The Dark Matter motivation for LLP searches at Belle II

Kai Schmidt-Hoberg

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

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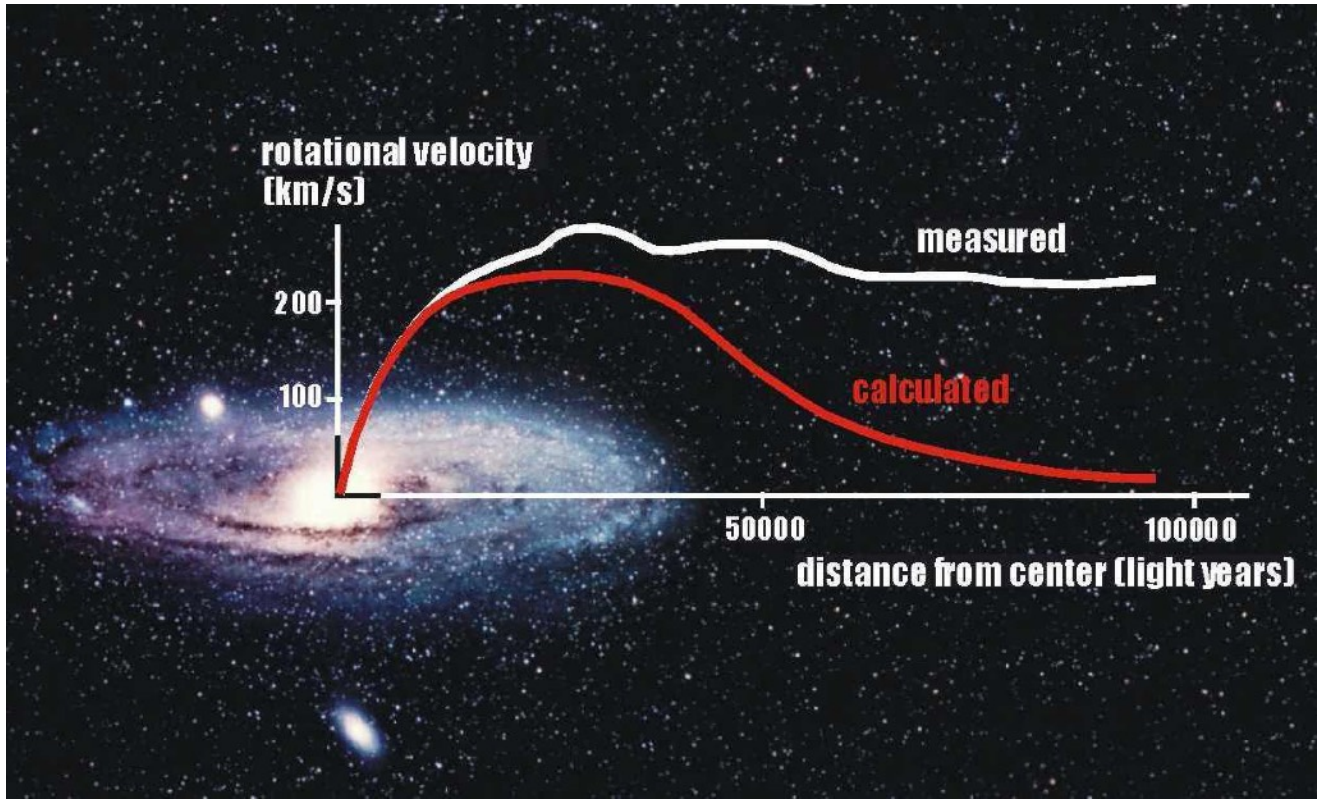
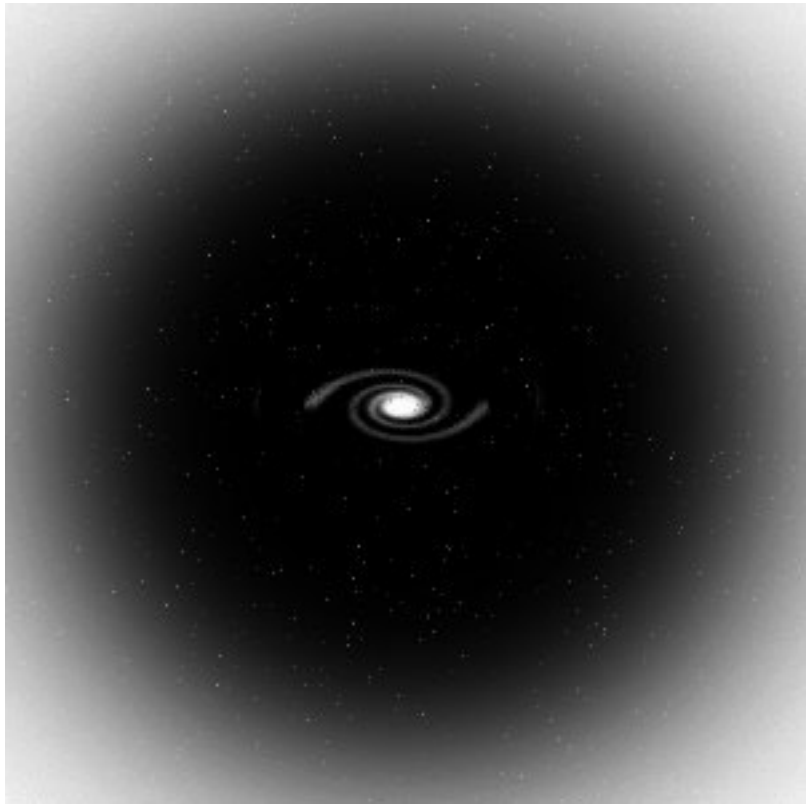
DESY.

Evidence for dark matter

Compelling evidence for dark matter on all astrophysical scales

- **galactic scales: Rotation curves of galaxies**





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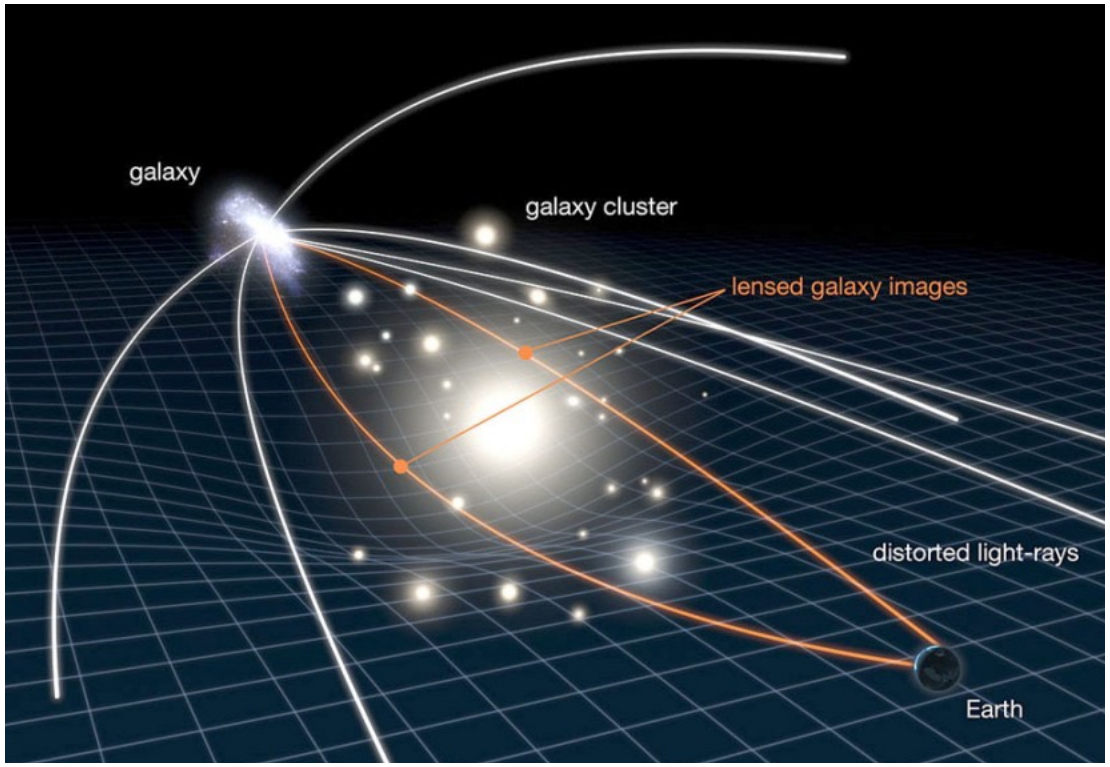
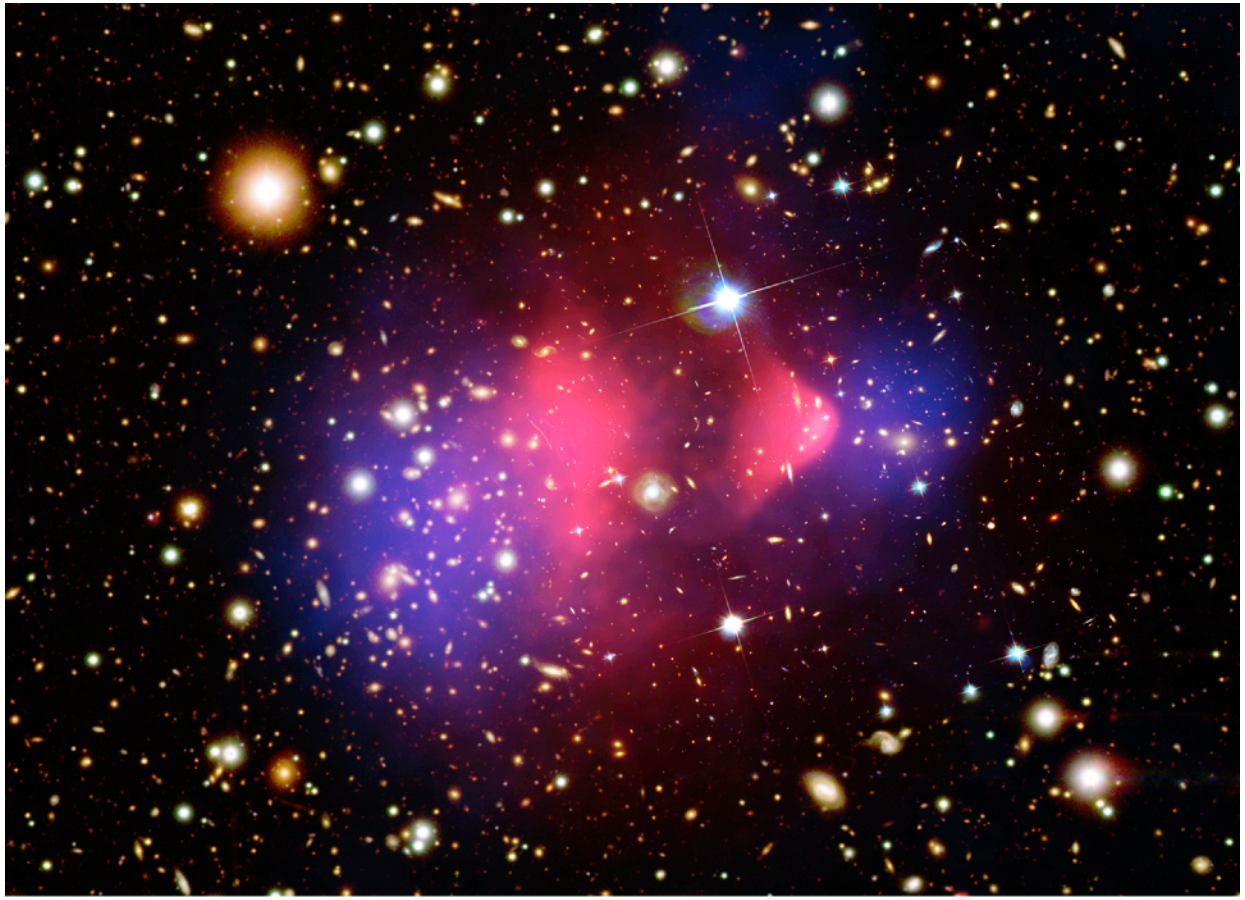
- **Cluster scales: Gravitational lensing**





