Light Dark Matter through Resonance Scanning

Durham University

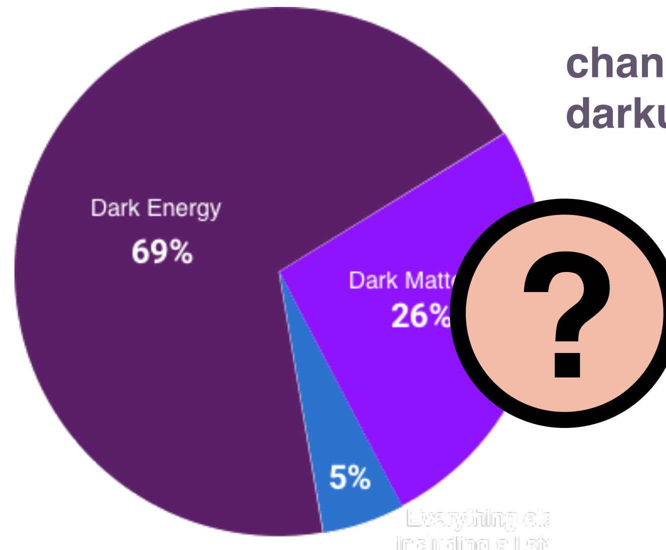
IP3

Rachel Houtz
Brookhaven Forum
November, 2021

In Collaboration with D. Croon and G. White (TRIUMF), H. Murayama (UC Berkeley), G. Elor (U. Washington), arXiv:2012.15284

Motivation for dark matter

- Significant evidence for a new particle beyond the SM



chandra.harvard.edu/
darkuniverse

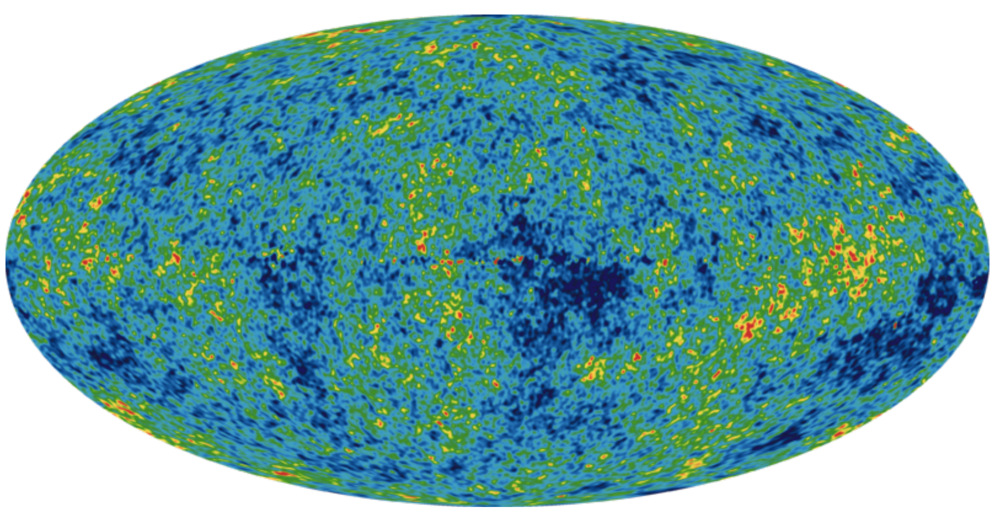
Galaxy rotation curves

ESA/Hubble

Gravitational lensing

nasa.gov
Markevitch et al., Clowe et al.

Cosmic Microwave Background



wmap.gsfc.nasa.gov

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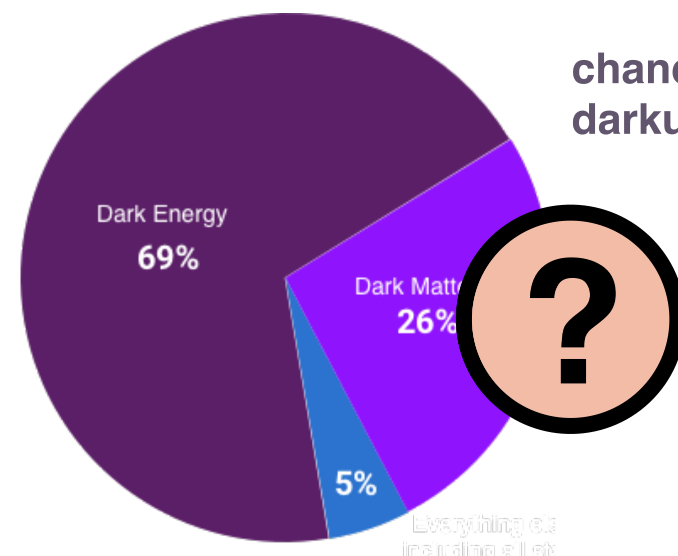

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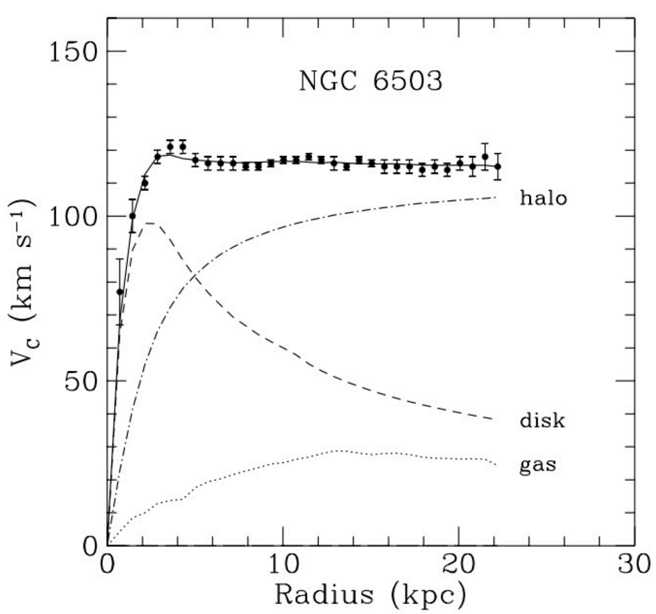
<u>Galaxy rotation curves</u>



Begeman, Broeils, Sanders (1991)

<u>Gravitational lensing</u>

nasa.gov
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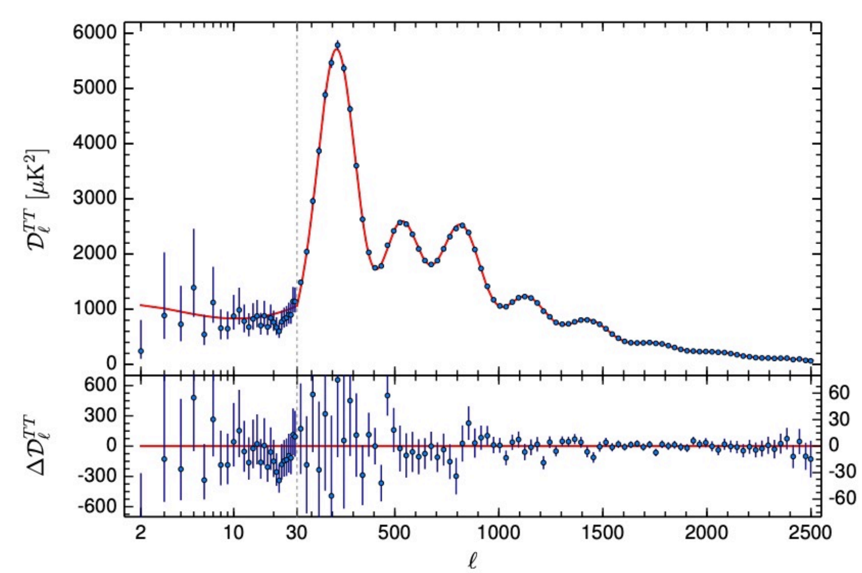
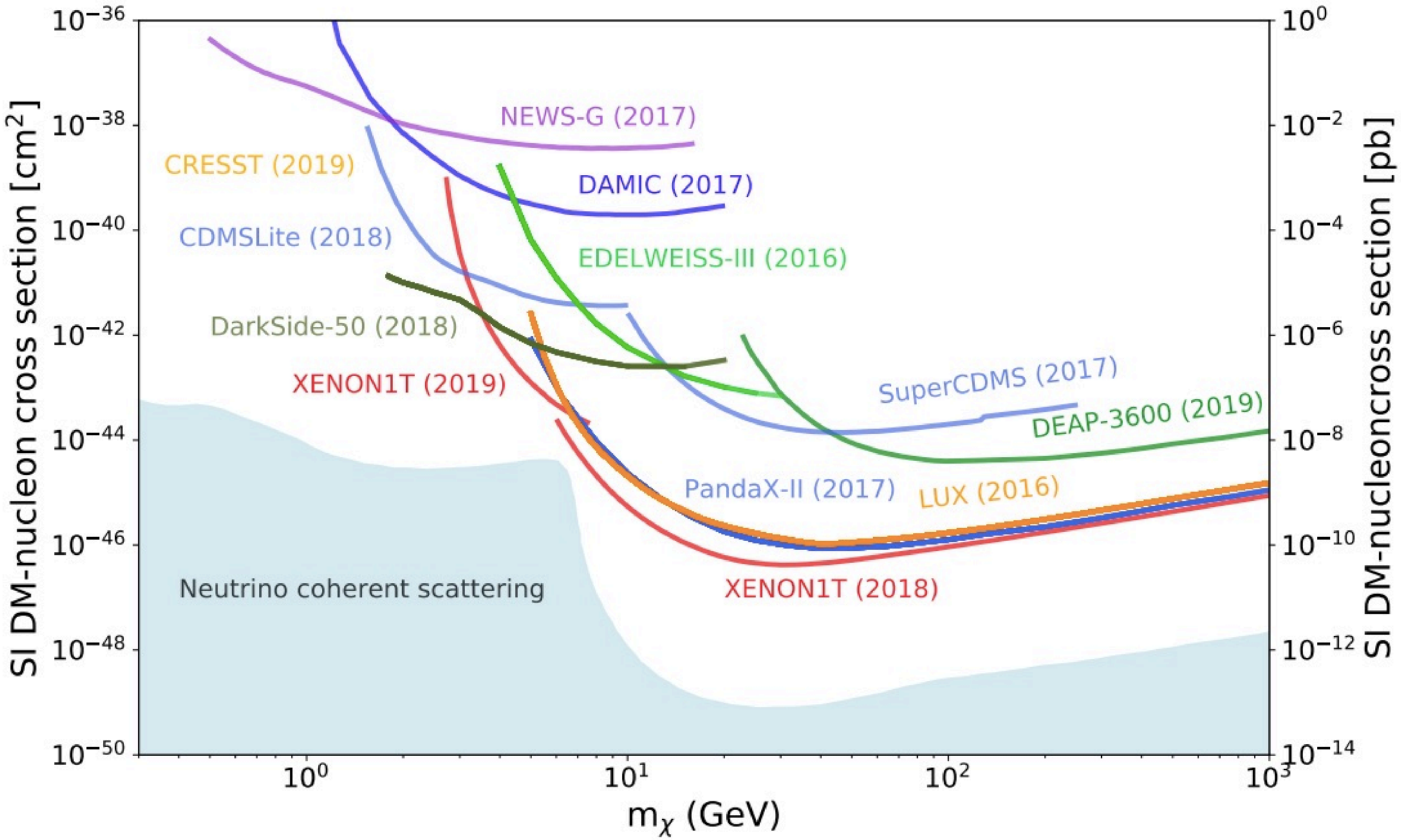
<u>Cosmic Microwave Background</u>



Planck Collaboration, arXiv:1502.01589

WIMP dark matter



Baudis, Profumo, Particle Data Group (2020)

The Higgs portal WIMP

- WIMP that interacts with the SM through the Higgs portal

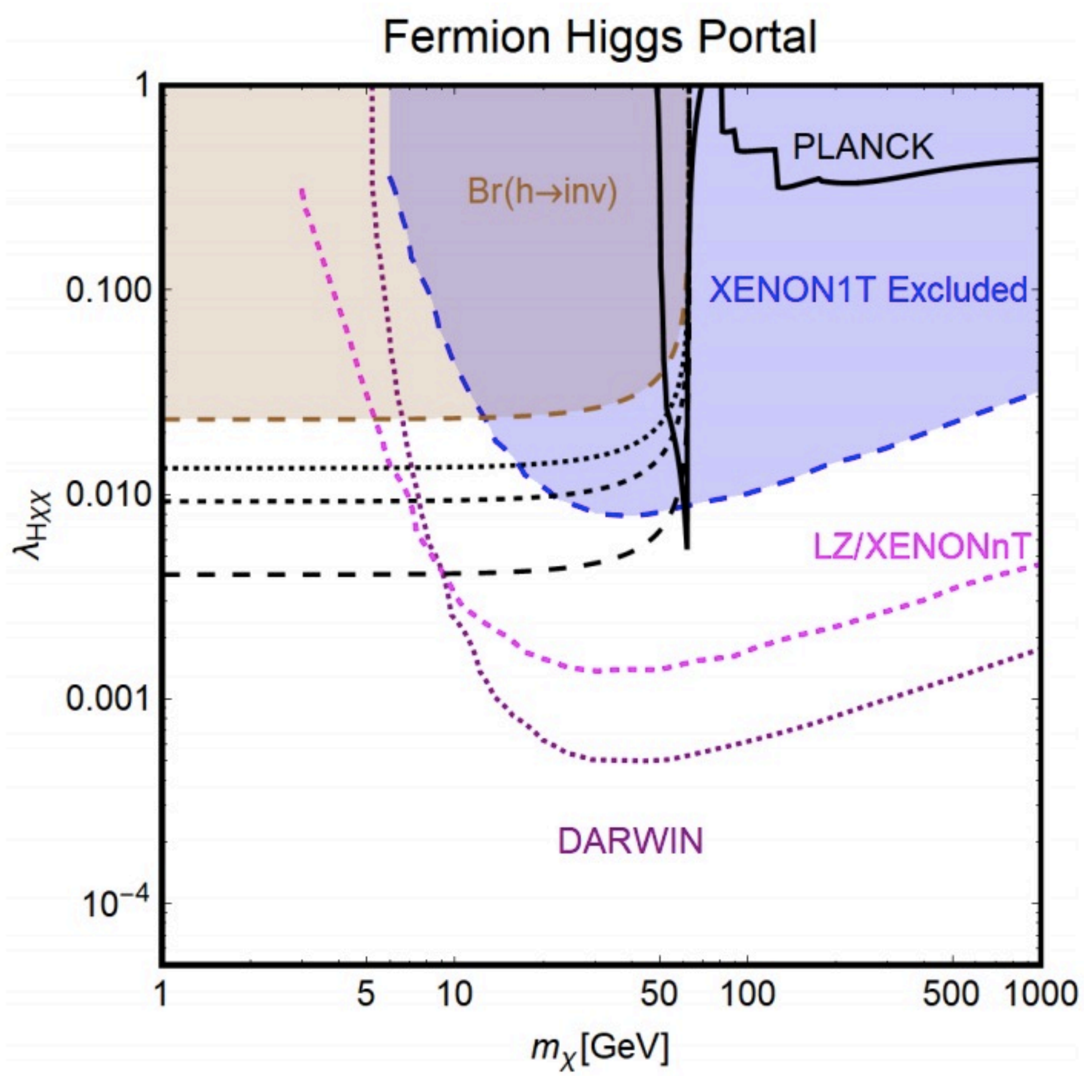
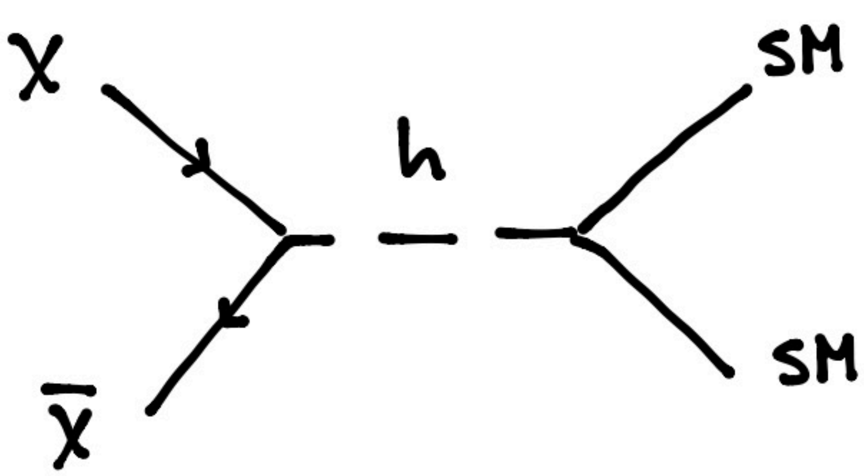


