

Implication of supercooling on DM in composite Higgs

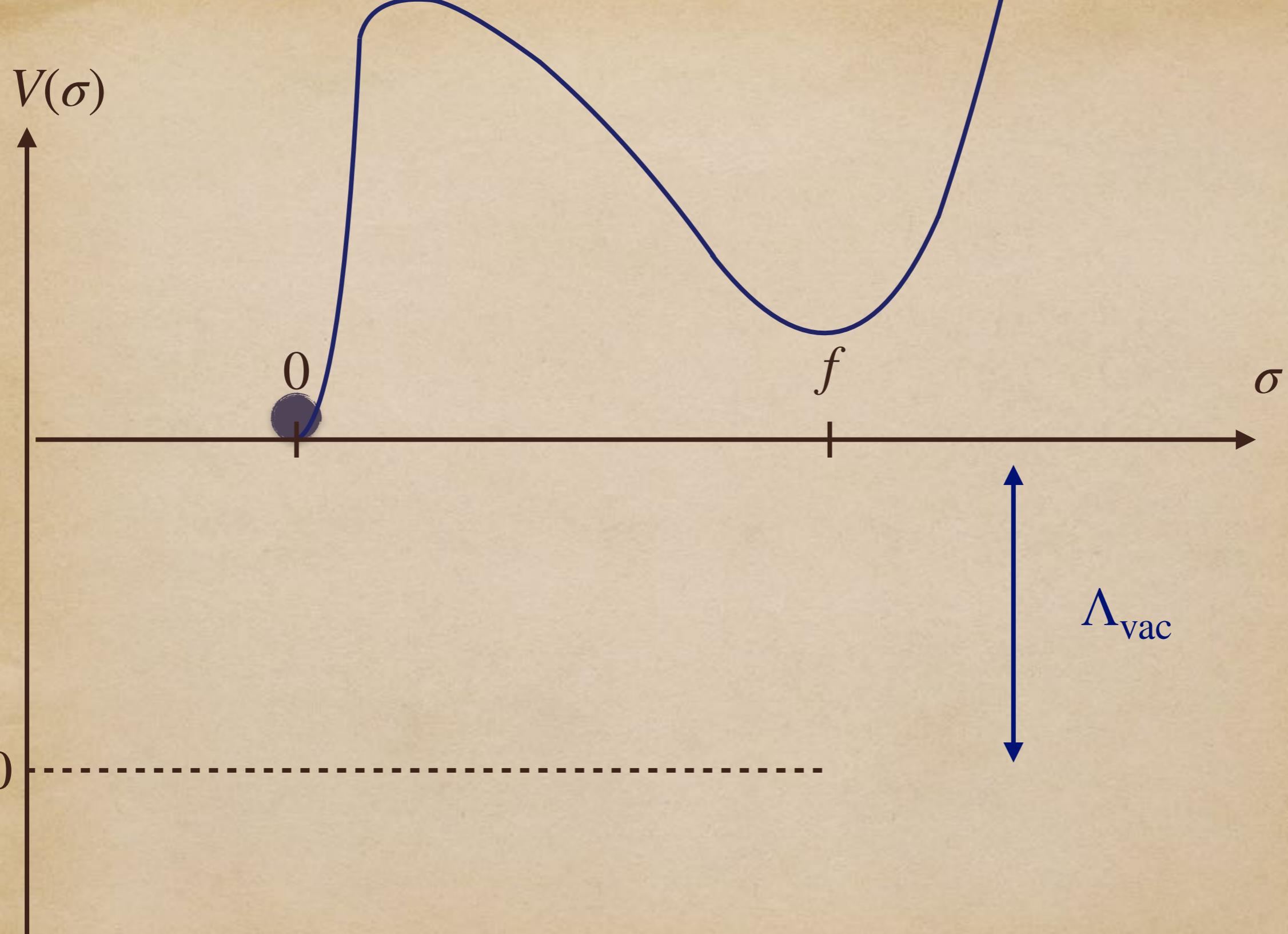
Yann Gouttenoire

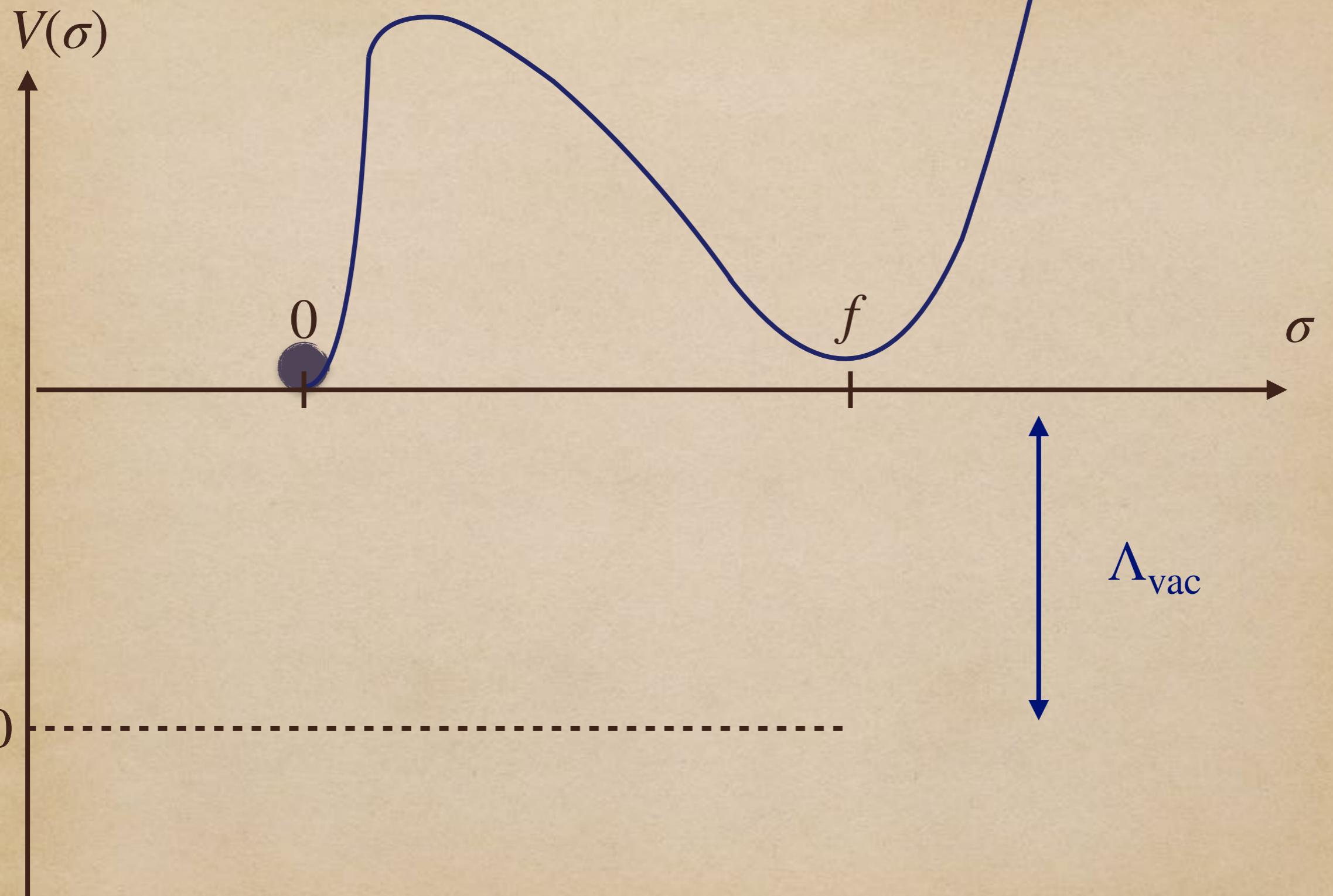
DESY - Hamburg

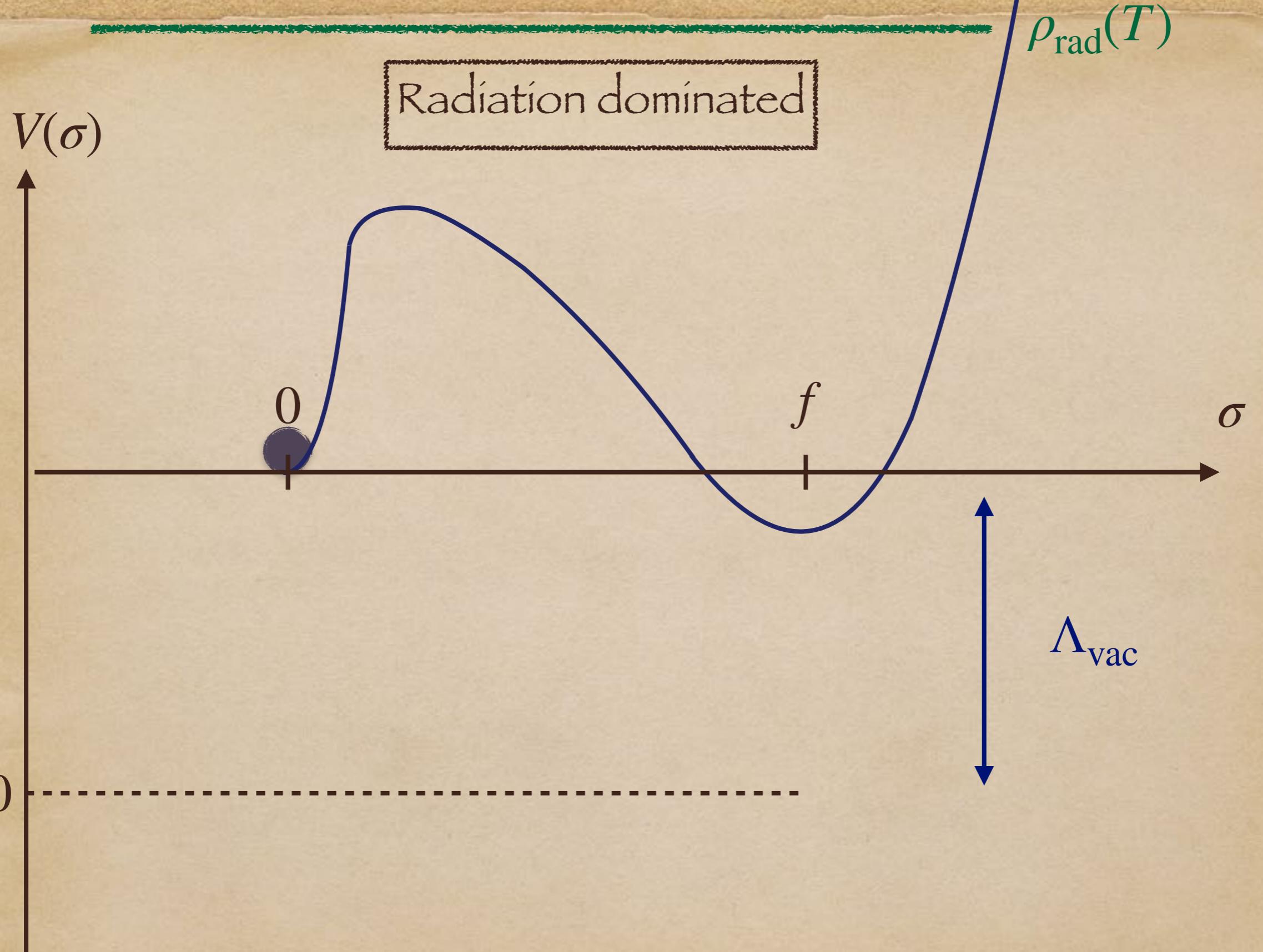
With Iason Baldes, Filippo Sala and Geraldine Servant

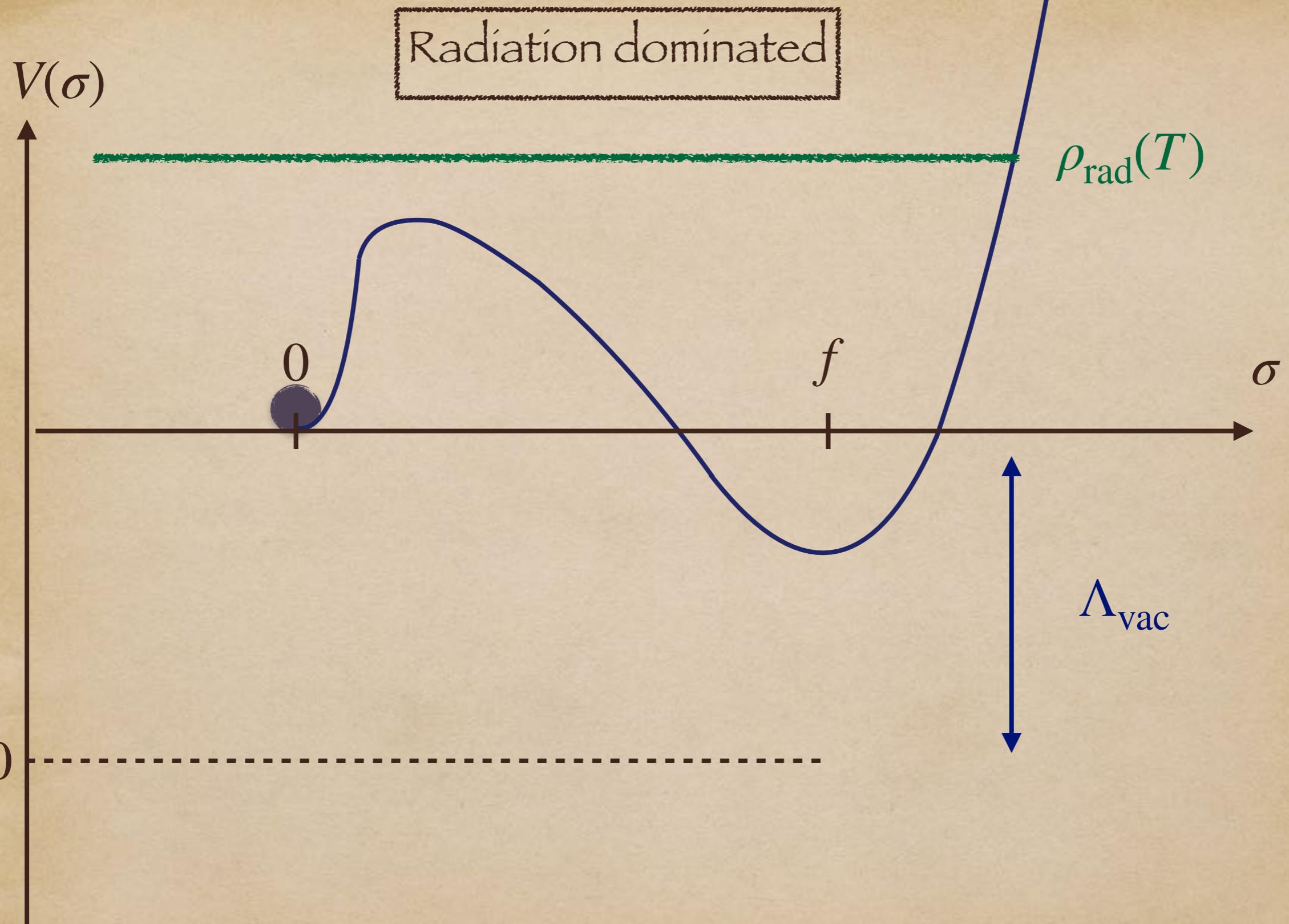
Benasque - April 2019

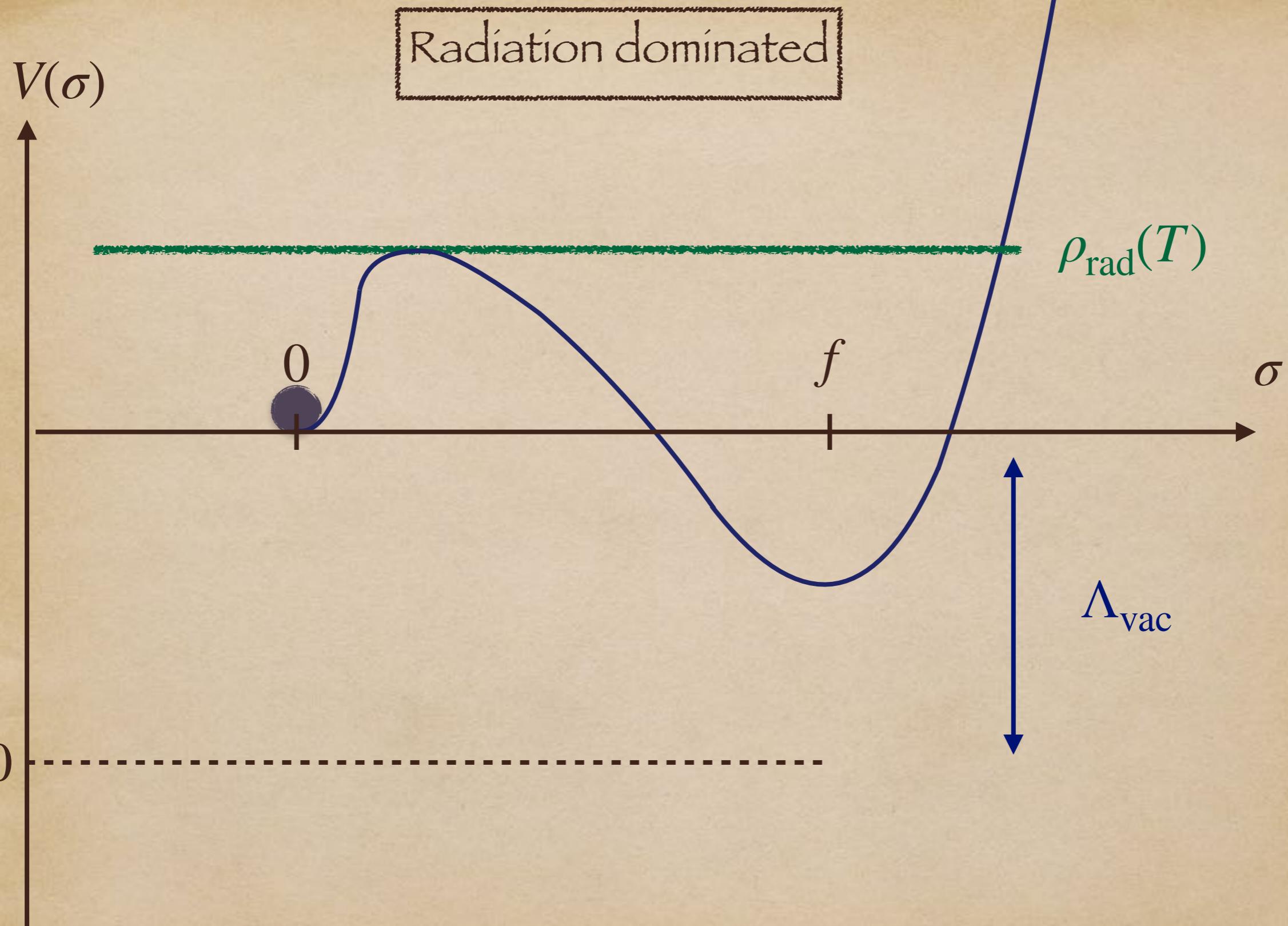
- Cosmological implications of a supercooled PT at TeV scale energies
 - large signal of GWs at LISA Konstandín, Servant 11
 - some e-fold of inflation: dilution of heavy DM
 - heavy particle production from bubble collisions
 - cold baryogenesis
- Down to QCD temperature
 - PT triggered by QCD condensation Iso, Serpico, Shimada 17
von Harling, Servant 17
 - cold EW baryogenesis using CP violation from QCD axion Servant 14
 - QCD axion relic abundance prediction modified: larger f_a Baratella, Pomarol, Rompíneve 18
- We know want to study WIMP DM phenomenology for DM candidates acquiring a mass during the PT Hambye, Strumia, Teresi 18
 - Naturally motivated in composite Higgs models

