HIDDEN PHYSICS ◦ DARK MATTER

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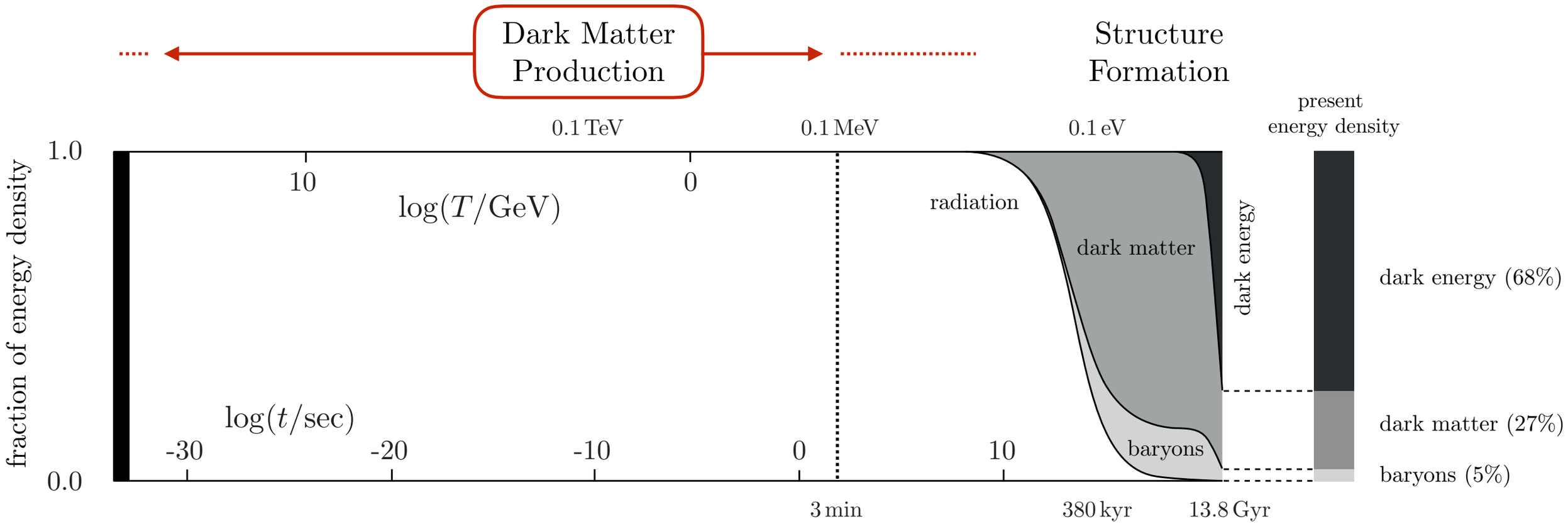
Hidden Physics at the LHC ◦ March 1-3, 2021 ◦ online

Hints from the early universe



freeze in

freeze out

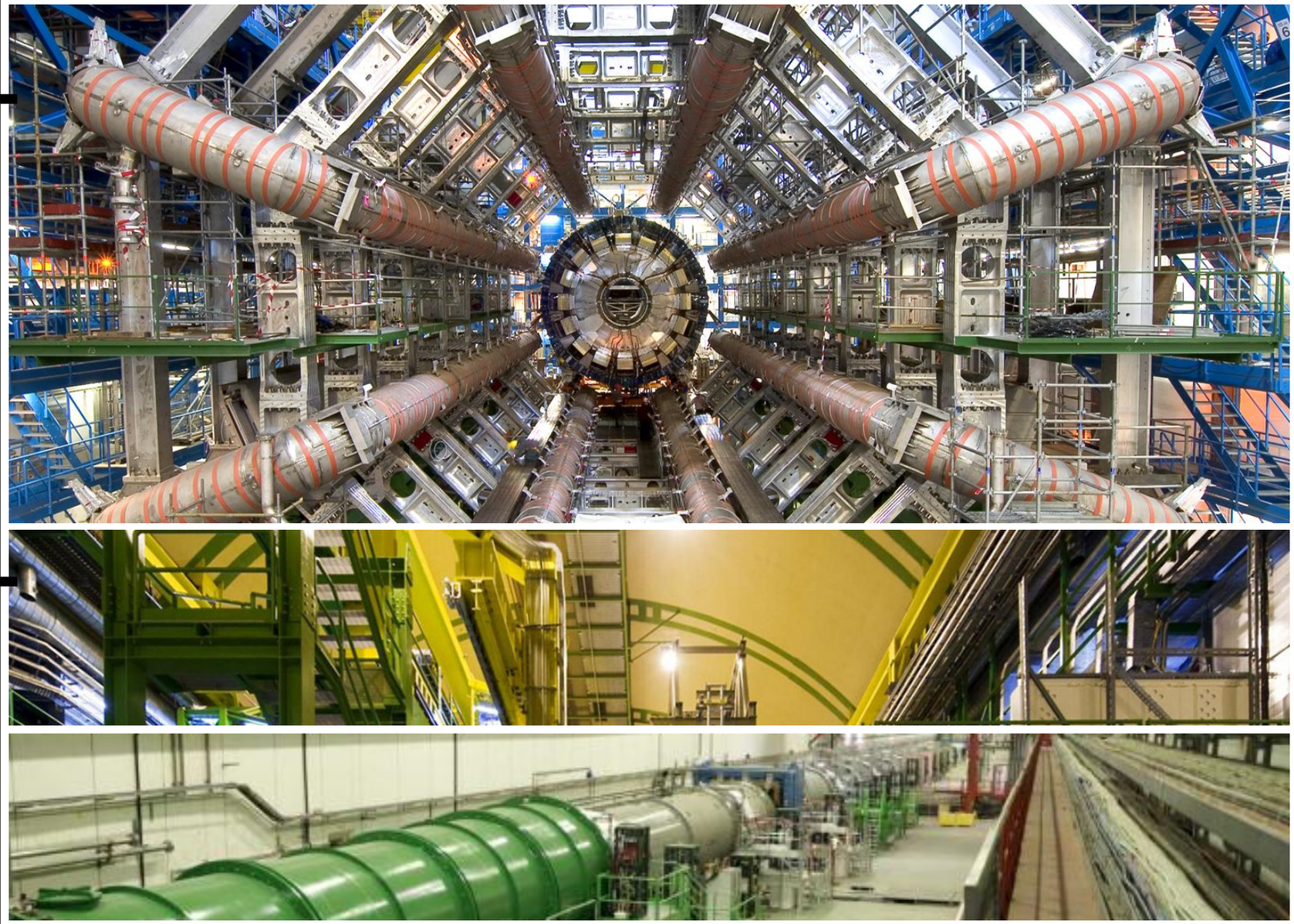
LHC?

picture: D. Baumann's lecture notes

Nothing?

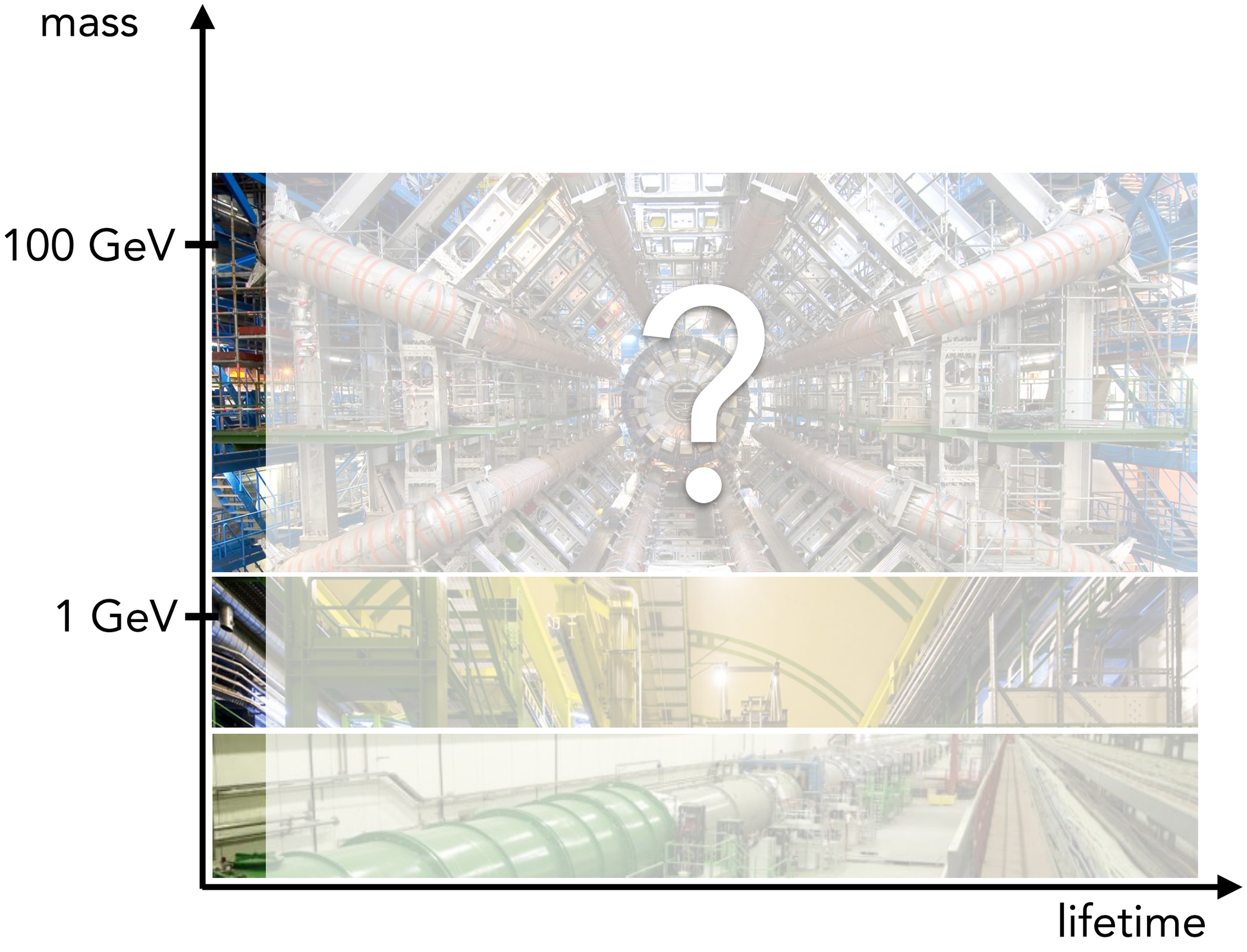
mass

100 GeV



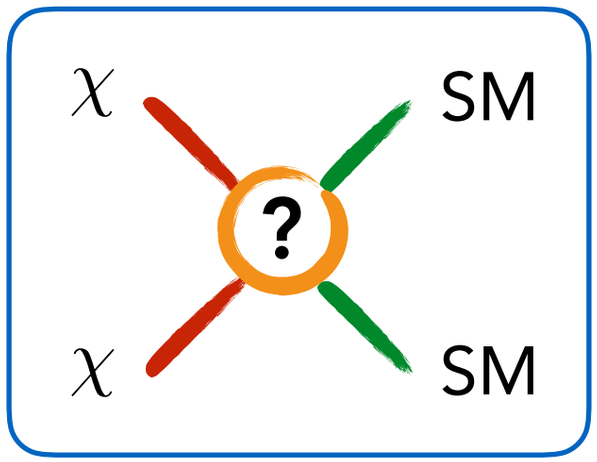
1 GeV

Anything?