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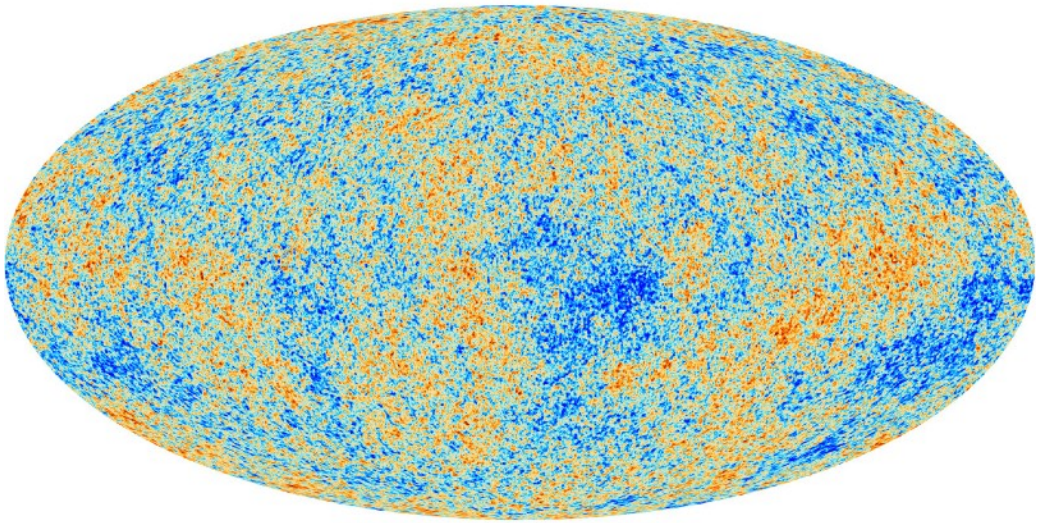
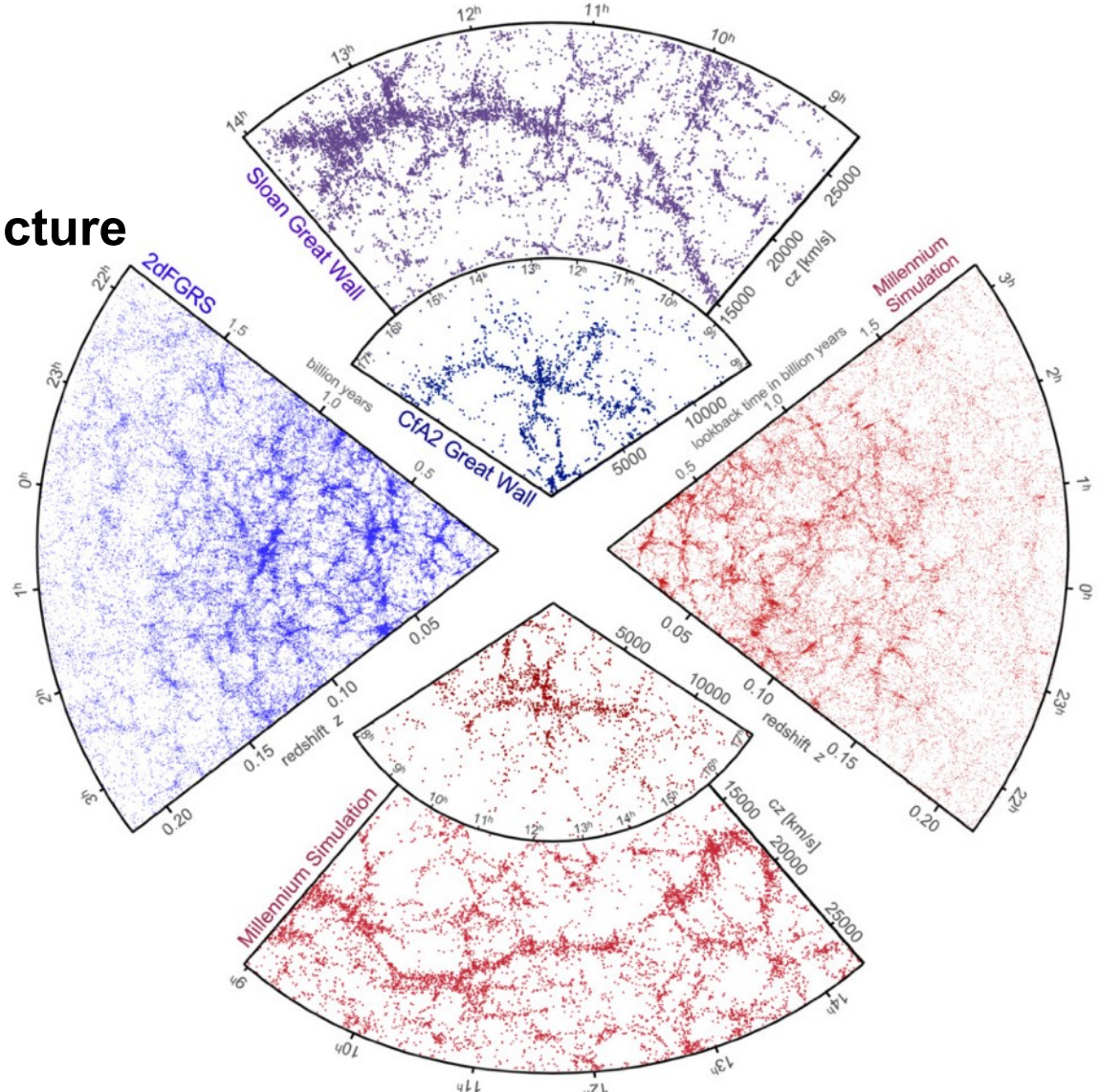
- **Cosmological scales: CMB and large scale structure**





Evidence for dark matter

Compelling evidence for dark matter on all astrophysical scales

- **galactic scales: Rotation curves of galaxies**
- **Cluster scales: Gravitational lensing**
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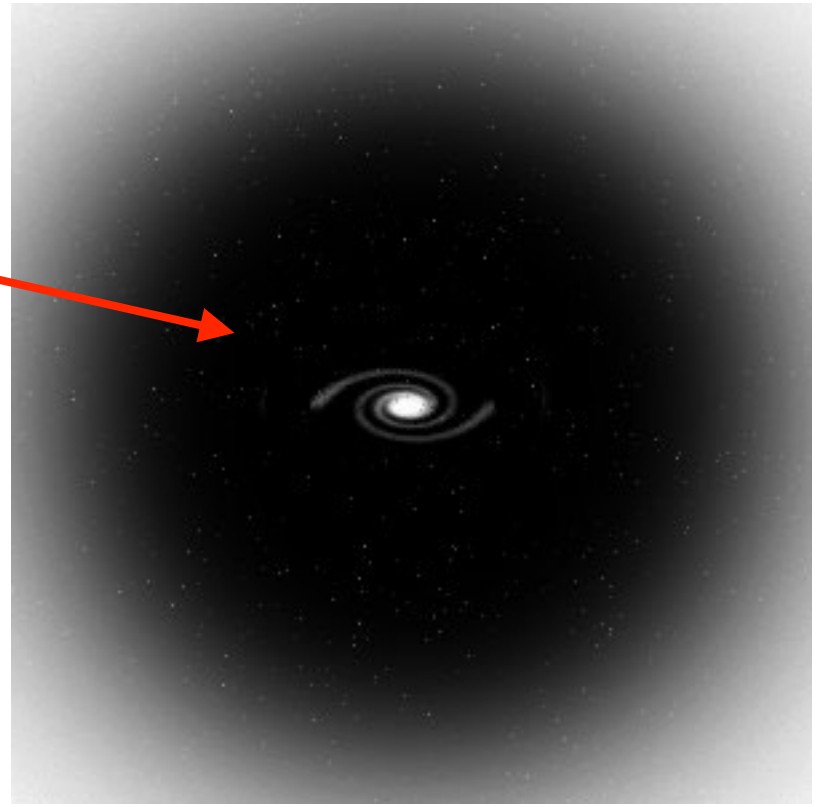
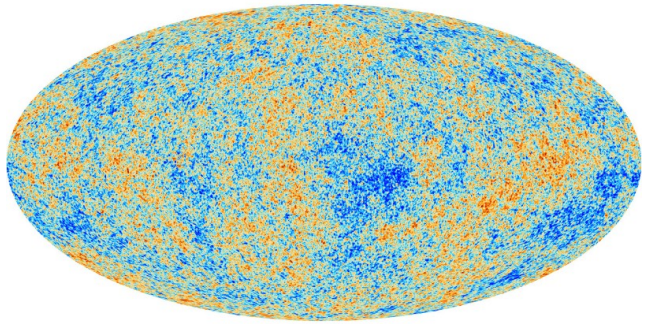
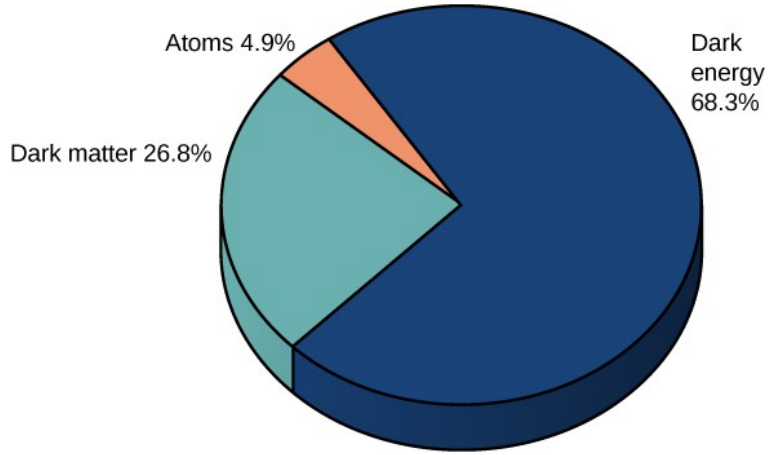
What is it?

What do we know?



What do we know?

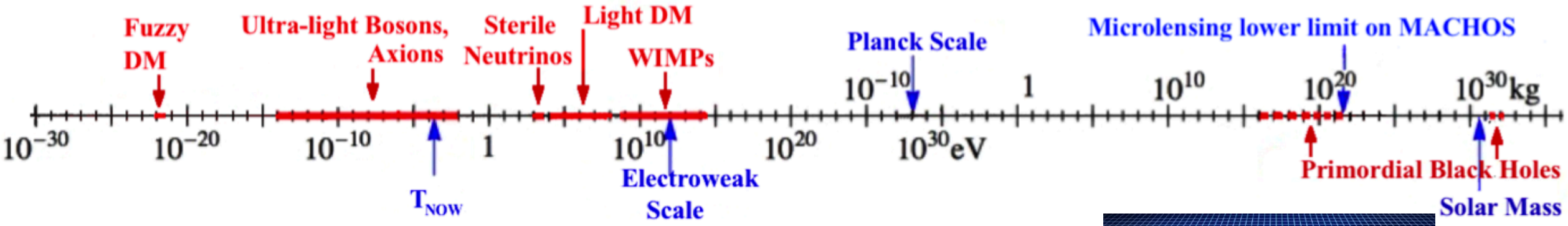


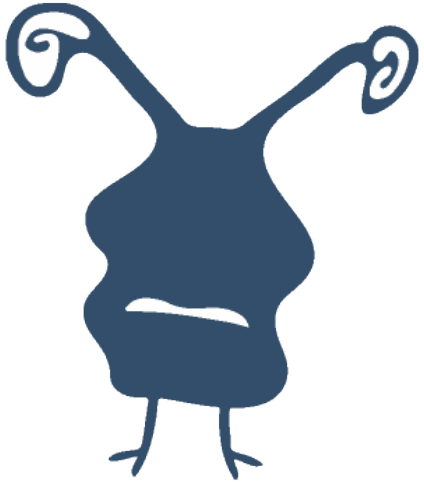


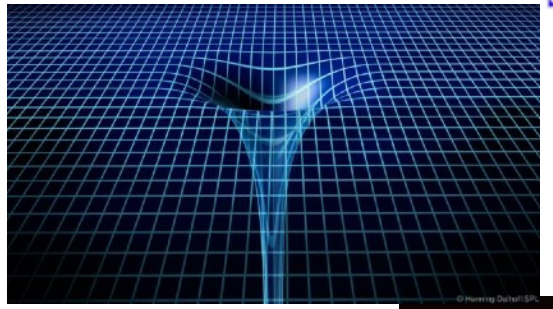
- How much: $\Omega \simeq 0.26$
- Dark
  - almost electrically neutral
  - probably colour neutral
- Stable
  - sufficiently long-lived
- Cold
  - non-relativistic (structure formation)
- Non-baryonic

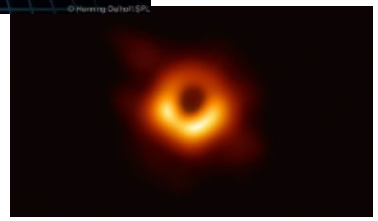
This leaves some room…

Gelmini, 1612.09137









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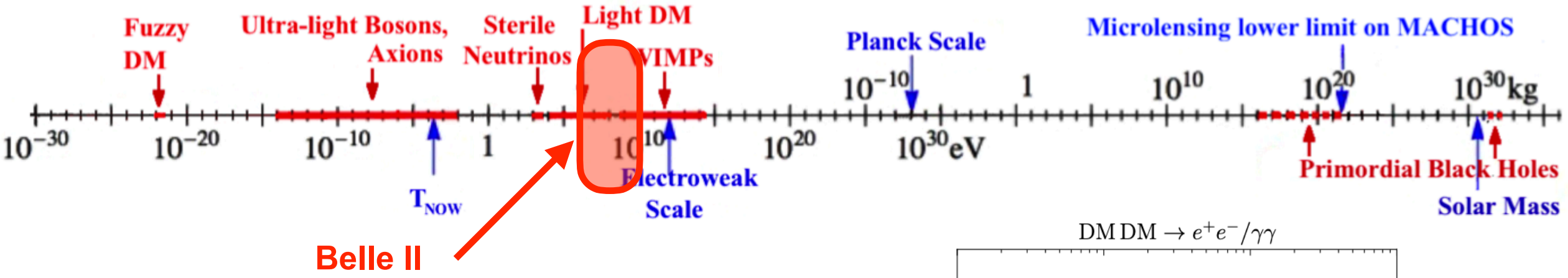
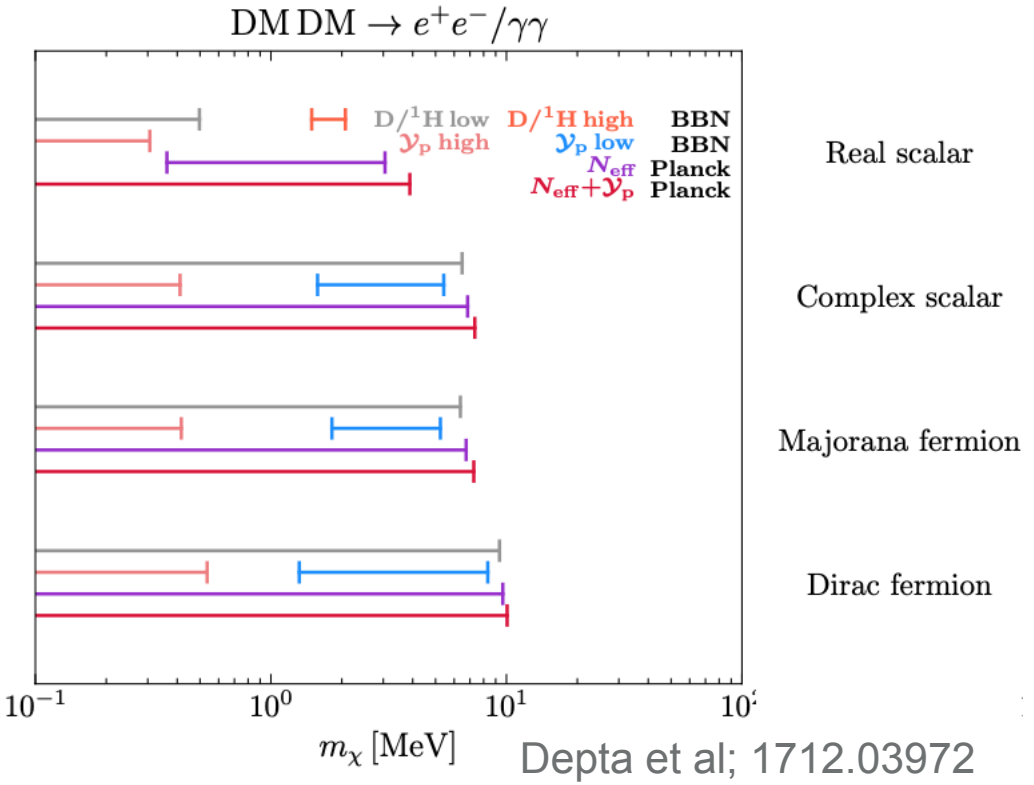