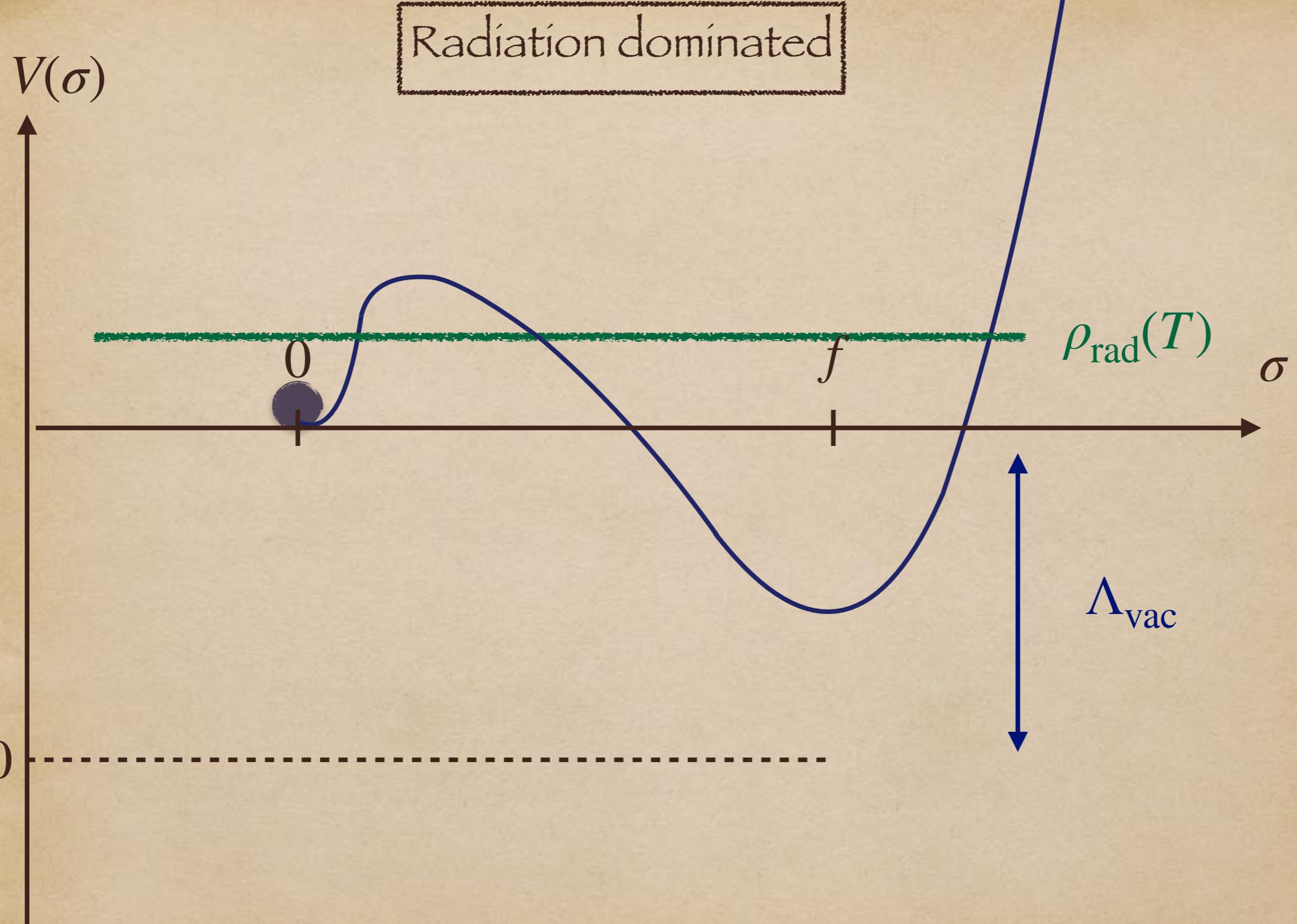


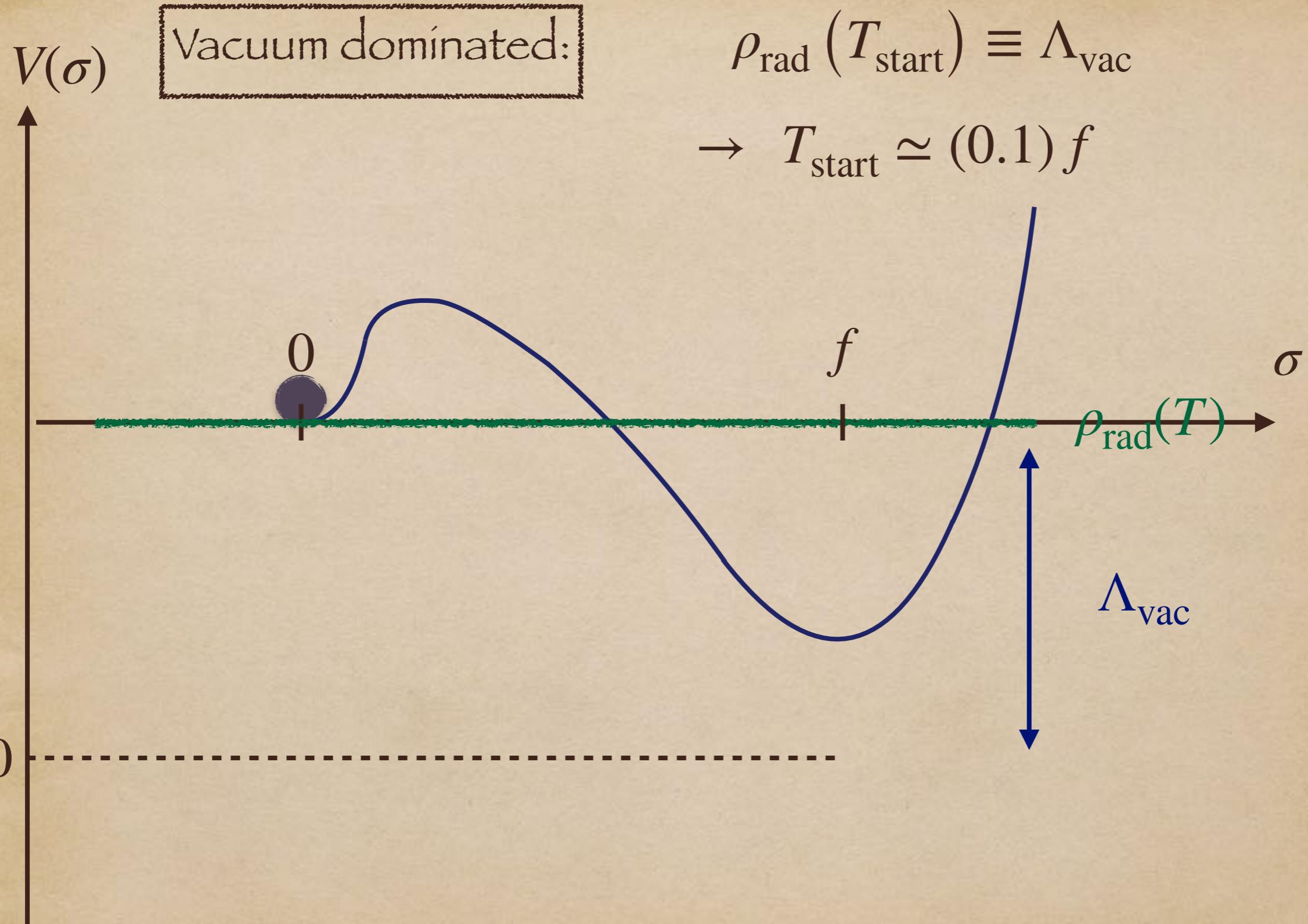




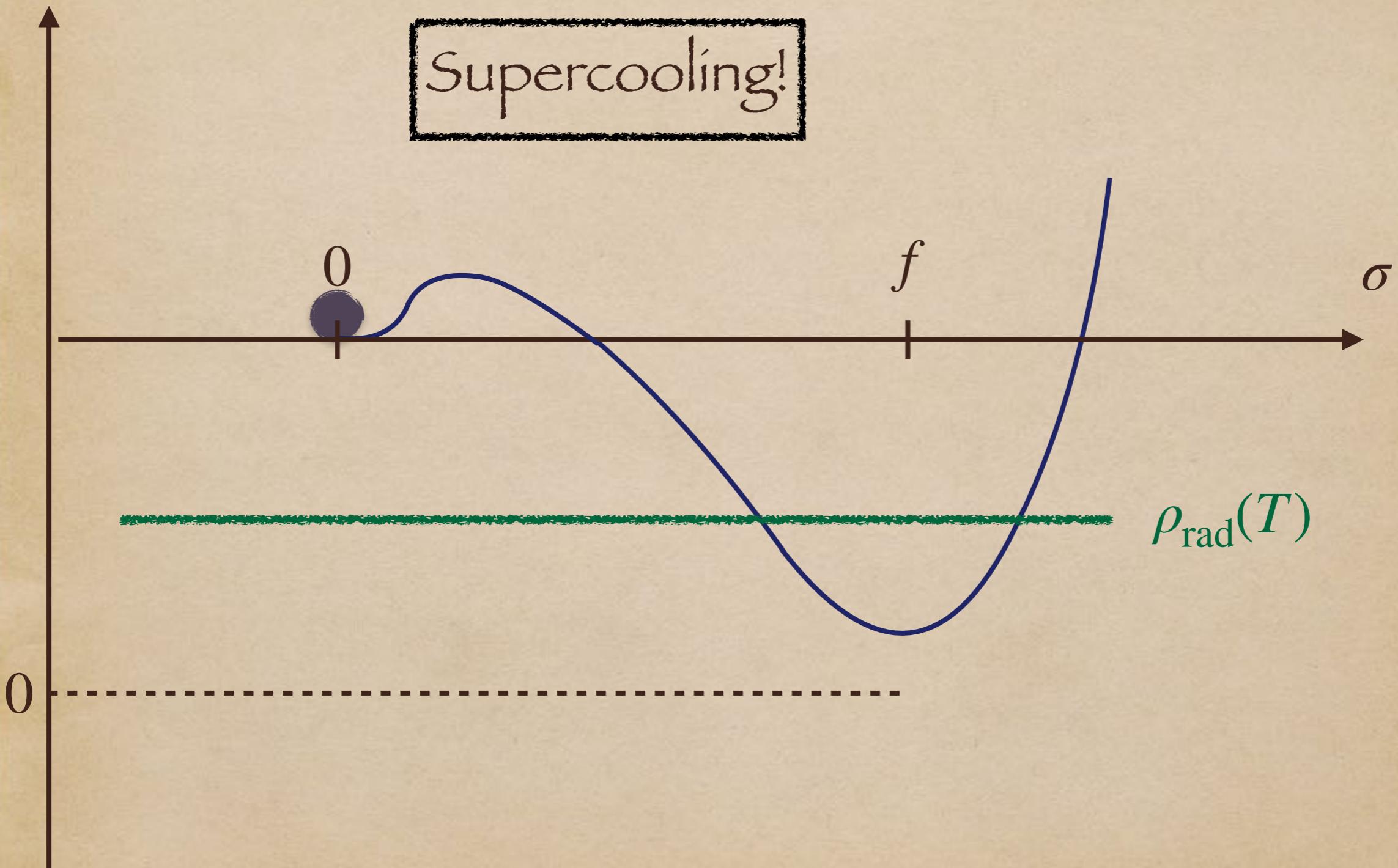








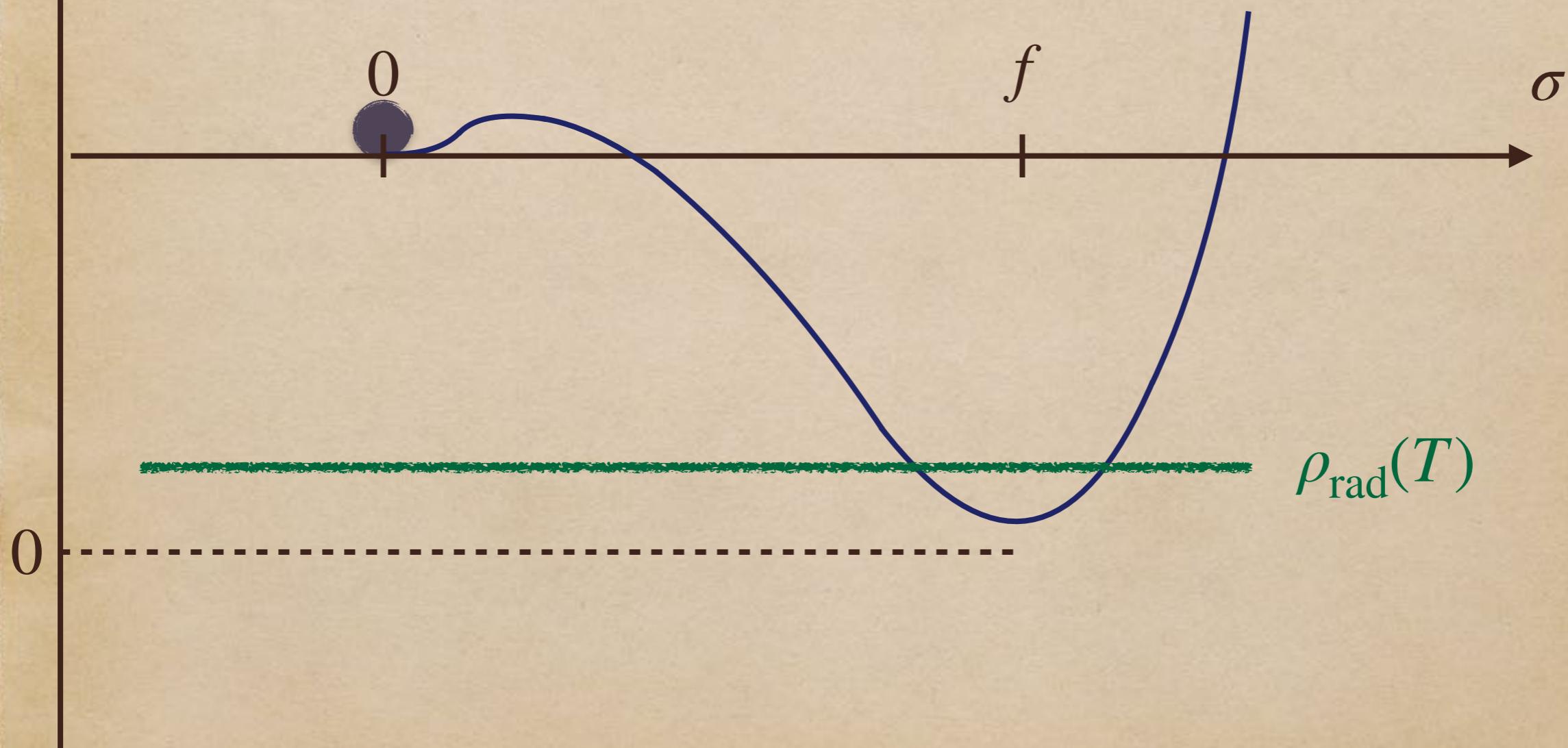
$$V(\sigma) \text{ Vacuum dominated: } T = T_{\text{start}} e^{-\sqrt{\frac{\Lambda_{\text{vac}}}{3}} t}$$



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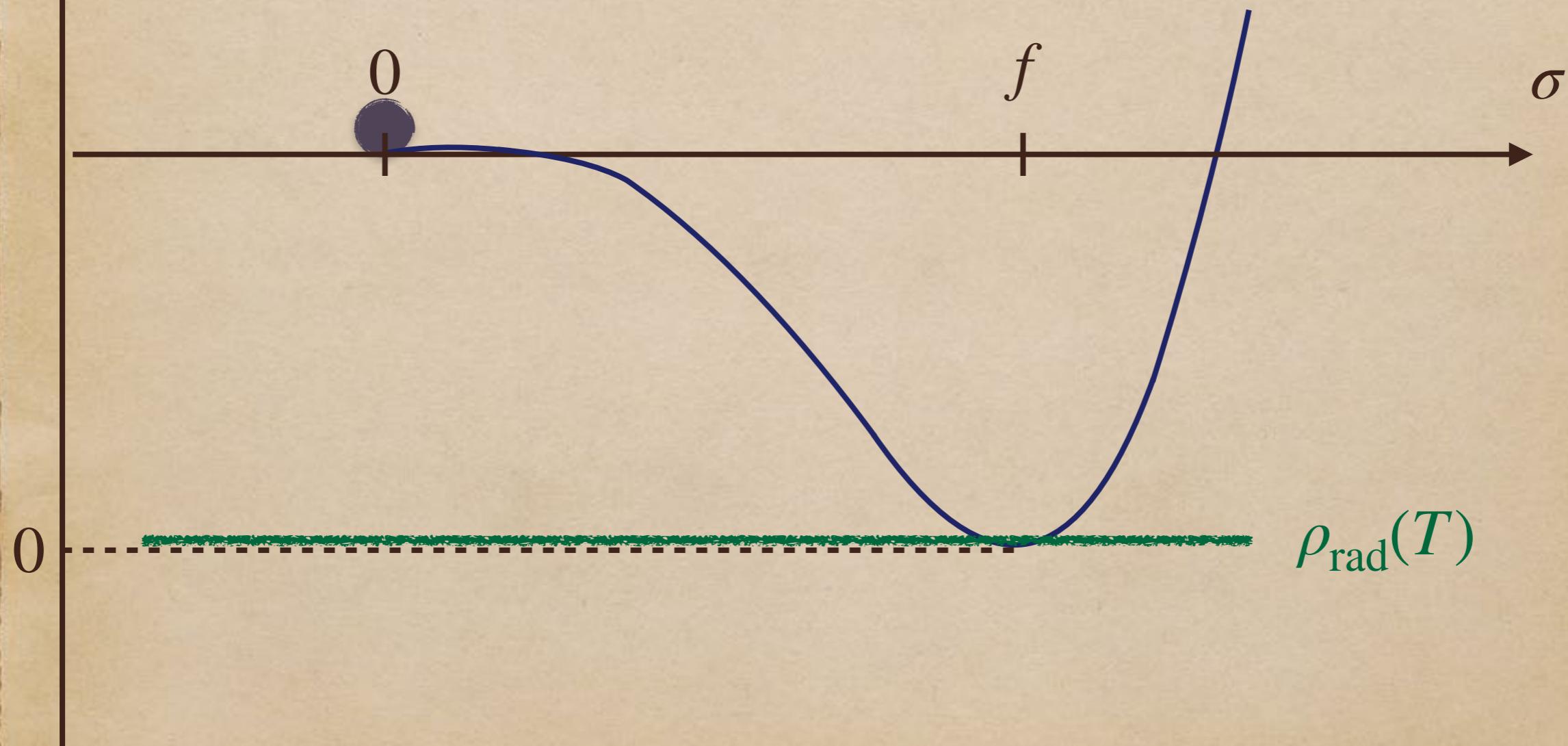
Supercooling!



