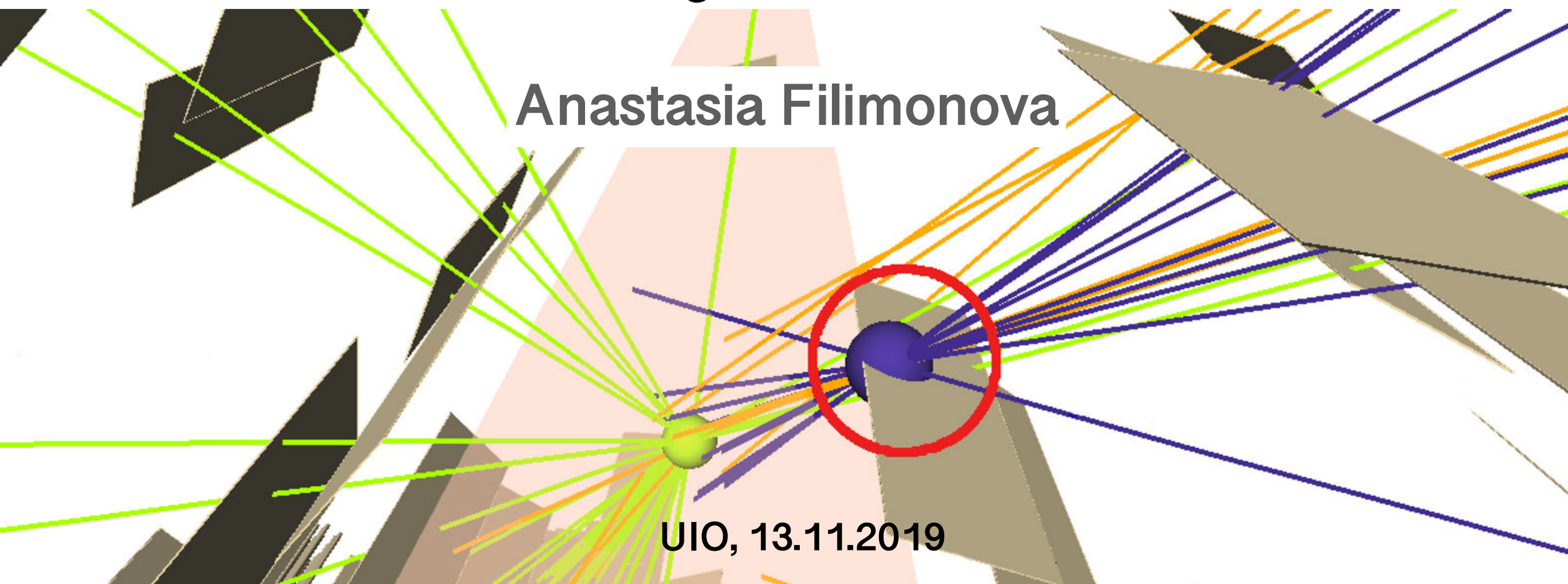
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Long-lived particles

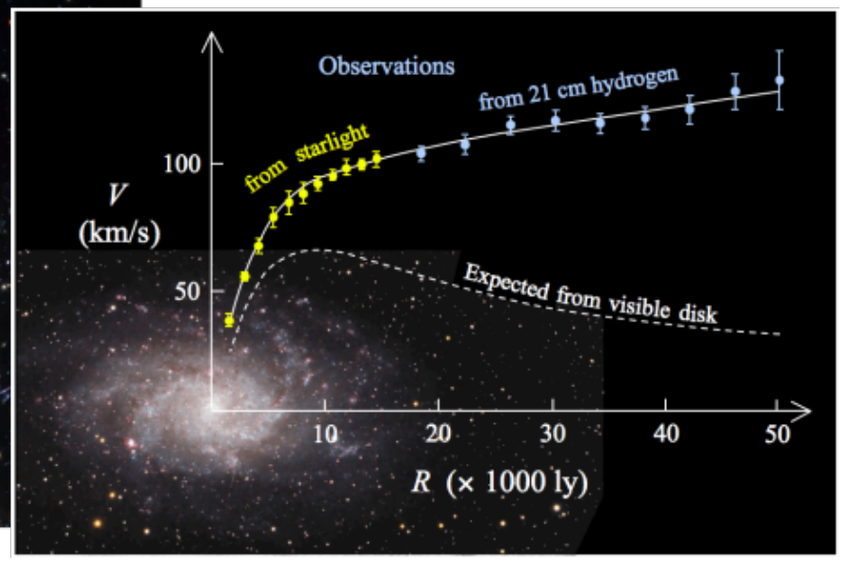
Connecting early universe dynamics to collider signatures

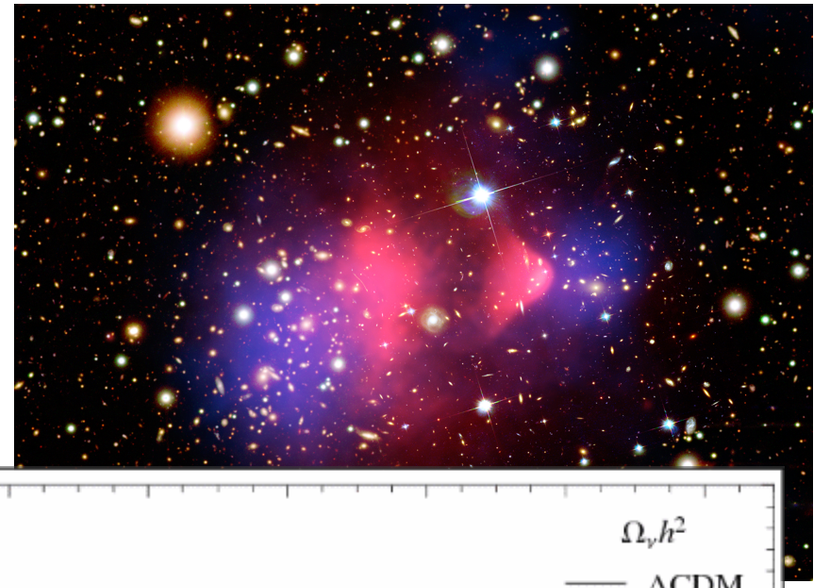
Anastasia Filimonova

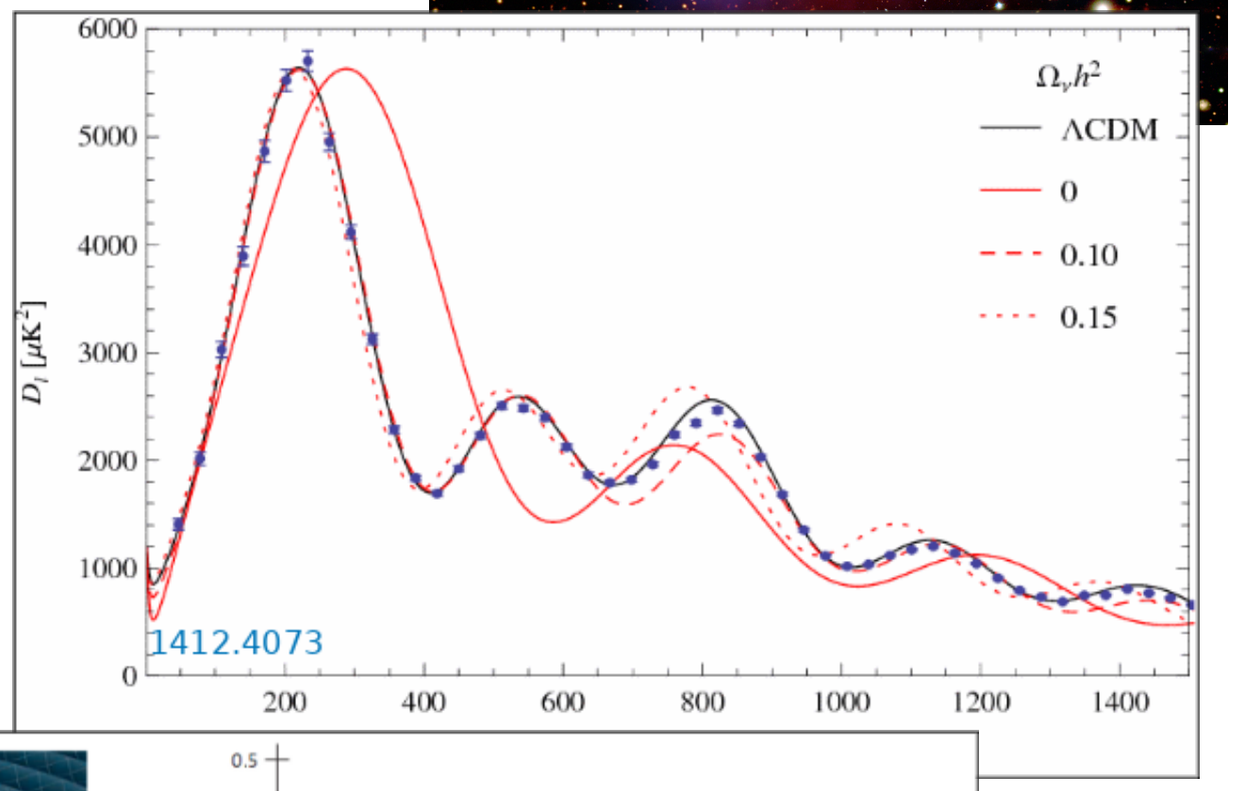


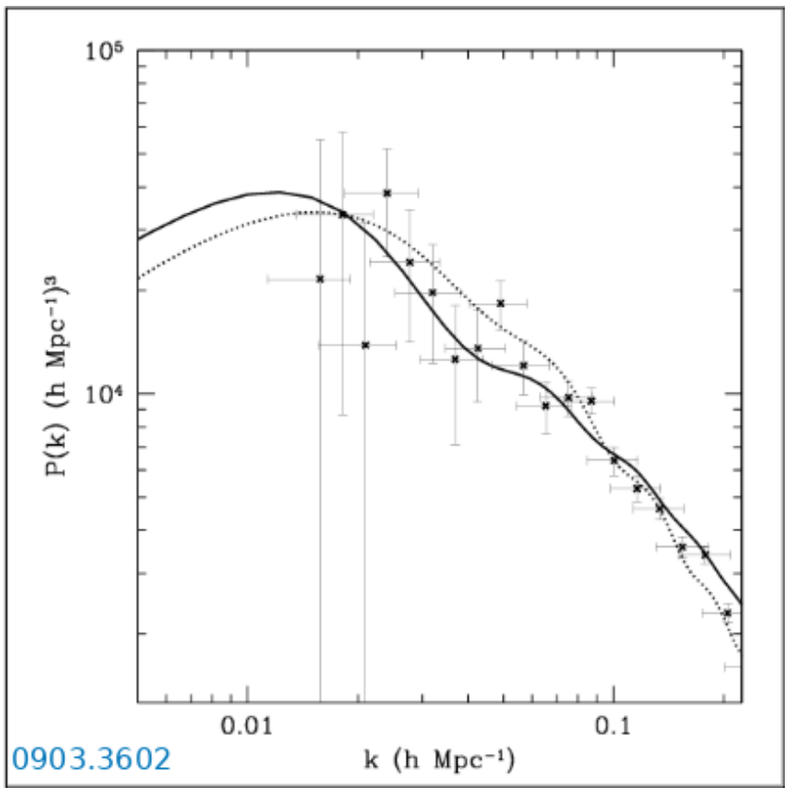
UIO, 13.11.2019

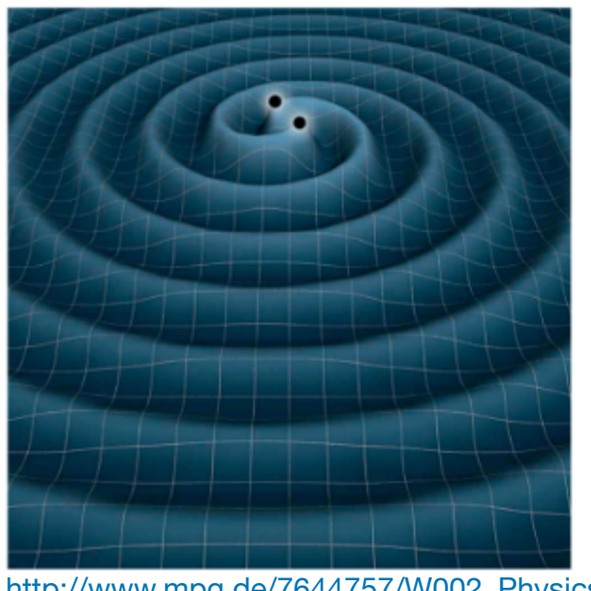
Why we believe it's a particle?

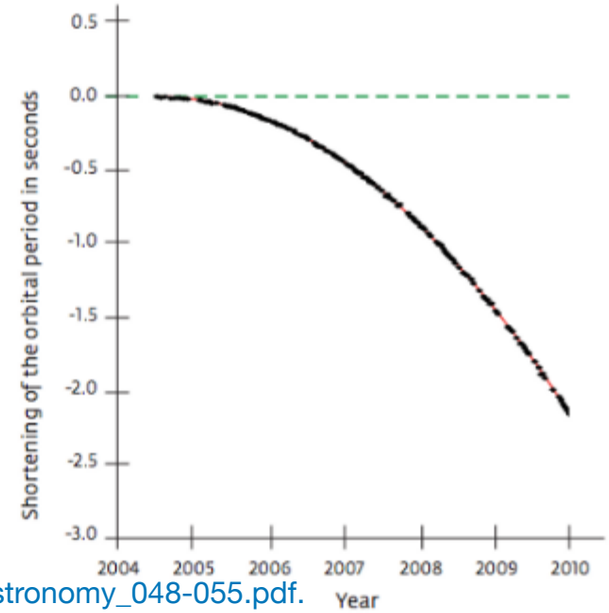












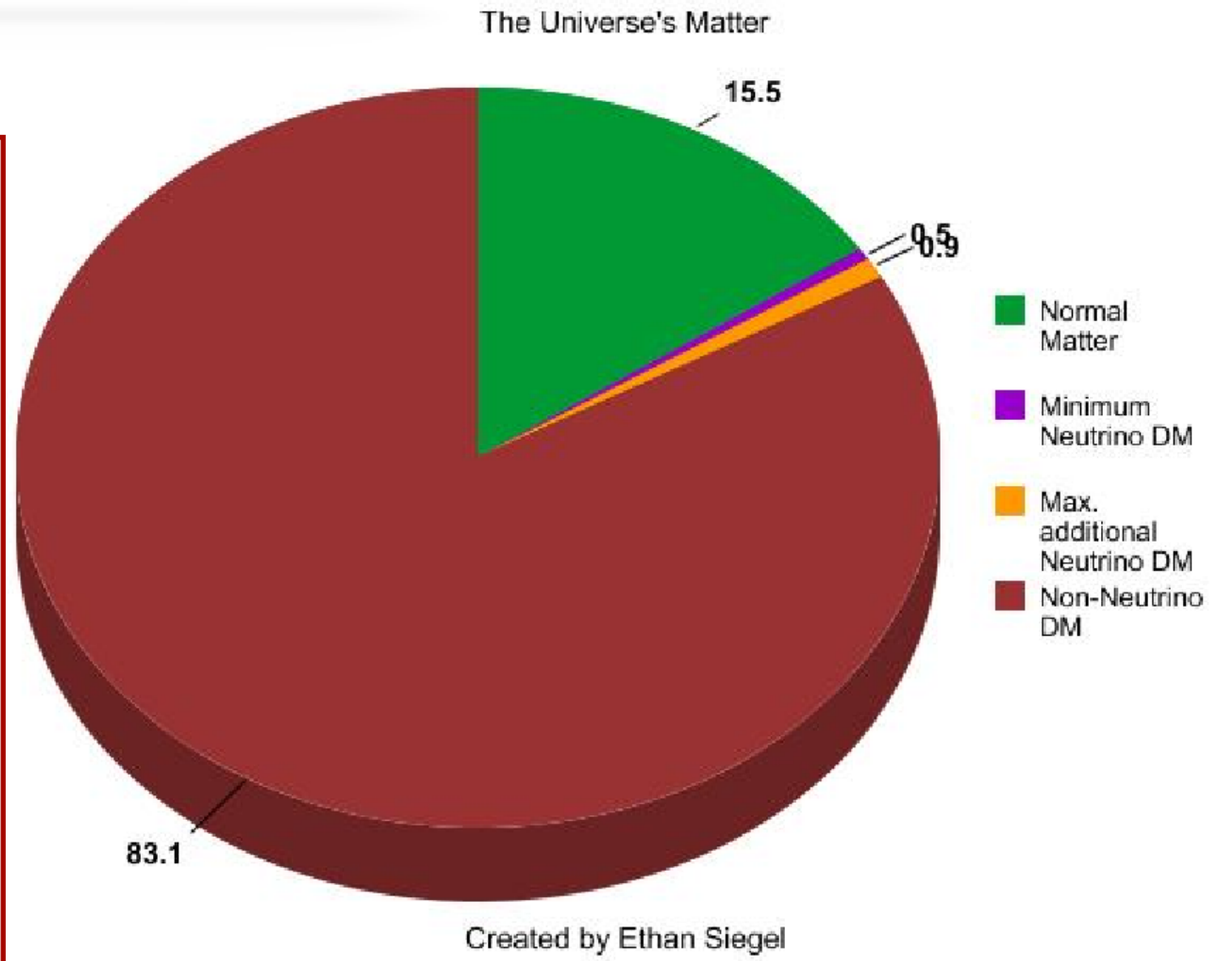
http://www.mpg.de/7644757/W002_Physics-Astronomy_048-055.pdf.

