Heidelberg University

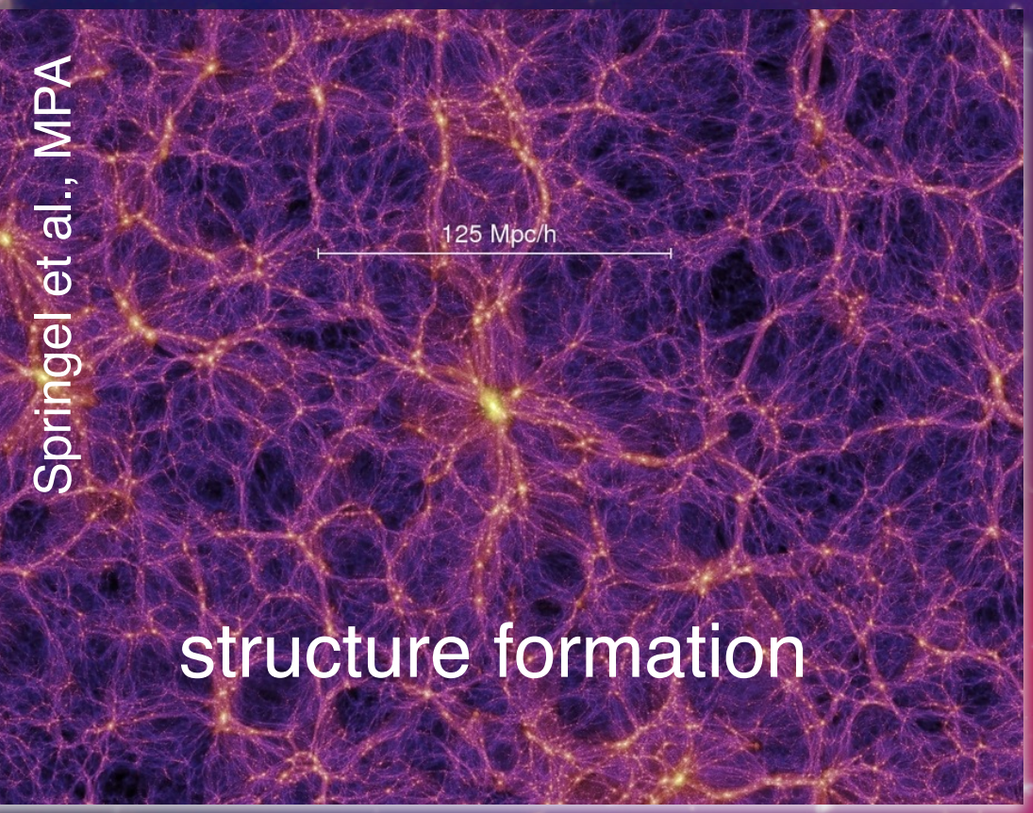
Carl Zeiss Foundation

DARK MATTER FROM LONG-LIVED PARTICLES

Susanne Westhoff

Seminar at MPIK Heidelberg — April 29, 2019

DARK MATTER IS REAL



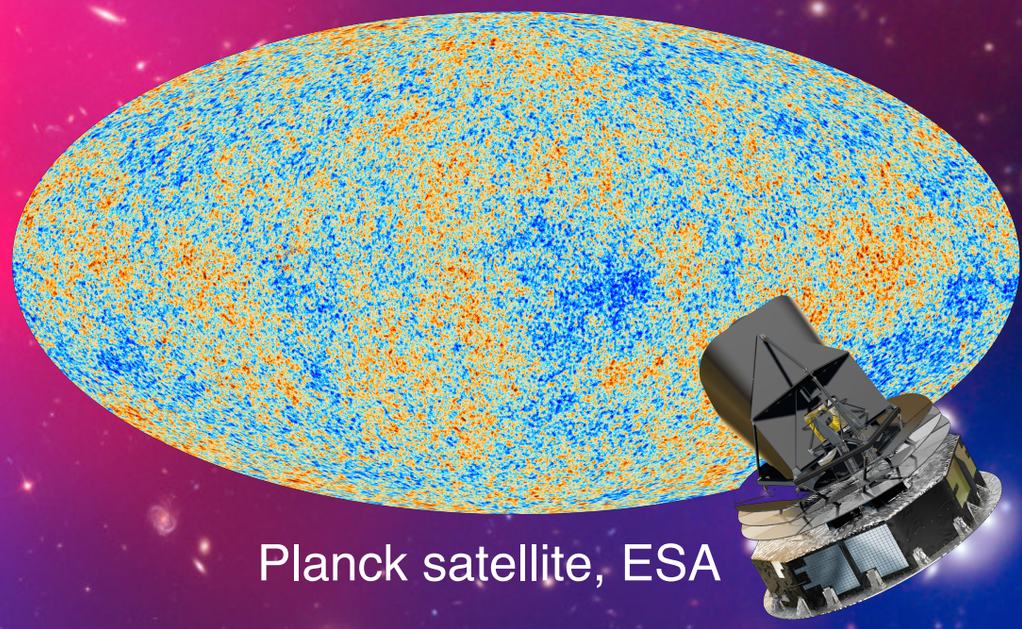
Springel et al., MPA

structure formation

galaxy clusters

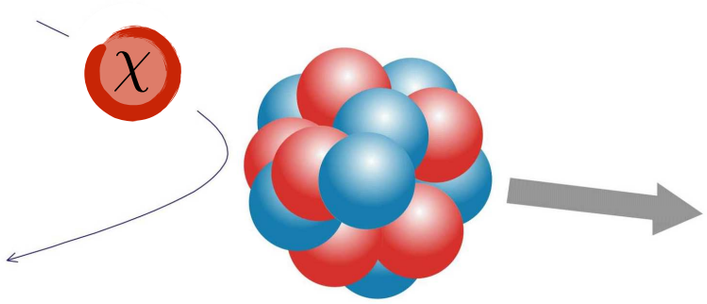
Mertens et al. 2011, Abell 2744

cosmic microwave background



Planck satellite, ESA

MESSAGE FROM DIRECT SEARCHES



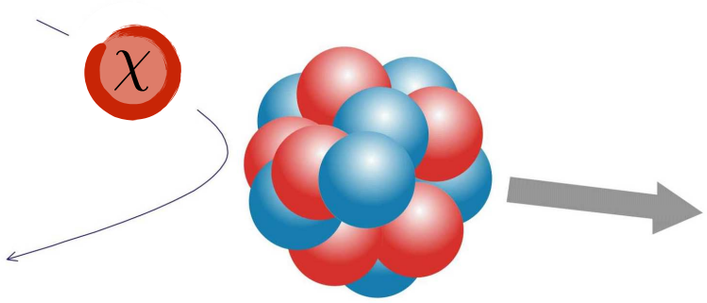
electrons

photons

phonons

Xenon experiment

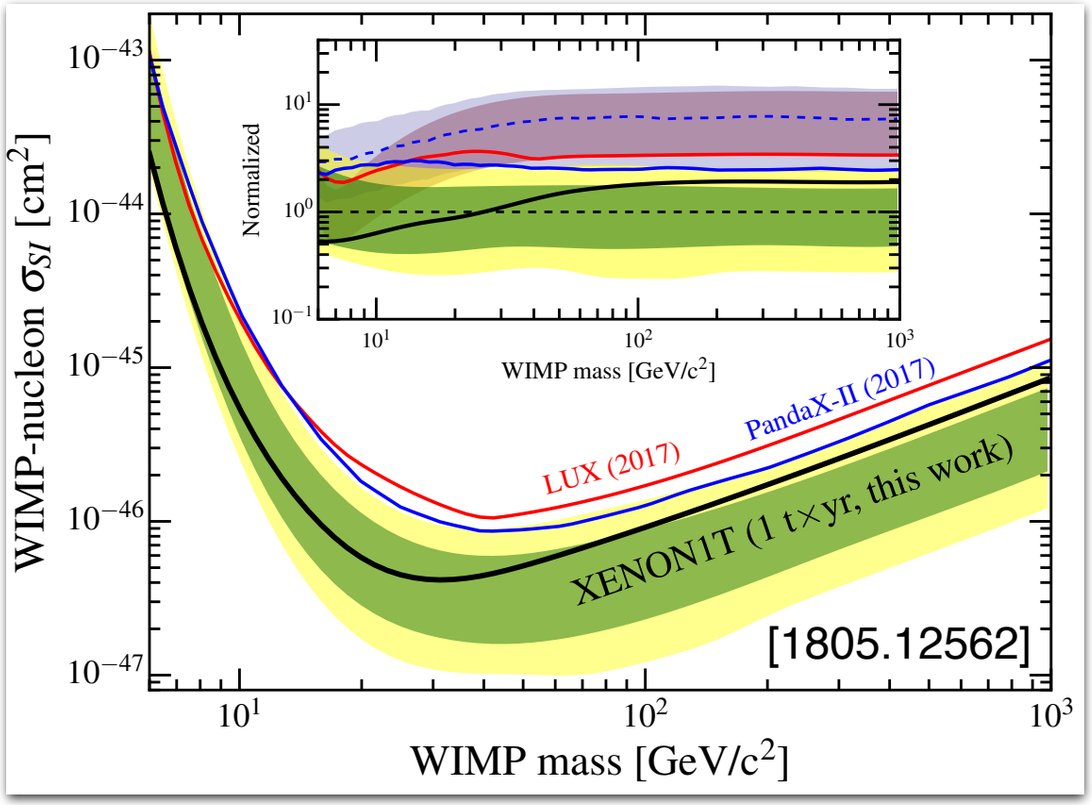
MESSAGE FROM DIRECT SEARCHES



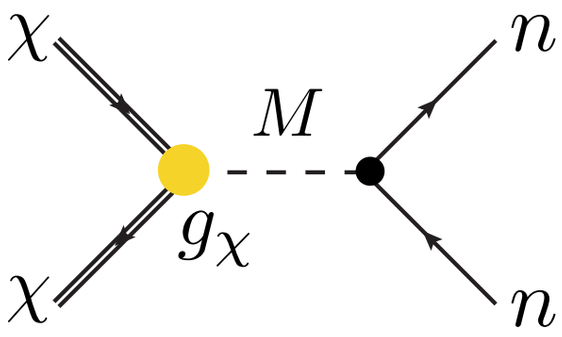
electrons

photons

phonons



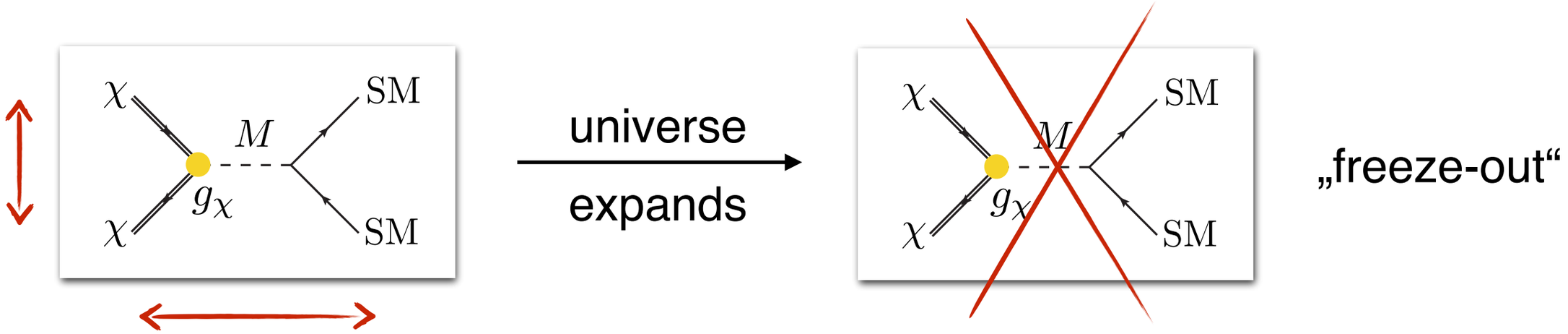
mediator M: Higgs, Z, NP



$$m_\chi \gtrsim 10\,\mathrm{GeV}: \quad \frac{g_\chi}{M} \ll \frac{1}{100\,\mathrm{GeV}}$$

Dark matter might couple very weakly to nucleons.

