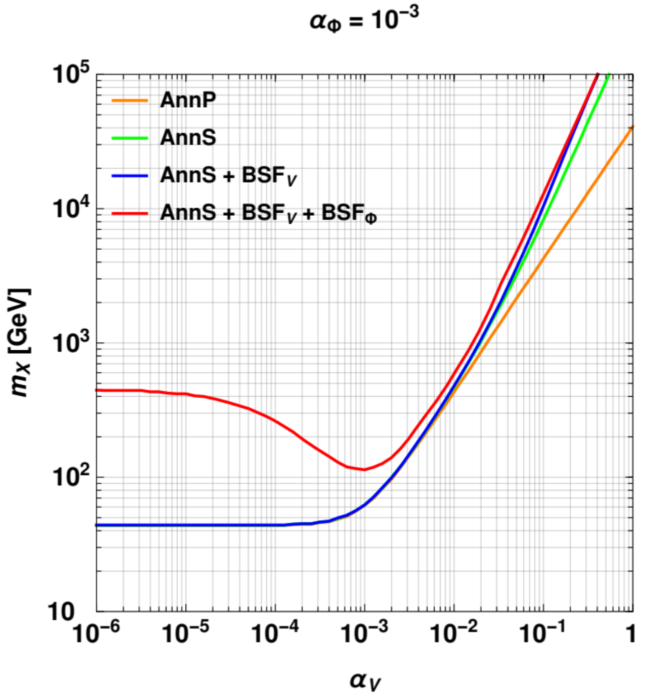

Changes all pheno predictions (DD, ID, colliders..)!

Oncala, Petraki [1911.02605]

+ Higgs portal models, Oncala, Petraki [2101.08666/7]

Why to care about bound states?

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⇓

Need a general formalism to account for bound states

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with $\lambda \equiv \sqrt{\frac{\pi}{45}} m_{\rm Pl}\, m\, g_*^{1/2}$ and $\Lambda \equiv \frac{\lambda}{s\, x^3} = \sqrt{\frac{45}{4\pi^3}} \frac{m_{\rm Pl}}{m^2} \frac{g_*^{1/2}}{g_{*S}}$

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with $\lambda \equiv \sqrt{\frac{\pi}{45}} m_{\rm Pl}\, m\, g_*^{1/2}$ and $\Lambda \equiv \frac{\lambda}{s\, x^3} = \sqrt{\frac{45}{4\pi^3}} \frac{m_{\rm Pl}}{m^2} \frac{g_*^{1/2}}{g_{*S}}$

However, in most models, this system can be simplified to **one effective Boltzmann equation**

Binder, AF, Petraki, White [2112.00042], see also Garny Heisig [2112.01499]

Conclusions

- Strong direct detection constraints point us to **less conventional** dark matter scenarios
- Viable scenarios are **very different** at different energy scales
- Well-known models have features that dramatically affect dark matter phenomenology, and therefore **change the search strategies** (e.g. existence of long-lived particles or bound states)
- At MeV-GeV scale, displaced and invisible searches at **electron colliders are very promising**
- Displaced and invisible searches are **complementary**. They both require attention when exploring the parameter space of a feebly-interacting model
- **Bound states are a whole new avenue** in dark matter community. We are still developing the framework to understand them but they will definitely change many of our predictions

Backup

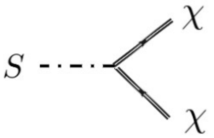
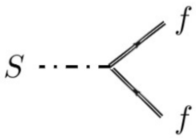
Dark scalar model

$$\mathcal{L} = -\frac{1}{2}m_\phi^2\phi^2 - \mu\,|H|^2\phi - y_\chi\bar{\chi}\chi\phi - \frac{1}{2}m_\chi\bar{\chi}\chi$$

