# Long-lived particle signatures of $t$-channel dark matter models

## Jan Heisig (UCL)

Chargé de recherches

**fnrs**
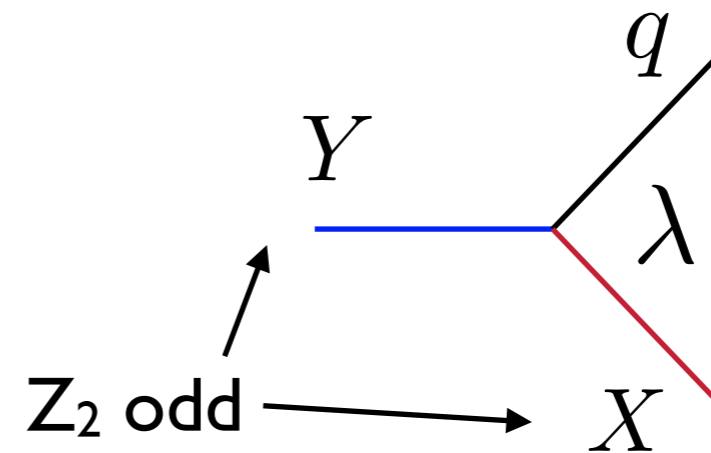LA LIBERTÉ DE CHERCHER

**UCLouvain** CP3

Spring 2020 LHC DM WG meeting:
DM models with $t$-channel mediators

April 28, 2020

# Classification: simplified dark matter models with *t*-channel mediators

| Field | Spin | Repr. | Self-conj. |
|-------|------|-------|------------|
| $\tilde{S}$ | 0 | $(\mathbf{1}, \mathbf{1}, 0)$ | yes |
| $S$ | 0 | $(\mathbf{1}, \mathbf{1}, 0)$ | no |
| $\tilde{\chi}$ | 1/2 | $(\mathbf{1}, \mathbf{1}, 0)$ | yes |
| $\chi$ | 1/2 | $(\mathbf{1}, \mathbf{1}, 0)$ | no |
| $\tilde{V}_\mu$ | 1 | $(\mathbf{1}, \mathbf{1}, 0)$ | yes |
| $V_\mu$ | 1 | $(\mathbf{1}, \mathbf{1}, 0)$ | no |
| $\varphi_Q = \begin{pmatrix} \varphi_Q^{(u)} \\ \varphi_Q^{(d)} \end{pmatrix}$ | 0 | $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ | no |
| $\varphi_u$ | 0 | $(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ | no |
| $\varphi_d$ | 0 | $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ | no |
| $\psi_Q = \begin{pmatrix} \psi_Q^{(u)} \\ \psi_Q^{(d)} \end{pmatrix}$ | 1/2 | $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ | no |
| $\psi_u$ | 1/2 | $(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ | no |
| $\psi_d$ | 1/2 | $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ | no |

dark matter X

*t*-channel mediator Y

[Arina, Fuks, Mantani 2001.05024]



$Z_2$ odd

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin}} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde{\chi})$$
$$+ \mathcal{L}_S(S) + \mathcal{L}_S(\tilde{S}) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde{V}),$$
$$\mathcal{L}_F(X) = \left[ \lambda_{\mathbf{Q}} \bar{X} Q \varphi_Q^\dagger + \lambda_{\mathbf{u}} \bar{X} u \varphi_u^\dagger + \lambda_{\mathbf{d}} \bar{X} d \varphi_d^\dagger + \text{h.c.} \right],$$
$$\mathcal{L}_S(X) = \left[ \hat{\lambda}_{\mathbf{Q}} \bar{\psi}_Q Q X + \hat{\lambda}_{\mathbf{u}} \bar{\psi}_u u X + \dots \right]$$
$$\mathcal{L}_V(X) = \left[ \hat{\lambda}_{\mathbf{Q}} \bar{\psi}_Q X \dots \right]$$

Luca's talk

# This talk

Consider exemplary setup:
one DM candidate $X$, one mediator $Y$, one quark flavor
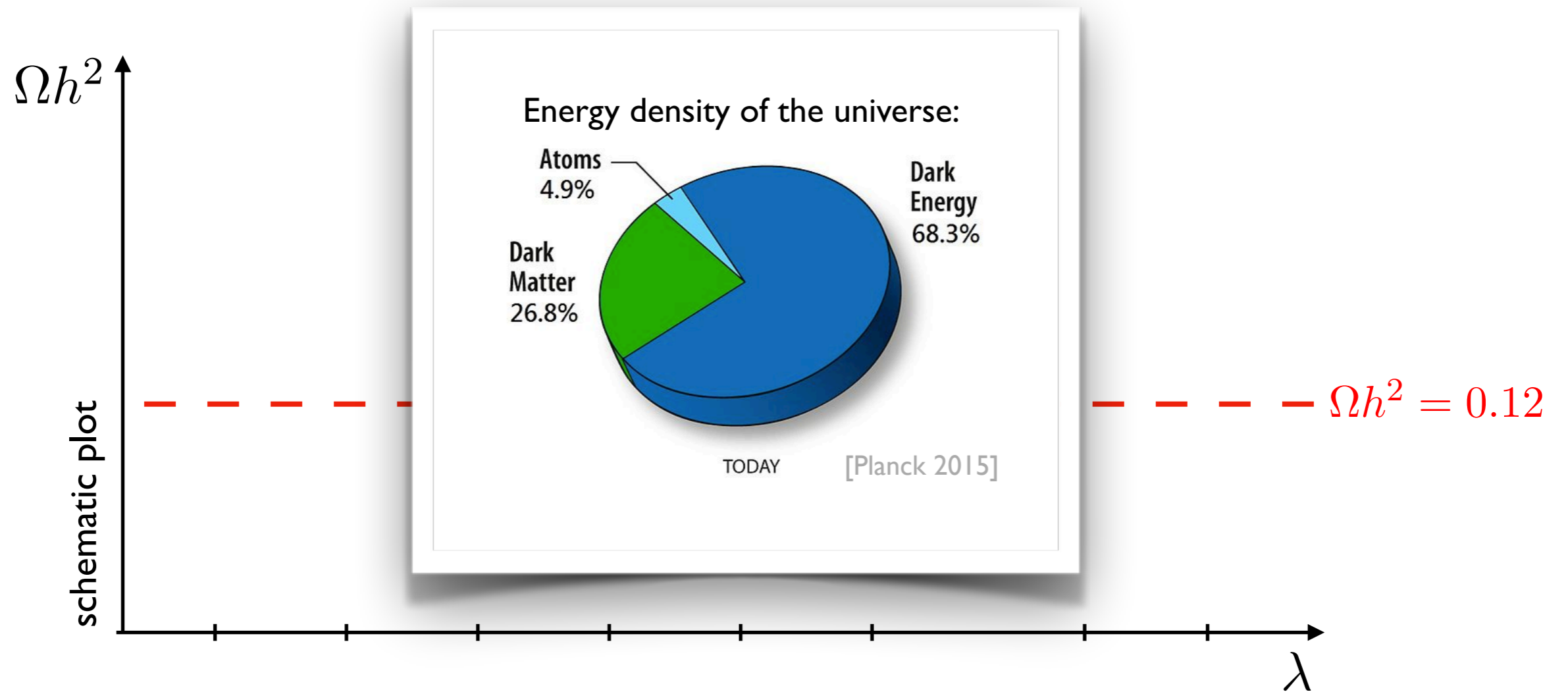$\Rightarrow$ 3 free parameters only

Starting point:
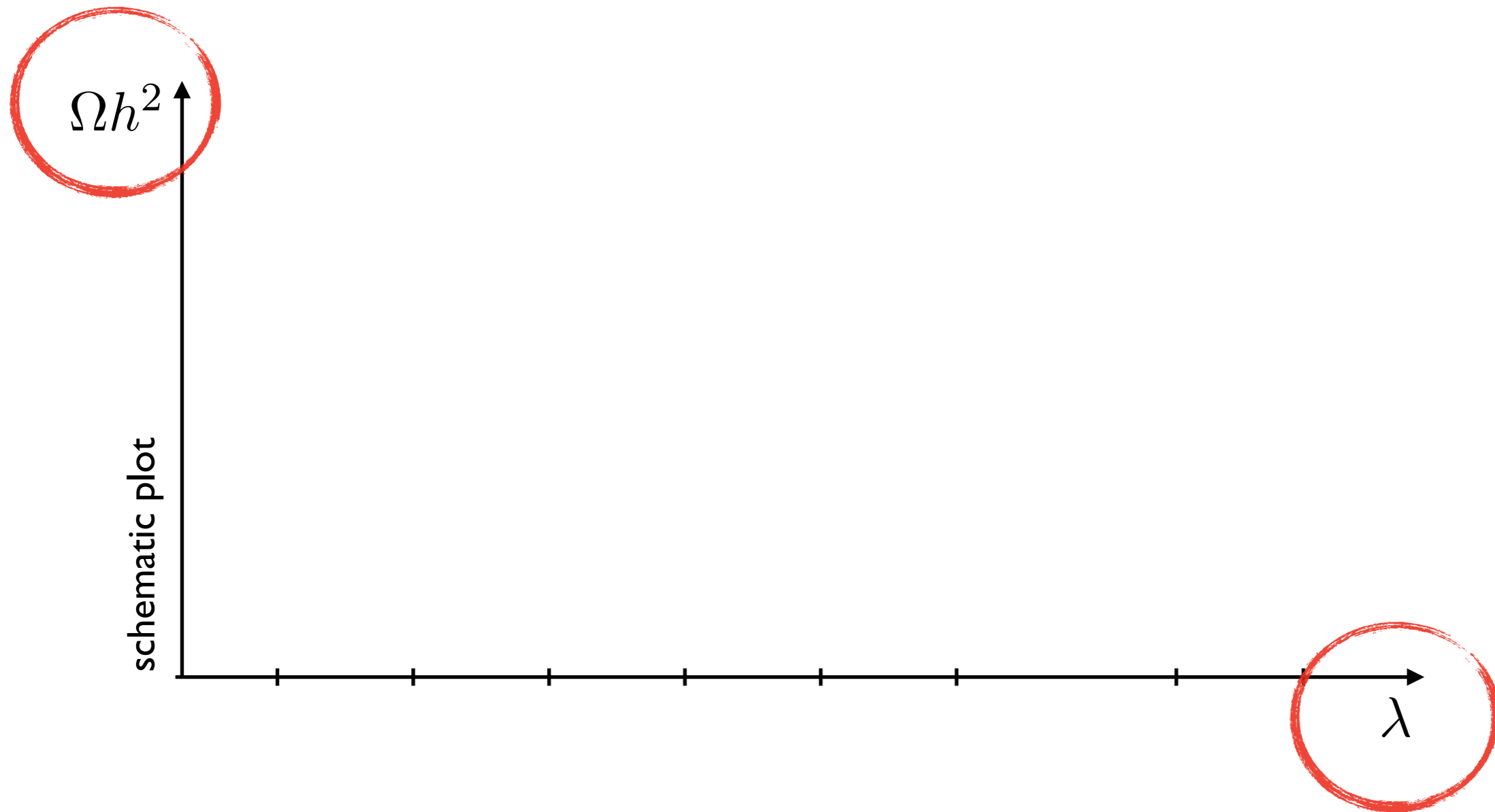What parameter regions are cosmologically motivated?