DARK MATTER ABUNDANCE



„freeze-out“

Relic abundance of thermal WIMP:

$$\Omega_\chi h^2 \approx \frac{330\,\mathrm{fb}}{\langle\sigma v\rangle} \approx 0.1 \left(\frac{0.01}{g_\chi}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2$$

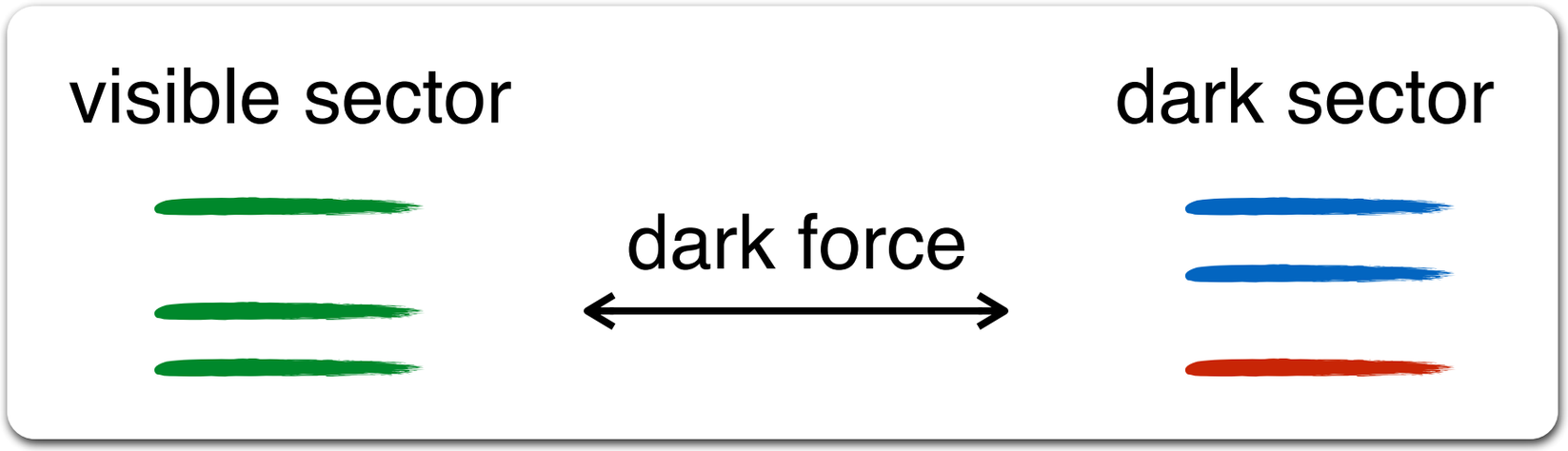
[cf. Planck, 1502.01589]

Direct detection (+ colliders): $g_\chi \ll g_w$

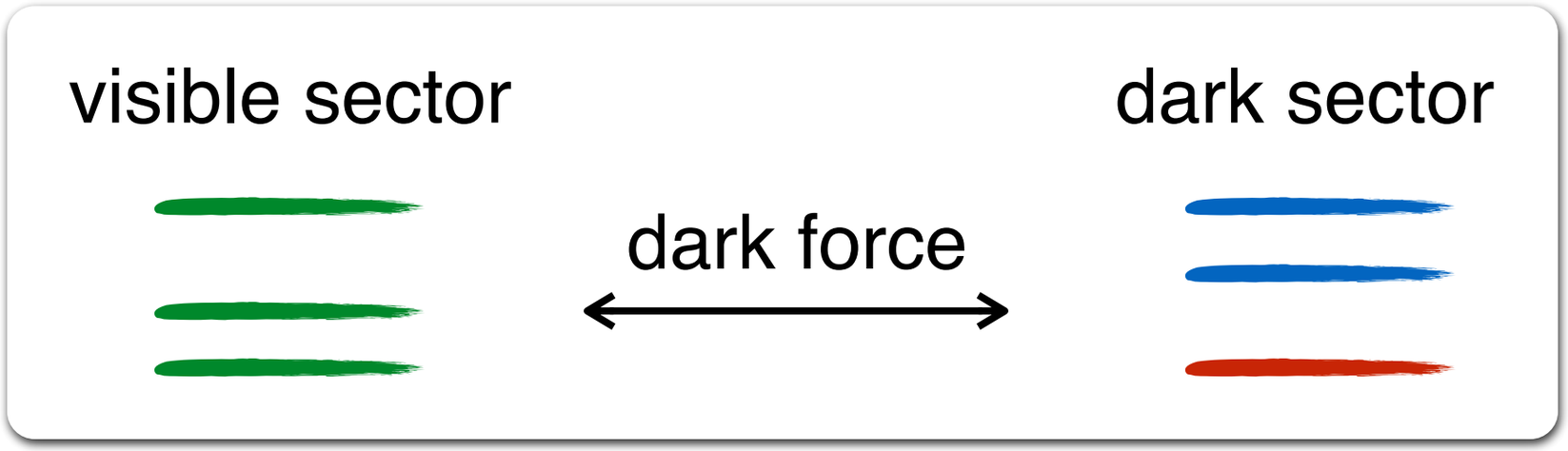
Thermal relics around the weak scale strongly constrained.

[see Arcadi et al., 1703.07364]

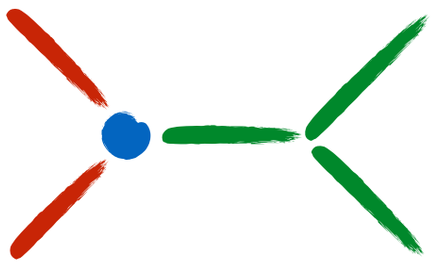
DARK SECTORS



DARK SECTORS



small dark couplings

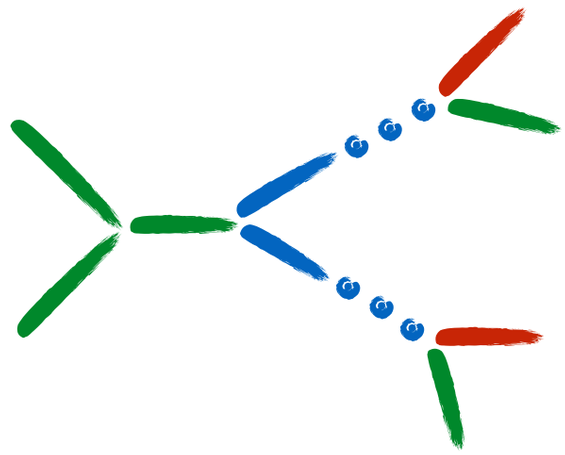


(no) direct detection

relic

abundance

long-lived mediators



LHC (+ annex)

A HIGGS PORTAL EXAMPLE

Naturally small portal coupling

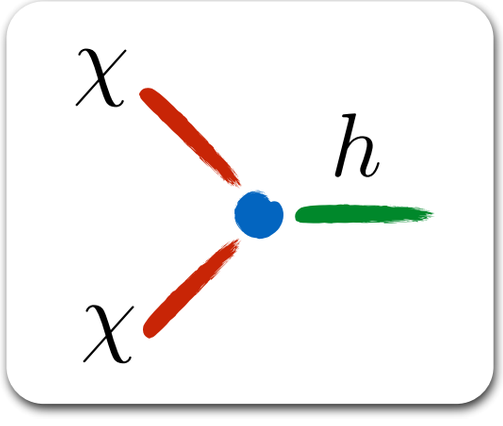
$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2}\overline{\chi}_S\chi S - \frac{m_T}{2}\overline{\chi}_T\chi_T + \frac{\kappa}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + \overline{\chi}_S(H^\dagger\chi_T H)\right]$$

Mixing via ew. symmetry breaking

$$\theta \sim \frac{\mu}{m_T - m_S} \quad \text{with} \quad \mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$$

Mass eigenstates

$$\chi_\ell^0 = \cos\theta\,\chi_S^0 - \sin\theta\,\chi_T^0$$
$$\chi_h^0 = \sin\theta\,\chi_S^0 + \cos\theta\,\chi_T^0$$
$$\chi^+,\ \chi^-$$



[Filimonova, SW, 1812.04628] [Bharucha et al., 1804.02357]
[similar to SUSY neutralinos, see Bramante et al., 1510.03460]

A HIGGS PORTAL EXAMPLE

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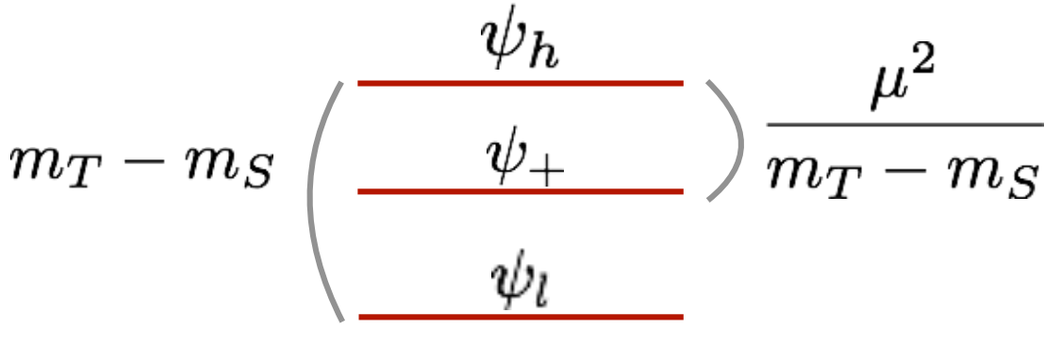
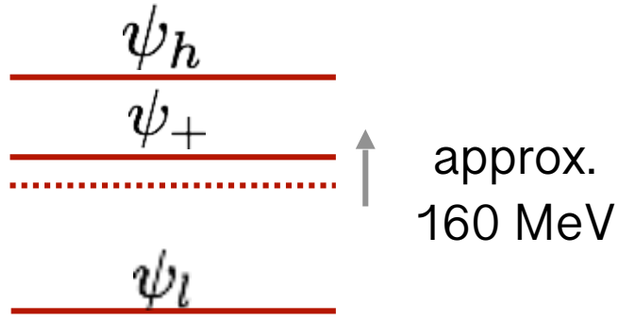
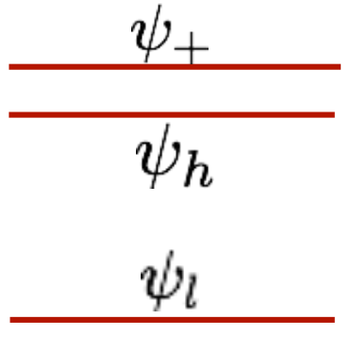
Tree-level structure:



Electroweak splitting:



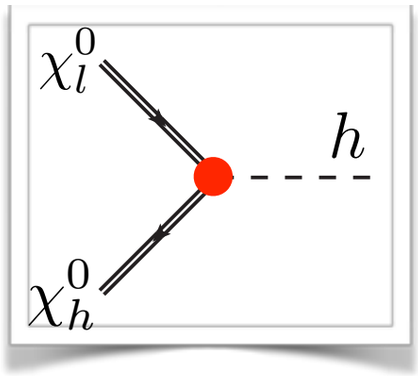
Small μ :

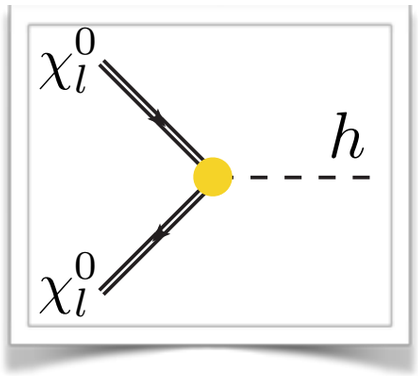


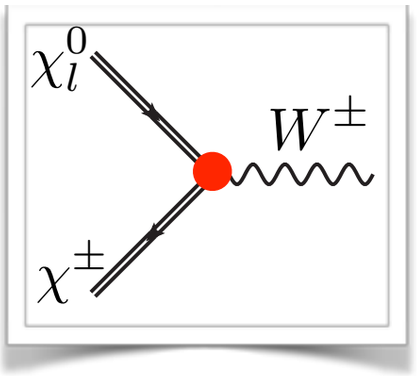
DARK MATTER INTERACTIONS

scalar:

$m_S > \mu^2/m_T$ $\quad \frac{\mu}{v}\cos(2\theta)$ $\quad \frac{\mu}{v}\sin(2\theta)$ $\quad g\sin\theta\,\gamma_\mu$







pseudo-scalar:

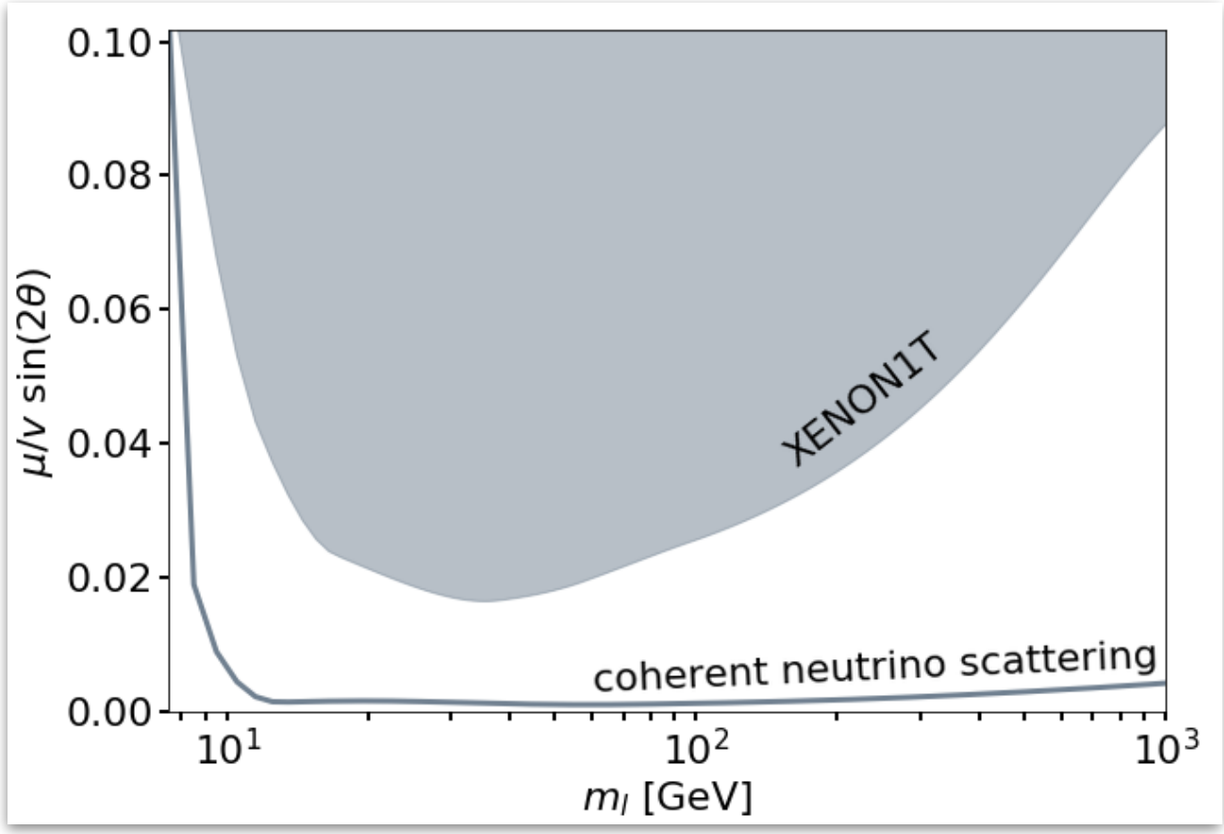
$m_S < \mu^2/m_T$ $\quad \frac{\mu}{v}\cos(2\theta)\,i\gamma_5$ $\quad \frac{\mu}{v}\sin(2\theta)$ $\quad g\sin\theta\,i\gamma_\mu\gamma_5$

related by chiral rotation: $\chi_\ell^0 \to i\gamma_5\chi_\ell^0$

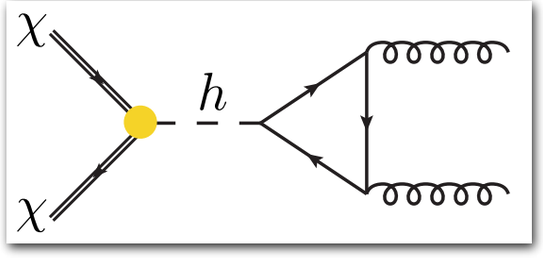
implies mass flip $m_\ell \to -m_\ell$

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

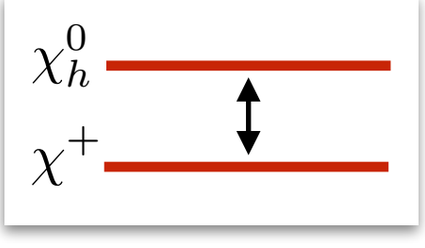
NUCLEON SCATTERING



Weak dark matter interactions. $\frac{\mu}{v}\sin(2\theta)$



Compressed spectrum. $m_h - m_c \approx \mu \sin(2\theta)/2$

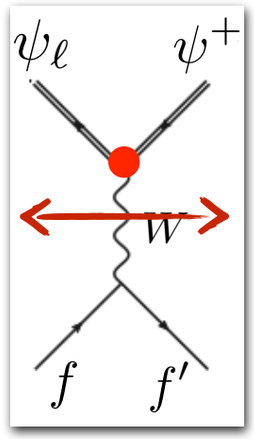


THERMAL FREEZE-OUT

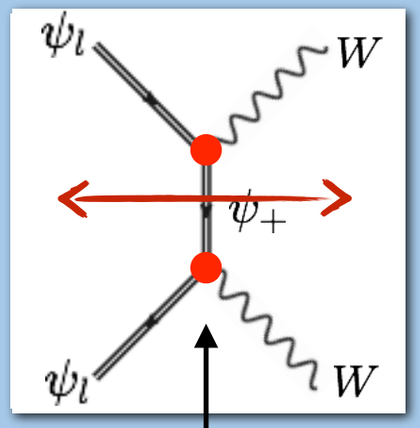
Initially: kinetic and chemical equilibrium

number density

$$n_\chi \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$$
$$n_f \sim T^3$$



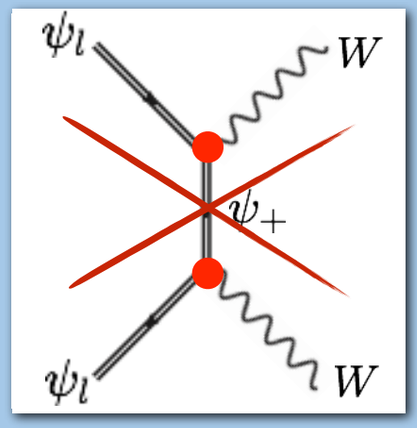
$n_\chi \langle \sigma_A v \rangle > H$



universe

expands

$n_\chi \langle \sigma_A v \rangle < H$



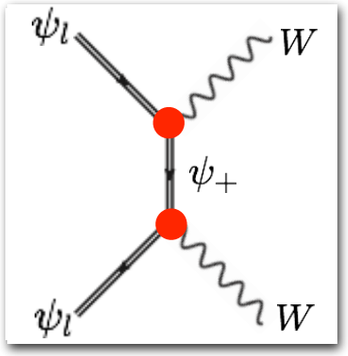
„freeze-out“

$$\sin\theta \sim \frac{\mu}{m_T - m_S}$$

Pair annihilation is suppressed for small fermion mixing.

