Composite scalar dark matter

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MF, Sylvain Lacroix, Alfredo Urbano, in preparation

New Perspectives in Dark Matter ☀ *Lyon 22-25/10/13*

Outline

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- a strongly-coupled sector at the multi-TeV scale and the Higgs as a composite pNGB
- DM as a composite pNGB coupled to the composite Higgs: the interactions are determined by global symmetries
- phenomenology: the effect of compositeness on the DM relic density, the Higgs searches & the DM searches

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- approximate symmetry: the scale of spontaneous SB is larger than the scale of explicit SB / the source of explicit SB are weak couplings

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- Explicit SB parameters induce both the pNGB mass & its couplings to the SM, that control its relic density: compelling correspondence between m_{DM} and Ω_{DM}

- Rationale for DM stability: either SB preserves a remnant global symmetry that forbids DM decays, or DM is sufficiently long-lived because the spontaneous SM scale f is very large, $\tau_{DM} \sim f^2$

A oversimplified set-up

- Before coming to compositeness, a light pNGB just means that the effective theory to be studied amounts to the SM plus a gauge singlet real scalar η
- Assuming a parity $\eta \to -\eta$, the only renormalizable coupling to the SM is the Higgs portal: $\lambda\, H^\dagger H\, \eta\, \eta$
- A warm-up exercise: let us compute the η relic density in this minimal case

Minimal renormalizable model extensively studied: Silveira Zee '85, McDonald '94, Burgess Pospelov ter Veldhuis '01, ...

The Higgs portal to dark matter

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\lambda}{2} H^\dagger H \, \eta \, \eta \qquad\qquad m_\eta^2 = \lambda v^2$$

(i) explicit SB induces a quartic coupling between H and a pNGB η

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At temperatures $T \sim m_h$ the interaction λ may or may not thermalize η

$$\Gamma(h \to \eta\eta) = \frac{1}{16\pi} \lambda^2 \frac{v^2}{m_h} \sqrt{1 - \frac{4m_\eta^2}{m_h^2}} \qquad \text{versus} \qquad \mathcal{H}(T = m_h) \simeq 17 \frac{m_h^2}{M_{Planck}}$$

Thermalization for: $\lambda \gtrsim 6 \times 10^{-8} \left(\frac{m_h}{125 \text{ GeV}} \right)^{3/2}$ or $m_\eta \gtrsim 42 \text{ MeV}$

Freeze-out or... freeze-in

$$-\mathcal{L}_{eff} \supset \frac{\lambda}{2} H^\dagger H\, \eta\, \eta$$

- Freeze-out: η thermalizes and later decouples, at $T \leq m_\eta$.
  To obtain the correct Ω_{DM} one needs $m_\eta \approx 50$ GeV.

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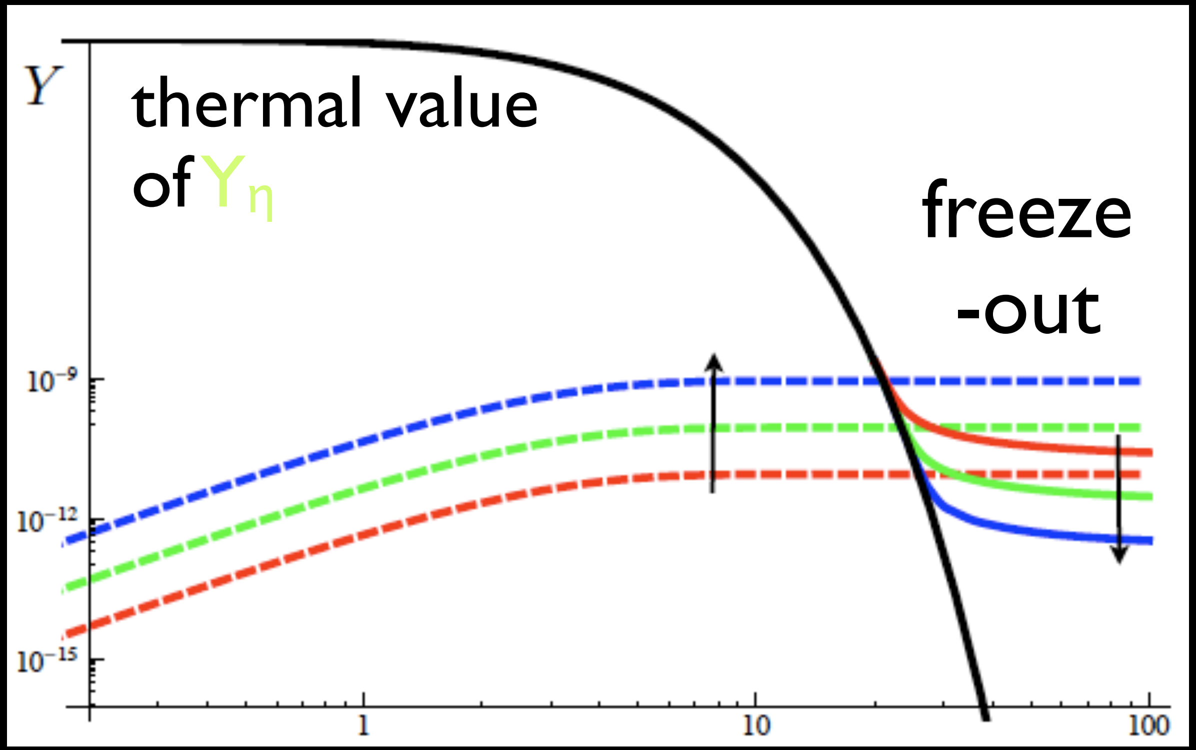

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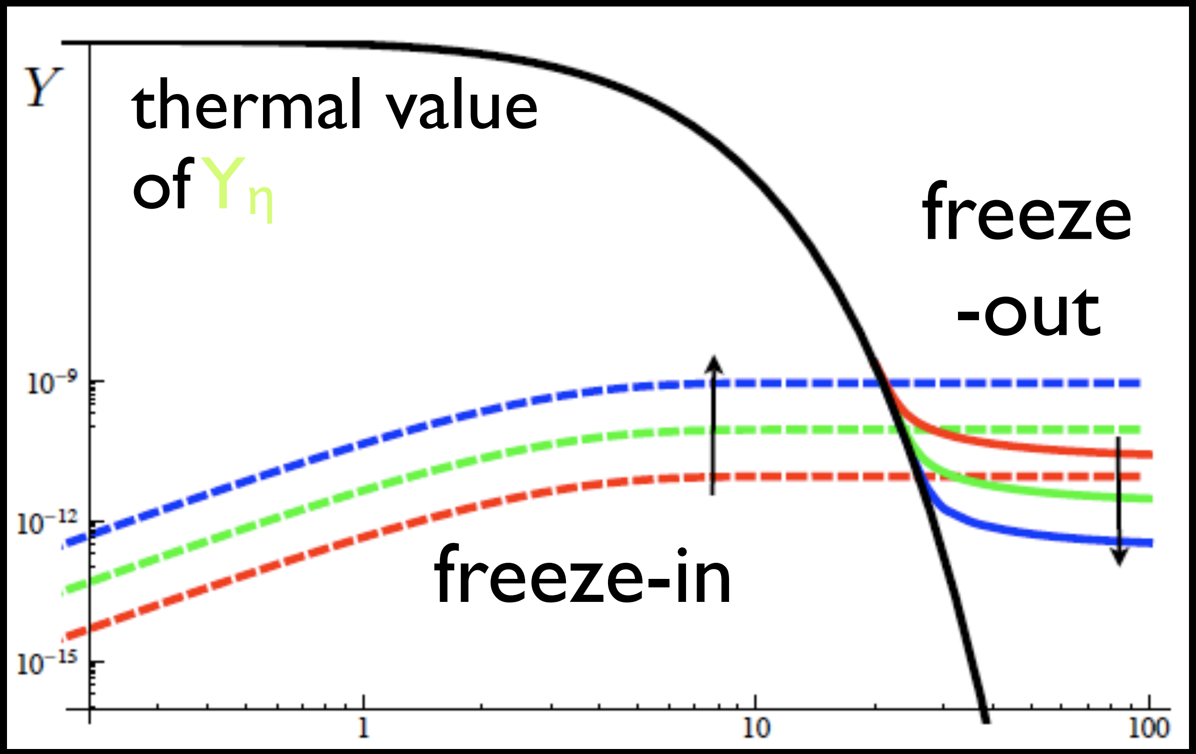

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- Freeze-in: a less-than-thermal population of η's is produced by the annihilation/decay of heavier particles, X= h, W, Z.
  The η number density reaches a plateau at $T \approx m_X$.
  We found that Ω_{DM} is reproduced for $m_\eta \approx 3$ MeV ($\lambda \approx 10^{-10}$).