Take-(at-)home message:
If **not** restricting to WIMP paradigm
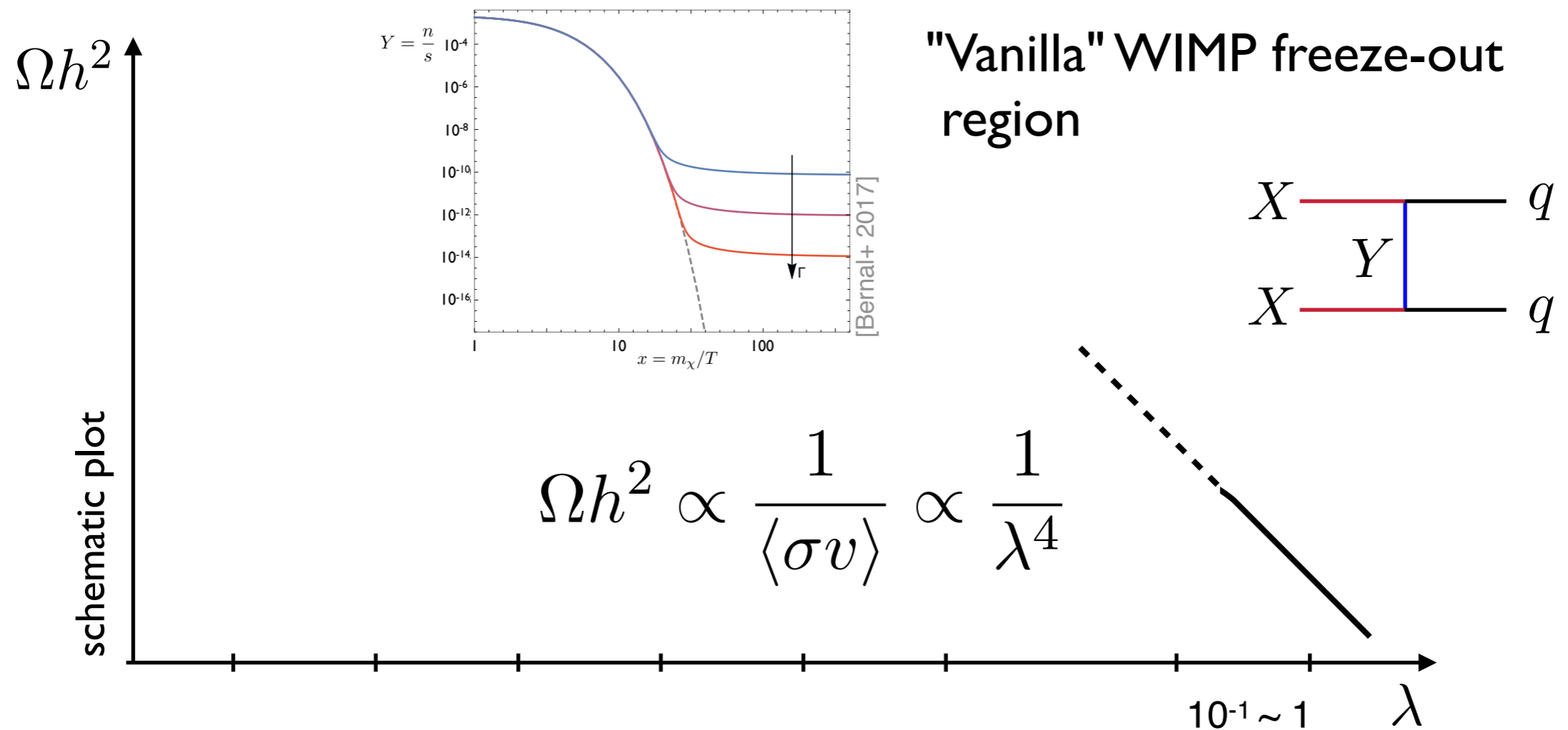huge range of $\lambda$, long-lived $Y$ rather rule than exception!
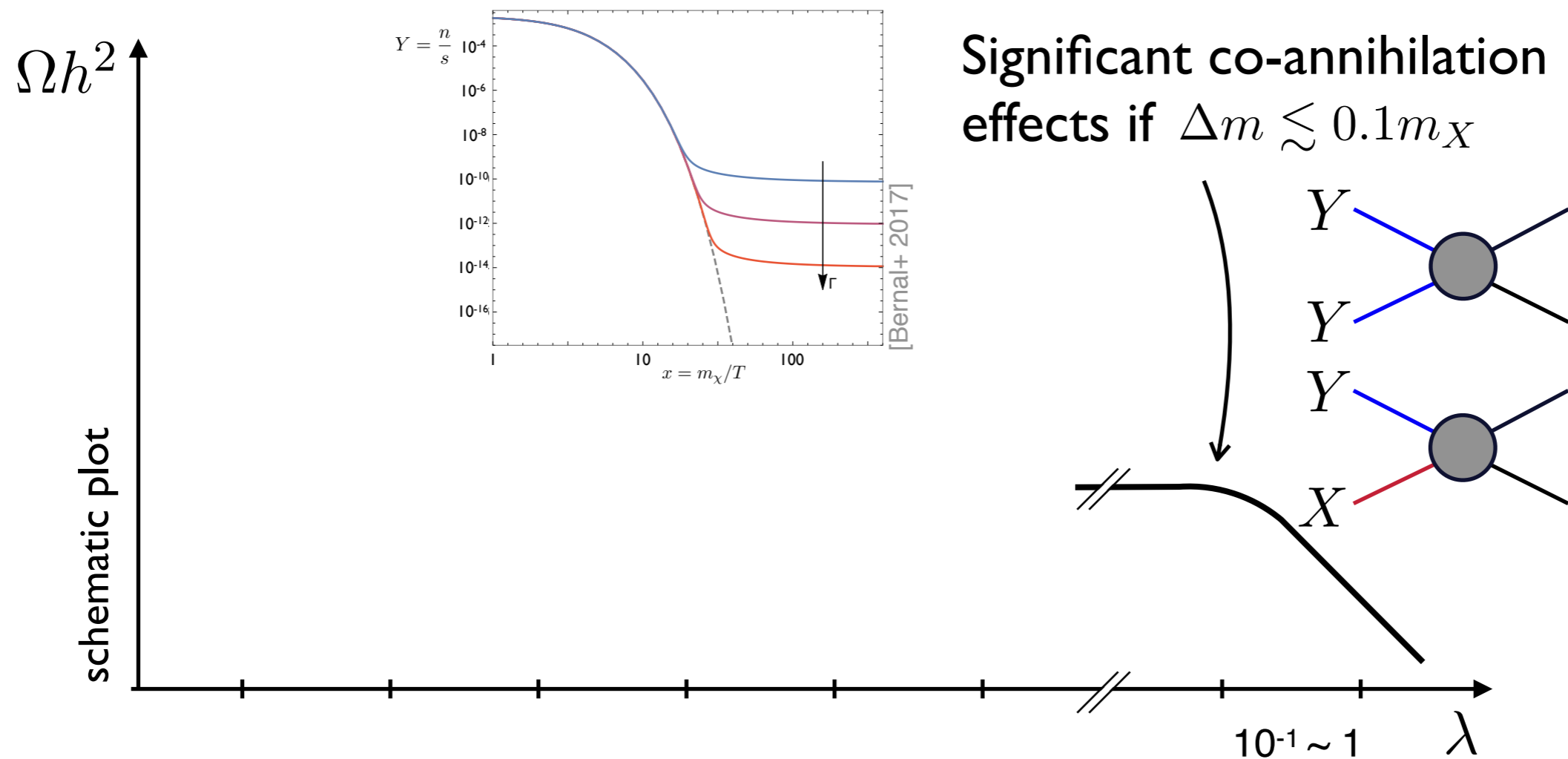
# What values of λ are cosmologically motivated?