Mass range

- **Belle II could produce DM with $m_\chi \lesssim 5$ GeV**
- **$m_\chi \gtrsim 10$ MeV required by BBN if thermal contact to SM**

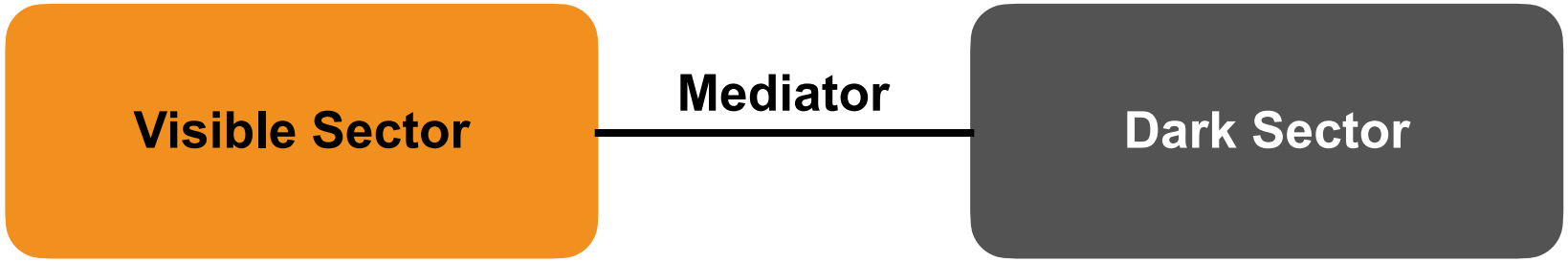
Couplings

- **couplings to SM states have to be small**
  → does lead to LLPs?



Depta et al; 1712.03972

Where does DM live?

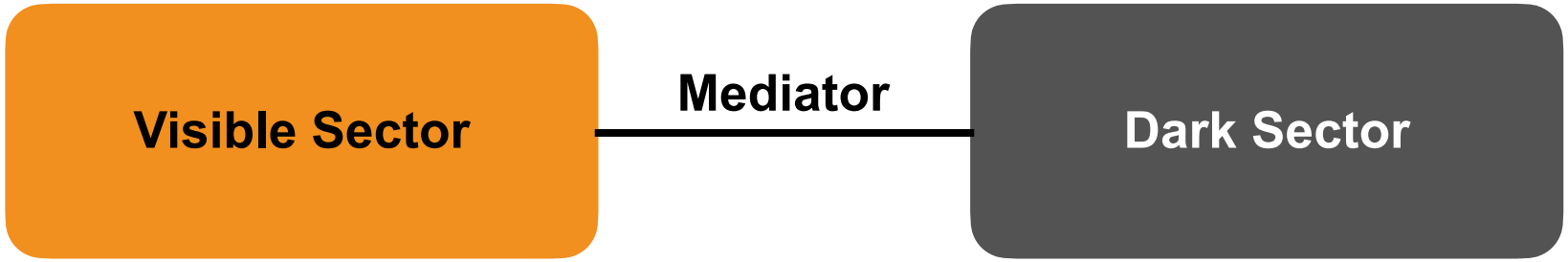


different possibilities to couple the two sectors

- empty dark sector: DM an exotic QCD bound state?
- change quantum numbers of SM, e.g. a new force such as $U(1)_{L_\mu - L_\tau}$ } not today
- leave the SM as is and couple to HS fields (not necessarily DM) as allowed by the symmetries

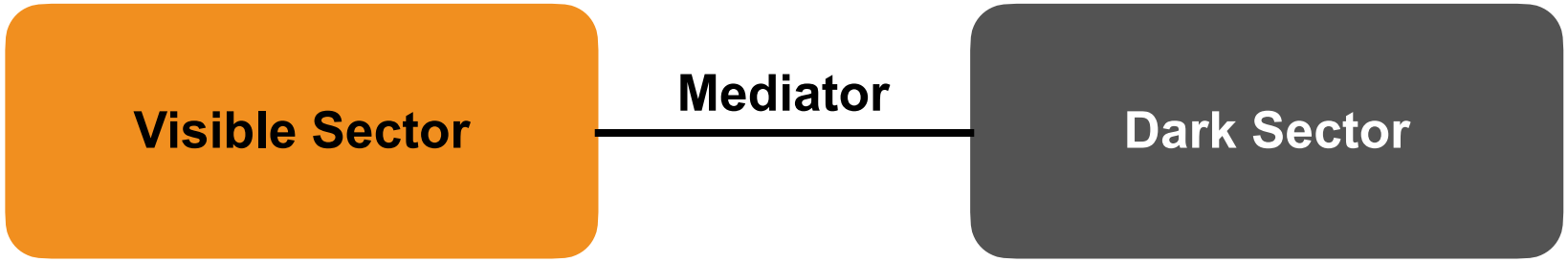
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}.$$

Hidden sector couplings



Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

Hidden sector couplings



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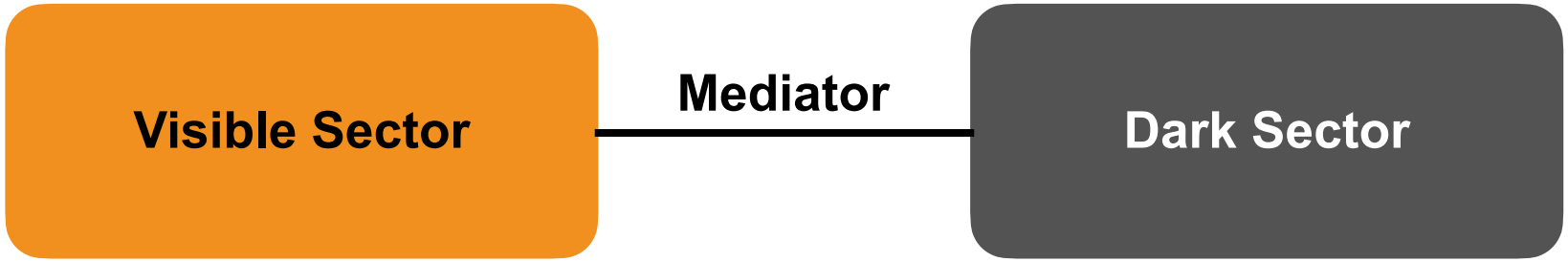
- could be dark matter if very light (long-lived) or protected by symmetry
- more often DM mediators (which can be searched for independently)

Hidden sector couplings



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today

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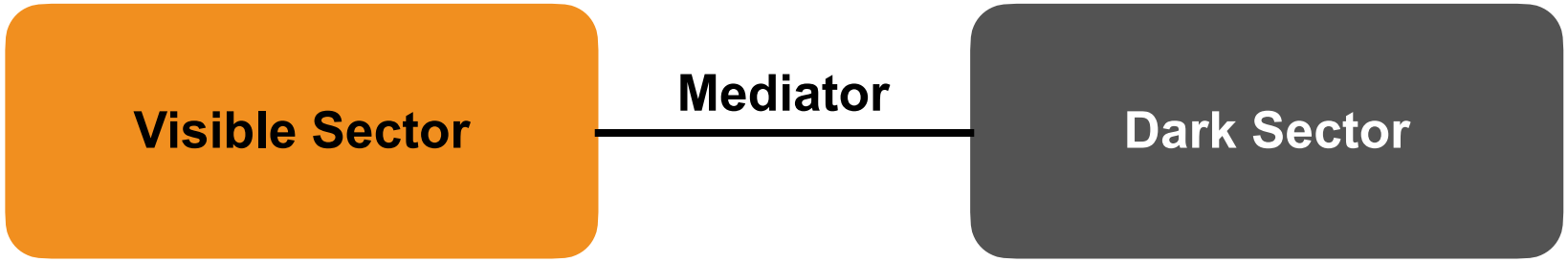

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Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	Elias
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$	Camilo
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Sterile Neutrino, N	$y_N L H N$	Kyrylo

today

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- more often DM mediators (which can be searched for independently)

Dark photons

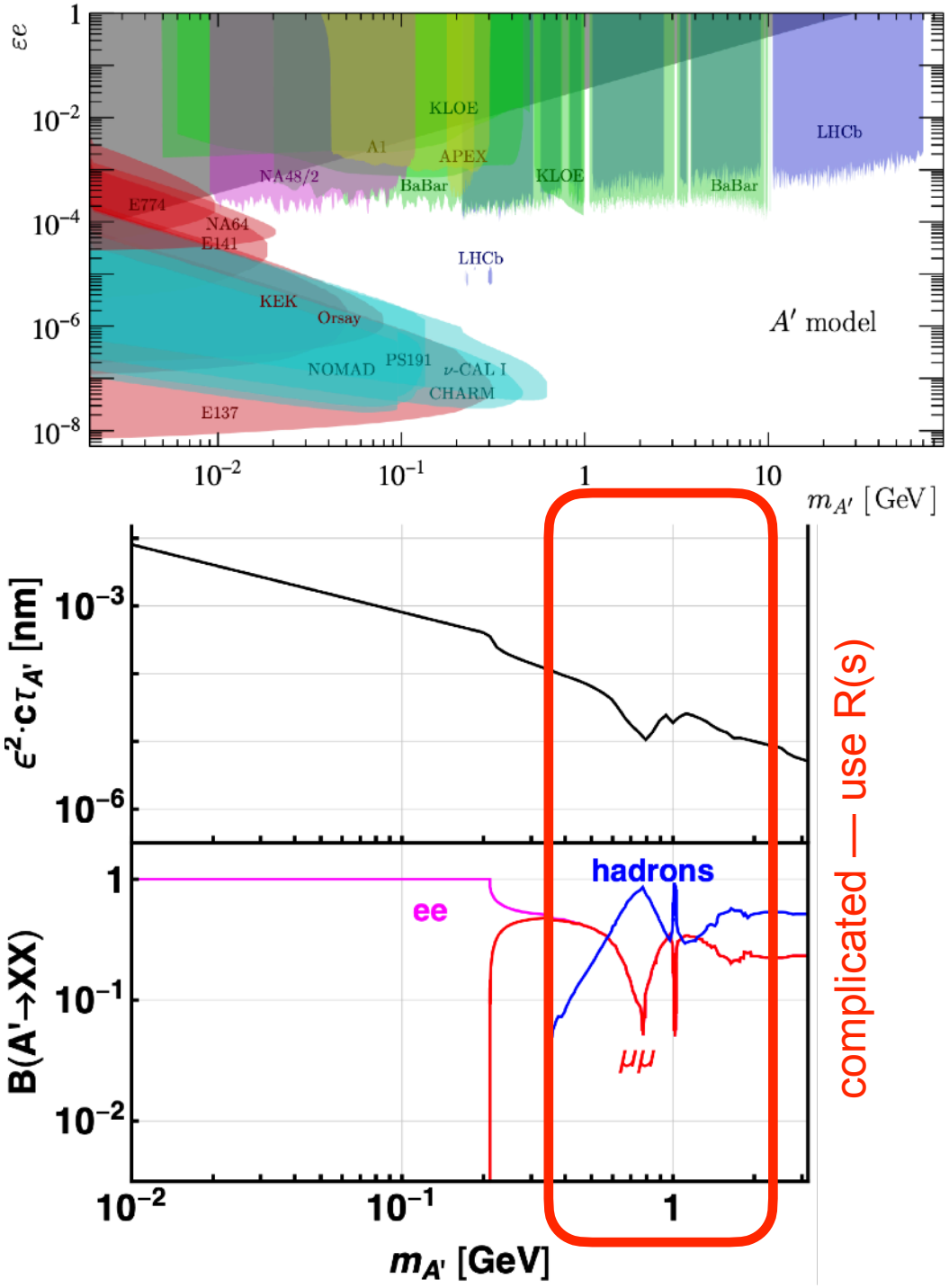
$$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

- Dark photons appear in many BSM constructions
- Kinetic mixing: photon-like couplings

  $(A' \to e^+e^-, \mu^+\mu^-, \dots)$
- Naive GUT expectation: $\epsilon \sim 10^{-3} - 10^{-6}$
- Could mediate the interactions with DM
- If kinematically allowed: decays into DS often dominate

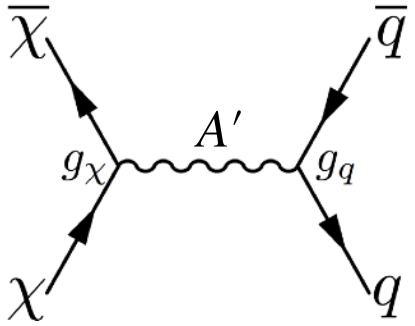
LLPs? Need small coupling or phase space suppression (small mass splitting)

Even for visible final state decays still rather prompt for ϵ relevant to Belle II