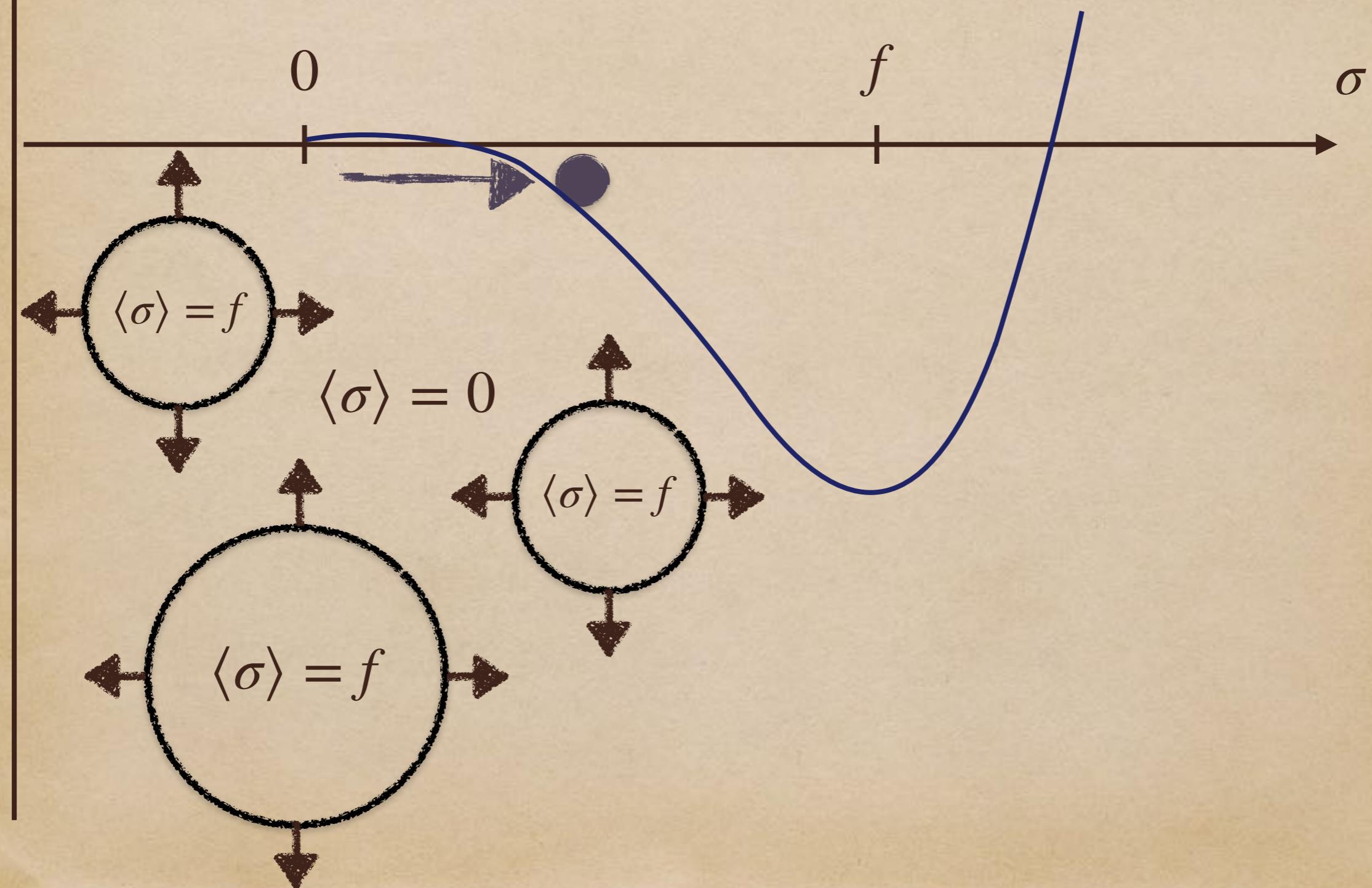
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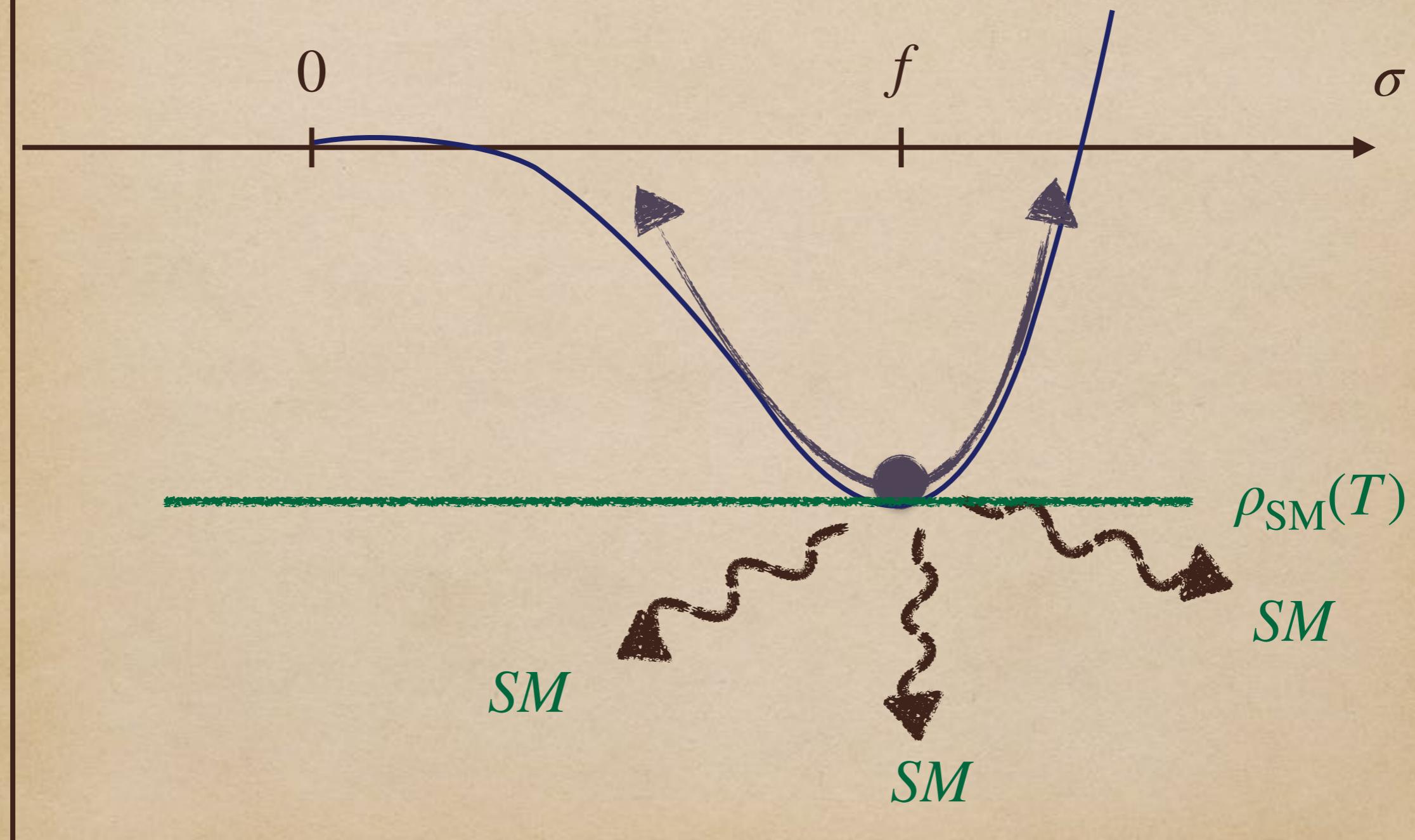
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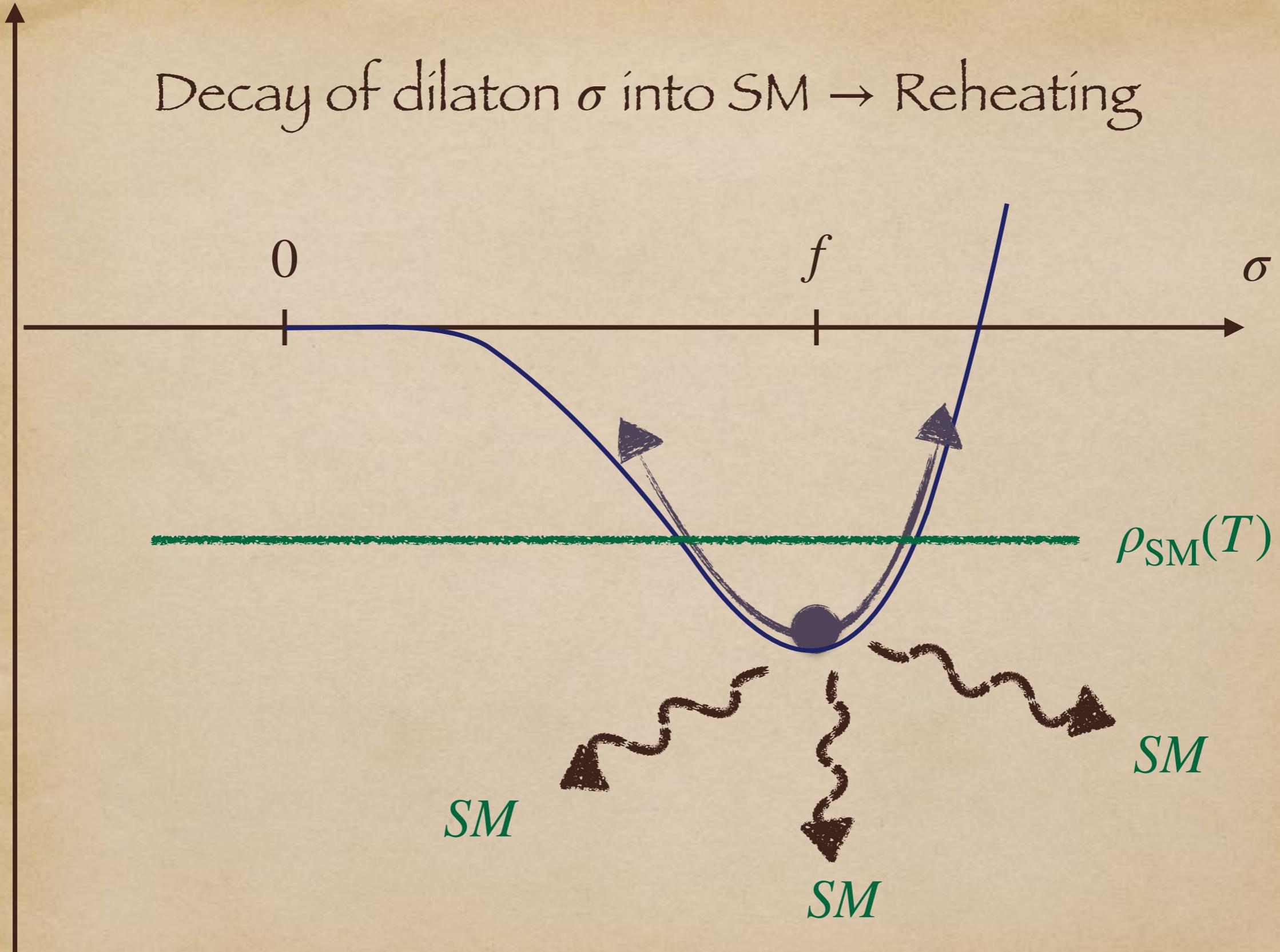
End of super-cooling through bubble nucleation



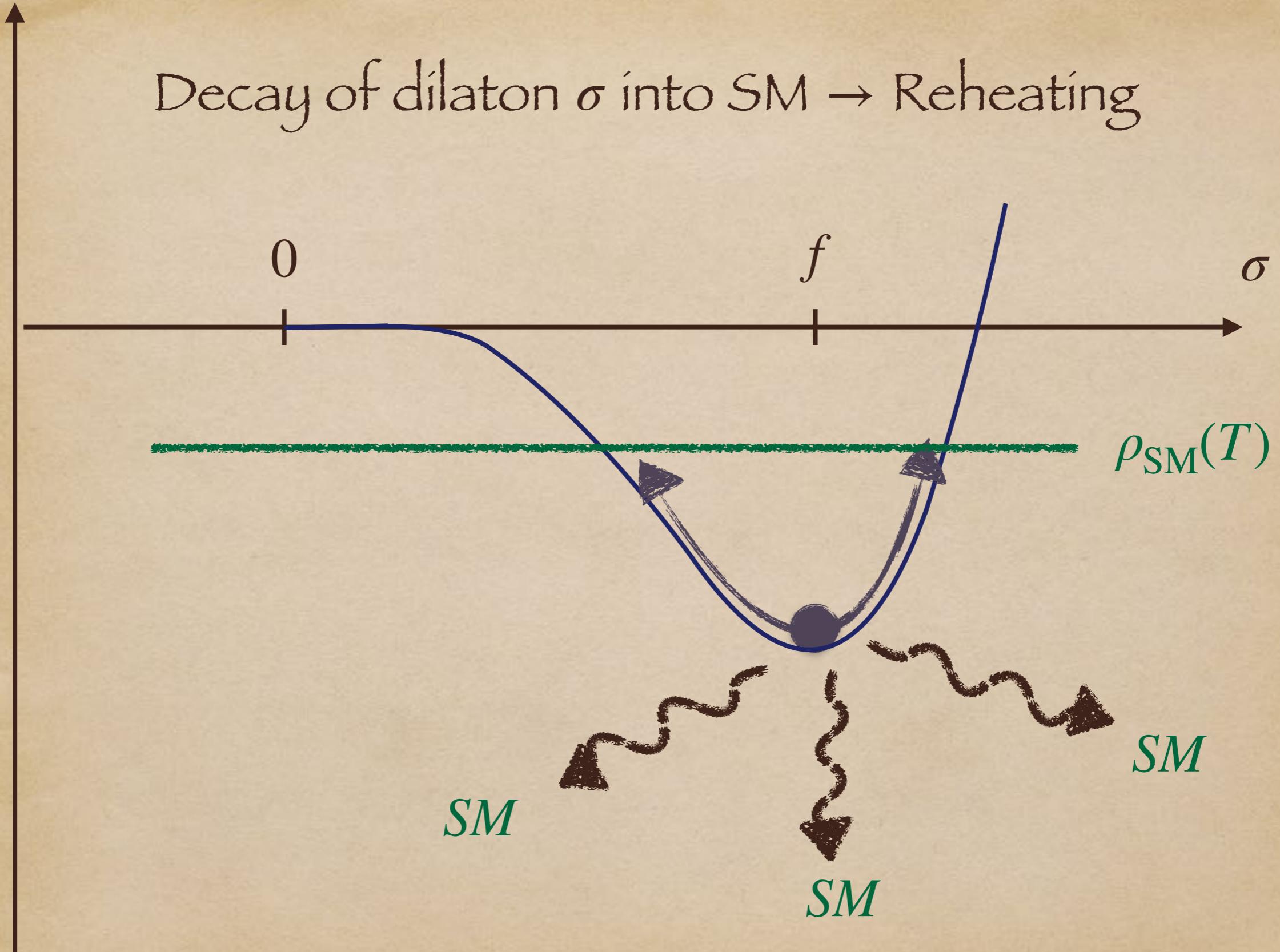
Decay of dilaton σ into SM \rightarrow Reheating



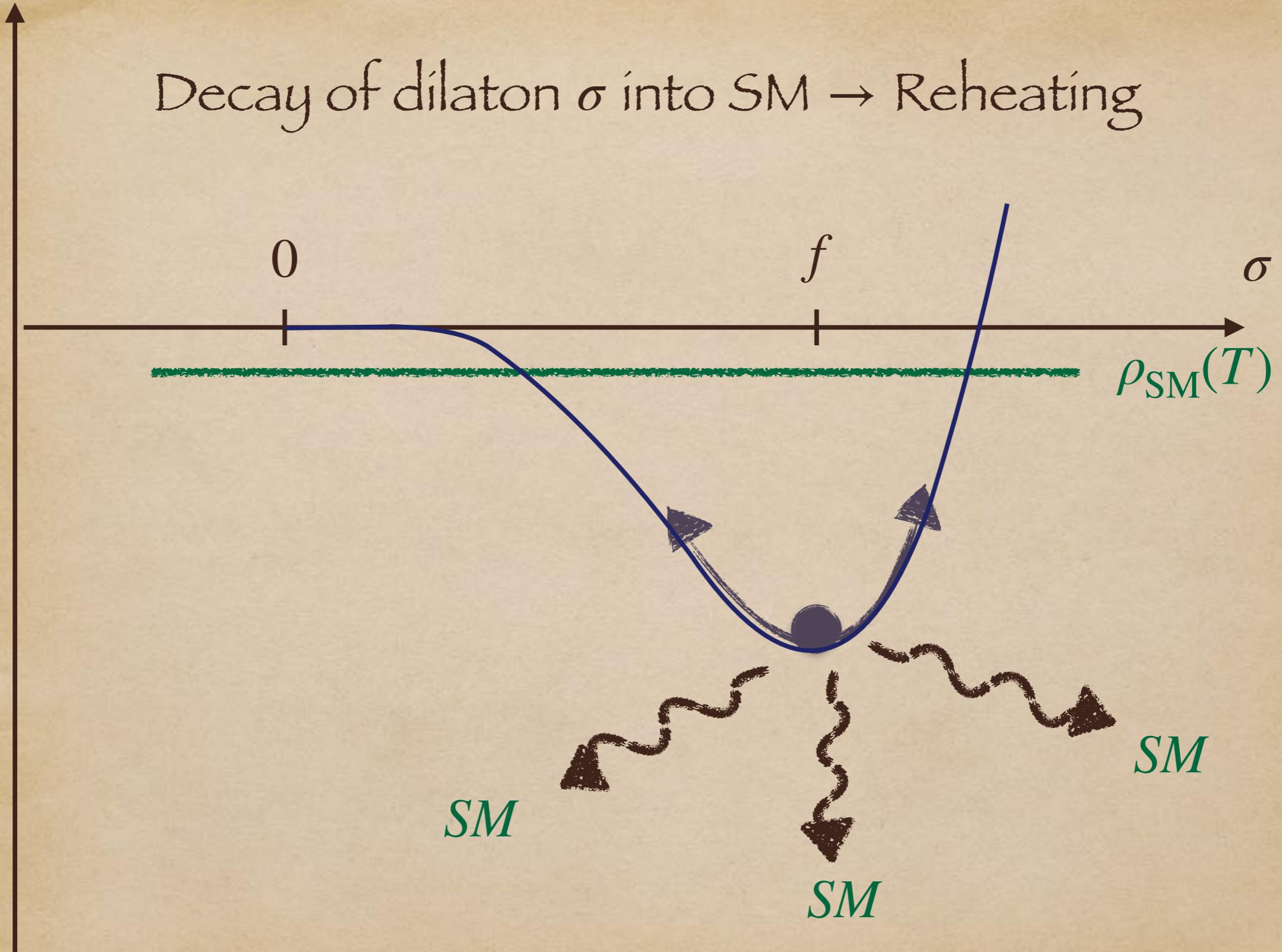
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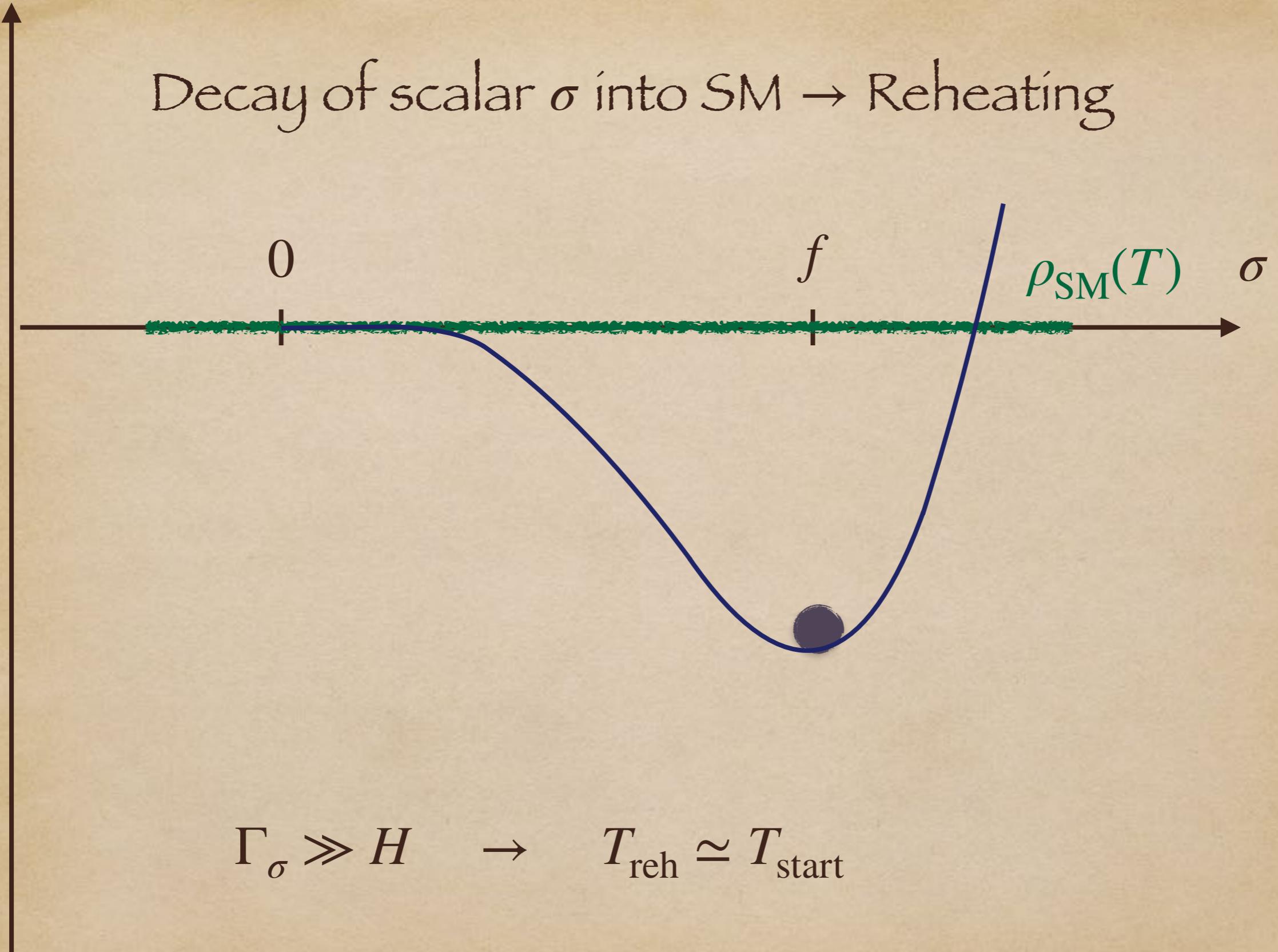
Decay of dilaton σ into SM \rightarrow Reheating



Decay of dilaton σ into SM \rightarrow Reheating



Decay of scalar σ into SM \rightarrow Reheating



$$\Gamma_\sigma \gg H \quad \rightarrow \quad T_{\text{reh}} \simeq T_{\text{start}}$$

DM abundance after supercooling

Hambye, Strumia, Teresi 18

Supercooling



Sub-thermal

DM abundance after supercooling

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Supercooling



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→ DM massless before
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$$Y_{\text{eq}} = \frac{45g_{\text{DM}}}{2\pi^4 g_s}$$

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→ Dilution by short
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$$Y_{\text{super-co}} = Y_{\text{eq}} \left(\frac{T_{\text{nuc}}}{T_{\text{start}}} \right)^3,$$

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$$\frac{dY_{\text{DM}}}{dz} = \frac{\lambda}{z^2} \left(Y_{\text{DM}}^2 - Y_{\text{DM}}^{2\text{eq}} \right), \quad z = \frac{m_{\text{DM}}}{T}$$

$$\lambda = M_{\text{pl}} m_{\text{DM}} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \sqrt{\frac{\pi g_{\text{SM}}}{45}}$$

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$$Y_{\text{sub-th}} \propto 10^{10} \exp \left(-2 \frac{M_{\text{DM}}}{T_{\text{reh}}} \right),$$

EWSB in composite Higgs

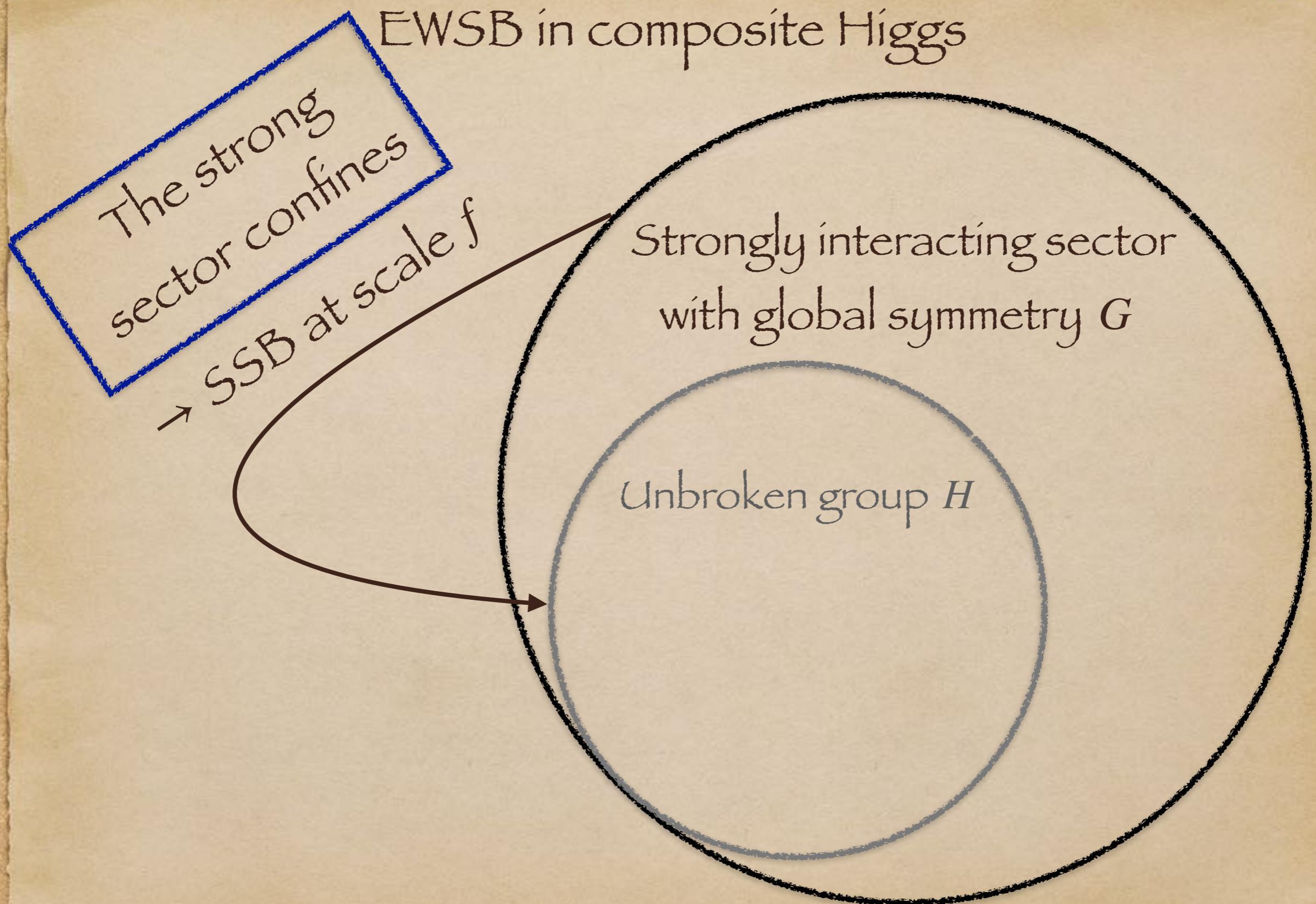
Strongly interacting sector
with global symmetry G