Nice review: https://medium.com/starts-with-a-bang/throwback-thursday-how-dark-matter-s-1-competitor-died-fdcb462d854d

DM particles: general properties

What we do know:

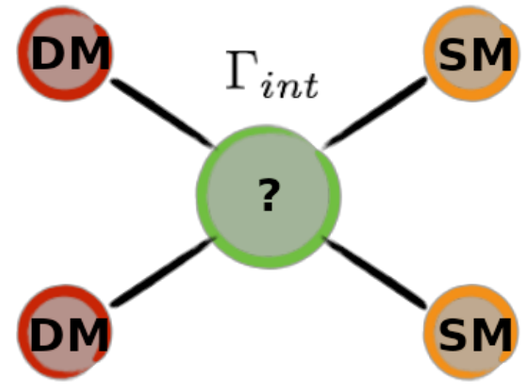
- Interact through gravity
- Massive (to cluster)
- If DM particles ever were relativistic – they should have slowed down early in the history of the Universe
- Electrically neutral (do not interact with photons)
- Stable on cosmological scales



What we don't know:

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

Why the electroweak scale?



Assumption:

thermal production

$\Gamma_{int} > H$ In equilibrium with plasma

$\Gamma_{int} < H$ Not in equilibrium with plasma

Relic abundance

Very simplified WIMPS

One new "heavy" particle

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_{DM}^2} + n_{DM} \langle \sigma v \rangle \sim H$$

at decoupling

$$\Omega_{DM} h^2 \sim 0.12 \frac{10^{-26} \mathrm{cm}^3 s^{-1} (\text{or } 10^{-9} [GeV]^{-2})}{\langle \sigma v \rangle}$$

Planck

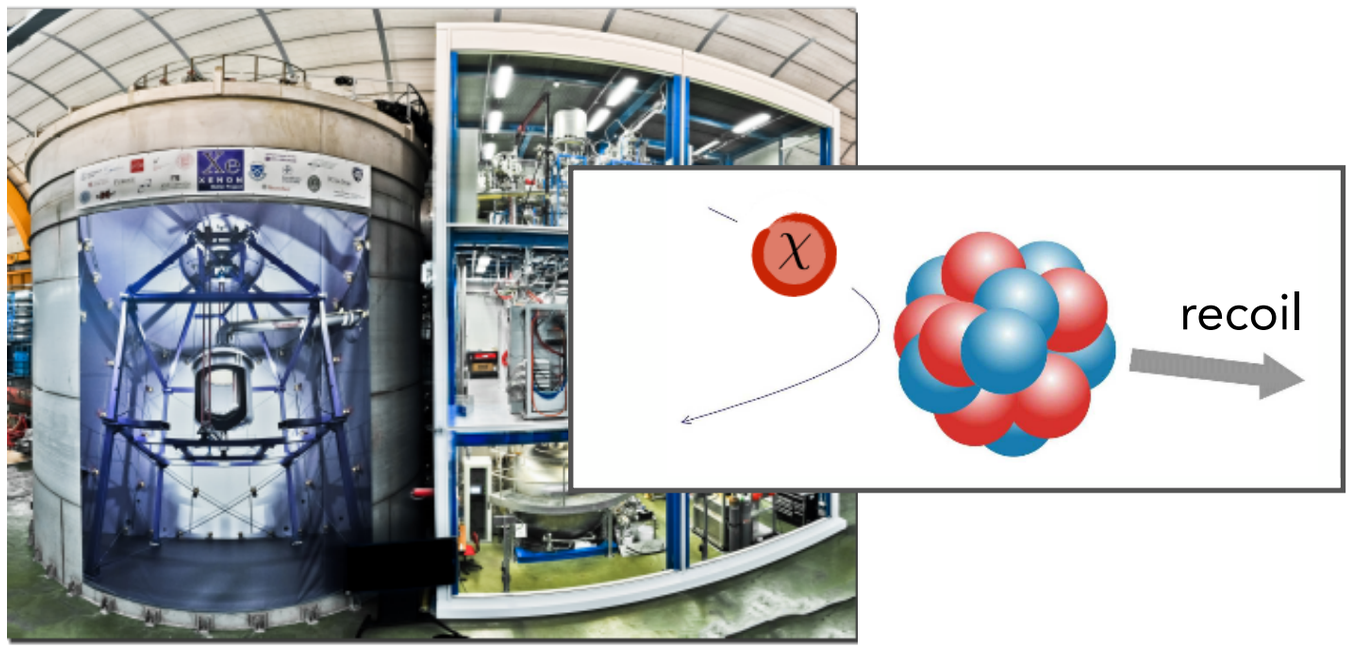
"Natural" choice:

$\alpha \sim \alpha_{EW}$

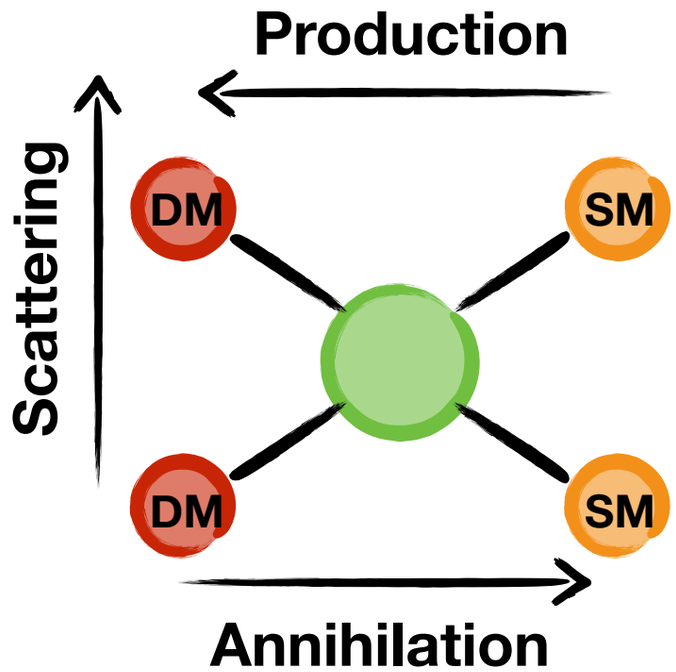
$m_{DM} \sim O(100\mathrm{GeV})$

Constraints

Scattering (direct detection)

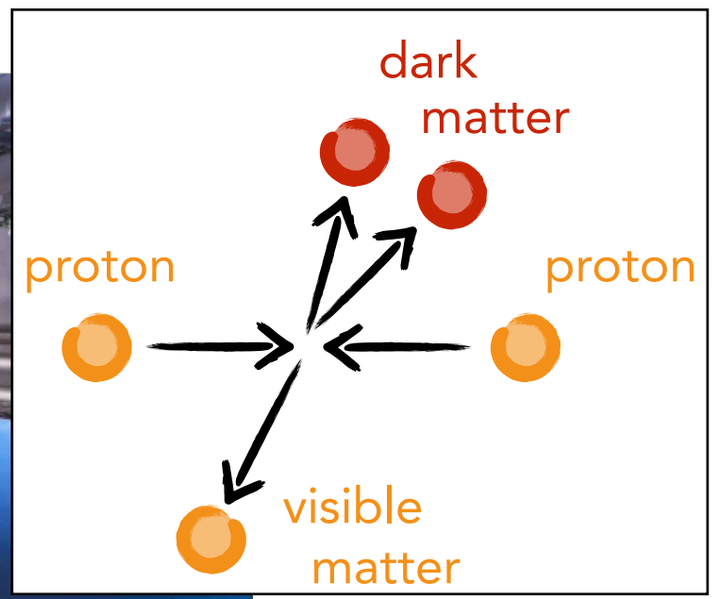


Xenon experiment



Production

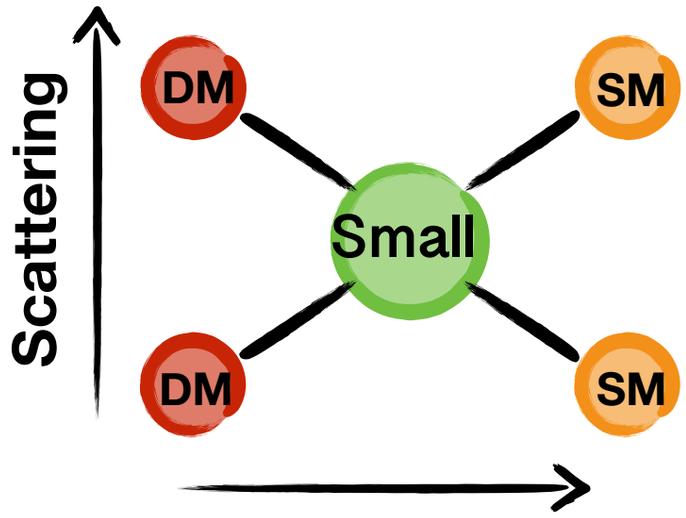
Large Hadron Collider

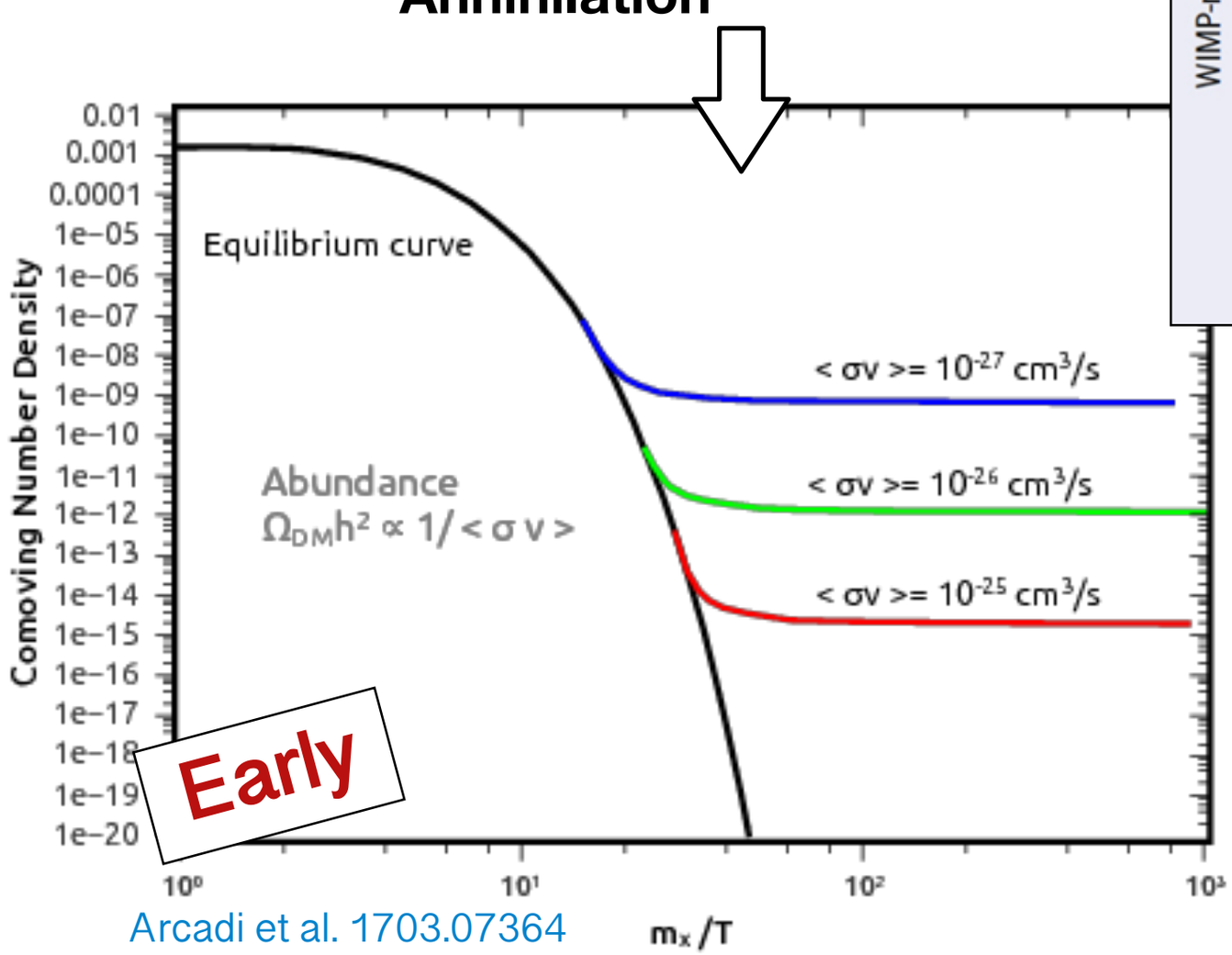


Annihilation (indirect detection)