The DM connection

- **Production of dark matter in the early universe via the A'**

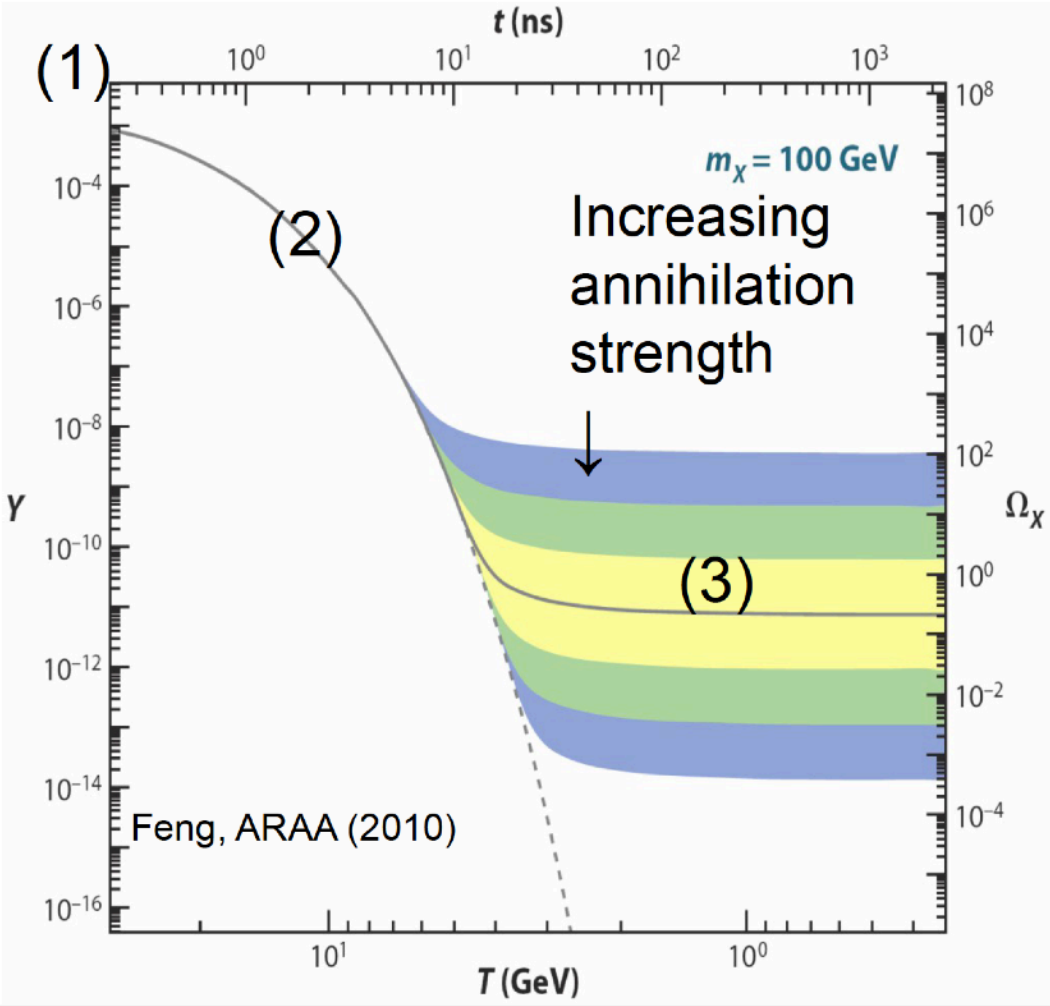


- **vanilla thermal freeze out**
  1. **for relevant ϵ DM χ in thermal equilibrium**

     $\chi\chi \leftrightarrows SM\ SM$
  2. **Universe cools**

     $\chi\chi \rightarrow SM\ SM$
  3. **Universe expands**

     $\chi\chi \nrightarrow SM\ SM$

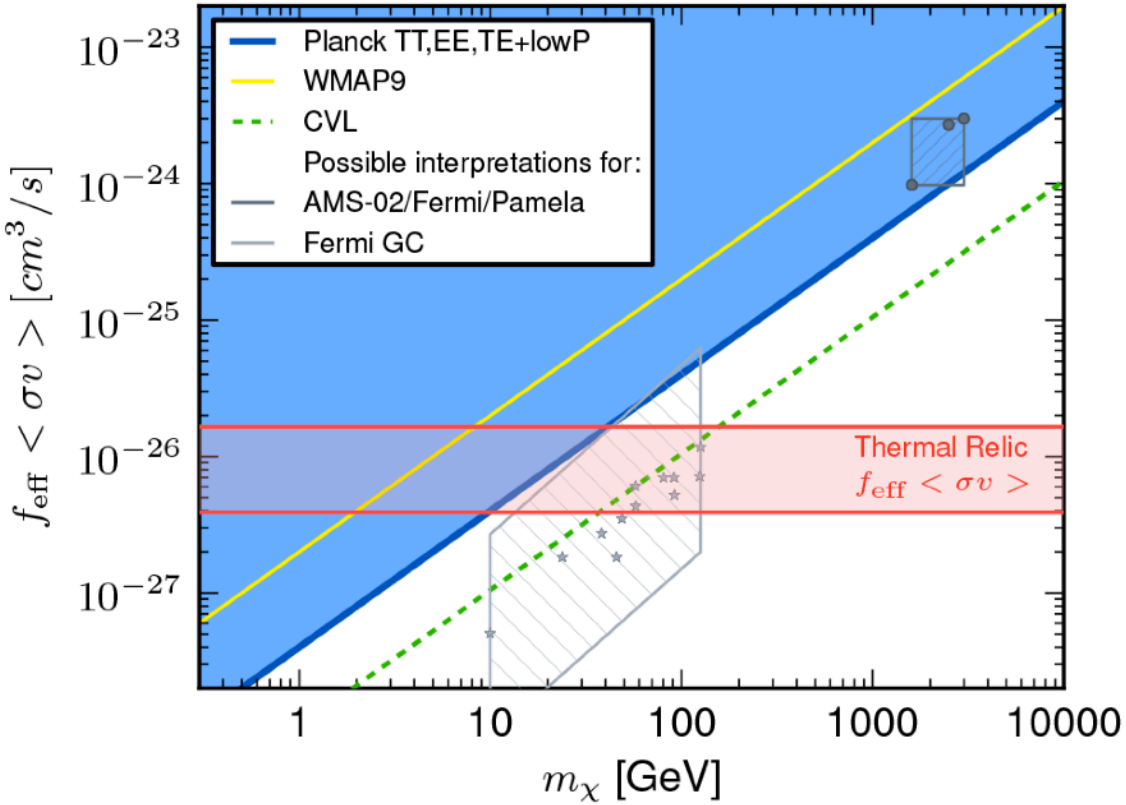


Light dark matter

- **Residual annihilations also later for** $v_{rel} \ll 1$
- **inject electromagnetic energy**
- **strong constraints from the CMB:** $v_{rel} \sim 10^{-8}$

$$\sigma\, v_{\rm rel} \;=\; \sigma_0 + \sigma_1\, v_{\rm rel}^2 + \mathcal{O}\left(v_{\rm rel}^4\right)$$

s-wave **p-wave**

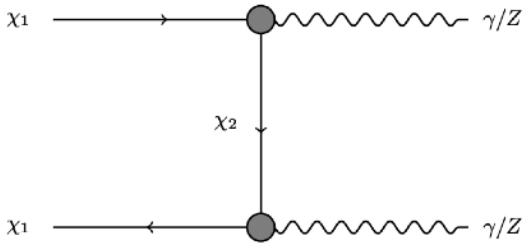


- **For** $m_\chi \lesssim 10\,\mathrm{GeV}$ **vanilla** A' **does not work (s-wave annihilation)**

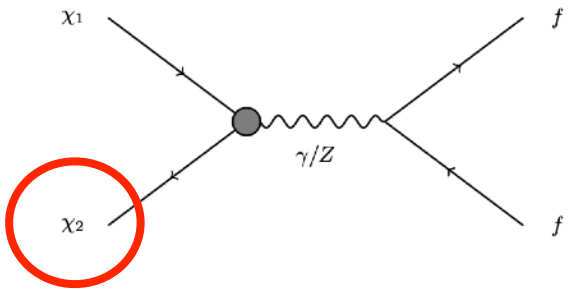
- **need p-wave (or some other trick…)**

Inelastic dark matter

- **need to suppress annihilations at late times / small velocities (or enhance it at freeze-out, resonant DM)** Berneuther et al; 2010.14522
- **possibility: make DM inelastic, i.e. split a Dirac fermion ψ into two Majorana states χ_1 and χ_2 with mass difference $\Delta \equiv m_{\chi_2} - m_{\chi_1}$ and off-diagonal coupling to A'**



$m_{A'} > m_{\chi_1}$



not present at late times

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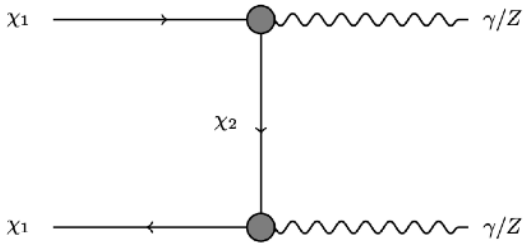
- **now χ_2 often long-lived (3-body decay and potentially small Δ)**



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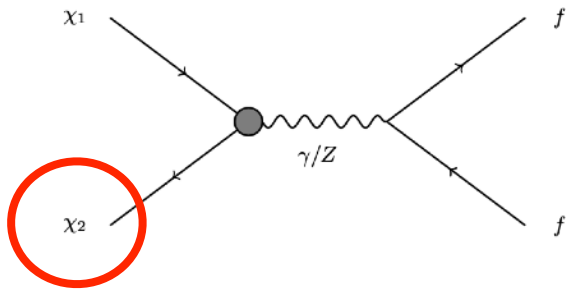

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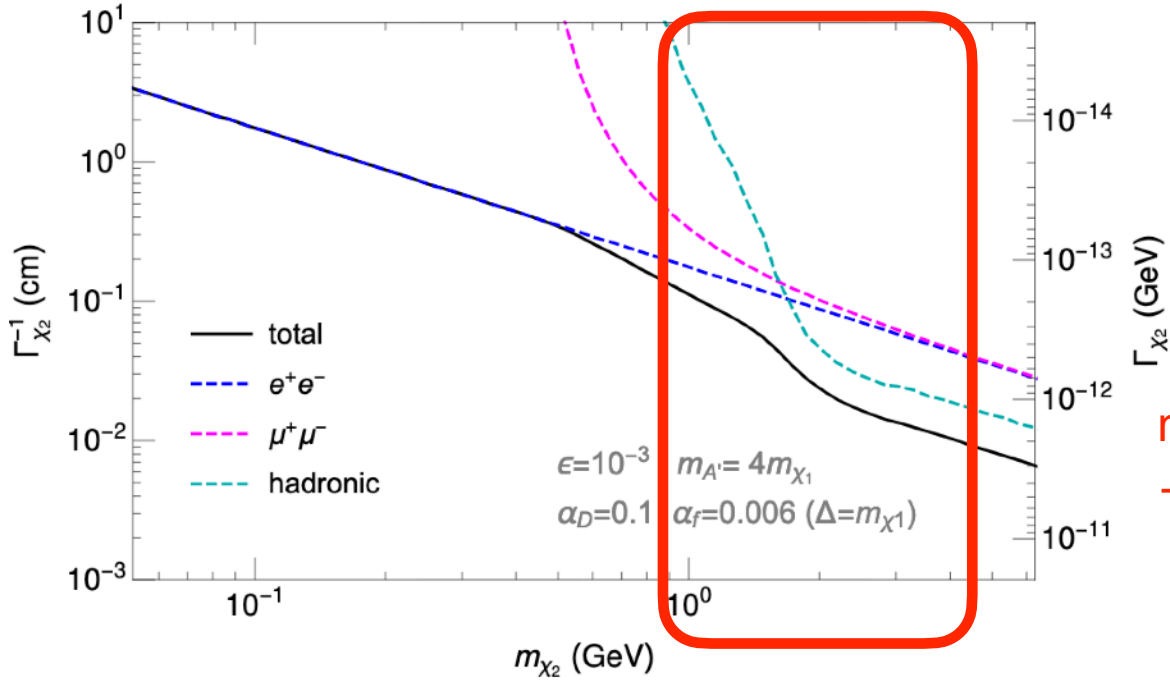
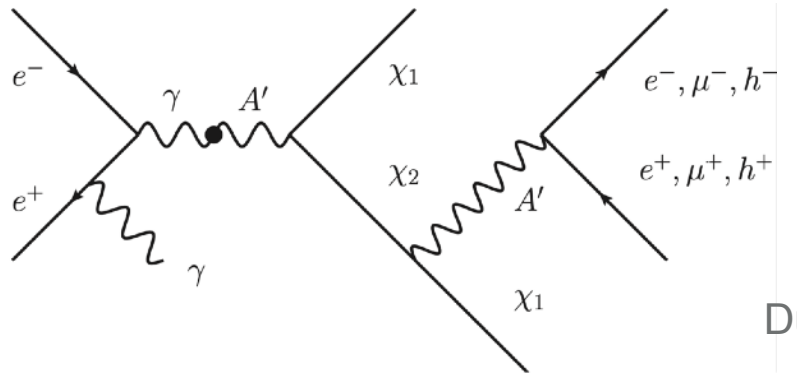