  Frigerio, Hambye, Masso 2011

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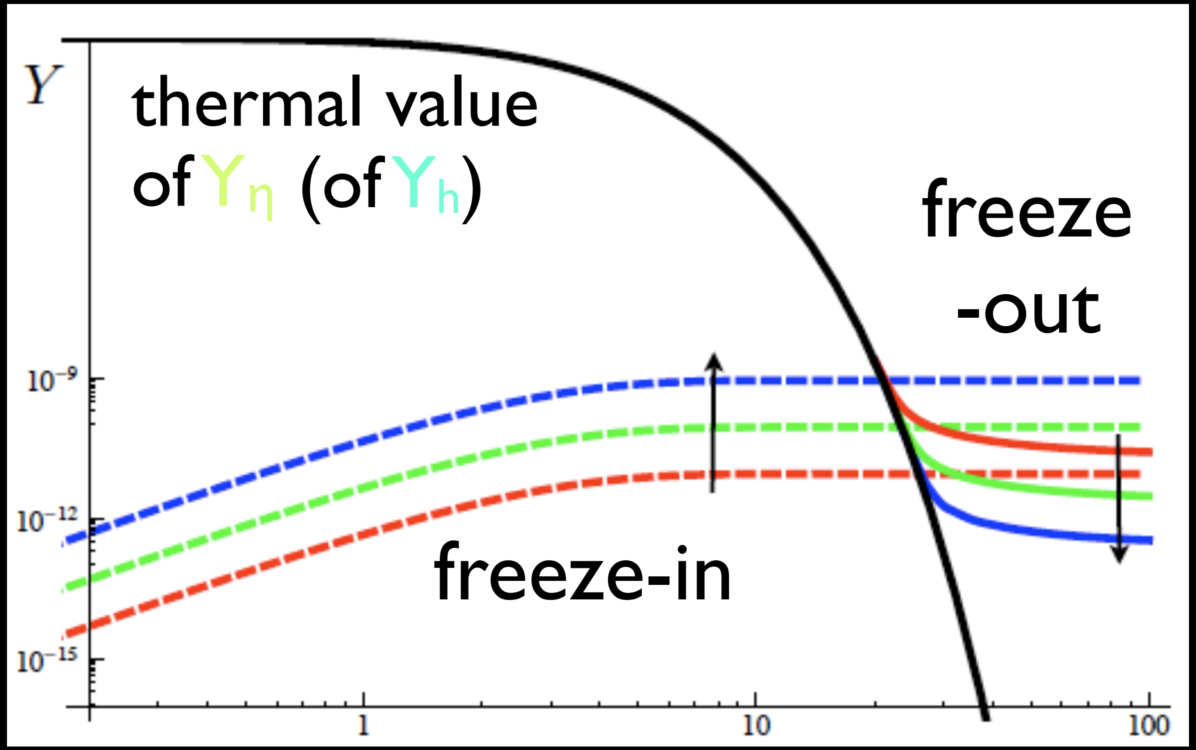

$z_{f.o.} = m_\eta/T$
$z_{f.i.} = m_h/T$

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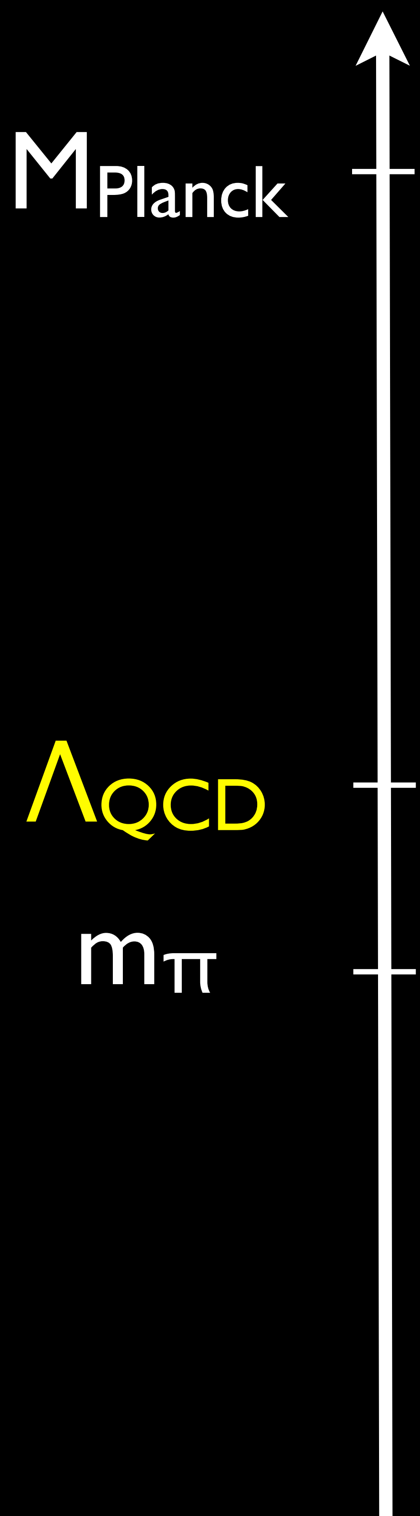
Composite pNGBs

The QCD scale and the pions



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dimensional transmutation
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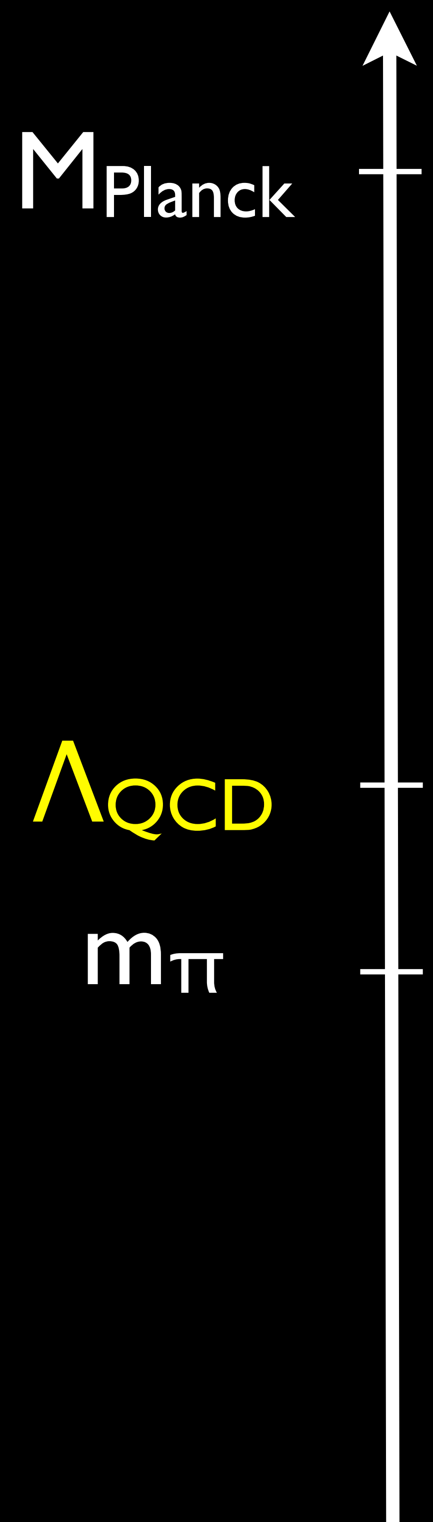

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$$\alpha_s \sim 1 \ , \quad SU(2)_L \times SU(2)_R \to SU(2)_V$$

Spontaneous breaking of chiral symmetry leads to
3 pNGBs: the composite mesons π^0, $\pi^\pm$
Explicit breaking by quark masses makes them massive

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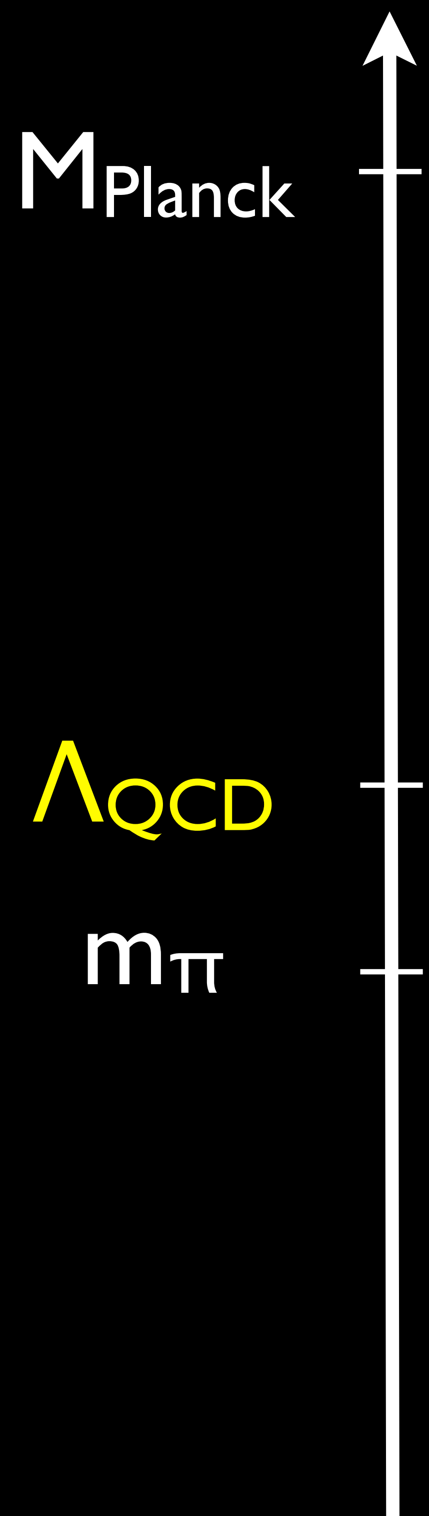

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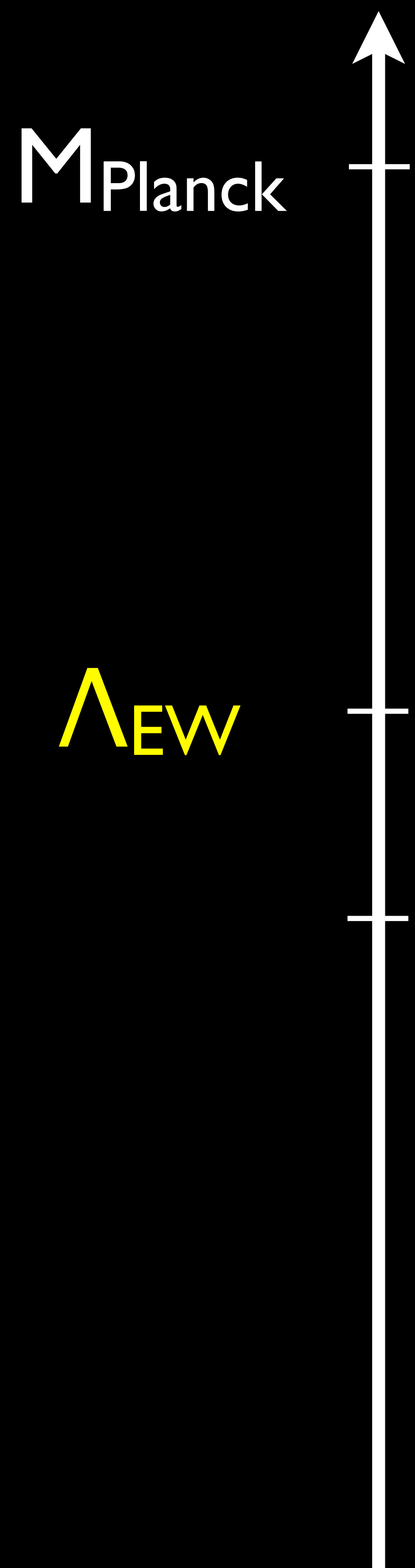
$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda_{QCD}^3$$