Dark matter interactions

dark sector

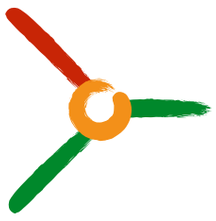


visible sector

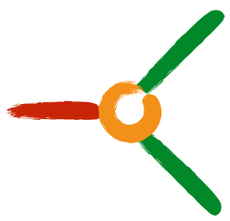
Portals:

$H^\dagger HSS$

$\overline{L}HN$



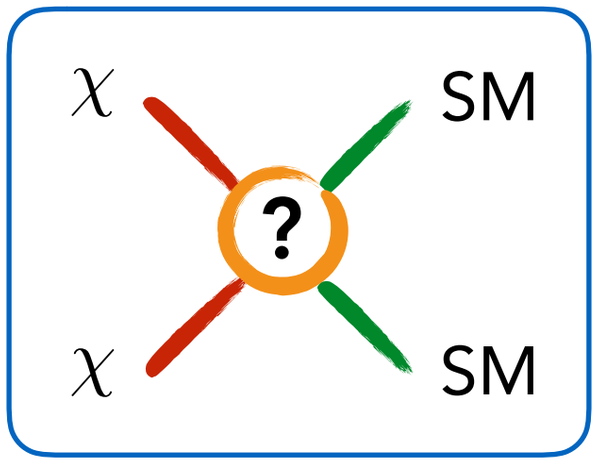
$\frac{a}{\Lambda}V^{\mu\nu}\widetilde{V}_{\mu\nu}$



→ Martin Bauer's talk

Dark matter interactions

dark sector



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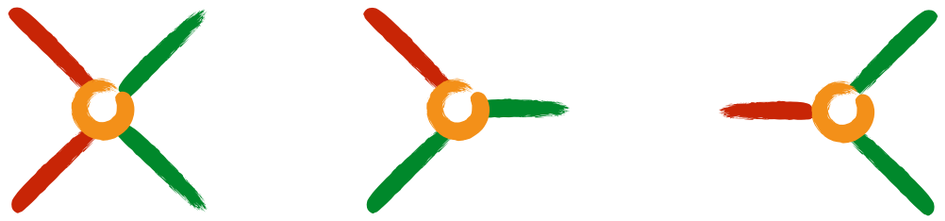
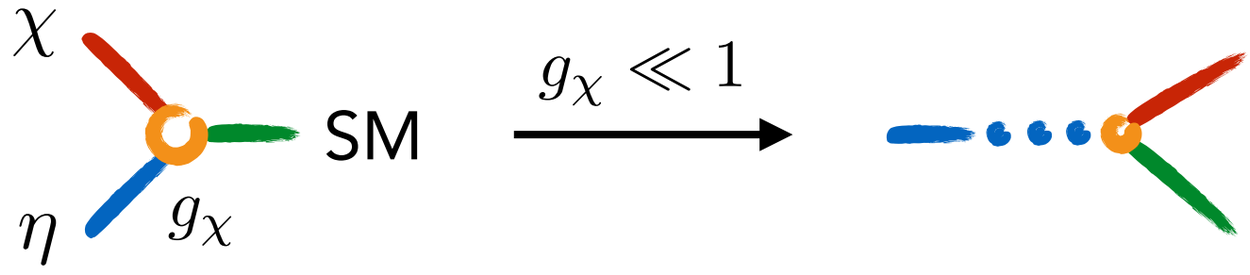


→ Martin Bauer's talk

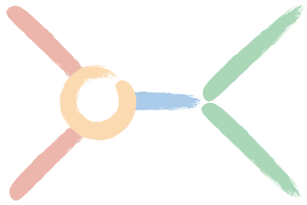
Mediators:



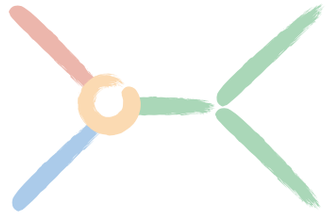
The new WIMP

In the early universe:

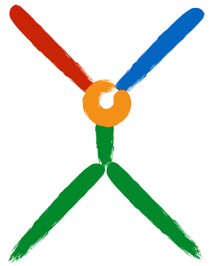
pair annihilation



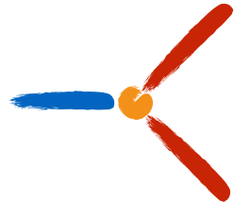
co-annihilation



co-scattering



freeze-in



Griest, Seckel 1991 Ruderman et al. 2017 Hall et al. 2009

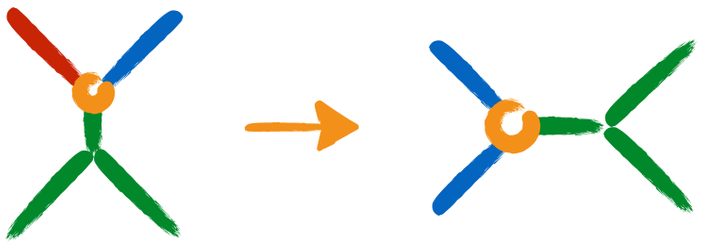
smaller coupling / longer lifetime

in thermal equilibrium

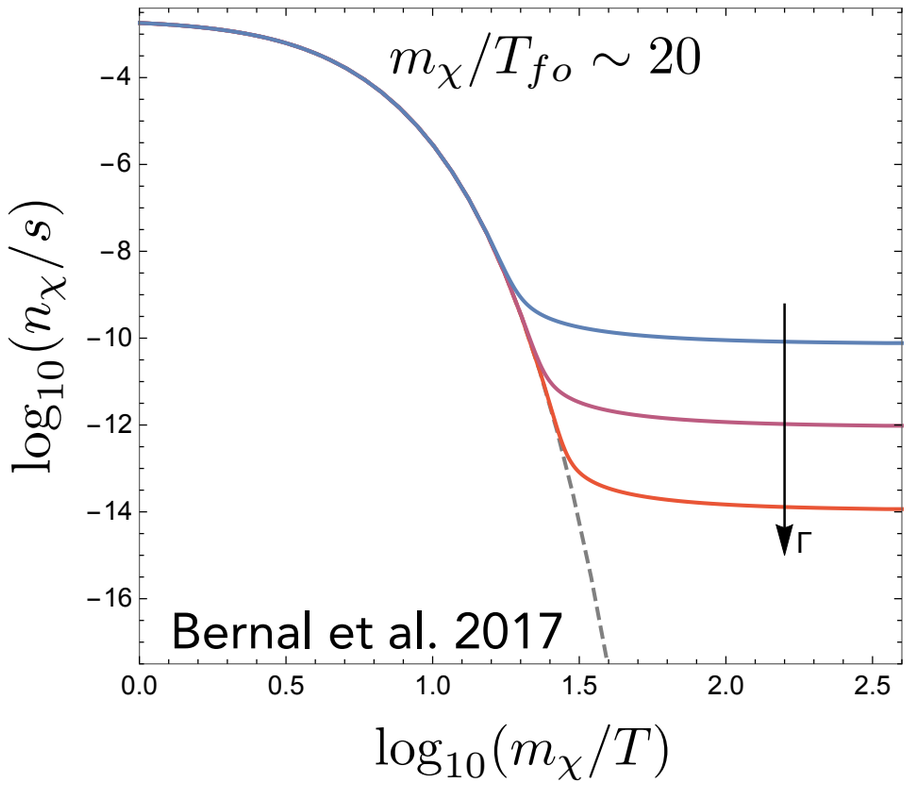
out of equilibrium

Relic abundance: freeze out

co-scattering / mediator annihilation

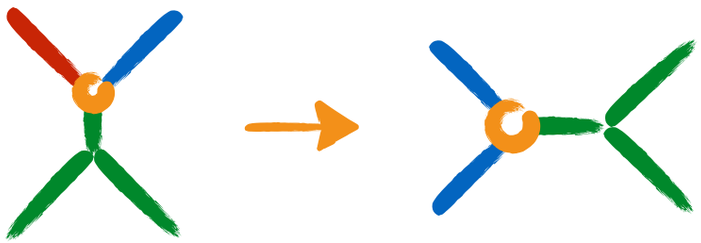


$$\Omega_\chi h^2 \sim \frac{m_\chi}{T_{fo}} \frac{\mathrm{GeV}^{-1}}{M_P \langle \sigma v \rangle}$$



Relic abundance: freeze out

co-scattering / mediator annihilation



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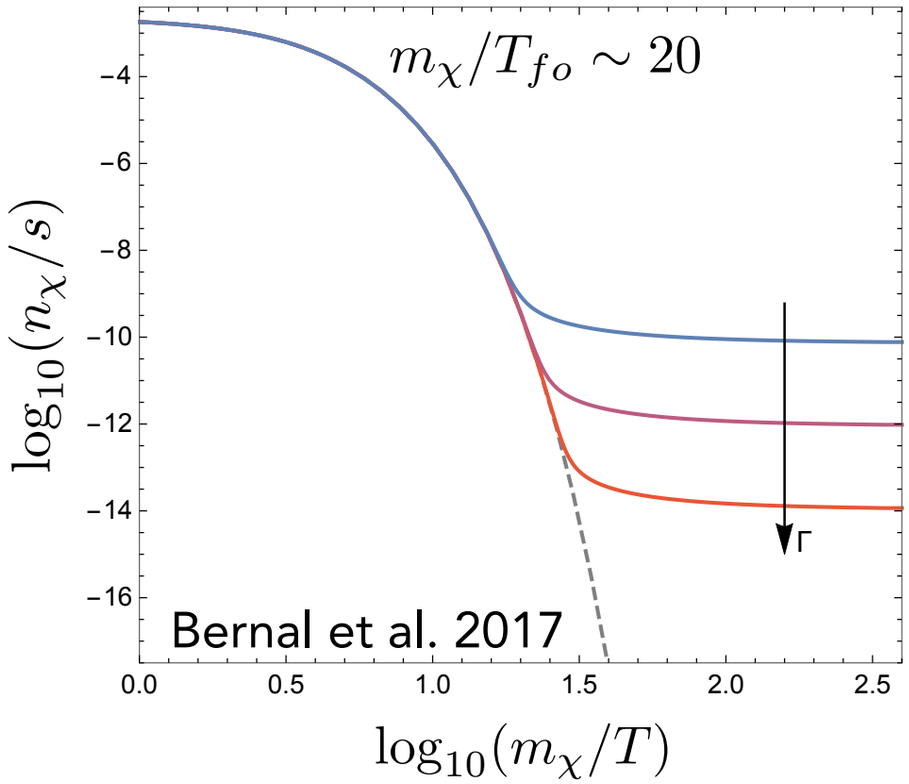