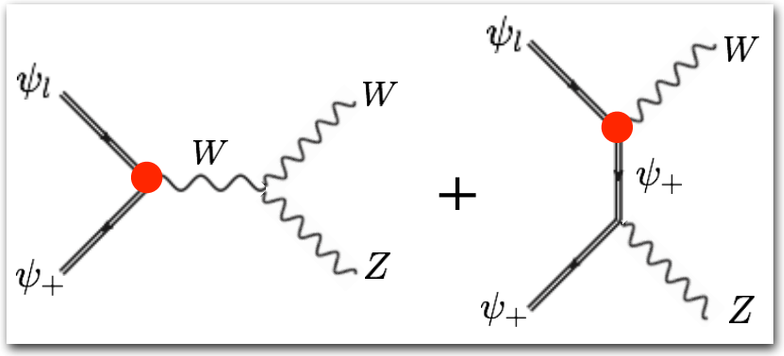
RELIC ABUNDANCE

pair annihilation

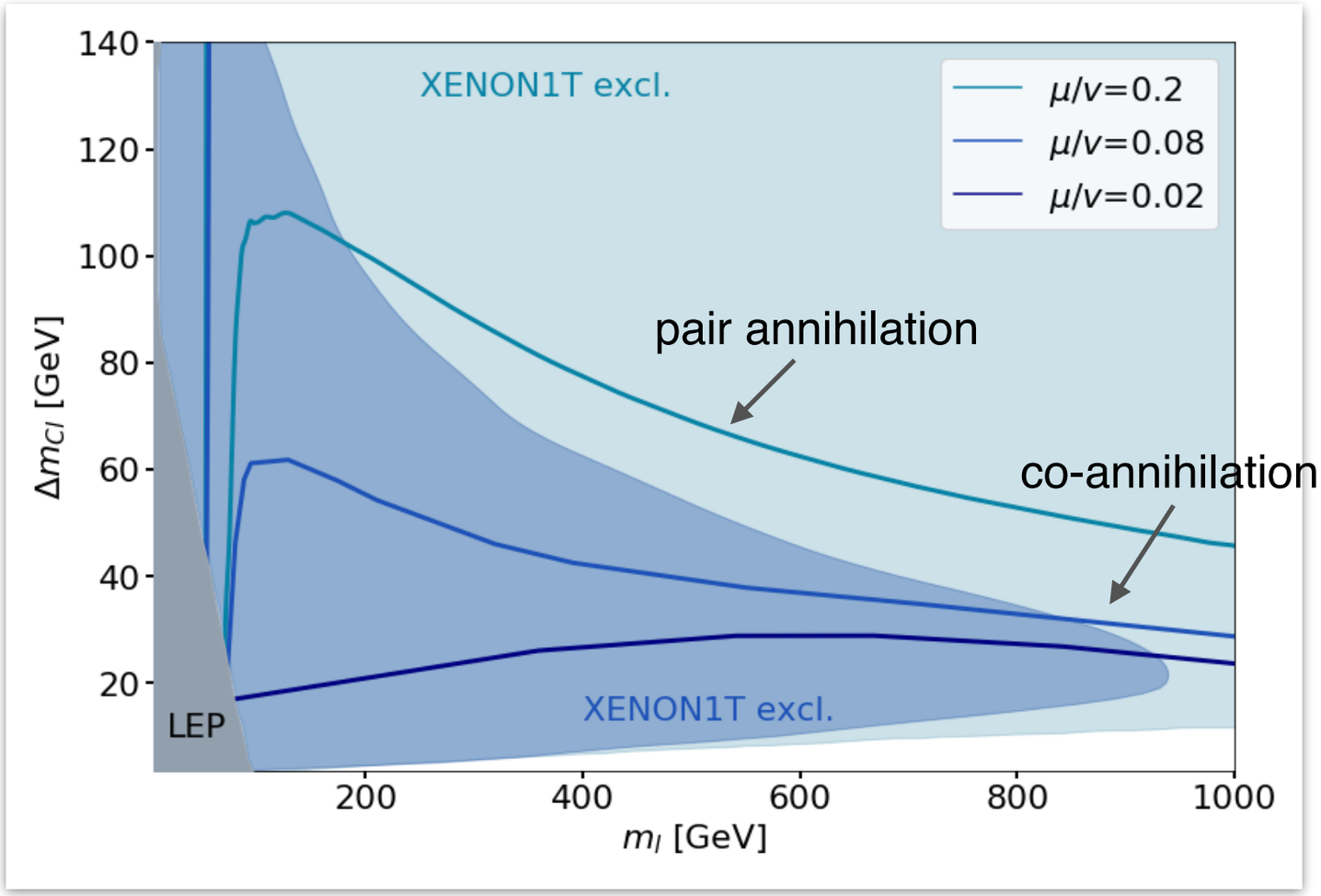


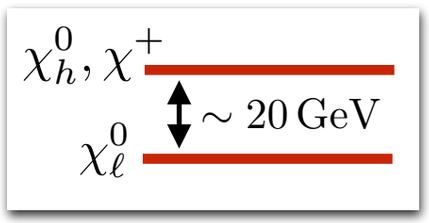
$(g \sin\theta)^2$

co-annihilation



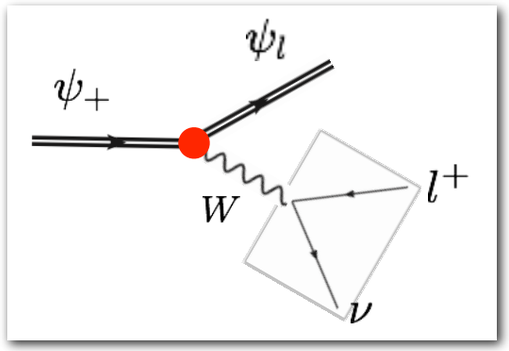
$g \sin\theta$





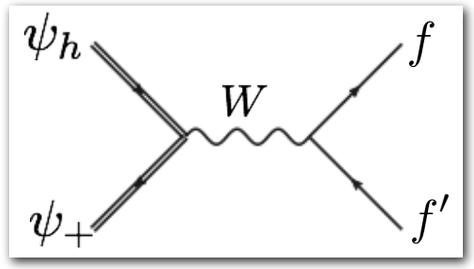
DECOUPLING THE DARK SECTOR

inverse decay

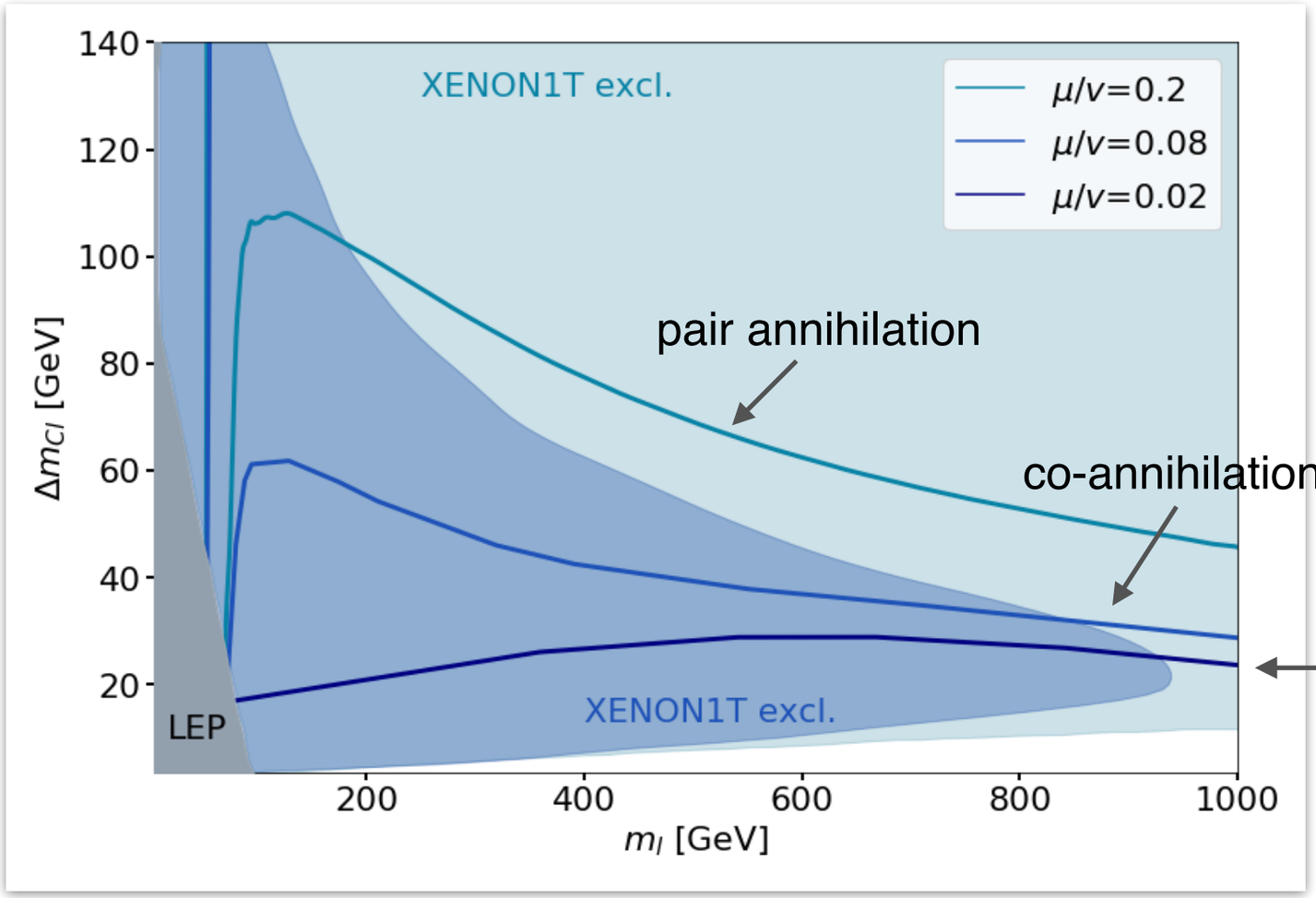


$g \sin\theta$

mediator annihilation



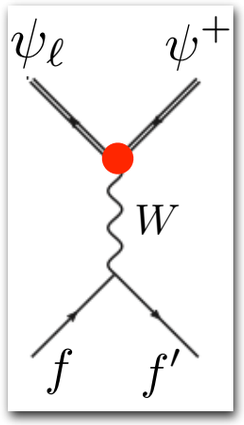
$g \cos\theta$



LEAVING CHEMICAL EQUILIBRIUM

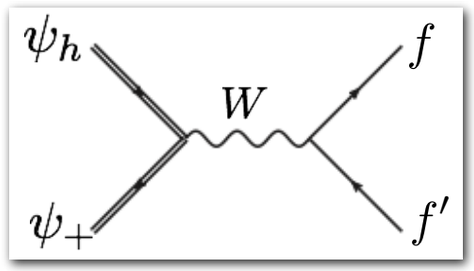
co-scattering

$$\Gamma_{\chi^+} \frac{n_{\chi^+}}{n_{\chi_\ell}} < H :$$

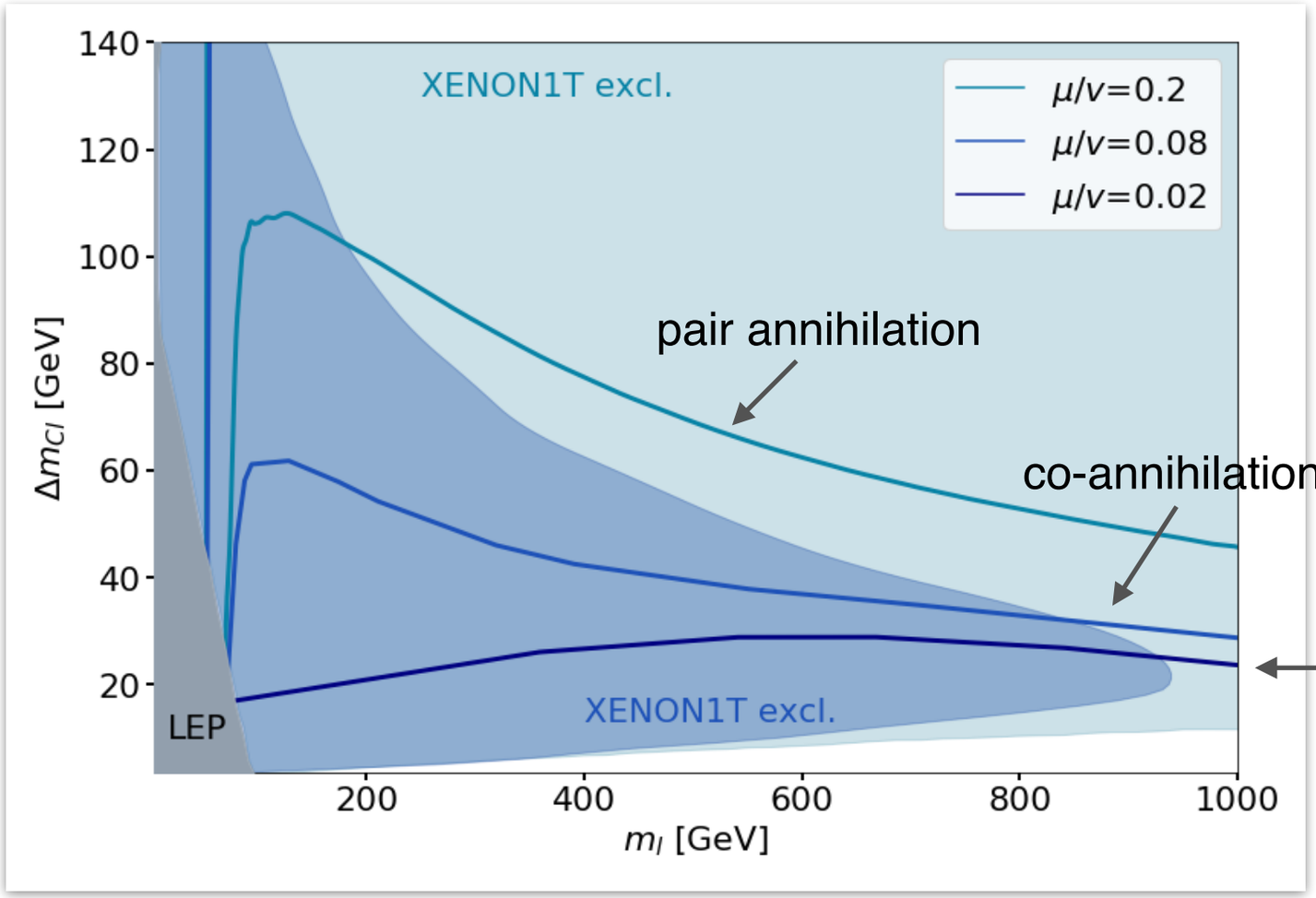


$g \sin\theta$

mediator annihilation

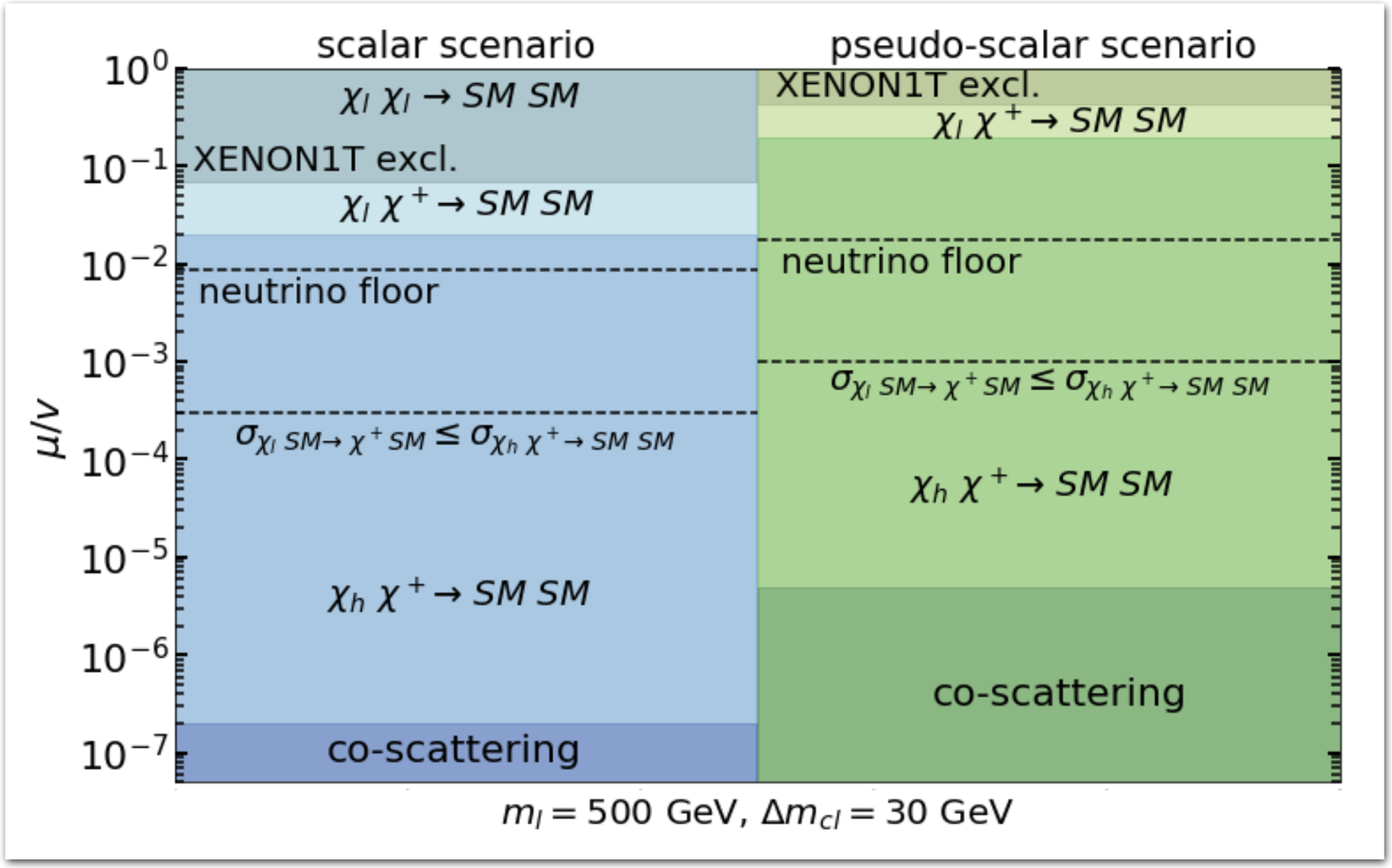


$g \cos\theta$