In fact the global symmetry turned out to be larger, leading to more pNGBs in the spectrum: kaons and η^0

$$\alpha_s \sim 1 \; , \quad SU(3)_L \times SU(3)_R \to SU(3)_V$$

The EW scale and the Higgs



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M_{Planck}

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The lightest states of a strong sector are the pNGBs associated to its global symmetries

Λ_{EW}

$$SO(5) \to SO(4) \qquad H \sim 4_{SO(4)}$$

Remnant symmetry is $SU(2)_L$ plus custodial

m_h

The pNGB composite Higgs h is naturally lighter than the new strongly-coupled physics: $m_h << \Lambda_{EW}$

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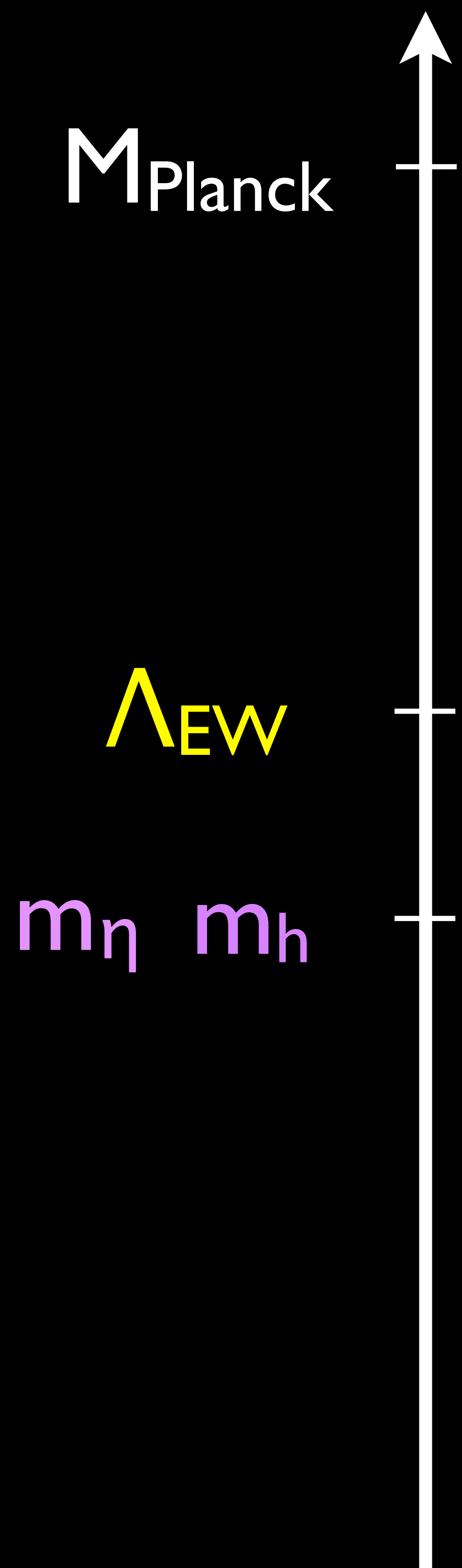
Gauge couplings g,g' and Yukawa couplings y_t, y_b, ... break explicitly $SO(5) \to SU(2)_L$ and induce EWSB radiatively

The EW scale and the DM



The global symmetry may be larger

In particular, the set of composite pNGBs can include the Higgs doublet H and a gauge singlet η

$$O(6) \to O(5) \qquad (H,\eta) \sim 5_{O(5)} = (4+1)_{SO(4)}$$

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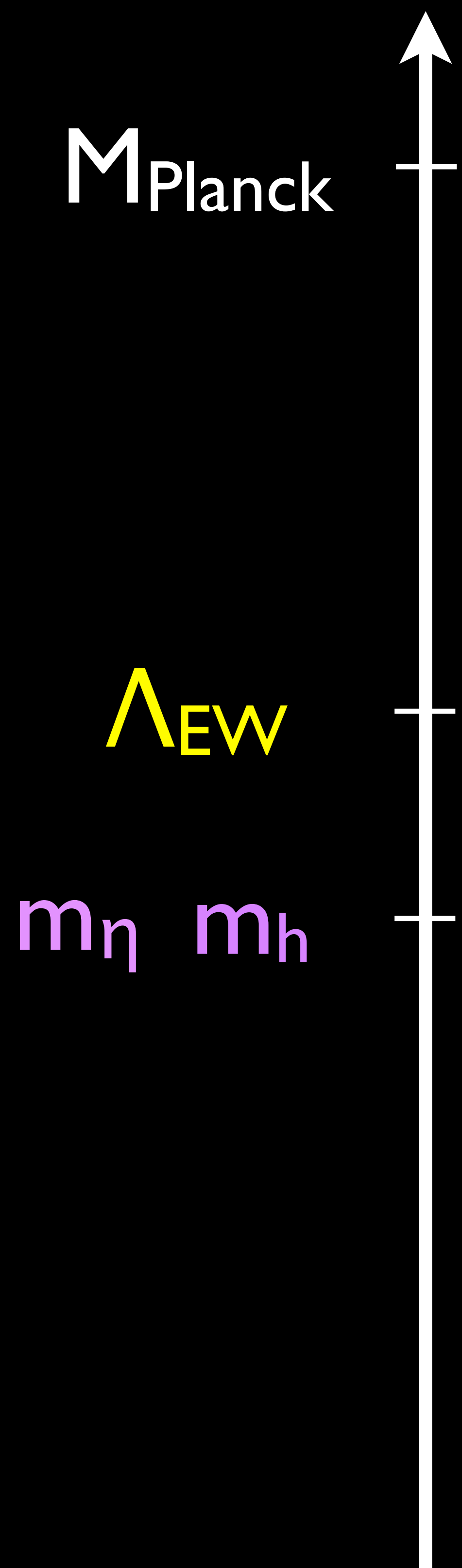

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The composite singlet η is born automatically
with the mass & the interactions of a WIMP

MF,Pomarol,Riva,Urbano'12

The composite sector (I)

$$\mathcal{L} = \mathcal{L}^{G_{SM}}_{elementary} + \mathcal{L}^{G\to K}_{composite} + \mathcal{L}^{G_{SM}}_{mixing}$$

SM + a new sector strongly coupled & approximately conformal from M_{Pl} down to $\Lambda_{EW} \sim$ TeV, where strong dynamics breaks conformal & global symmetries: $G \to K$

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$$\begin{aligned} G &= O(6)\times U(1) \\ K &= O(5)\times U(1) \supset SU(2)_L \times U(1)_Y \text{ with custodial} \end{aligned}$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos\theta_W^2} = 1 \ , \quad \text{without custodial } \Delta\rho \simeq \frac{v^2}{f^2} \lesssim 10^{-3}$$

The composite sector (II)

The couplings of elementary fields with composite operators break explicitly (weakly) G, while preserving G_{SM}

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$m_\rho = g_\rho f$ — composite resonances with mass $m_\rho \approx$ few TeV and inter-composite coupling $1 < g_\rho < 4\pi$

f — the characteristic scale of the pNGBs chiral lagrangian

$v = 246$ GeV — A non-zero $V_{eff}(H,\eta)$ is generated radiatively by gauge and fermion loops. At the minimum $\langle H \rangle = v$ realizes EWSB.

Giudice-Grojean-Pomarol-Rattazzi '07

The DM global symmetries

At $\Lambda_{EW} \sim$ 3-4 TeV, the strong dynamics breaks spontaneously $O(6) \rightarrow O(5)$

The coset of this non-linear σ-model:

$$\boxed{\Sigma = \exp\left(i\frac{\sqrt{2}\pi^a T^a}{f}\right)\Sigma_0 = \frac{1}{f}\left(h_1,\, h_2,\, h_3,\, h_4,\, \eta,\, \sqrt{f^2 - h^2 - \eta^2}\right)^T}$$

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The DM mass is protected by a shift symmetry $\eta \rightarrow \eta + \alpha$

$$SO(6) \supset SO(4)\times SO(2)_\eta = SU(2)_L \times SU(2)_R \times U(1)_\eta$$

DM effective Lagrangian

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Derivative interactions fixed by the O(6)/O(5) symmetry

$$\mathcal{L}^{\eta}_{kin} = \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2f^2}\partial_\mu |H|^2 \partial^\mu \eta^2 + \ldots$$

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$$\mathcal{L}^{\eta}_{fermions} = \frac{\eta^2}{f^2}\left(c_t y_t\ \overline{q_L}\tilde{H} t_R + c_b y_b\ \overline{q_L} H b_R + h.c.\right) + \ldots$$

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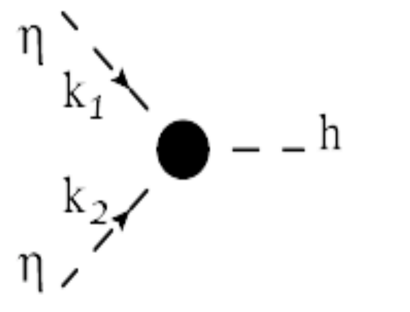
Effective potential generated by fermion loops

$$\mathcal{L}^{\eta}_{pot} = \frac{1}{2}\mu_\eta^2 \eta^2 + \lambda |H|^2 \eta^2 + \ldots$$

m_η > O(100) GeV for c_t = O(1)
m_η > O(10) GeV for c_b = O(1)