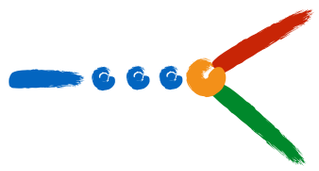
- number densities in dark sector → compressed spectrum

$$\frac{n_\eta}{n_\chi} \sim e^{-\frac{\Delta m}{T}} \sim 1$$

$$\frac{\Delta m}{m} \ll 1$$

- observed abundance for → long-lived mediators

$$g_\chi^2 \sim e^{-\frac{m_\chi}{T}} g^2_{\mathrm{WIMP}} \ll 1$$

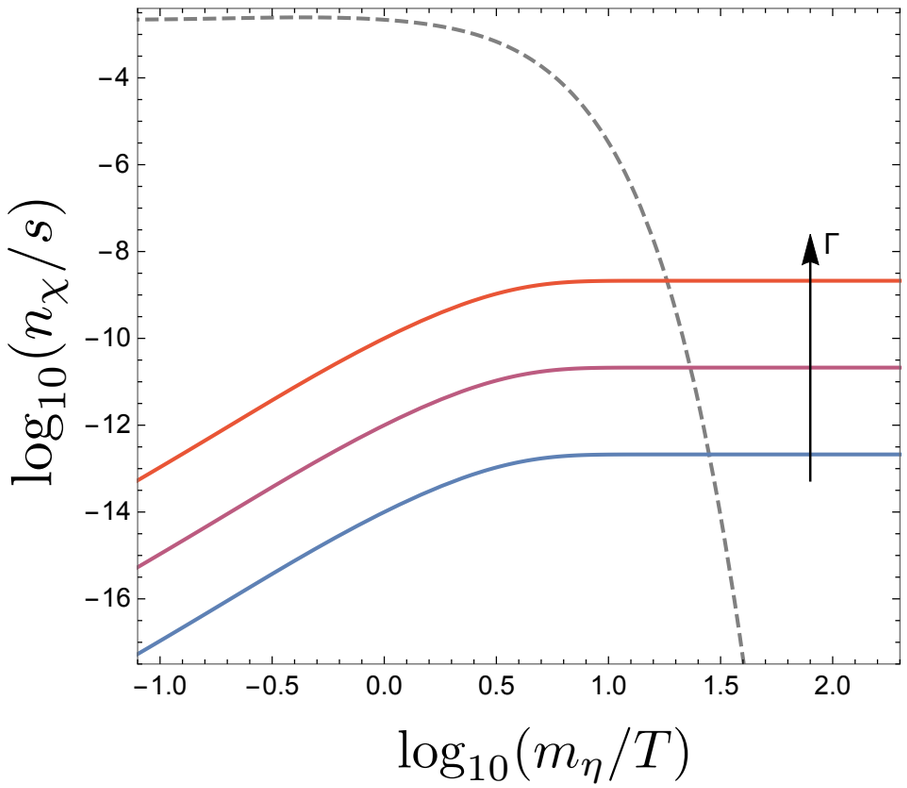


$$c\tau_\eta \sim \frac{1}{g_\chi^2 m_\eta} \left(\frac{m}{\Delta m}\right)^n$$

Relic abundance: freeze in

mediator decay / scattering

$$\Omega_\chi h^2 \sim \frac{m_\chi}{\mathrm{GeV}} \frac{M_P \Gamma_\eta}{T_{fi}^2}$$



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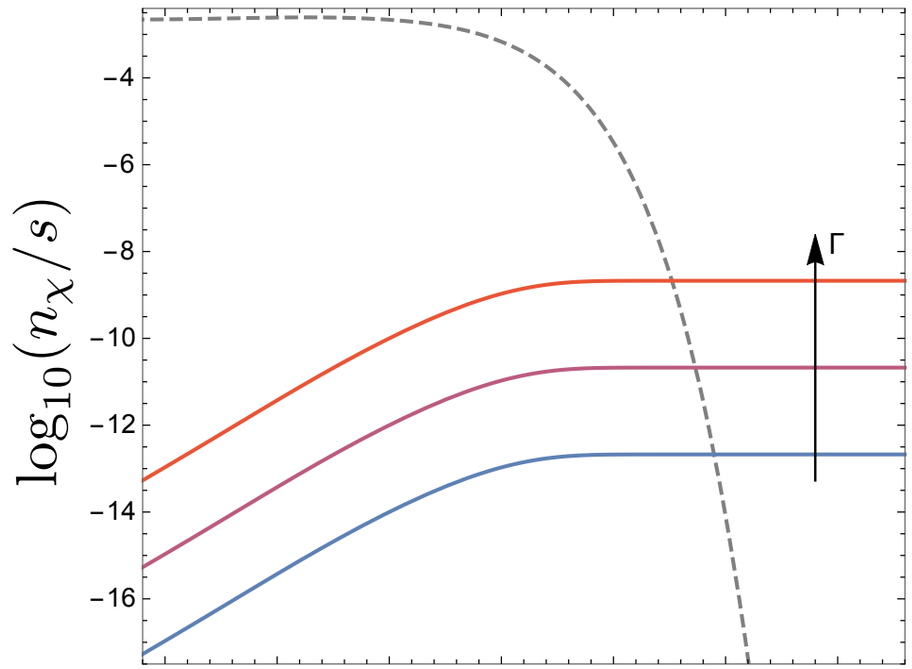


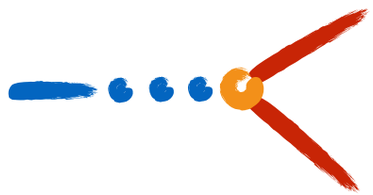
- mediator sets freeze-in time → split spectrum

$$T_{fi} \approx m_\eta/3$$

$$\frac{m_\eta^2}{m_\chi} \sim 10^9\,\mathrm{GeV}$$

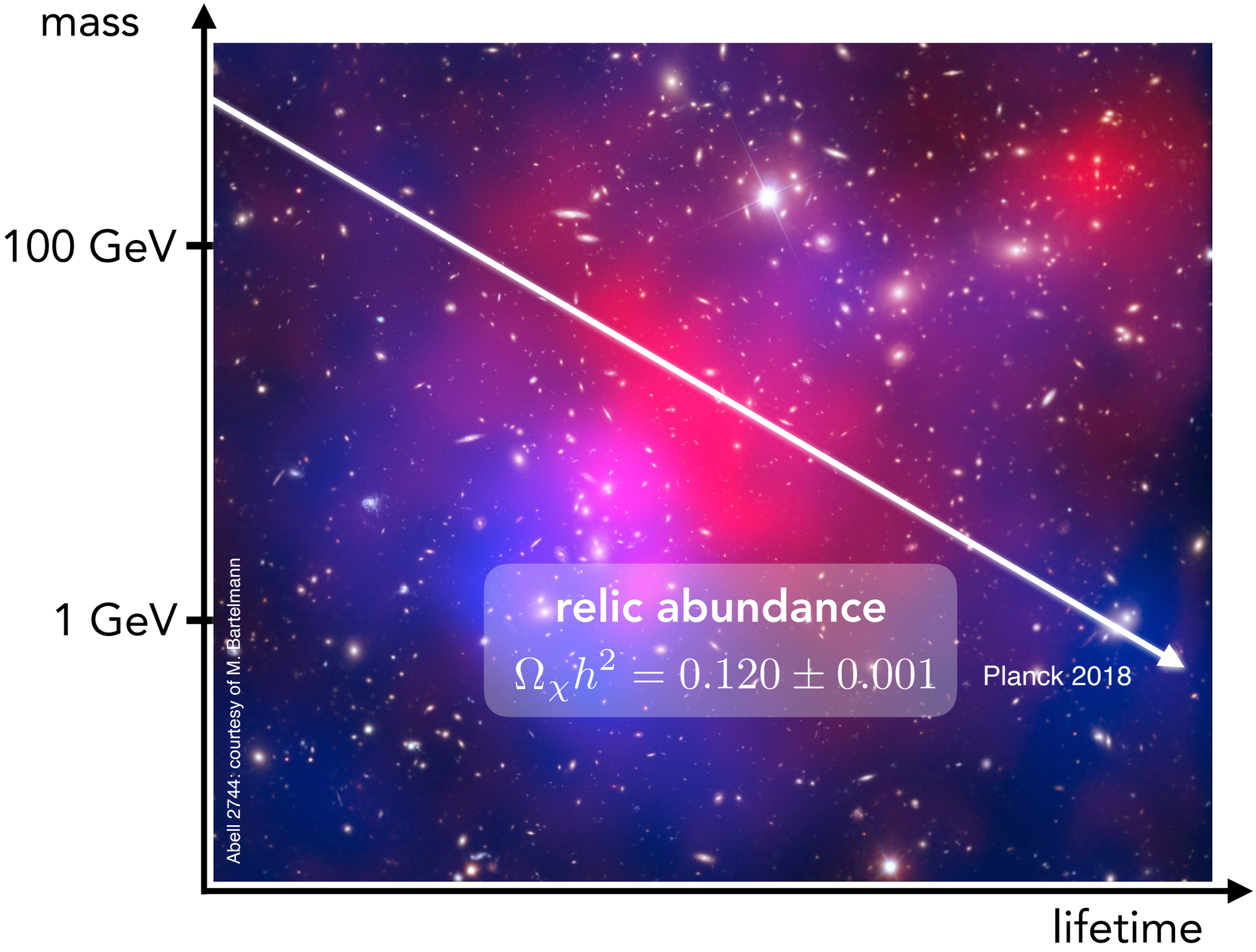
- dark matter out of equilibrium → long-lived mediators