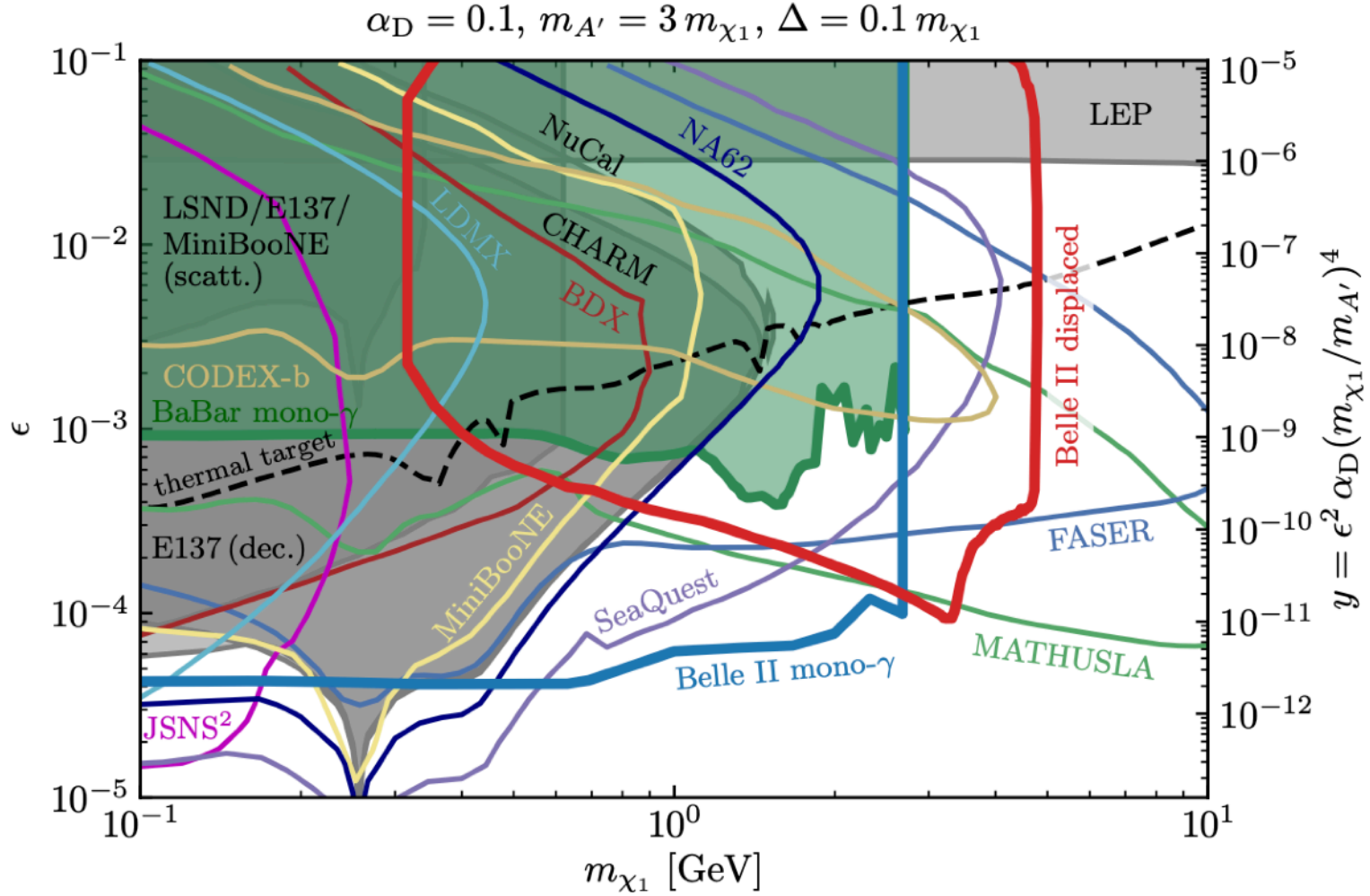
more complicated — use R(s)
→ Camilo

Inelastic dark matter

- **displaced signature in Belle II (single photon, displaced pair of electrons, missing energy)**
- **need displaced vertex trigger to achieve full sensitivity**



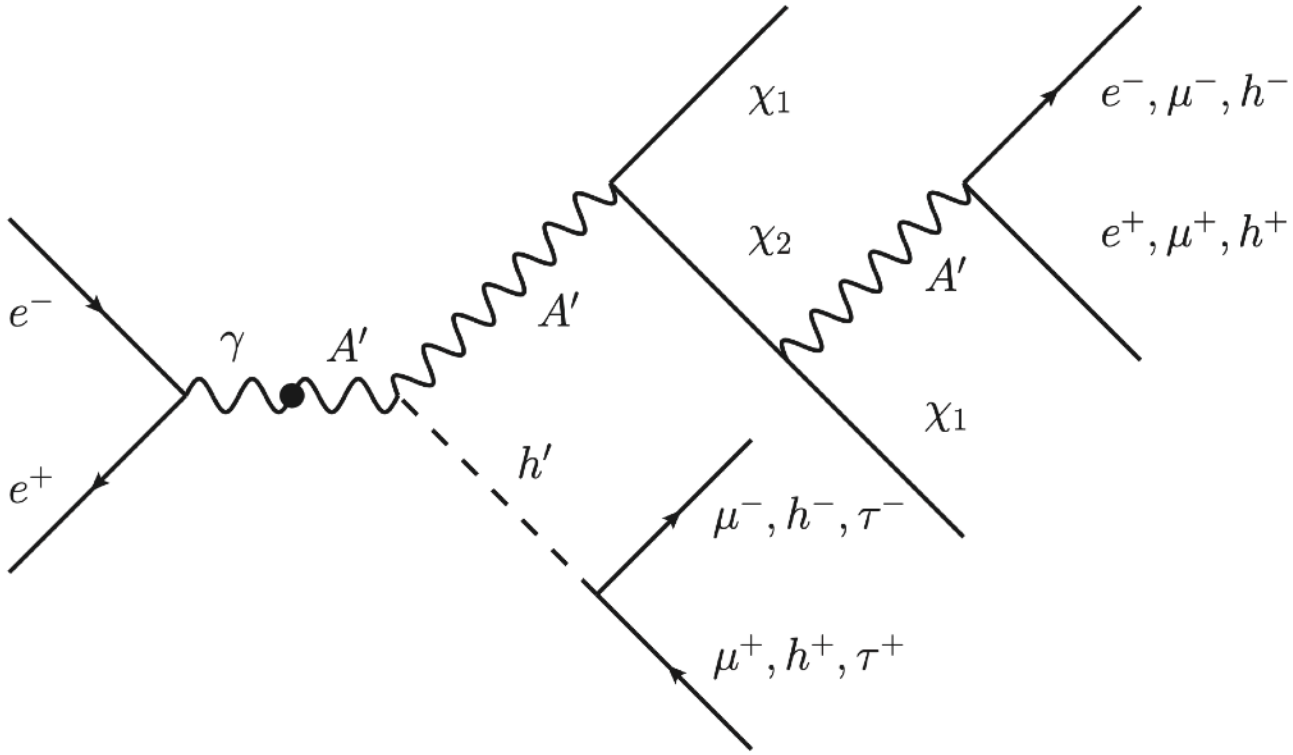
Duerr et al; 1911.03176



Dark Higgs

- **how does the mass splitting Δ arise in the underlying model?**
  $\rightarrow$ dark Higgs field…
- **also naturally present to give mass to A'**
- **cannot be too heavy due to unitarity considerations**
- **two portals!**

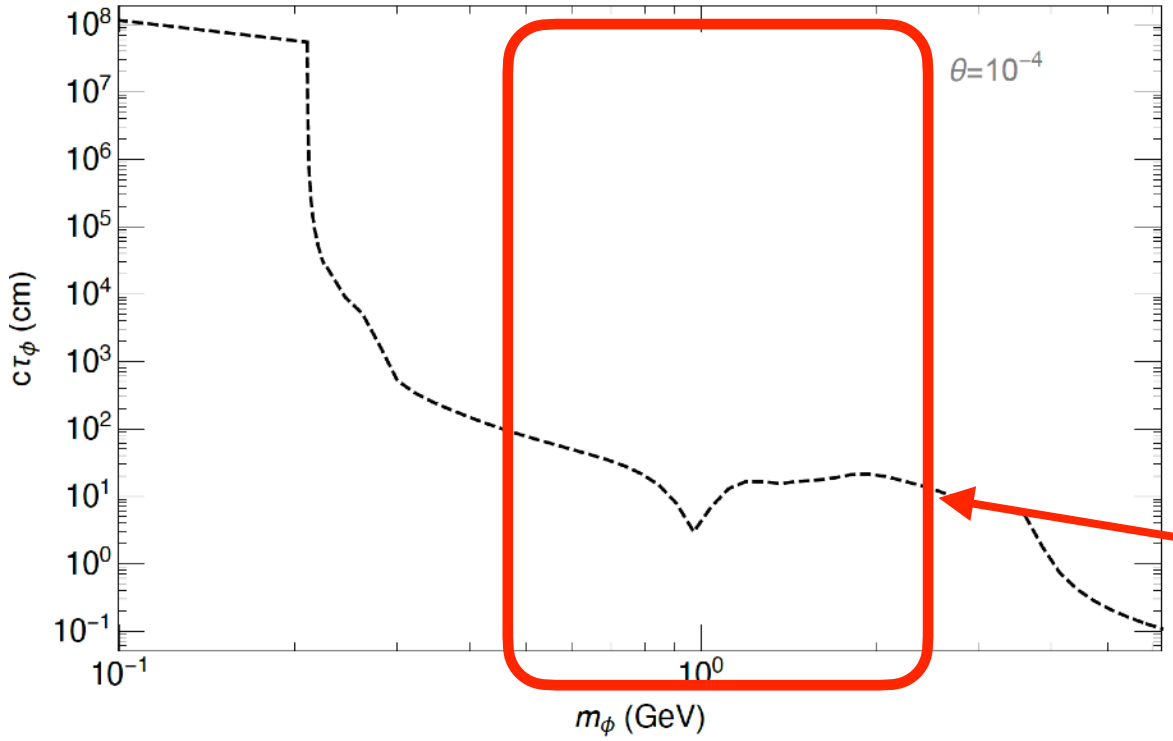
Talk by Camilo



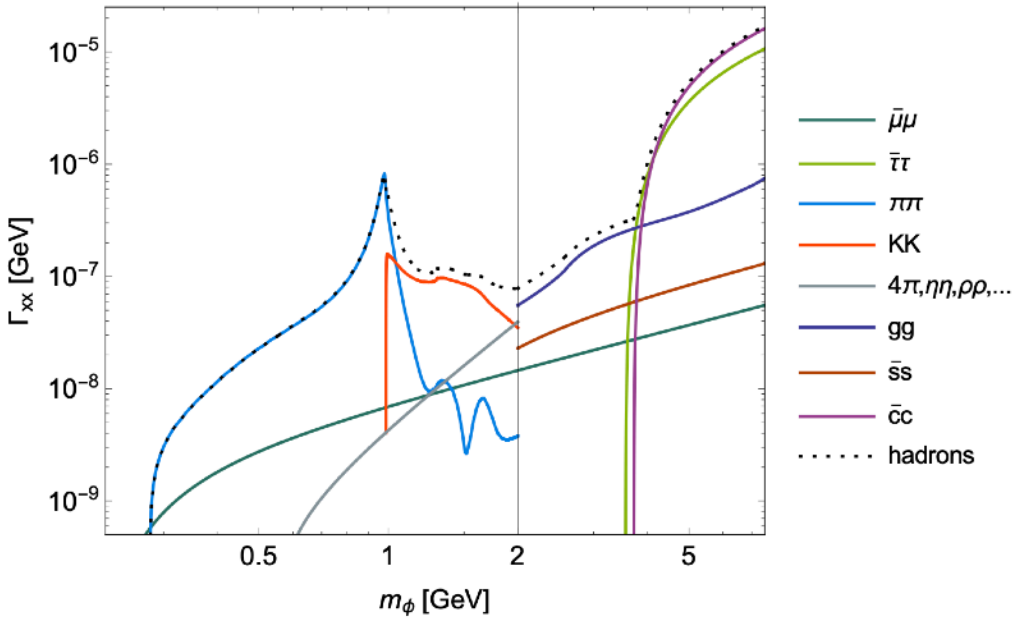
Scalar portal

Talk by Nastya

- a scalar coupled to DM naturally results in p-wave annihilation
- additional Yukawa suppression of the couplings leads to sizeable lifetimes: basically always displaced…



Winkler; 1809.01876

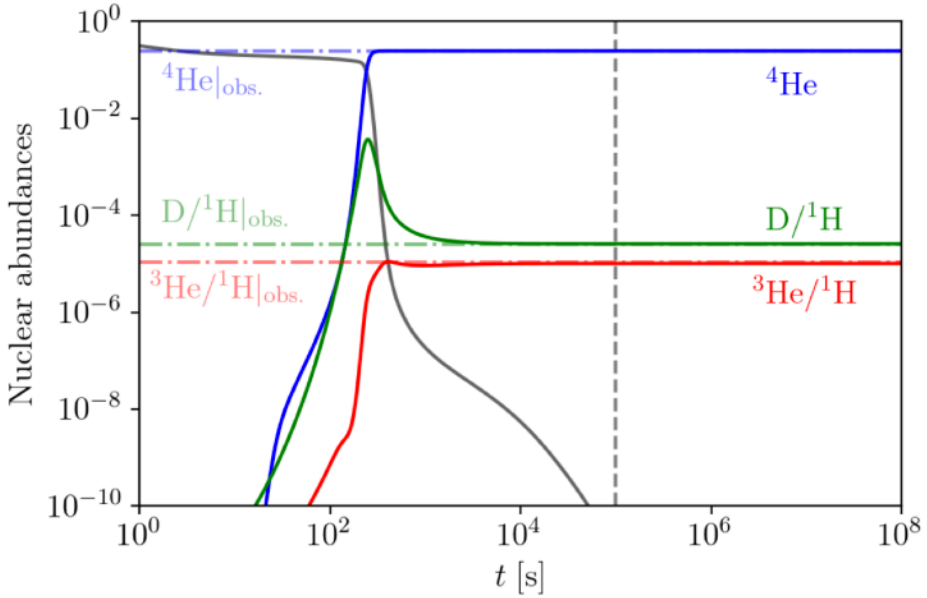


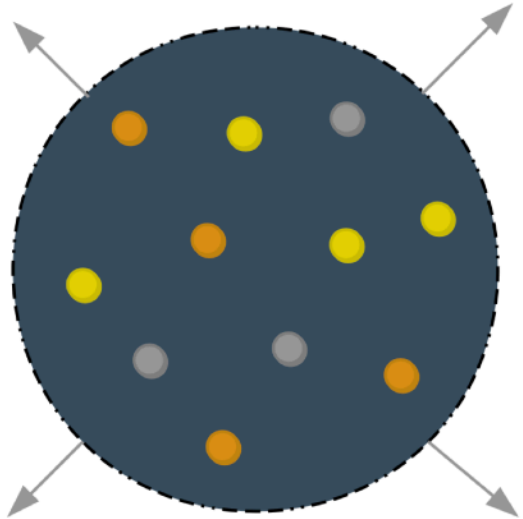
again complicated — ask Martin Winkler

- can be very long-lived (missing energy) → BBN?