PHASES OF FREEZE-OUT

dark sector decouples



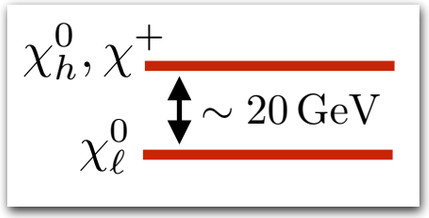
Dark sector features

- compressed spectrum
- tiny couplings to known particles

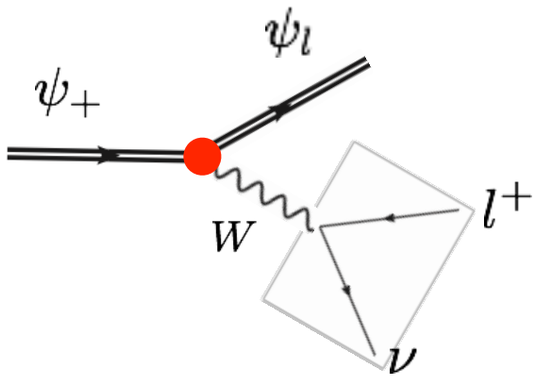
see also: [Garny et al., 1705.09292] [D'Agnolo et al., 1705.08450] [Junius et al., 1904.07513]

LONG-LIVED MEDIATORS

decay suppressed as $\Gamma_\chi \sim g_\chi^2 (\Delta m)^x$

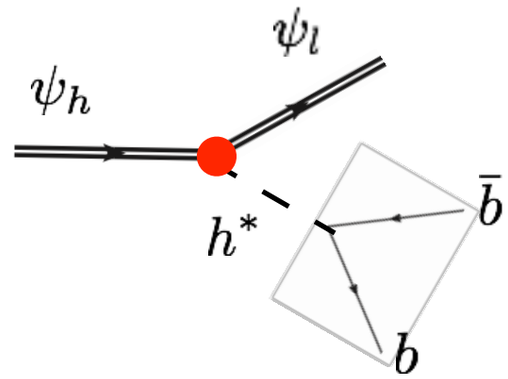


weak decays



$$\Gamma_c^S \sim \sin^2\theta\,(m_c - m_\ell)^5 > \Gamma_c^P$$

Higgs decays

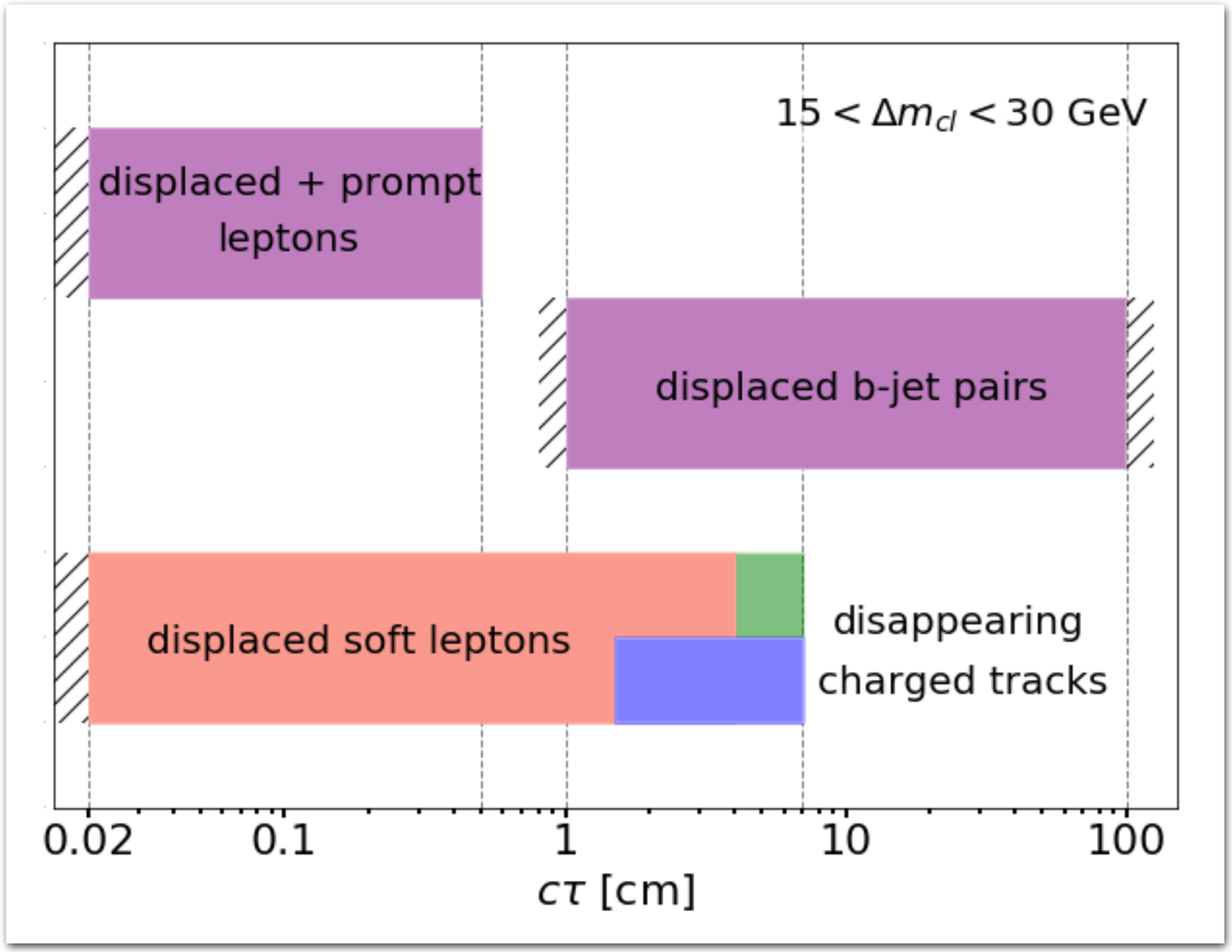


$$\Gamma_h^S \sim \frac{\mu^2}{v^2}\cos^2(2\theta)(m_h - m_\ell)^5 > \Gamma_h^P$$

$$\Gamma_h^P \sim (m_h - m'_\ell)^7$$ p-wave suppressed

Mediators in pseudo-scalar scenario live longer.