$\Omega h^2$

schematic plot

$$\Omega h^2 = 0.12$$

$\lambda$

Energy density of the universe:

Atoms 4.9%

Dark Matter 26.8%

Dark Energy 68.3%

TODAY    [Planck 2015]

# What values of λ are cosmologically motivated?

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"Vanilla" WIMP freeze-out region

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle} \propto \frac{1}{\lambda^4}$$

$10^{-1} \sim 1$

# What values of λ are cosmologically motivated?

$\Omega h^2$

schematic plot

$Y = \frac{n}{s}$

$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$

$\Gamma$

1   10   100

$x = m_\chi/T$

[Bernal+ 2017]

Significant co-annihilation effects if $\Delta m \lesssim 0.1 m_X$

$Y$
$Y$
$Y$
$X$

$10^{-1} \sim 1$   $\lambda$

# What values of λ are cosmologically motivated?



$\Omega h^2$

schematic plot

[Garny, JH, Lülf, Vogl 2017; D'Agnolo *et al.* 2017]
**Conversion-driven freeze-out**

$10^{-2}$
$10^{-6}$
$10^{-10}$
$10^{-14}$
$10^{-18}$

abundance $Y$

$Y_X$

$Y_{\tilde{b}}$

$n_{\text{eq}}$

1    10    100    1000

$x = m_{X_1}/T$

$X$    $Y$    $Y$

$Y$    $Y$

$10^{-7} \sim 10^{-3}$    $10^{-1} \sim 1$    $\lambda$

# What values of λ are cosmologically motivated?

So far: thermalized dark matter
$\Rightarrow$ initial conditions (after inflation) washed out

$\Omega h^2$

schematic plot

$10^{-7} \sim 10^{-3}$   $10^{-1} \sim 1$   $\lambda$

# What values of λ are cosmologically motivated?

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[Covi *et al.* 1999; Feng *et al.* 2003]

superWIMPs (late decays)

$\Omega h^2$

schematic plot

$10^{-13} \sim 10^{-6}$

$10^{-7} \sim 10^{-3}$

$10^{-1} \sim 1$

$\lambda$

# What values of λ are cosmologically motivated?

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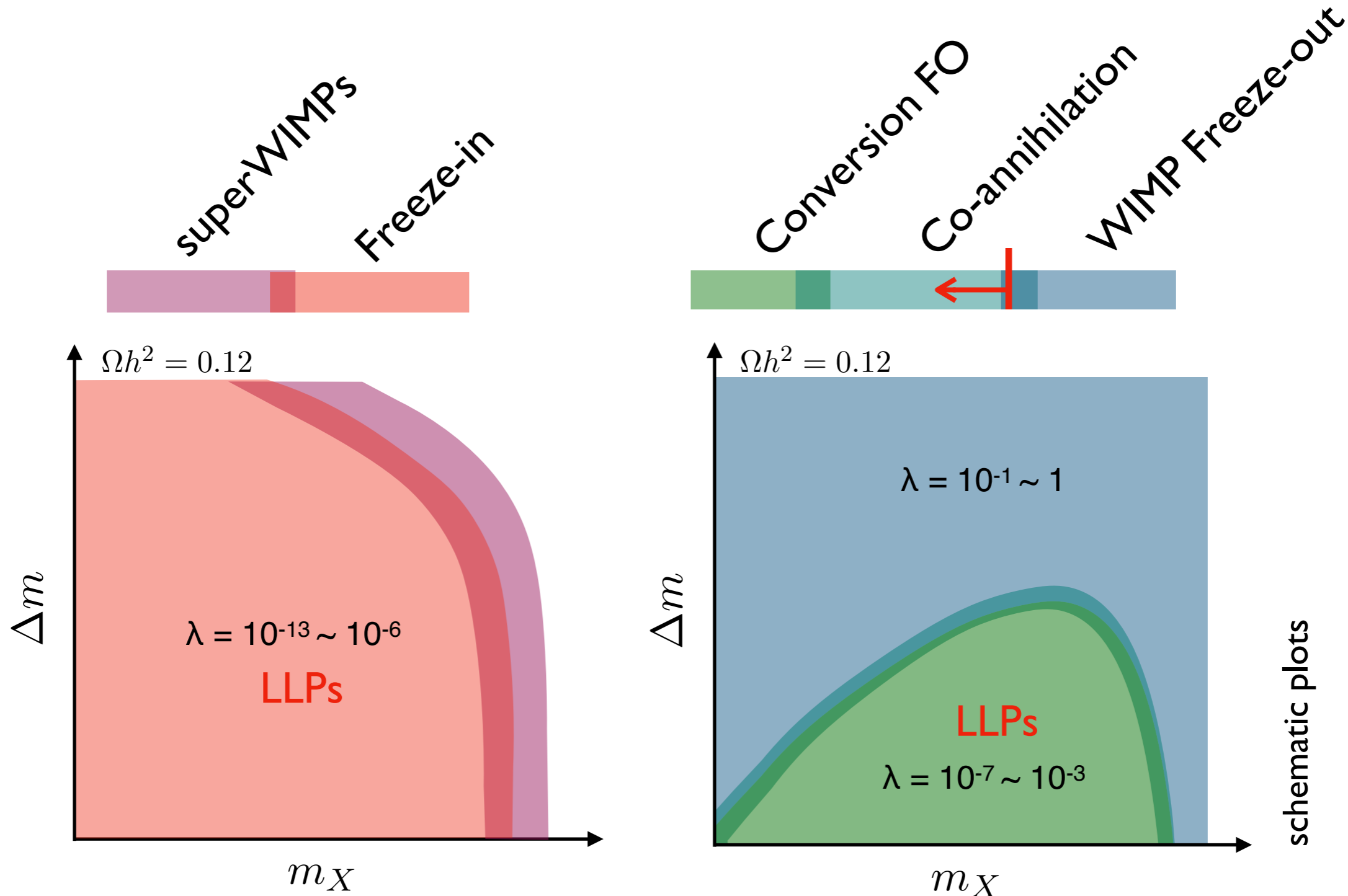
# What values of λ are cosmologically motivated?

superWIMPs

Freeze-in

Conversion FO

Co-annihilation

WIMP Freeze-out

$\Omega h^2$

Long-lived particles at LHC!