Big Bang Nucleosynthesis

- 1 second after the Big Bang temperature was about 1 MeV
- light elements form from protons and neutrons
- agrees well with SM





Big Bang Nucleosynthesis

- 1 second after the Big Bang temperature was about 1 MeV
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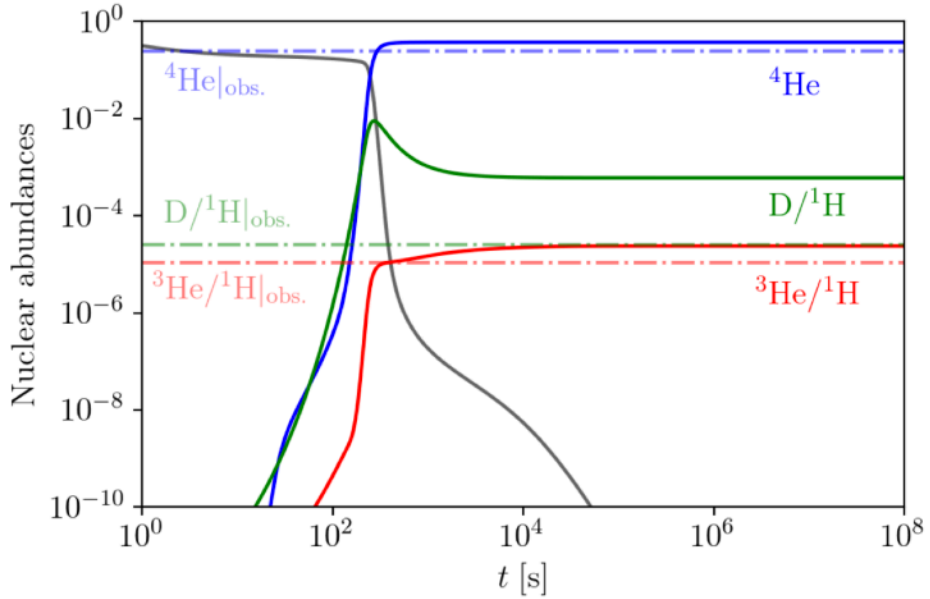
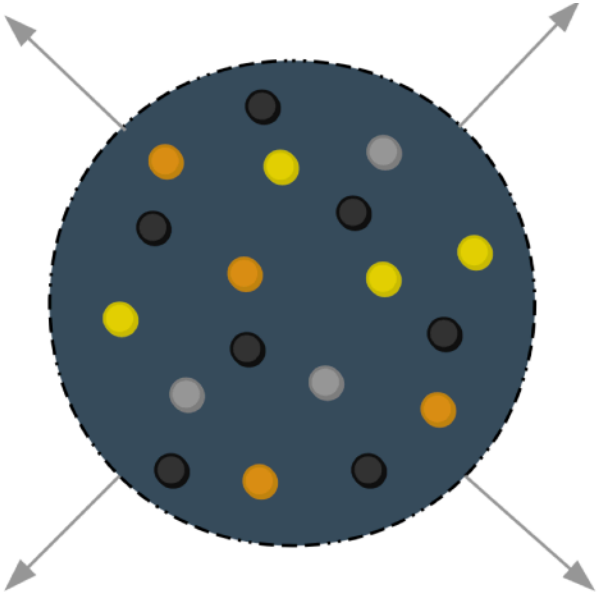
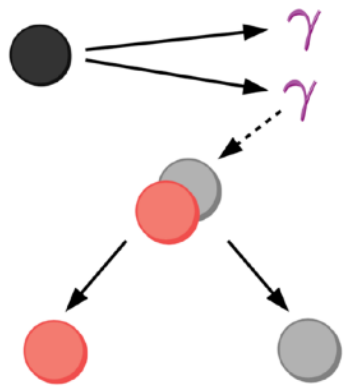
- strong constraints on additional degrees of freedom
  - increased Hubble rate
  - entropy injection
  - photo-dissociaton







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- strong constraints on additional degrees of freedom
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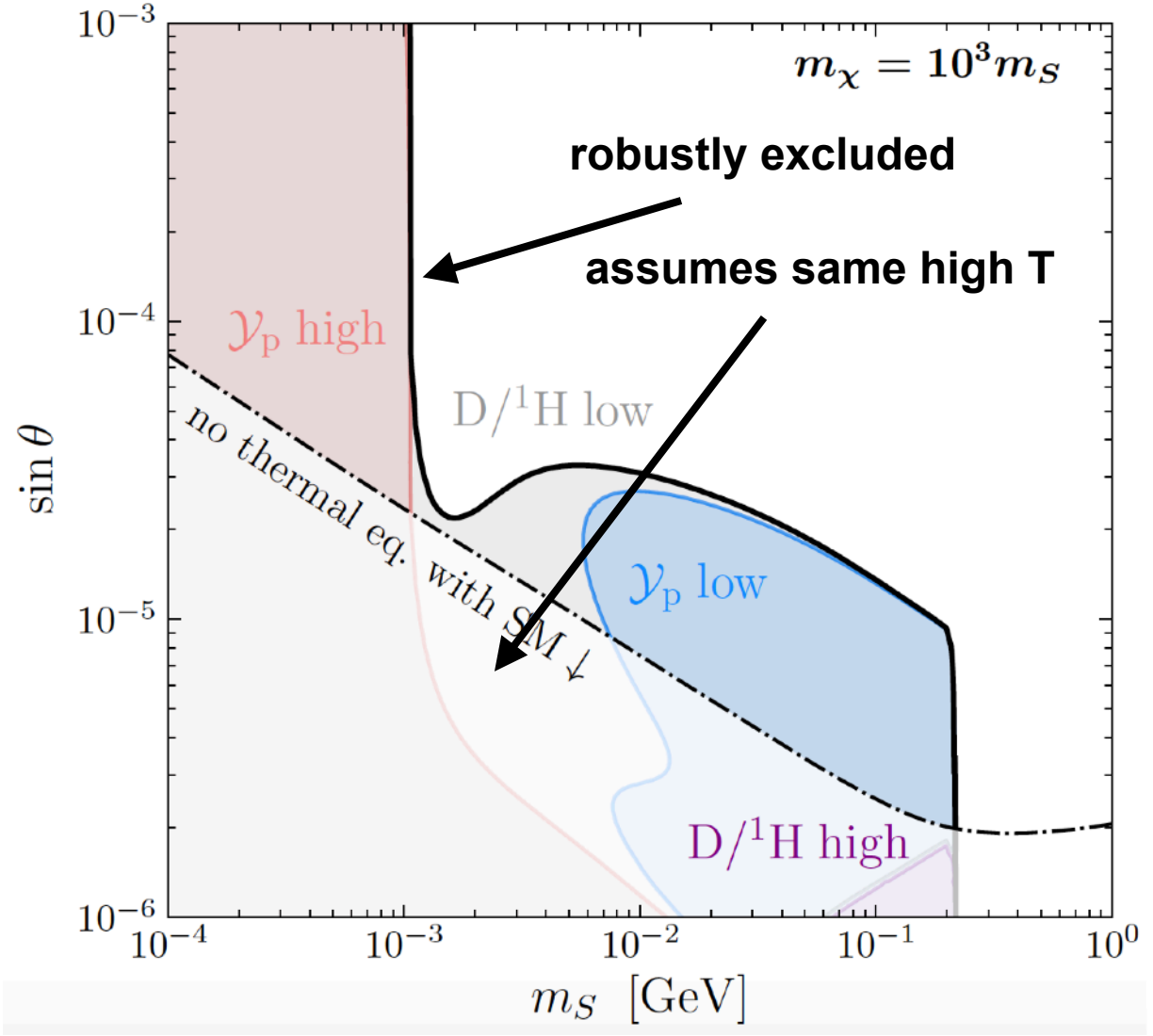
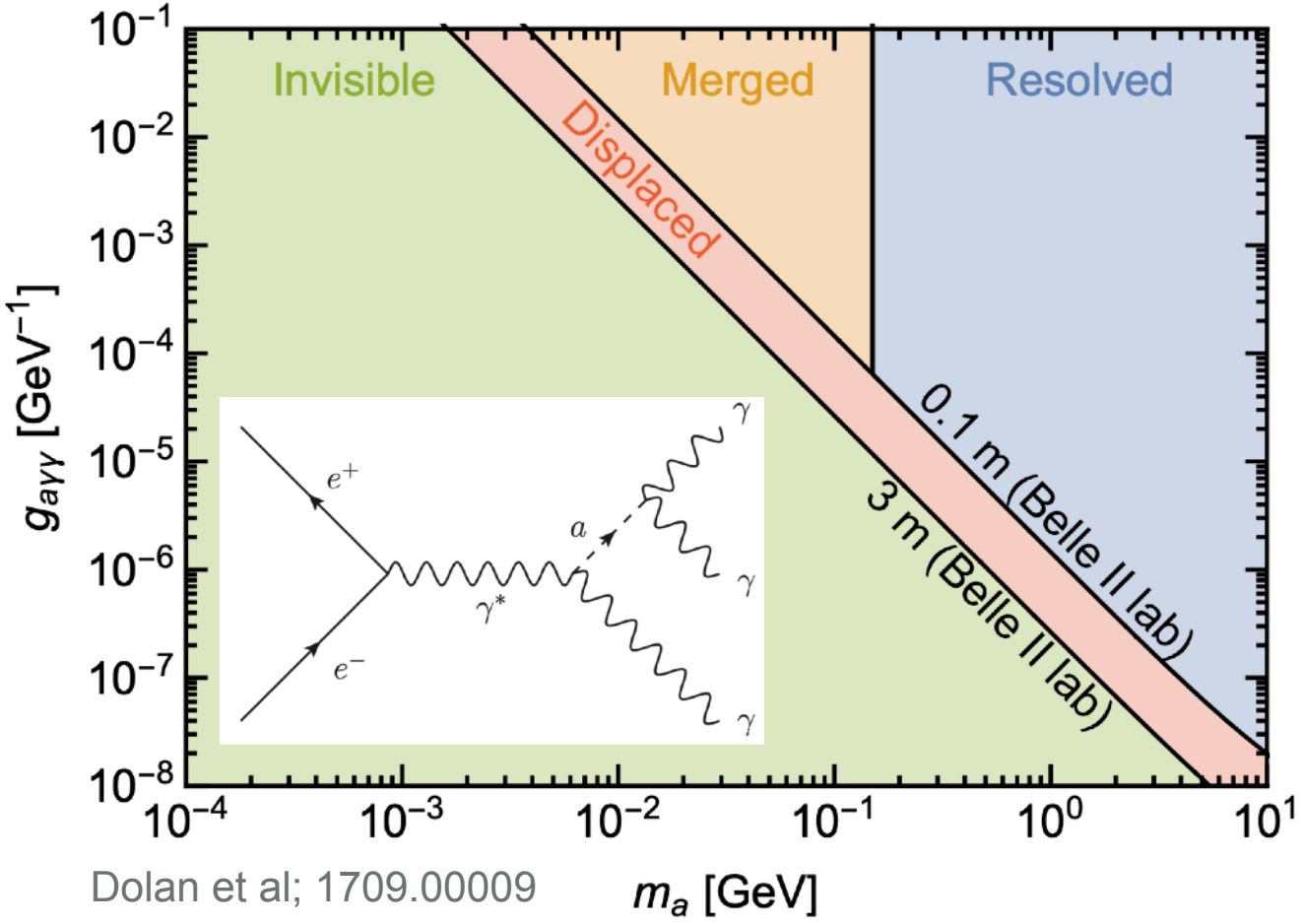
  - entropy injection
  - photo-dissociaton
- only relevant at small masses for this case