EWSB in composite Higgs

The strong
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Strongly interacting sector
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EWSB in composite Higgs

The strong
sector confines
→ SSB at scale f

Strongly interacting sector
with global symmetry G

$Higgs \in G/H$

$Higgs$ is a pNGBs

$$\rightarrow m_{\text{Higgs}} \lesssim m_* = g_* f$$

nearly-conformal strong sector

- Hyp:
- strong sector conformally invariant in the UV
 - Scale invariance explicitly broken by a slightly relevant operator $\mathcal{L} \supset \epsilon O_\epsilon$, $[O_\epsilon] = 4 + \gamma_\epsilon$

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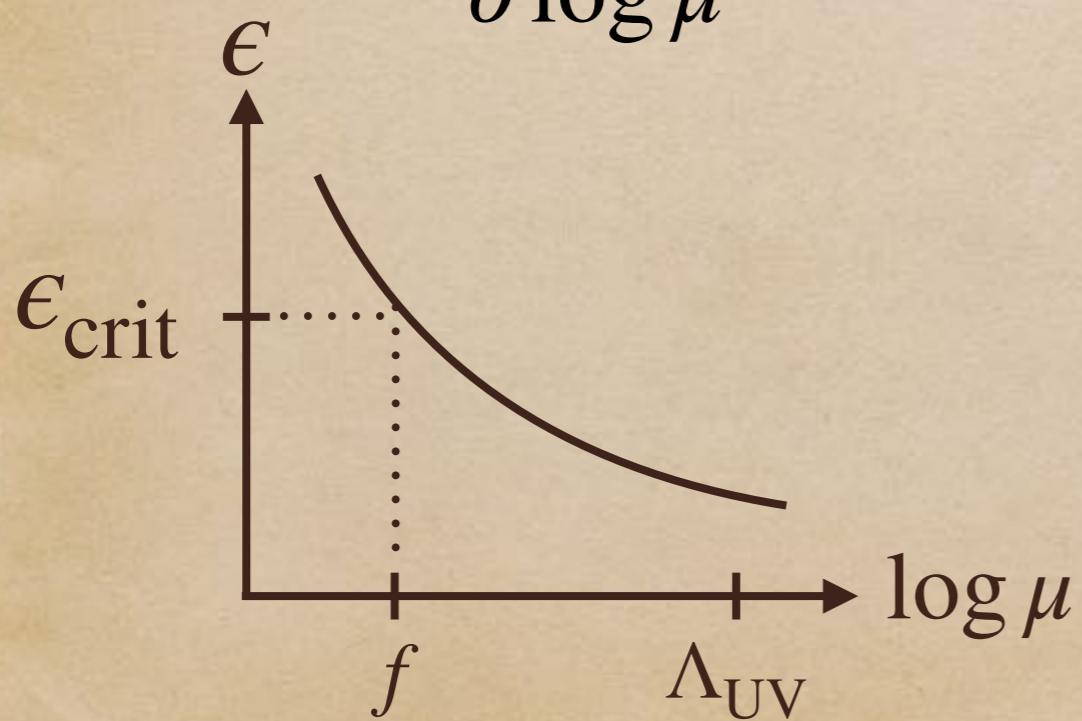
RGE:

$$\frac{\partial \epsilon}{\partial \log \mu} \simeq \gamma_\epsilon \epsilon \quad \rightarrow \quad \epsilon = g_\sigma^2 \left(\frac{\mu}{f} \right)^{\gamma_\epsilon}, \quad \gamma_\epsilon < 0$$

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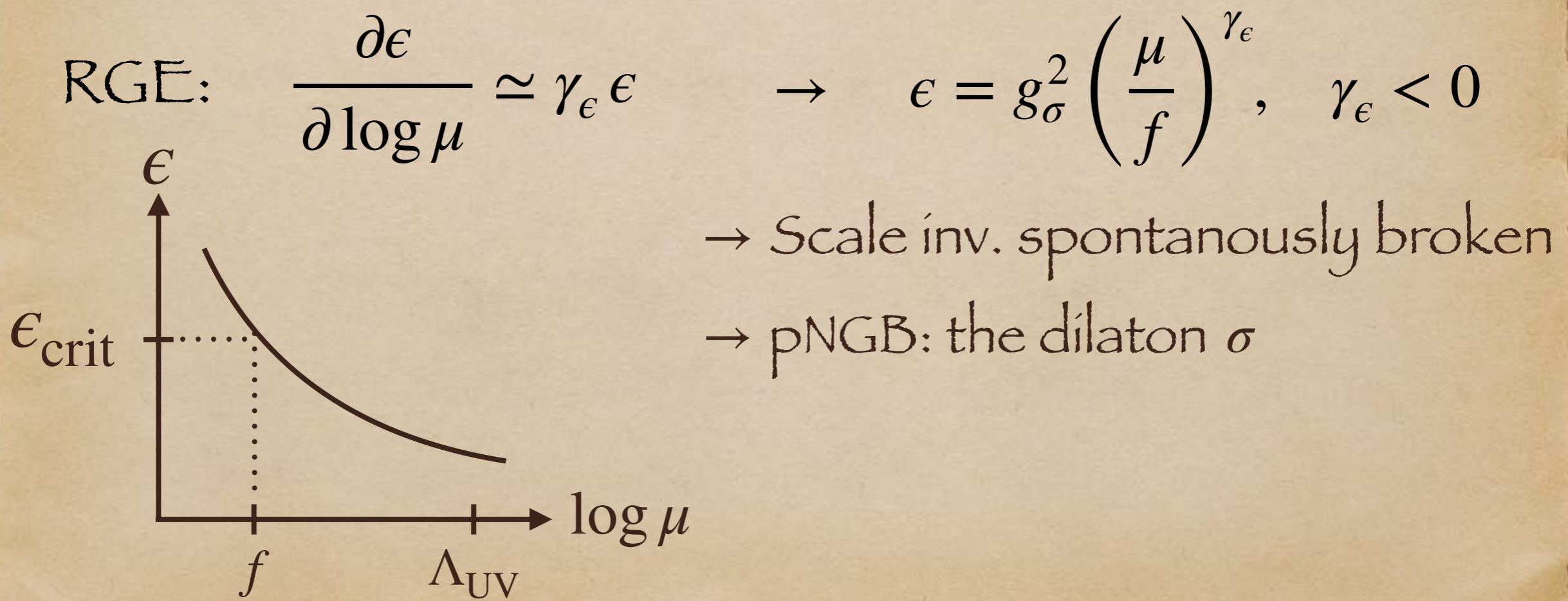
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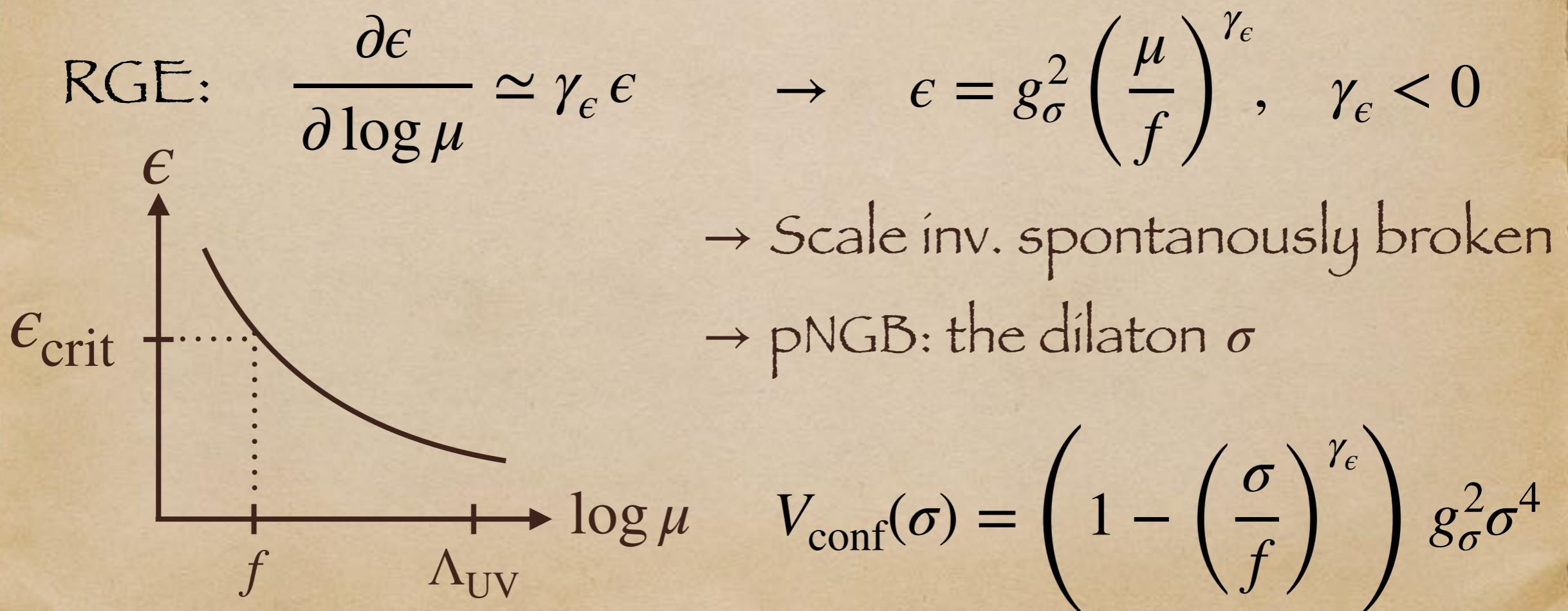
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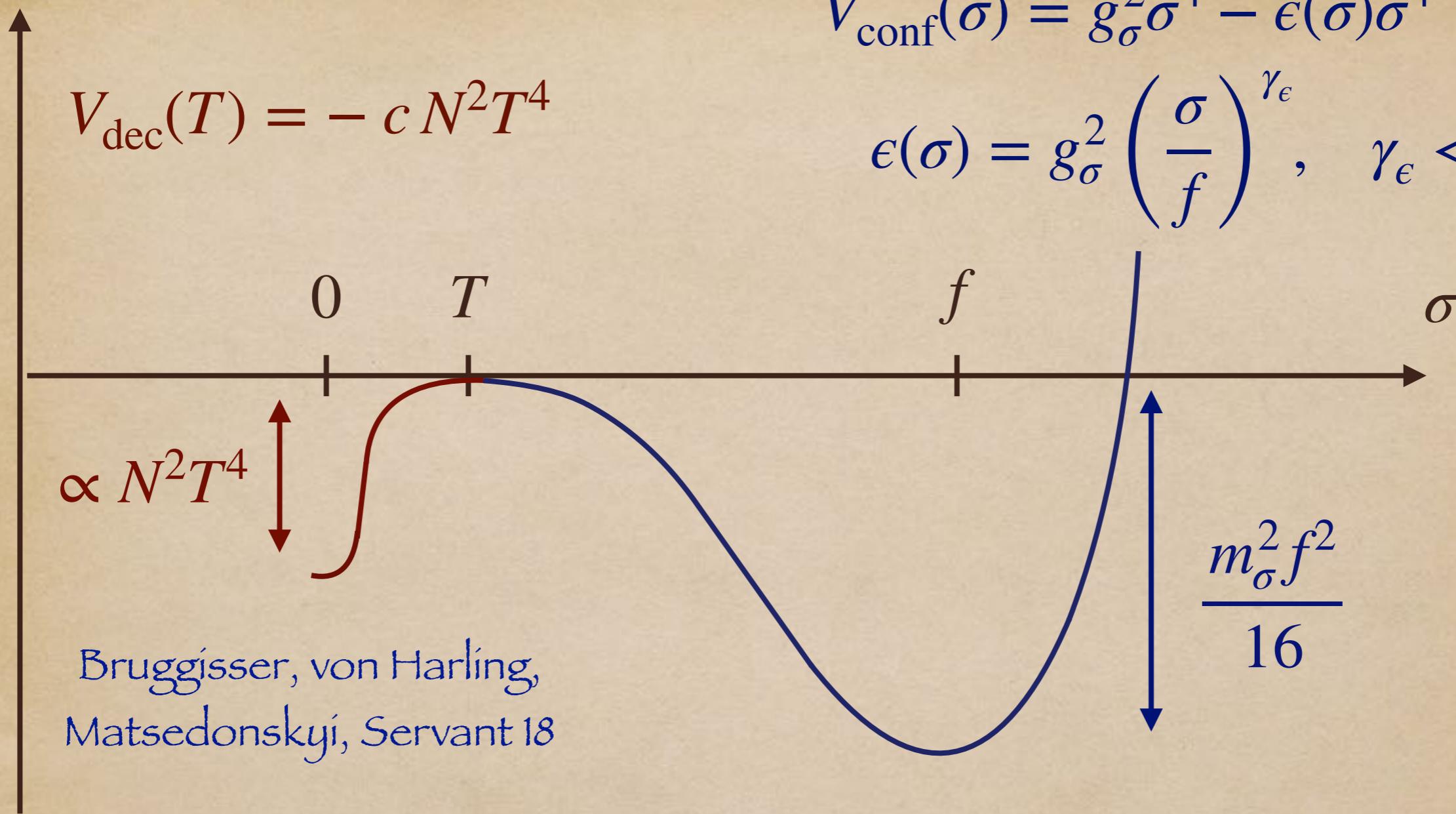
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Super-cooling starts for: $T_{\text{start}} = (0.1) \sqrt{m_\sigma f}$

ends for: $T_{\text{nuc}} \propto c_1 f \text{ Exp} - c_2 \frac{f^2}{m_\sigma^2}$

DM in composite Higgs

pNGB DM :

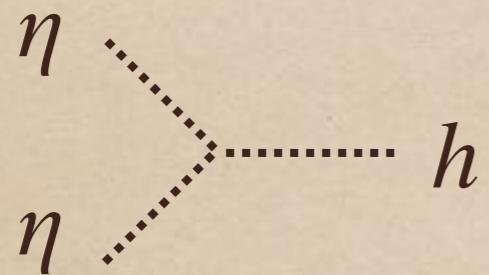
$$SO(6)/SO(5)$$

Frigerio, Pomarol, Riva, Urbano 12

Balkin, Ruhdorfer, Salvioni, Weiler 17 and 18

Marzocca, Urbano 14

Chala, Gröber, Spannowsky 18



$$\mathcal{L}_{DM} \supset \frac{\eta}{f} \partial\eta \partial h + v \frac{\lambda_{h\eta}}{2} \eta^2 h$$

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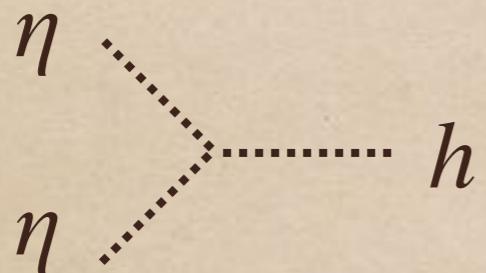
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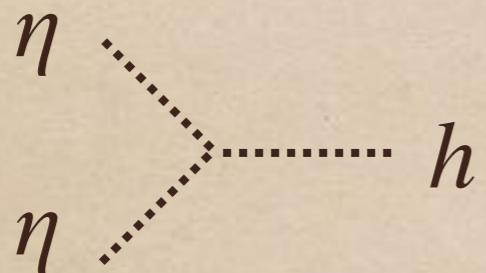
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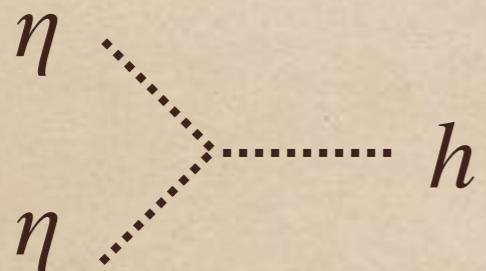
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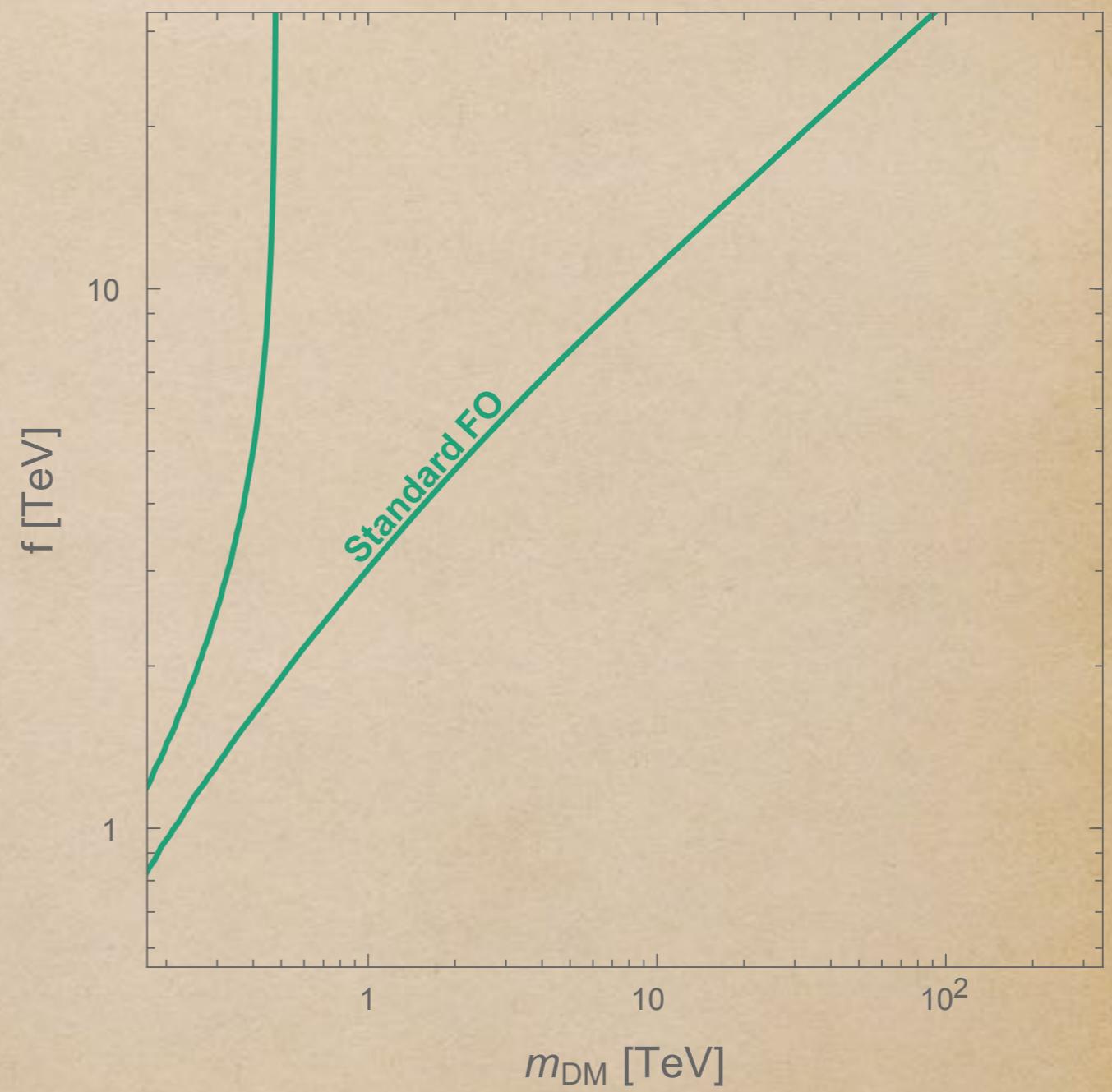
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Fermion DM:

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- pNGB DM
- Scalar DM
- Fermion DM