schematic plot

$10^{-15} \sim 10^{-6}$

$10^{-7} \sim 10^{-3}$

$10^{-1} \sim 1$

$\lambda$
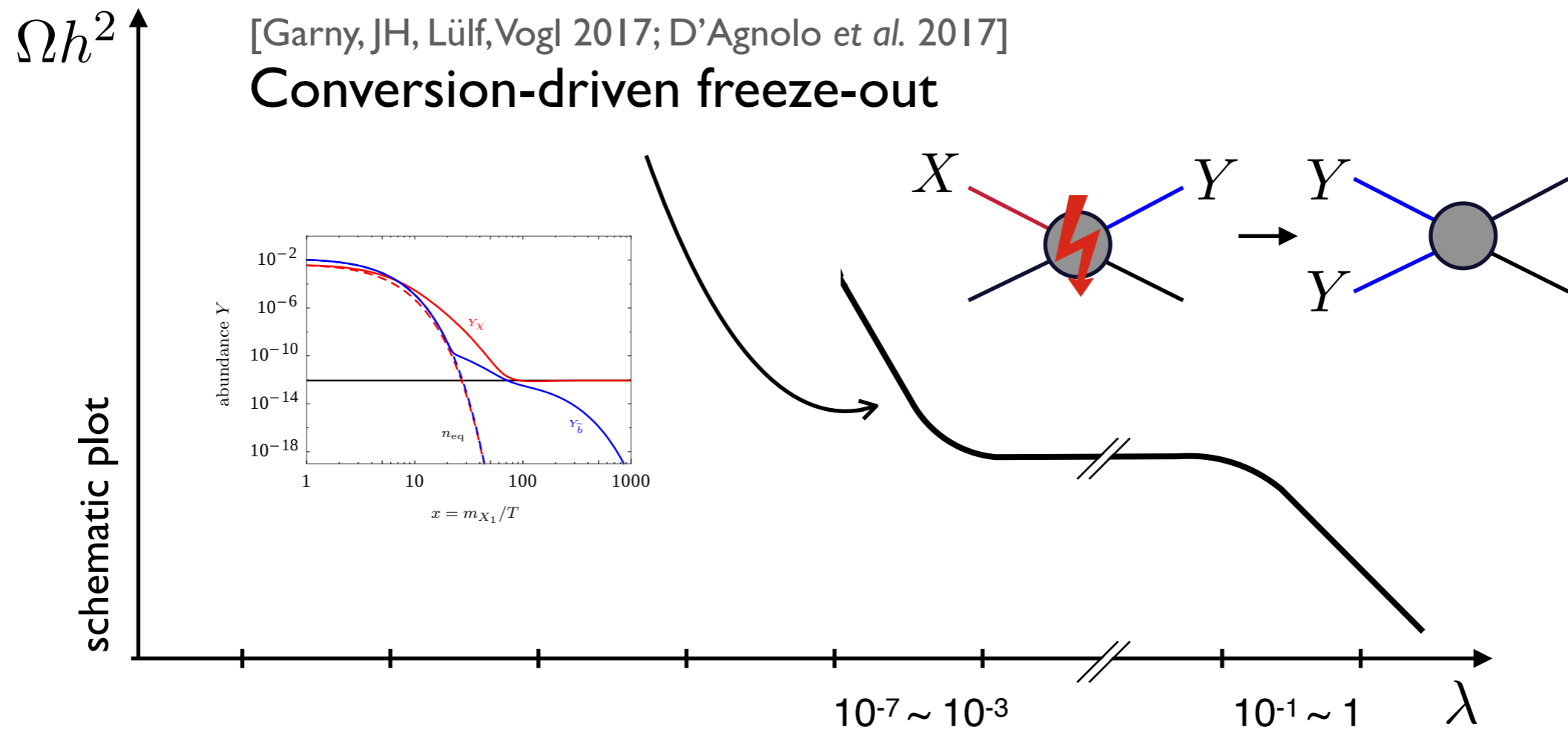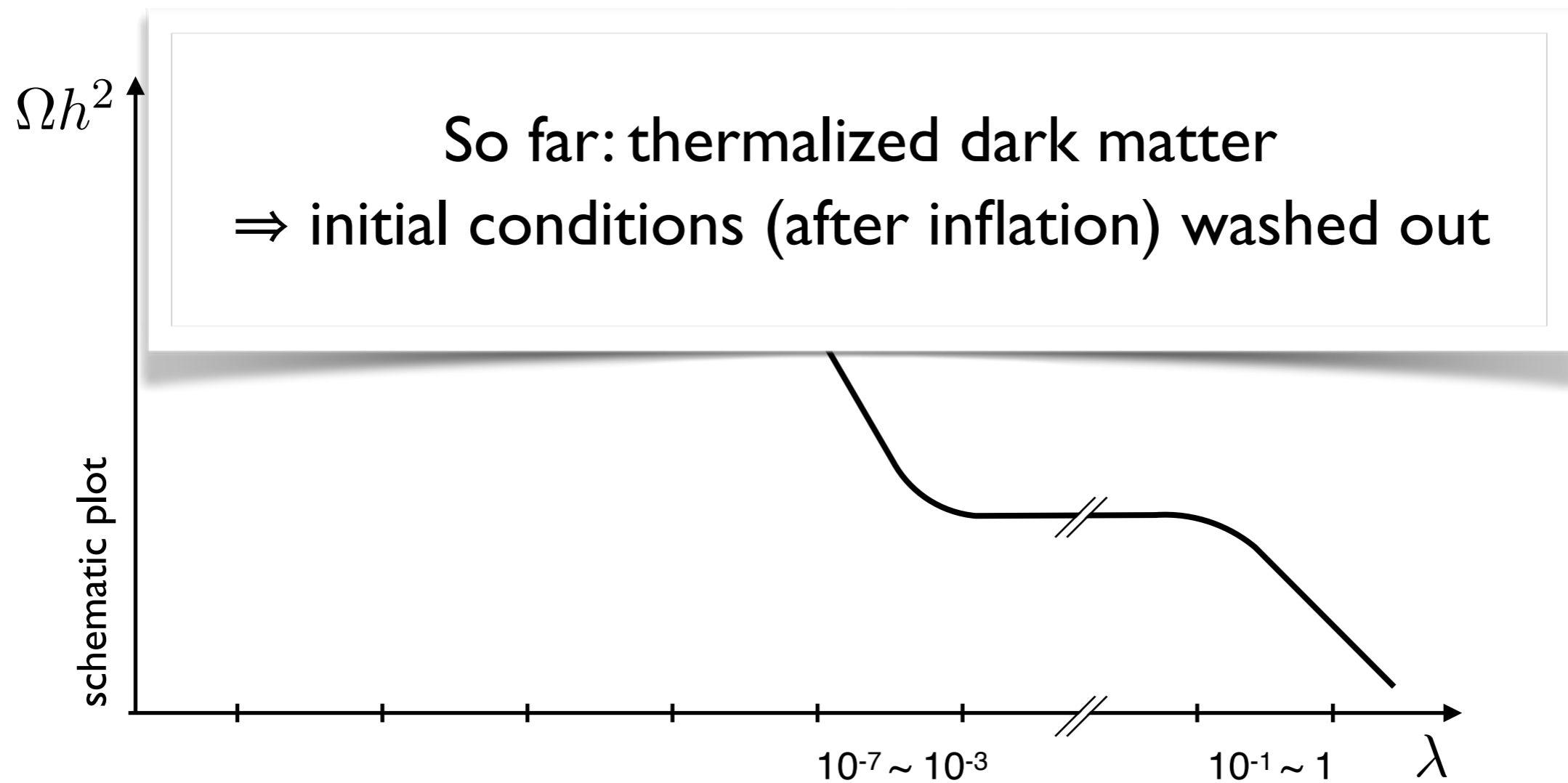