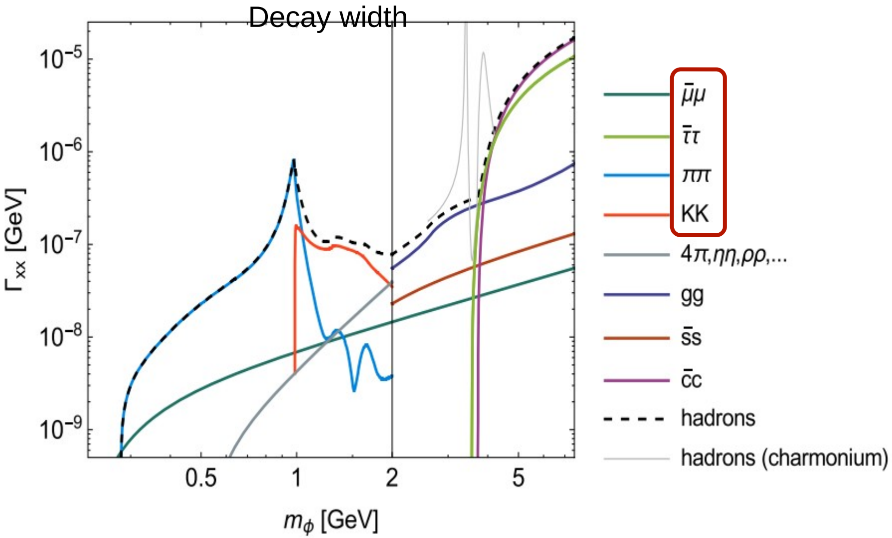
Can play role of DM candidate

Search regions

$$\Gamma_S = c_\theta^2\Gamma_{\chi\bar{\chi}} + s_\theta^2\Gamma_{\mathrm{SM}}$$