Figure from Arcadi, Djouadi, Raidal, arXiv:1903.03616

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi - \frac{1}{2}m_\chi\bar{\chi}\chi - \frac{1}{2}\lambda_{h\chi}h\bar{\chi}\chi$$

- The Higgs portal is only open right on the resonance $2m_\chi \approx m_h$



The Higgs portal WIMP

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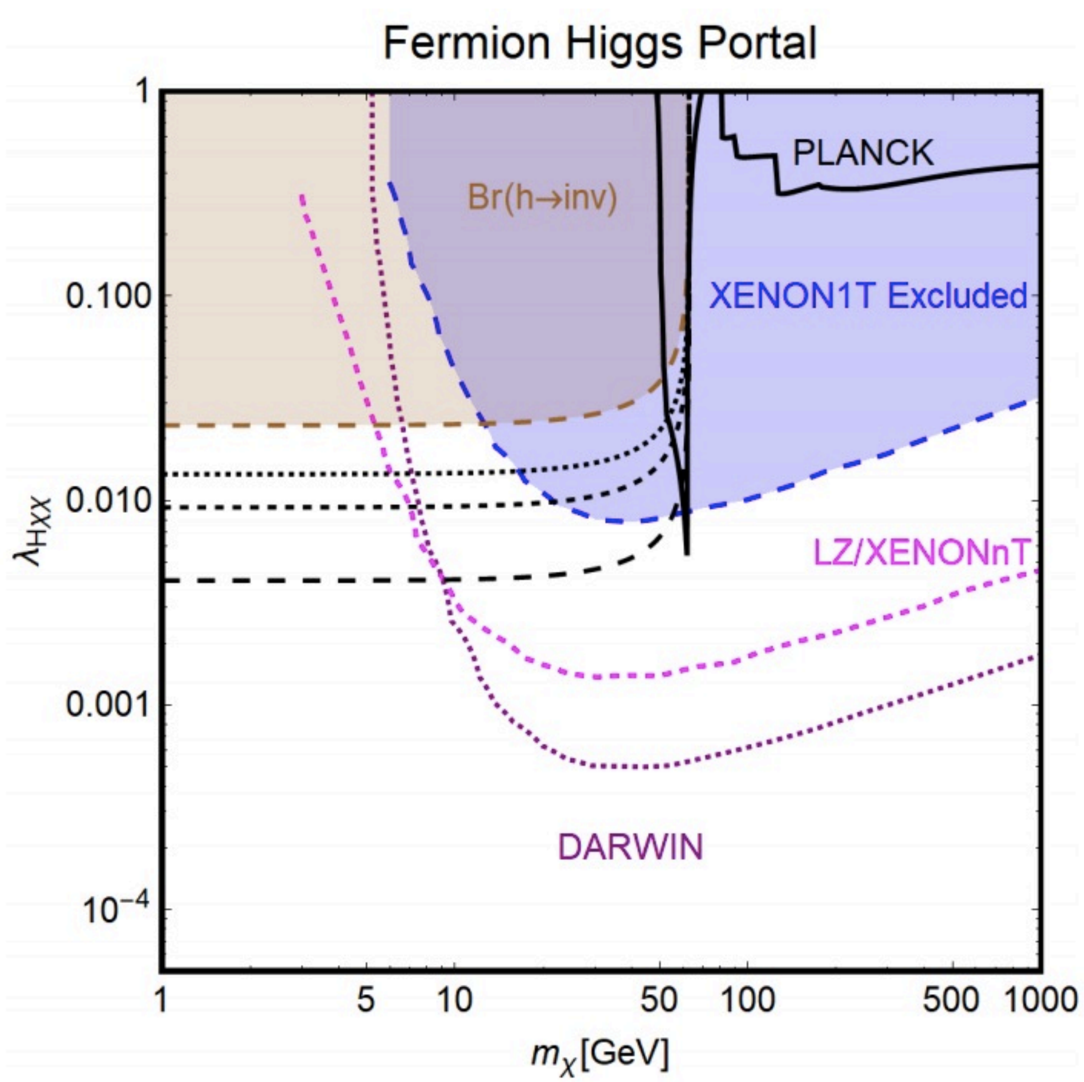


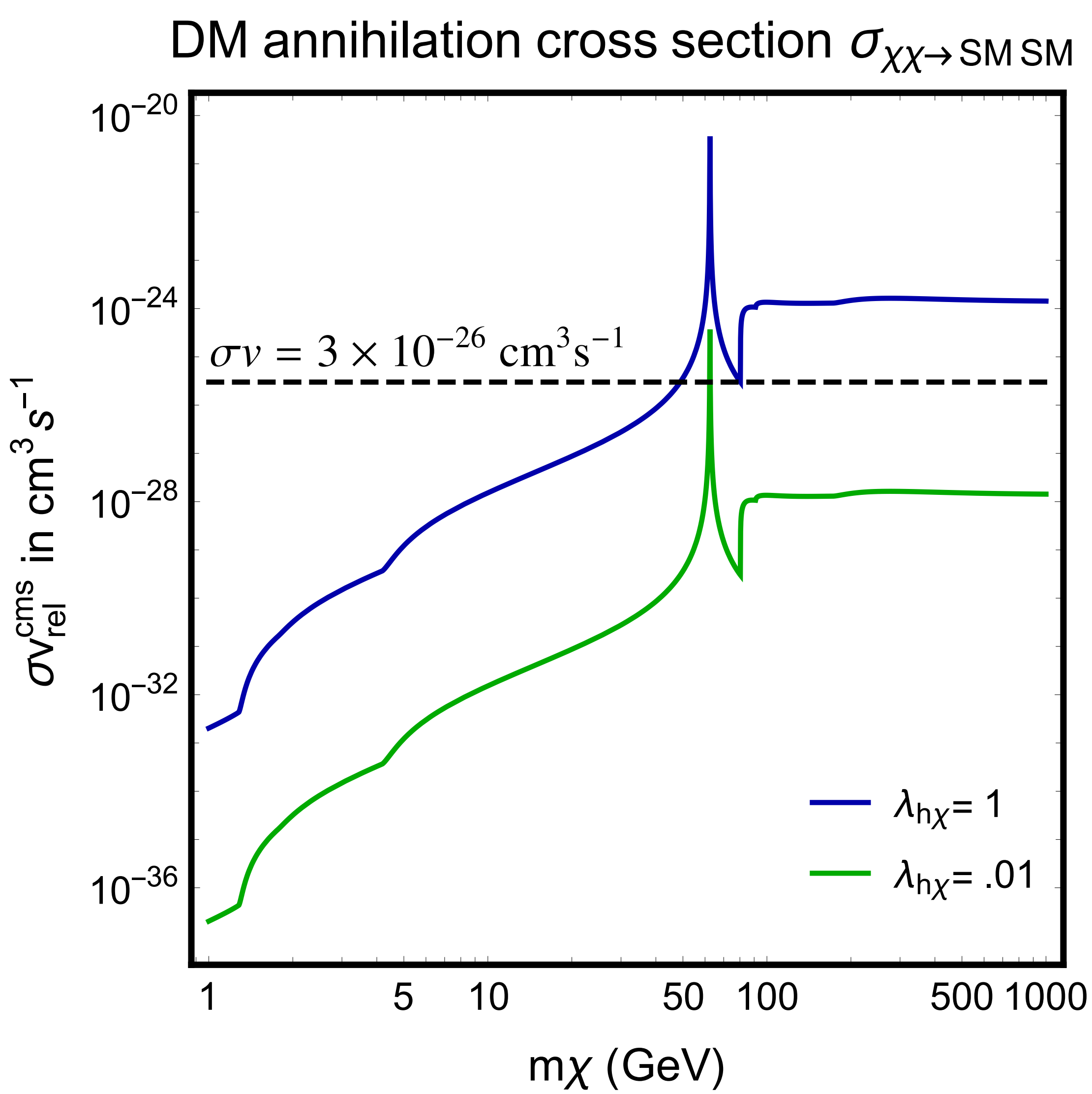
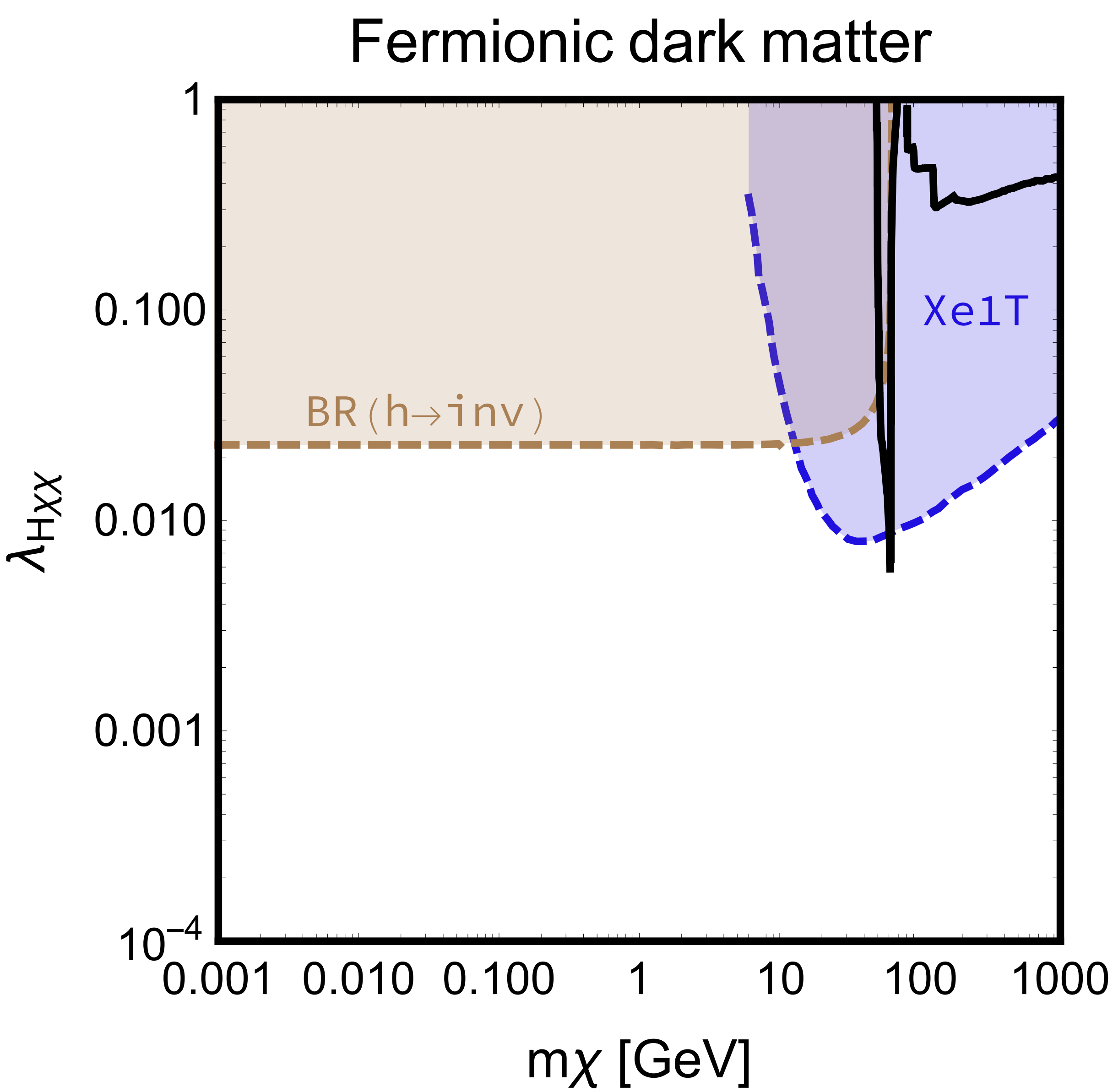


Figure from Arcadi, Djouadi, Raidal, arXiv:1903.03616

Opening the Higgs portal

- Is there some way to increase the parameter space that benefits from resonant enhancement?

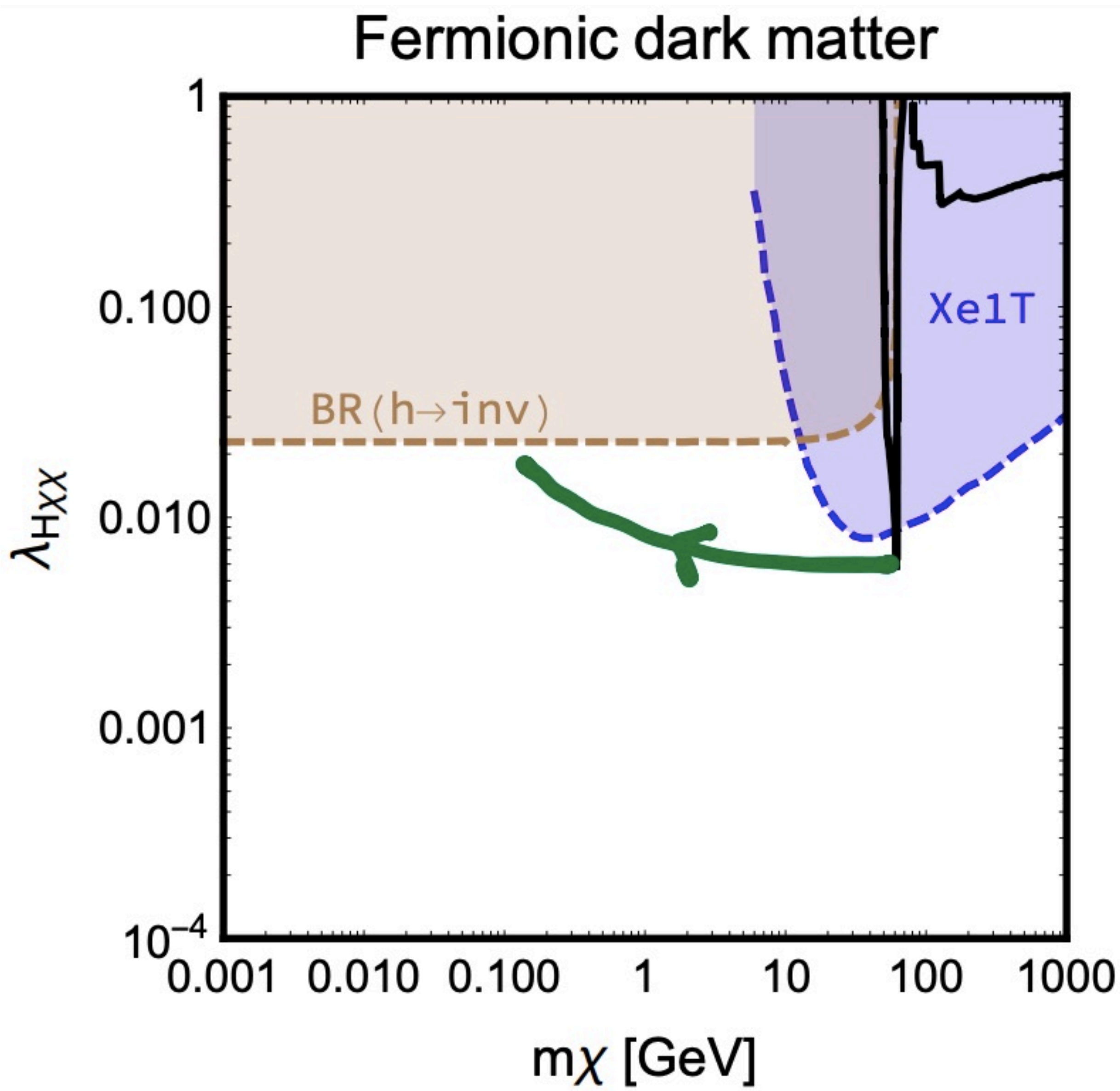


Opening the Higgs portal

- Is there some way to increase the parameter space that benefits from resonant enhancement?
- Dark matter that remembers the resonance:

$$\Rightarrow m_\chi(T)$$

- Temperature-dependent mass



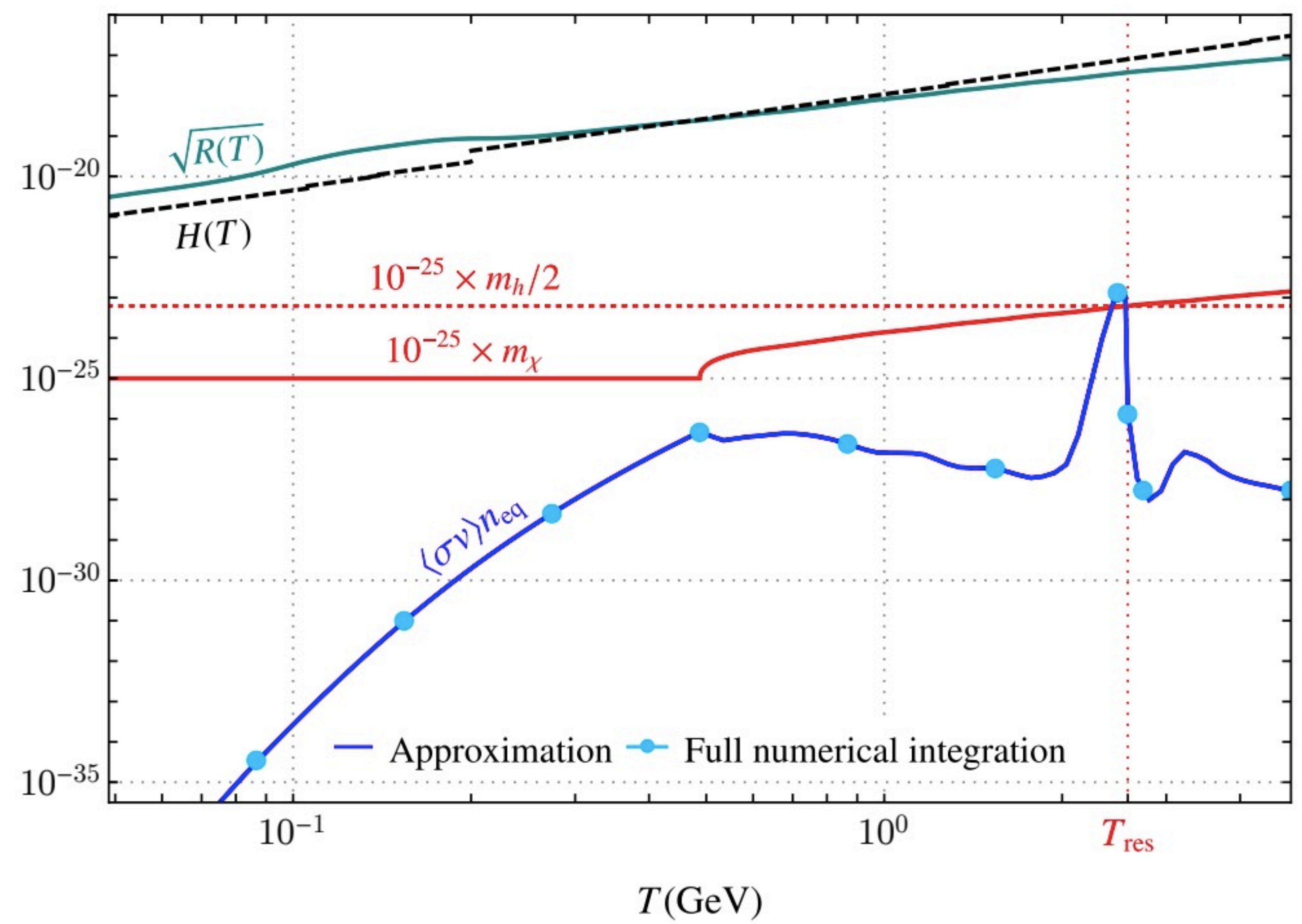
Baker, Kopp, arXiv:1608.07578
Cohen, Morrissey, Piece, arXiv:0808.3994

Heurtier, Partouche, arXiv:1912.02828

Resonance scanning

(all quantities plotted are in GeV)

- Higgs portal dark matter whose mass *decreases* with decreasing temperature
- The dark matter mass generically scans through the resonance at some point in its history



- Dark matter obtains its final light mass *after* losing contact with the thermal bath

Croon, Elor, RH, Murayama, White
arXiv:2012.152

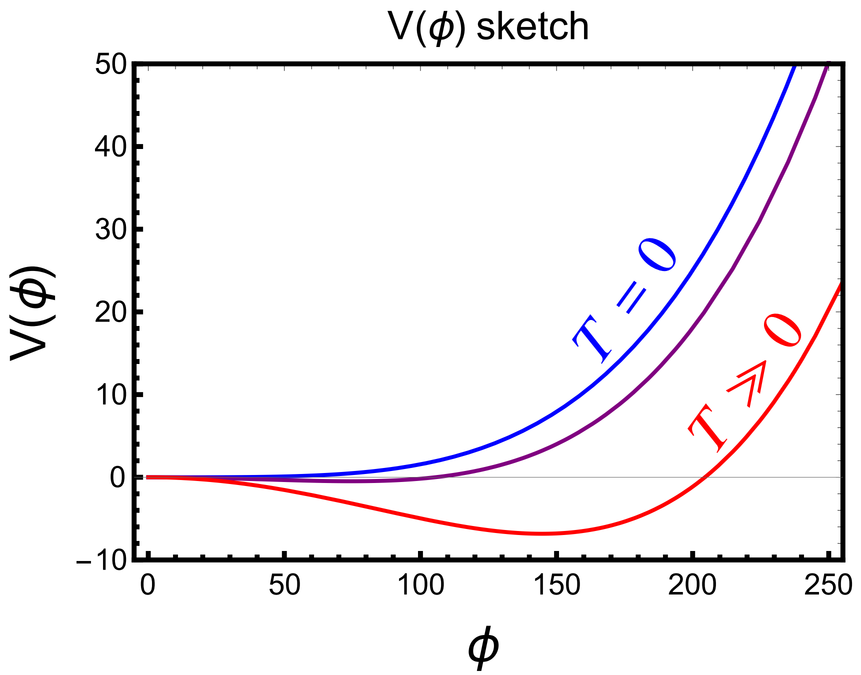
Morphing the dark matter mass

- Dirac fermion dark matter with typical Higgs portal interactions

$$V \ni \frac{1}{2} m_\chi \bar{\chi}\chi + \frac{1}{2}\lambda_{h\chi} h \bar{\chi}\chi + i y_{\phi\chi} \phi \bar{\chi}\gamma_5\chi$$

- The dark matter couples to a pseudoscalar ϕ called the *morphon*

- The morphon then *morphs* the dark matter mass



$$m_\chi^2(T) = \left[m_{\chi,0} + \lambda_{h\chi} v_h\right]^2 + y_\phi^2 v_\phi^2(T)$$

$$v_\phi(T) > v_\phi(T=0)$$

Ricci morphon

- The morphon couples to the Ricci scalar

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}\xi R\phi^2 + \frac{1}{4}\lambda_\phi\phi^4$$

Sonego, Faraoni (1993)

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt, hep-ph/0403019

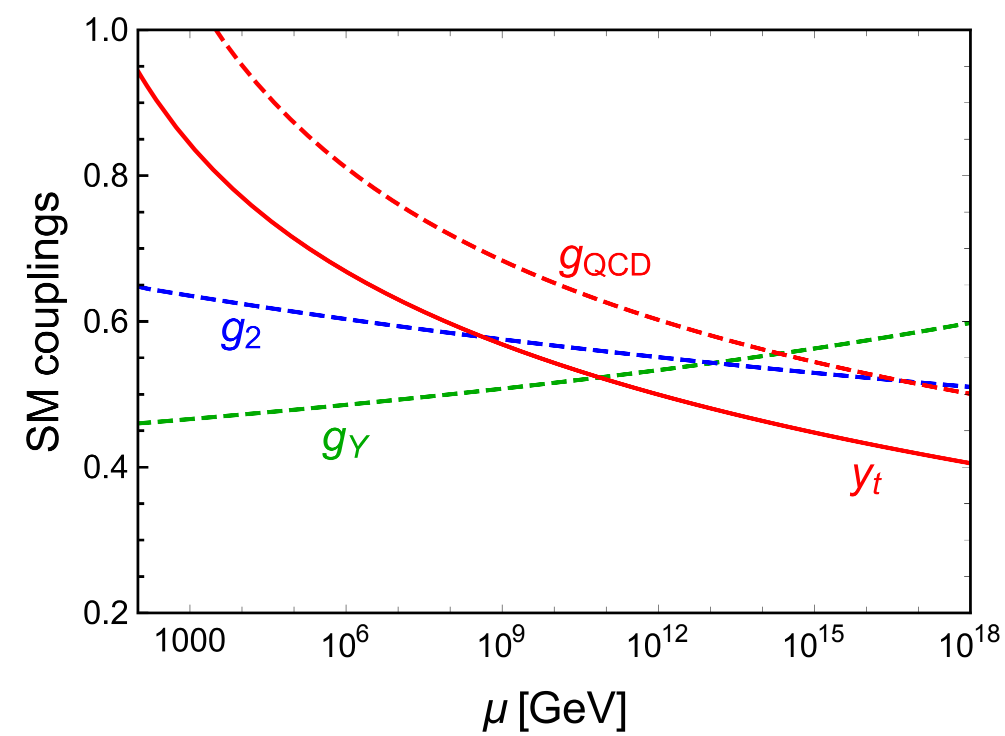
Opferkuch, Schwaller, Stepanek, arXiv:1905.06823

- For constant w, $R = -3(1-3w)H^2$, $w \approx 1/3$

- However, $R = -8\pi G T^\mu_\mu$

and the trace anomaly gives:

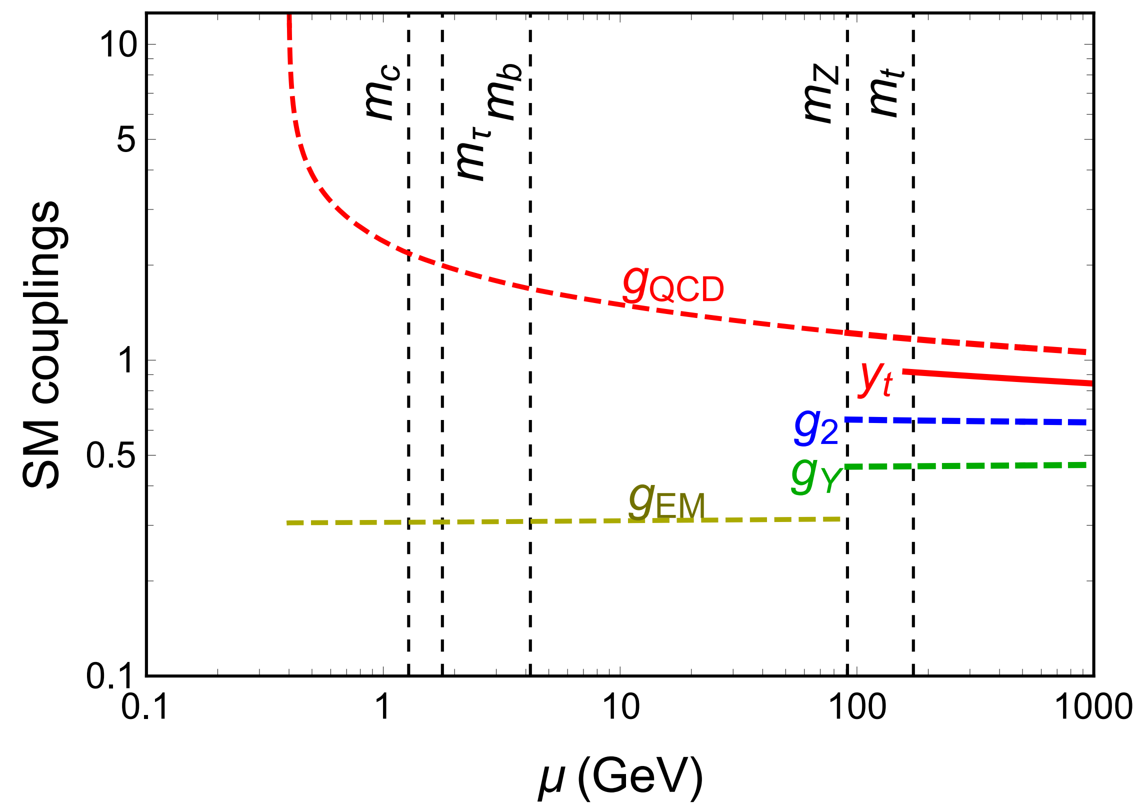
$$T^\mu_\mu \neq 0 \Leftrightarrow \text{~~scale invariance~~}$$

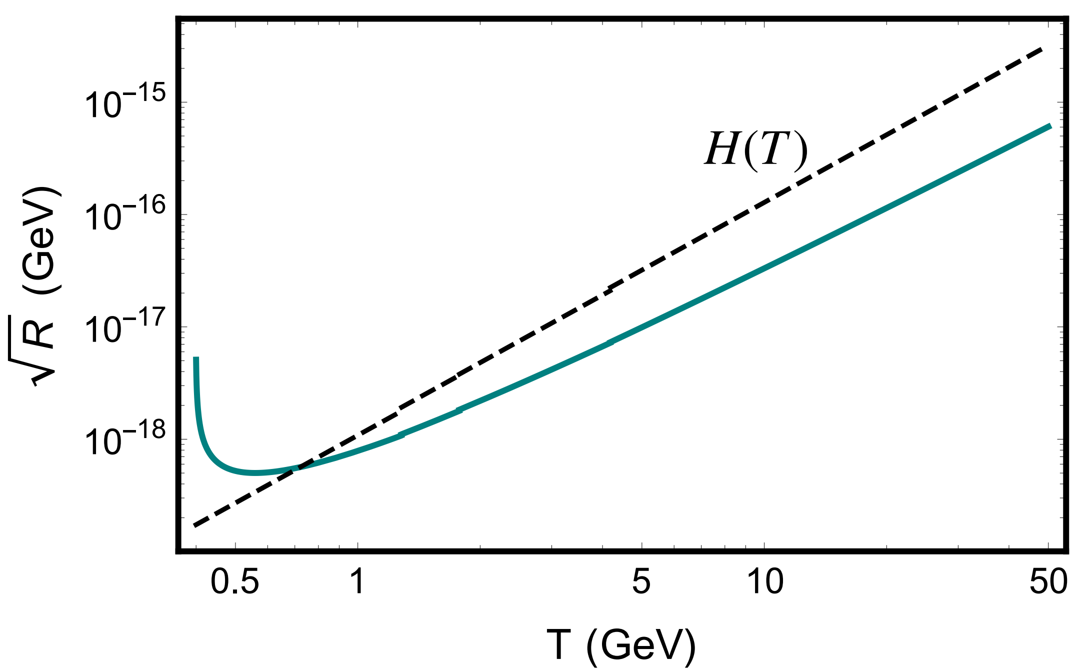


Sources of breaking scale invariance

In the region of interest for DM morphing:

- Running couplings
- QCD confinement
- Mass thresholds/decoupling





- We can estimate R based on the perturbative running of the couplings

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt, hep-ph/0403019

Ricci evolution

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}\xi R\phi^2 + \frac{1}{4}\lambda_\phi\phi^4$$