Composite DM interactions

$\xi \equiv (v/f)^2$



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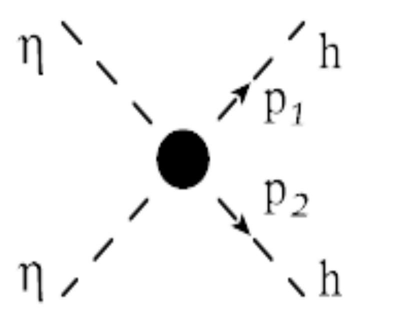
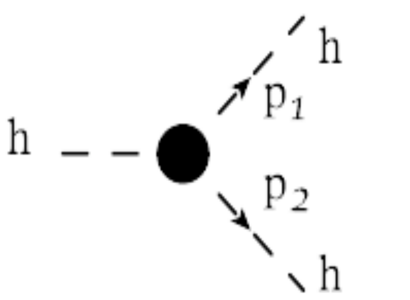
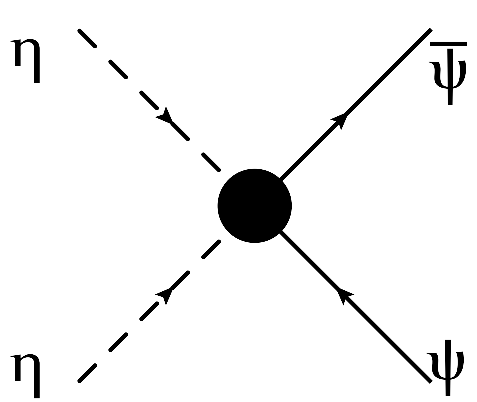


$$\boxed{-2i\lambda}(1-\xi) + \frac{i(1+\xi)(p_1+p_2)^2}{f^2(1-\xi)} - \frac{2i\xi\, p_1\cdot p_2}{f^2(1-\xi)}$$



$$\boxed{\frac{-3im_h^2}{v}}\sqrt{1-\xi} + \frac{2iv}{f^2\sqrt{1-\xi}}\left[(p_1+p_2)^2 - p_1\cdot p_2\right]$$



$$\frac{\sqrt{2}\,ivy_\psi}{f^2}\left[\mathrm{Re}(c_\psi) + i\ \mathrm{Im}(c_\psi)\gamma^5\right]$$

Couplings in the case SM + singlet with no compositeness

Composite DM interactions

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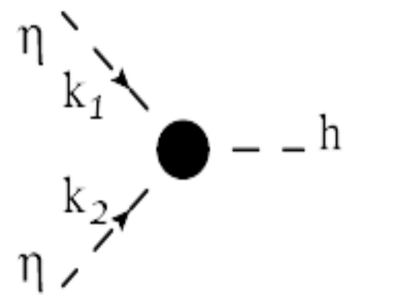

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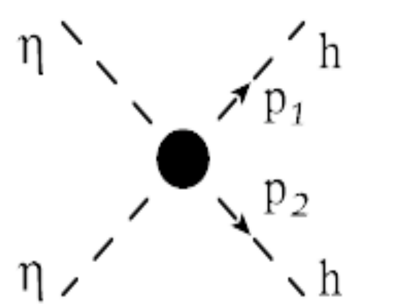

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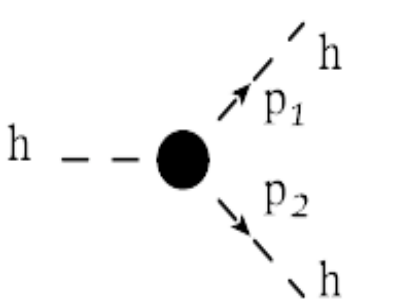

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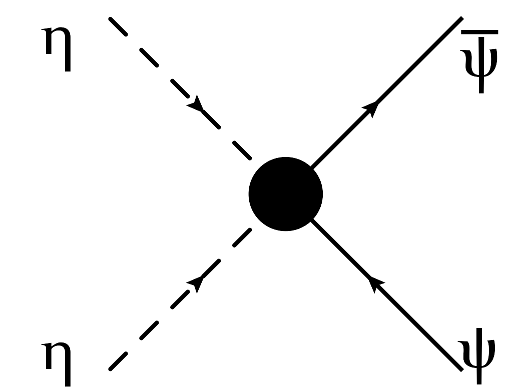

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Three main effects of compositeness:

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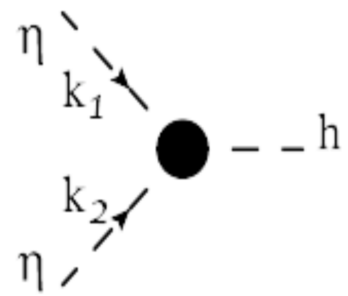
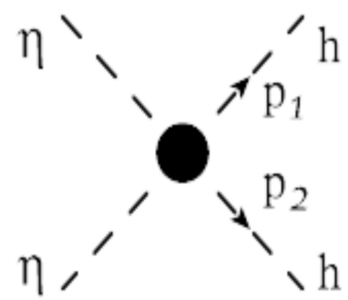
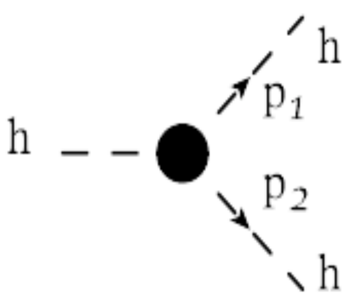
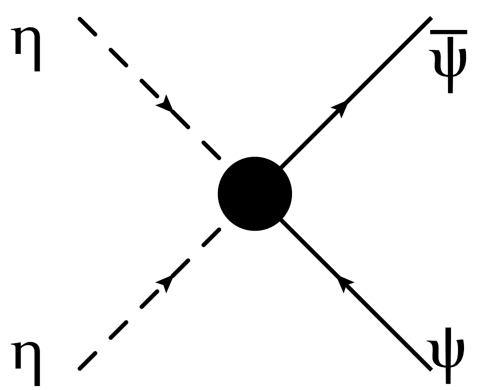
	$\boxed{-2iv\lambda}\sqrt{1-\xi} + \frac{iv(k_1+k_2)^2}{f^2\sqrt{1-\xi}}$
	$\boxed{-2i\lambda}(1-\xi) + \frac{i(1+\xi)(p_1+p_2)^2}{f^2(1-\xi)} - \frac{2i\xi\, p_1 \cdot p_2}{f^2(1-\xi)}$
	$\boxed{\frac{-3im_h^2}{v}}\sqrt{1-\xi} + \frac{2iv}{f^2\sqrt{1-\xi}}[(p_1+p_2)^2 - p_1 \cdot p_2]$
	$\frac{\sqrt{2}\, ivy_\psi}{f^2}\left[\mathrm{Re}(c_\psi) + i\ \mathrm{Im}(c_\psi)\gamma^5\right]$

Couplings in the case SM + singlet with no compositeness

Three main effects of compositeness:

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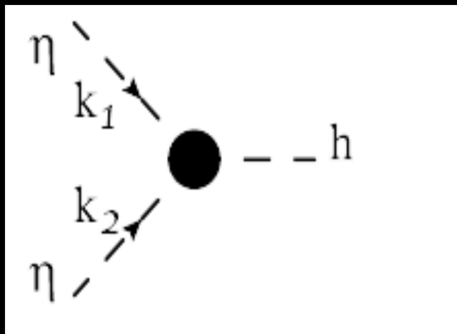
Composite DM interactions

$\xi \equiv (v/f)^2$



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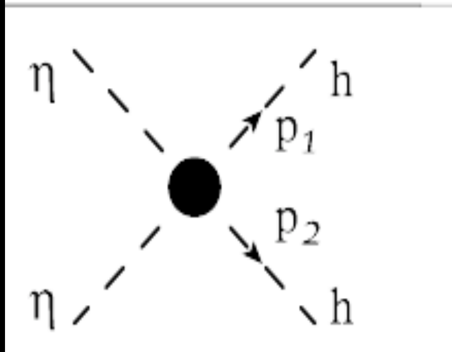

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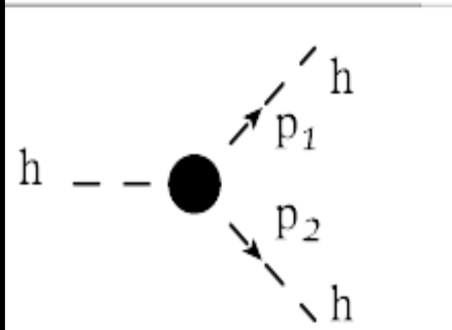

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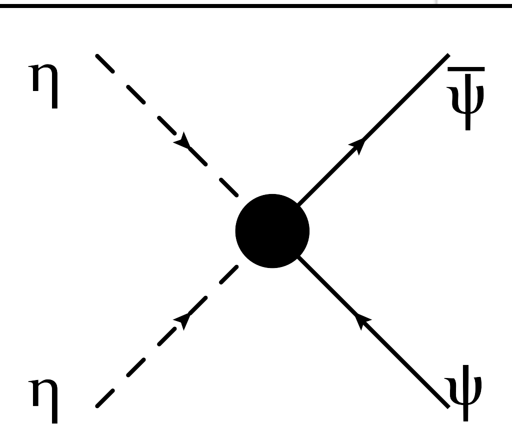

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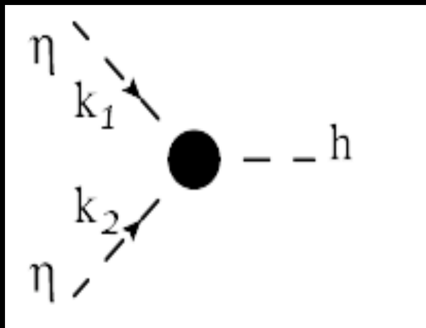

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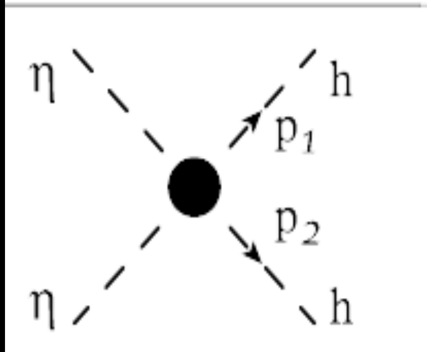