Fermi satellite

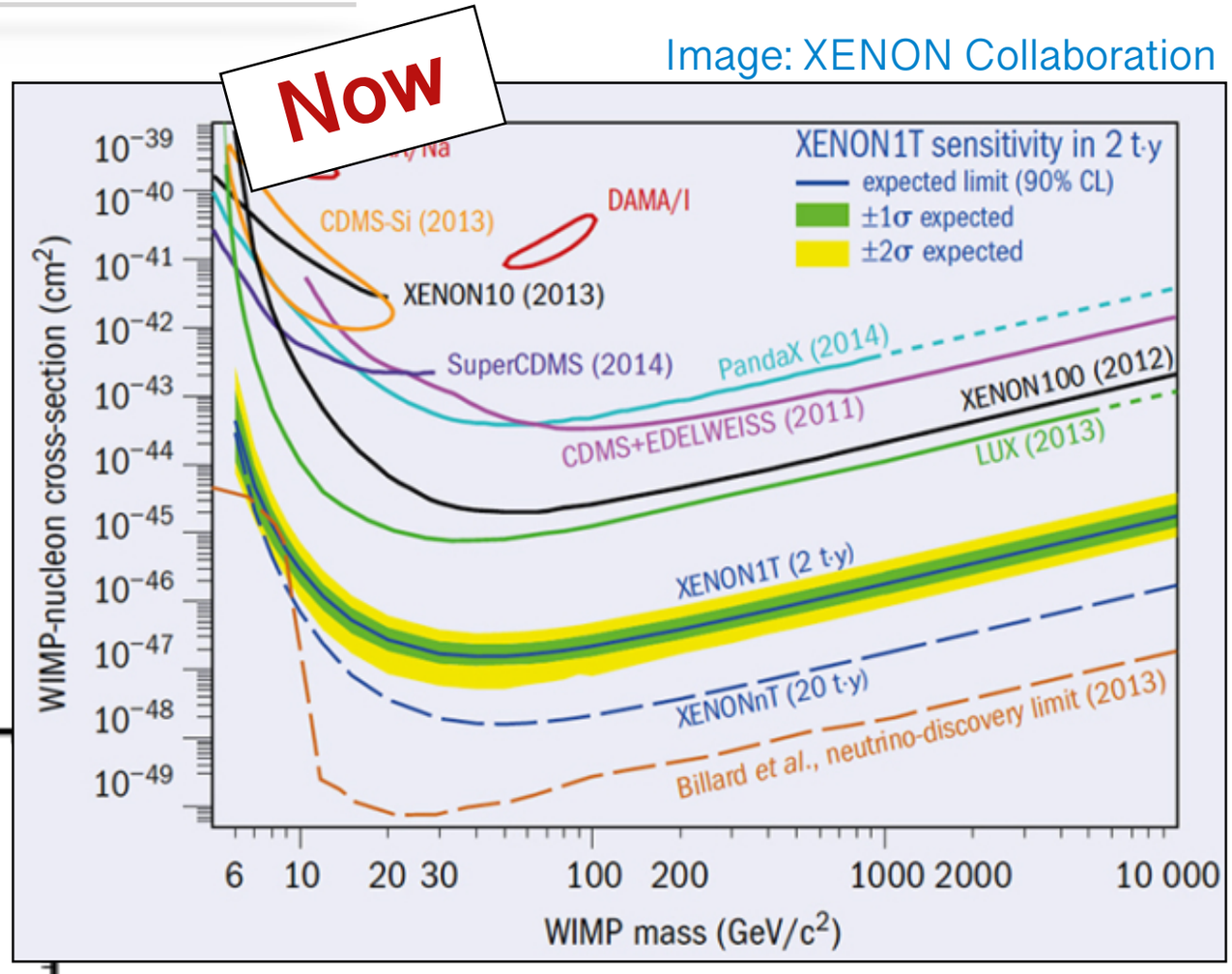
Main problem: direct detection





Arcadi et al. 1703.07364

Image: XENON Collaboration



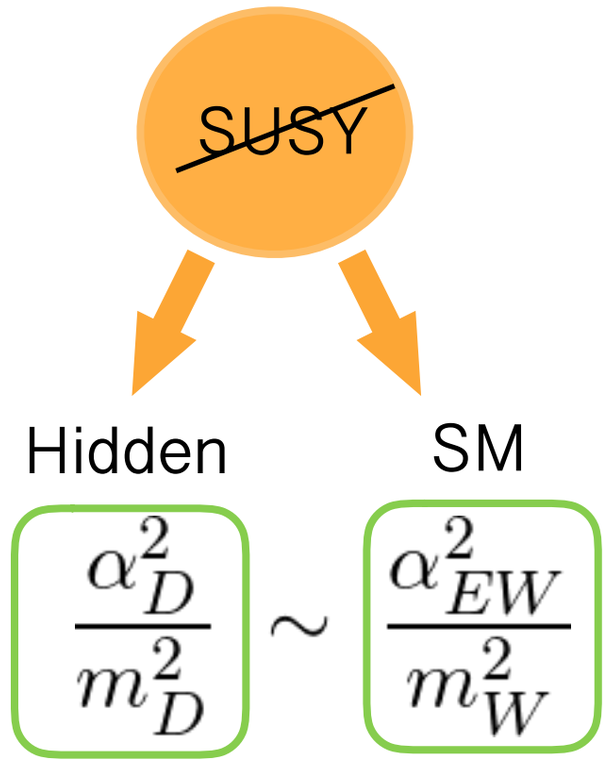
Overabundance

"Exceptions"

"WIMPless miracle"

Feng & Kumar [0905.3039]

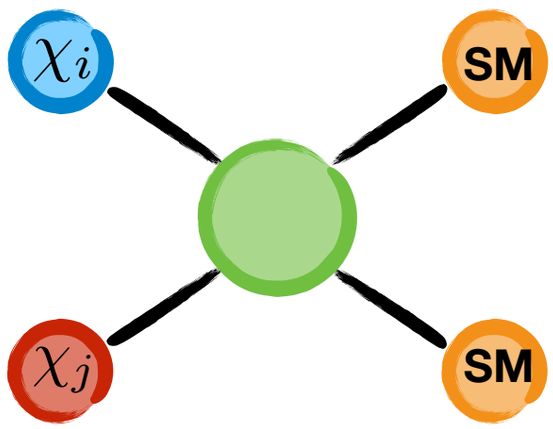
$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_{DM}^2}$$



Co-annihilation

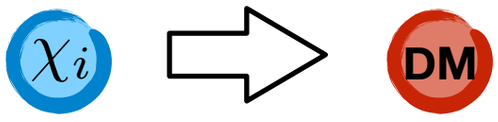
Griest & Seckel 1991

$$\sum_{ij}$$



$\langle \sigma v \rangle_{eff}$ ↑

at decoupling

But eventually 

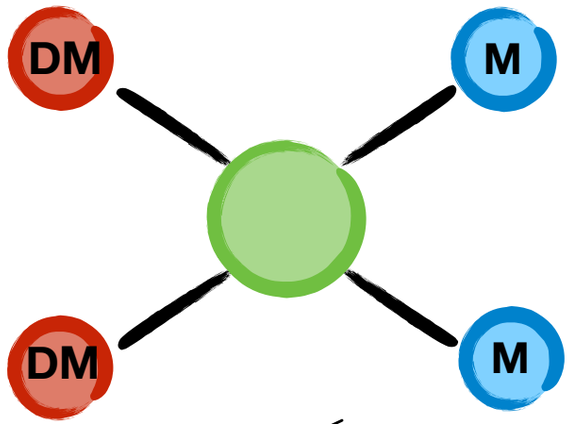
No Direct detection signal

"Exceptions"

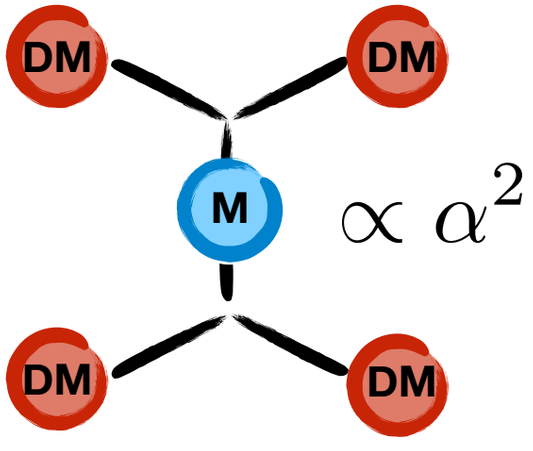
"Forbidden" DM D'Agnolo & Ruderman [1505.07107]

Exponentially suppressed by $\frac{m_M - m_{DM}}{T}$ ⇨ Allows for large α and light DM

From thermal tail



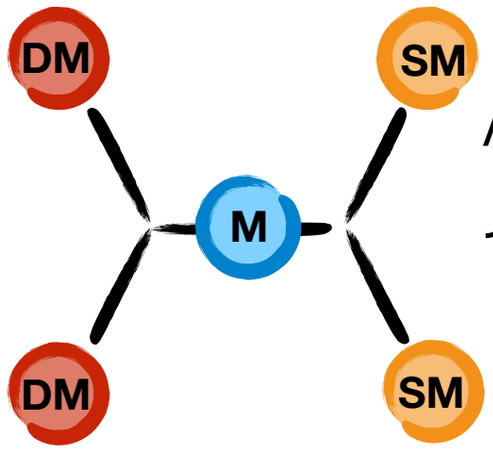
$m_{DM} < m_\chi$



$\propto \alpha^2$

Induces self-interactions

Resonant production Fenq & Smolinskv [1707.03835]

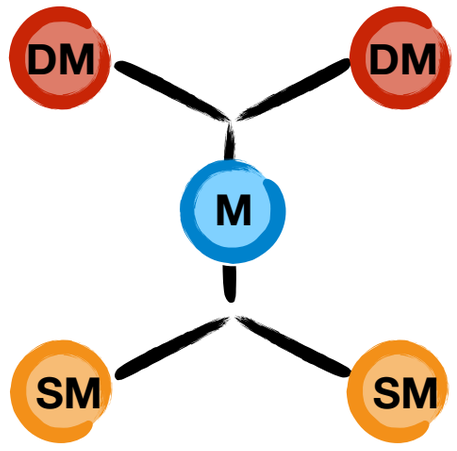


Allows for couplings

10-100 times smaller

$m_M = 2m_{DM}$

Can happen when

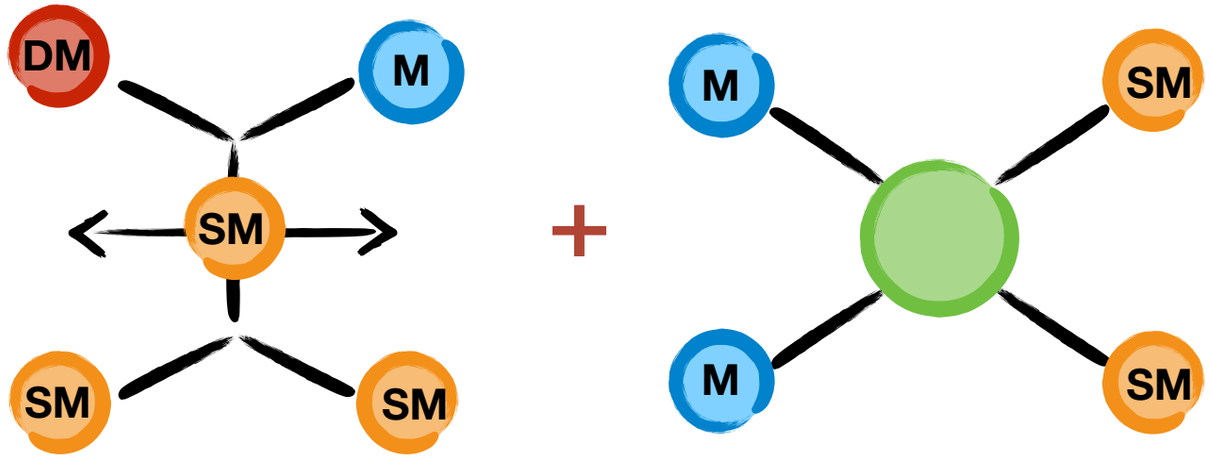


$O(10)$ effect on Ω

is out of equilibrium

Binder, Bringmann, Gustafsson, Hrzczuk [1805.00526]

“4th" exception: co-scattering

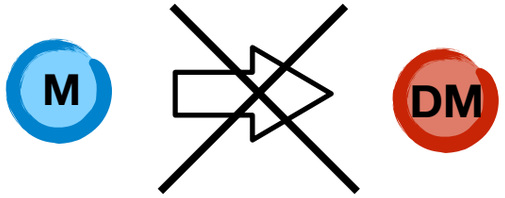


$$n_{SM}\langle\sigma v\rangle_{DM\to M} \sim H$$

Very high

Correct relic abundance

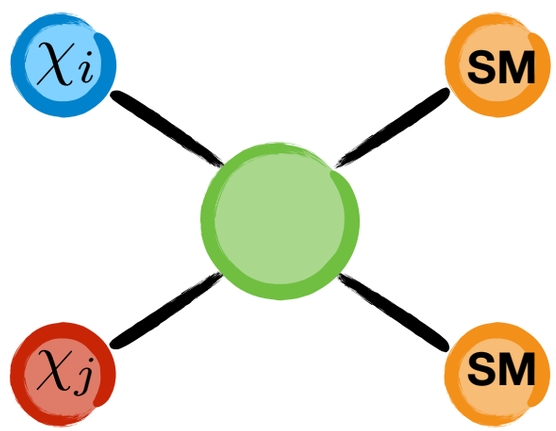
for much smaller couplings



Compare to (co-)annihilation:

$$n_{dark}\langle\sigma v\rangle_{eff} \sim H$$

Boltzmann suppressed



Example: singlet-triplet model

2 majorana fields: $SU(2)$ singlet χ_S and triplet χ_T

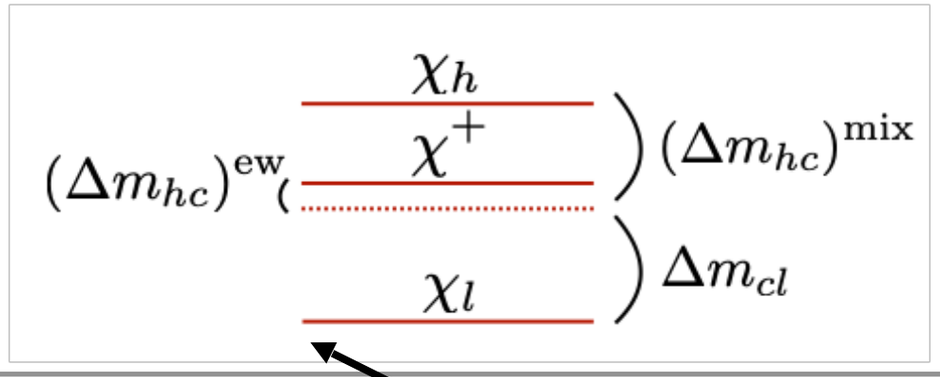
Naturally small

$$\mathcal{L}_{\text{eff}} \supset -\frac{m_S}{2}\overline{\chi}_S\chi_S - \frac{m_T}{2}\text{Tr}[\overline{\chi}_T\chi_T] + \frac{\kappa_{ST}}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + h.c.\right]$$

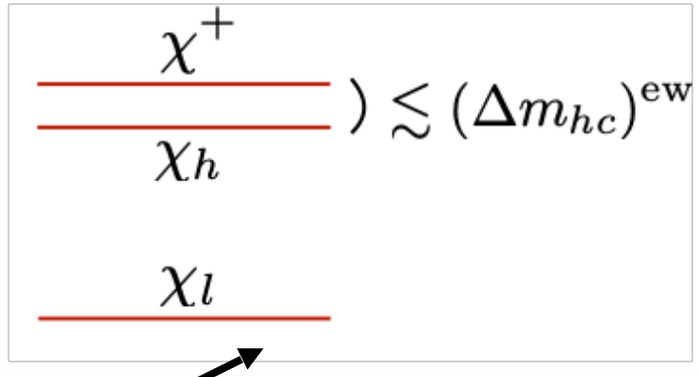
with $\chi_S = \chi_S^0, \quad \chi_T = \begin{pmatrix} \chi_T^0/\sqrt{2} & \chi^+ \\ \chi^- & -\chi_T^0/\sqrt{2} \end{pmatrix}$

- Three new parameters: $m_S,\ m_T,\ \mu = \frac{\kappa_{ST}v^2}{\sqrt{2}\Lambda}$
- Freedom in the field definitions: can choose $m_T,\ \kappa_{ST} > 0$