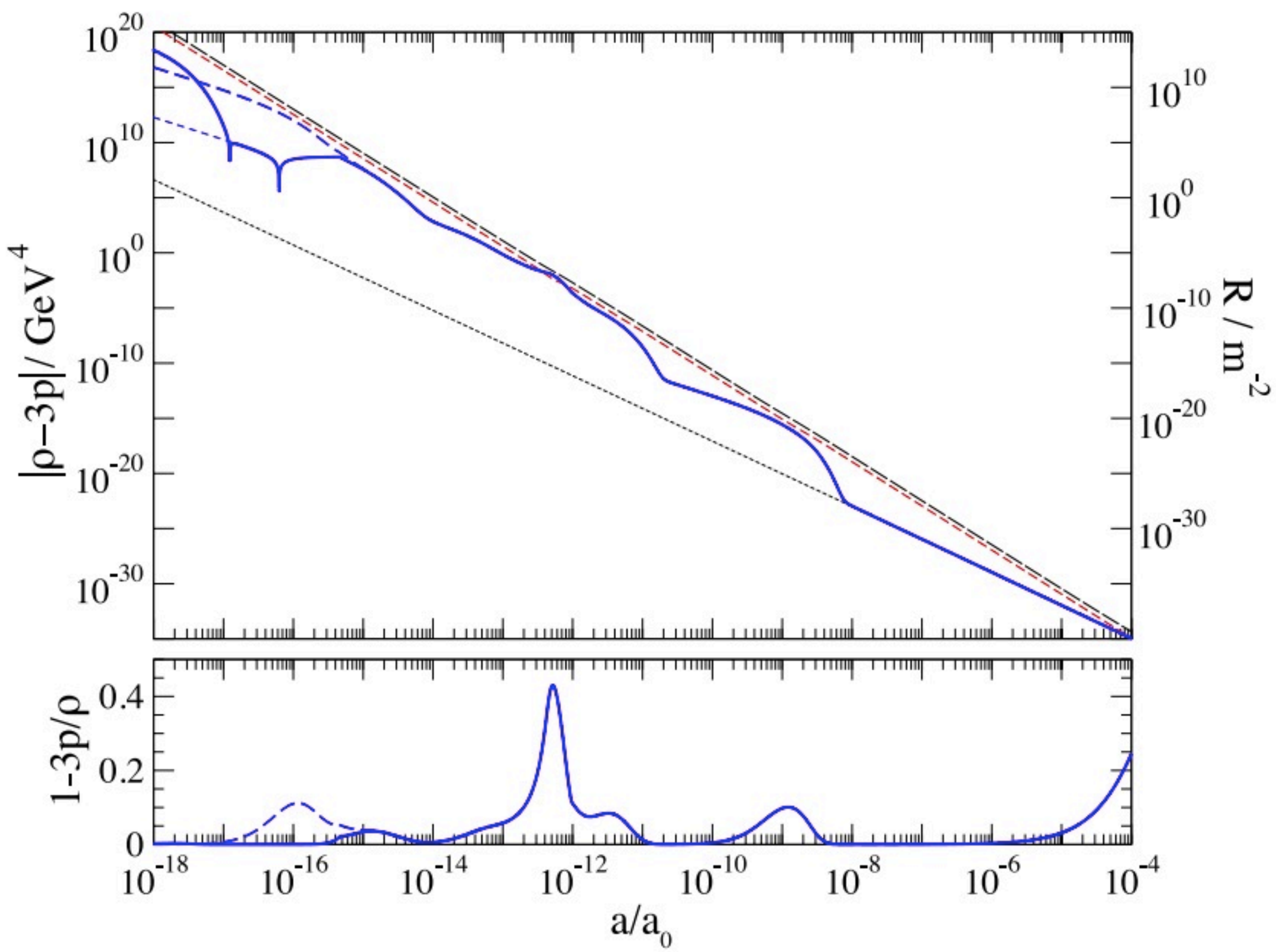
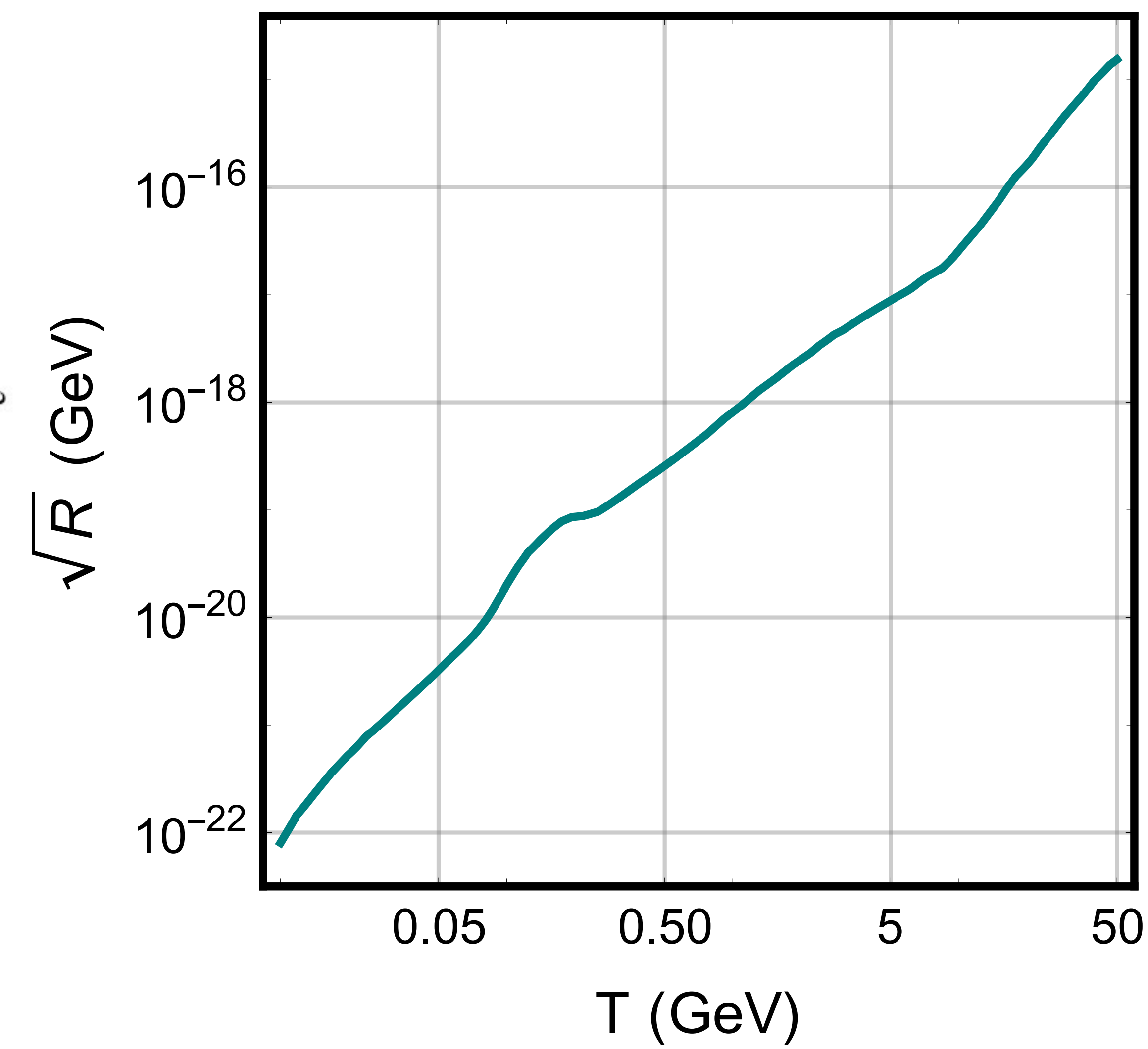


Figure from from Caldwell, Gubser, arXiv:1302.1201



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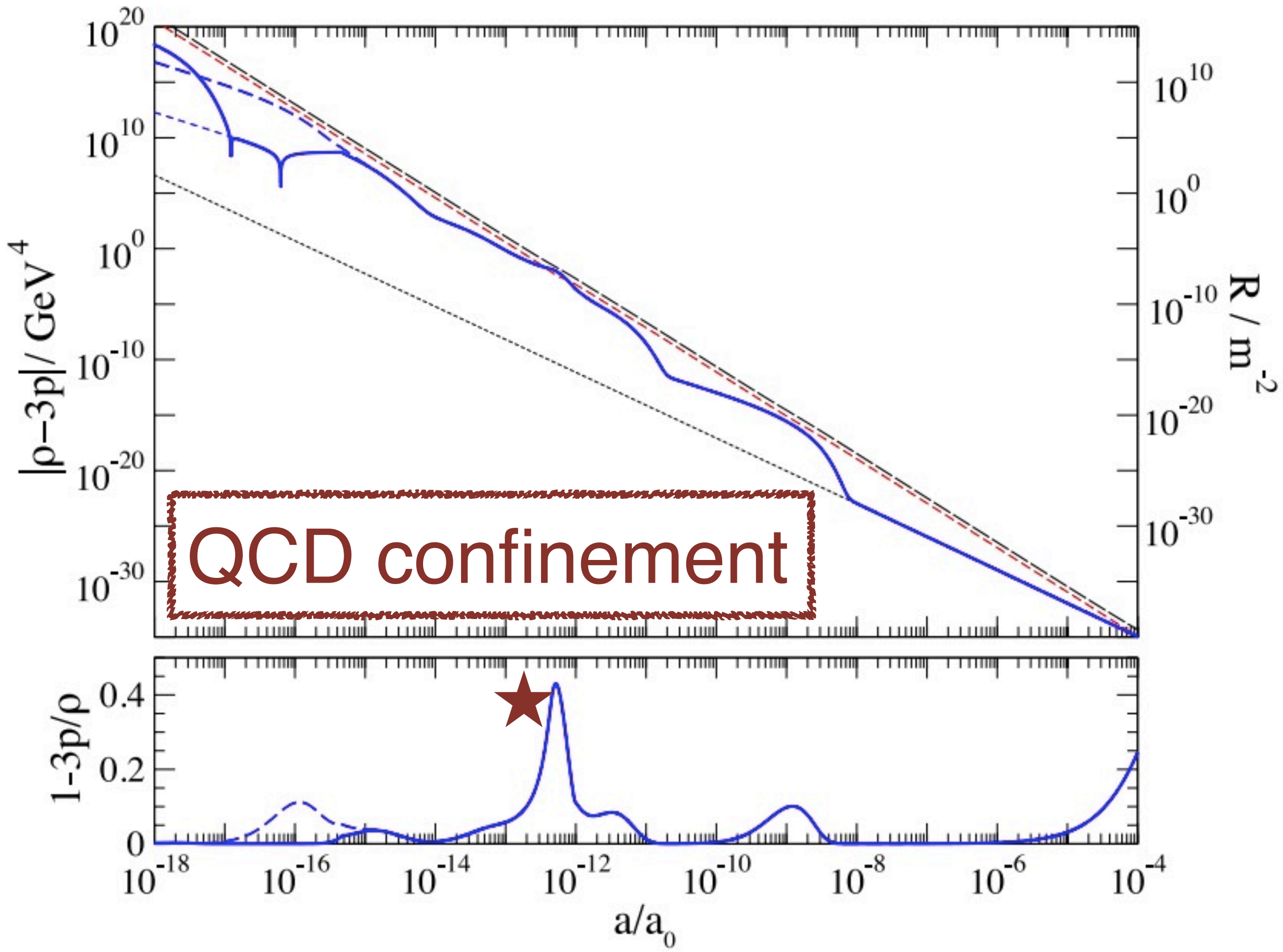

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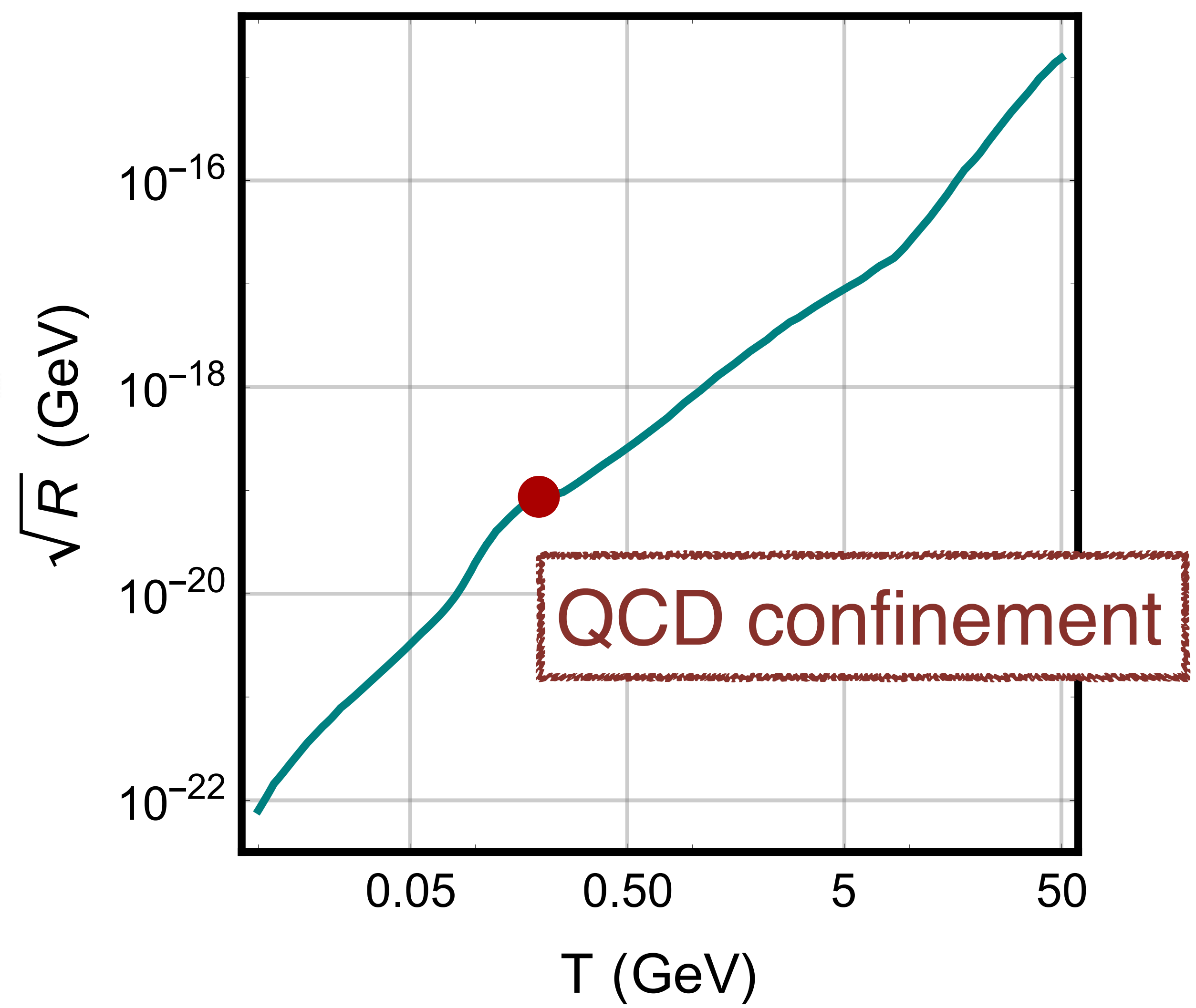
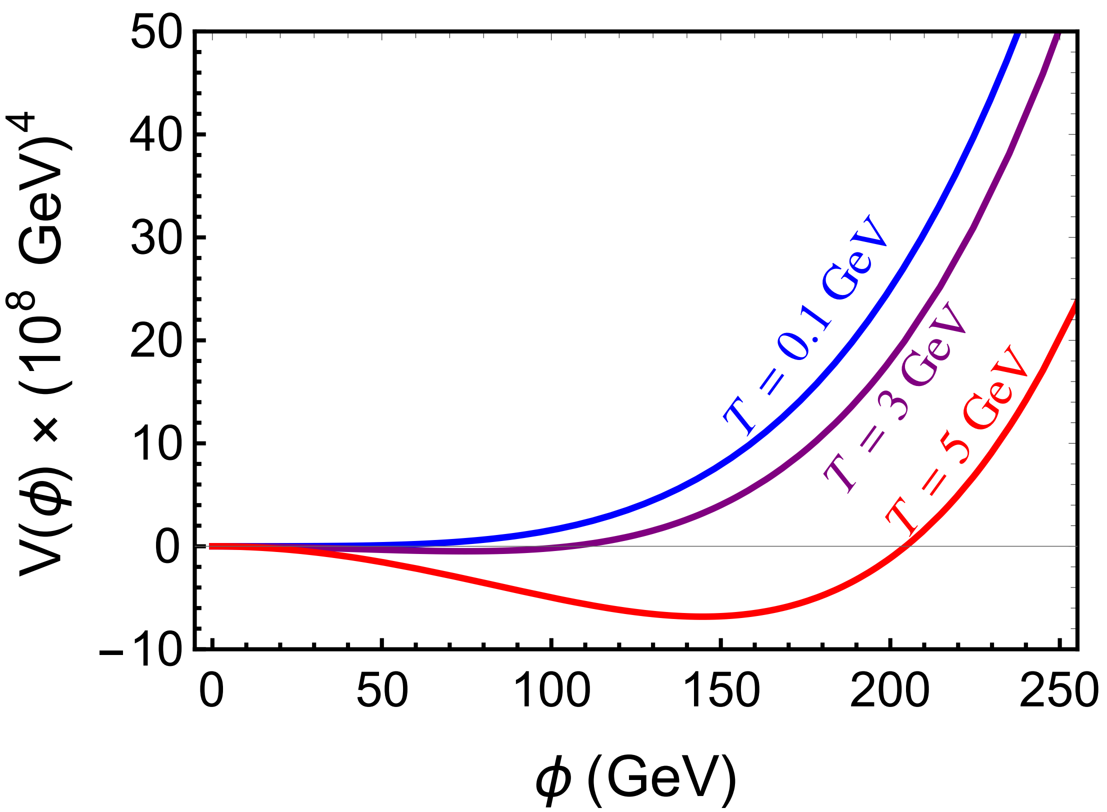
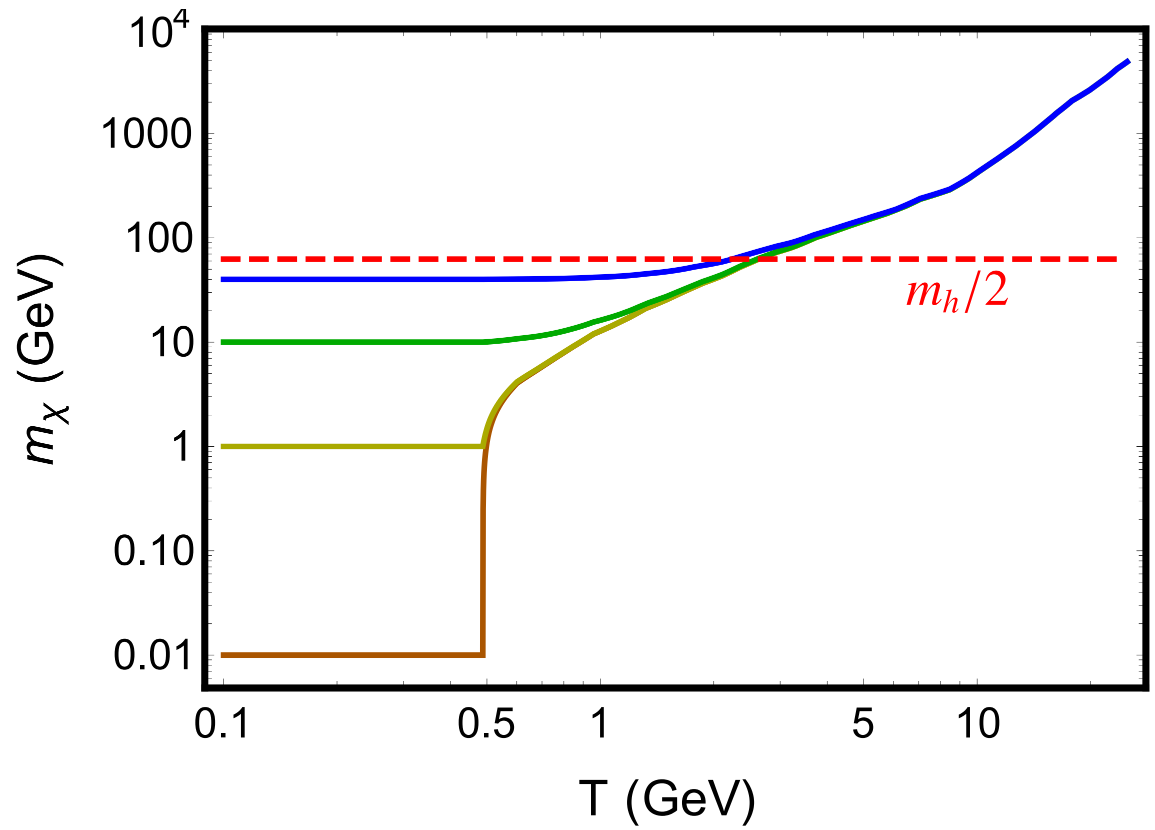