Bondarenko et al; 1909.08632

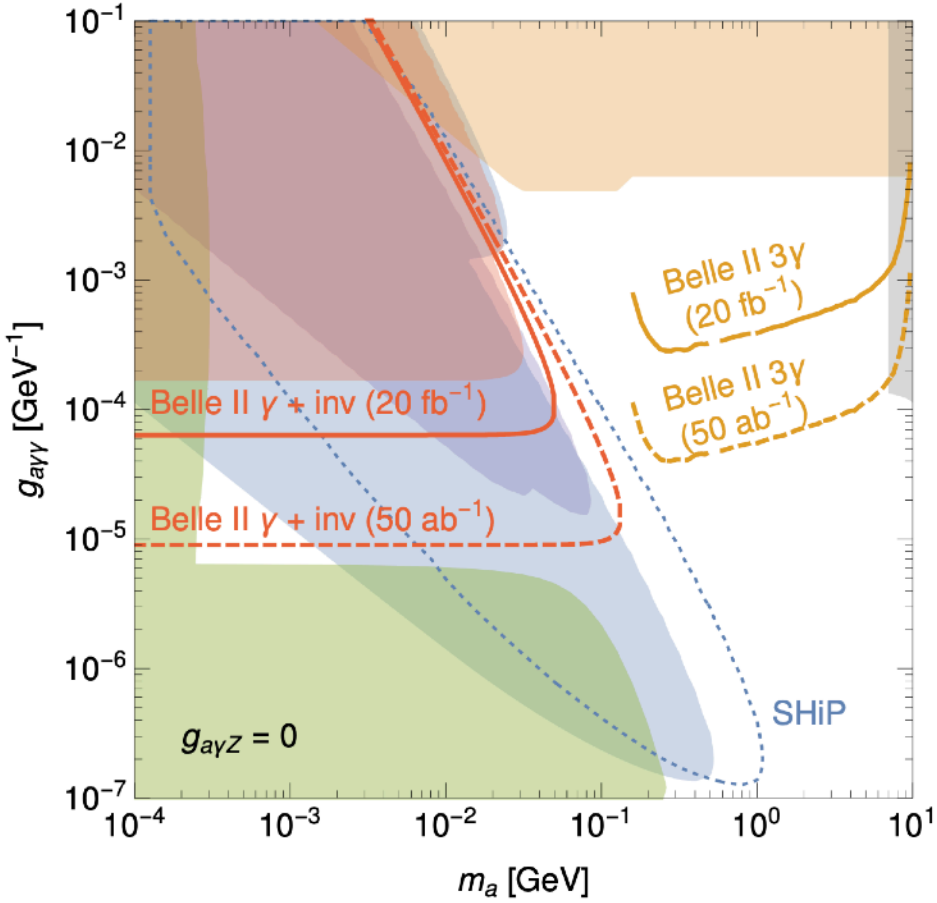


Axion like particles

Axion, a $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

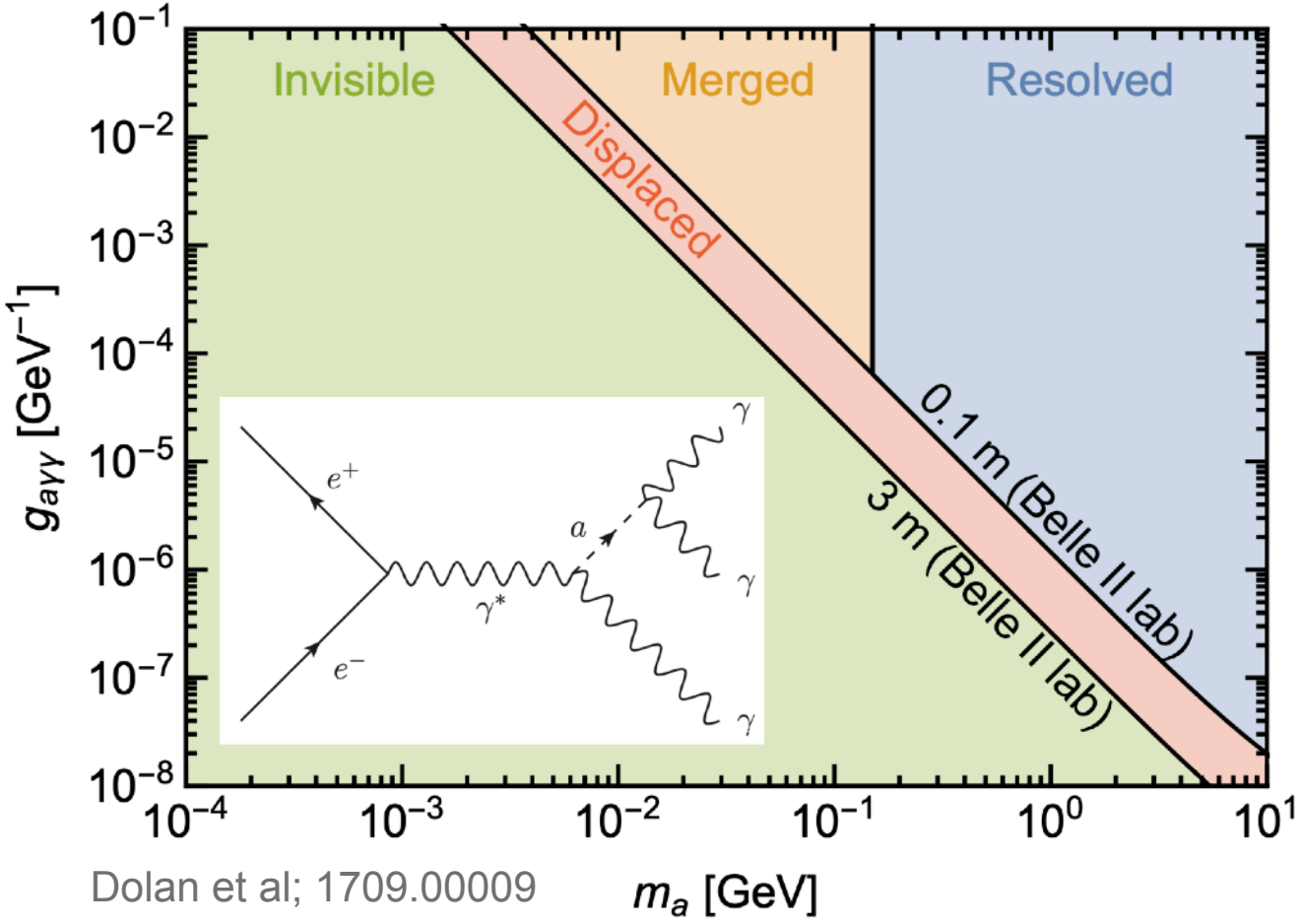


Dolan et al; 1709.00009

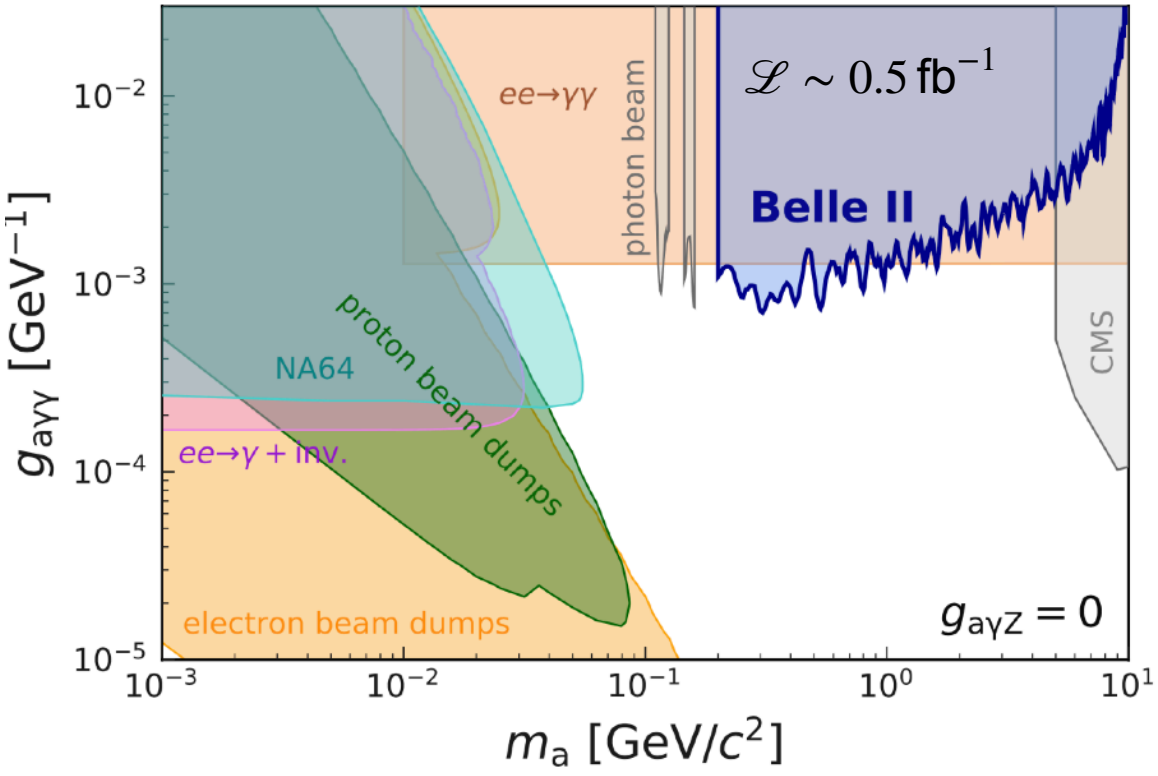


Axion like particles

Axion, a $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$



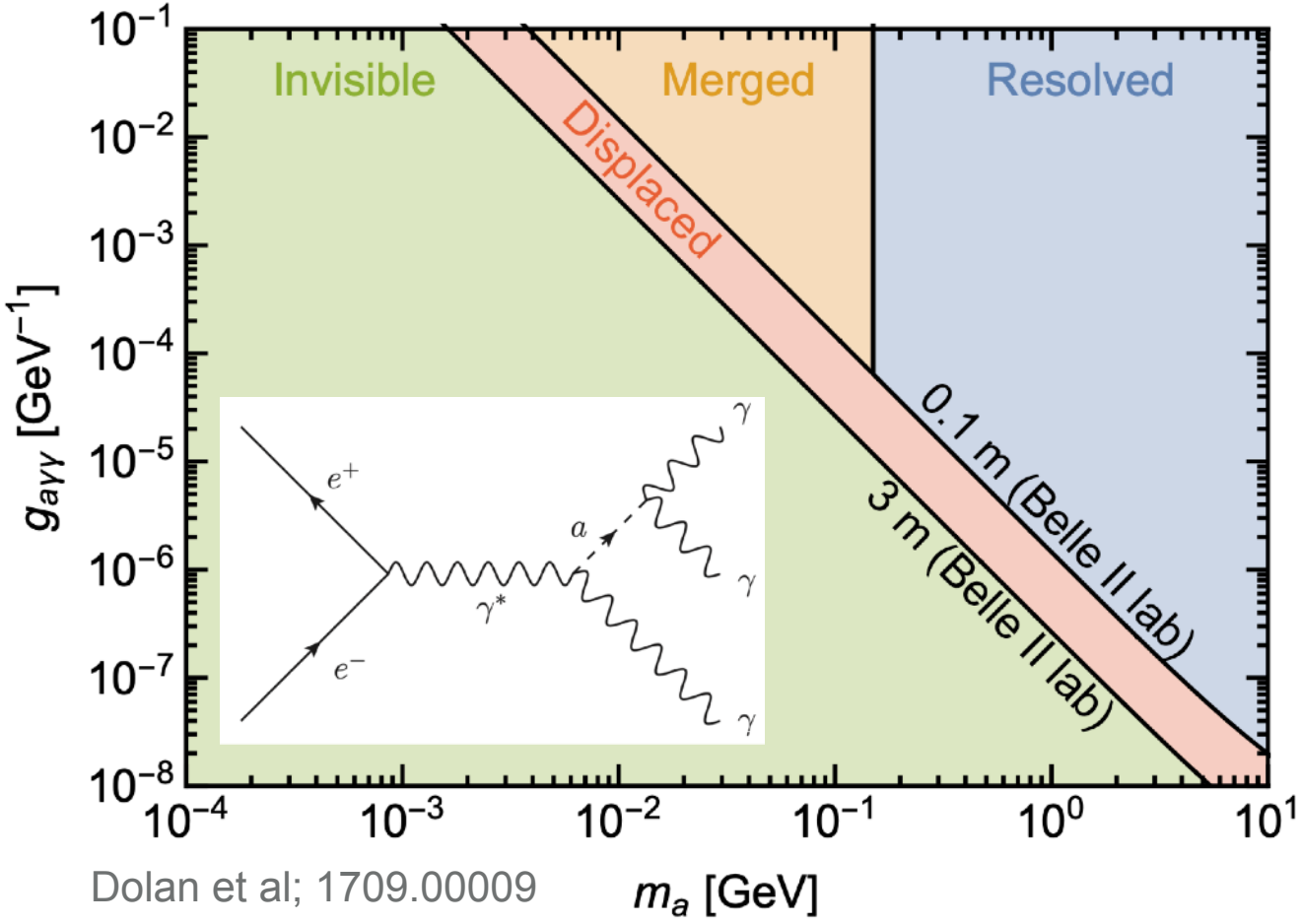
Dolan et al; 1709.00009



Belle II; 2007.13071

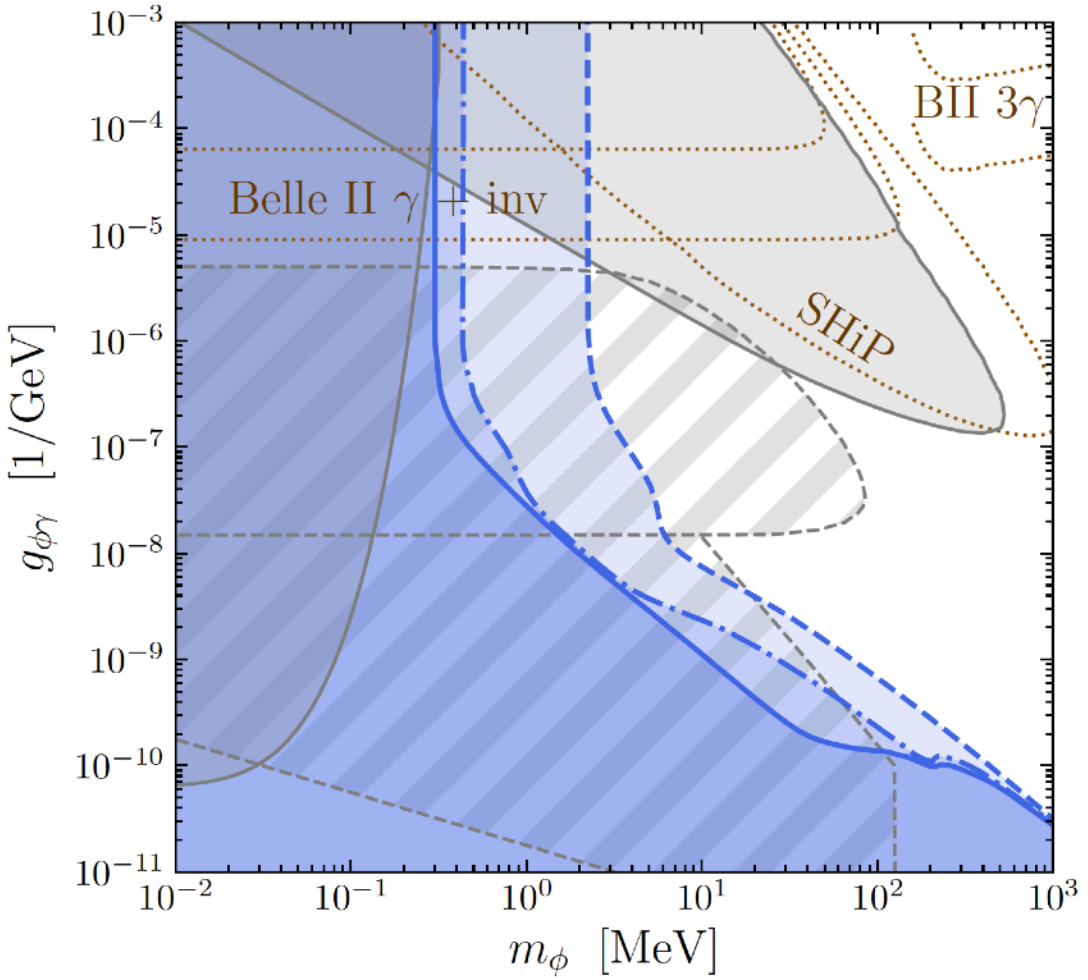
Axion like particles

Axion, a $\quad \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$



Dolan et al; 1709.00009

Depta et al; 2002.08370



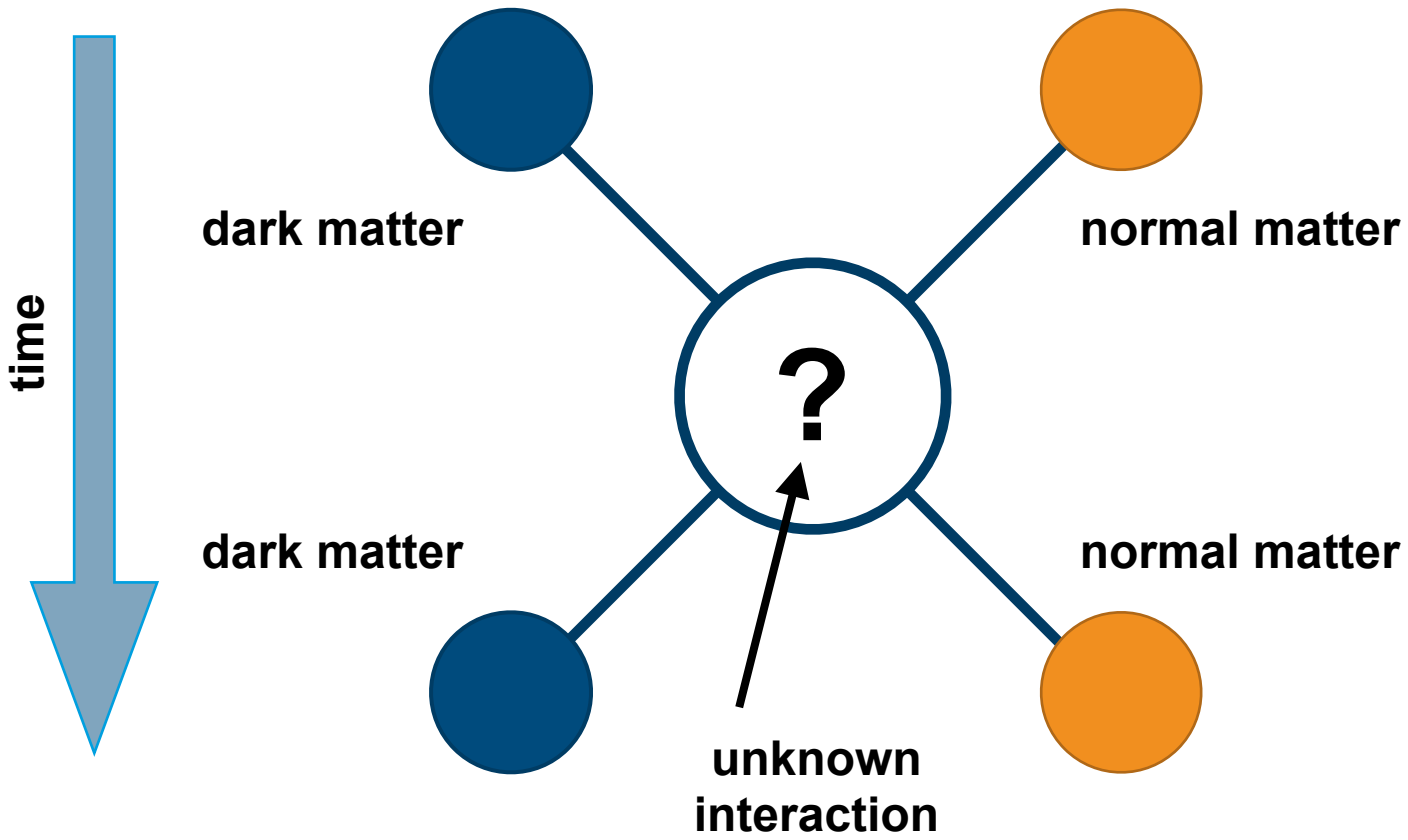
BBN limits can be robust

Summary

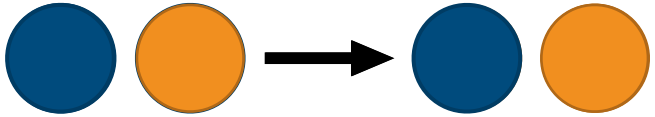