Tree-level structure + electroweak corrections:



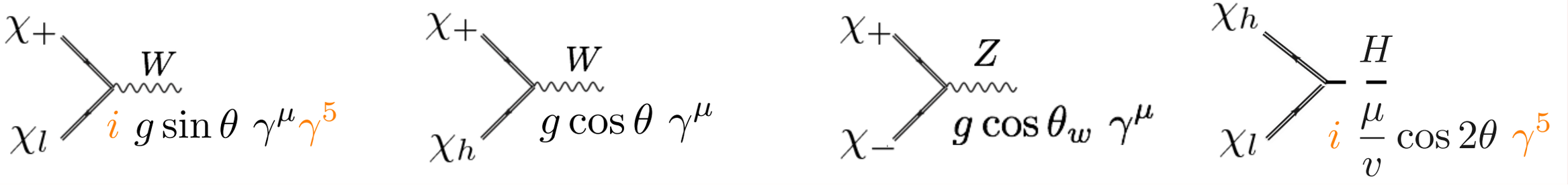
Small μ:



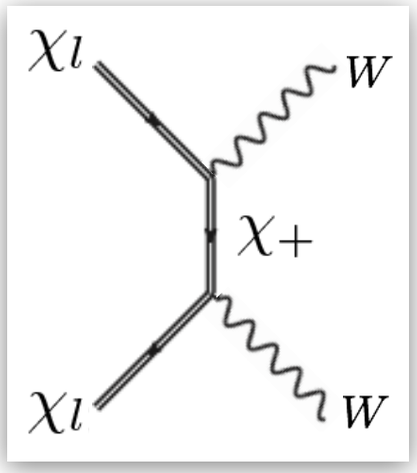
Dark matter candidate

Conventional processes

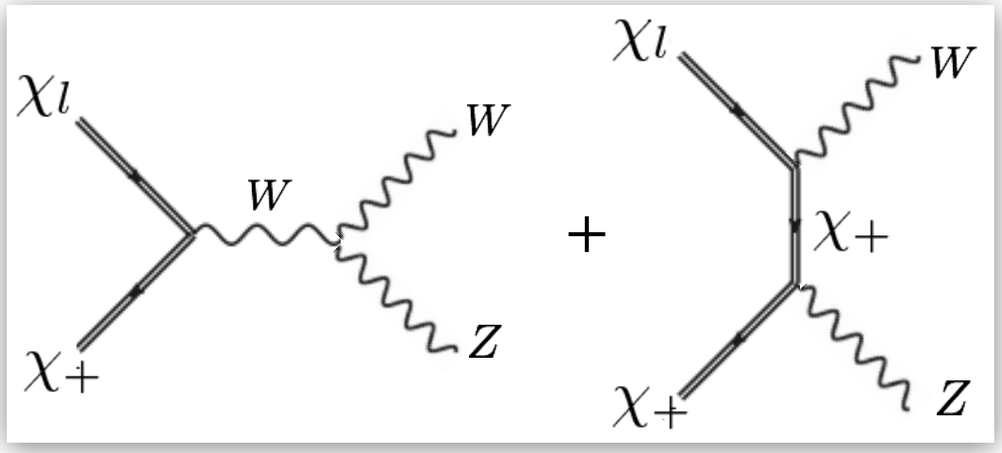
Gauge and Higgs couplings



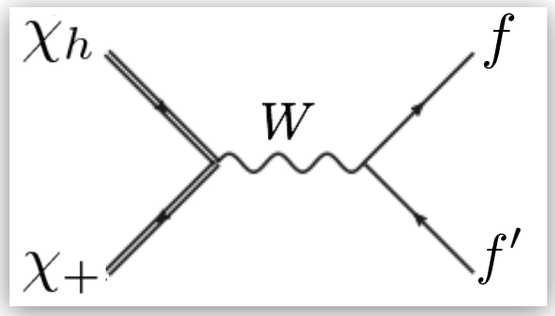
Main contributions from:



Annihilation

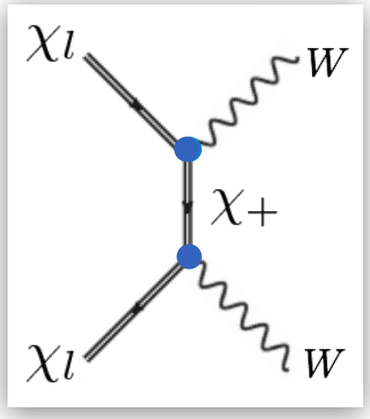


Co-annihilation



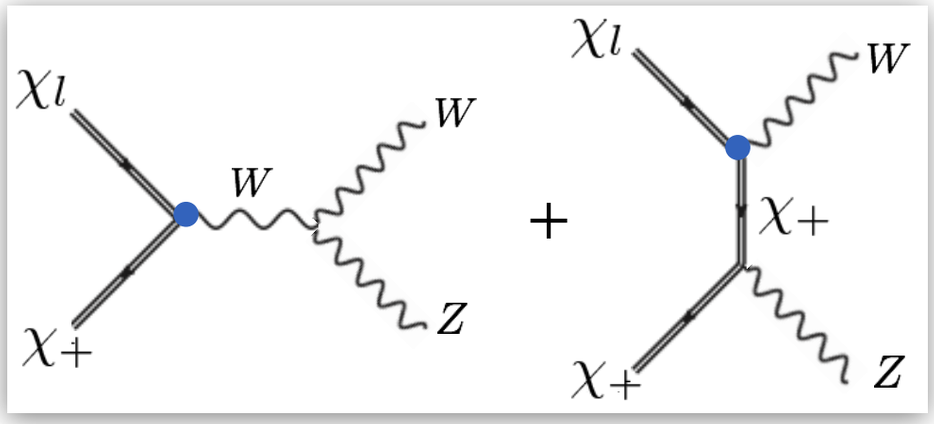
Mediator annihilation
+ further decay to χ_l

Naive picture



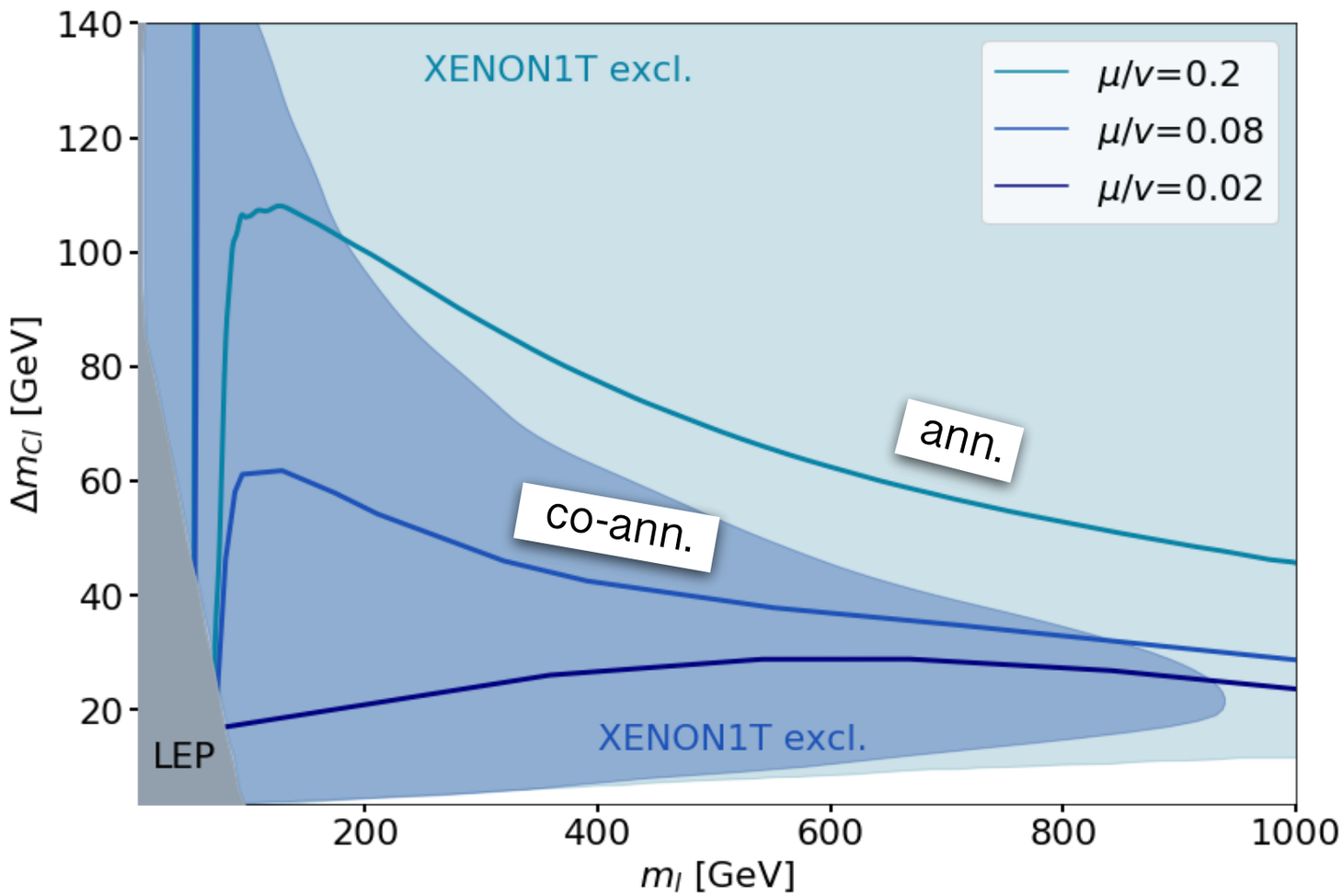
$(g \sin\theta)^4$

Annihilation



$(g \sin\theta)^2$

Co-annihilation



χ^+
χ_l — $15 - 30$ GeV

Lines: $\Omega_\psi h^2 = 0.1199 \pm 0.0022$ [Planck coll., 1502.01589]

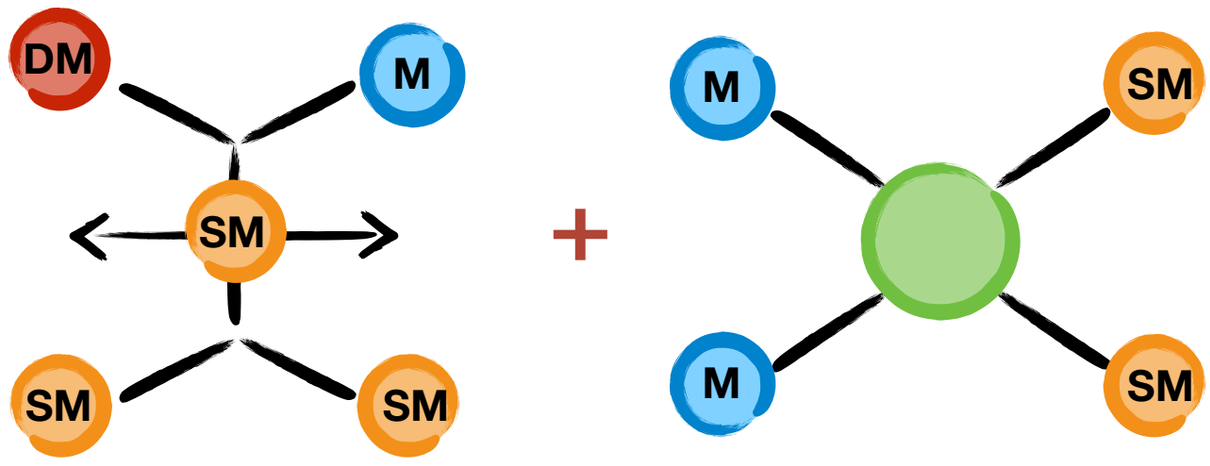
Co-scattering

Small portal coupling

	process	scaling		process	scaling
pair annihilation	$\chi_\ell\chi_\ell \to W^+W^-$ $\chi_\ell\chi_\ell \to h^* \to f\bar{f}, VV$ $\chi_\ell\chi_\ell \to hh$	$(g\sin\theta)^4$ $(\mu\sin(2\theta)/v)^2$ $(\mu\cos(2\theta)/v)^4$	mediator annihilation	$\chi_h\chi_h \to W^+W^-$ $\chi_h\chi^+ \to f\bar{f}', VV$ $\chi^+\chi^- \to f\bar{f}, VV$	$(g\cos\theta)^2$ $(g\cos\theta)^2$ g^2
co-annihilation	$\chi_\ell\chi^+ \to f\bar{f}', VV$ $\chi_\ell\chi_h \to W^+W^-$ $\chi_\ell\chi_h \to h^* \to f\bar{f}, VV$	$(g\sin\theta)^2$ $(g\sin\theta)^2$ $(\mu/v)^2$	mediator decays	$\chi^+ \to \chi_\ell f f'$ $\chi_h \to \chi_\ell f\bar{f}$	$(g\sin\theta)^2$ $(\mu/v)^2$
co-scattering	$\chi_\ell f \to \chi^+ f'$ $\chi_\ell f \to \chi_h f$	$(g\sin\theta)^2$ $(\mu/v)^2$	scattering	$\chi_\ell f \to \chi_\ell f$	$(\mu\sin\theta/v)^2$

- Mediator annihilations are still in chemical equilibrium
- Decays become very slow
- Equilibrium is lost for dark matter

Relic abundance:
co-scattering + mediator annihilation

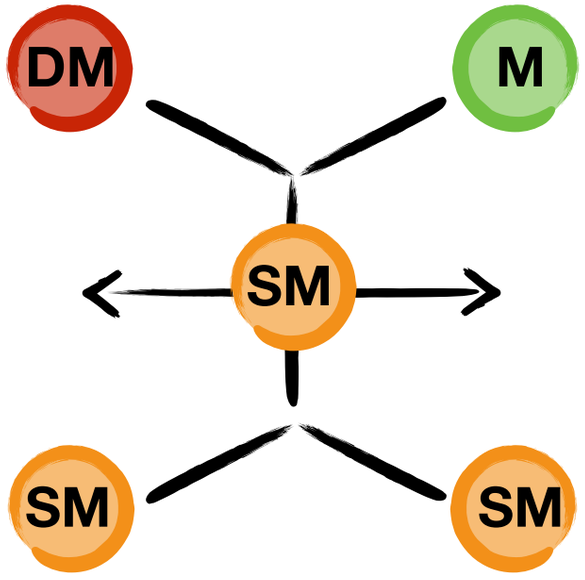


Very abundant

Is a common feature of theories with nontrivial dark sector in a small-coupling regime

See also Garny et. al[1705.09292] and D'Agnolo et al. [1705.08450], [1803.02901], [1906.09269]

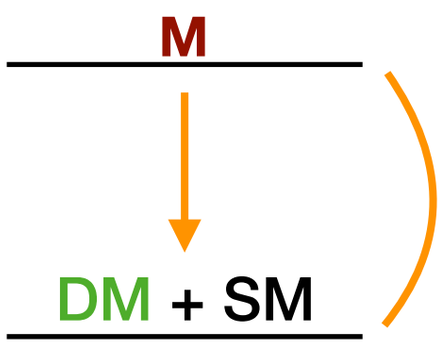
So just continue searching?



- Mediator decays are slow during decoupling.
- **But they are also long-lived at colliders!**

- Both dark states present at decoupling—**compressed spectrum**.