Ricci morphon VEV

- At high temperatures the morphon develops a nonzero VEV:

$$v_\phi(T) = \begin{cases} \sqrt{\frac{1}{\lambda_\phi}\left(\xi R - m_\phi^2\right)} & \xi R > m_\phi^2 \\ 0 & \text{otherwise} \end{cases} \qquad m_\chi(T) = m_{\chi,f} + y_\phi v_\phi(T)$$

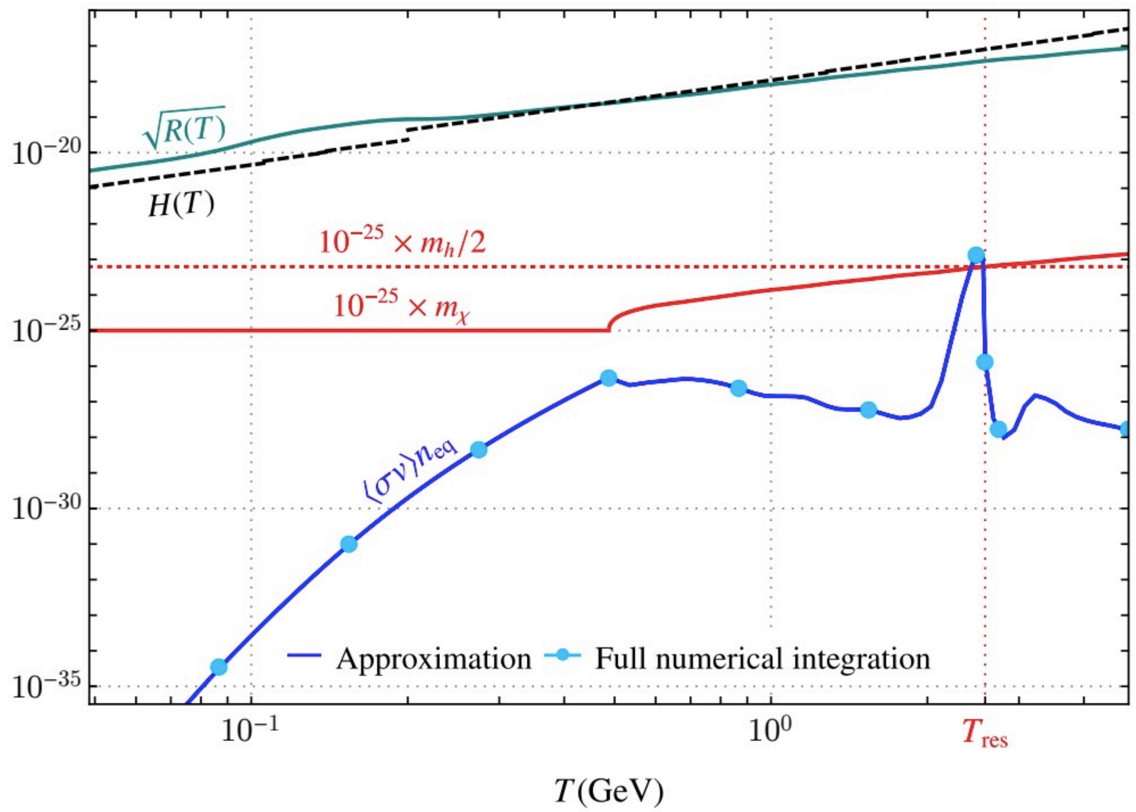




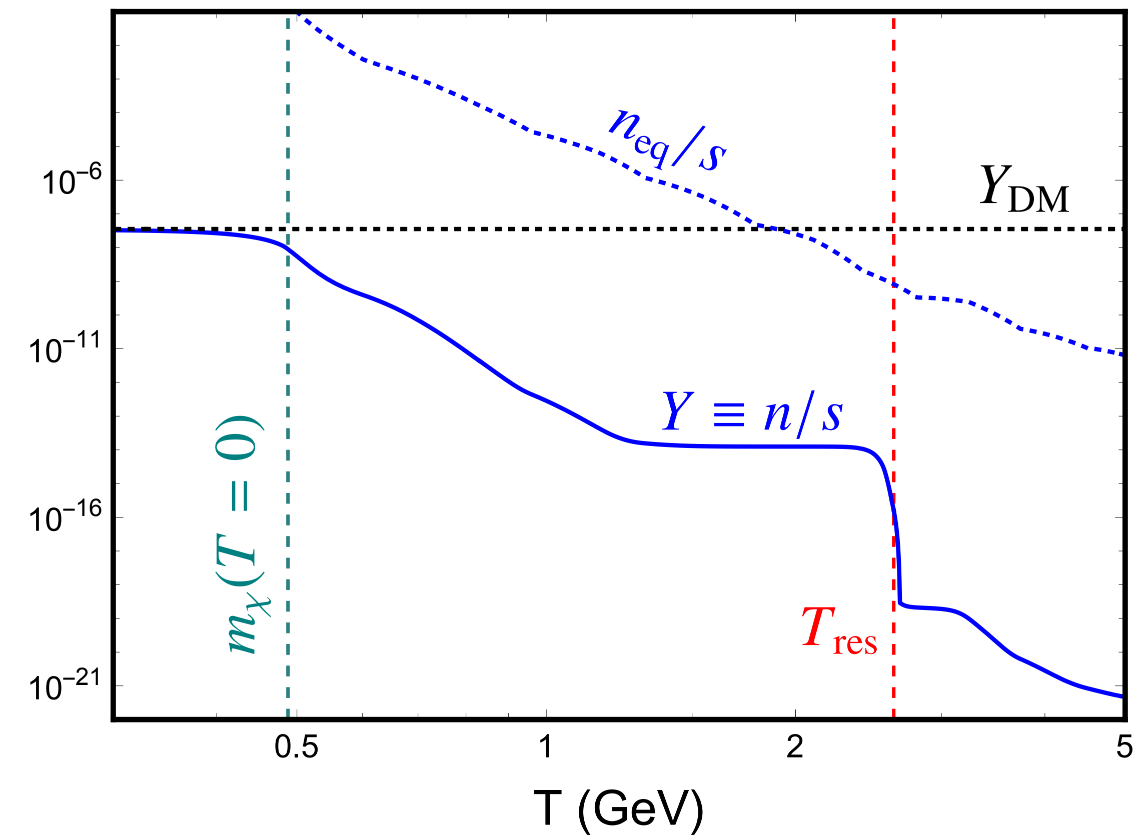
Scanning through the resonance

$m_{\chi,f} = 1\ \mathrm{GeV}$

(all quantities plotted are in GeV)

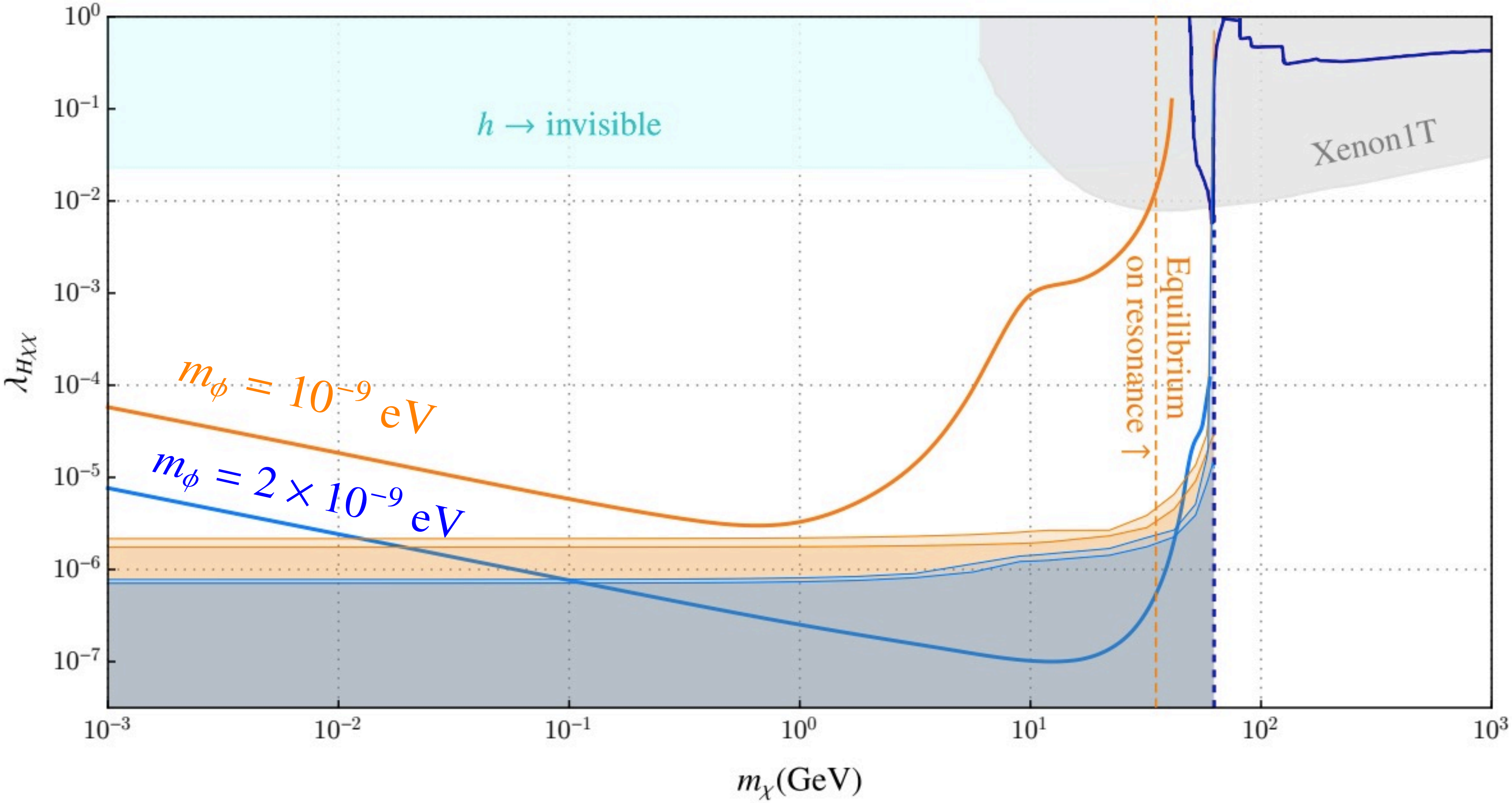


$m_{\chi,f} = 10\ \mathrm{MeV}$



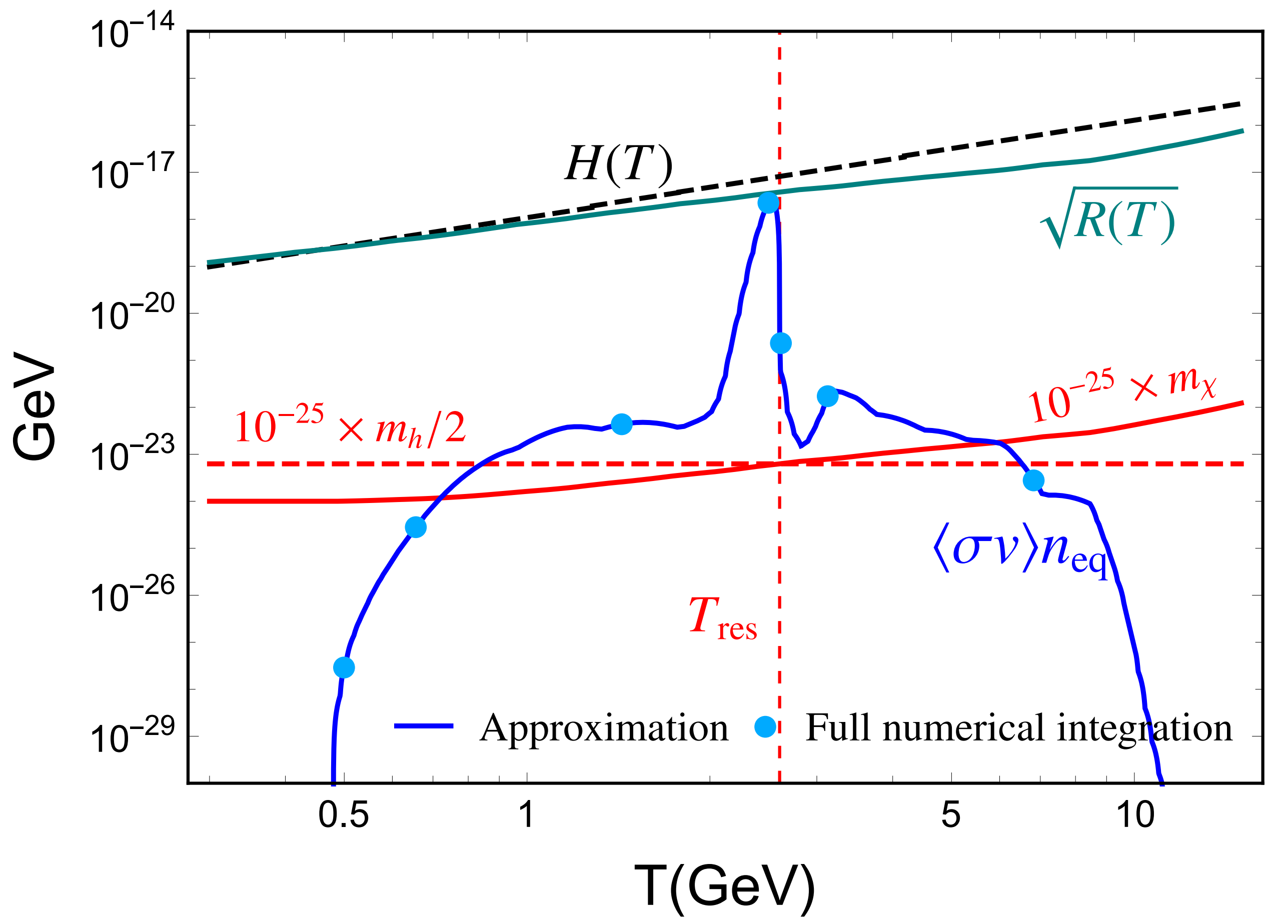
- Relic abundance mostly controlled by $n_{eq}(T)$