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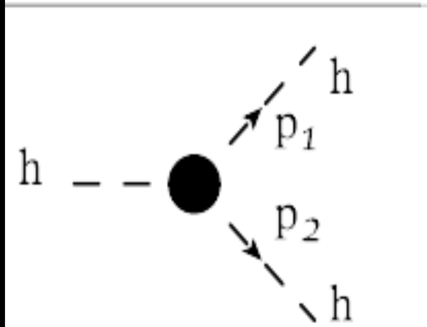

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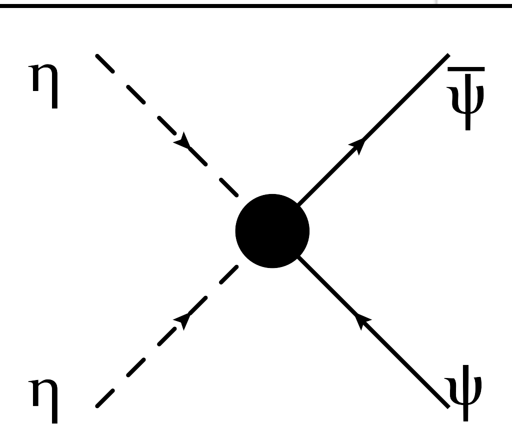

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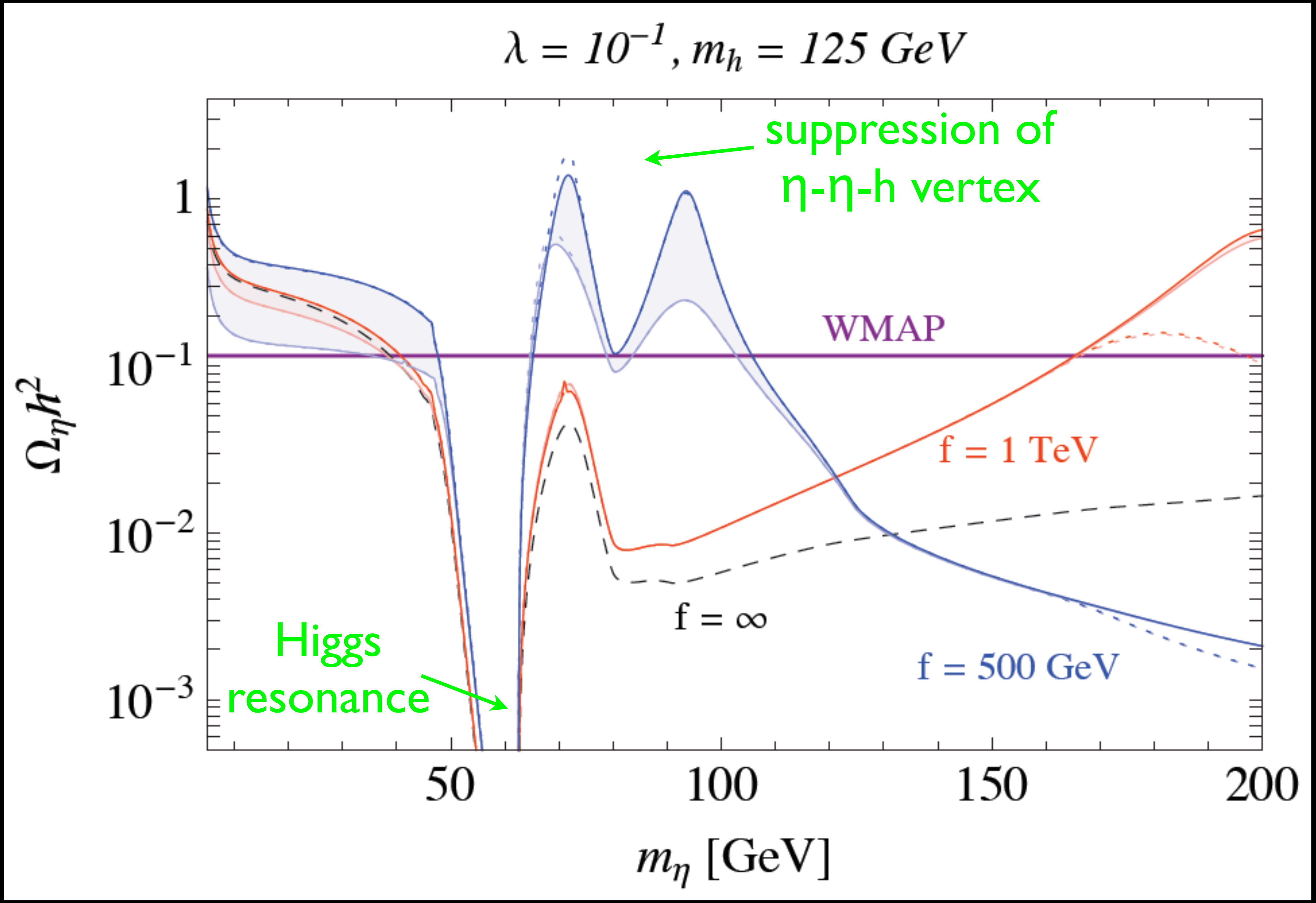
- order ξ corrections to the Higgs couplings

The relic density of η



dashed line: no compositeness (SM + singlet)

solid lines: compositeness with the bottom coupled to η

(dotted lines: compositeness with also the top coupled to η)

Bounds from DM searches

Invisible Higgs decays into DM: $h \to \eta\eta$
(plus visible decays corrected at order ξ)

$$\Gamma_{inv} = \frac{v^2}{32\pi m_h}\sqrt{1-\frac{4m_\eta^2}{m_h^2}}\left(\frac{m_h^2}{v^2}\frac{\xi}{\sqrt{1-\xi}} - 2\lambda\sqrt{1-\xi}\right)^2 \vartheta(m_h - 2m_\eta)$$

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DM annihilations today: $\eta\,\eta \to b$ b-bar, WW, $\gamma\gamma$, ... (work in progress)

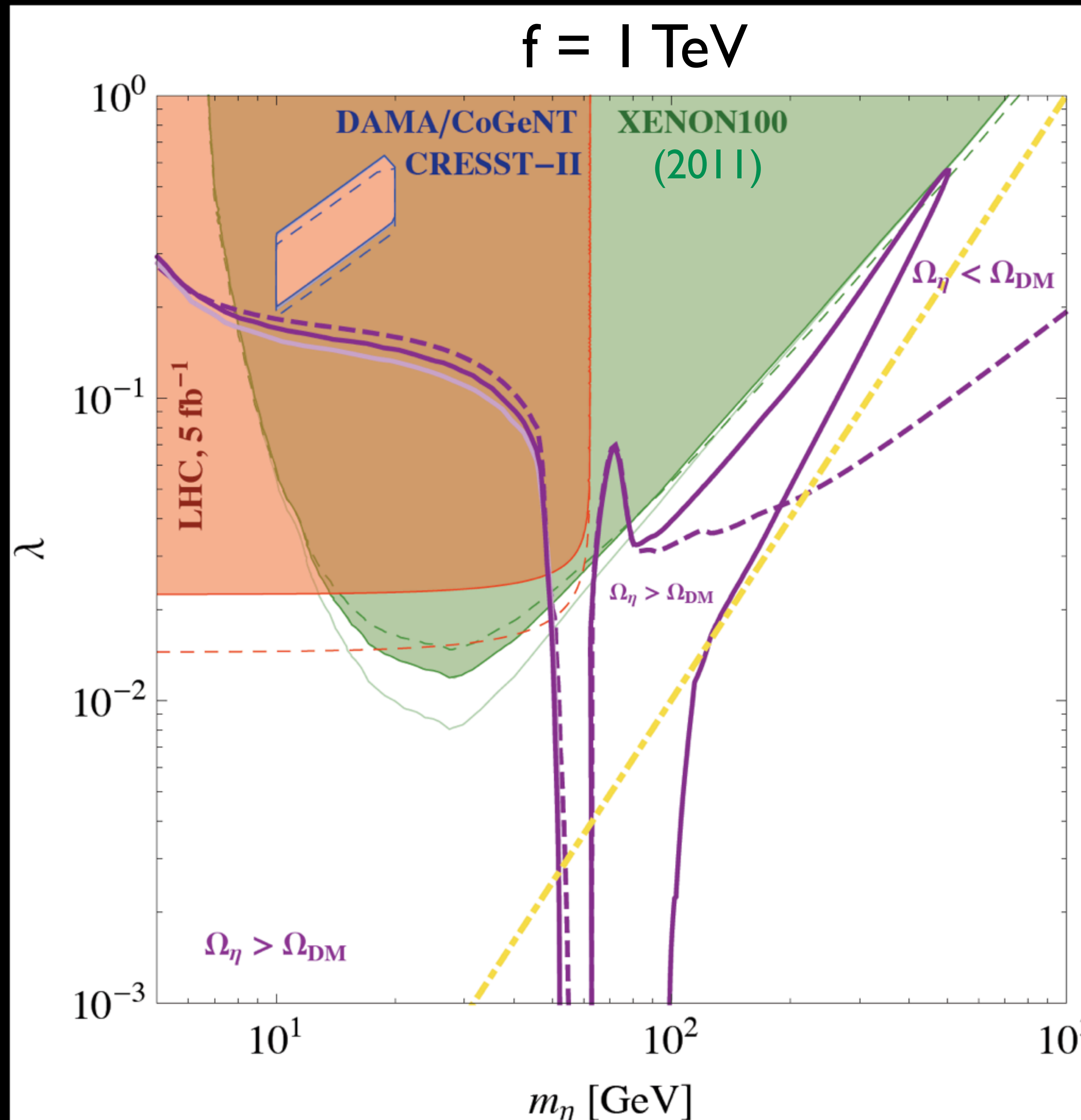
The signal is enhanced close to the Higgs resonance, where $\langle\sigma v_{rel}\rangle$ differs significantly from the freeze-out one. Constraints from FERMI-LAT, AMS, ...