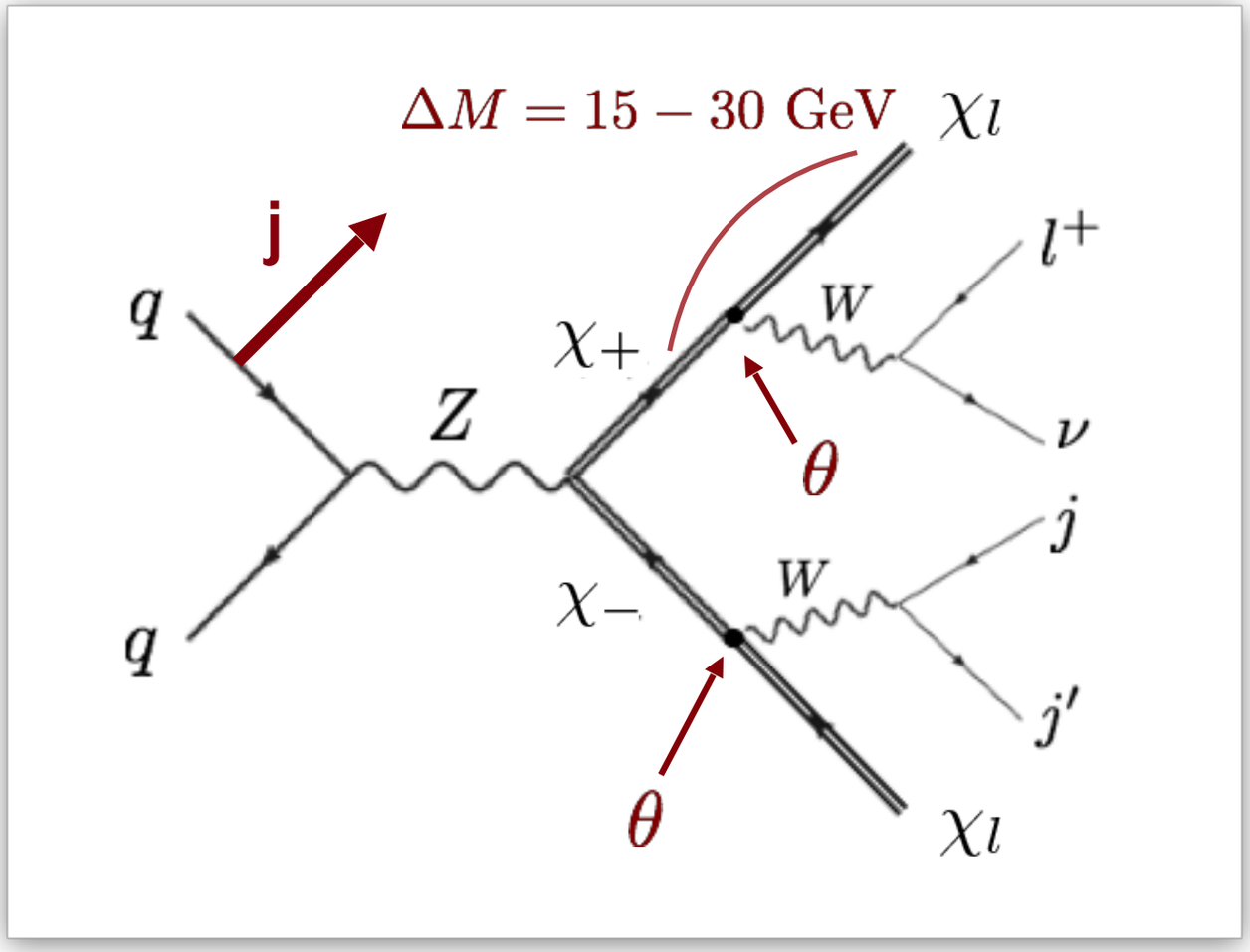
We search for:



Defines p_T of SM ⇨ **Particles are soft**

Prompt searches are having a hard time

Example: soft leptons



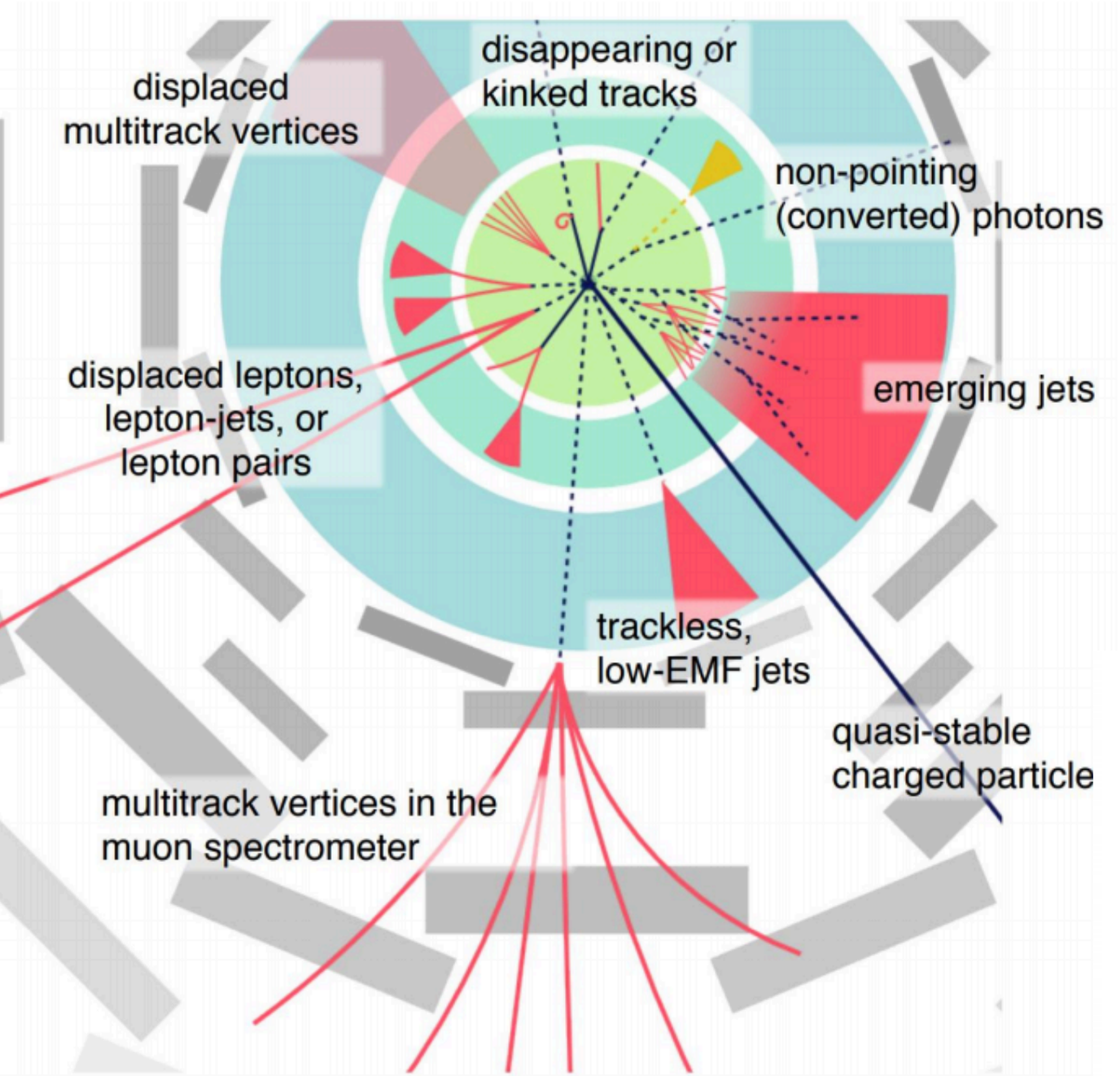
σ_{prod}

Only light masses are probed

Bharuchaa, Brümmer, Desai [1804.02357]
CMS [1206.3949]

LLP analyses at ATLAS & CMS since October 2018

[R. Rosten's talk at 5th LLP Workshop]



CMS

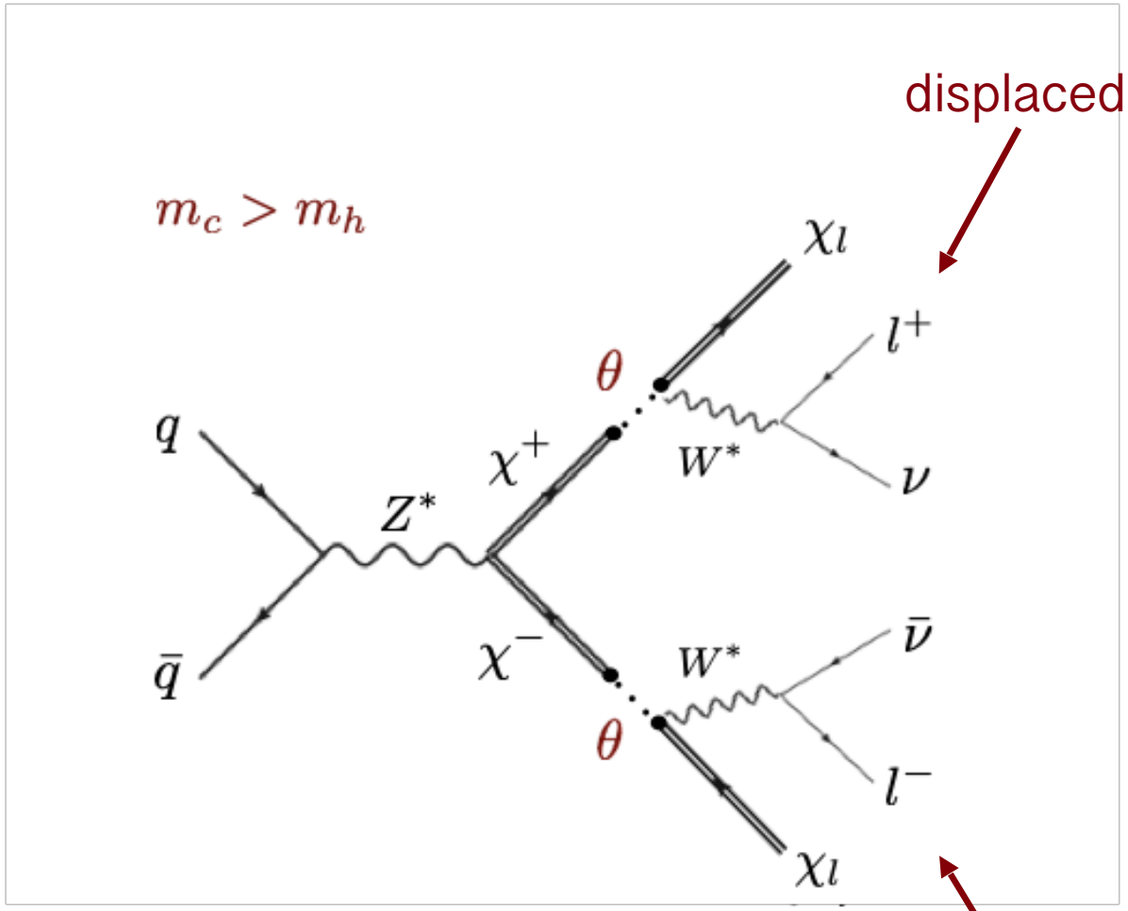
Search	arXiv
Delayed Jets	EXO-19-001
Disappearing Tracks	SUS-19-005
Displaced Jets	1811.07991

ATLAS

Search	arXiv
Highly ionizing particles/monopoles	1905.10130
Disp (& prompt) heavy neutral leptons	1905.09787
Displaced hadronic (CalRatio) jets	1902.03094
Heavy charged LLPs	1902.01636
Displaced vertex + displaced muon	CONF-2019-006
Multi-charged LLPs	1812.03673
Muon vertex	1811.07370
Z + Displaced hadronic (CalRatio) jet	1811.02542