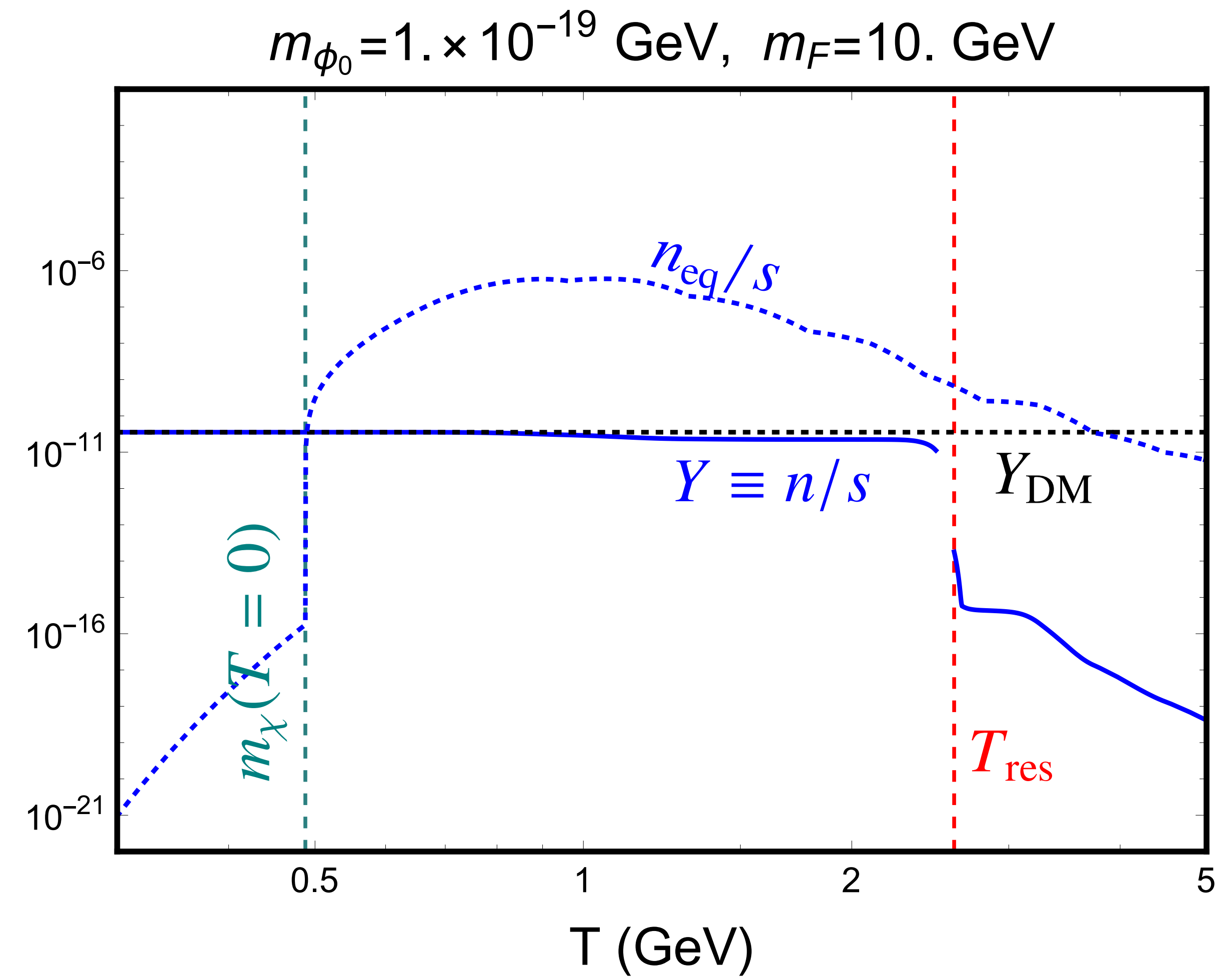
Relic abundance curve



- Shaded regions violate : $\Gamma_{\rm scatt} > H$ (Top) $\Gamma_{\rm scatt} > \dfrac{\dot{m}}{m}$ (Bottom)

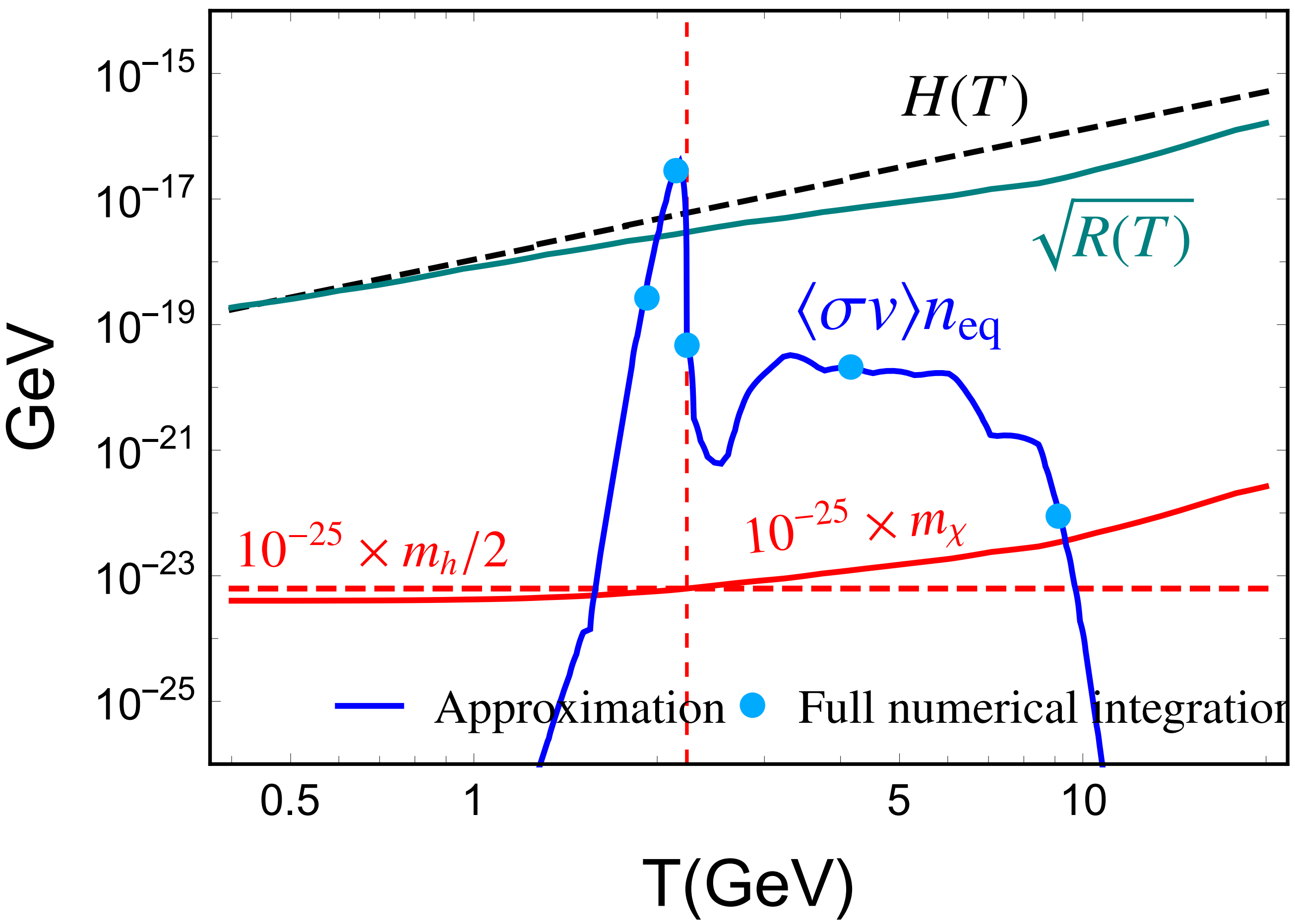
Benchmark $m_{\chi,f} = 10\ \mathrm{GeV}$

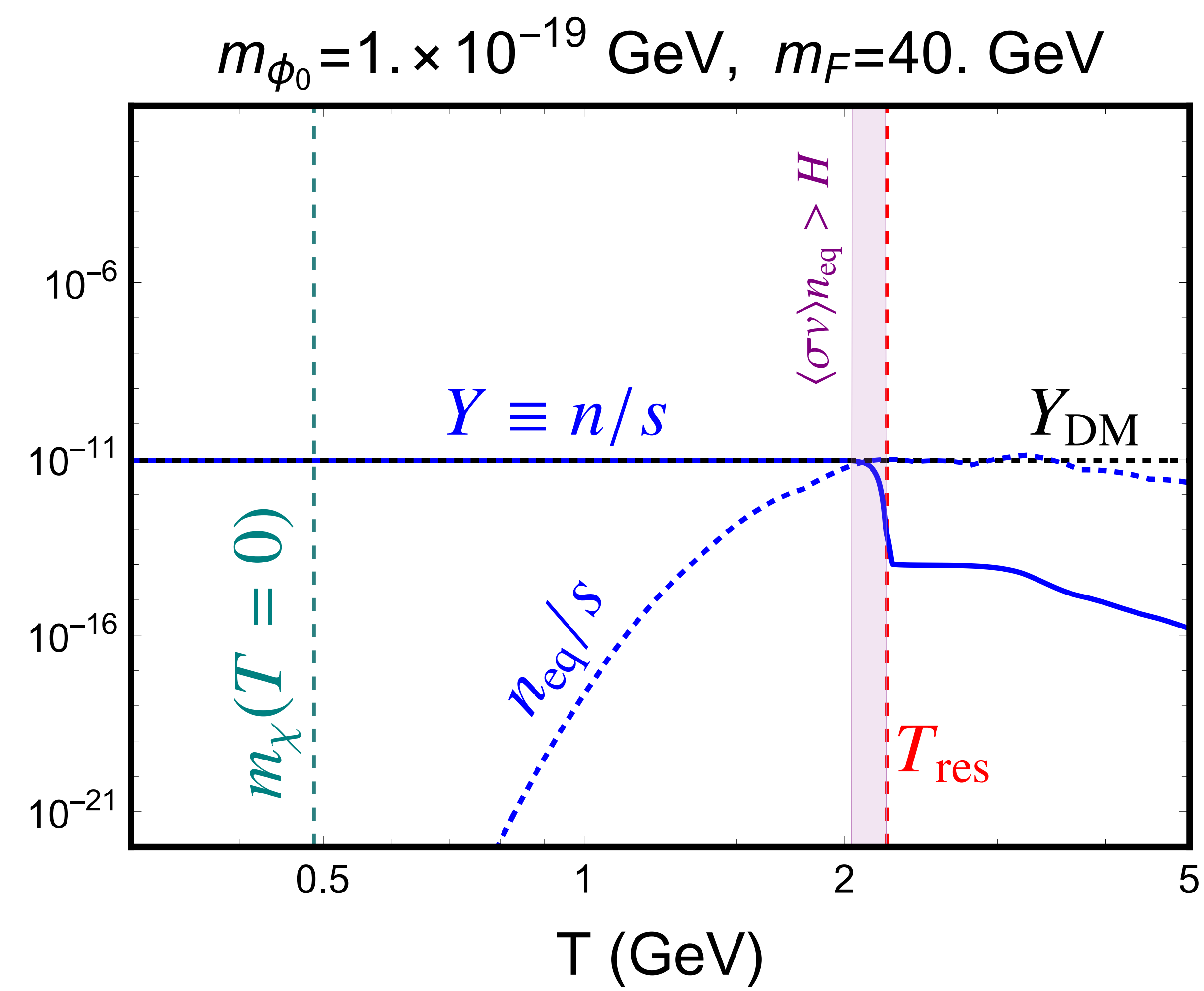




- Relic abundance mostly controlled by the resonance

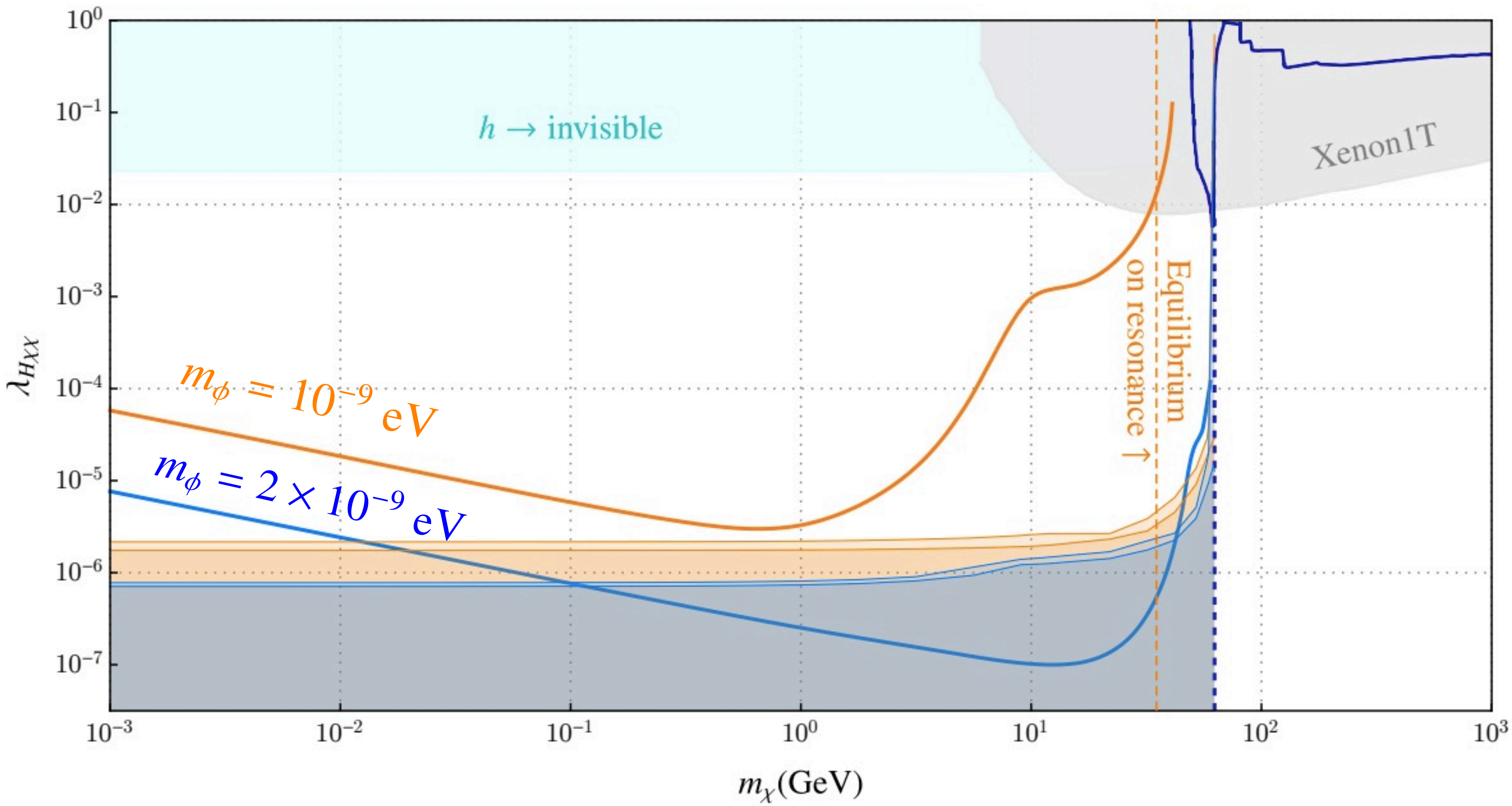
Benchmark $m_{\chi,f} = 40\ \mathrm{GeV}$