non-composite case: Cline-Kainulainen-Scott-Weniger '13

Composite DM parameter space

dashed: elementary DM

solid: composite DM
with f = 1 TeV



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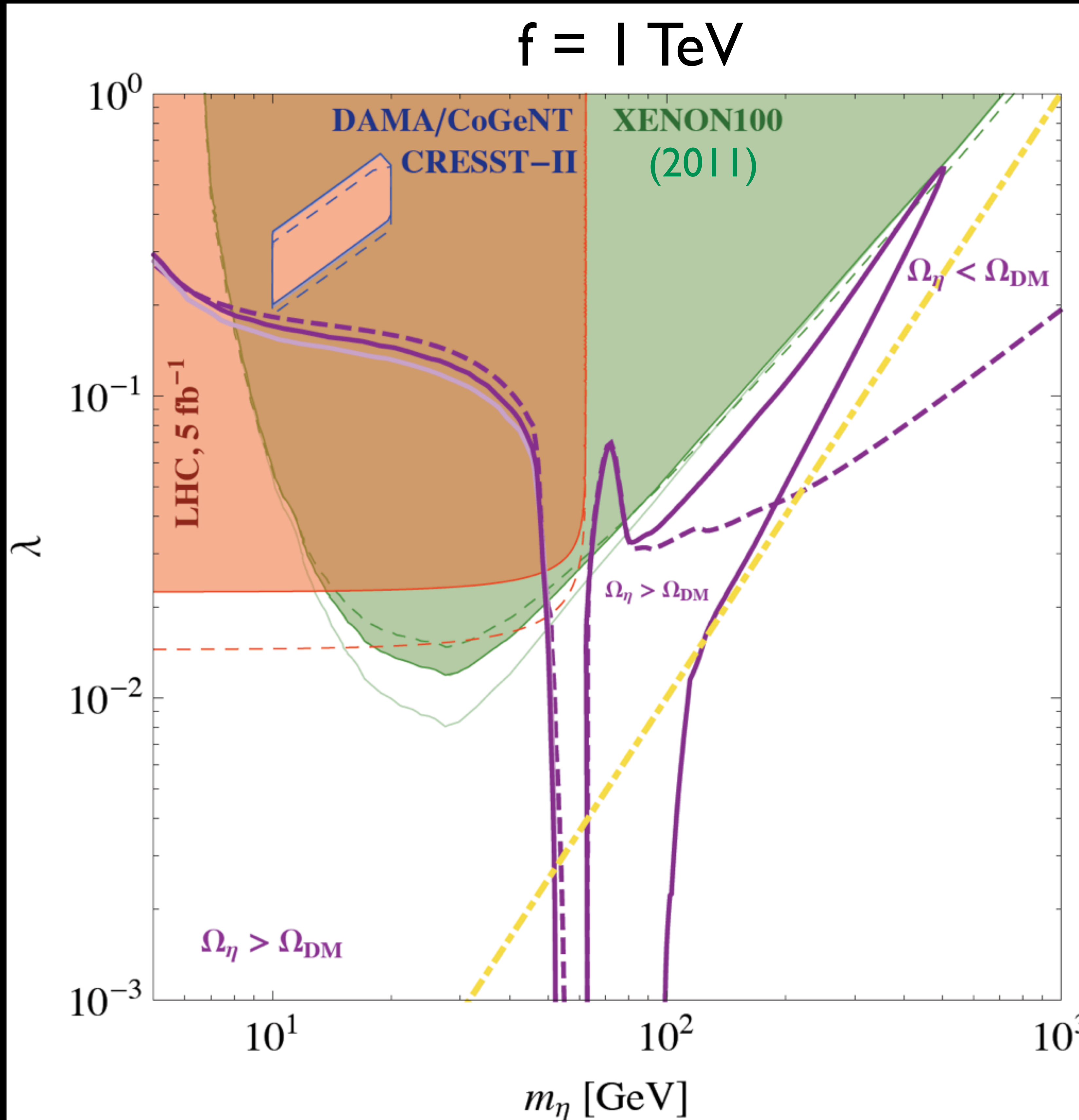

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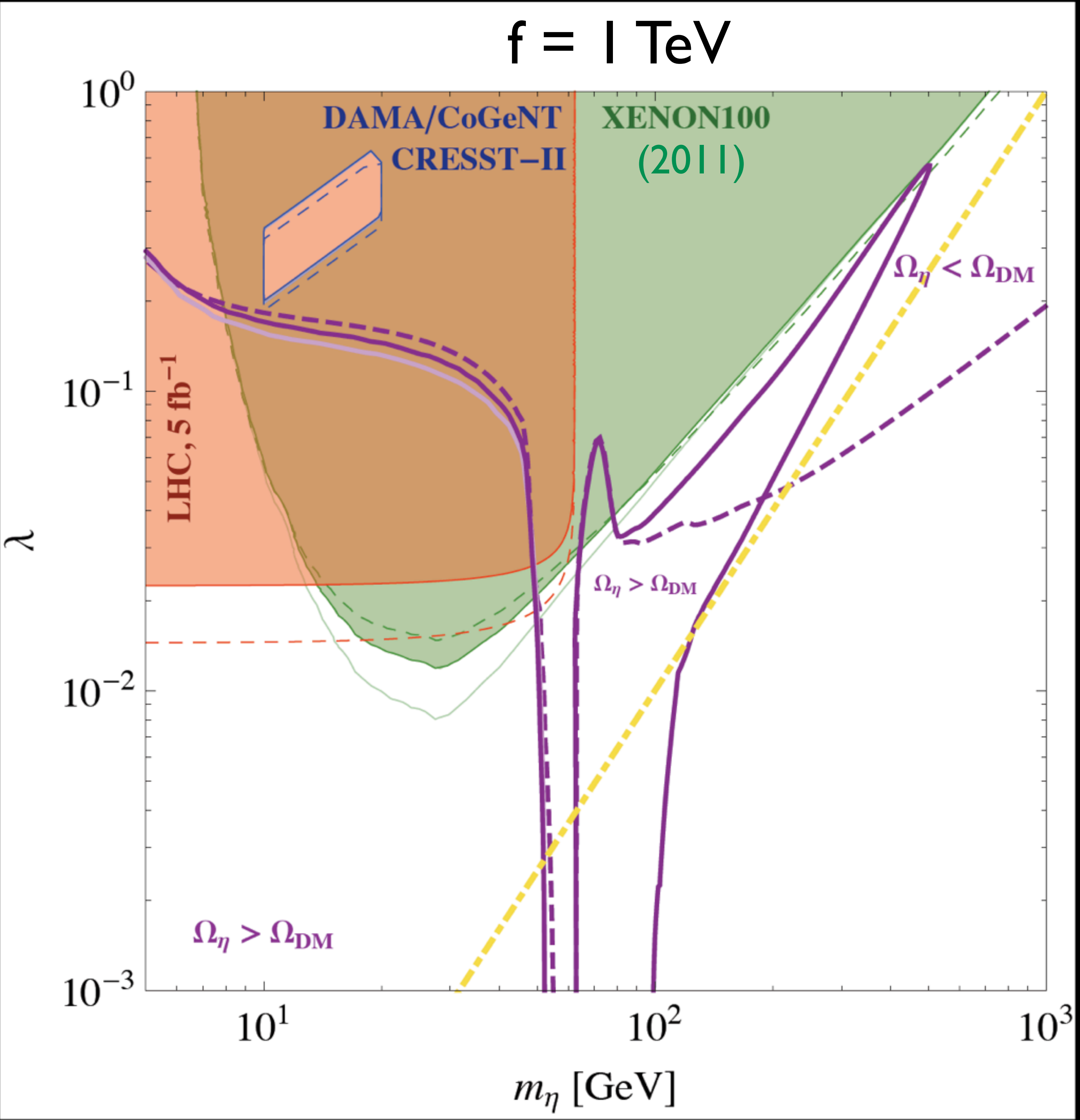

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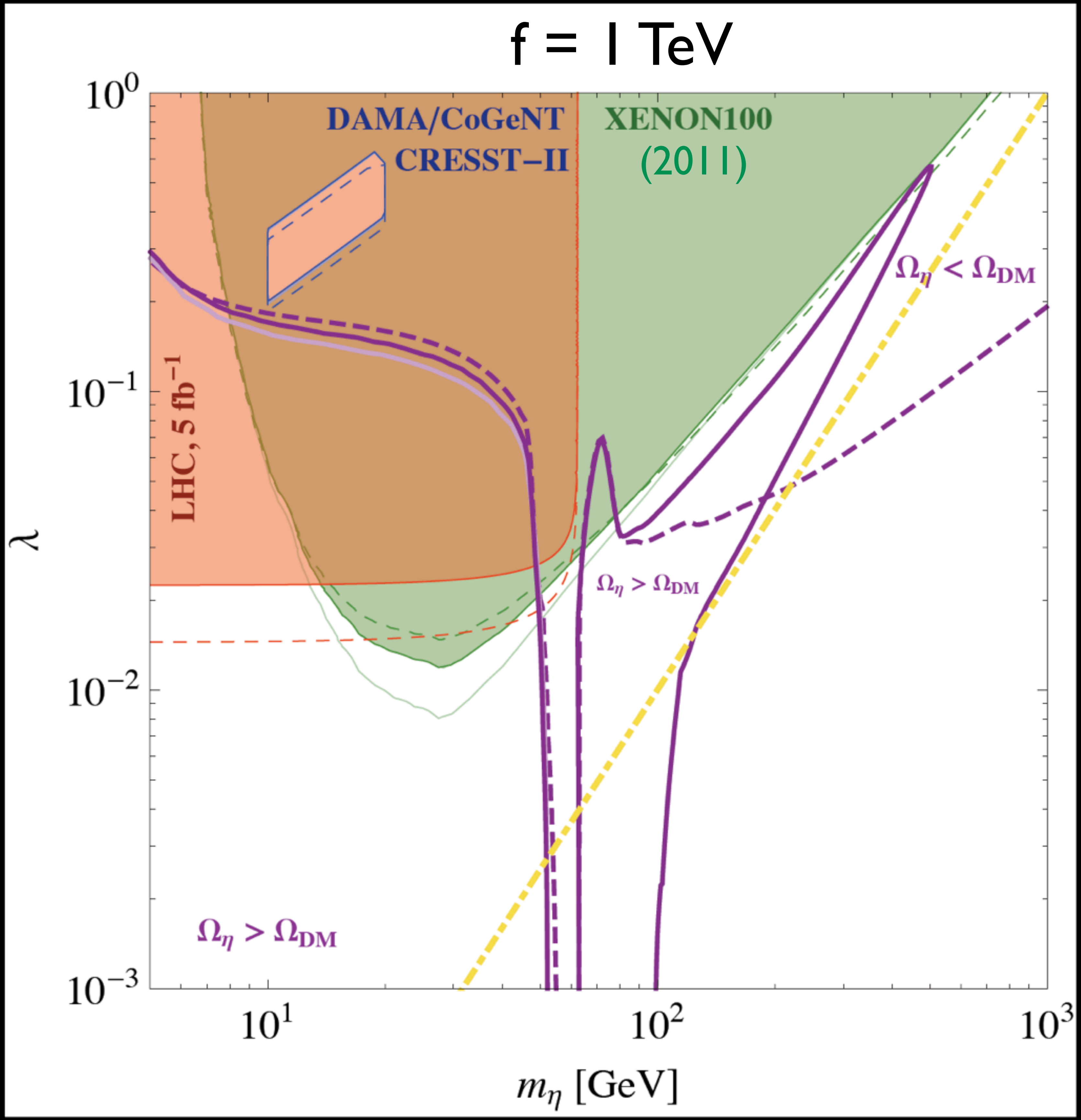