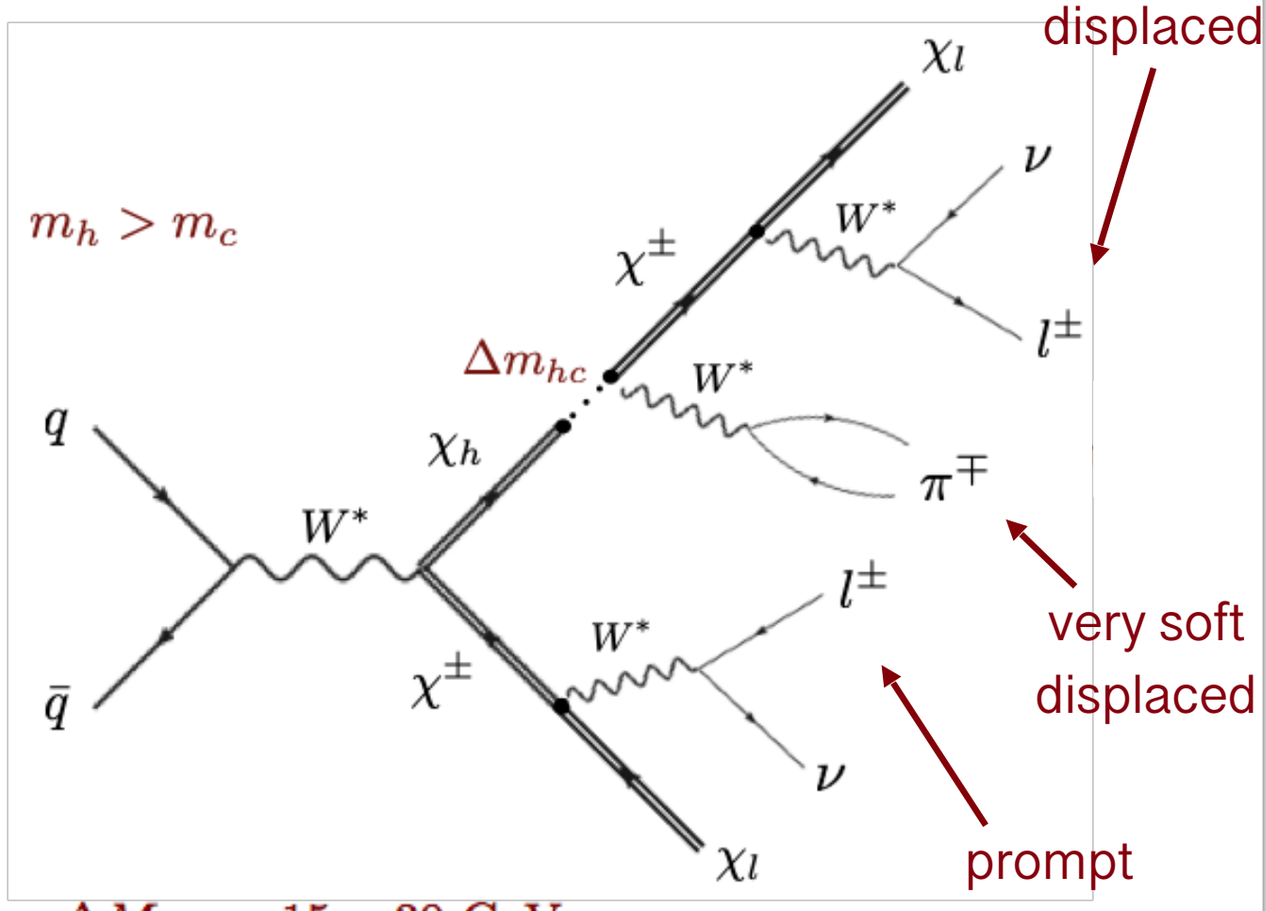
Promising soft displaced signatures

Soft displaced lepton pair



$\Delta M_{+,l} = 15 - 30$ GeV

Displaced soft leptons + prompt jets

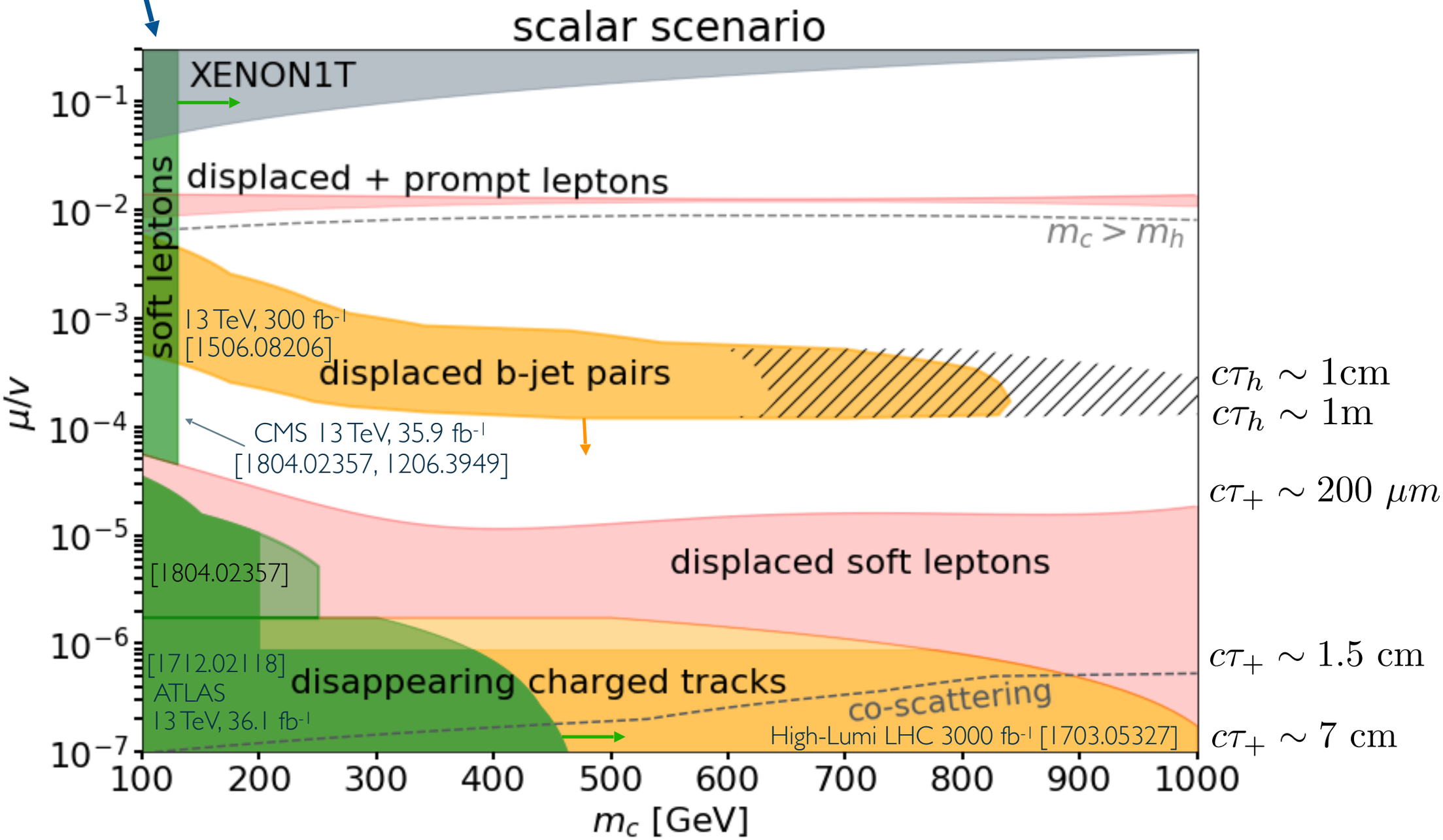


$\Delta M_{+,l} = 15 - 30$ GeV

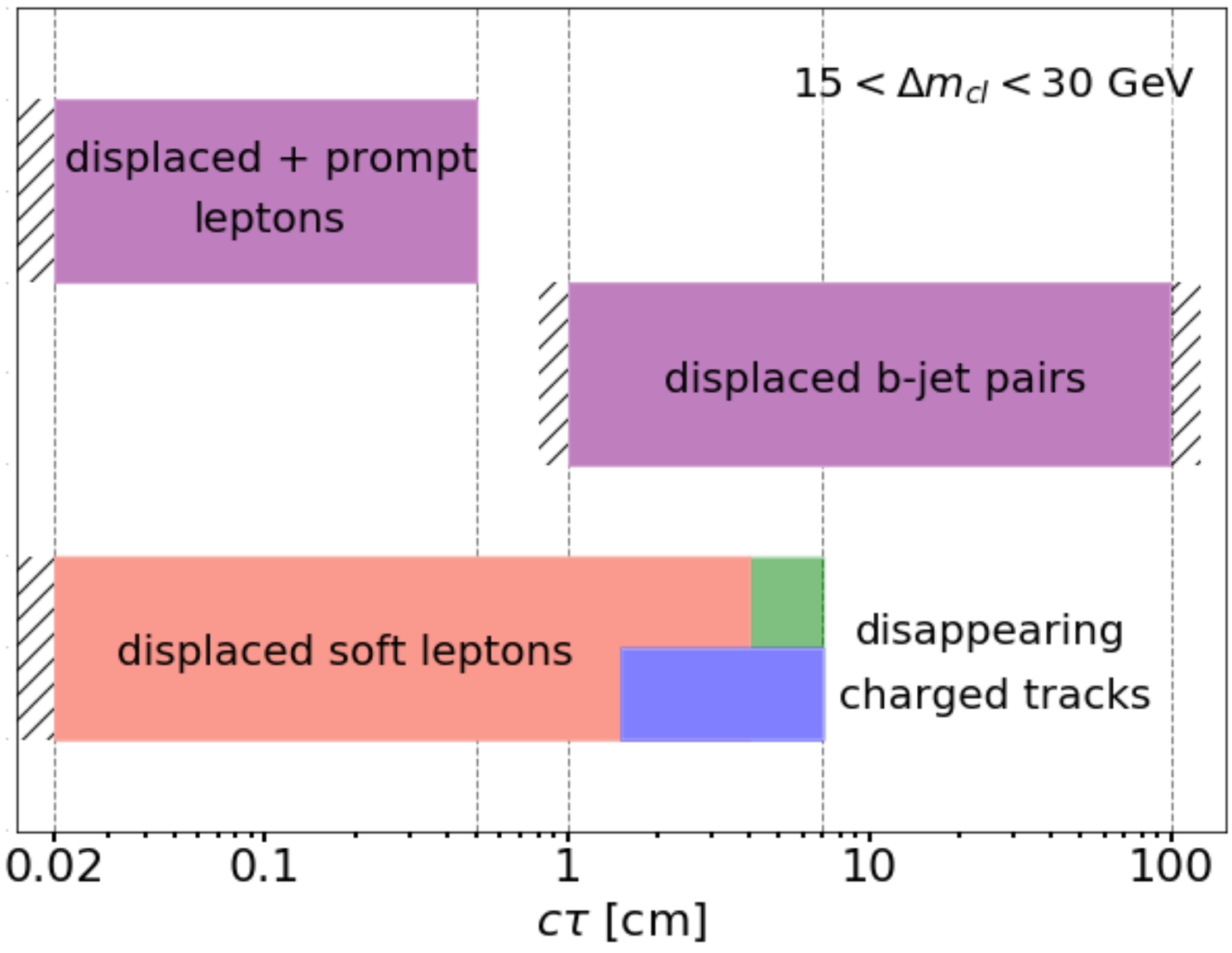
$\Delta M_{+,h}$ arbitrarily small

Collider searches

Prompt searches can not help

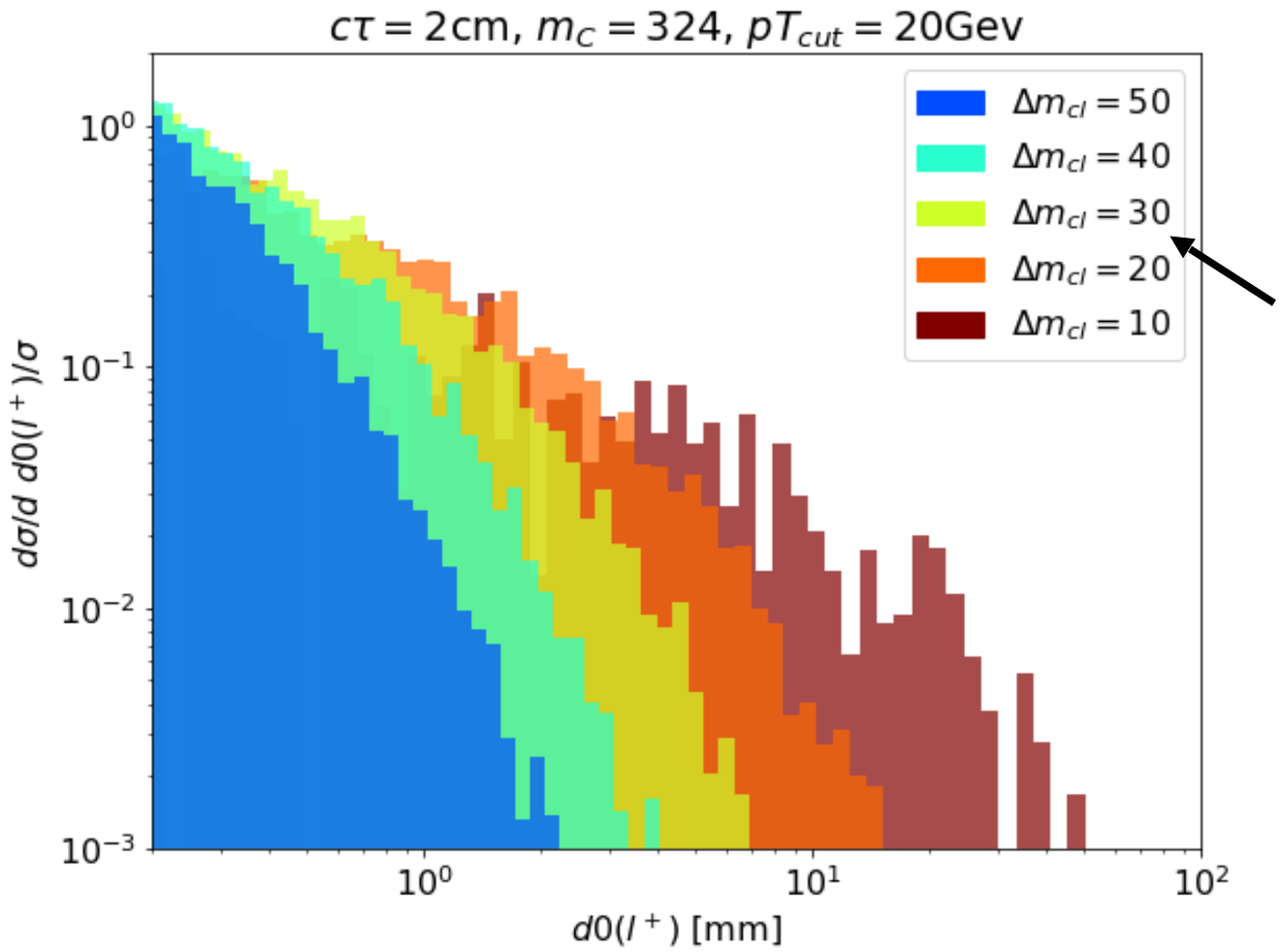


Lifetimes accessible @ LHC

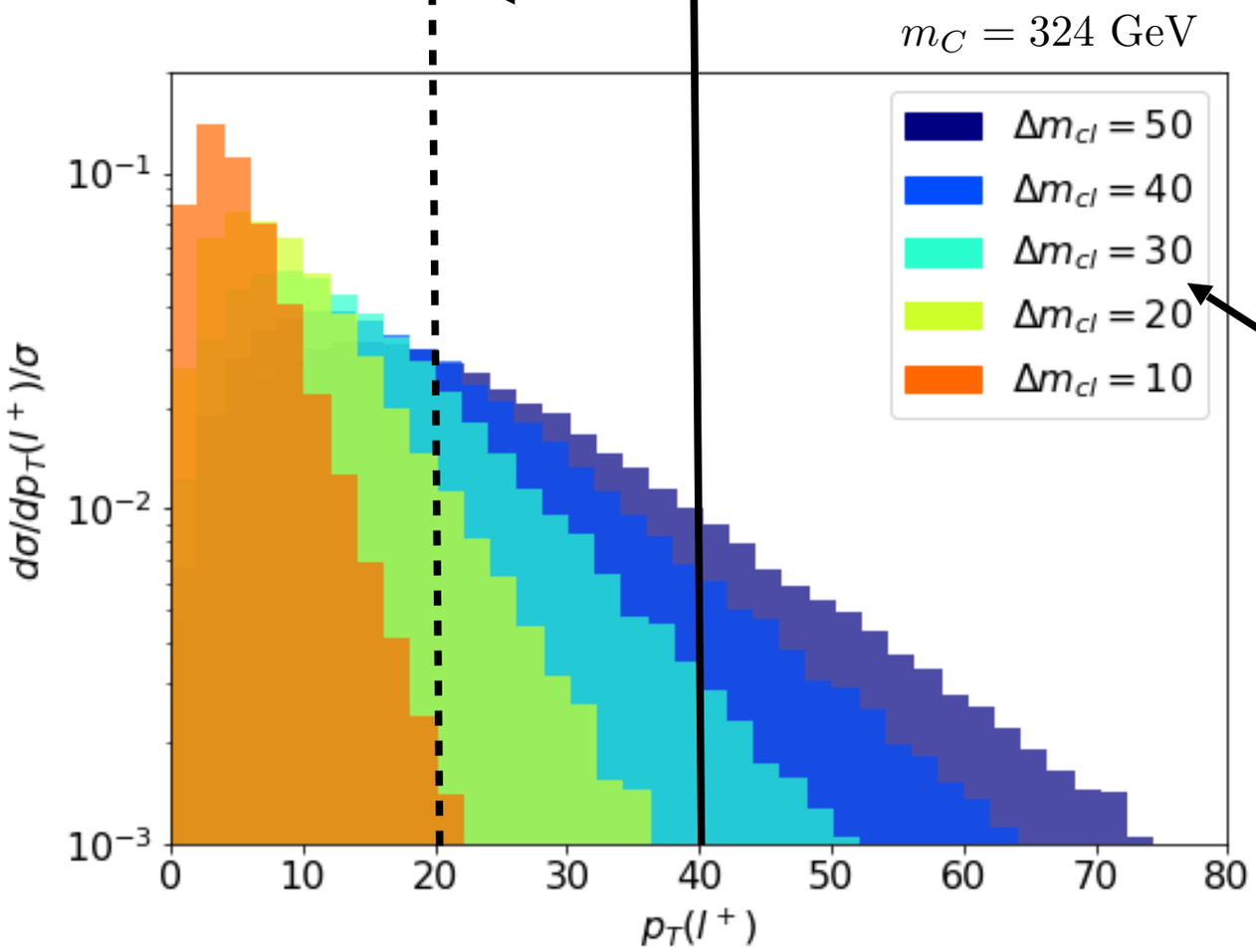


How displaced/soft?