- **Light dark sectors naturally require small couplings to be viable**
- **LLPs naturally emerge when assuming couplings to light dark matter and requiring consistent cosmology**
- **very long lifetimes: need to check BBN limits (but not relevant for small displacements)**

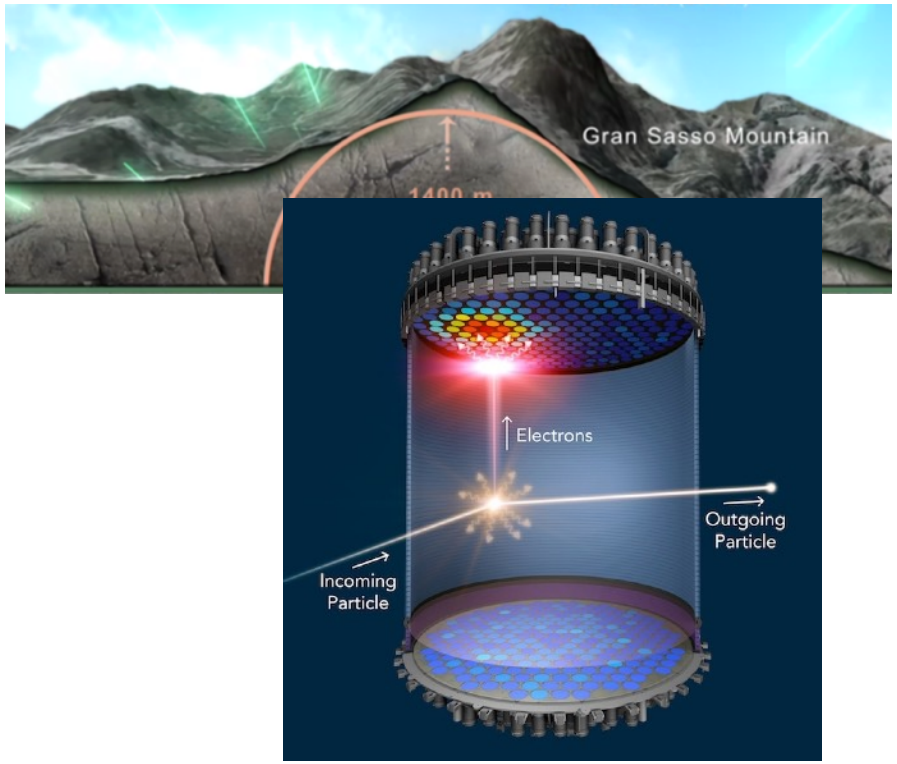
Thank you!

Searches for dark matter - direct detection



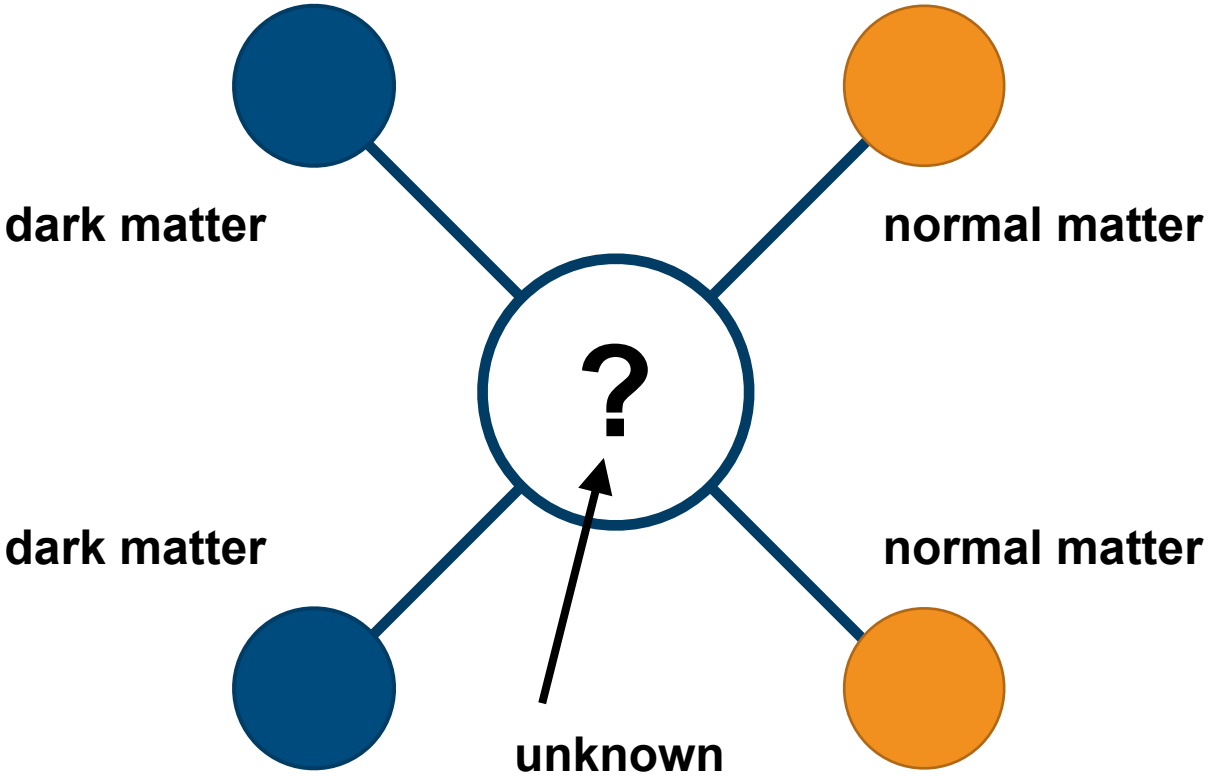
scattering

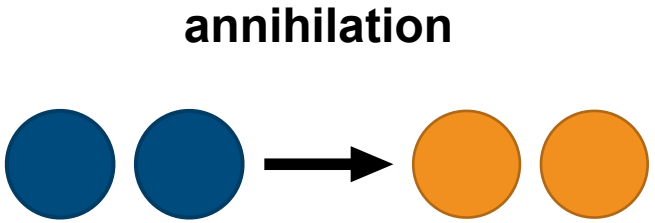




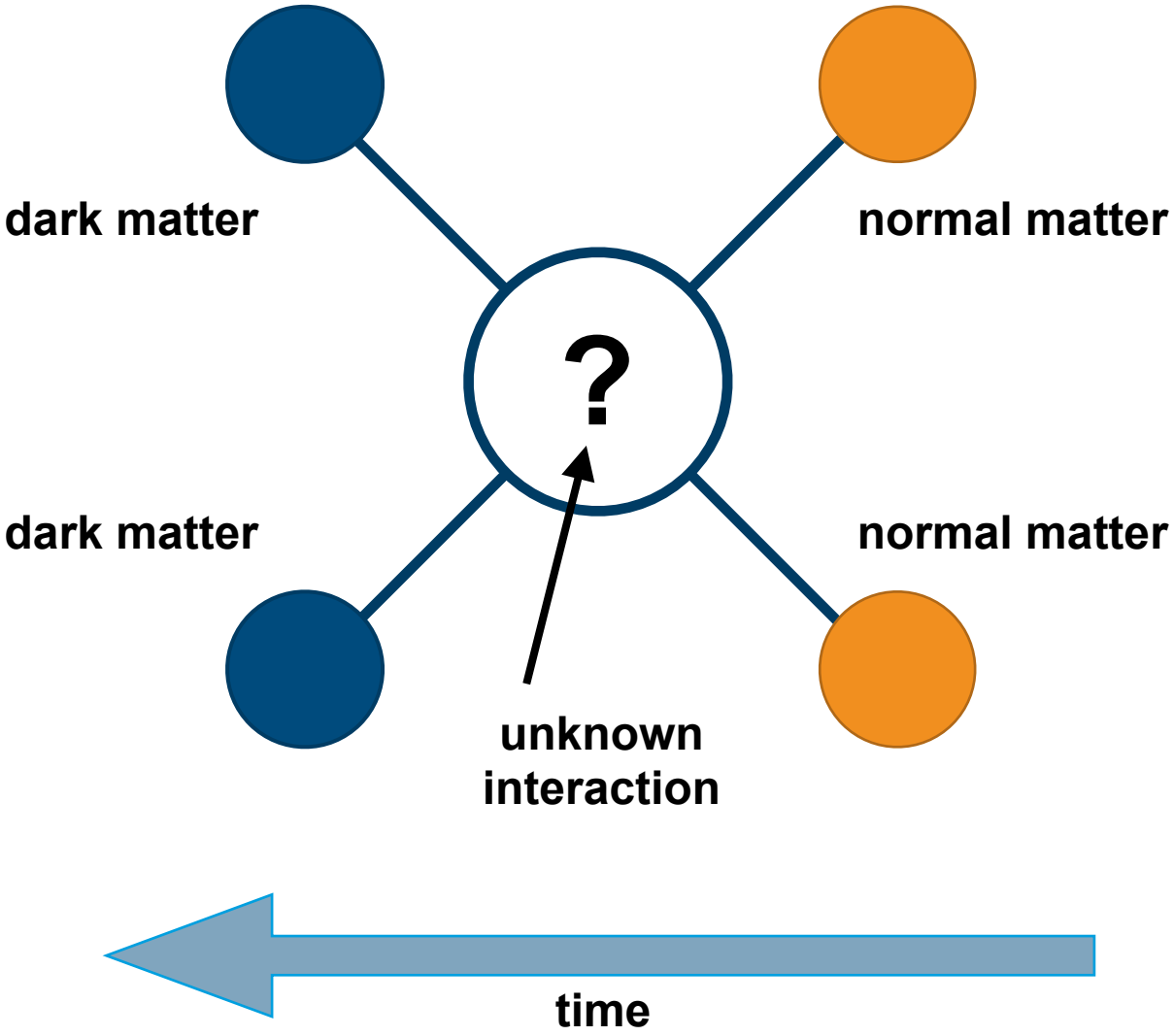
- Searches deep underground to minimise background
- very rare event (~ less than 1 event per kg per year)

Searches for dark matter - indirect detection





Searches for dark matter - colliders



DM production