DM abundance lines for
standard freeze-out

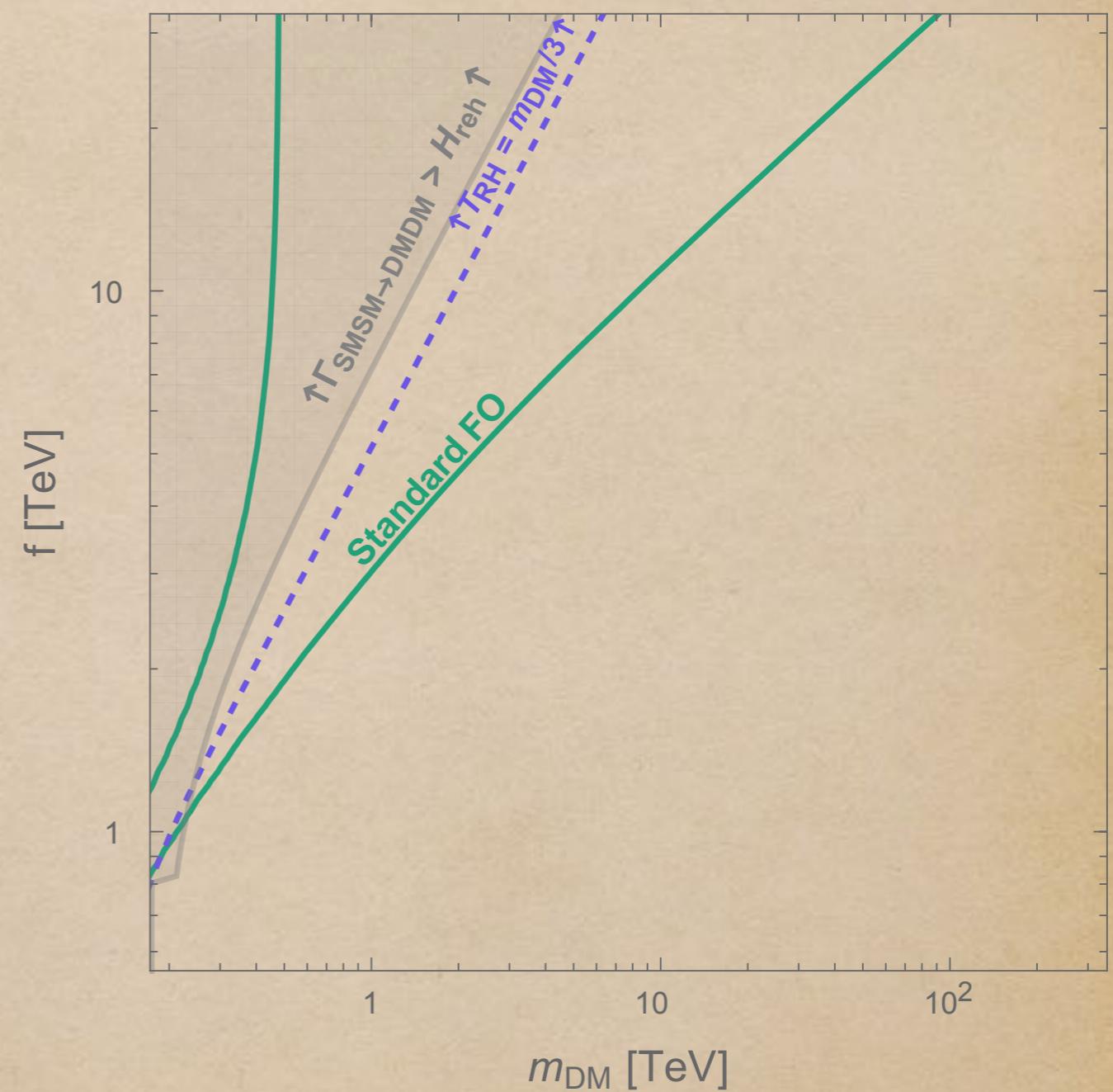


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DM abundance lines for standard freeze-out

Supercool DM abundance fixed by freeze-out when

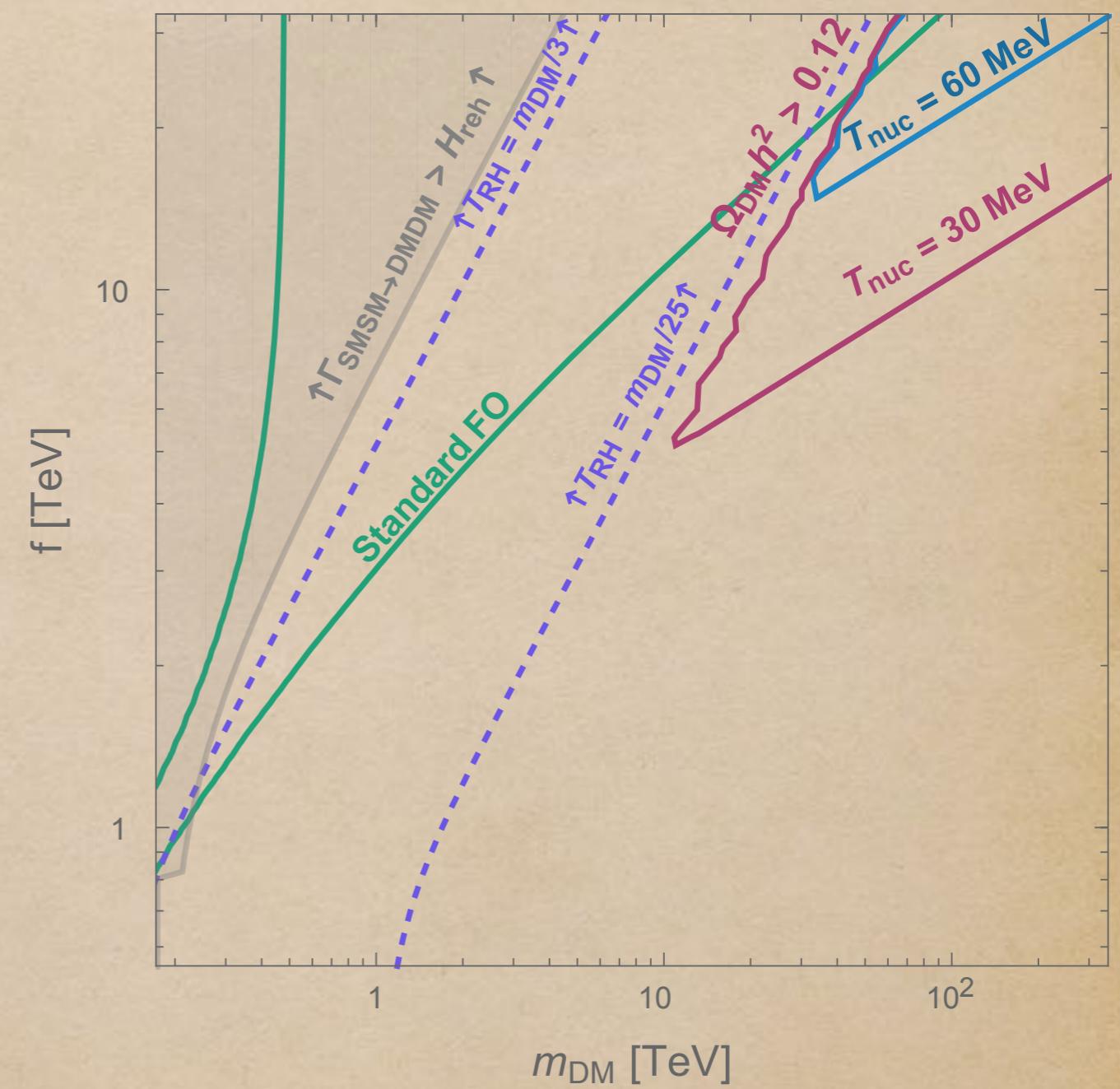
$$\Gamma_{\text{SMSM} \rightarrow \text{DMDM}} \gtrsim H_{\text{reh}}$$



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Supercool DM abundance:

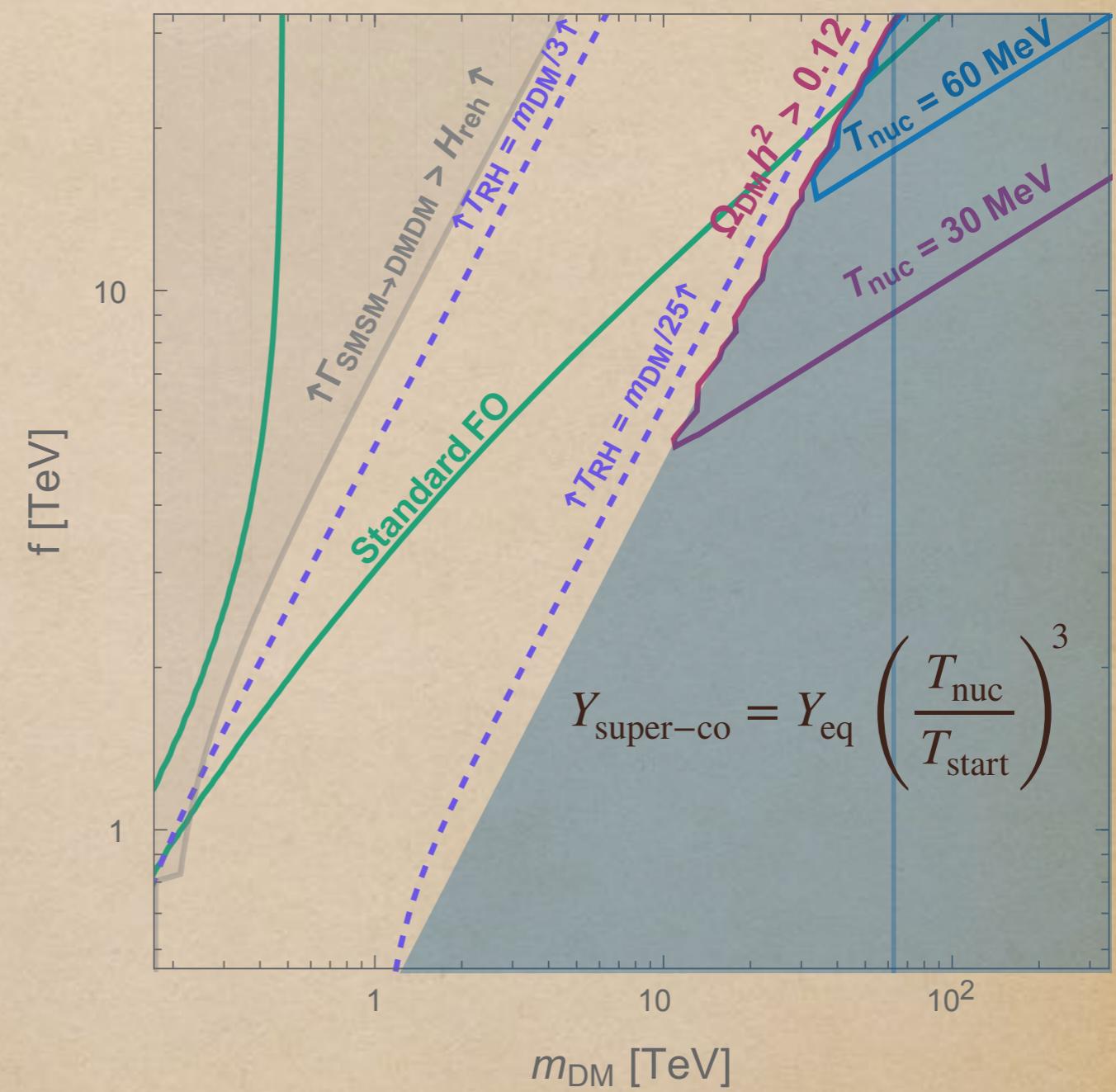
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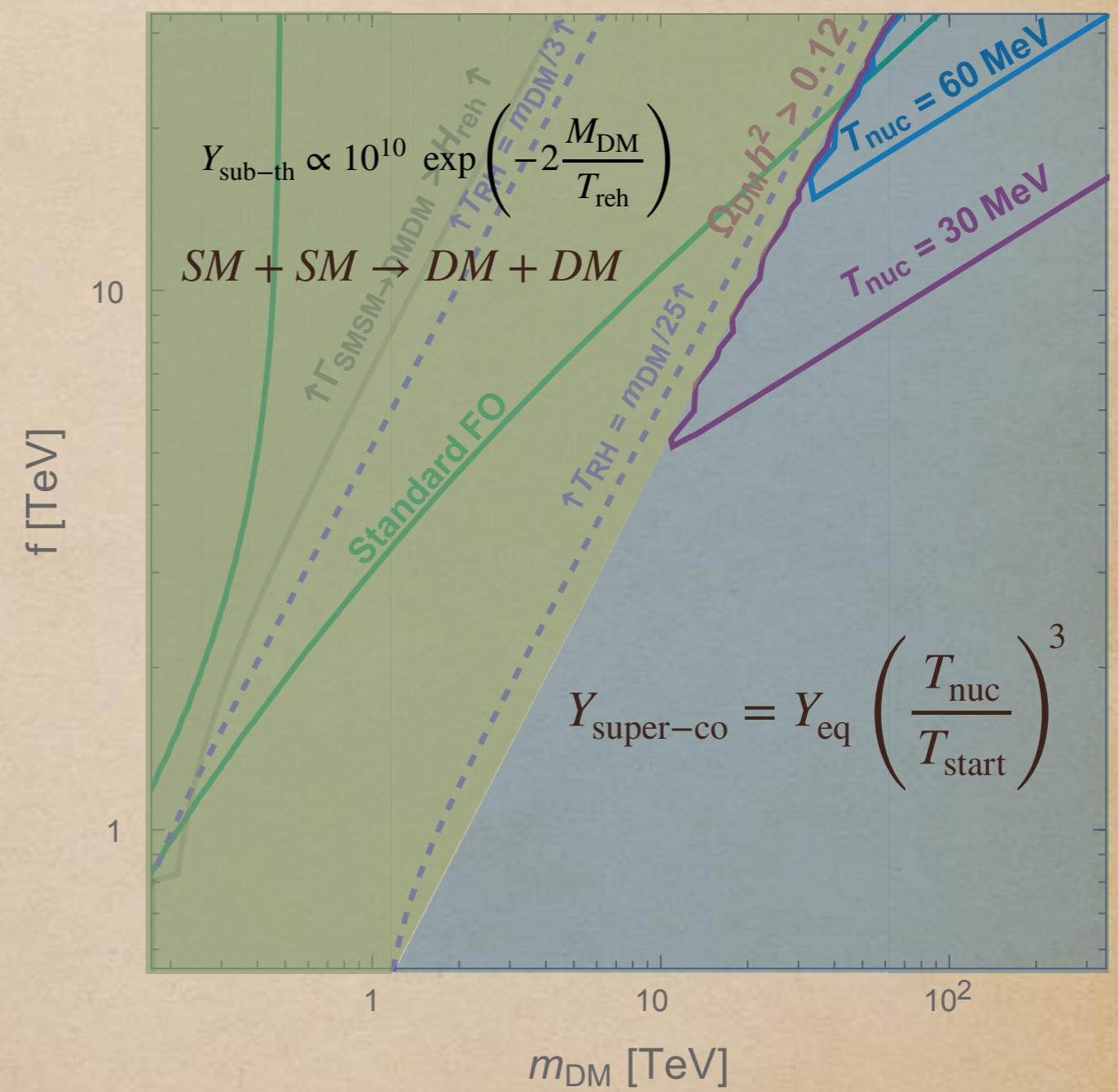
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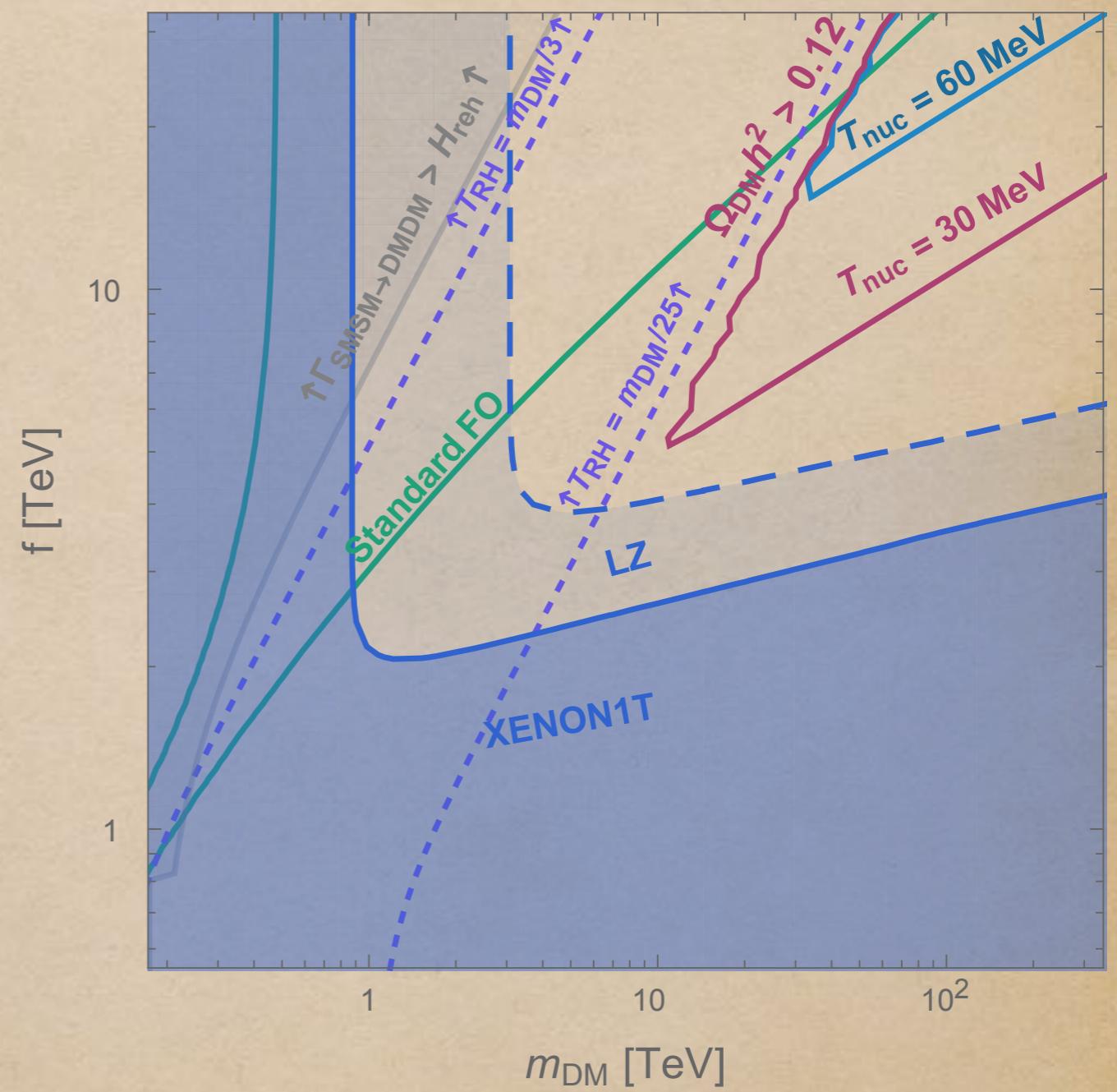


PNGB DM

pNGB DM :

Direct detection

$N = 10$ - $m_\sigma = 0.1 f$ - pNGB DM - $\lambda_{h\eta} = 0.065$

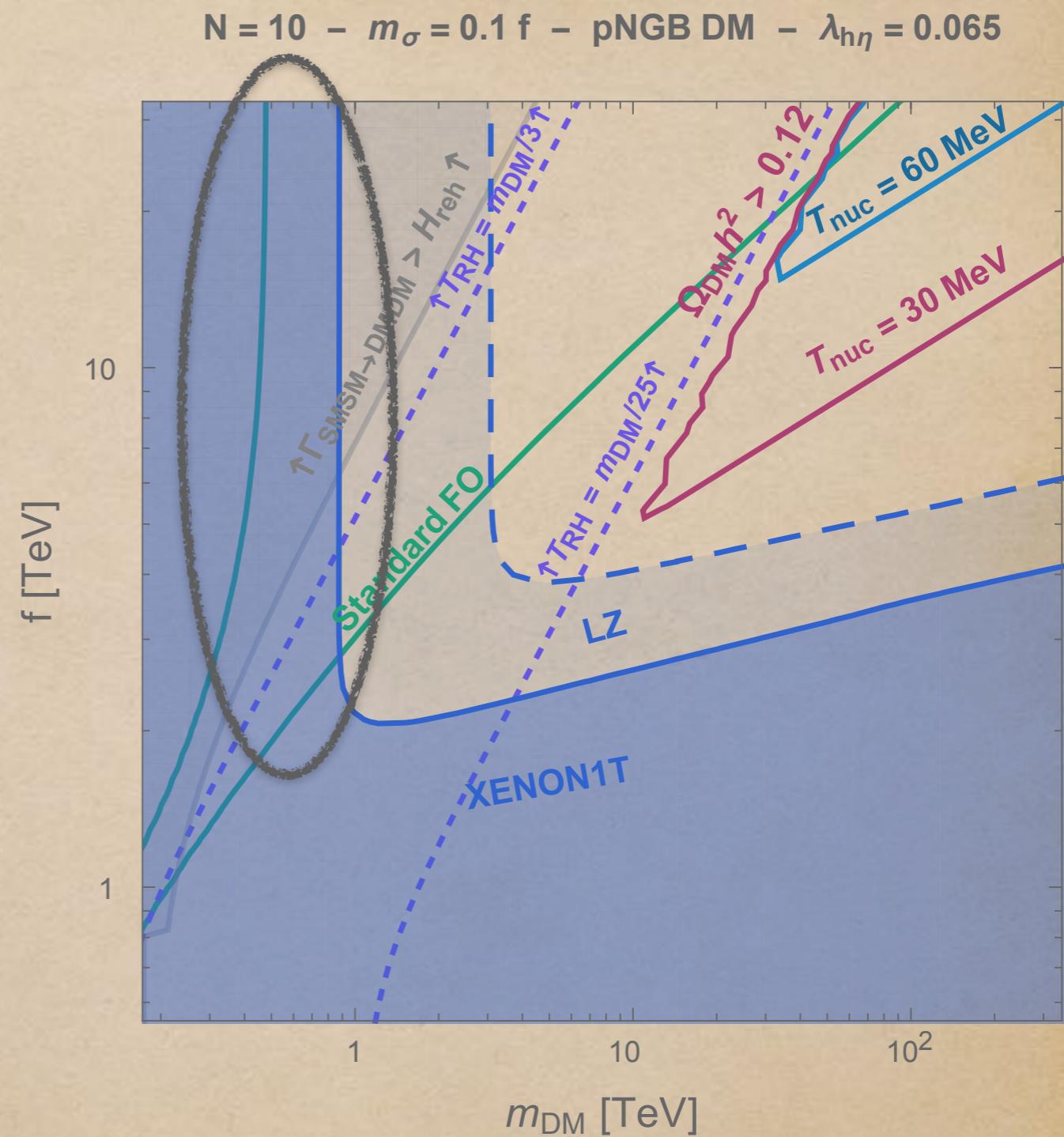


pNGB DM :