Displacement for proposed cut



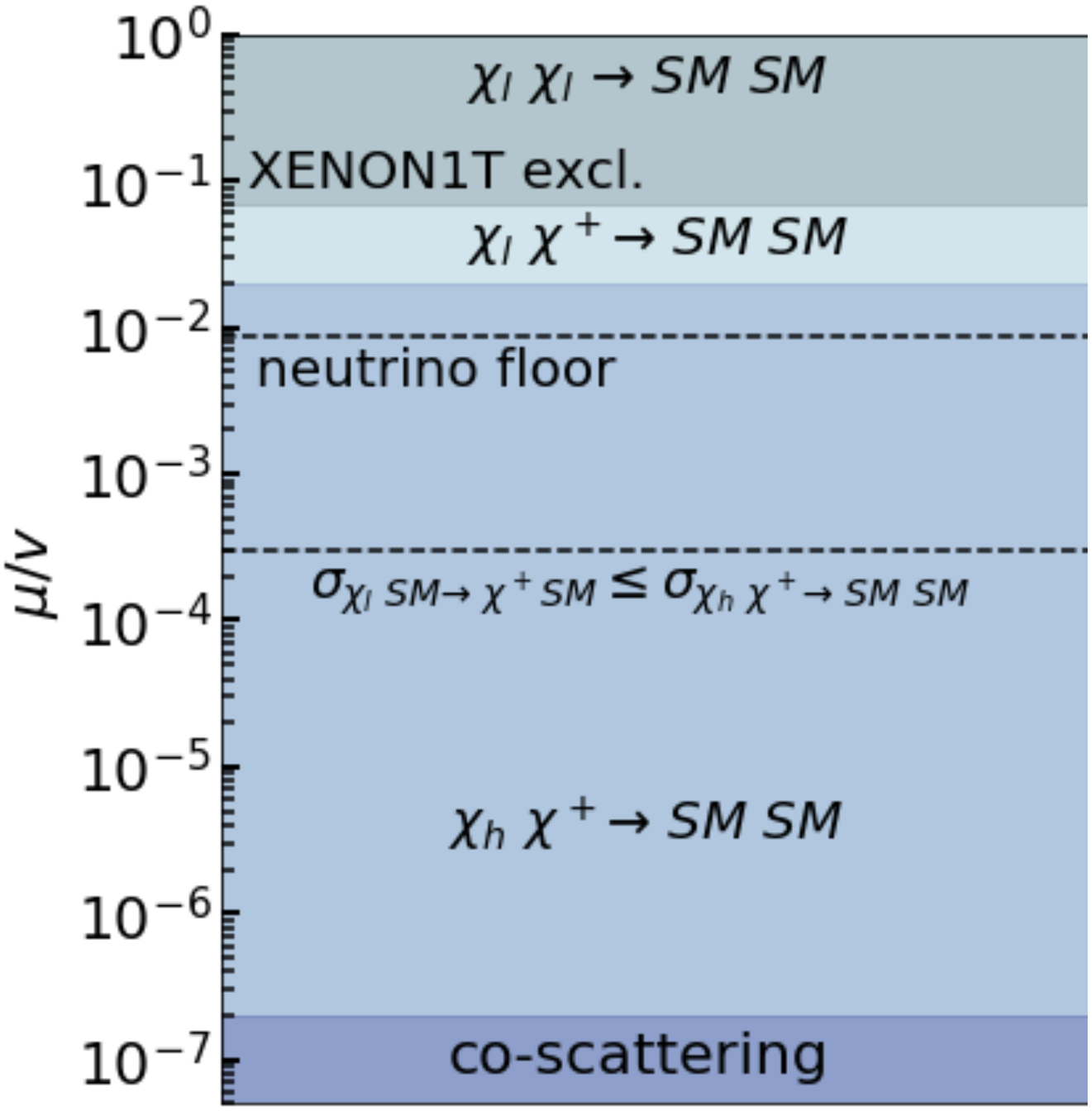
Current cut
[CMS-PAS-EXO-16-022]

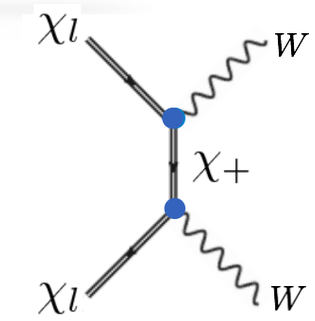


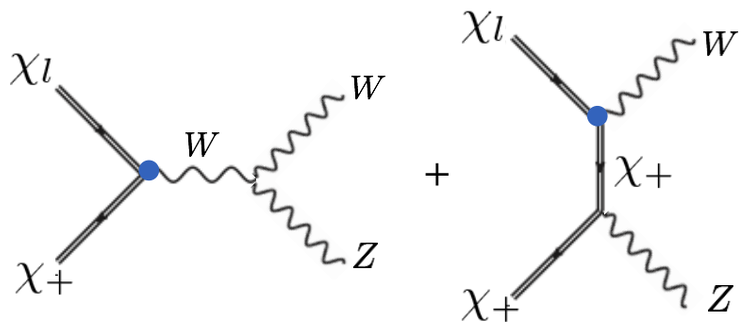
thermal relic

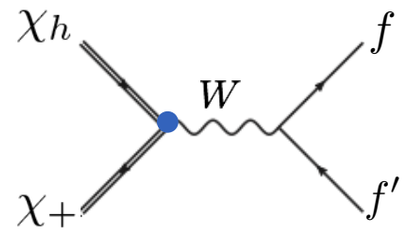
PRELIMINARY

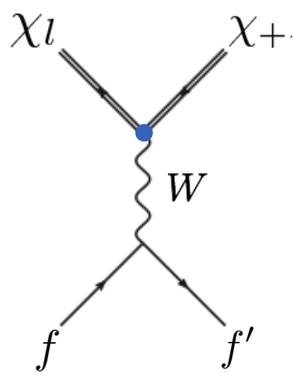
Higgs portal again: freeze-out phases











Back to relic density: implementation

Co-scattering processes are important for accurate prediction of dark matter relic density.

Not included in publics codes e.g. MicrOMEGAs, MadDM, DarkSUSY

Complication:

the DM particles are frequently not in thermal equilibrium

In principle

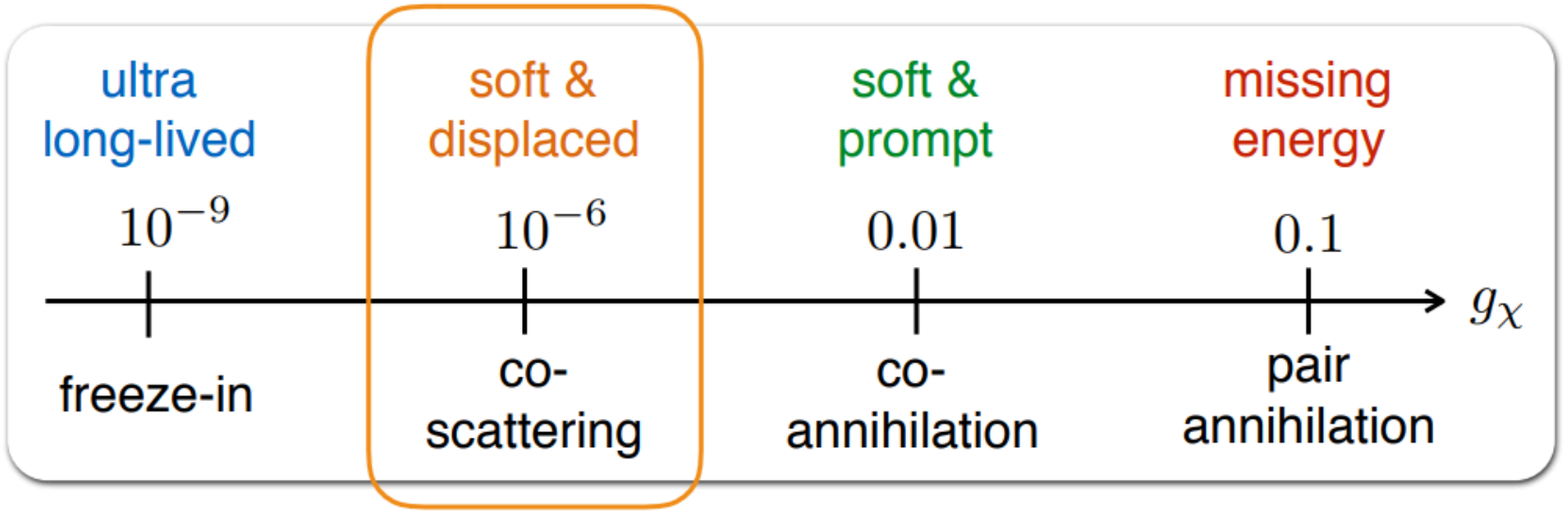
the coupled system non-integrated Boltzmann equations for all dark states must be solved

However, in many cases simplified approaches are possible

(see Binder at al. 1805.00526, D'Agnolo et al. 1906.09269)

Summary

- Strong direct detection constraints point us to a very weakly coupled dark sectors.
- Consequently, the “non-conventional" processes set the DM relic abundance.
- This also leads to a natural appearance of the long-lived states at collier scales. The most promising collider signatures involve displaced particles.
- New searches are needed to conclusively test this scenario: displaced soft leptons, appearing tracks, etc.



[S.Westhoff's talk at 5th LLP Workshop]

Open questions

- How powerful are displaced searches?

- Which experiments can probe the co-scattering regime (are the lifetimes at the scale of ATLAS/CMS or beyond i.e. FAZER/ MATHUSLA/ShiP…)?

- What happens for even weaker couplings? At which point we switch to the freeze-in scenario?

- Are there any hints from cosmological observations about the properties of the non-thermal dark matter momentum distribution?

Thank you!

Singlet-triplet model: mass basis

Scalar scenario

$$m_S > \mu^2/m_T$$

$$\begin{pmatrix}\chi_\ell\\ \chi_h\end{pmatrix} = \begin{pmatrix}\cos\theta\,\chi_S^0 - \sin\theta\,\chi_T^0\\ \sin\theta\,\chi_S^0 + \cos\theta\,\chi_T^0\end{pmatrix}$$

$$m_{h,\ell} = \tfrac{1}{2}\Big(m_T + m_S \pm \Delta m_{h\ell}\Big)$$

$$m_c = m_T$$

Pseudo-scalar scenario

$$m_S < \mu^2/m_T$$

$$\begin{pmatrix}\chi_\ell\\ \chi_h\end{pmatrix} = \begin{pmatrix}\cos\theta\,\chi_S^0 + \sin\theta\,i\gamma_5\chi_T^0\\ \sin\theta\,i\gamma_5\chi_S^0 + \cos\theta\,\chi_T^0\end{pmatrix}$$

$$m'_{h,\ell} = \tfrac{1}{2}\Big(\Delta m_{h\ell} \pm (m_T + m_S)\Big) = \pm\, m_{h,\ell}$$

$$m_c = m_T$$

with $\Delta m_{h\ell} = \sqrt{(m_T - m_S)^2 + 4\mu^2}$ $\qquad \theta \simeq \dfrac{\mu}{m_T - m_S}$

In both scenarios $m_\ell/m'_\ell > 0$

Couplings of dark fermions

Two physical scenarios, depending on parameters of the theory:

Scalar case:

Couplings $\propto 1, \gamma_\mu$

Pseudo-scalar case:

Couplings $\propto \gamma_5, \gamma_\mu\gamma_5$

Connected through chiral rotation:

$$\chi_l \to i\gamma_5\chi_l$$

- Changes the sign of the mass term:

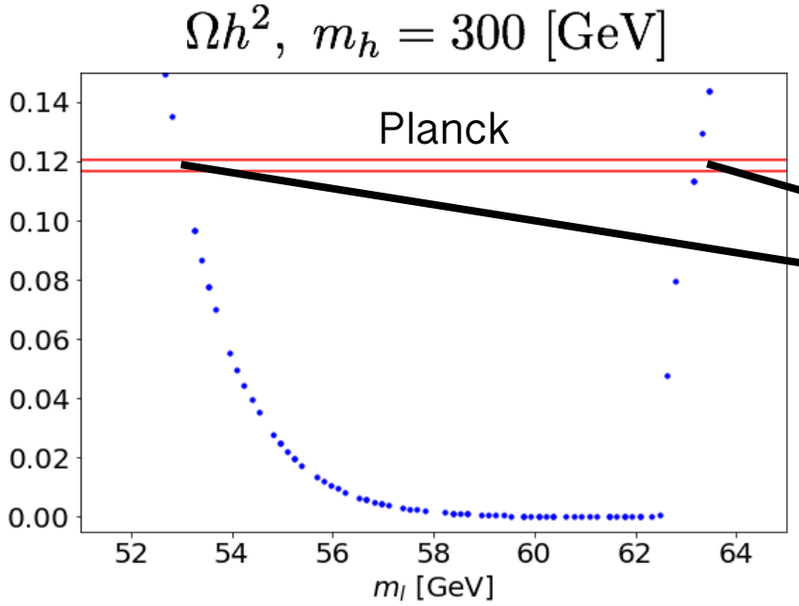
$$-m_l\bar{\chi}_l\chi_l \to m_l\bar{\chi}_l\chi_l$$

- Leads to pseudo-scalar (axial-vector) interactions:

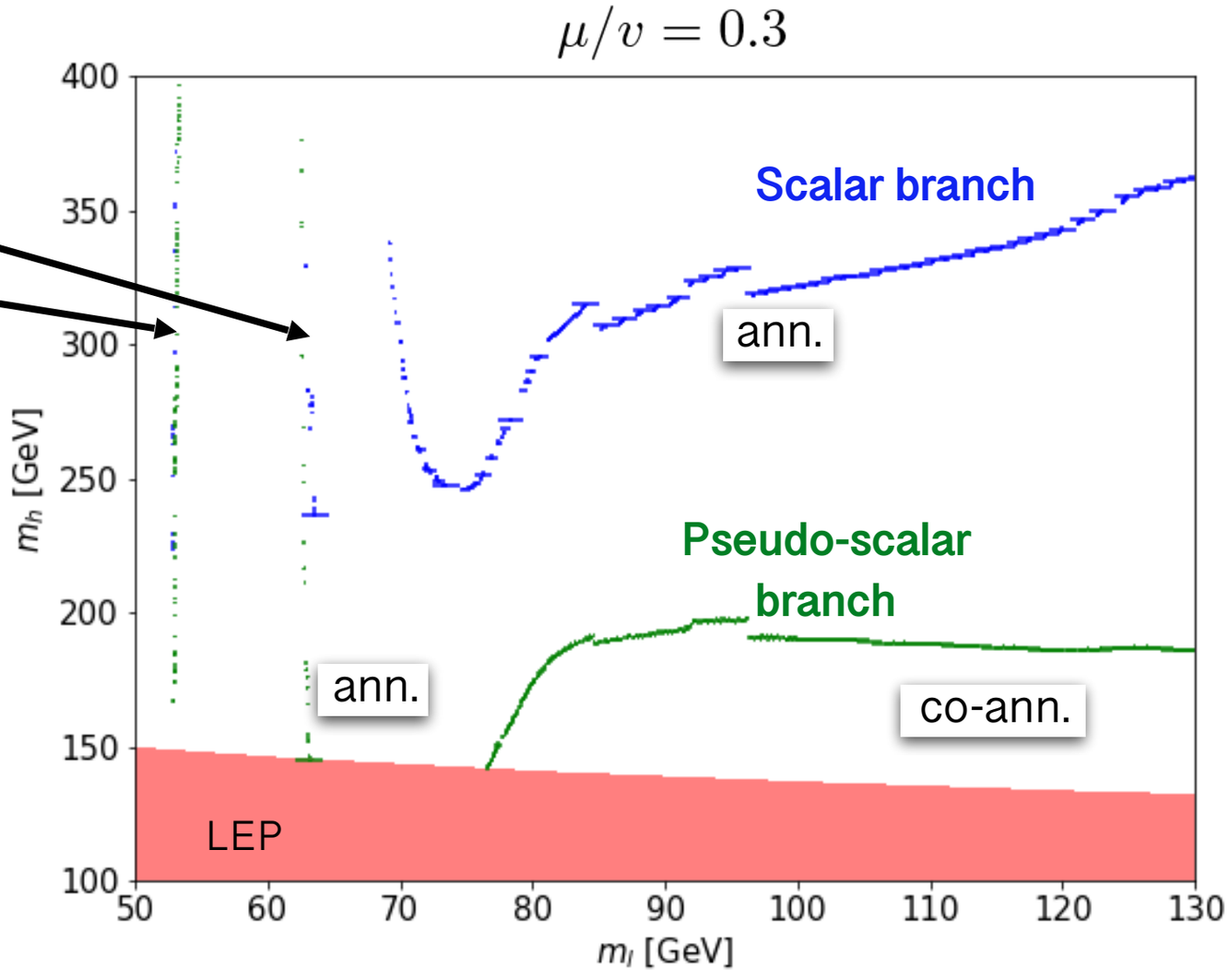
$$\bar{\chi}_h\chi_l \to i\bar{\chi}_h\gamma_5\chi_l$$
$$\bar{\chi}_+\gamma^\mu\chi_l \to i\bar{\chi}_+\gamma^\mu\gamma_5\chi_l$$