MEDIATOR DECAY LENGTH

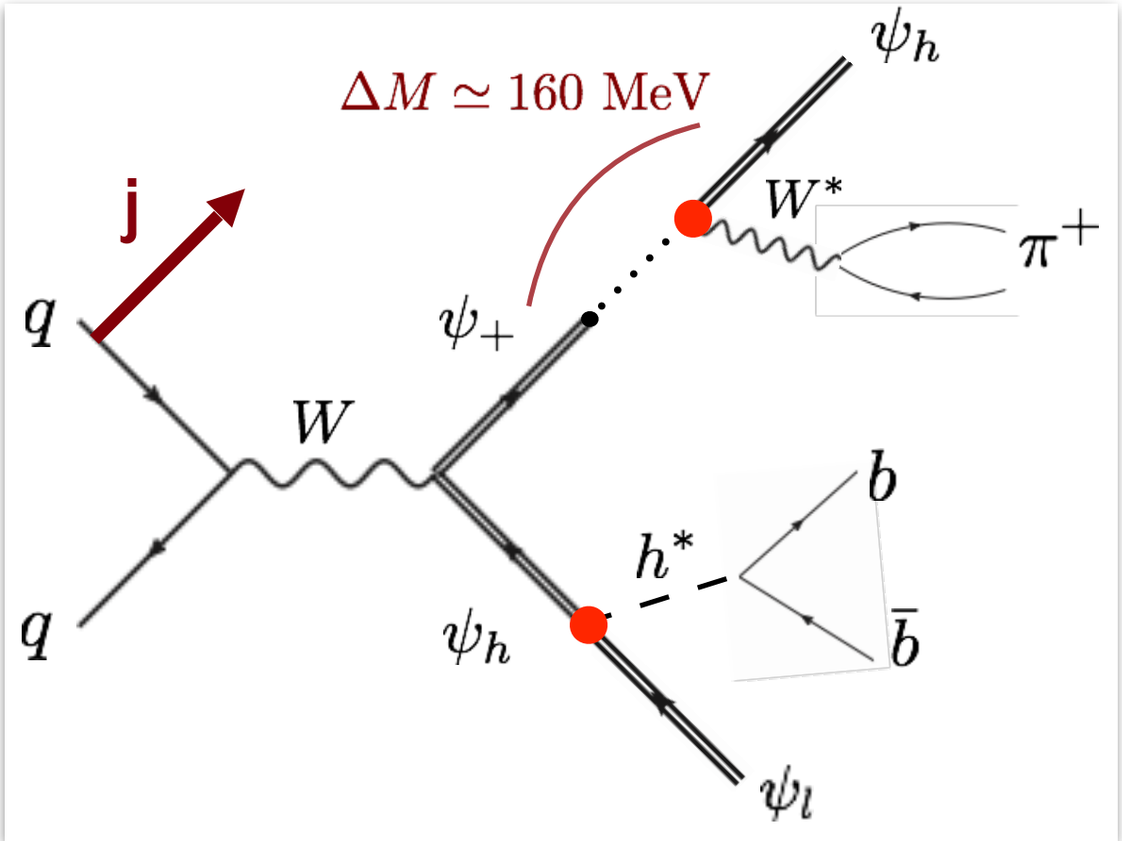


Mediators decay within the ATLAS and CMS detectors.

LHC SIGNATURES

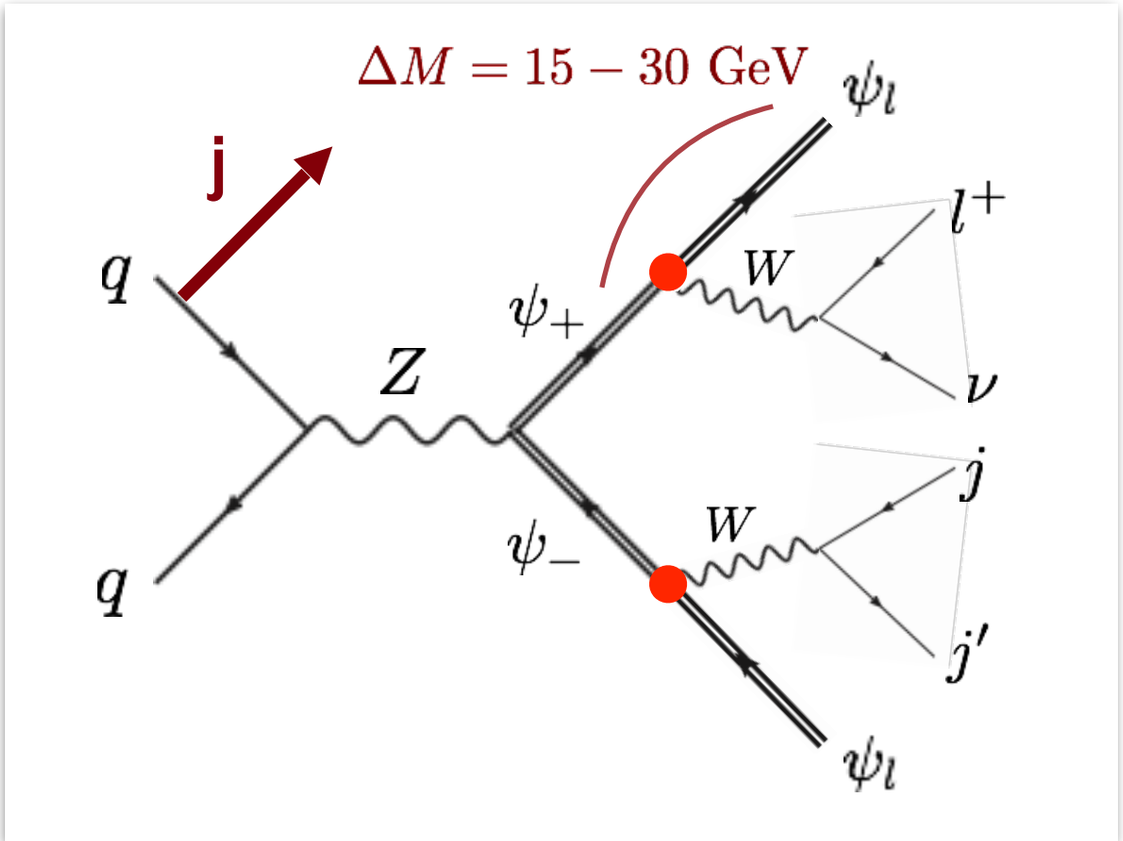
disappearing tracks

[Mahbubani et al., 1703.05327]



displaced b-jet pairs

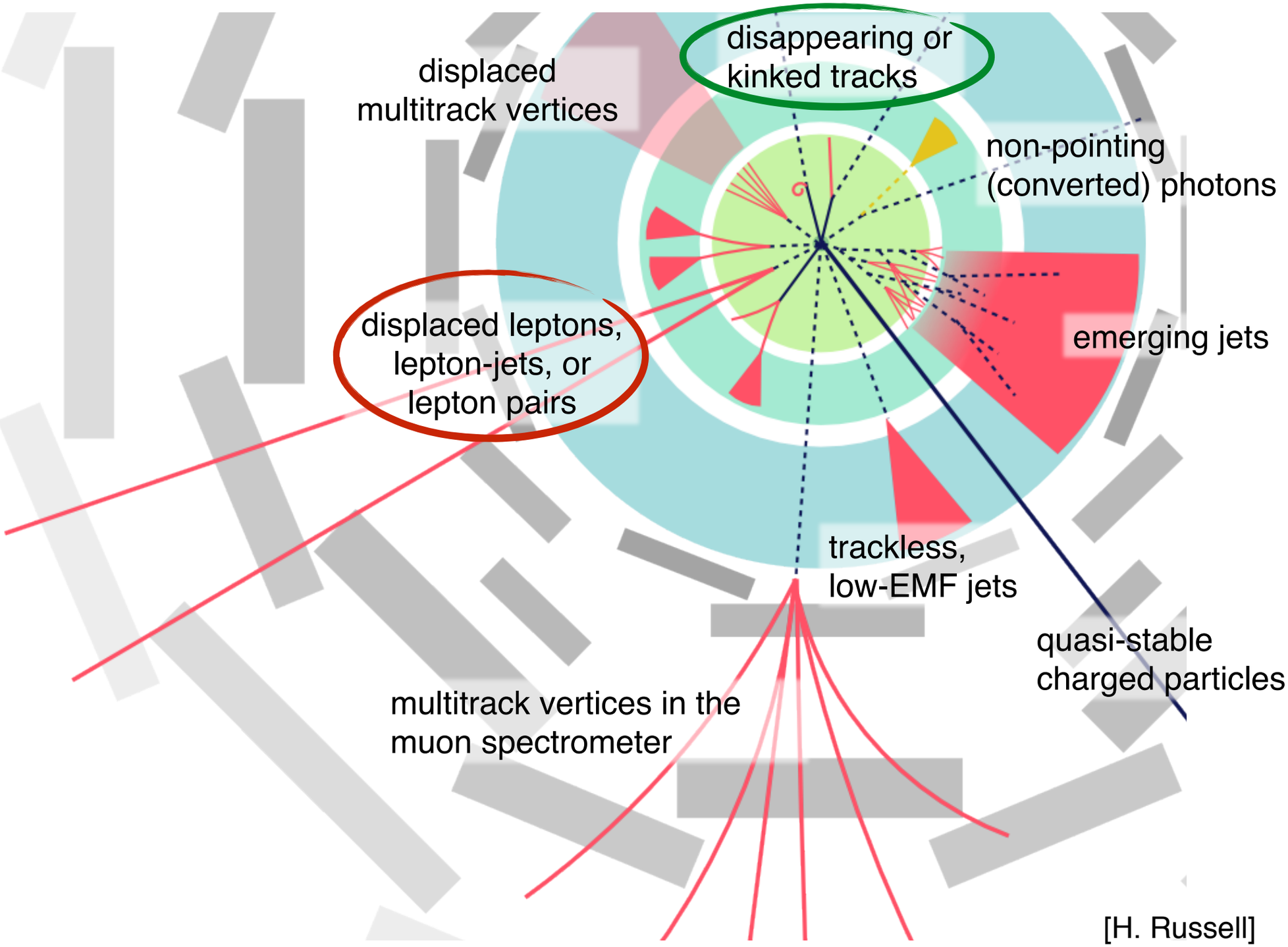
[Nagata, Otono, Shirai, 1506.08206]



displaced soft leptons/jets

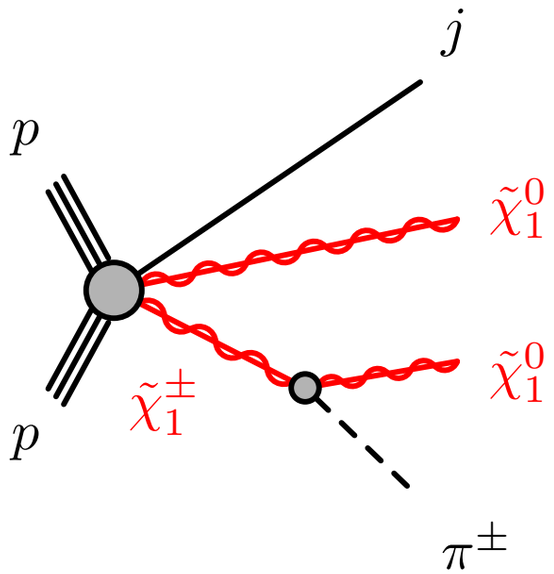
[Filimonova, SW, 1812.04628]