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Higgs-mediated

$$\sigma_{\eta n} \propto \lambda_{h\eta}^2$$



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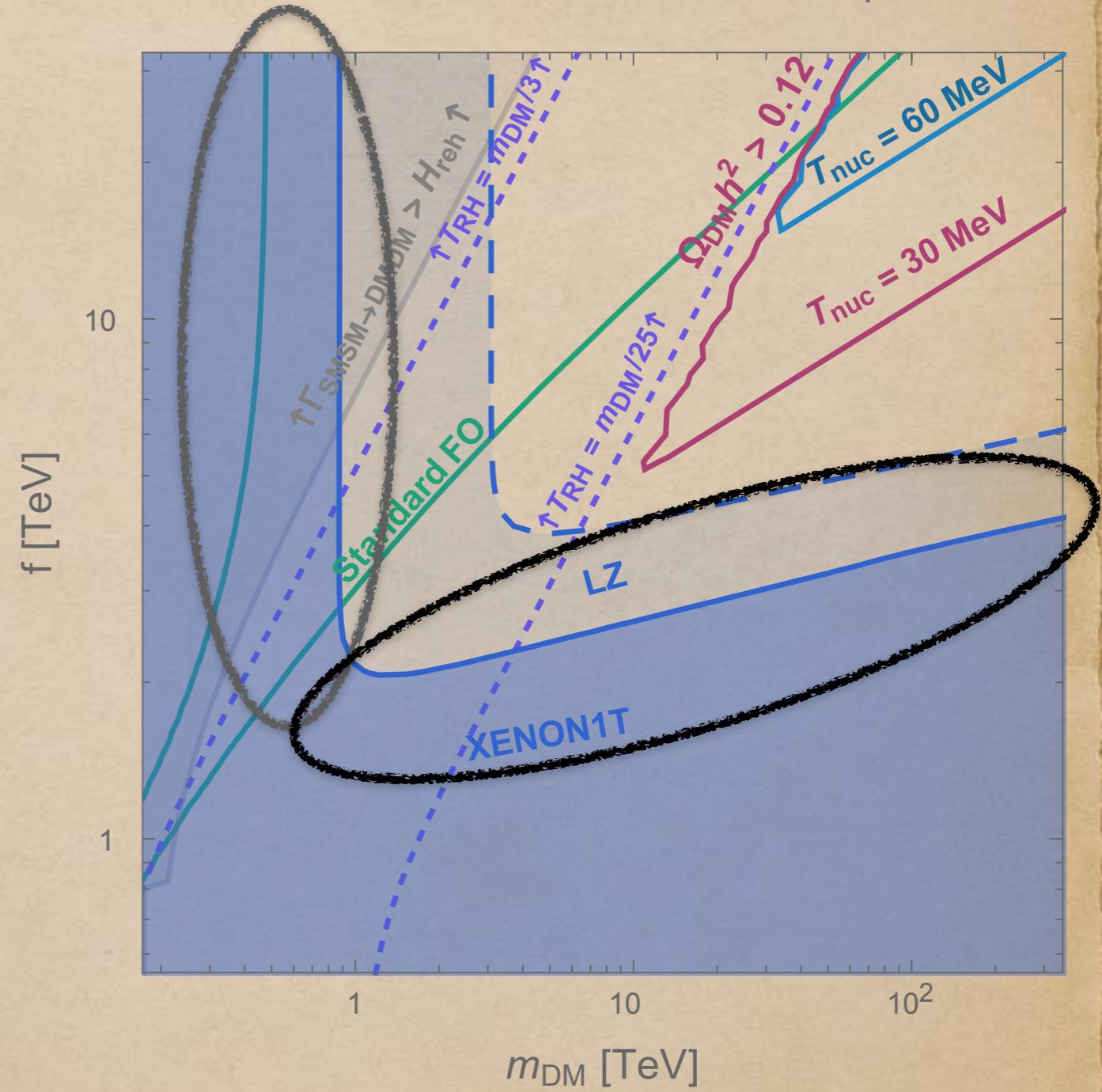
Higgs-mediated

$$\sigma_{\eta n} \propto \lambda_{h\eta}^2$$

Dilaton-mediated

$$\sigma_{\eta n} \propto \frac{1}{m_\sigma^4}$$

$N = 10 - m_\sigma = 0.1 f -$ pNGB DM $- \lambda_{h\eta} = 0.065$



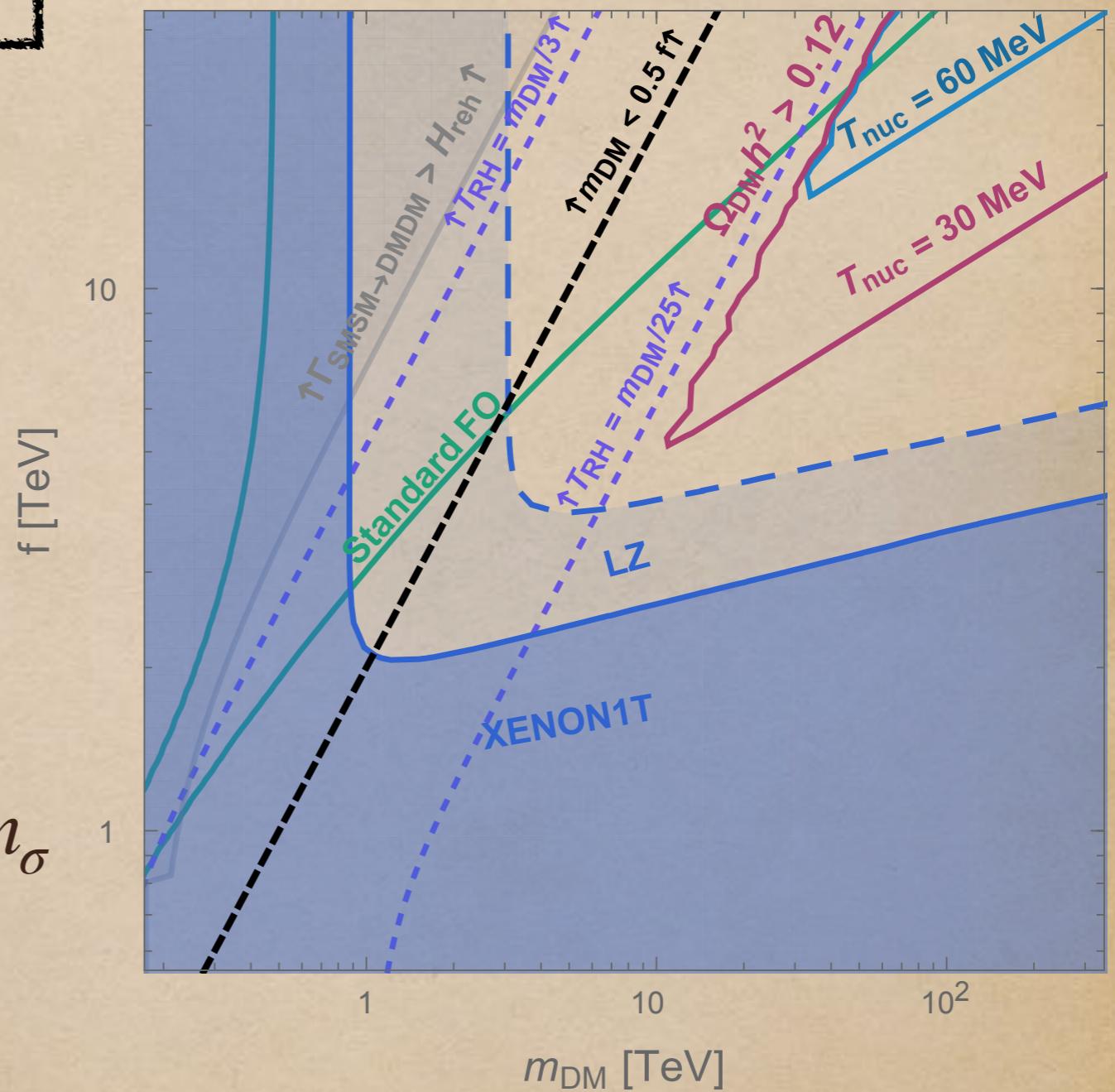
Max pNGB DM mass:

$$\rightarrow m_\eta \lesssim \frac{f}{\nu} m_h \simeq 0.5f$$

Since $T_{\text{reh}} \propto \sqrt{m_\sigma}$

\rightarrow Need to go to small m_σ

$N = 10 - m_\sigma = 0.1 f - \text{pNGB DM} - \lambda_{h\eta} = 0.065$



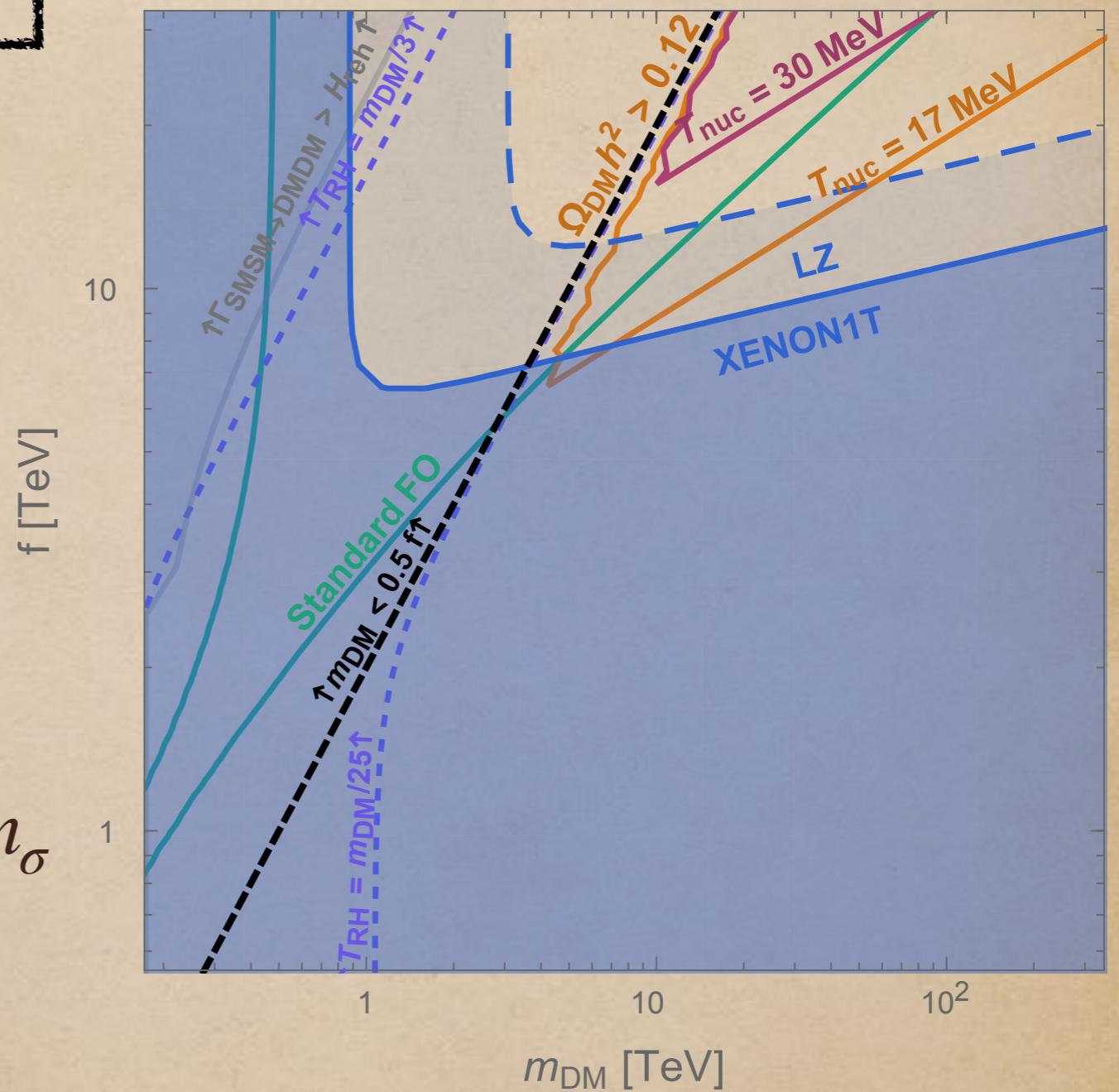
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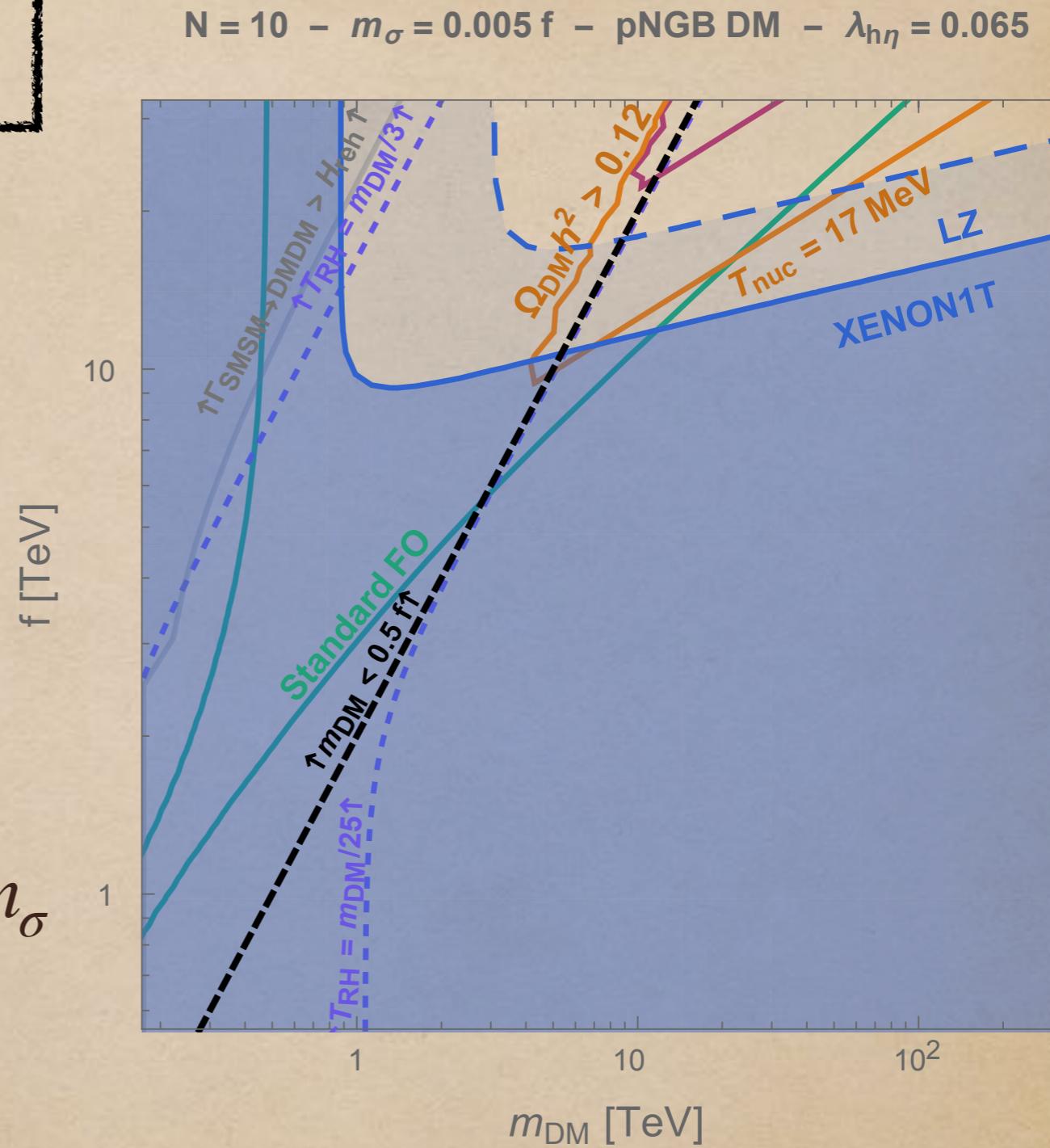


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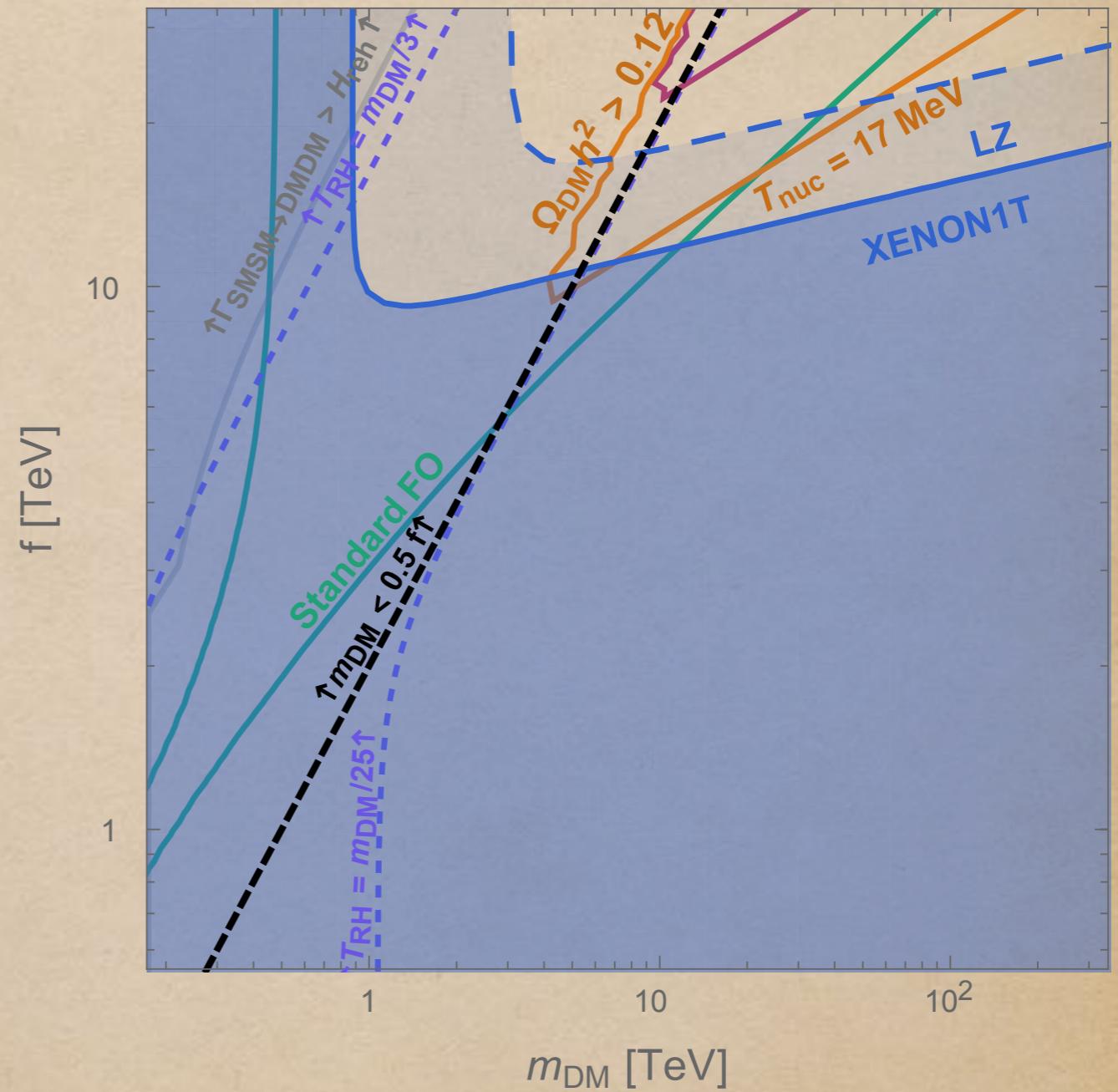
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Conclusion