See also [hep-ph/0702148]

Relic density: threshold effects



Higgs resonance region

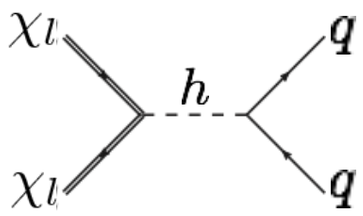


$$\theta \simeq \frac{\mu}{m_T - m_S}$$

Blue/green: $\Omega_\psi h^2 = 0.1199 \pm 0.0022$

[Planck coll., 1502.01589]

Direct detection

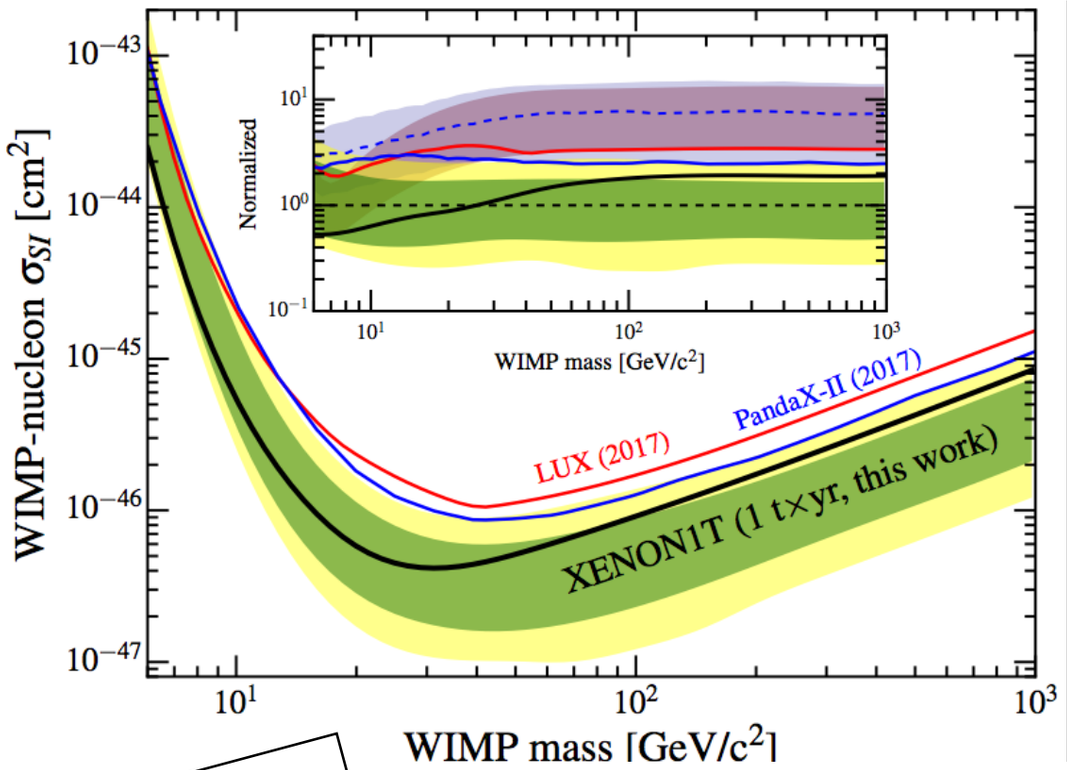


$$\propto \mu/v \sin(2\theta)$$

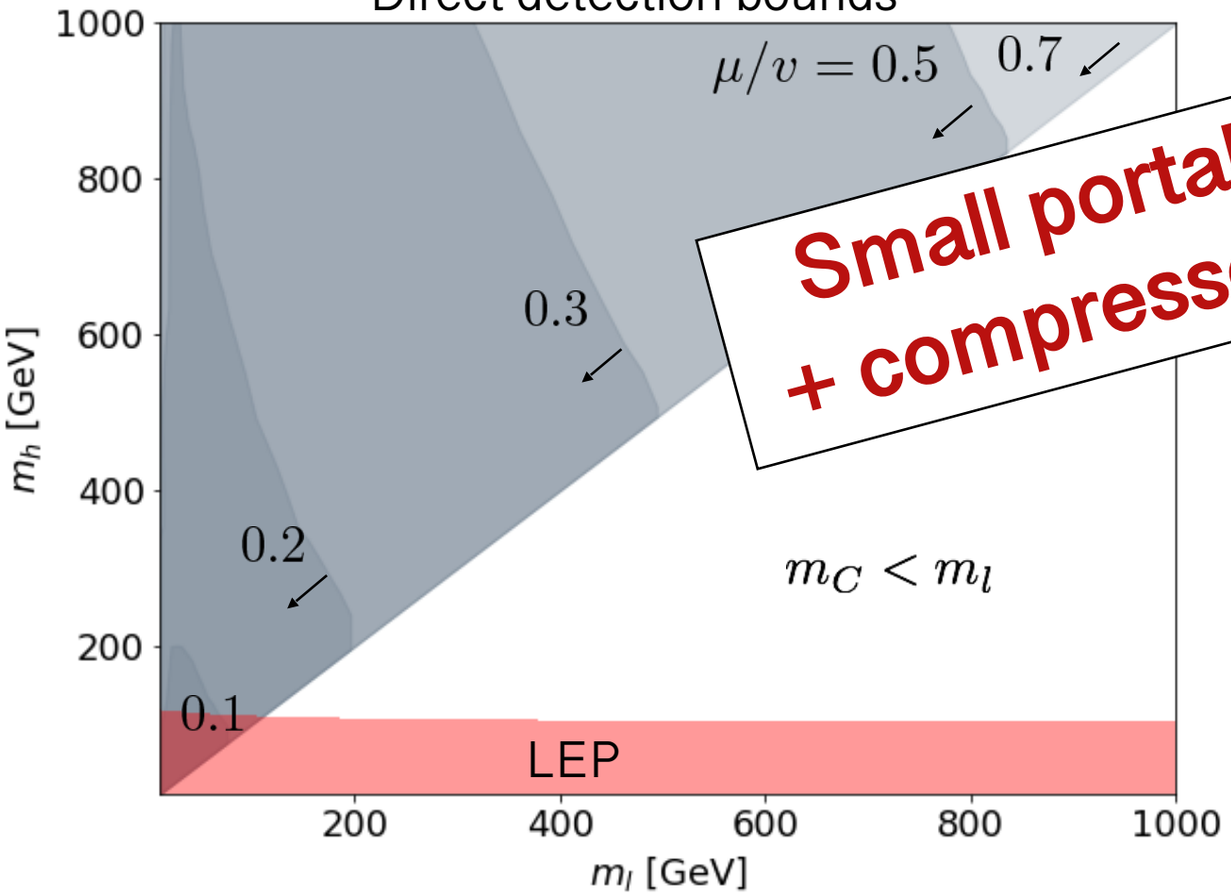
χ_h — χ^+

$$(\Delta m_{hc})^{\rm mix} \simeq \mu \sin(2\theta)/2$$

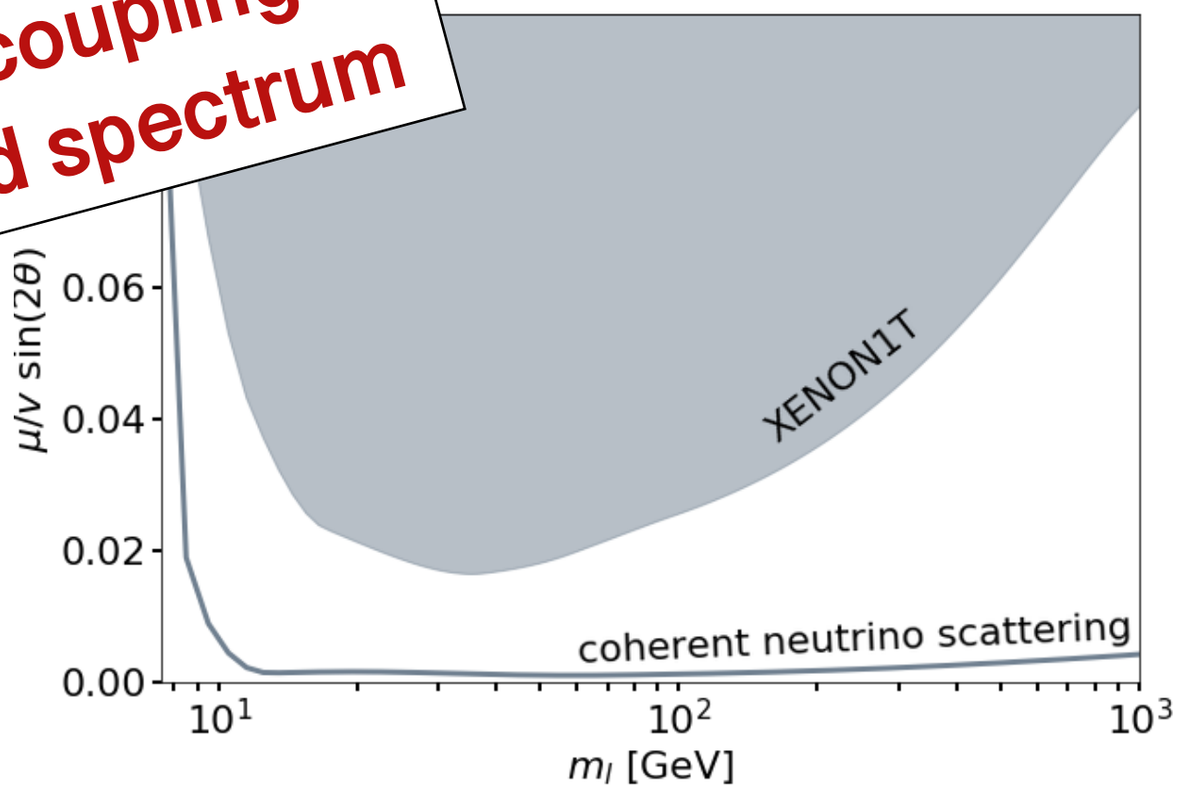
[1805.12562]



Direct detection bounds

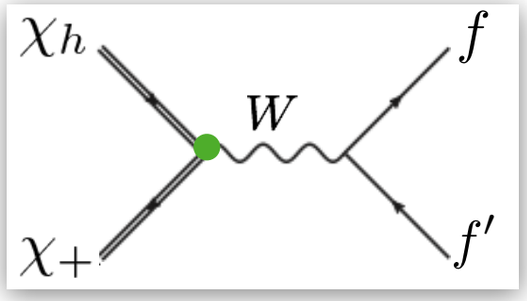


Small portal couplings + compressed spectrum

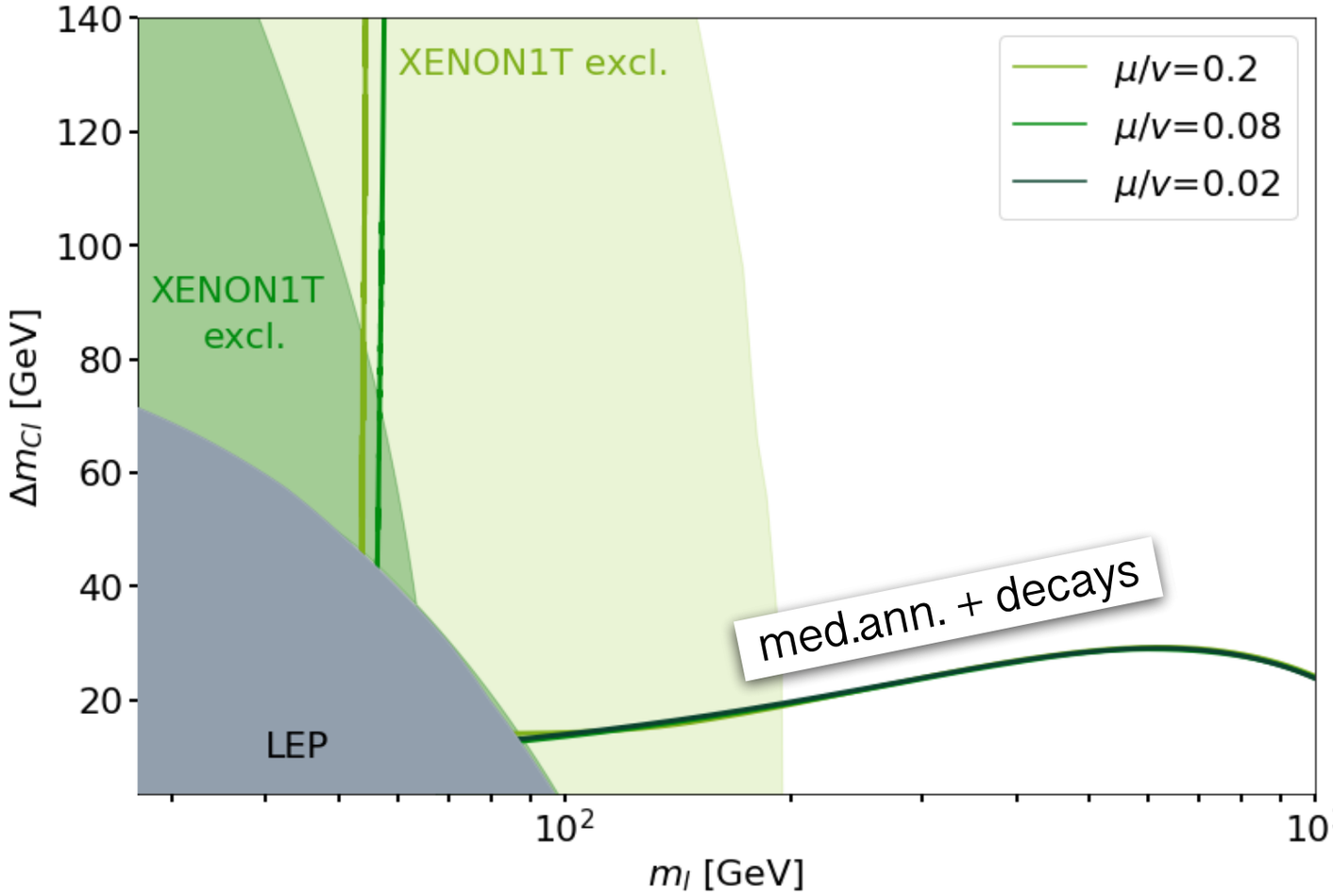


Surviving regions: pseudoscalar case

Mediator annihilation + further decays to χ_l



$(g\cos\theta)^2$



χ^+
χ_l $15 - 30$ GeV

Lines: $\Omega_\psi h^2 = 0.1199 \pm 0.0022$ [Planck coll., 1502.01589]

Collider searches: details