$$g_\chi \lesssim 10^{-7}$$

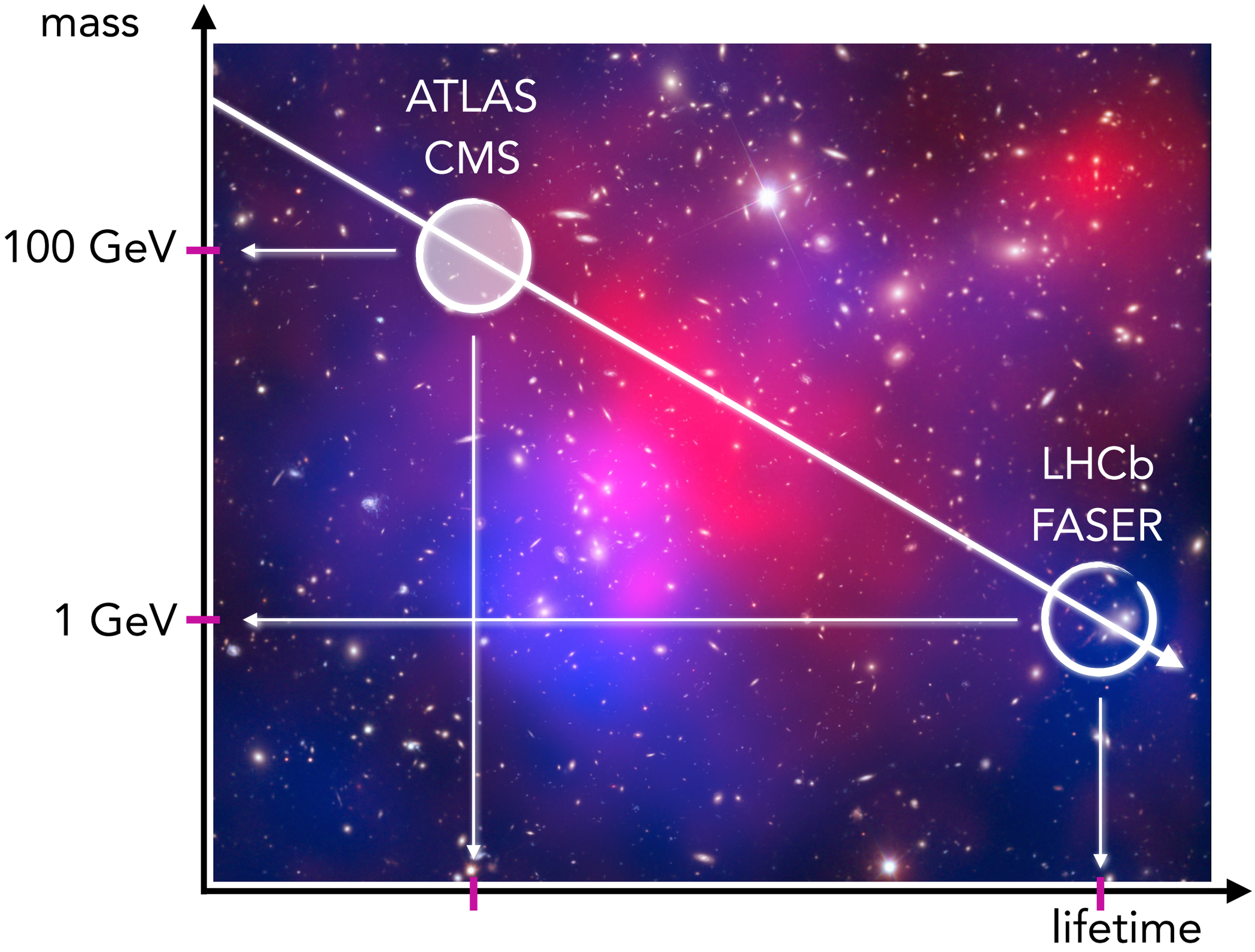


$$c\tau_\eta \sim \frac{m_\chi}{m_\eta^2}$$

Dark matter at the LHC



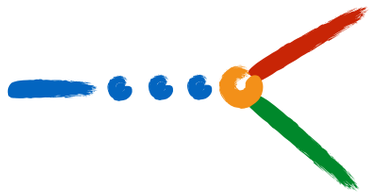
Dark matter at the LHC



Weak-scale dark sectors

co-scattering:

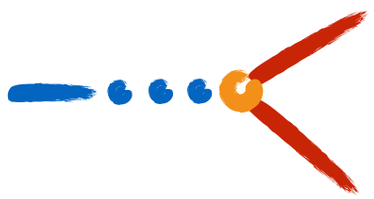
Blekman et al. 2007.03708 (electroweakinos)



$$c\tau_\eta \approx 1\,\mathrm{cm}\left(\frac{6\times10^{-5}}{g_\chi}\right)^2\left(\frac{20\,\mathrm{GeV}}{m_\eta - m_\chi}\right)^5\left(\frac{m_\eta}{80\,\mathrm{GeV}}\right)^4$$

freeze-in (radiation era):

No, Tunney, Zaldivar 1908.11387

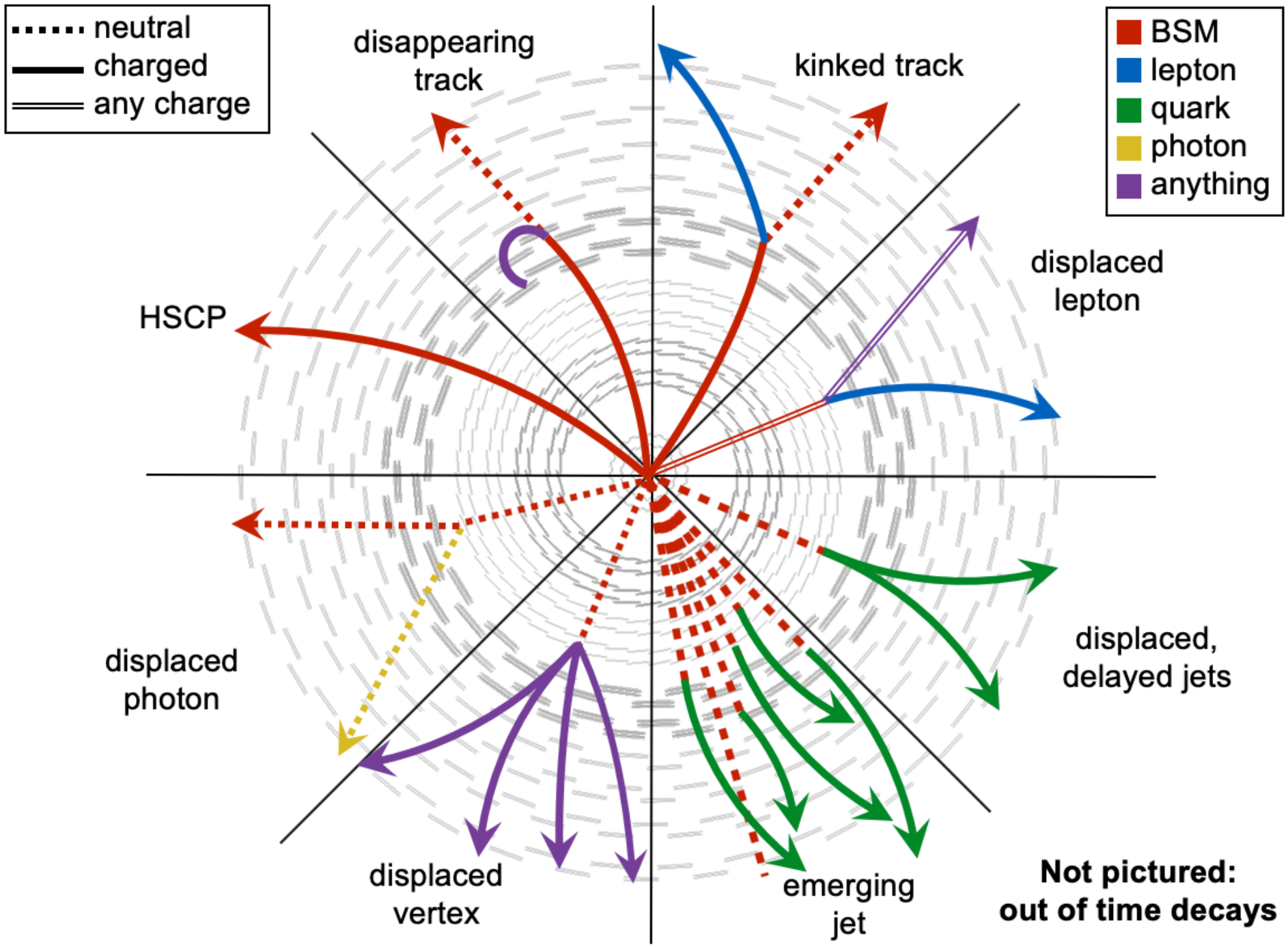


$$c\tau_\eta \approx 3.6\,\mathrm{m}\left(\frac{m_\chi}{100\,\mathrm{keV}}\right)\left(\frac{300\,\mathrm{GeV}}{m_\eta}\right)^2$$

Observable at the LHC: $200\,\mu\mathrm{m} \lesssim d = (\beta\gamma)c\tau_\eta \lesssim 1\,\mathrm{m}$

Mediator lifetimes are in reach at colliders!

The LLP playground



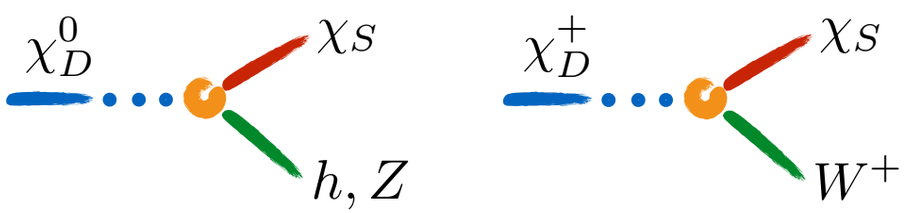
picture: talk by J. Alimena

Dark sectors with weak interactions

- higgsino-bino-like:

$$\mathcal{L} \supset -\frac{m_S}{2}\overline{\chi}_S\chi_S - \frac{m_D}{2}\overline{\chi}_D\chi_D - y_\chi\,\overline{\chi}_D H\chi_S + h.c.$$

Mediator decays:

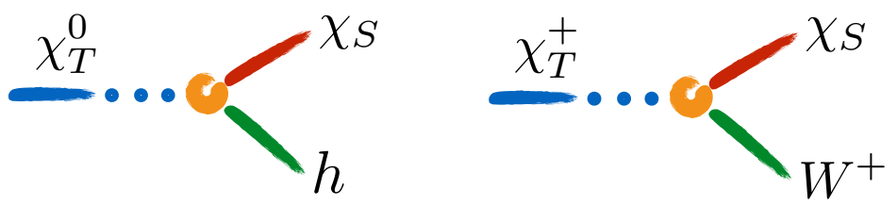


$$c\tau_{\chi_D} \sim \frac{1}{y_\chi^2}$$

- wino-bino-like:

$$\mathcal{L} \supset -\frac{m_S}{2}\overline{\chi}_S\chi_S - \frac{m_D}{2}\overline{\chi}_T\chi_T + \frac{\kappa}{\Lambda}(H^\dagger\overline{\chi}_T H)\chi_S + h.c.$$

Mediator decays:

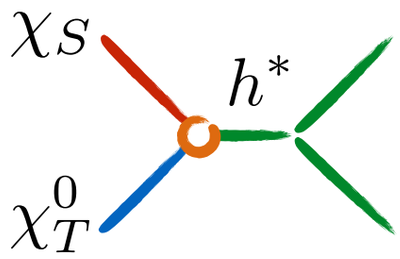


$$c\tau_{\chi_T} \sim \frac{\Lambda^2}{(\kappa v)^2}$$

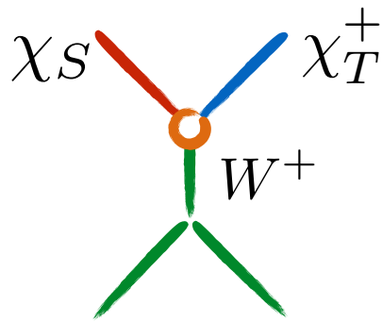
e.g. Arkani-Hamed, Delgado, Giudice 2006

LHC signatures

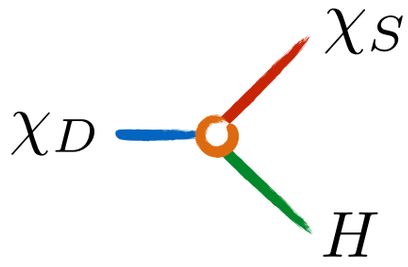
co-annihilation?