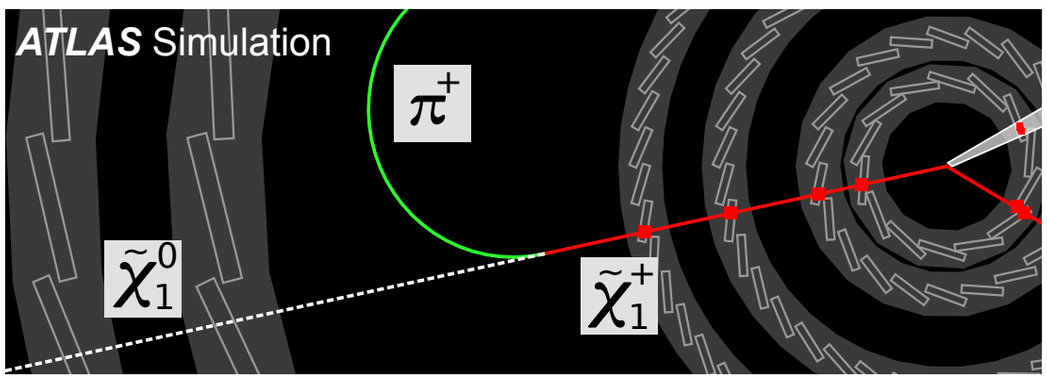
LONG-LIVED PARTICLE SEARCHES



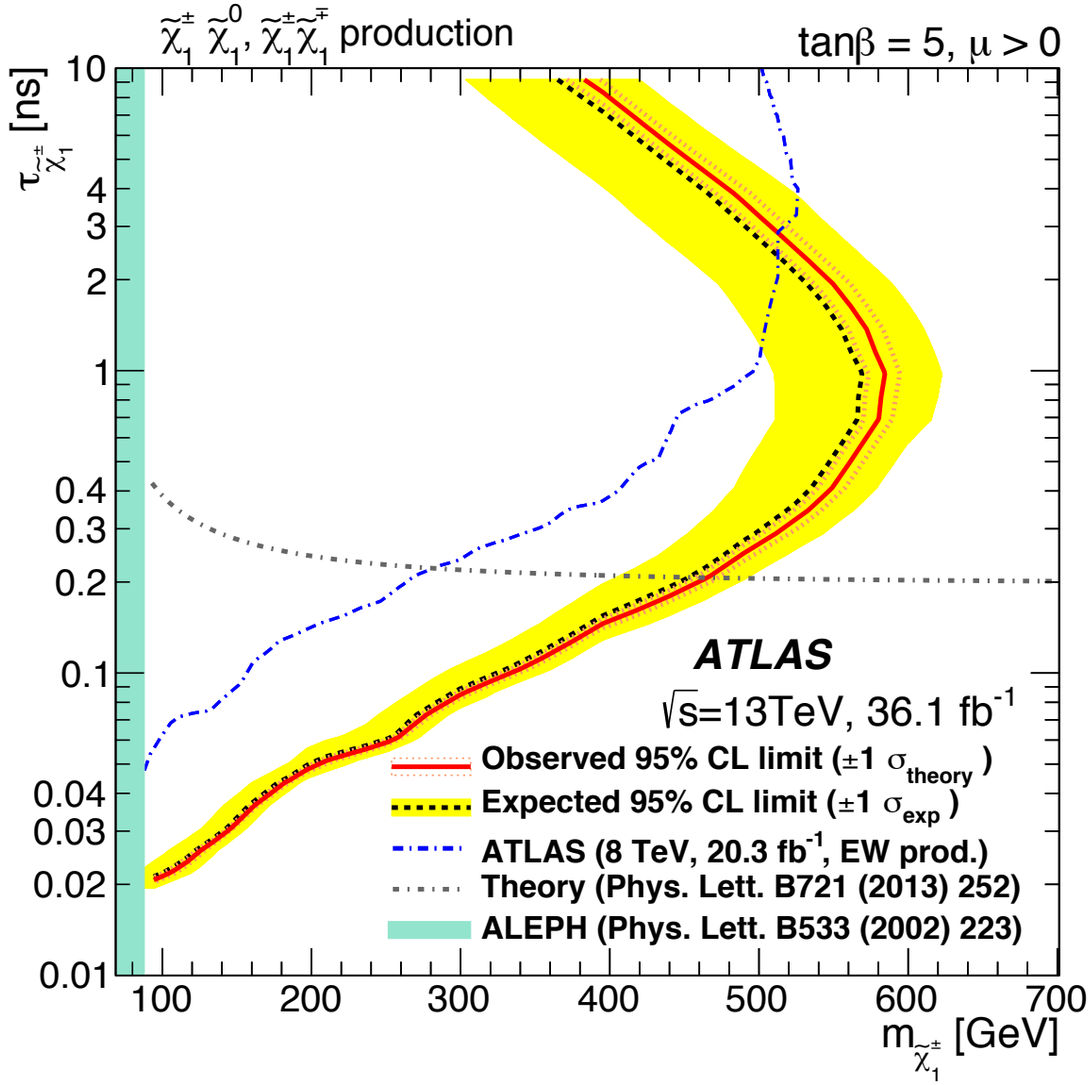
DISAPPEARING TRACKS

Long-lived charged mediators leave trace in pixel detector.



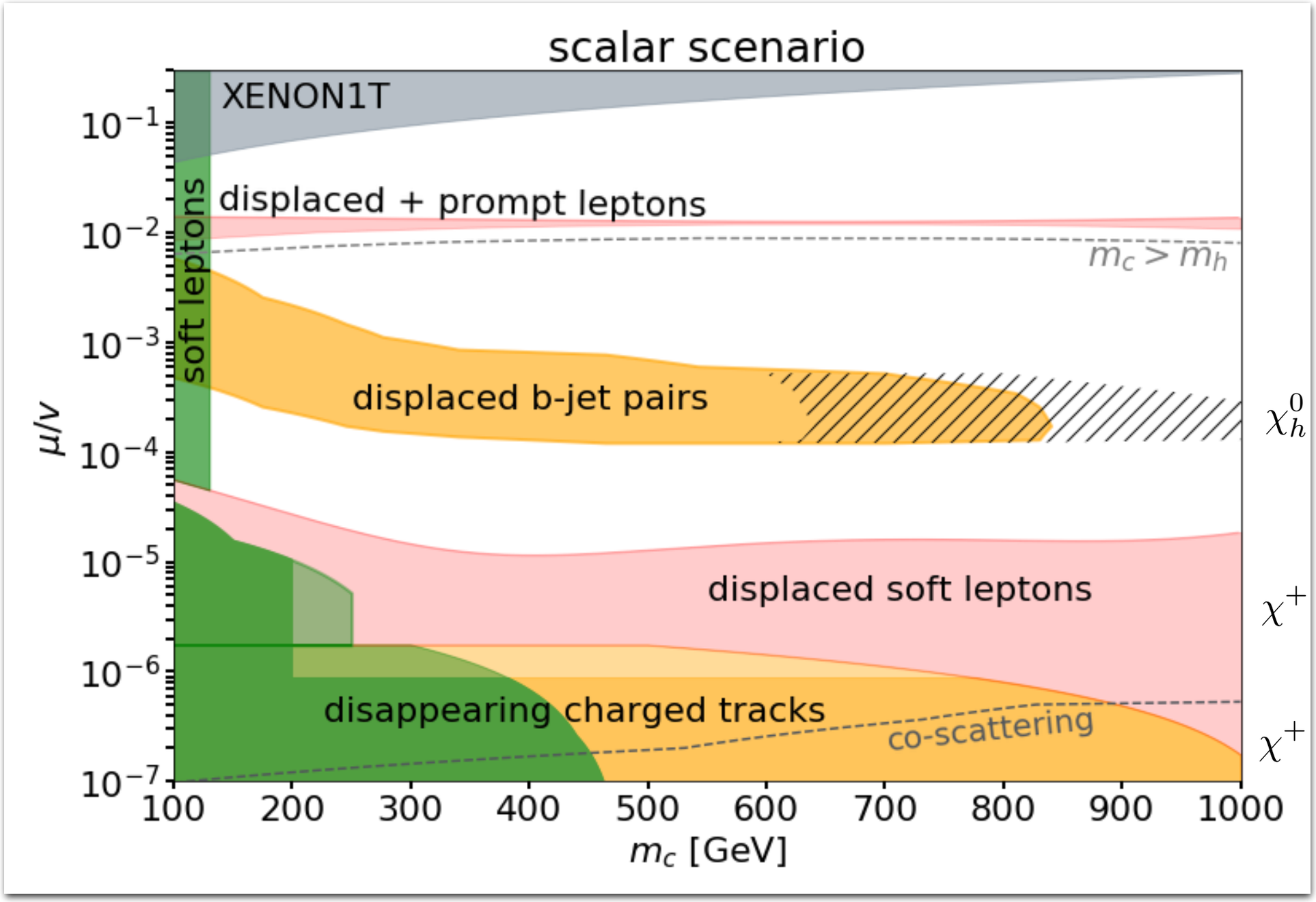


[ATLAS, 1712.02118]
[see also CMS, 1804.07321]