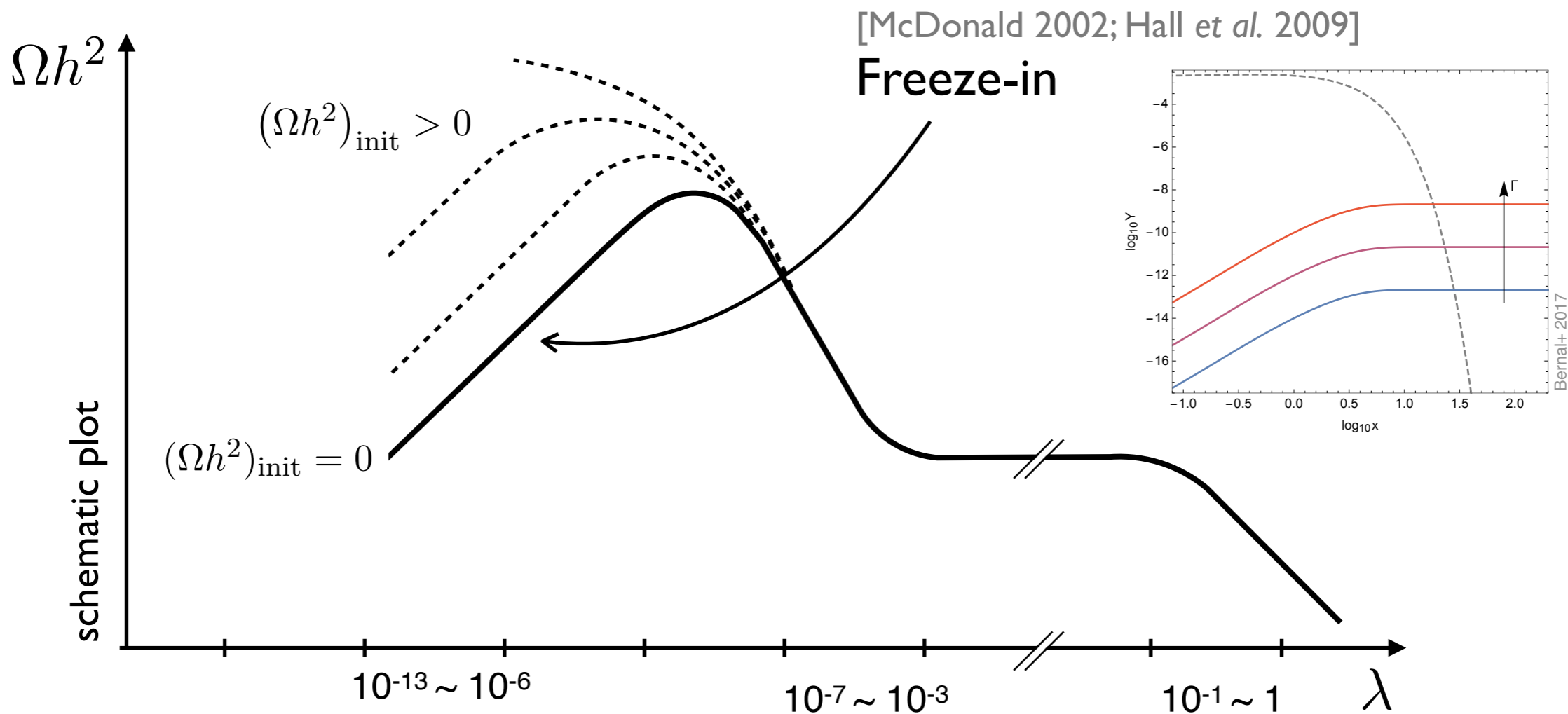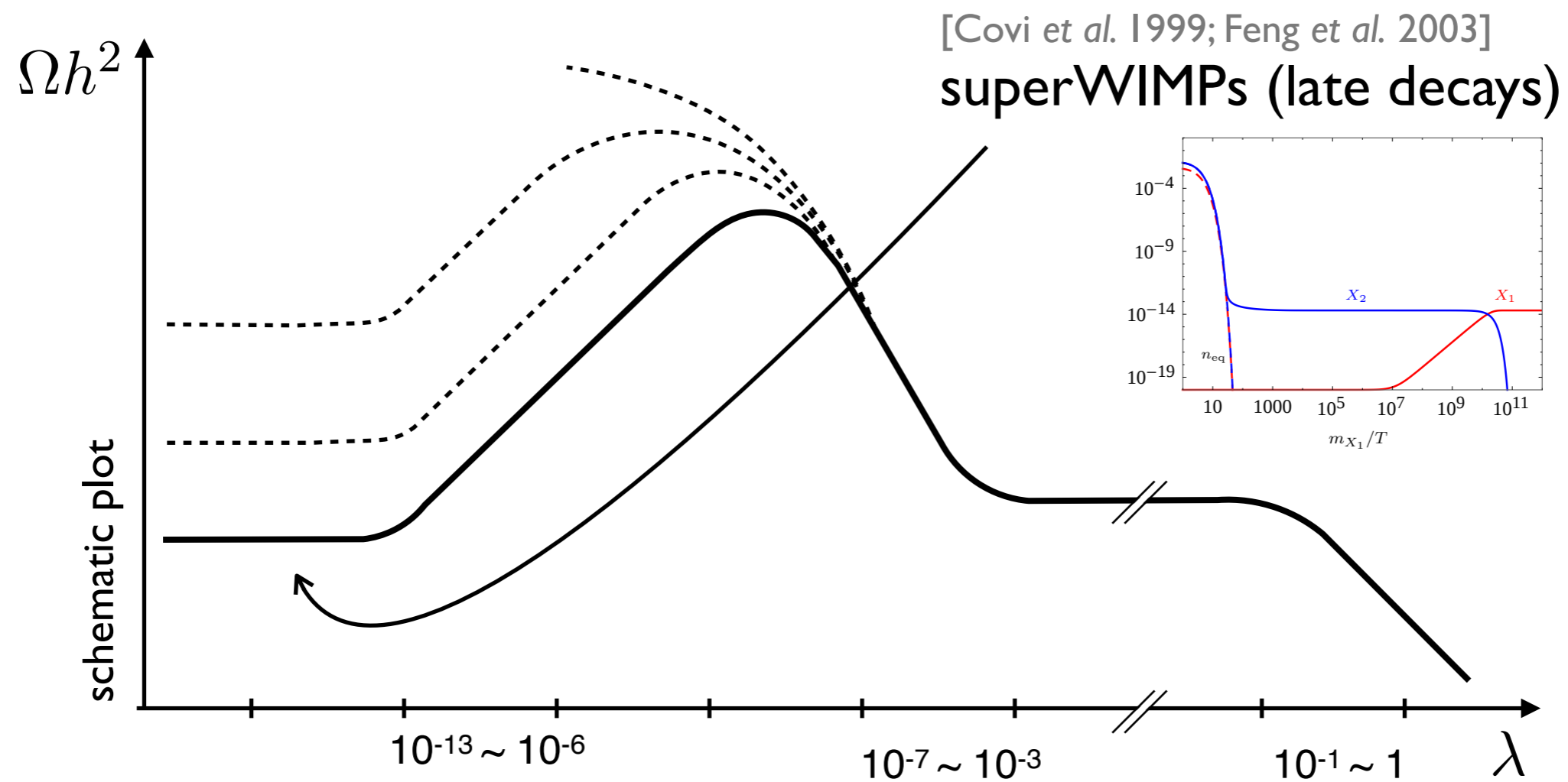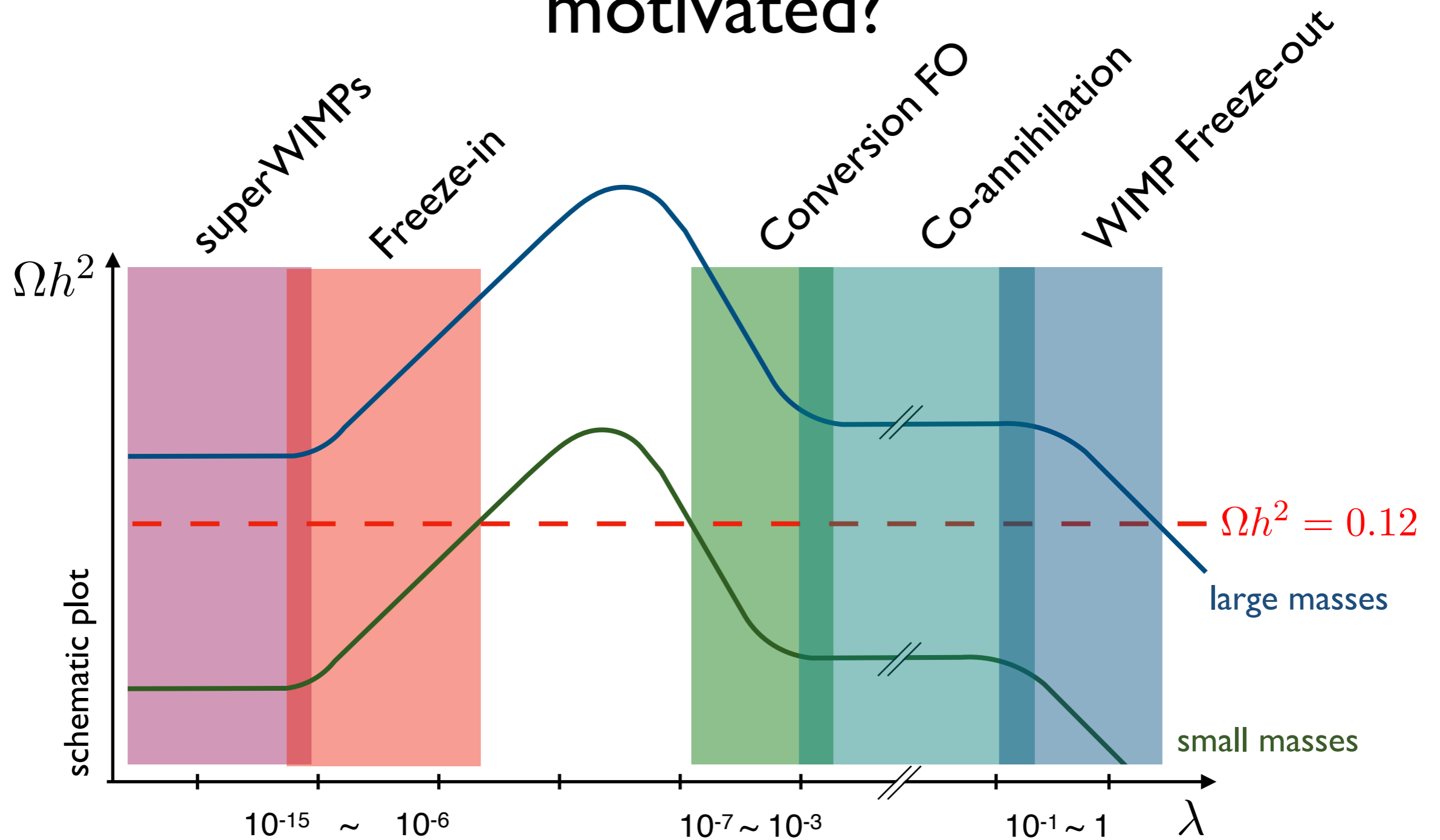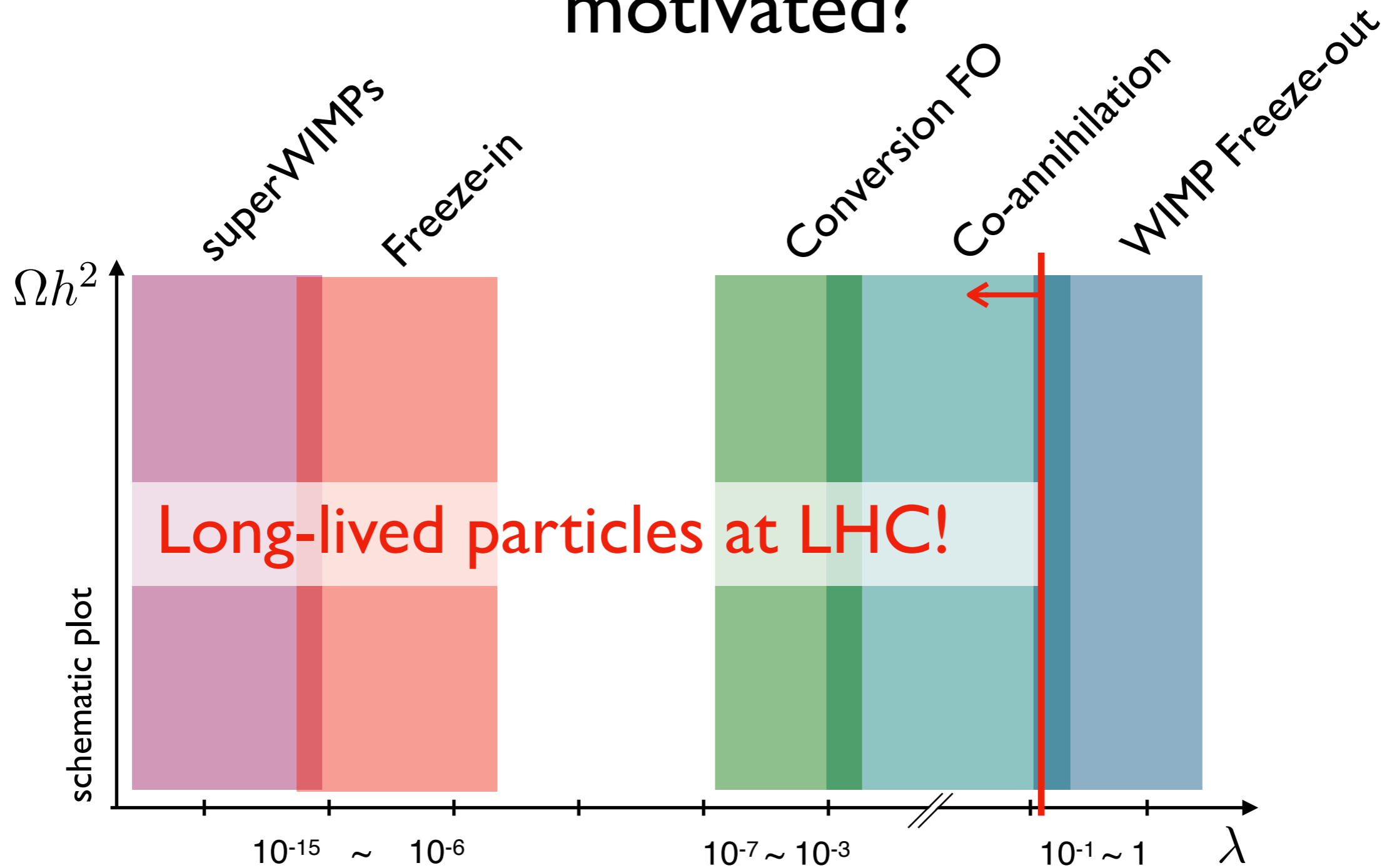
[see e.g. JH 1805.07361]