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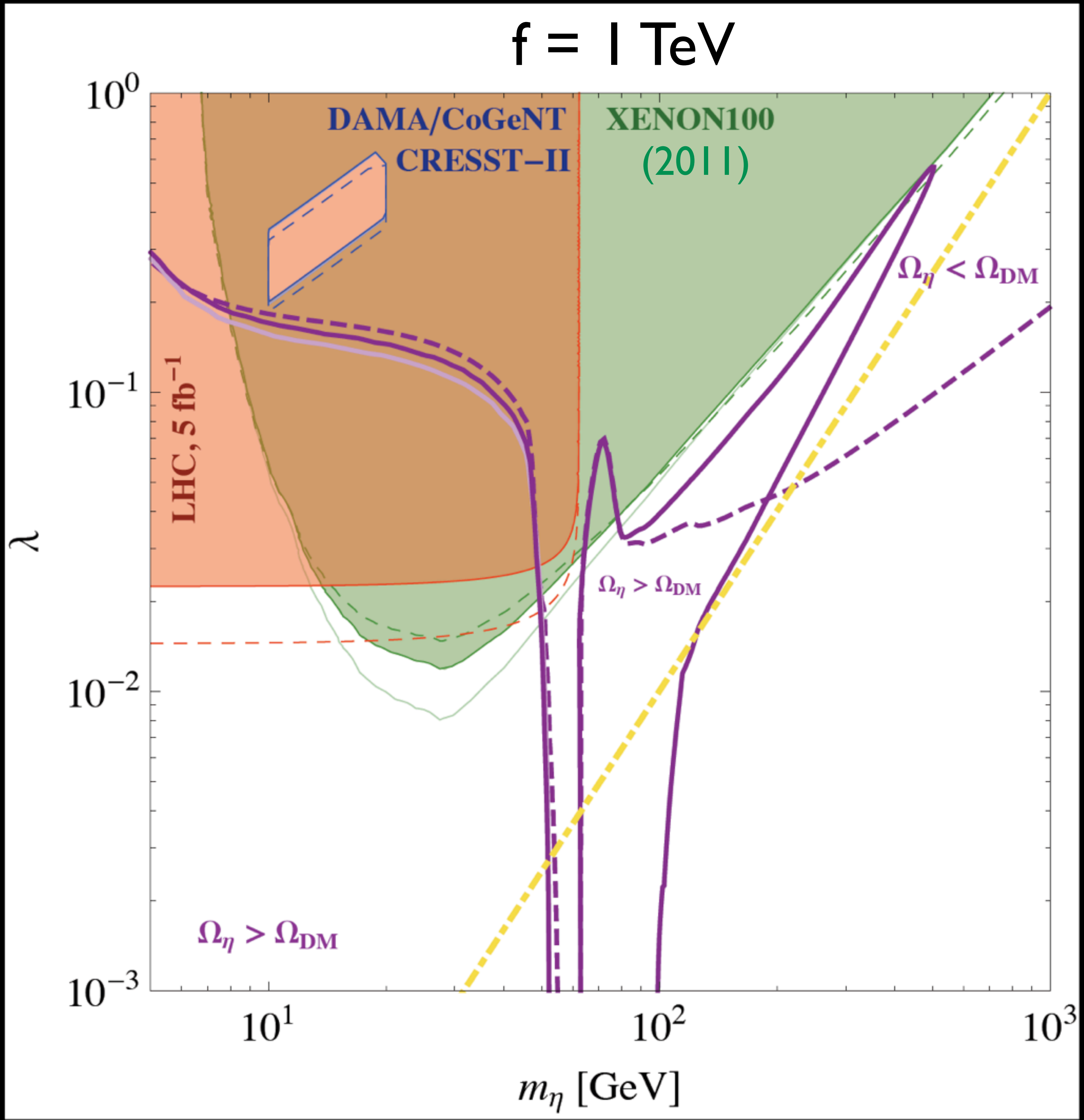

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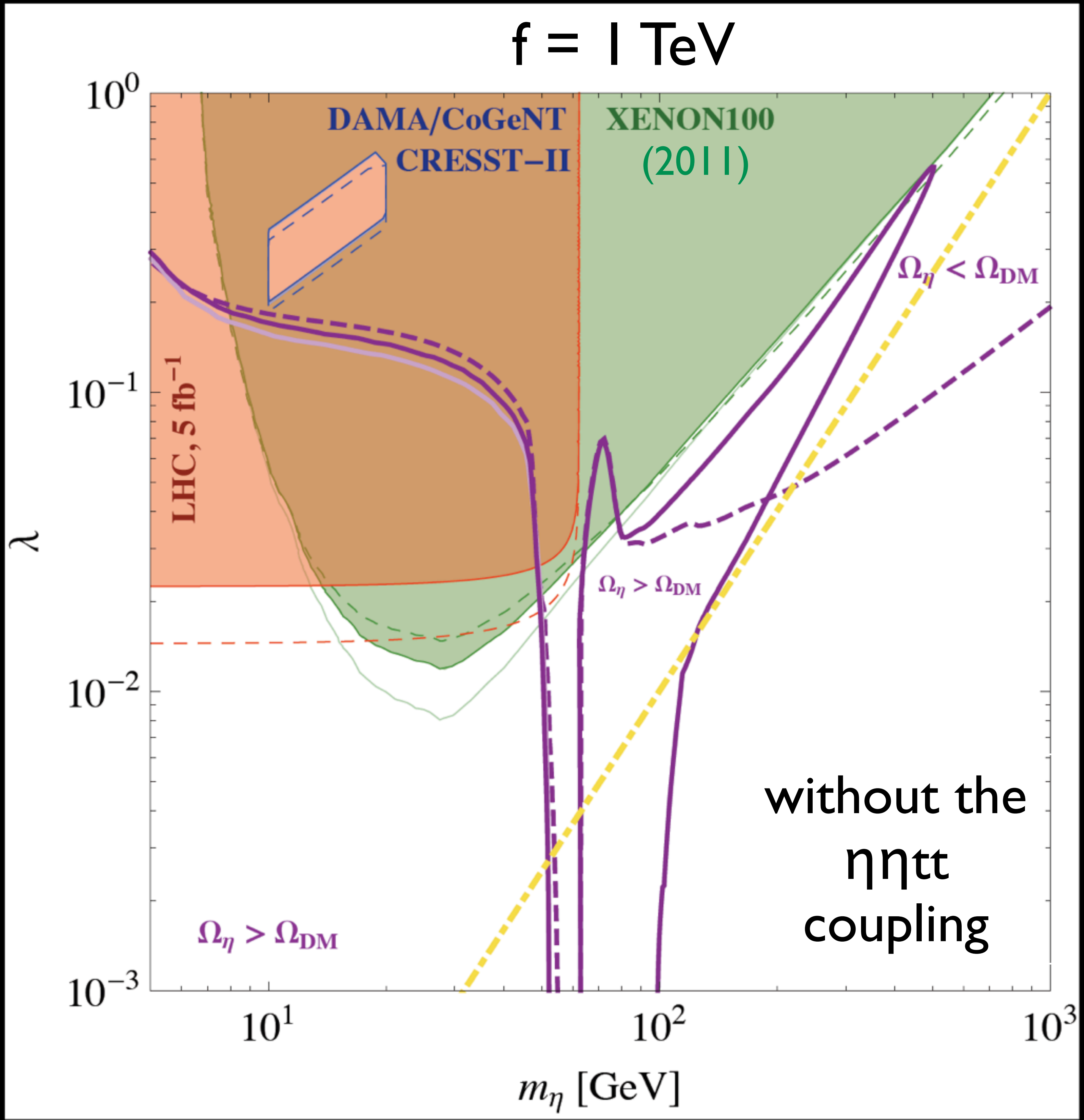