$m_S > 2m_\chi$	$m_S < 2m_\chi$
Invisible decays dominate	Visible decays only
	
Missing energy	Displaced searches

One new coupling



$$h,\ S$$

Higgs

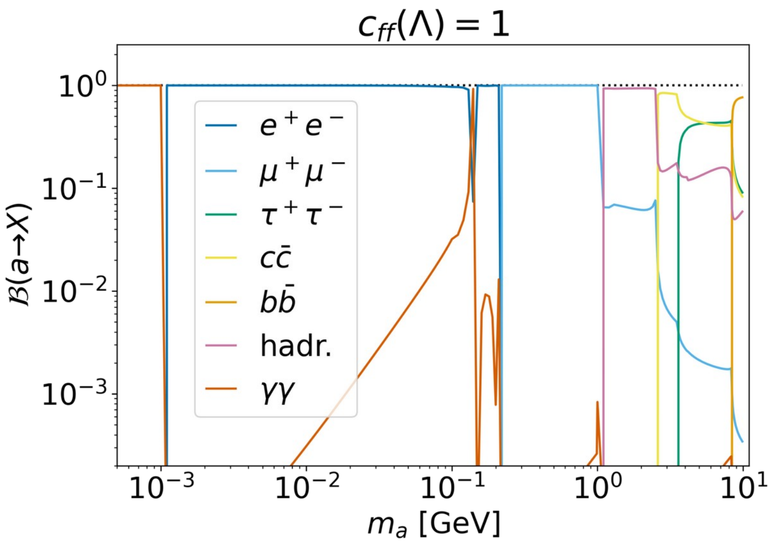
New scalar

ALP model

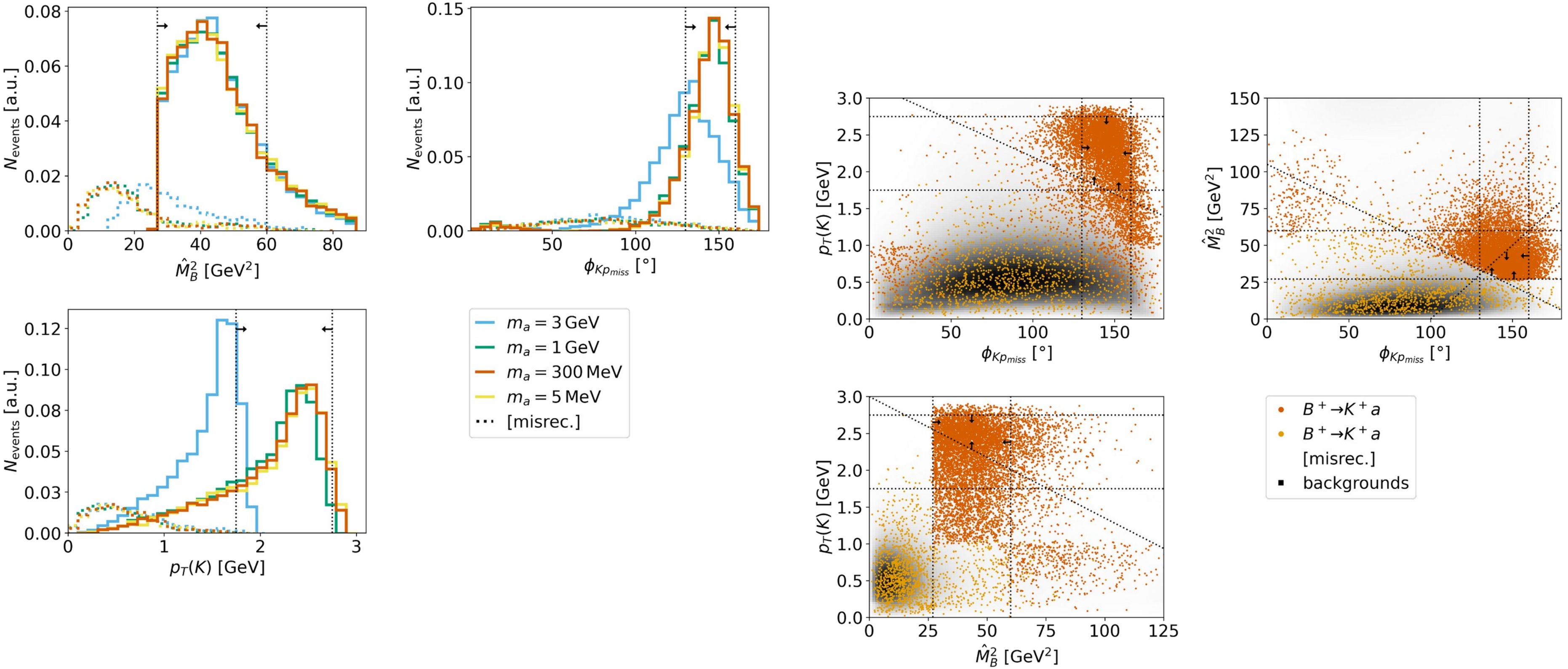
$$\mathcal{L}_{\text{eff}}(\mu > \mu_w) = \sum_f \frac{c_{ff}(\mu)}{2} \frac{\partial^\mu a}{f_a}(\bar{f}\gamma_\mu\gamma_5 f) + c_{WW}(\mu)\frac{a}{f_a}\frac{\alpha_2}{4\pi} W^A_{\mu\nu}\widetilde{W}^{\mu\nu,A}$$

$$\mathcal{B}(B^+ \to K^+ a) = 0.03 \left(\frac{c_{ff}(\Lambda)}{f_a\,[\text{TeV}]} + 0.0032\,\frac{c_{WW}(\Lambda)}{f_a\,[\text{TeV}]}\right)^2 \frac{f_0^2(m_a^2)}{f_0^2(0)} \frac{\lambda^{1/2}(m_B^2, m_K^2, m_a^2)}{m_B^2 - m_K^2}$$

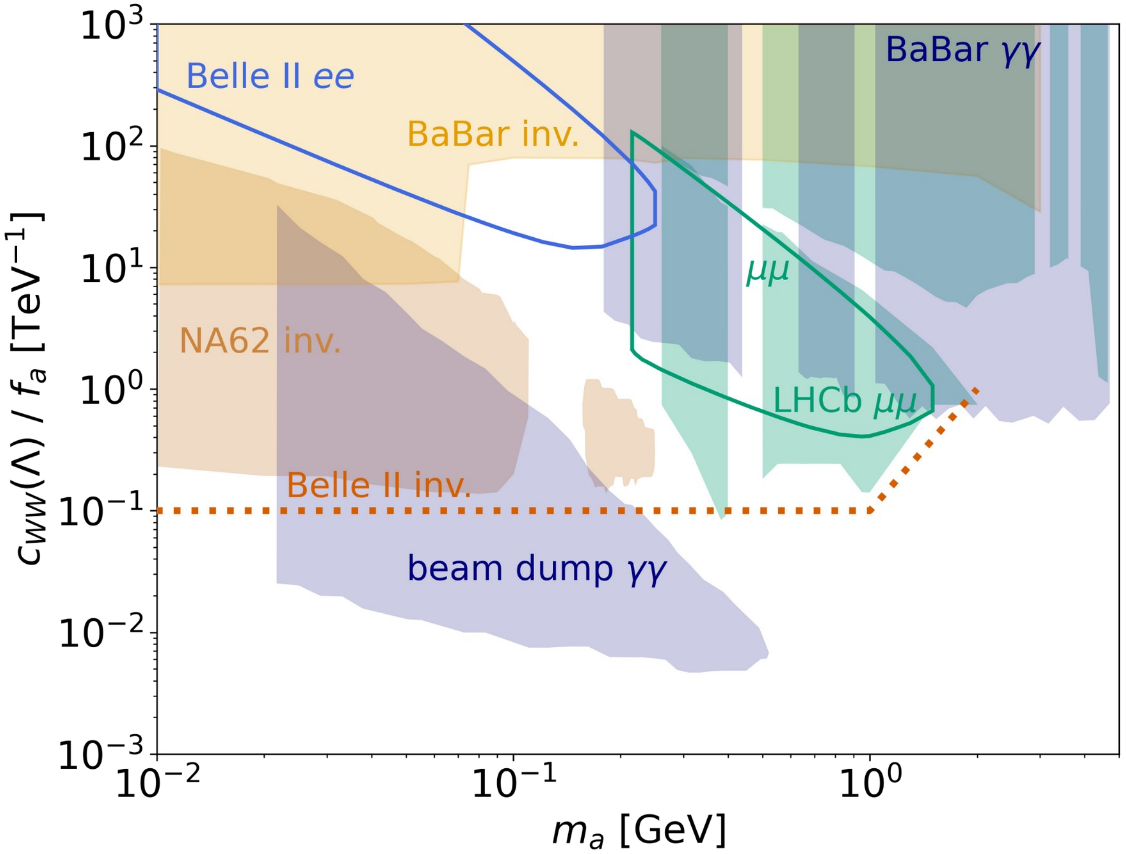
$$\Gamma_{a\to\ell\bar{\ell}} = 2\pi m_a \frac{\left|C^{\text{eff}}_{\ell\ell}(m_a)\right|^2 m_\ell^2}{\Lambda^2}\sqrt{1 - \frac{4m_\ell^2}{m_a^2}}$$