# For which masses?

# Top-philic simplified dark matter model

[*cf.* Ibarra, Pierce, Shah, Vogl 1501.03164; Delgado, Martin, Raj 1608.05345]

- ■ Consider SUSY-inspired model:

$$\mathcal{L}_{\text{int}} = |D_\mu \tilde{t}|^2 + \lambda_\chi \tilde{t}\,\bar{t}\,\frac{1 - \gamma_5}{2}\chi + \text{h.c.}$$
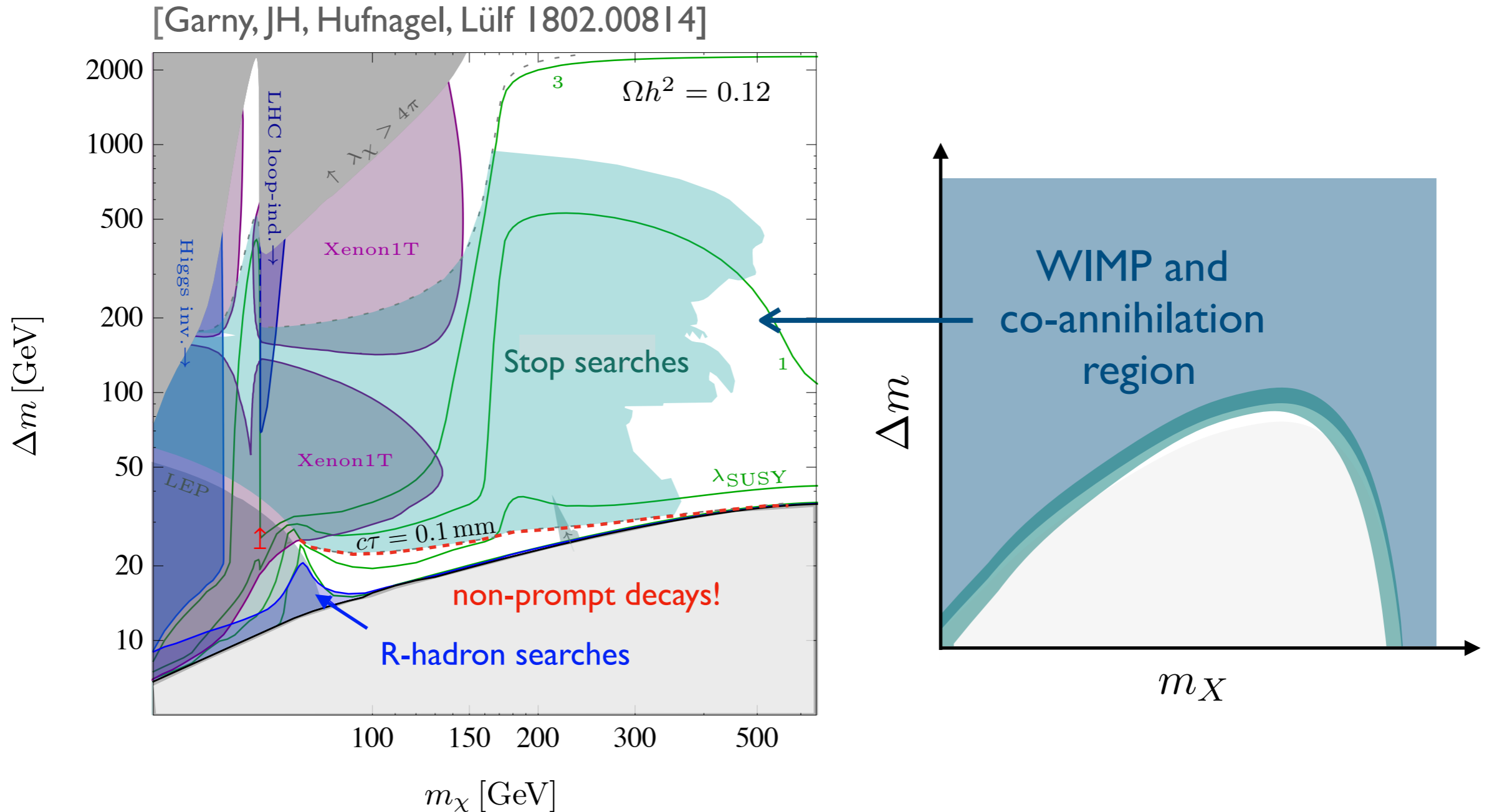
- ■ Majorana DM and ("right-handed") scalar top-partner
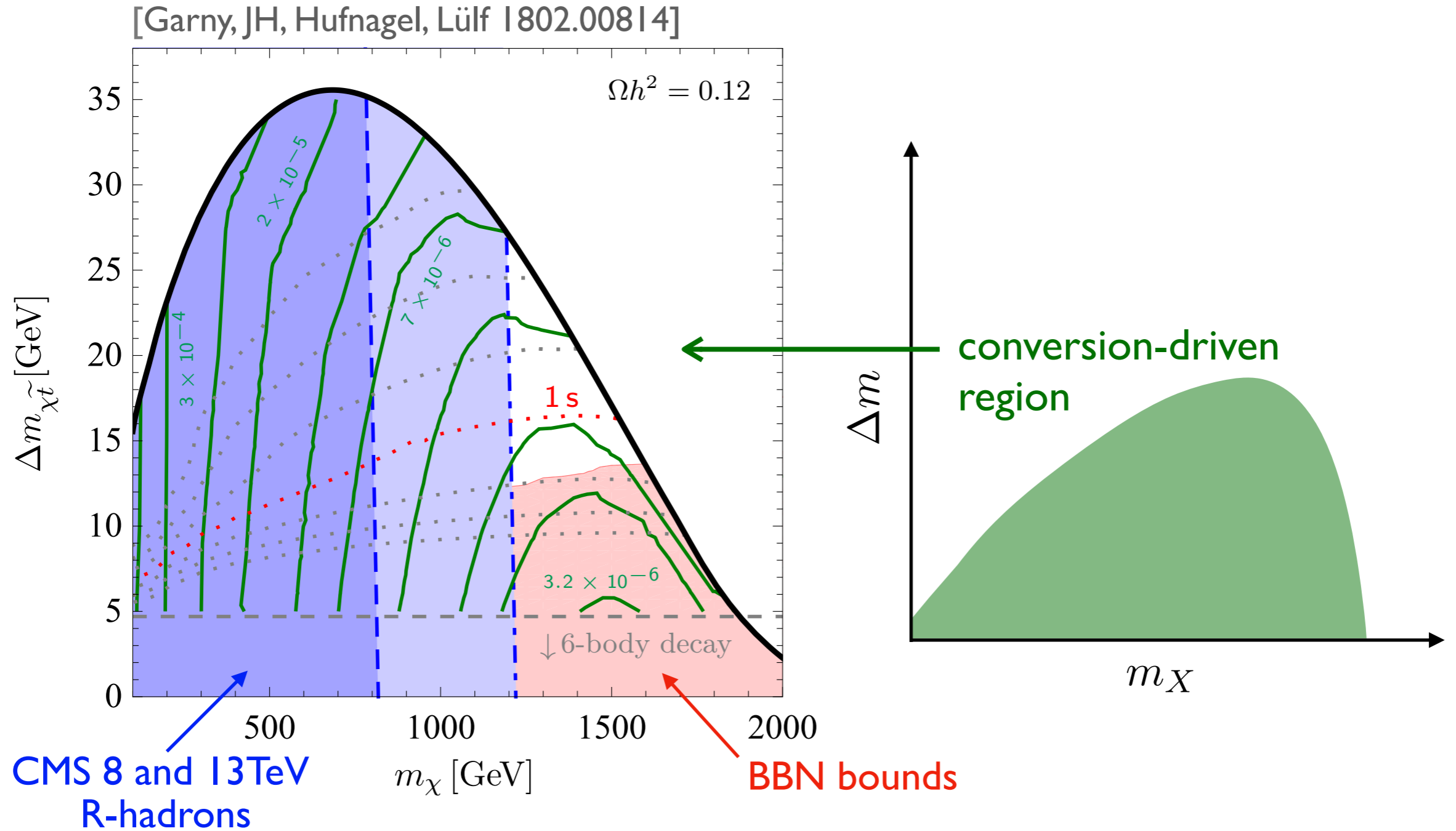