In case of supercooling
DM as a pNGB is not
natural

$$N = 10 - m_\sigma = 0.005 f - \text{pNGB DM} - \lambda_{h\eta} = 0.065$$



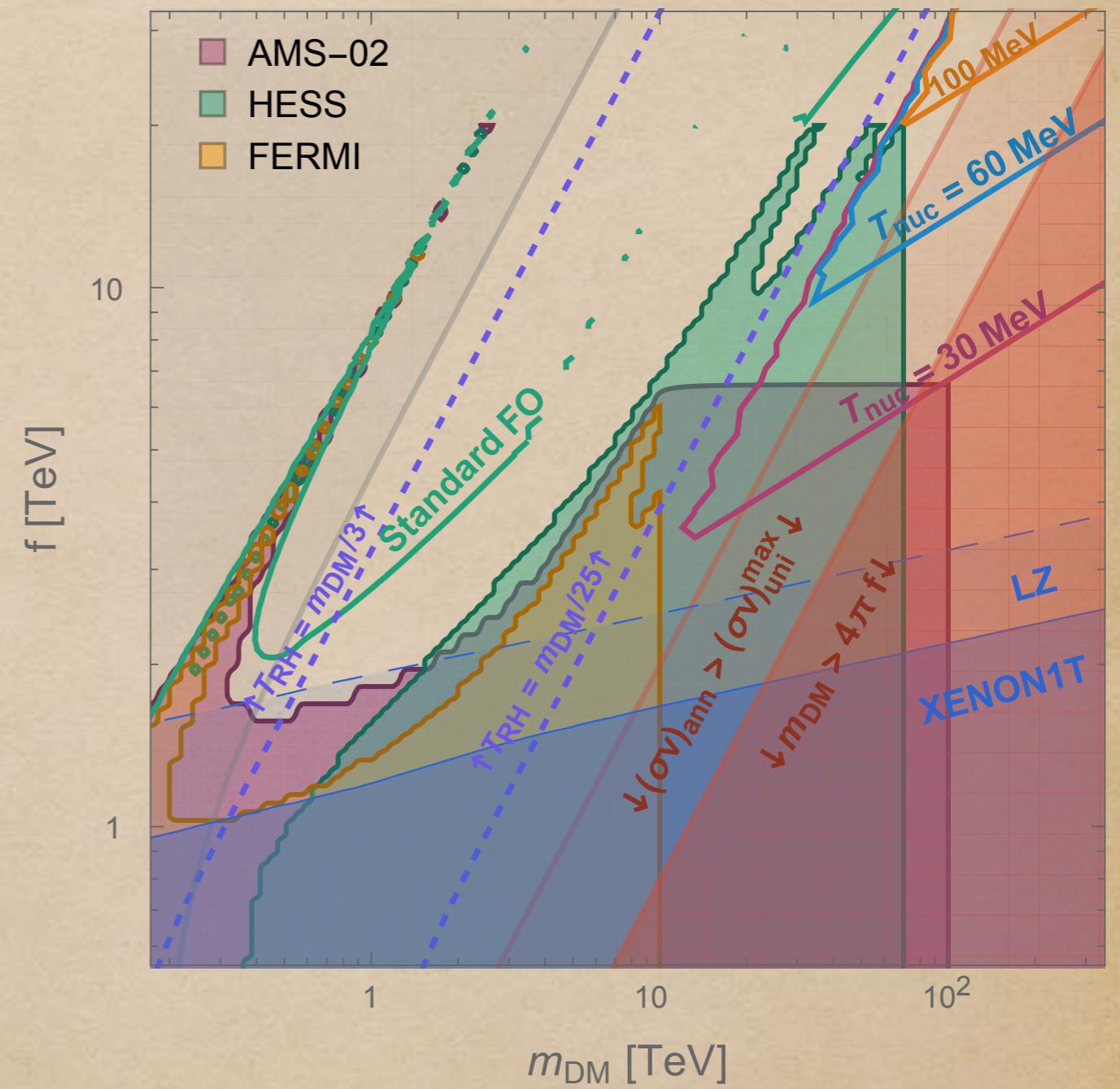
Scalar DM (not pNGB)

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$$\mathcal{L}_{DM} \supset - \left(2\frac{\sigma}{f} + \frac{\sigma^2}{f^2} \right) \frac{1}{2} m_\eta^2 \eta^2$$

→ Constrained by
Indirect Detection

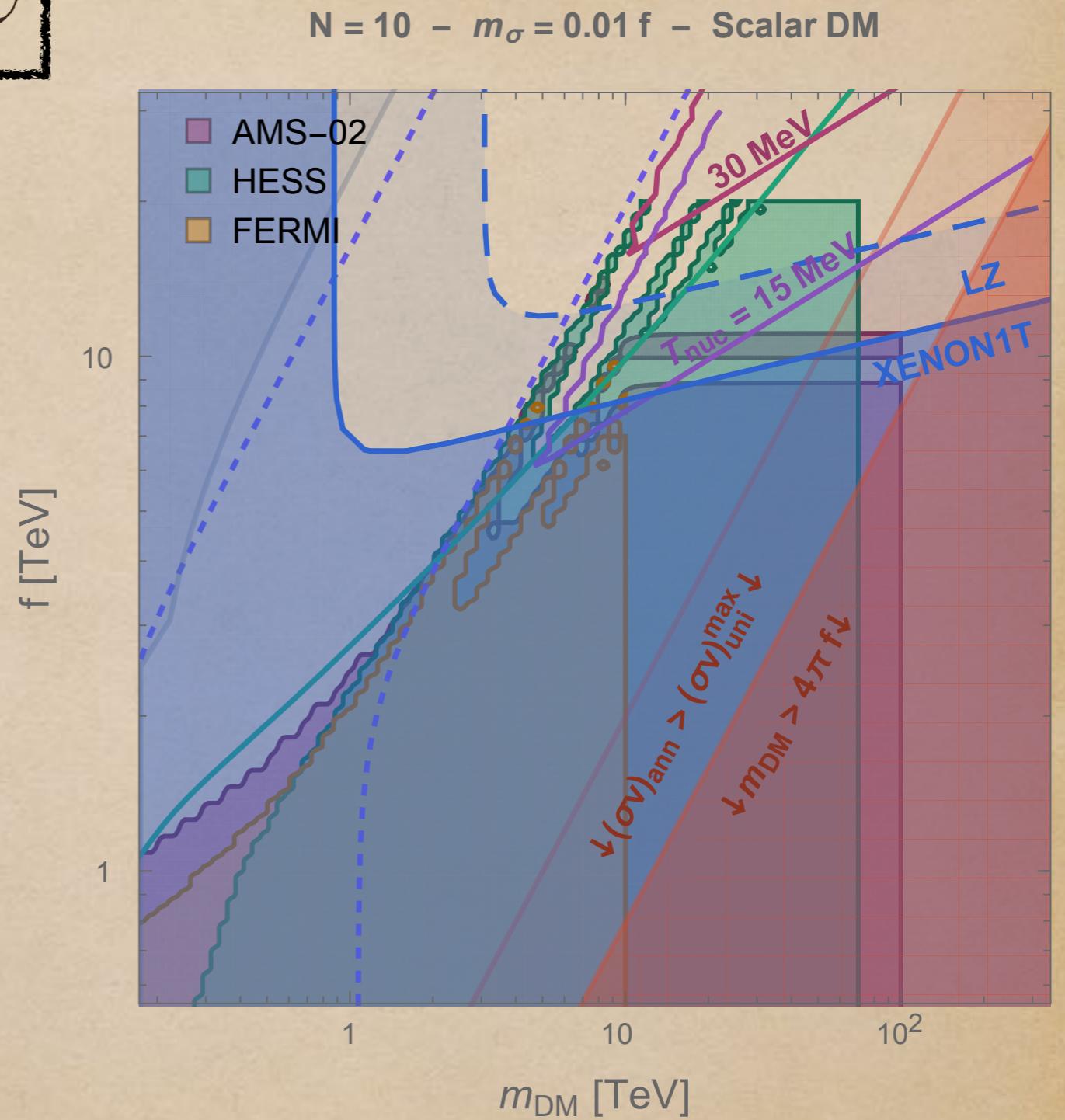
$N = 10$ – $m_\sigma = 0.25 f$ – Scalar DM



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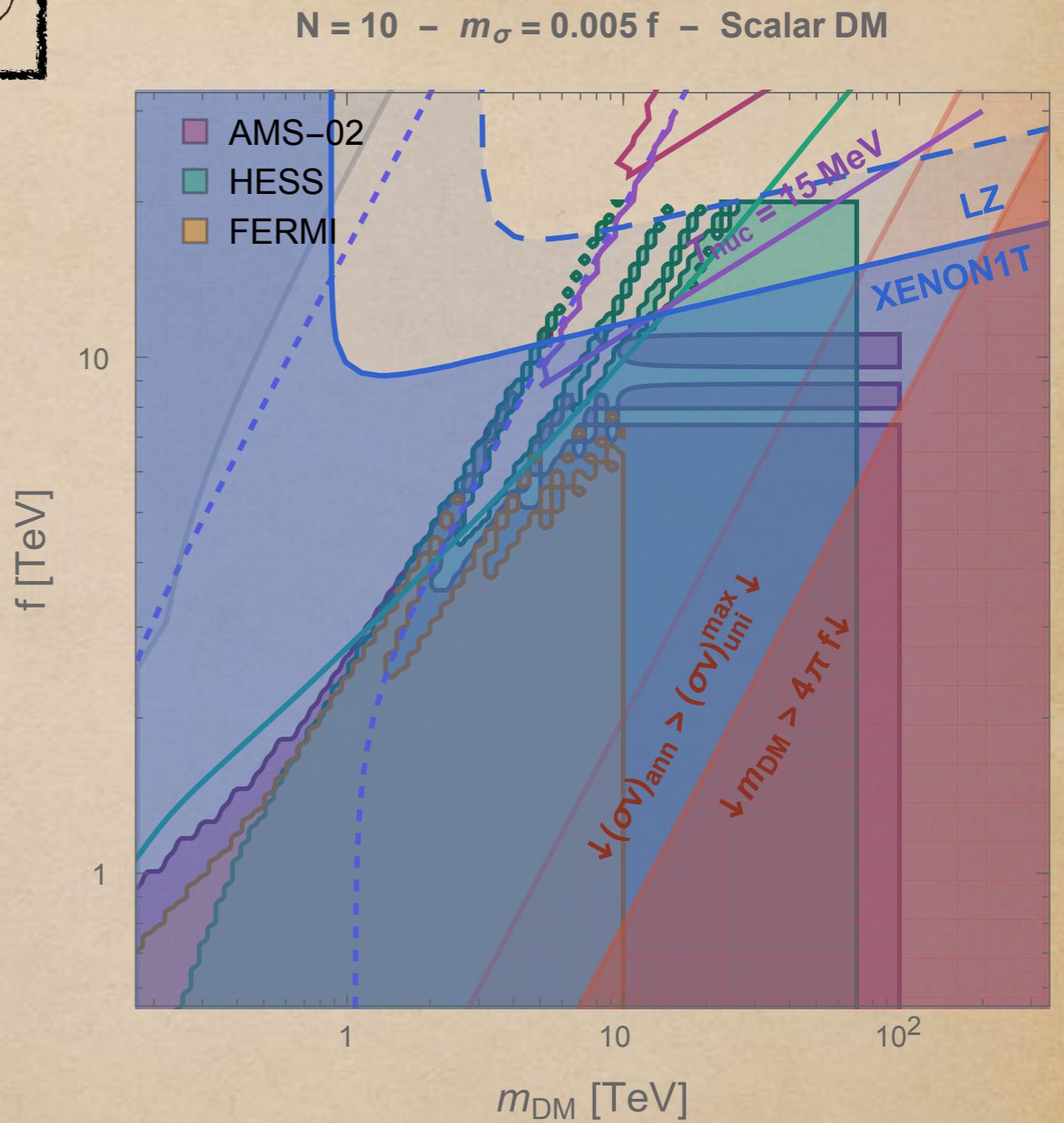
- Constrained by Indirect Detection
- Go to small m_σ
- Constrained by Direct Detection
- $f \gtrsim 10$ TeV



Scalar DM (not pNGB)

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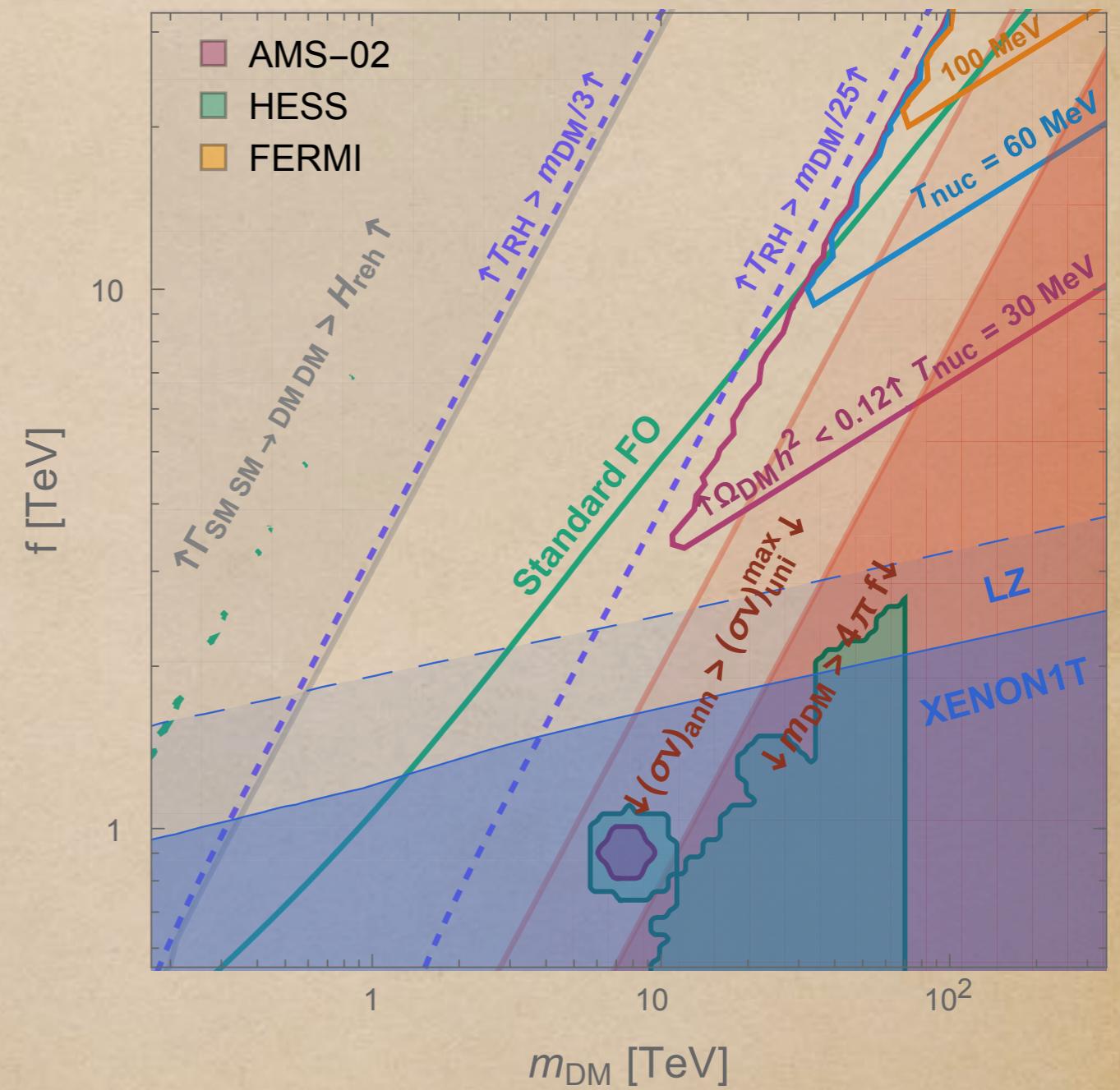
Fermion DM

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$$\mathcal{L}_{DM} \supset -\frac{\sigma}{f} m_\eta \bar{\eta} \eta$$

- $(\sigma v)_{\text{ann}}$ is p – wave
- ID is weakened

$N = 10 - m_\sigma = 0.25 f - \text{Fermion DM}$



Fermion DM

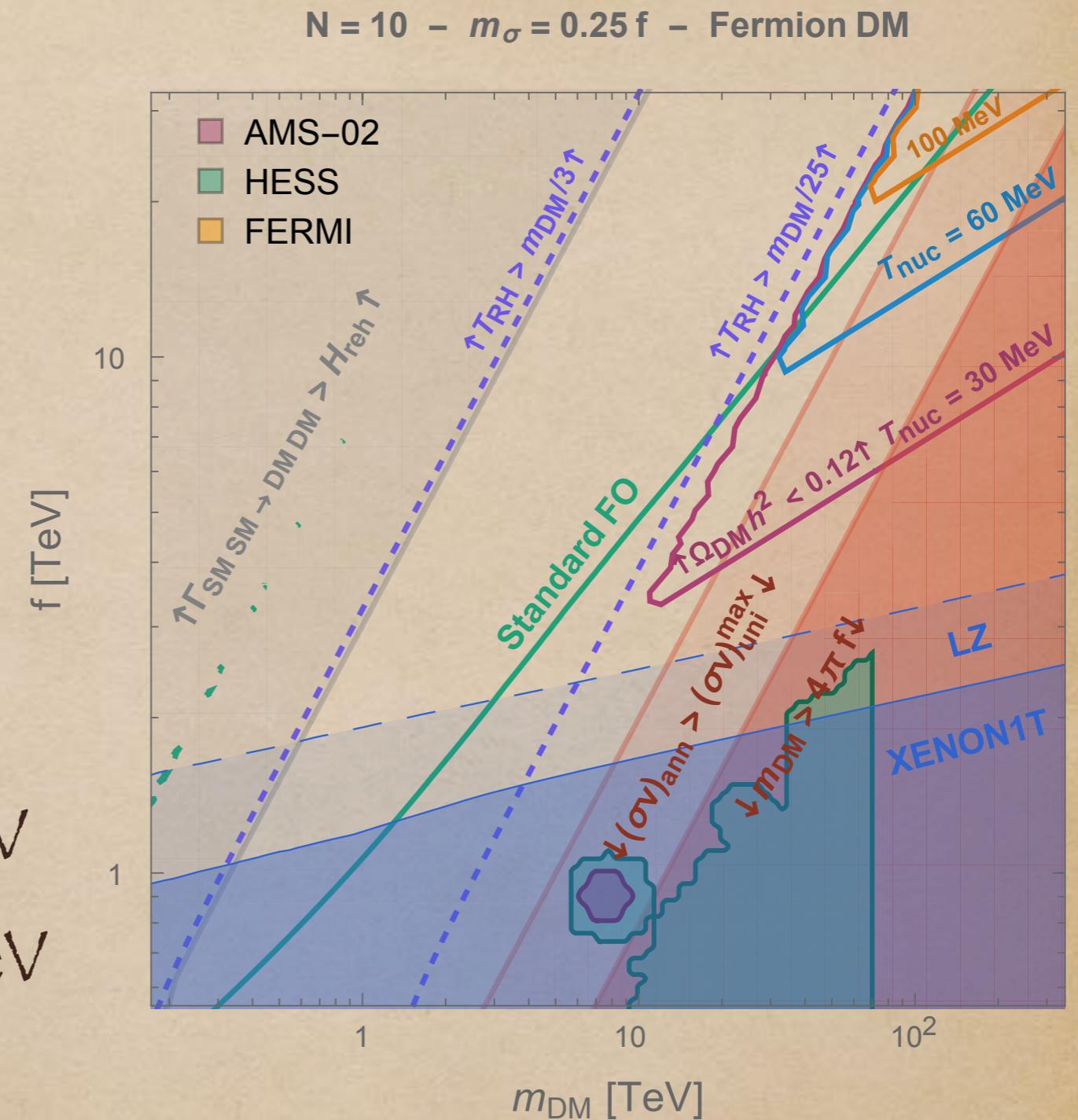
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→ Viable for

- $f \gtrsim \text{TeV}$
 - $T_{\text{nuc}} \lesssim 100 \text{ MeV}$
 - $m_{\text{DM}} \sim O(10) \text{TeV}$



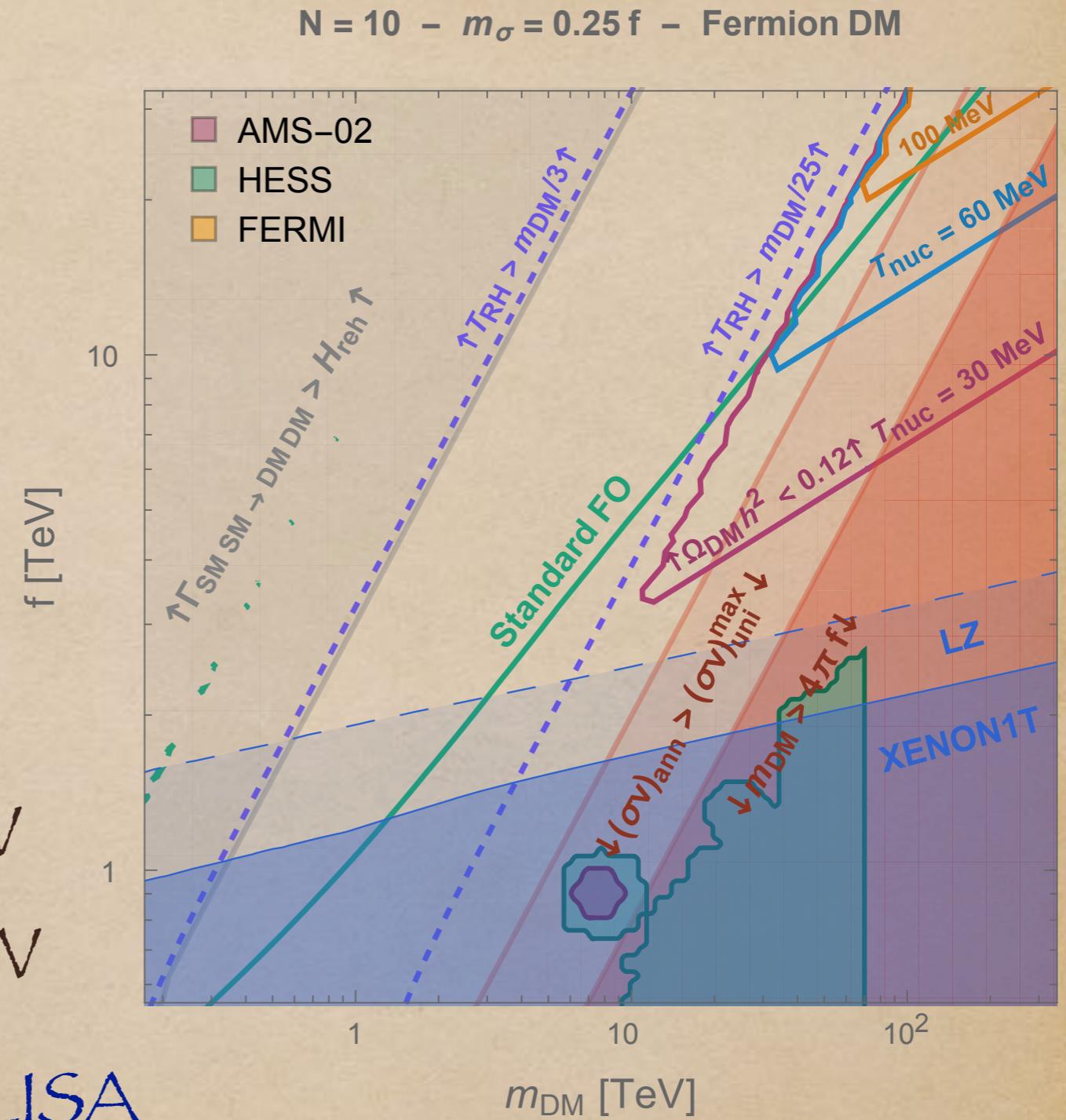
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 - $f \gtrsim \text{TeV}$
 - $T_{\text{nuc}} \lesssim 100 \text{ MeV}$
 - $m_{\text{DM}} \sim O(10) \text{ TeV}$
- Will be probed by LISA