ALP invisible searches: kinematics and selection criteria



ALP model: projections for photon coupling only



Binder, AF, Petraki, White [2112.00042]

Coupled system of Boltzmann equations

$$\frac{dY_j}{dx} = -\frac{\lambda}{x^2}\sum_i \langle\sigma_{ji}^{\rm ann} v_{\rm rel}\rangle \left(Y_j Y_i - Y_j^{\rm eq} Y_i^{\rm eq}\right) - \frac{\lambda}{x^2}\sum_i\sum_{\mathcal{B}} \langle\sigma_{ji\to\mathcal{B}}^{\rm BSF} v_{\rm rel}\rangle \left(Y_j Y_i - \frac{Y_{\mathcal{B}}}{Y_{\mathcal{B}}^{\rm eq}} Y_j^{\rm eq} Y_i^{\rm eq}\right)$$

$$- \Lambda\, x \sum_i \langle\Gamma_{j\to i}\rangle \left(Y_j - \frac{Y_i}{Y_i^{\rm eq}} Y_j^{\rm eq}\right)$$

$$\frac{dY_{\mathcal{B}}}{dx} = -\Lambda\, x \left[\langle\Gamma_{\mathcal{B}}^{\rm dec}\rangle \left(Y_{\mathcal{B}} - Y_{\mathcal{B}}^{\rm eq}\right) + \sum_{i,j}\langle\Gamma_{\mathcal{B}\to ij}^{\rm ion}\rangle \left(Y_{\mathcal{B}} - \frac{Y_i Y_j}{Y_i^{\rm eq} Y_j^{\rm eq}} Y_{\mathcal{B}}^{\rm eq}\right) + \sum_{\mathcal{B}'\neq\mathcal{B}} \langle\Gamma_{\mathcal{B}\to\mathcal{B}'}^{\rm trans}\rangle \left(Y_{\mathcal{B}} - \frac{Y_{\mathcal{B}'}}{Y_{\mathcal{B}'}^{\rm eq}} Y_{\mathcal{B}}^{\rm eq}\right)\right]$$

However:

- Assume fast transitions $\Gamma_{i\leftrightarrow j} \to Y_i/Y_i^{eq} = w$
- At high temperatures, ionisations are efficient;
  at low temperatures - decays (directly or via transitions) are fast $\to \frac{dY_B}{dx} \simeq 0$

This approximation was first proposed by Ellis, Luo Olive [1503.07142]

One effective Boltzmann equation

Binder, AF, Petraki, White [2112.00042]
also see Garny Heisig [2112.01499]

Some definitions:

Total DM yield

$$Y \equiv \sum_j Y_j$$

Total rates for a given bound state

$$\langle \Gamma^{\rm ion}_{\mathcal{B}} \rangle \equiv \sum_{i,j} \langle \Gamma^{\rm ion}_{\mathcal{B}\to ij} \rangle$$

$$\langle \Gamma^{\rm trans}_{\mathcal{B}} \rangle \equiv \sum_{\mathcal{B}' \neq \mathcal{B}} \langle \Gamma^{\rm trans}_{\mathcal{B}\to \mathcal{B}'} \rangle$$

$$\langle \Gamma^{\rm tot}_{\mathcal{B}} \rangle \equiv \langle \Gamma^{\rm dec}_{\mathcal{B}} \rangle + \langle \Gamma^{\rm ion}_{\mathcal{B}} \rangle + \langle \Gamma^{\rm trans}_{\mathcal{B}} \rangle$$

Matrix notations

$$\mathbb{\Gamma}^{\rm dec}_{\mathcal{B}\mathcal{B}'} \equiv \delta_{\mathcal{B}\mathcal{B}'} \langle \Gamma^{\rm dec}_{\mathcal{B}} \rangle$$

$$\mathbb{\Gamma}^{\rm ion}_{\mathcal{B}\mathcal{B}'} \equiv \delta_{\mathcal{B}\mathcal{B}'} \langle \Gamma^{\rm ion}_{\mathcal{B}} \rangle$$

$$\mathbb{\Gamma}^{\rm trans}_{\mathcal{B}\mathcal{B}'} \equiv \delta_{\mathcal{B}\mathcal{B}'} \langle \Gamma^{\rm trans}_{\mathcal{B}} \rangle$$

$$\mathbb{\Gamma}^{\rm tot}_{\mathcal{B}\mathcal{B}'} \equiv \delta_{\mathcal{B}\mathcal{B}'} \langle \Gamma^{\rm tot}_{\mathcal{B}} \rangle = \mathbb{\Gamma}^{\rm dec}_{\mathcal{B}\mathcal{B}'} + \mathbb{\Gamma}^{\rm ion}_{\mathcal{B}\mathcal{B}'} + \mathbb{\Gamma}^{\rm trans}_{\mathcal{B}\mathcal{B}'}$$

$$\mathbb{T}_{\mathcal{B}\mathcal{B}'} \equiv \langle \Gamma^{\rm trans}_{\mathcal{B}'\to \mathcal{B}} \rangle$$

$$\frac{dY}{dx} = -\frac{\lambda}{x^2} \langle \sigma^{\rm eff} v_{\rm rel} \rangle \left[Y^2 - (Y^{\rm eq})^2 \right]$$

$$\langle \sigma^{\rm eff} v_{\rm rel} \rangle \equiv \sum_{i,j} \frac{g_{i,\rm eff}\, g_{j,\rm eff}}{g^2_{\rm eff}} \left(\langle \sigma^{\rm ann}_{ij} v_{\rm rel} \rangle + \sum_{\mathcal{B}} r_{\mathcal{B}} \langle \sigma^{\rm BSF}_{ij\to \mathcal{B}} v_{\rm rel} \rangle \right)$$

$$r_{\mathcal{B}} \equiv \sum_{\mathcal{B}'} \langle \Gamma^{\rm dec}_{\mathcal{B}'} \rangle \left(\mathbb{\Gamma}^{\rm tot} - \mathbb{T} \right)^{-1}_{\mathcal{B}'\mathcal{B}}$$

Bound state efficiency factor

$$0 \leq r_{\mathcal{B}} \leq 1$$

Binder, AF, Petraki, White [2112.00042]

Saha ionisation equilibrium for **metastable** bound states

(Algebraic) eq. for bound states + detailed balance + definition of efficiency factor:

$$\frac{n_{\mathcal{B}}}{n_{\mathcal{B}}^{\rm eq}} = \left(\frac{n_{\rm free}}{n_{\rm free}^{\rm eq}}\right)^2 - \left[\left(\frac{n_{\rm free}}{n_{\rm free}^{\rm eq}}\right)^2 - 1\right] r_{\mathcal{B}}$$

$$\mu_{\mathcal{B}}/T = 2\mu_{\rm free}/T + \ln\left[1 - (1 - e^{-2\mu_{\rm free}/T}) r_{\mathcal{B}}\right]$$

$$r_{\mathcal{B}} \ll 1$$

$$\mu_{\mathcal{B}} = 2\ \mu_{free}$$

(familiar expression)

$$r_{\mathcal{B}} \to 1$$

$$\mu_{\mathcal{B}} = 0$$