- An example of thermal production, DM enters equilibrium on resonance

Relic abundance curve

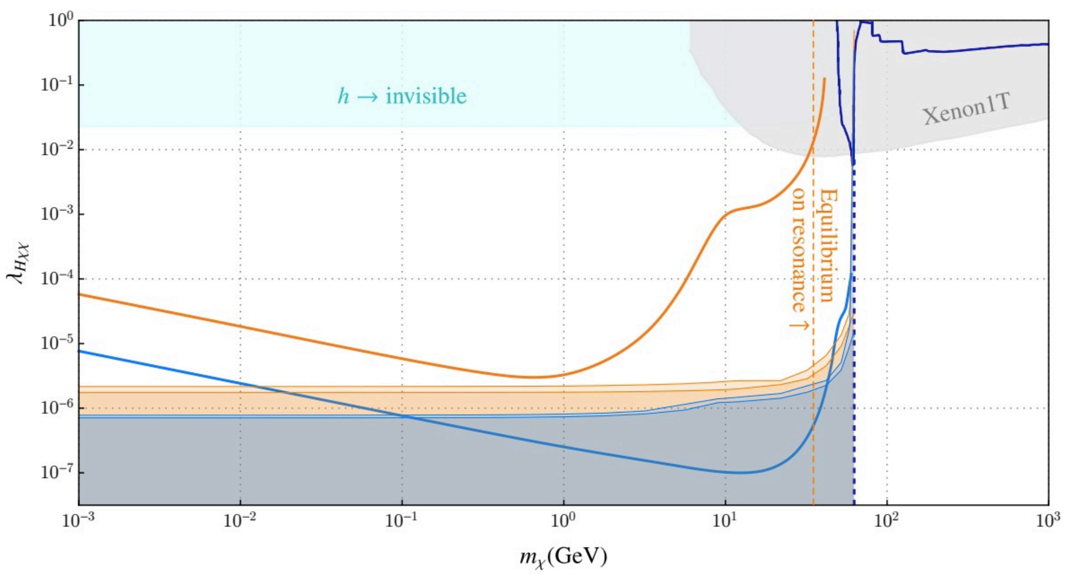


- Shaded regions violate : $\Gamma_{\mathrm{scatt}} > H$ (Top) $\Gamma_{\mathrm{scatt}} > \frac{\dot{m}}{m}$ (Bottom)

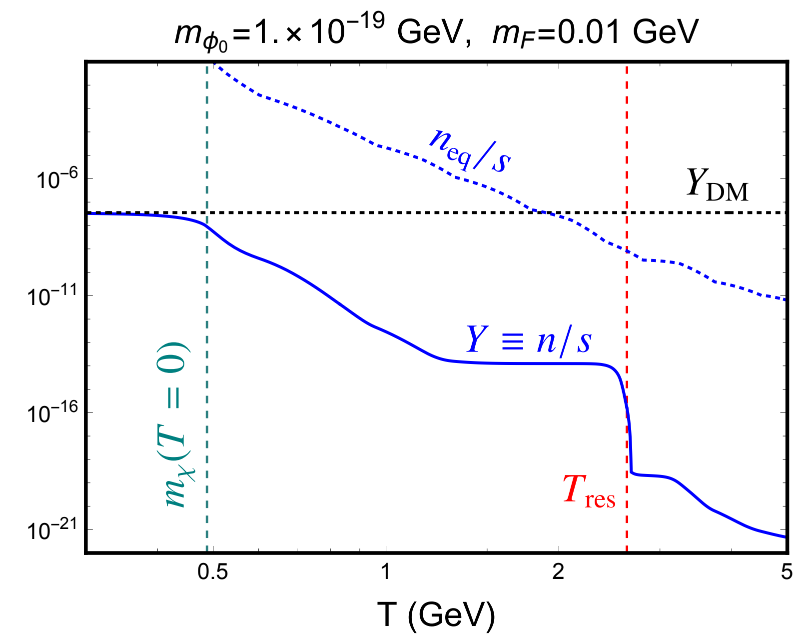
Summary

- New mechanism for light dark matter production

- The dark matter mass decreased with temperature, scanning through the Higgs resonance $2m_\chi \approx m_h$



- Our production mechanism gives much smaller portal couplings than the standard freeze-out scenario due to both:
  - History of the resonant enhancement
  - Behavior of $n_{eq}(T)$ during the PT

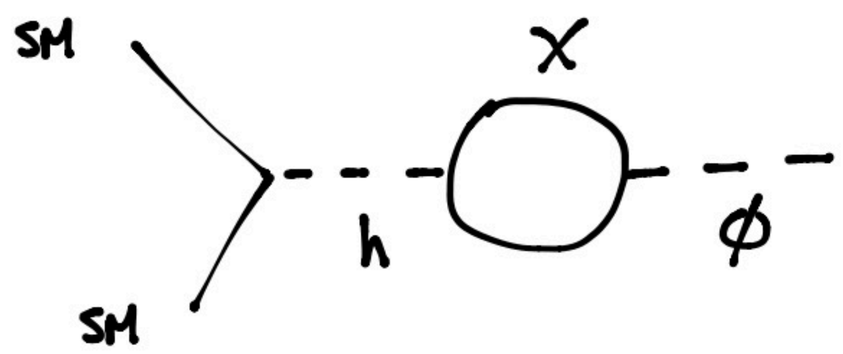


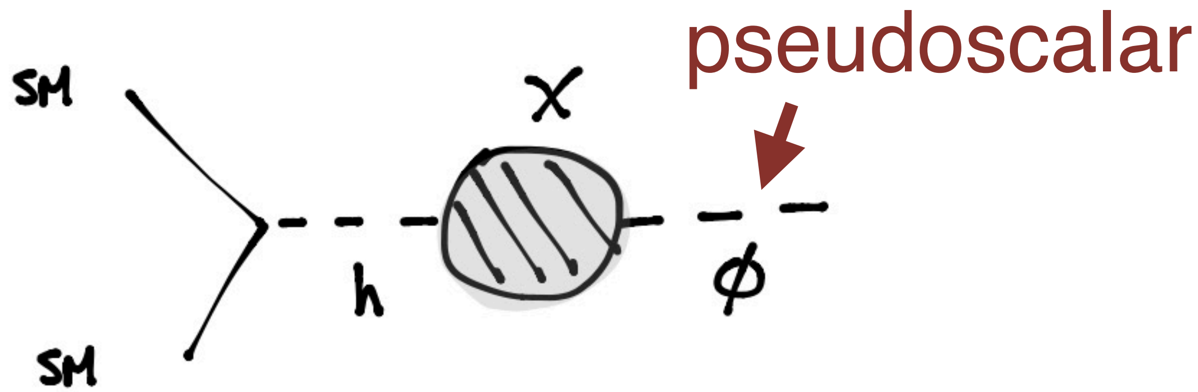
Thank you!

Back-up Slides

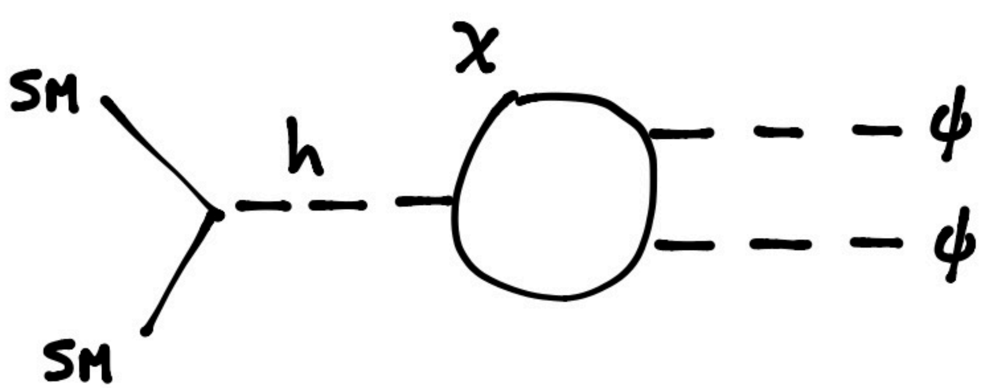
Light morphon constraints

- Fifth force constraints: ϕ-h mixing forbidden





- Morphon pair production



$$\Gamma \sim \lambda_{h\chi}^2 y_{\phi\chi}^4 y_f^2 \left(\frac{m_\chi}{m_h^2}\right)^2 \times n_{eq,f}$$

Light morphon constraints

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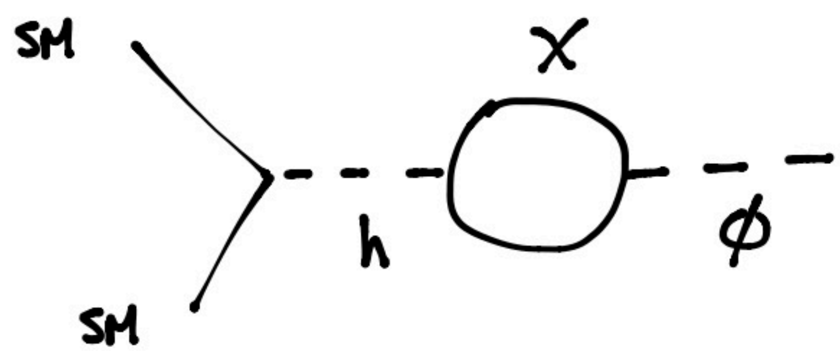
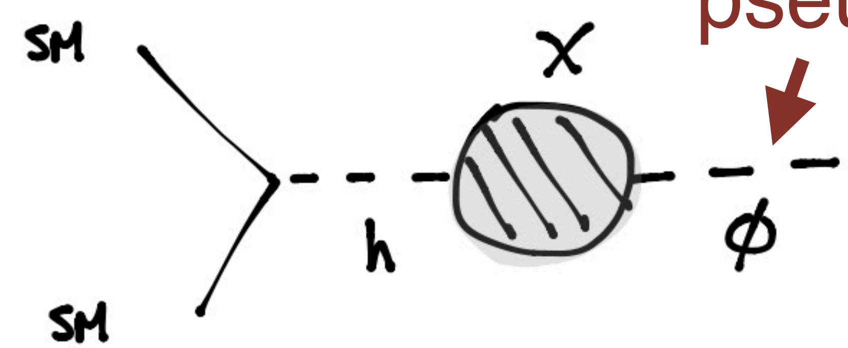
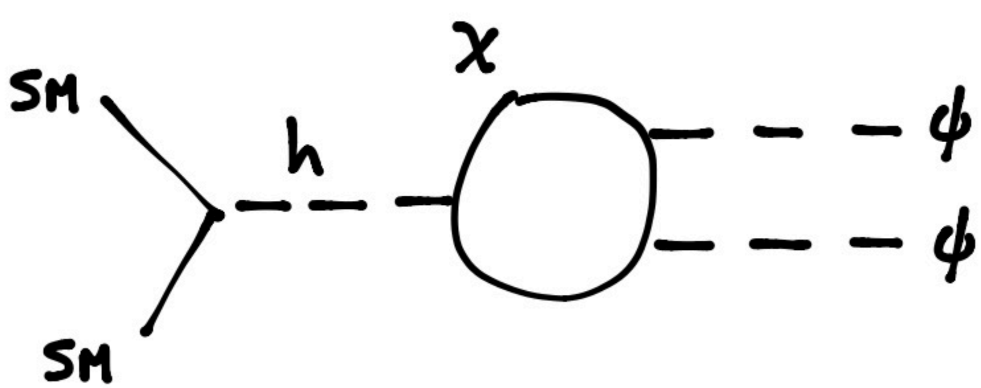




- Morphon pair production $T_{\text{dec}} \sim 1 \text{ GeV}$



$$\Delta N_{\text{eff}} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_*^s\,(T_{\text{CMB}})}{g_*^s\,(T_{\text{dec}})}\right)^{4/3}$$