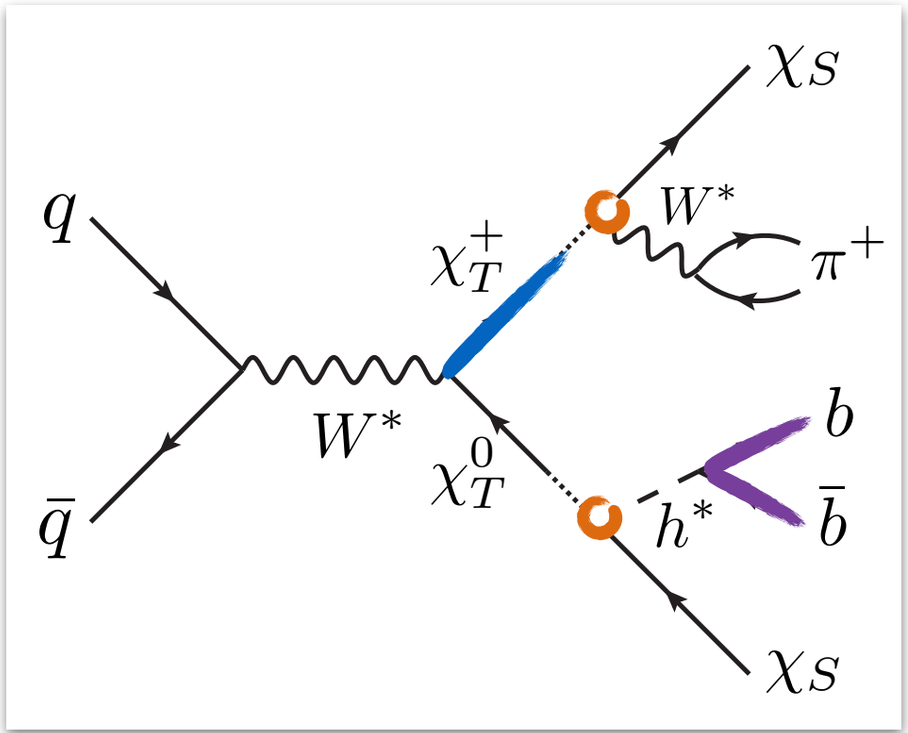


co-scattering?



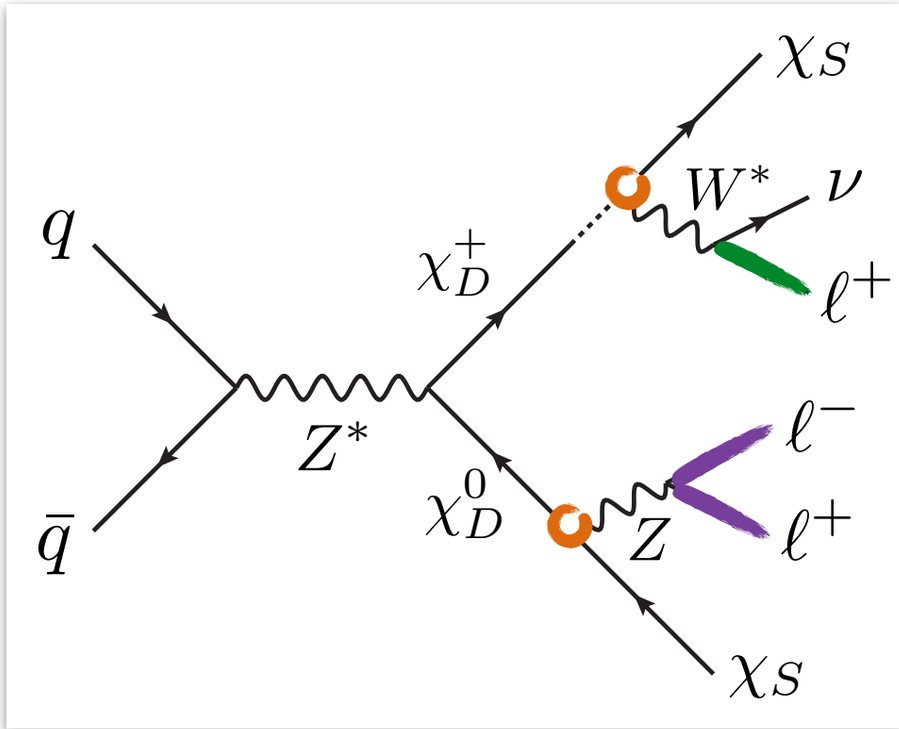
freeze-in?





disappearing track / HSCP

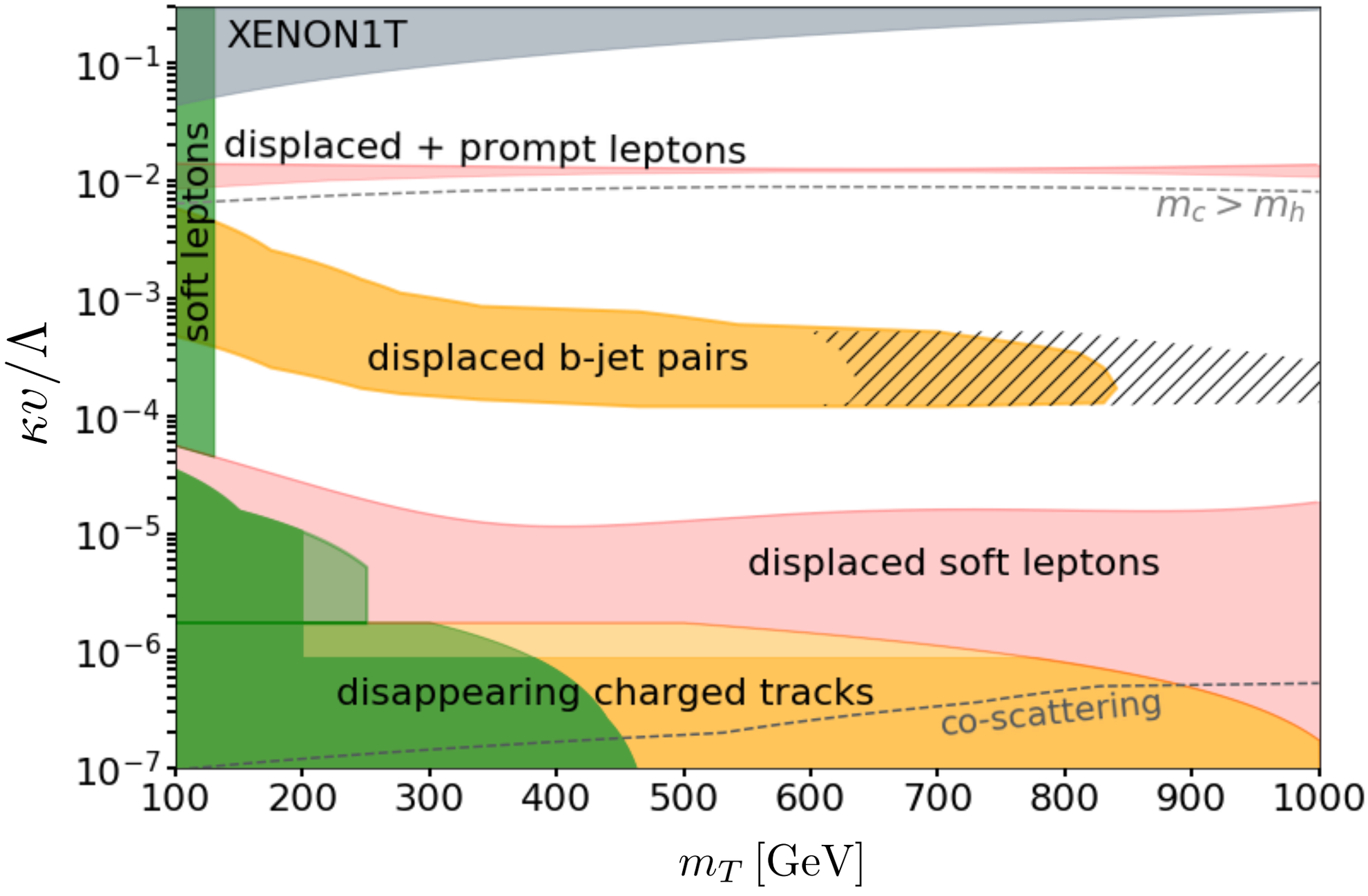
displaced b-jet vertex



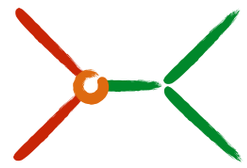
displaced soft leptons

displaced lepton/jet vertex

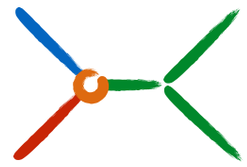
Dark matter signals at the LHC



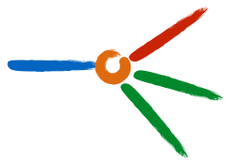
pair annihilation



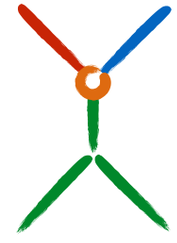
co-annihilation



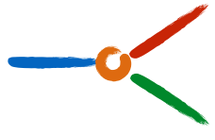
inverse decays



co-scattering



freeze-in



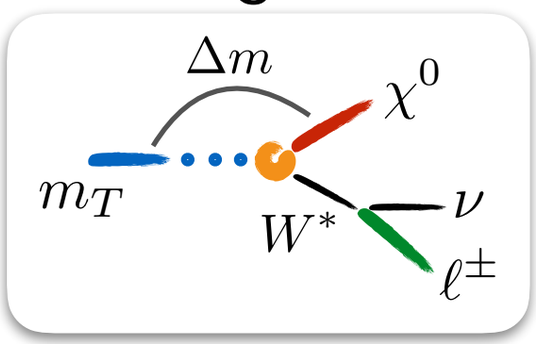
Mediator lifetime indicates production mechanism.