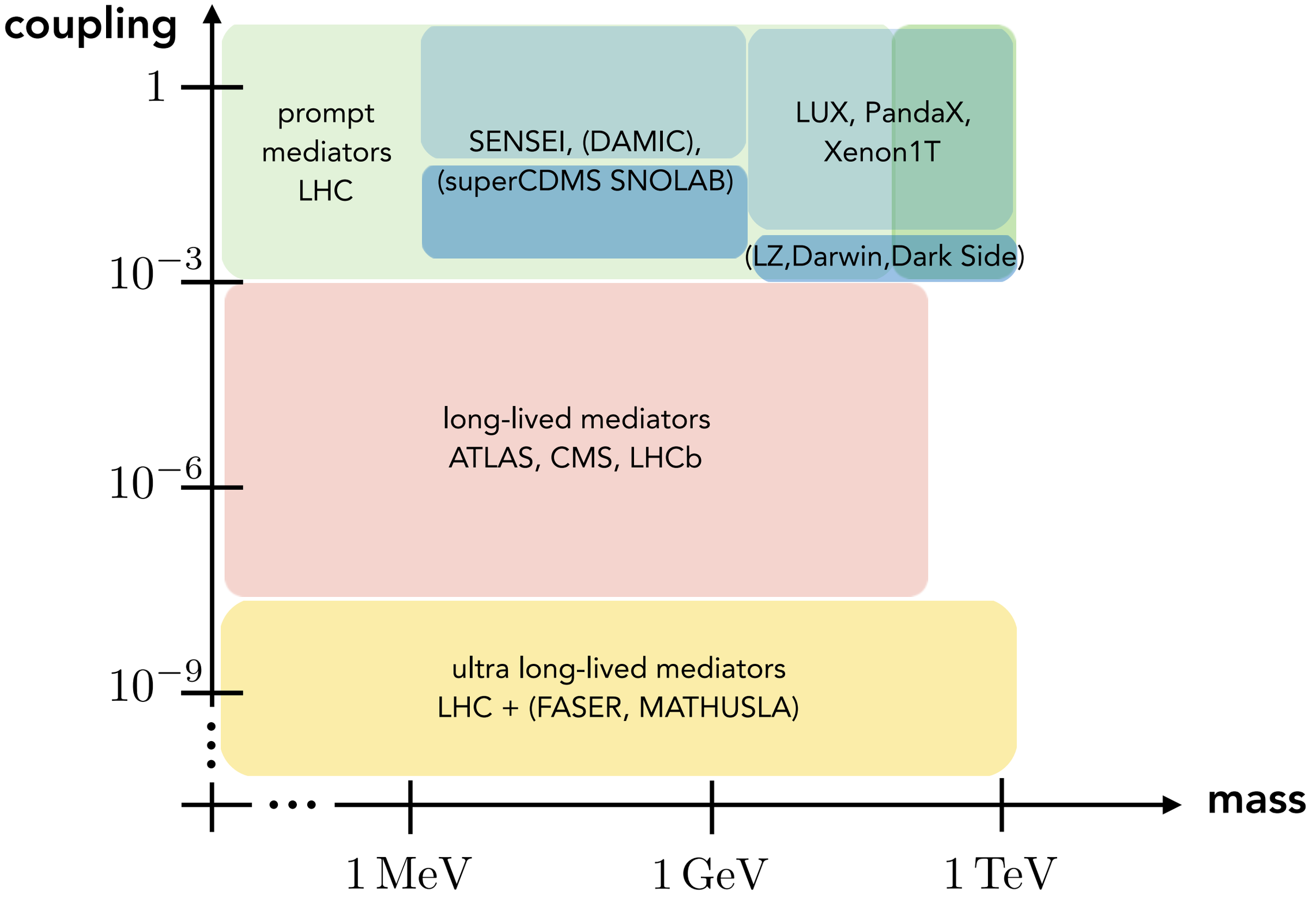


Probes mediator masses up to 600 GeV.

LHC PROBES TINY DARK COUPLINGS



TOWARDS A COMPLETE PICTURE



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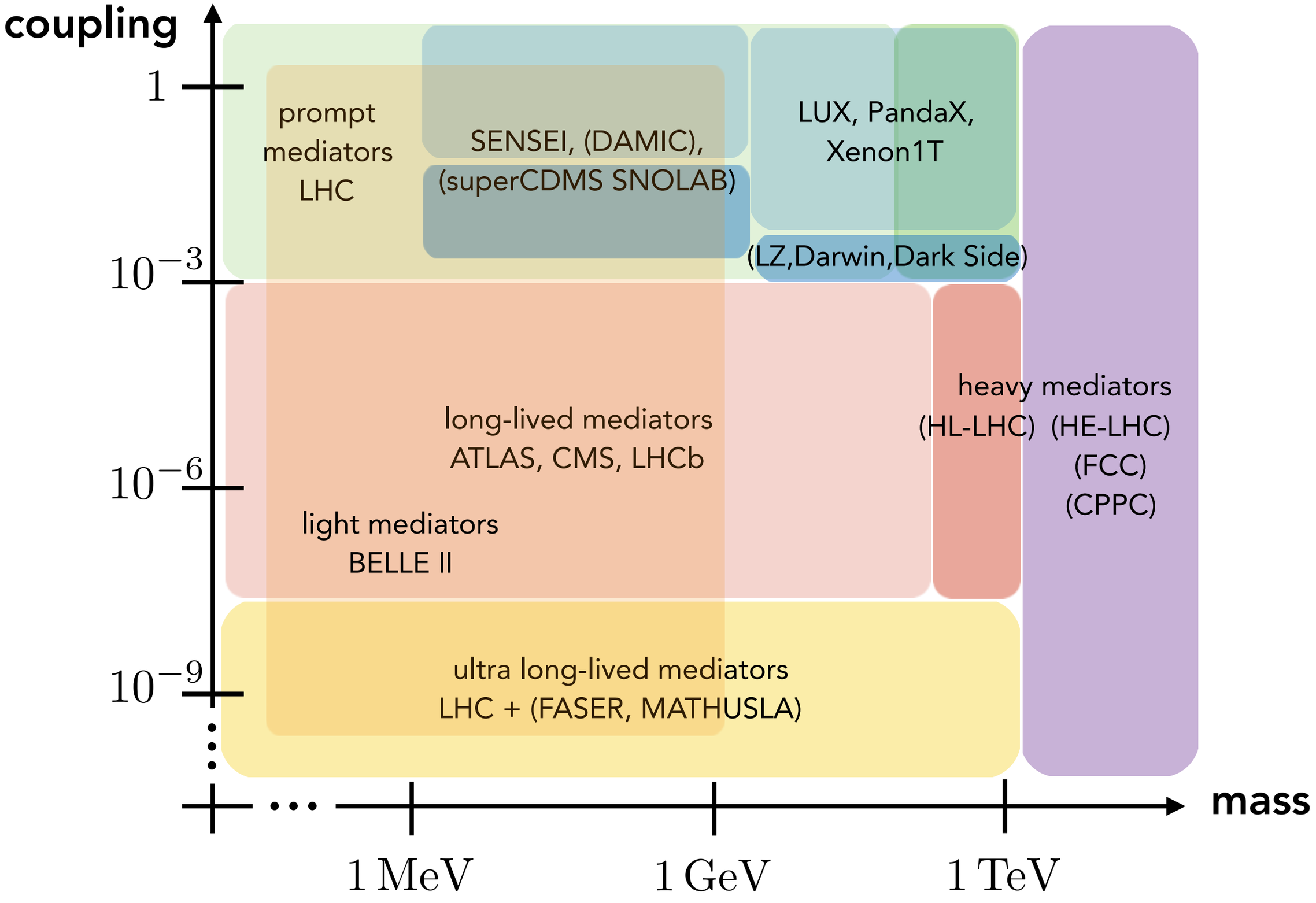
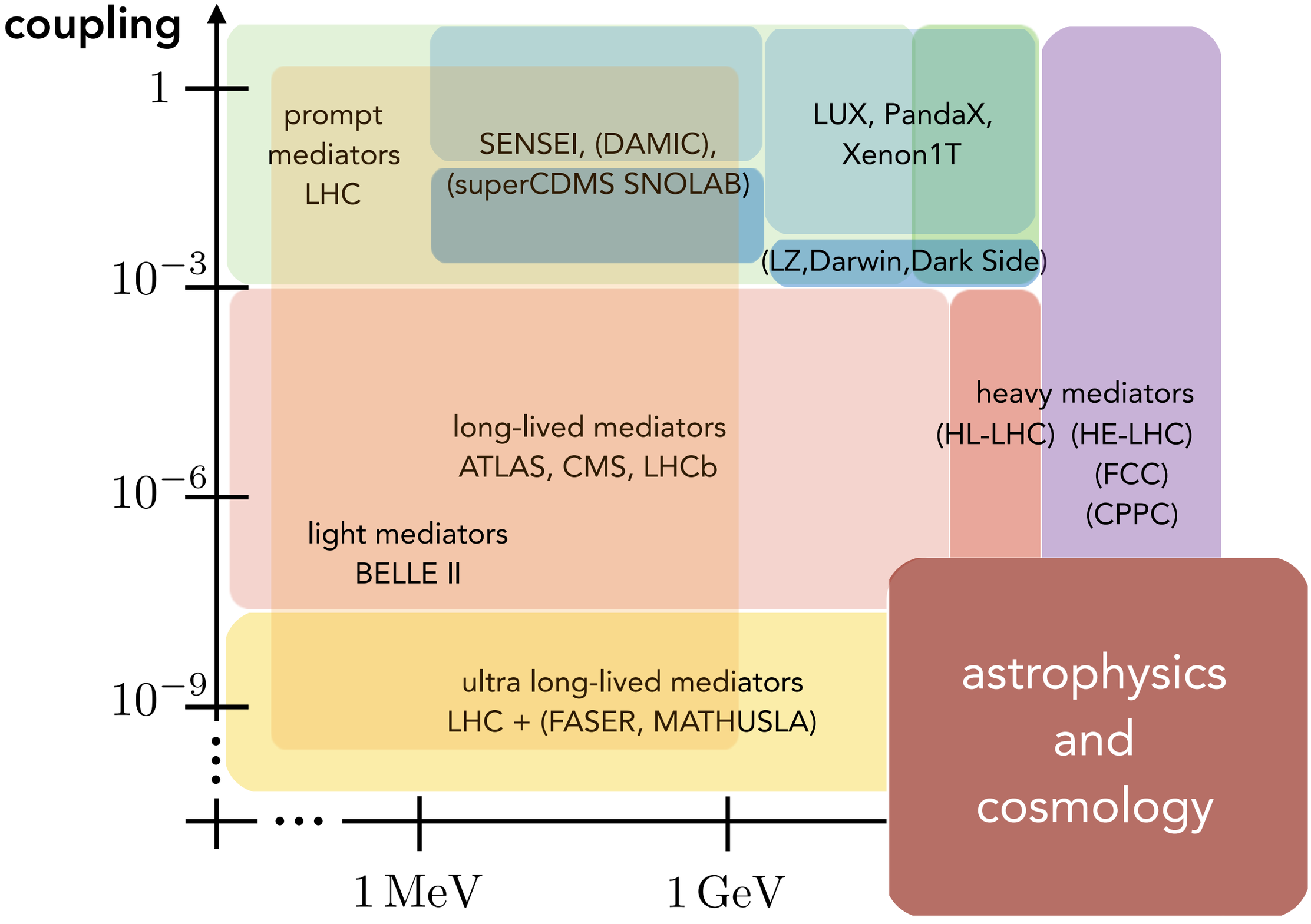
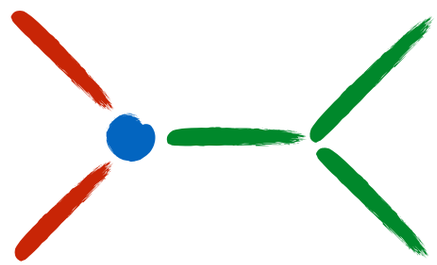


TOWARDS A COMPLETE PICTURE



CONCLUSION

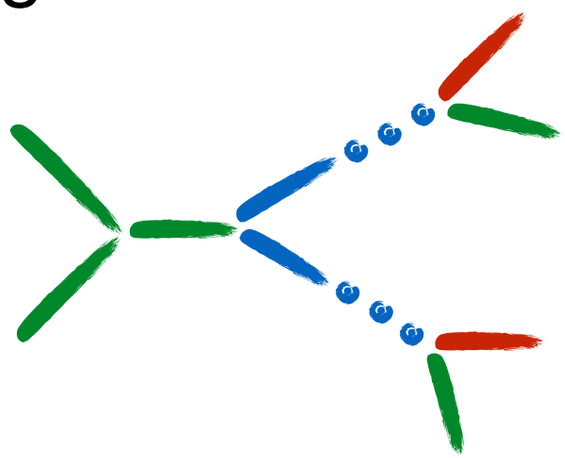
small dark couplings



thermal

relic

long-lived mediators



LHC observables:

- disappearing charged tracks
- displaced b-jet pairs
- displaced soft leptons