- ■ Yukawa-type interaction:
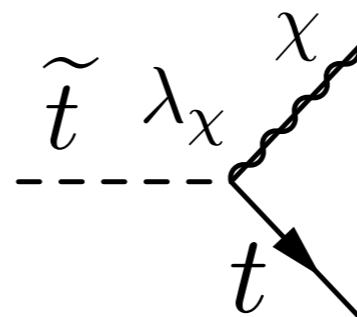


$\lambda_\chi$ is a free parameter here

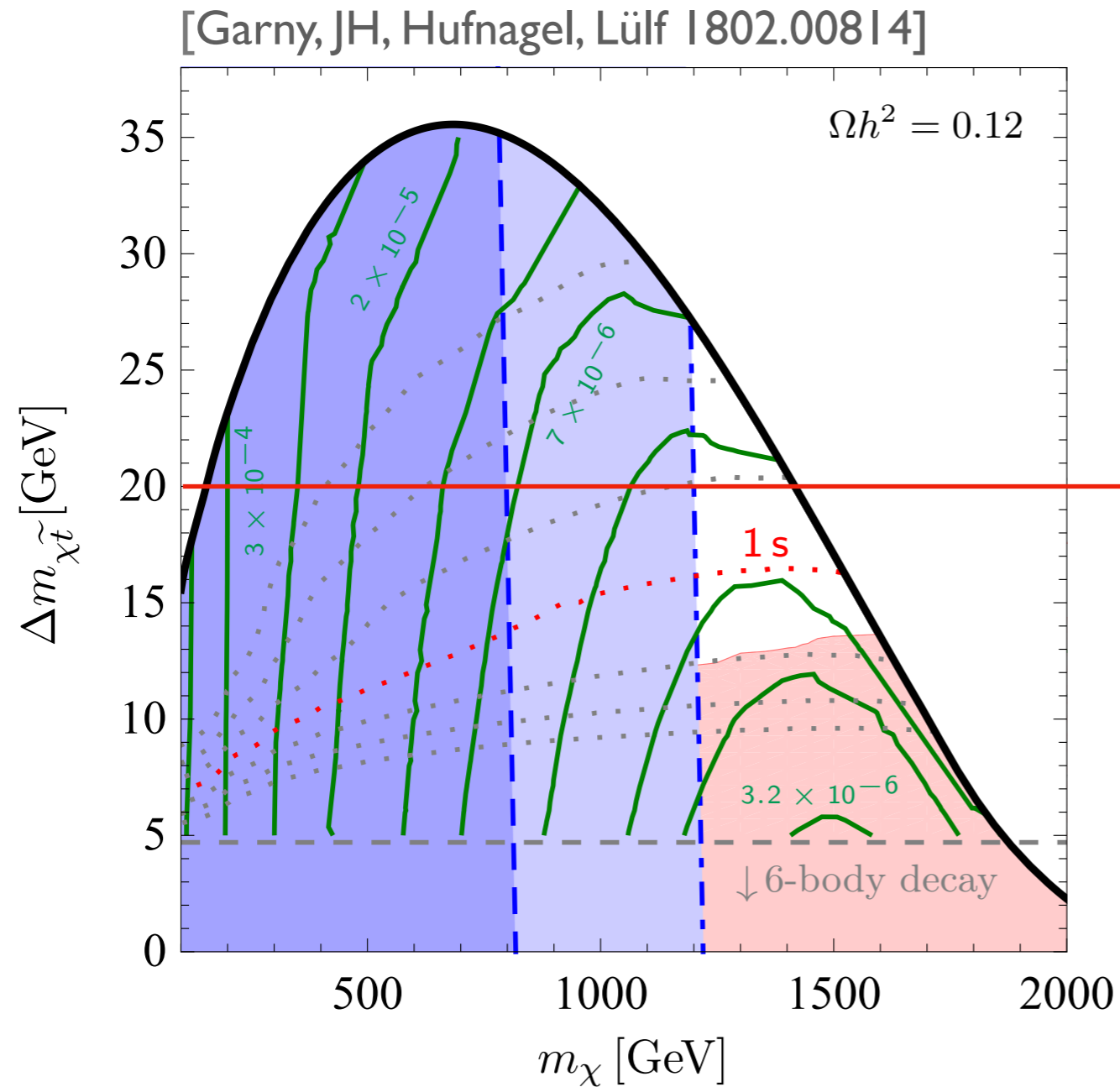[see Belanger *et al.* hep-ph/0505142 for SUSY realization (NMSSM)]
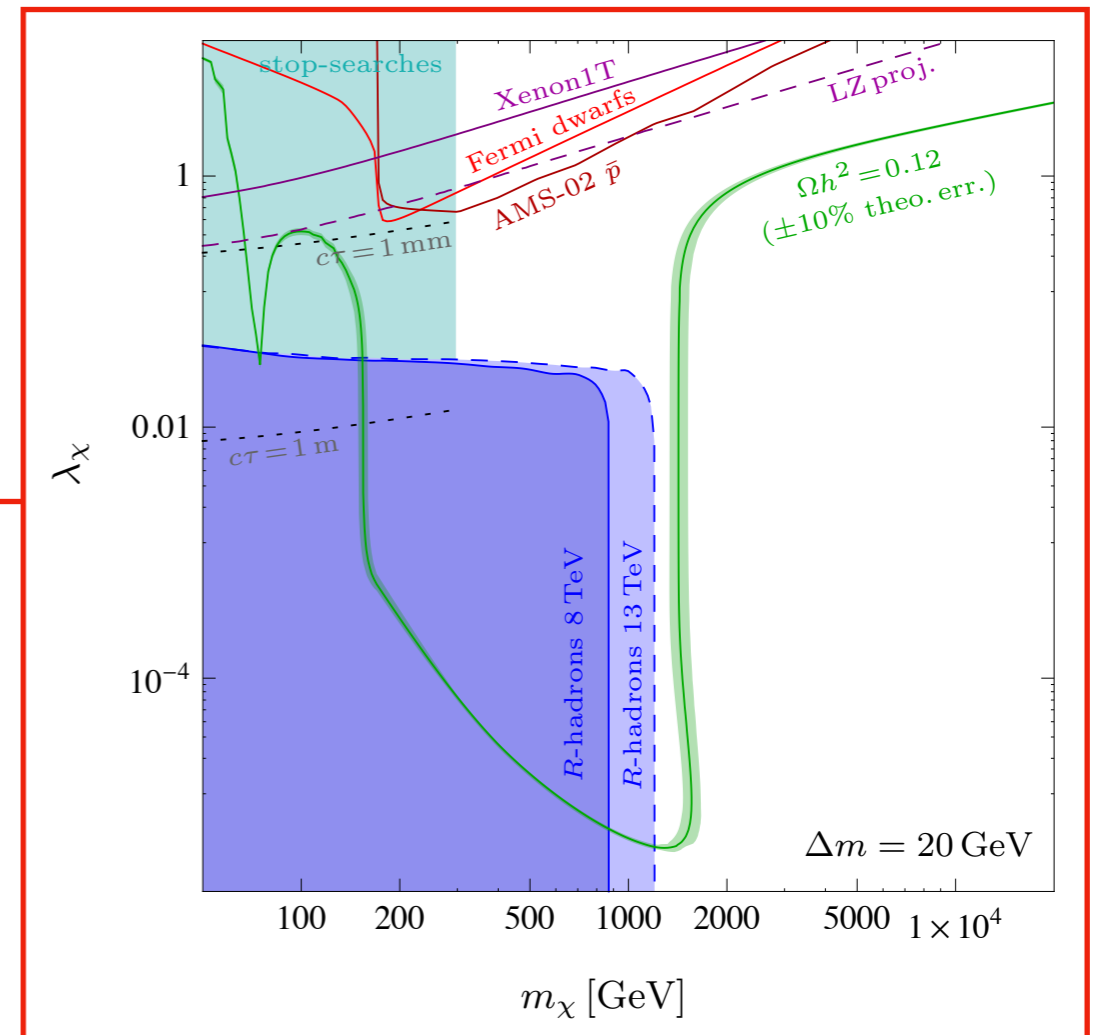
# Experimental constraints



[Garny, JH, Hufnagel, Lülf 1802.00814]

# Experimental constraints



[Garny, JH, Hufnagel, Lülf 1802.00814]

$\Omega h^2 = 0.12$

conversion-driven region

CMS 8 and 13 TeV R-hadrons

BBN bounds

# Experimental constraints



[Garny, JH, Hufnagel, Lülf 1802.00814]

Slice at $\Delta m = 20\,\mathrm{GeV}$:

# Same with a bottom partner

[Garny, JH, Lülf, Vogl 1705.09292]

**Conversion-driven freeze-out:**

$$\Omega h^2 = 0.12$$
— $\lambda_\chi / 10^{-7}$
⋯ $c\tau/\text{cm}$

[Fuks, JH, Lessa, No, Sekmen, Sengupta, Zurita, Les Houches 2019 report]

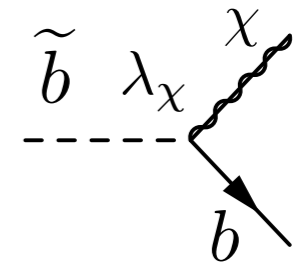ATLAS displaced vertices [1710.04901]

ATLAS disappearing track [1712.02118]