Blennow, Fernandez-Martinez, Mena, Redondo, Serra, arXiv:1203.5803

The Higgs portal WIMP Update

- WIMP that interacts with the SM through the Higgs portal

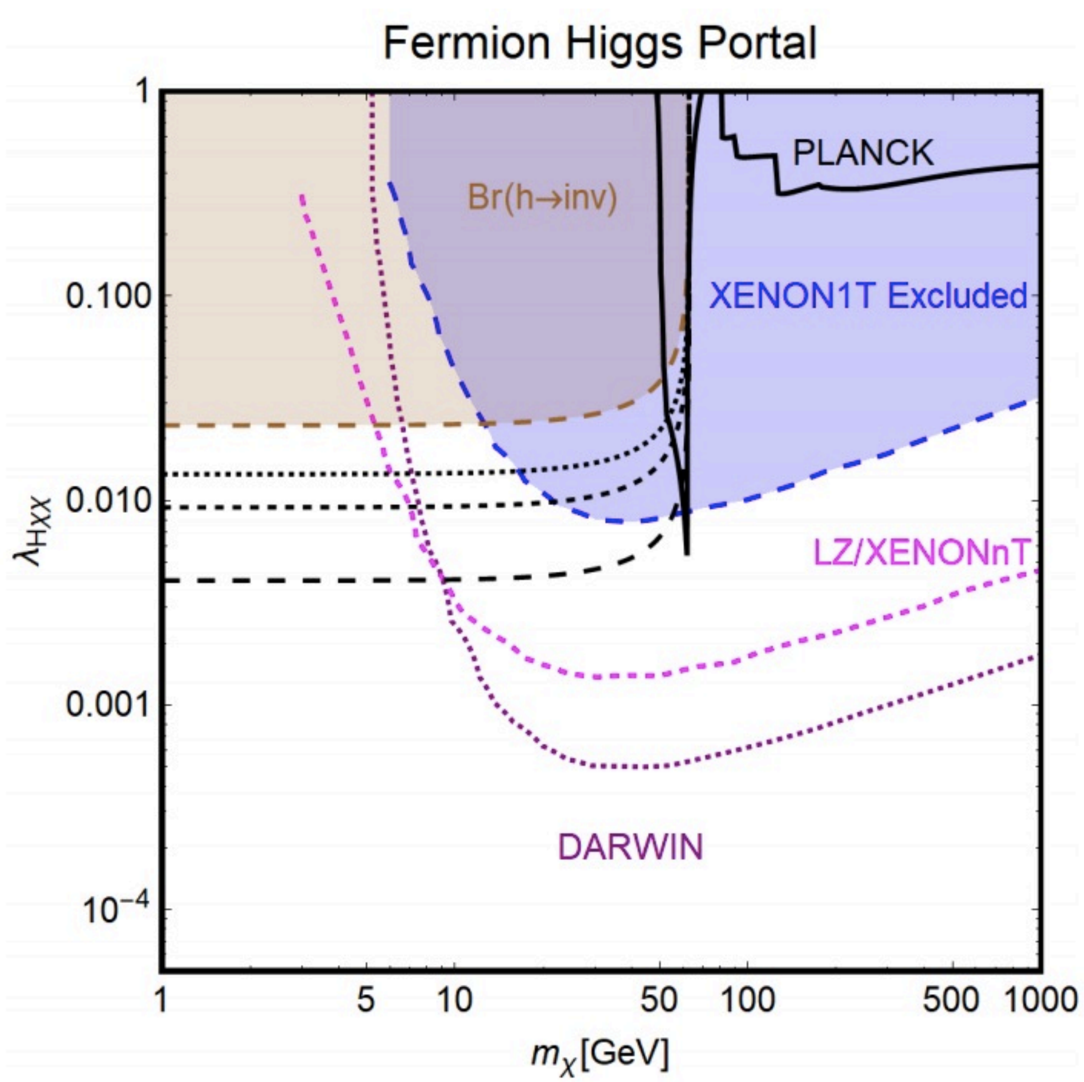


Figure from Arcadi, Djouadi, Raidal, arXiv:1903.03616

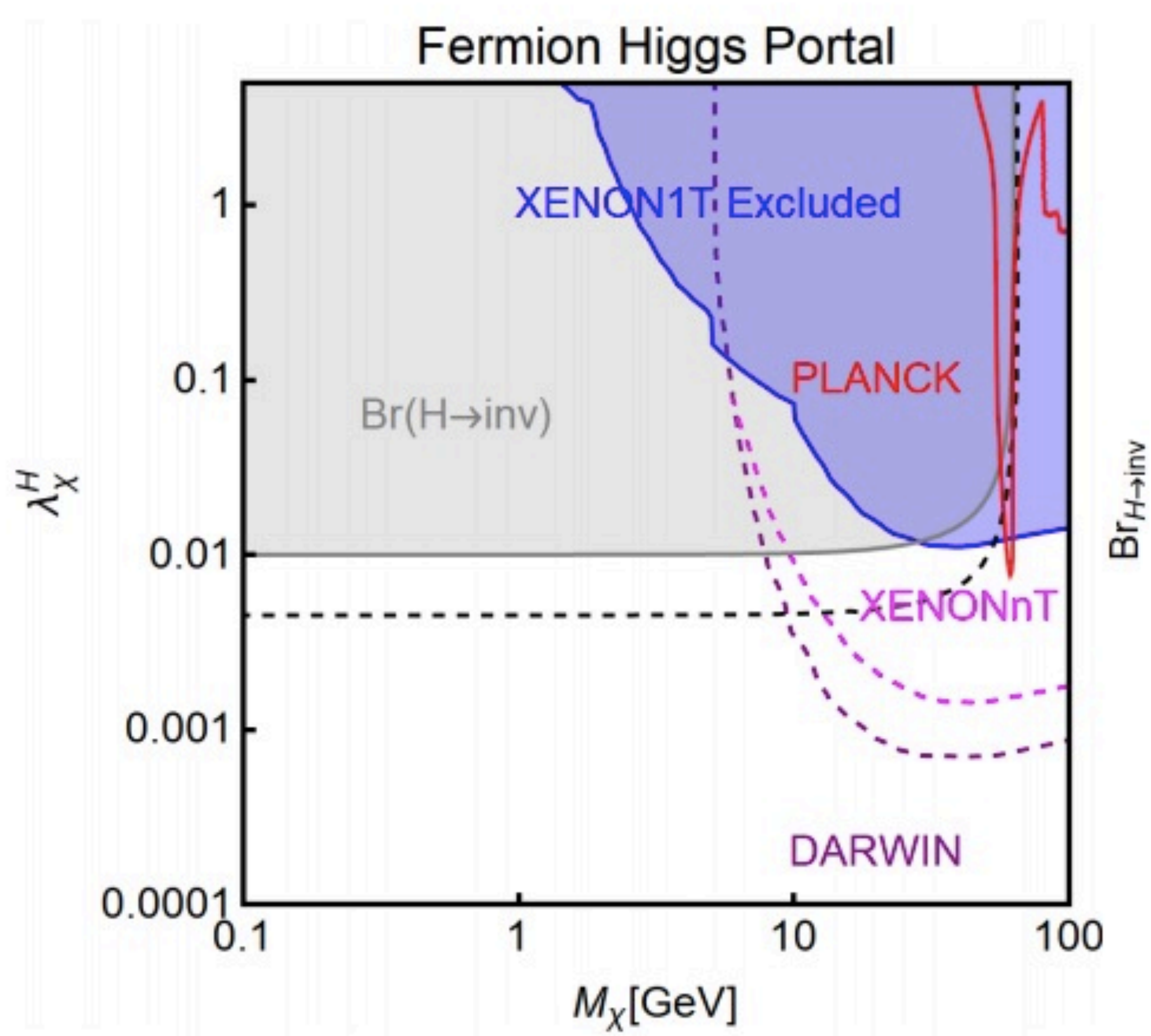


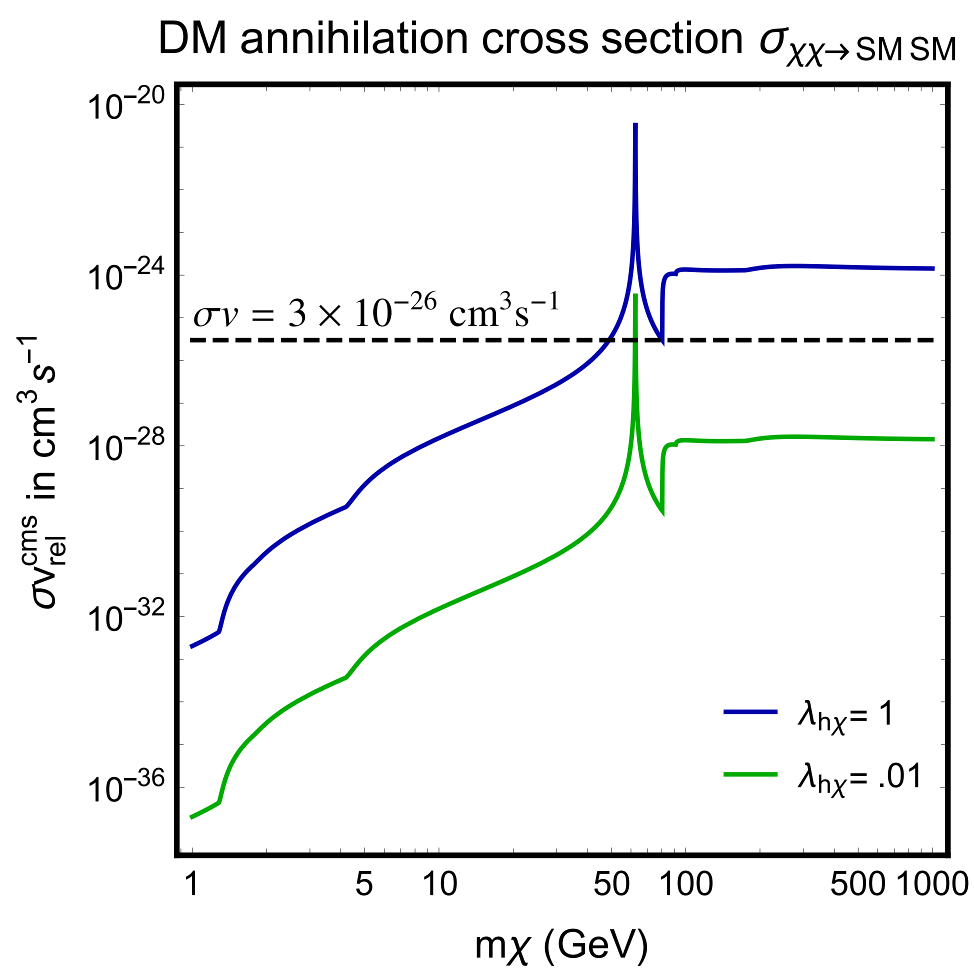
Figure from Arcadi, Djouadi, Kado, arXiv:2101.02507

More Back-up Slides

Dark matter production

- Standard way to calculate the evolution of dark matter number density:

$$\frac{dn}{dt} + 3Hn = -\left(n^2 - n_{eq}^2\right)\langle\sigma_{\bar{\chi}\chi}v\rangle$$



- Use the narrow width approximation to calculate $\sigma_{\bar{\chi}\chi}$ near the resonance peak

$$\sigma v_{\mathrm{rel}}^{\mathrm{cms}} = P_\chi \frac{2\lambda_{h\chi}^2 v_h^2}{\sqrt{s}} \frac{\Gamma_h\left(m_h^* = \sqrt{s}\right)}{\left(s - m_h^2\right)^2 + m_h^2\Gamma_h^2(m_h)}$$

$$P_\chi = \frac{s}{2}\left(1 - \frac{4m_\chi^2}{s}\right)$$

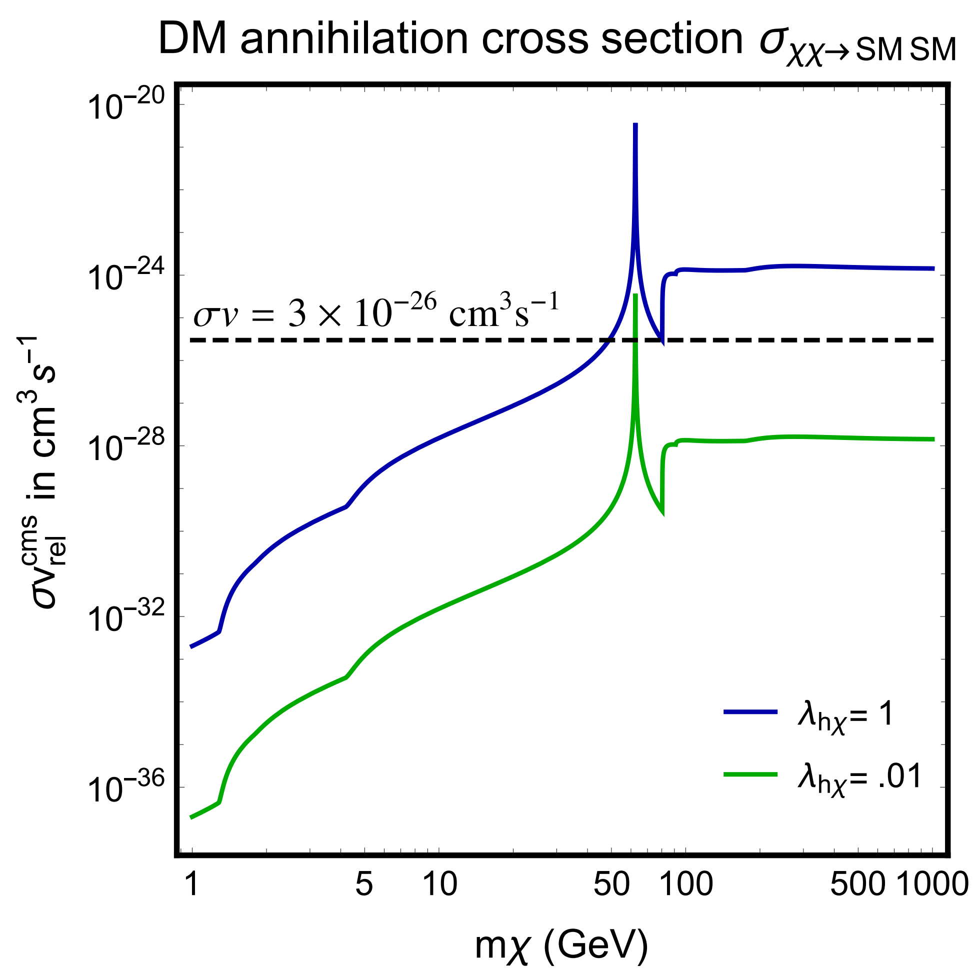
Gambit Collaboration, arXiv:1808.10465

Dark matter production

- Standard way to calculate the evolution of dark matter number density:

$$\frac{dn}{dt} + 3Hn = -\left(n^2 - n_{eq}^2\right)\langle\sigma_{\bar{\chi}\chi}v\rangle$$

Requires thermal averaging



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$$P_\chi = \frac{s}{2}\left(1 - \frac{4m_\chi^2}{s}\right)$$

Gambit Collaboration, arXiv:1808.10465

Thermal averaging quickly around the peak

- The standard thermal averaging procedure is slow where the cross section varies rapidly near the resonance

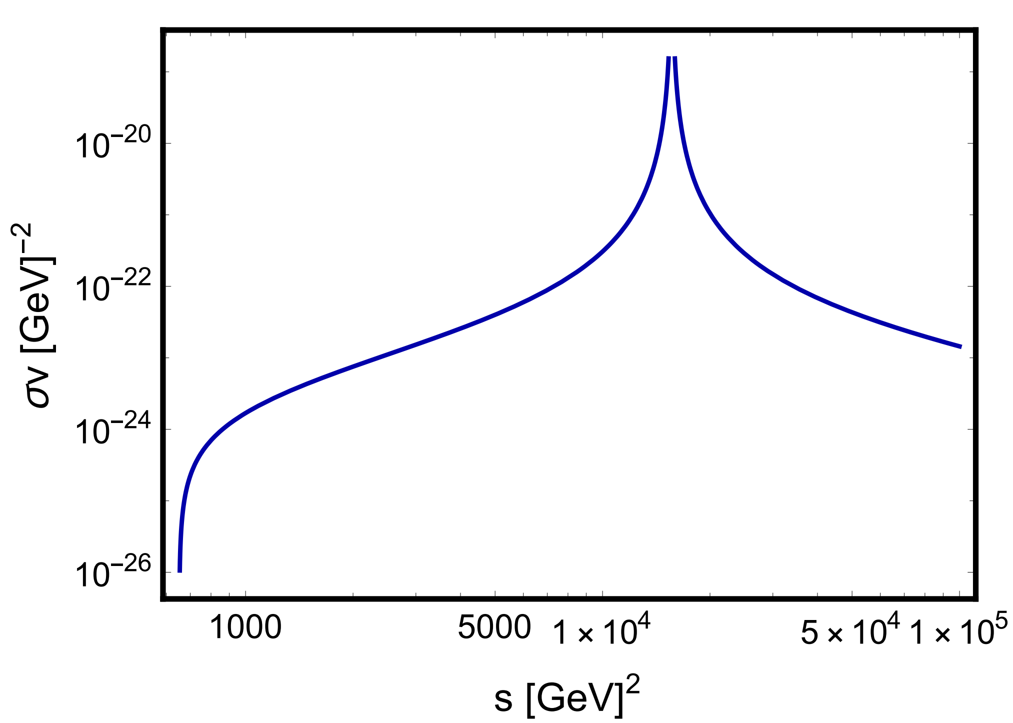
$$\langle \sigma v \rangle = \int_{4m_\chi^2}^{\infty} ds \frac{s\sqrt{s - 4m_\chi^2} K_1\left(\sqrt{s}/T\right)}{16 T m_\chi^4 K_2(m/T)^2} \sigma v$$

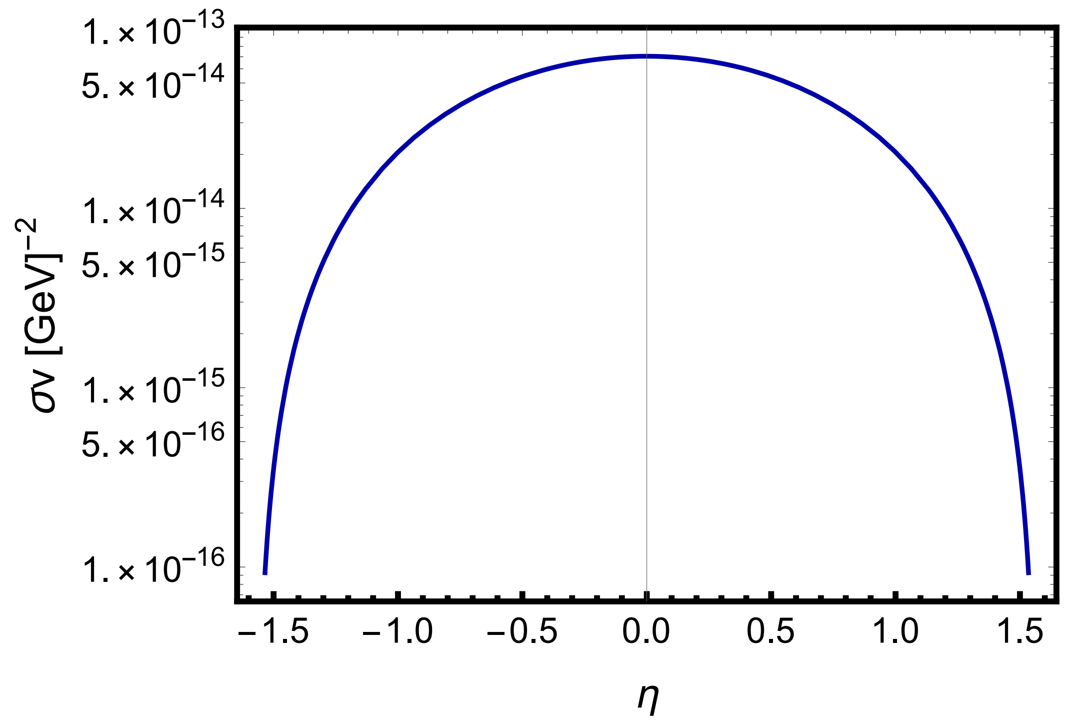
- Near resonance, change variables

$$s = m_h^2 + m_h \Gamma_h \tan \eta$$

- σv is flat in η near the peak, but varies rapidly away from the resonance peak
- Break up the integral and switch sampling in each variable

Thermal averaging quickly around the peak





$T = 1$ GeV

$\lambda_{h\chi} = 10^{-5}$

$$s = m_h^2 + m_h \Gamma_h \tan \eta$$

- σv is flat in η near the peak, but varies rapidly away from the resonance peak
- Break up the integral and switch sampling in each variable

Consistent thermal averaging

- Do we understand the distribution functions of the dark matter if its mass is changing with temperature?

$$\langle \sigma v \rangle = \int_{4m_\chi^2}^{\infty} ds \frac{s\sqrt{s - 4m_\chi^2} K_1\left(\sqrt{s}/T\right)}{16 T m_\chi^4 K_2(m/T)^2} \sigma v$$

Gondolo, Gelmini (1990)

$$\langle \sigma v \rangle = \frac{\int \sigma v e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2}{\int e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2}$$

Consistent thermal averaging

- Do we understand the distribution functions of the dark matter if its mass is changing with temperature?

1. Kinetic equilibrium $\Gamma_{\mathrm{scatt}} > H$
2. Reactions that establish kinetic equilibrium are faster than the mass change $\Gamma_{\mathrm{scatt}} > \frac{\dot{m}}{m}$
3. Adiabatic condition: avoid nonperturbative particle production $\frac{dm_\chi}{dt} < m_\chi^2$