Co-scattering: soft displaced leptons

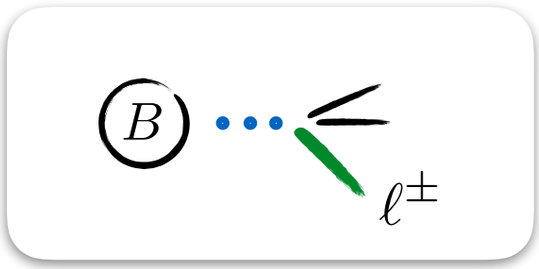
compressed dark sector: $\dfrac{\Delta m}{m} \ll 1$

$p_T^\ell > 40\,\mathrm{GeV} \to 20\,\mathrm{GeV}$

signal



background



$c\tau_B \sim 0.5\,\mathrm{mm}$

Blekman, Sahasransu, Desai, Filimonova, Westhoff 2007.03708

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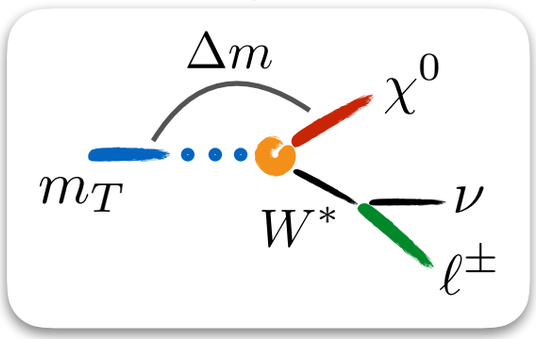

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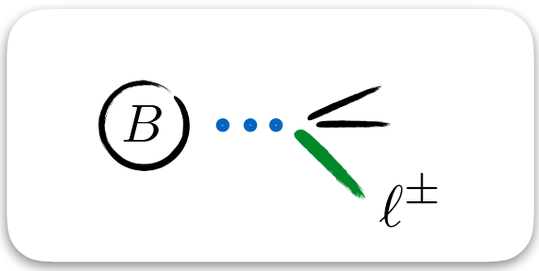

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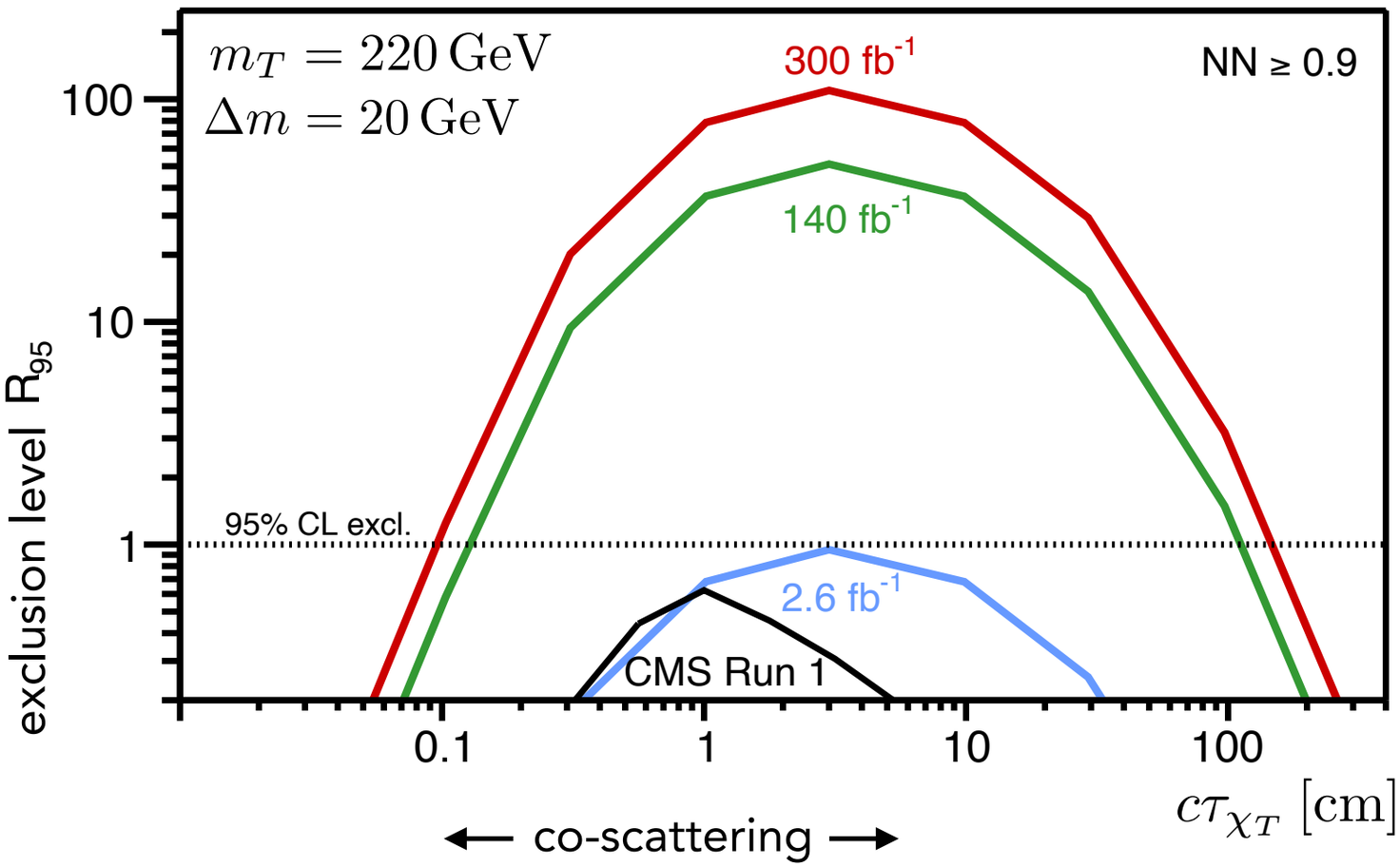
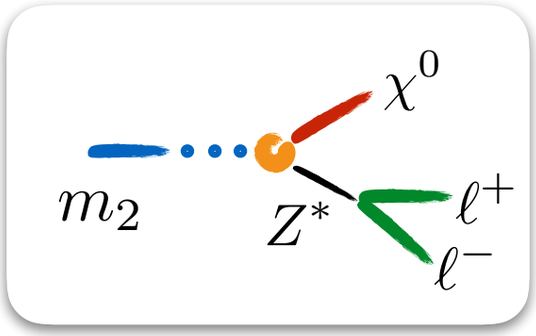


Displaced leptons with $c\tau_{\chi T} > 2\,\mathrm{mm}$ accessible with Run 2+ data.

Blekman, Sahasransu, Desai, Filimonova, Westhoff 2007.03708

Freeze-in: radiation era

signal



relic abundance:

$$\frac{m_2^2}{m_\chi} \sim 10^9\,\mathrm{GeV}$$

structure formation:

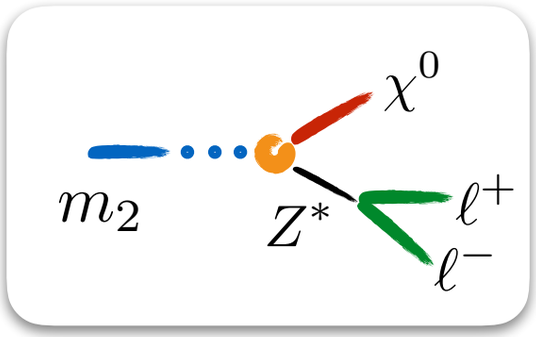
$$m_\chi \gtrsim 10\,\mathrm{keV}$$

Boulebnane et al. 1709.07283

Ballesteros et al. 2011.13458

Freeze-in: radiation era

signal



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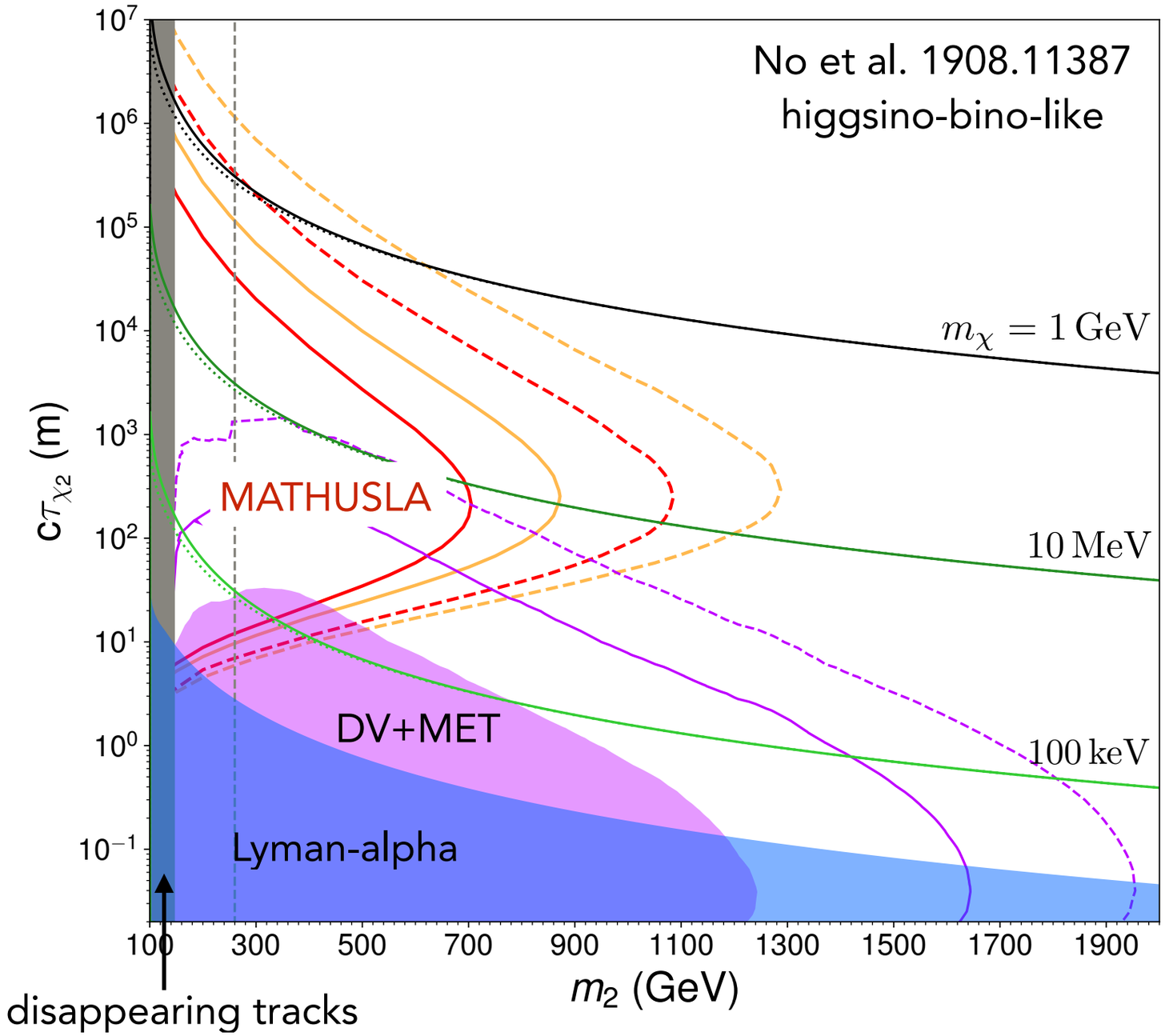


(Sub-) MeV dark matter from freeze-in is within LHC reach.