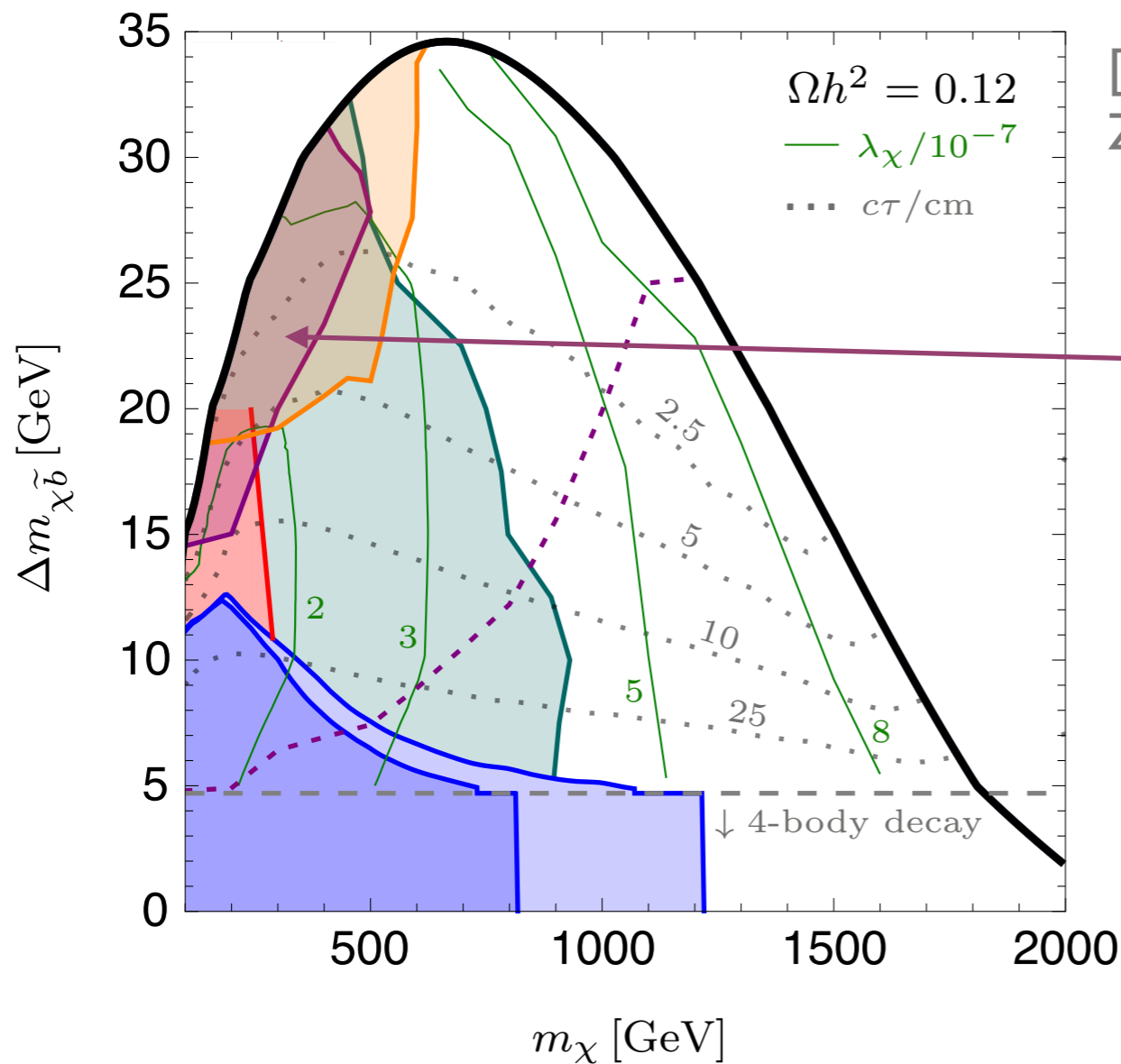CMS 8 and 13TeV R-hadrons

*ATLAS multijet [ATLAS-CONF-2019-040]

**ATLAS monojet [1604.07773]

# Same with a bottom partner
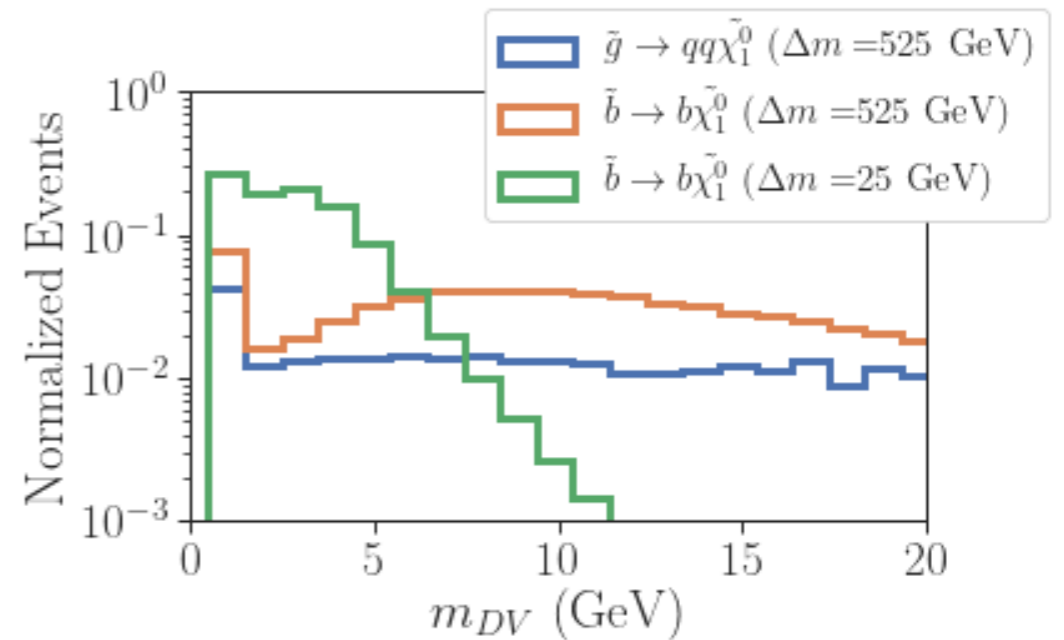
[Garny, JH, Lülf, Vogl 1705.09292]
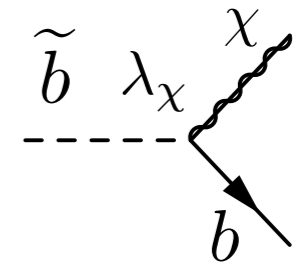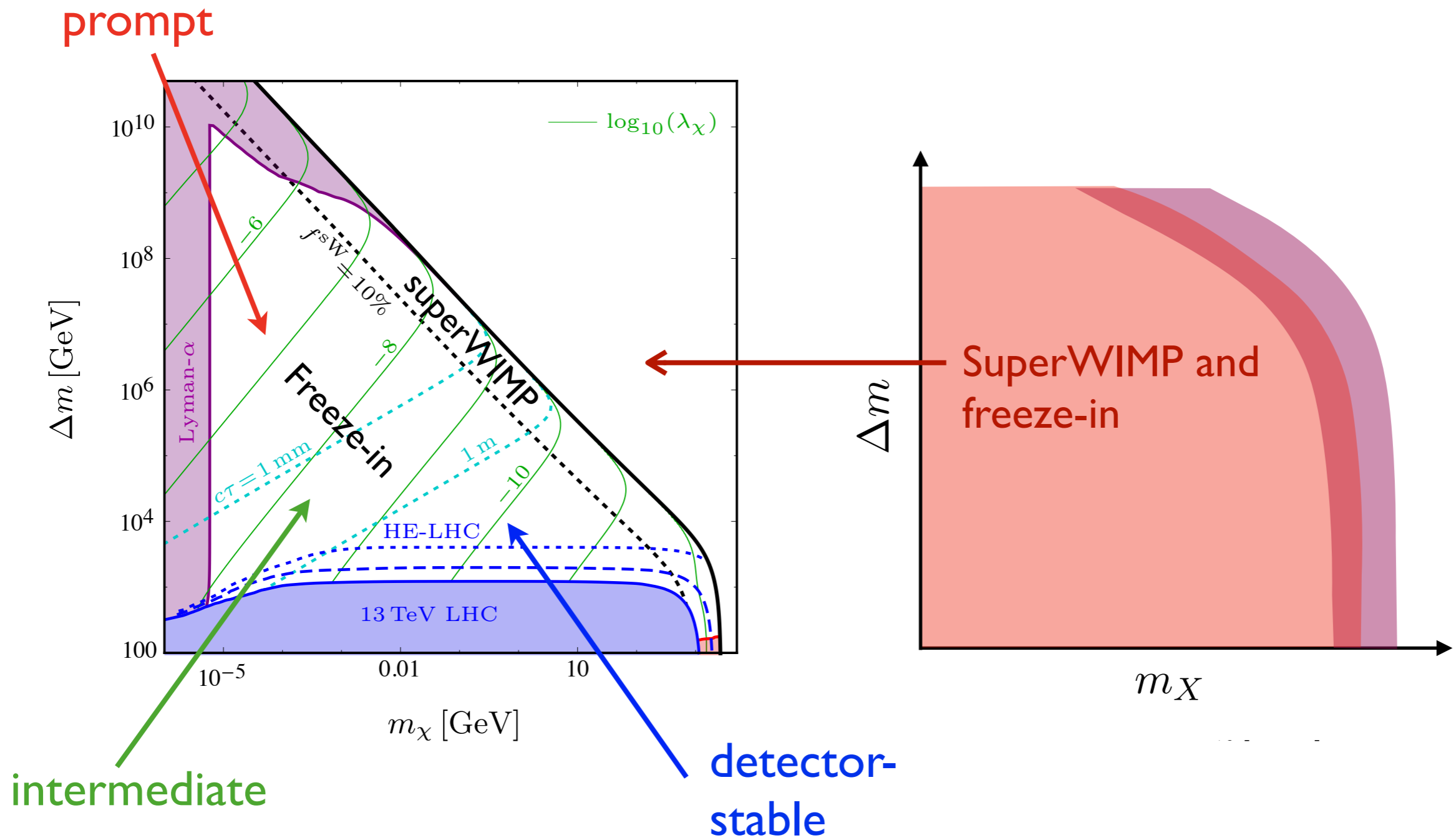


Conversion-driven freeze-out:

[Fuks, JH, Lessa, No, Sekmen, Sengupta, Zurita, Les Houches 2019 report]

ATLAS displaced vertices [1710.04901]

# Non-thermalized dark matter

[Garny, JH 1809.10135]



prompt

intermediate

detector-stable

SuperWIMP and freeze-in

[see also Bélanger *et al.* 1811.05478]

# Thermalized dark matter

- Three cosmologically viable regions:
  - WIMP dark matter
  - Strong co-annihilations
  - Conversion-driven freeze-out } Long-lived particles

- Characteristic: relatively small mass splitting O(10GeV) up very small coupling

- Blind spots: apply prompt searches to non-prompt decays?

# Non-thermalized dark matter

- Cosmologically viable: SuperWIMP / freeze-in

- Characteristic: even smaller couplings, not necessarily small mass splittings

# Take-(at-)home messages

- There's much more than the WIMP!
  Even in such simple $t$-channel models

- Huge range of couplings cosmologically interesting

- Long-lived particles rather rule than exception

- Pheno similar for entire class of $t$-channel models
  Some interesting peculiarities though [more work in progress: Arina, Fuks, JH, Krämer, Mantani, Mawatari, Mies, Panizzi, Salko]

# Thank you