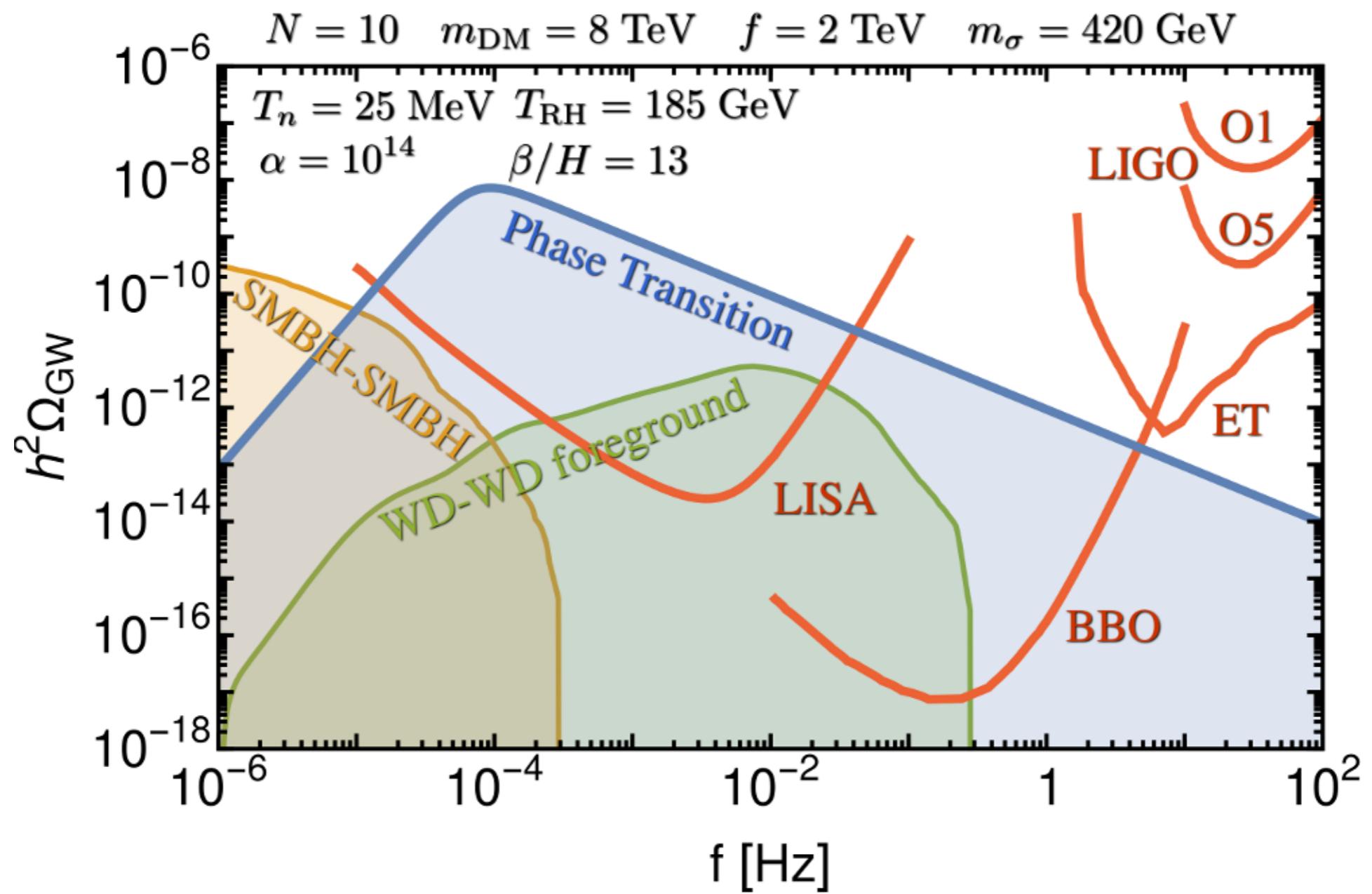
Randall, Servant 06

Konstandin, Nardini, Quiros 10



Baldes, García-Cely 18

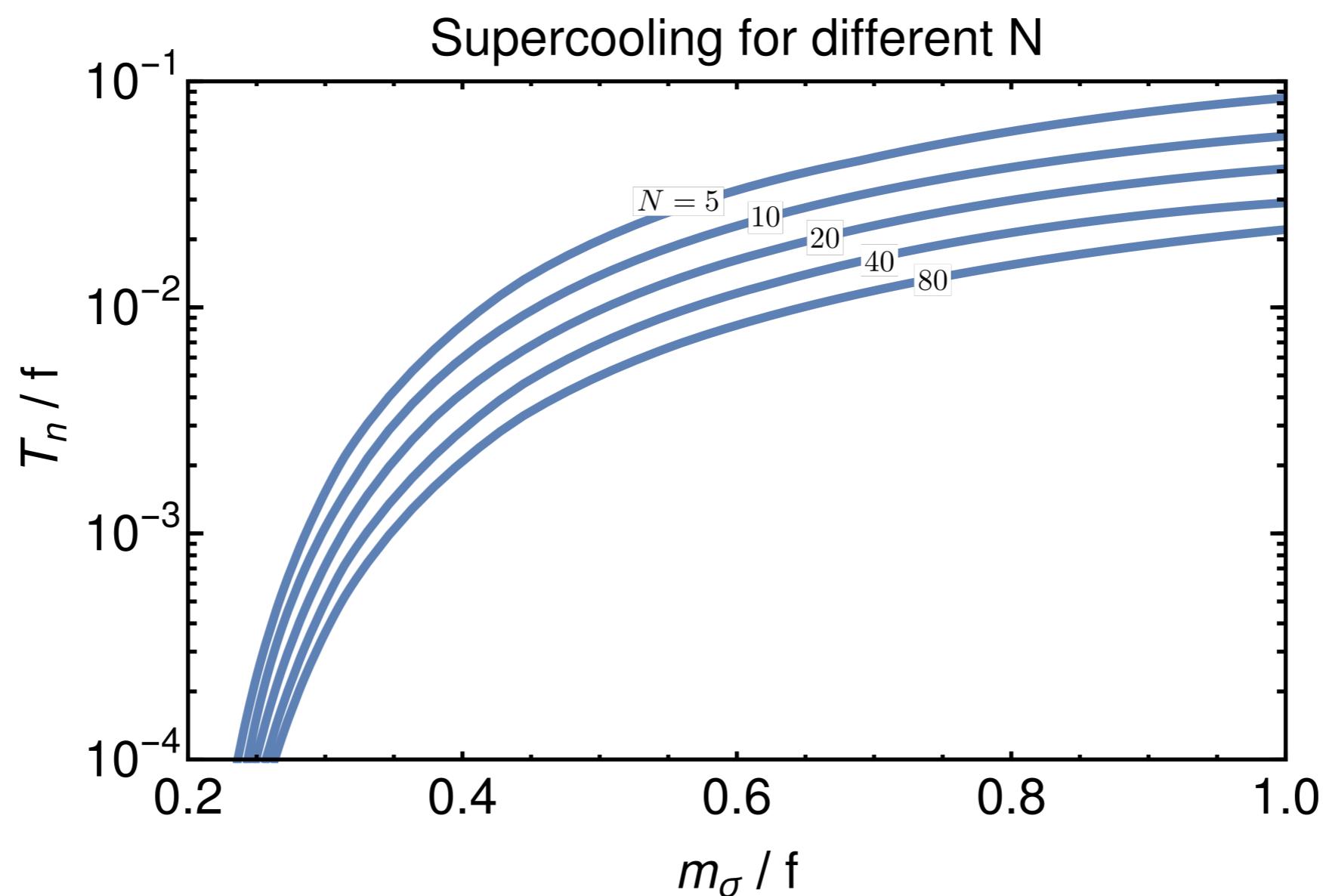
Baratella, Pomarol, Rompineve 18



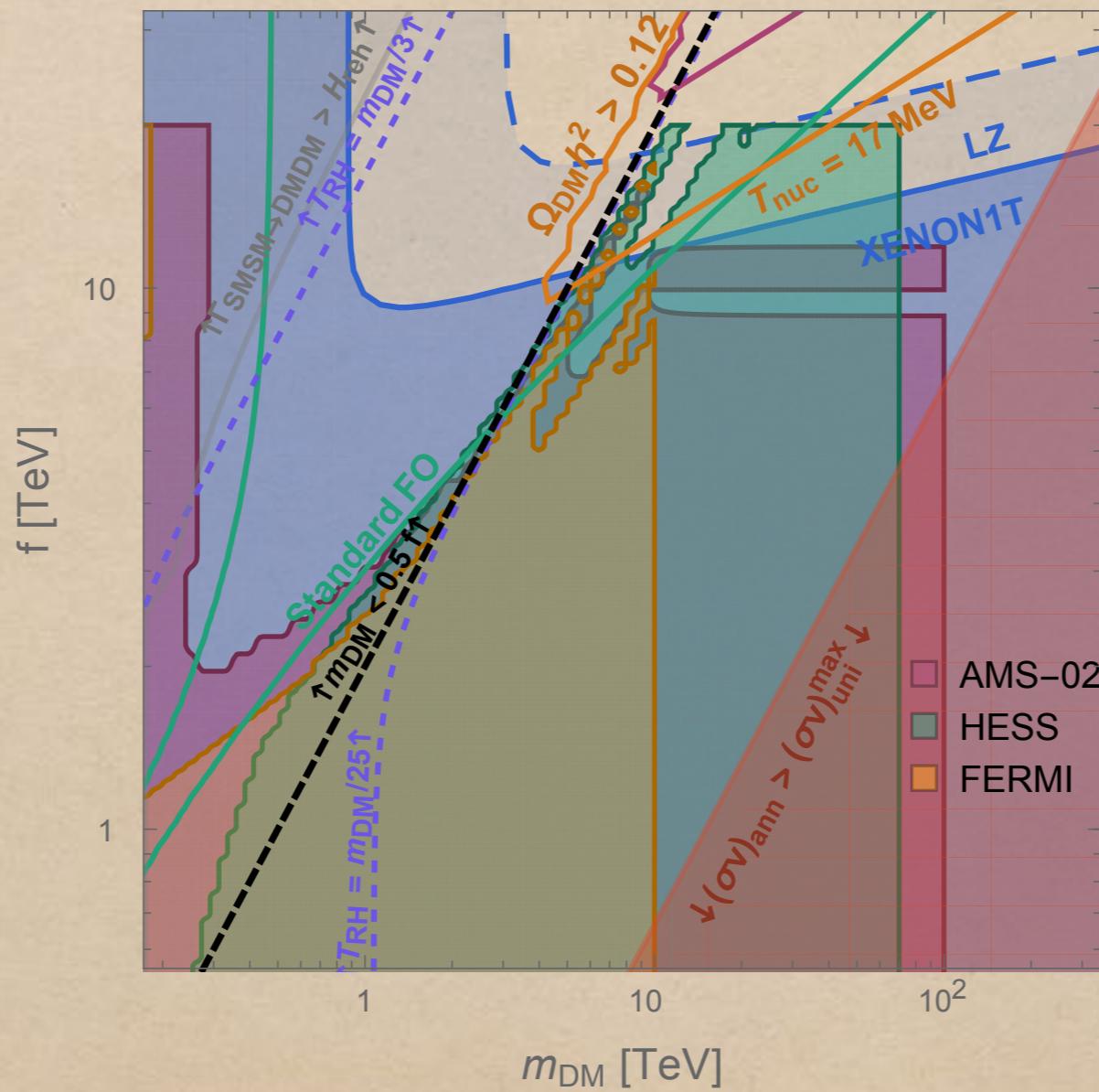
Conclusion

- Supercooled EW phase transition is well motivated in composite Higgs
- DM abundance diluted and generated sub-thermally
- pNGB DM: Direct Detection $\rightarrow f \gtrsim 10 \text{ TeV}$
- Scalar DM: ID and DD $\rightarrow f \gtrsim 10 \text{ TeV}$
- Fermion DM:
 - $f \gtrsim \text{TeV}$
 - $T_{\text{nuc}} \lesssim 100 \text{ MeV}$
 - $m_{\text{DM}} \sim O(10) \text{TeV}$
 - Will be probed by LISA

Back-up slides



$N = 10$ – $m_\sigma = 0.005 f$ – pNGB DM – $\lambda_{h\eta} = 0.065$



MCHM: $SO(5) \rightarrow SO(4)$

$$\mathcal{L}_C = \frac{1}{2} D_\mu \vec{\phi}^T D^\mu \vec{\phi} - \frac{g_*^2}{8} \left(\vec{\phi}^T \vec{\phi} - f^2 \right)^2 \quad \vec{\phi} : \mathbf{5} \text{ of } SO(5)$$

NGBs:

$$\vec{\phi} = e^{i\frac{\sqrt{2}}{f}\Pi_i(x)\hat{T}_i} \begin{bmatrix} \vec{0} \\ f + \sigma(x) \end{bmatrix} = (f + \sigma) \begin{bmatrix} \sin \frac{\Pi}{f} \frac{\vec{\Pi}}{\Pi} \\ \sin \frac{\Pi}{f} \end{bmatrix}$$

$\vec{\Pi}$ transforms as the $\mathbf{4} = (2, 2)$ of $SO(4) \simeq SU(2)_L \times SU(2)_R$

$\mathbf{4} = (2, 2) \rightarrow \mathbf{2}_{1/2}$ under $SU(2)_L \times U(1)_Y$

Invert $(H^c, H) = \frac{1}{\sqrt{2}}(i\sigma_\alpha \Pi^\alpha + L_2 \Pi^4) \longrightarrow \Pi(H)$

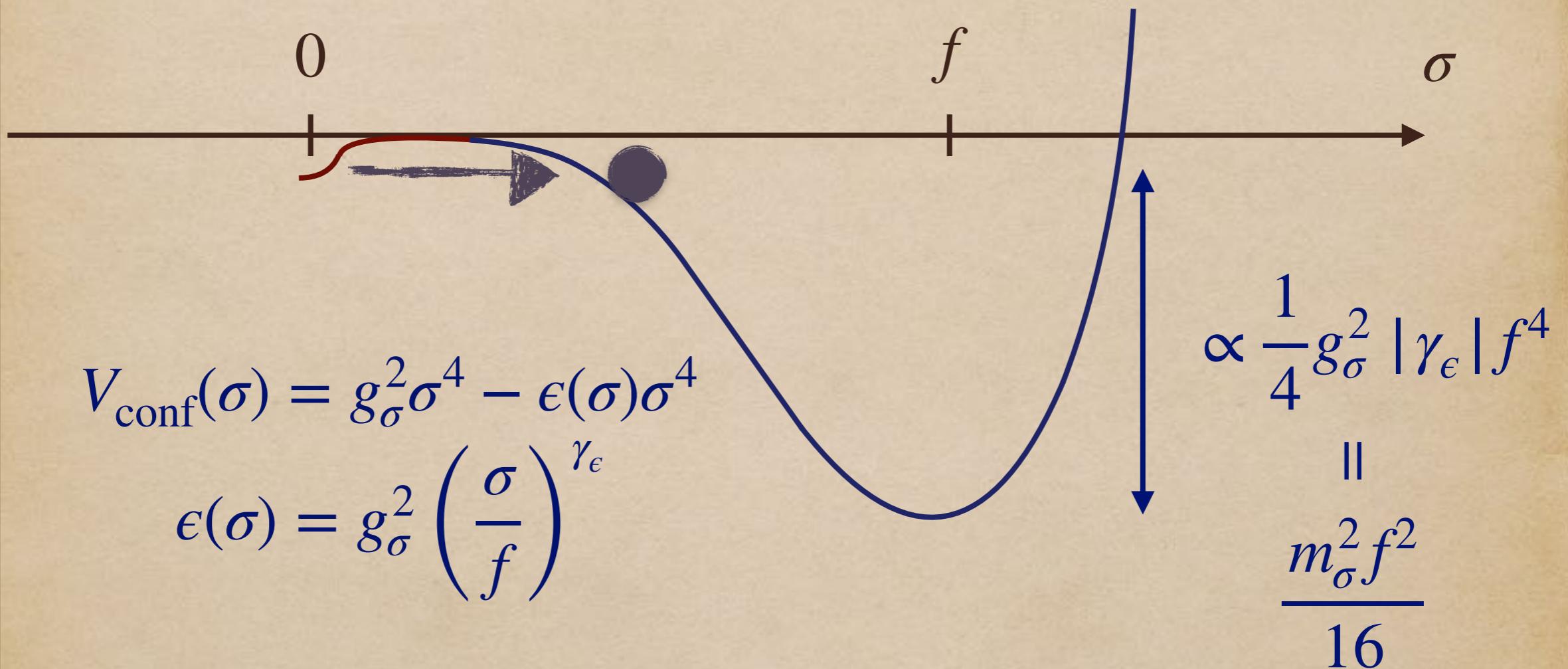
$$\mathcal{L}_C \supset \frac{f^2}{2\left|H\right|^2}\sin^2\frac{\sqrt{2}\left|H\right|}{f}D_{\mu}H^{\dagger}D^{\mu}H \quad + \quad V_{\text{1-loop}}(H)$$

$$H=\begin{bmatrix}0\\ \frac{V+h(x)}{\sqrt{2}}\end{bmatrix},\qquad v=f\sin\frac{V}{f}$$

$$\mathcal{L}_C \supset \frac{g^2v^2}{4}\left(\left|W\right|^2+\frac{1}{2c_w^2}Z^2\right)\left[2\sqrt{1-\xi}\frac{h}{v}+(1-2\xi)\frac{h^2}{v^2}+\dots\right]$$

$$\xi \equiv \frac{v^2}{f^2} \lesssim 0.2 \qquad @ 95\,\% \qquad {\rm ATLAS}$$

Confinement phase transition through
bubble nucleation and end of Supercooling



$$T_{\text{nuc}}/f \propto c_1 \gamma_\epsilon e^{-c_2/\gamma_\epsilon}$$

$$m_\sigma = 4g_\sigma^2 |\gamma_\epsilon| f^2$$

DM abundance after supercooling

Supercooling

Sub-thermal



$$\frac{dY_{\text{DM}}}{dz} = \frac{\lambda}{z^2} \left(Y_{\text{DM}}^2 - Y_{\text{DM}}^{2\text{eq}} \right) \quad z = \frac{m_{\text{DM}}}{T}$$

$$Y_{\text{super-co}} = Y_{\text{eq}} \left(\frac{T_{\text{nuc}}}{T_{\text{start}}} \right)^3,$$

$$Y_{\text{eq}} = \frac{45g_{\text{DM}}}{2\pi^4 g_s} = \frac{4}{\pi^4 N} \quad T_{\text{start}}^4 = \frac{m_\sigma^2 f^2}{6\pi^2 N^2}$$

$$T_{\text{nuc}}^4 \simeq \frac{m_\sigma^2 f^2}{2\pi^2 N^2} e^{-c \frac{f^2}{m_\sigma^2}}$$

$$Y_{\text{super-co}} = \frac{0.1}{N} \exp \left(-c_1 \frac{f^2}{m_\sigma^2} \right)$$

$$\lambda = M_{\text{pl}} m_{\text{DM}} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \sqrt{\frac{\pi g_{\text{SM}}}{45}}$$

$$Y_{\text{sub-th}} \propto 10^{10} \exp \left(-2 \frac{M_{\text{DM}}}{T_{\text{reh}}} \right)$$

$$\lambda = 10^{10} \left(\frac{g_{\text{DM}}}{4} \right)^2 \left(\frac{110}{g_s} \right)^{3/2} \frac{M_{\text{DM}}}{\text{TeV}} \frac{\sigma v}{10^{-9}}$$

$$Y_{\text{sub-th}} \propto 10^{10} \exp \left(-9.5 \frac{M_{\text{DM}}}{\sqrt{m_\sigma f}} \right)$$