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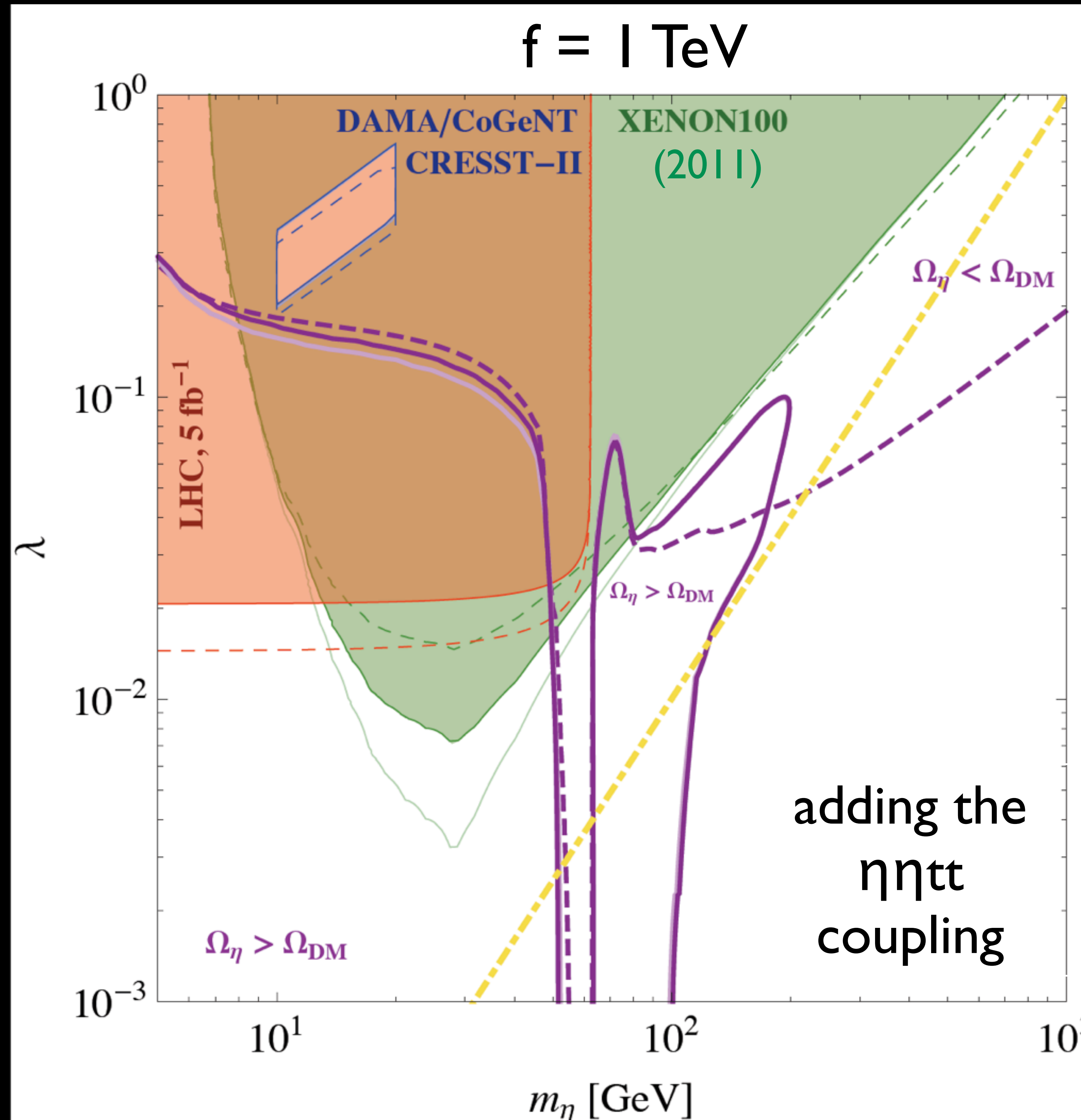

Composite DM parameter space

dashed: elementary DM

solid: composite DM with f = 500 GeV

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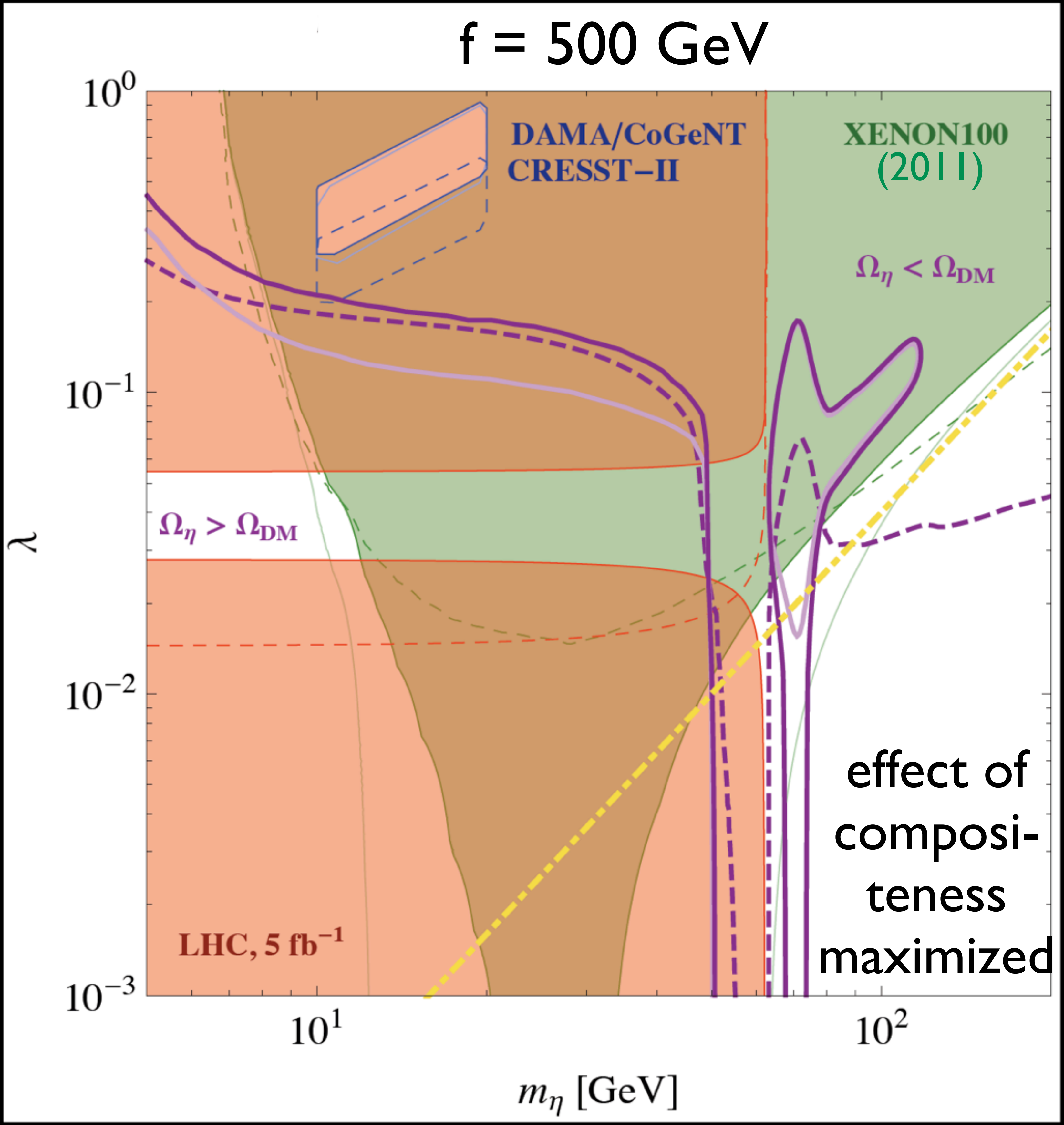

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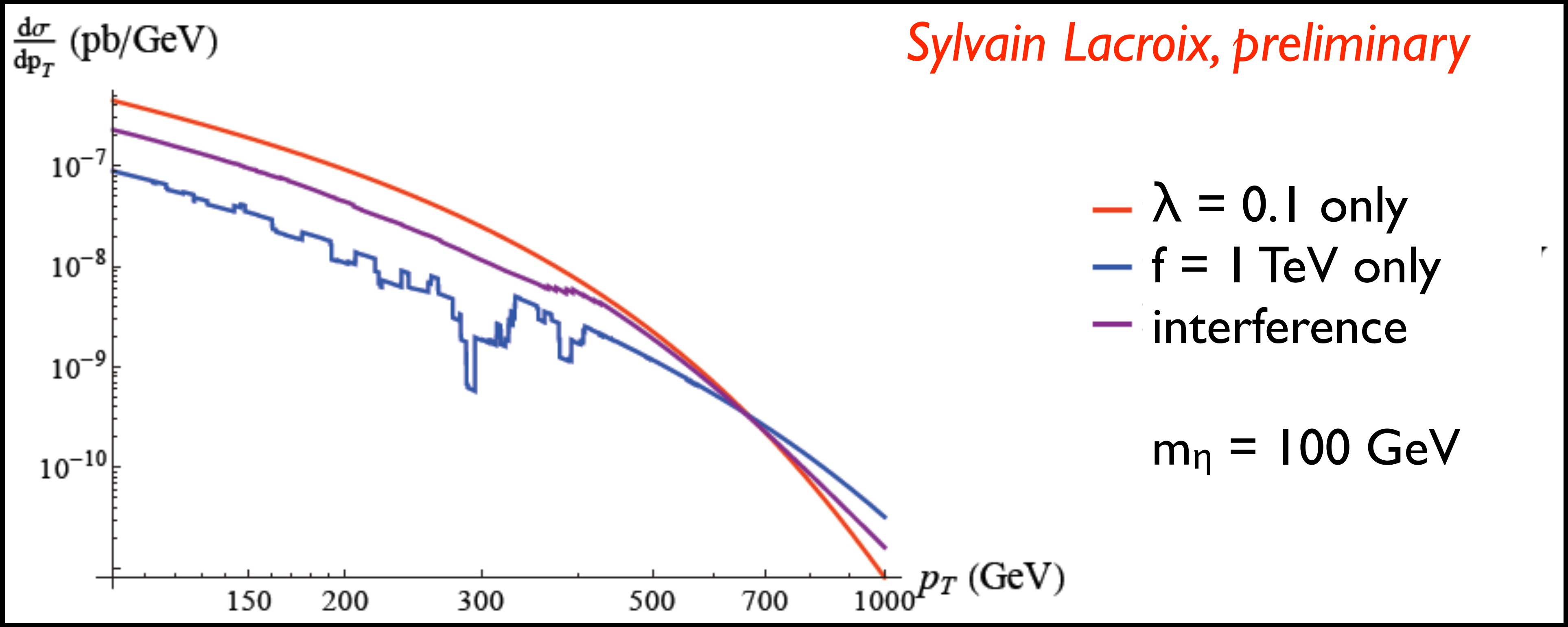

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- composite scalar DM has mass in the range 60 to 500 GeV and can be probed very effectively in collider searches and DM searches