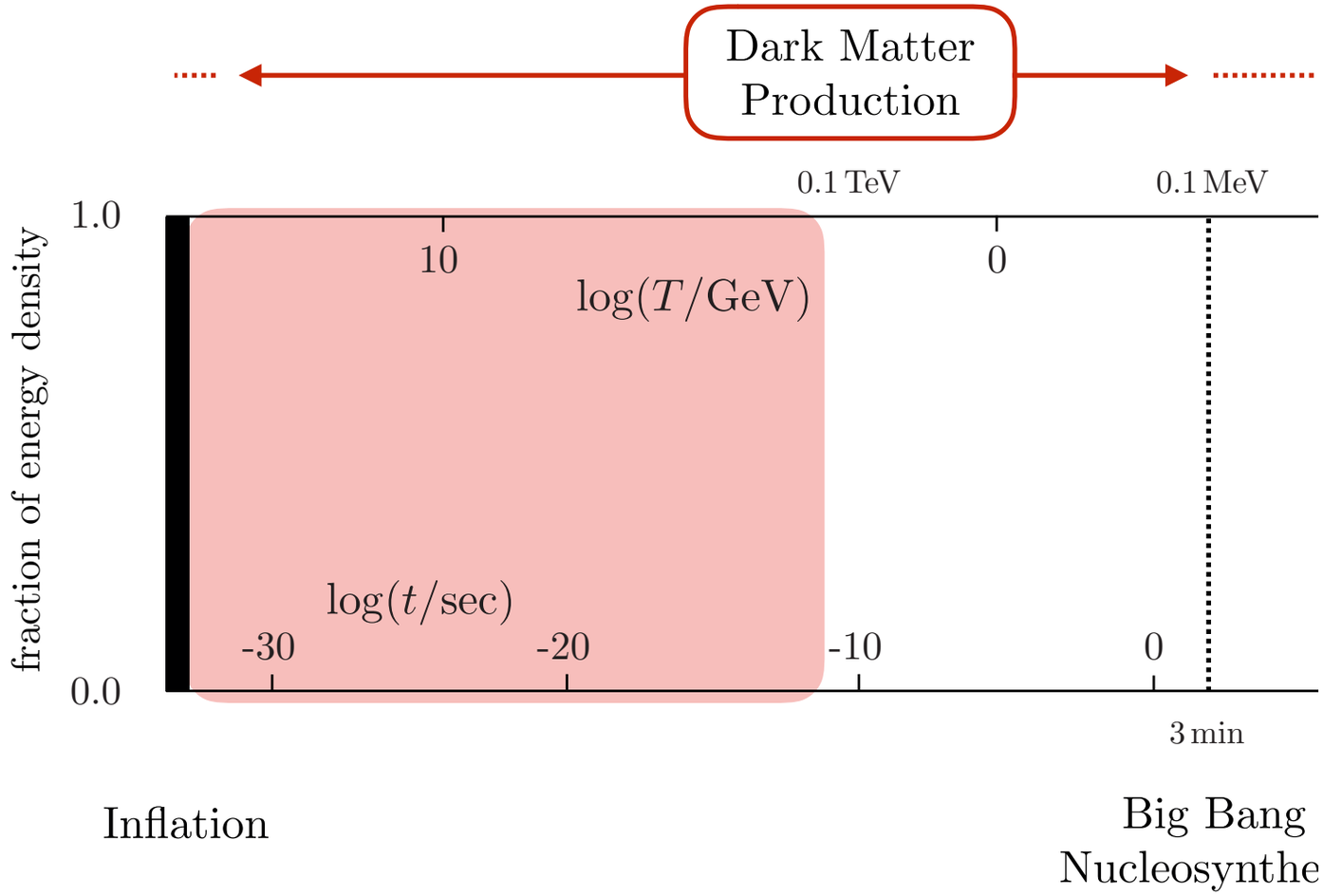
Freeze-in: early matter dominance

less efficient:

Co et al. 1506.07532

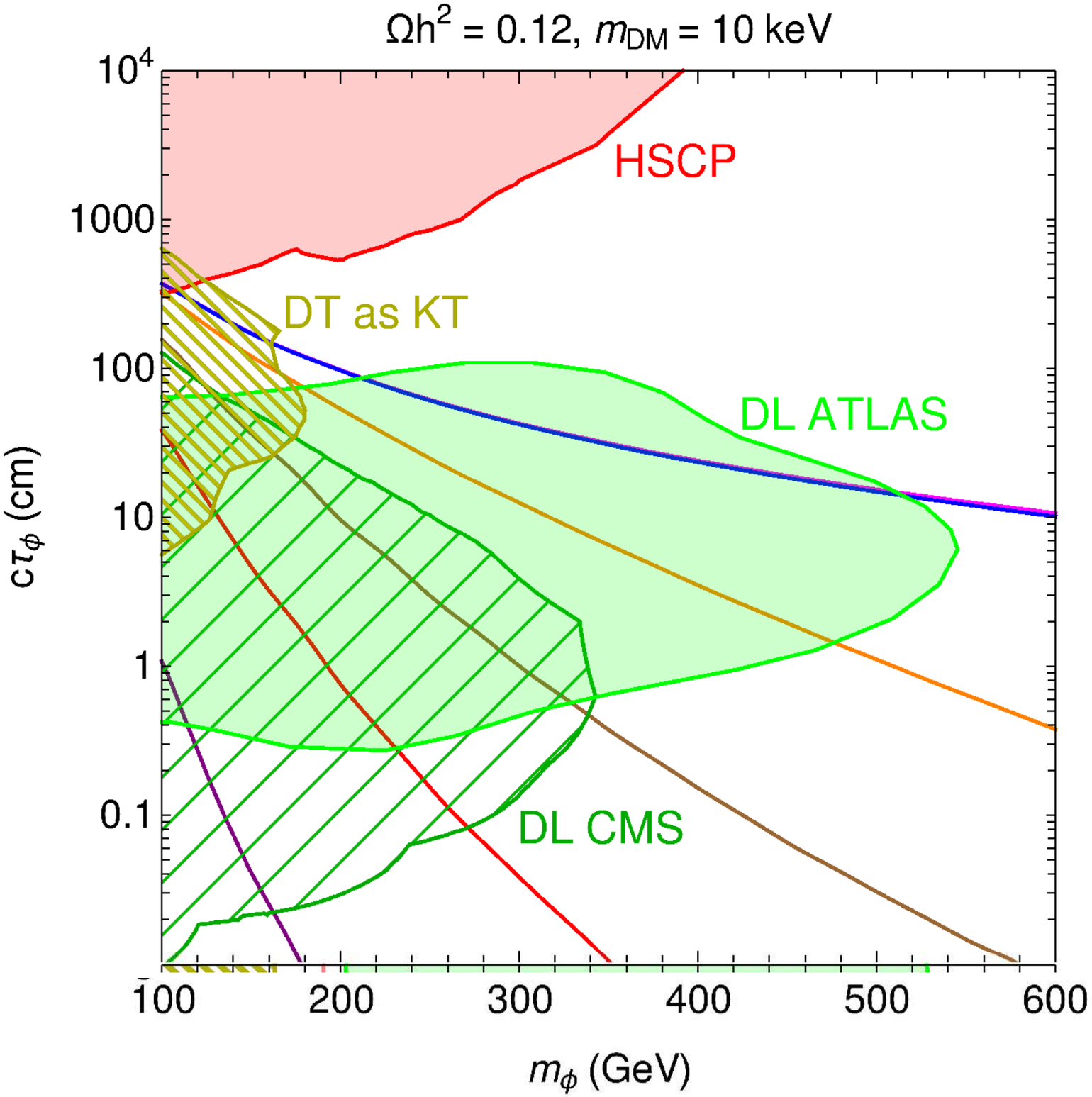
$$\Omega_\chi h^2 \sim \left(\frac{T_R}{m_\eta}\right)^7 \frac{m_\chi}{\mathrm{GeV}} \frac{M_P \Gamma_\eta}{m_\eta^2}$$

$$\Gamma_\eta^{\mathrm{MD}} > \Gamma_\eta^{\mathrm{RD}}$$



Mediators have shorter lifetimes than in radiation era freeze-in.

Freeze-in: early matter domination



Reheating:

— $T_R = 10^4$ GeV

— $T_R = 10^3$ GeV

— $T_R = 100$ GeV

— $T_R = 50$ GeV

— $T_R = 25$ GeV

— $T_R = 10$ GeV

Calibbi et al. 2102.06221
leptophilic

Opportunities for ATLAS and CMS

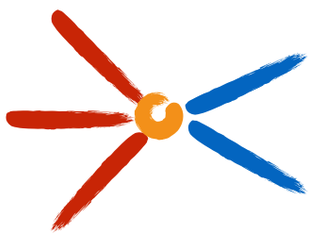
Co-scattering: soft displaced particles

- dedicated LLP triggers → LLP WG white paper
- flavor tagging for LLPs

Freeze-in: long lifetimes

- LLP searches in muon chamber
- synergy with FASER + future far-distance detectors

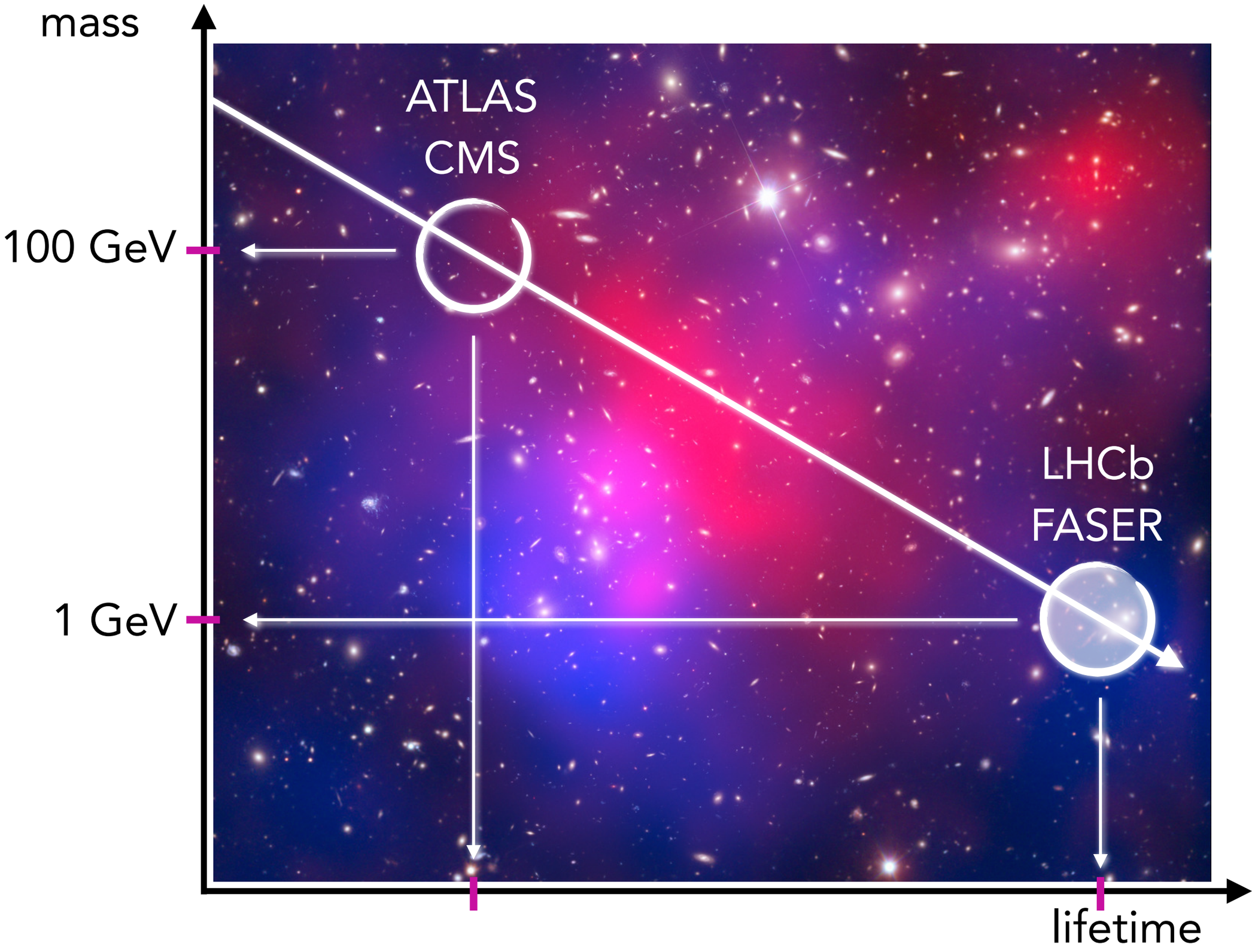
Self interactions:



- strong interactions → dark showers

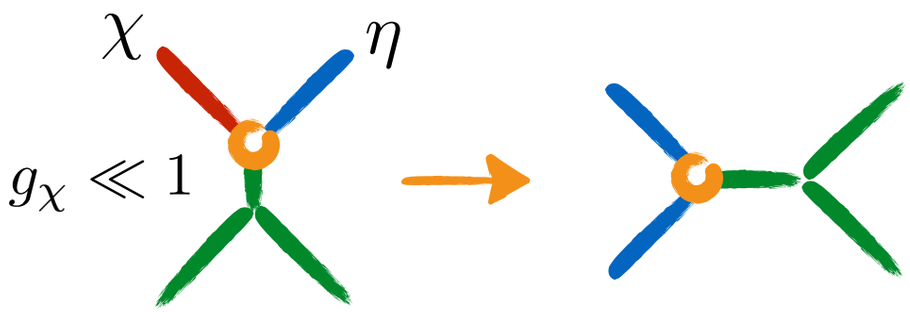
Hochberg et al. 1402.5143 +

New WIMPs across the scales



GeV-scale dark matter production

Co-scattering: not tied to a mass scale



relative number densities

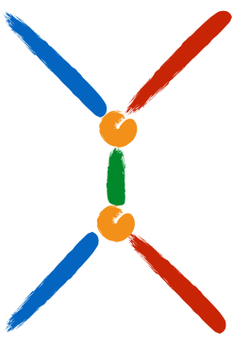
$$\frac{n_\eta}{n_\chi} \sim e^{-\frac{\Delta m}{T}} \sim 1$$

η —————

χ —————

$$\frac{\Delta m}{m} \ll 1$$

Freeze-in: scattering, annihilation, or decays of heavy particles

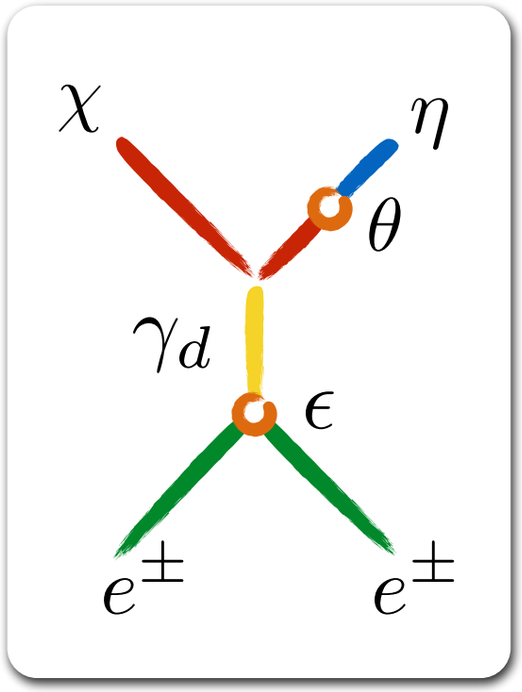


$$\Omega_\chi h^2 \sim m_\chi \int_{T_R}^{T_0} dT \, \frac{dY_\chi}{dT}$$

e.g. Hambye et al. 1908.09864

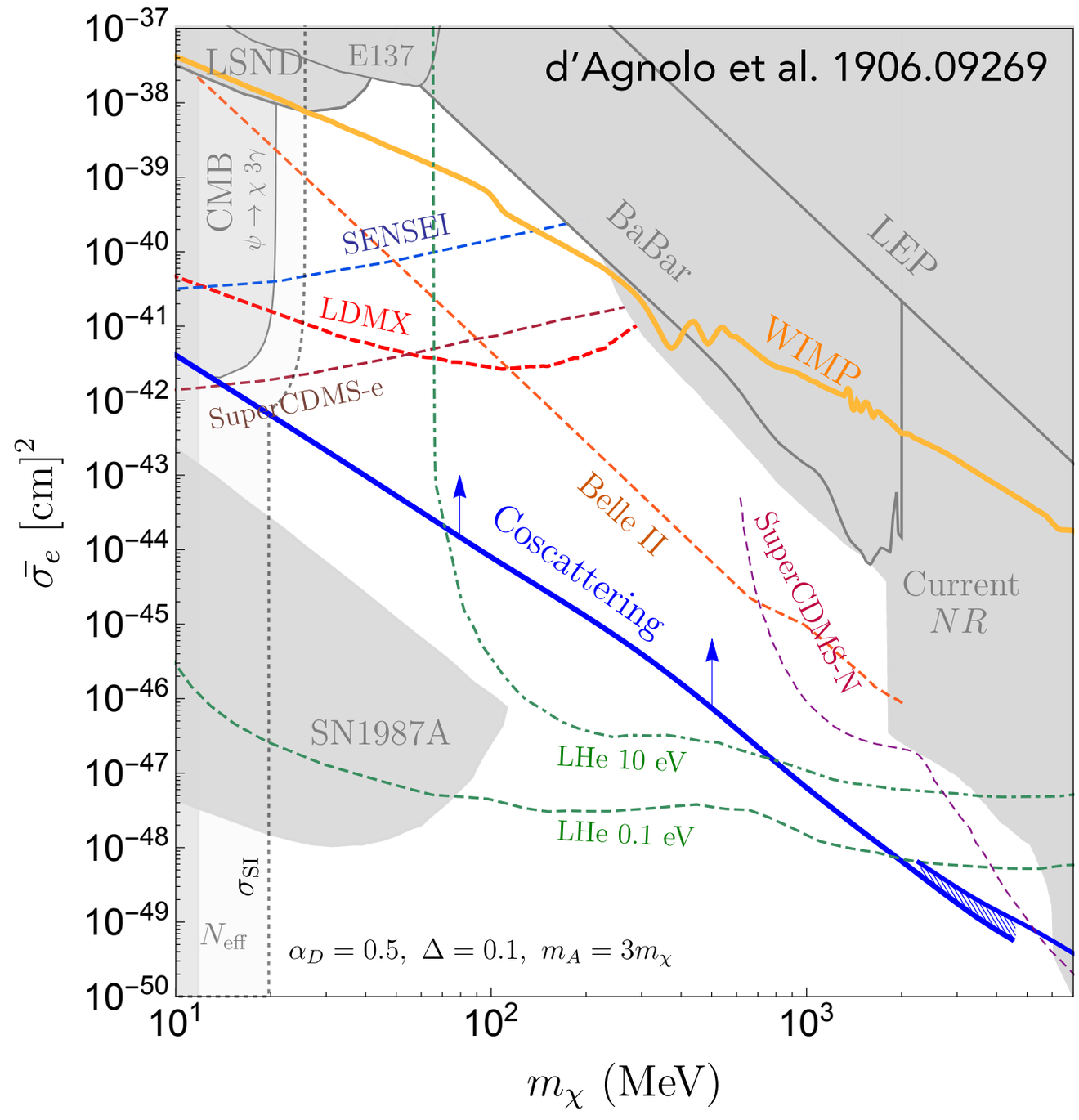
Belanger et al. 2005.06294

Co-scattering around the GeV scale



$\theta \sim 0.01$: scalar mixing

$\epsilon \sim 10^{-4}$: kinetic mixing

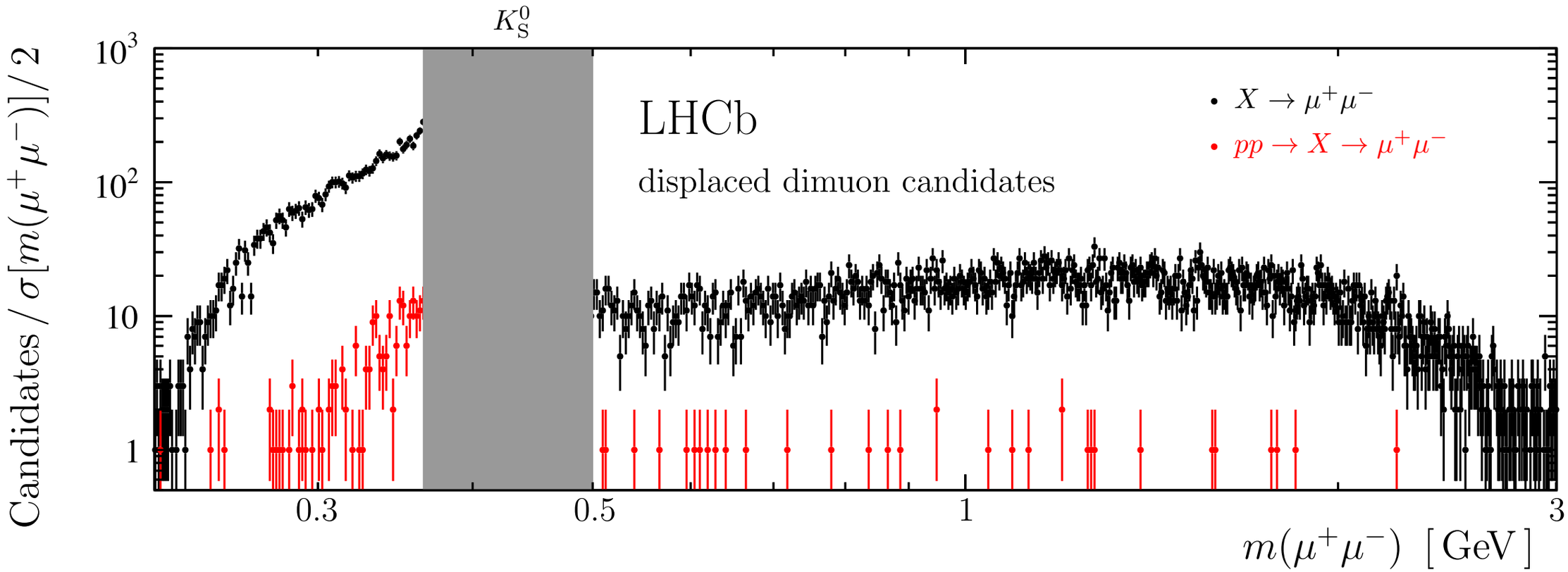


Where is LHCb?

Opportunities for LHCb

Model-independent search for displaced muons

LHCb 2007.03923



Explore LHCb's potential for LLP searches: → white paper

- excellent vertex reconstruction and mass resolution
- downstream tracks: long lifetimes

Summary

Long-lived particles are sensitive probes of dark matter.

Predictions from early-universe dynamics:

- small couplings → long-lived mediators
- compressed spectra → soft decay products

Explore LHC's full potential to discover LLPs:

- dedicated LLP triggers
- timing information
- complementarity of ATLAS, CMS / LHCb / FASER

Learn from connections:

- Belle II, fixed-target, neutrino experiments
- direct detection (electron scattering)
- astrophysics (structure formation)

Thank you for discussions!
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Nishita Desai, Laura Lopez-Honorez
Sam Junius, Alberto Mariotti.