Probing New Physics with MeV Telescopes

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SCIPP

SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

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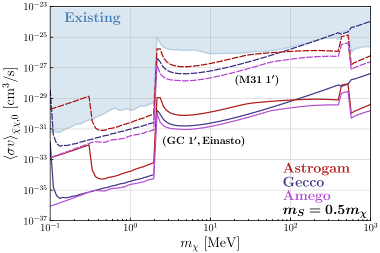
Preview

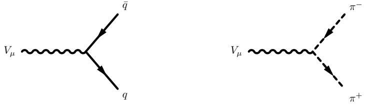
- Dark matter with $m_\chi <$ GeV is an exciting prospect
- Exciting upcoming MeV γ-ray telescopes could probe the dark sector to unprecedented sensitivity
- New tools developed explicity for studying MeV physics

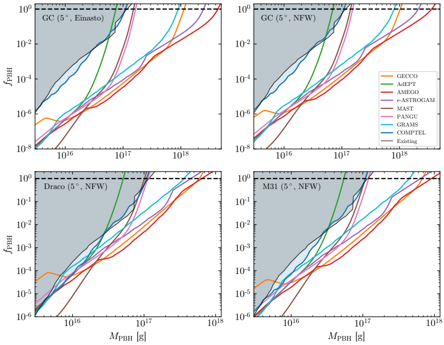
Preview



Dictionary

$$\mathcal{L}_{\mu \gtrsim \mathrm{GeV}} \longrightarrow \mathcal{L}_{\mathrm{ChiPT}}$$





Overview

Why MeV Dark Matter?

Motivation

1. **For decades, WIMPs have been the de facto DM candidates**

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    1. **Natuarally produce DM with correct relic density via freeze-out**

$$\frac{\Omega_{\chi}h^2}{0.12} \sim \left(\frac{2\times 10^{-9}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)\left(\frac{80}{g_{\star}}\right)^{1/2}\left(\frac{x_f}{23}\right)$$

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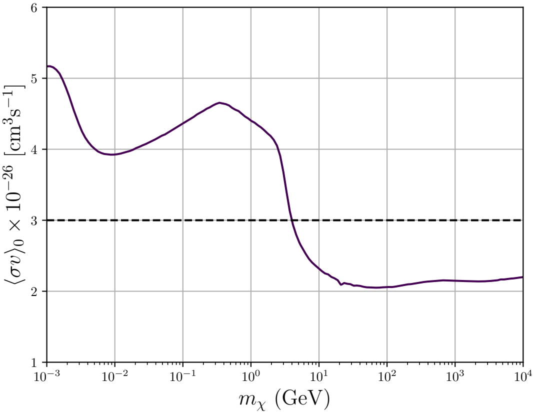

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2. No evidence for WIMPs
3. **Experiments are putting tight constraints on WIMP models**

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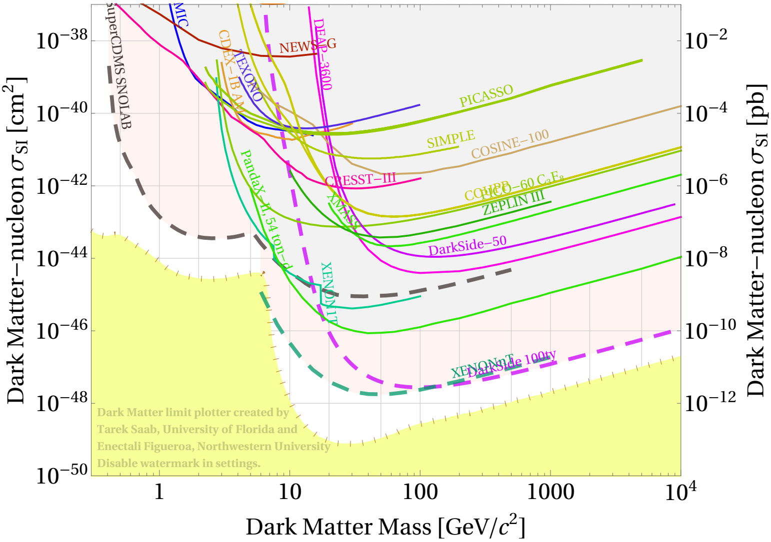
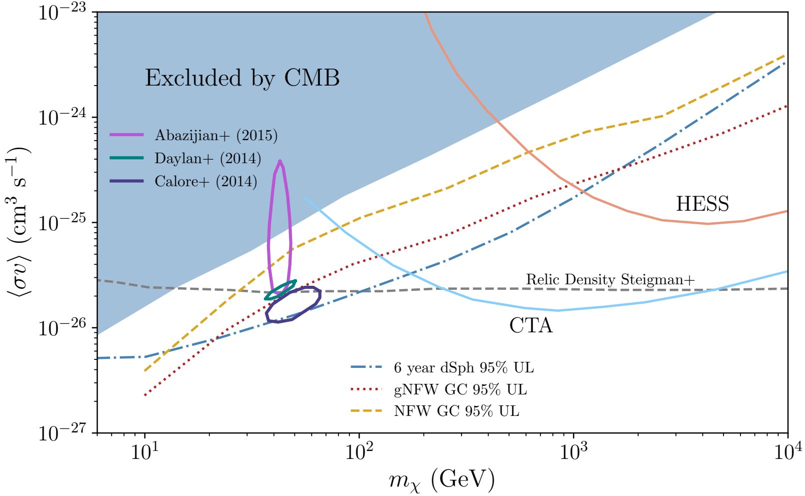


Dark Matter–nucleon σ_{SI} [cm^2]
Dark Matter–nucleon σ_{SI} [pb]
Dark Matter Mass [GeV/c^2]
superCDMS SNOLAB
NEWS-G
DEAP-3600
CDEX-1B AM
TEXONO
PICASSO
SIMPLE
COSINE-100
CRESST-III
PICO-60 C_3F_8
ZEPLIN III
XMASS
PandaX-II, 54 ton-d
DarkSide-50
XENON1T
XENONnT
DarkSide 100ty
Dark Matter limit plotter created by
Tarek Saab, University of Florida and
Enectali Figueroa, Northwestern University
Disable watermark in settings.

Motivation



Excluded by CMB
Abazijian+ (2015)
Daylan+ (2014)
Calore+ (2014)
HESS
Relic Density Steigman+
CTA
6 year dSph 95% UL
gNFW GC 95% UL
NFW GC 95% UL
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\langle\sigma v\rangle$ (cm^3 s^{-1})
10^1
10^2
10^3
10^4
m_χ (GeV)

Alternative to WIMPs: MeV DM

1. **No WIMPs $\Longrightarrow$ Explore different mass ranges/mediators**

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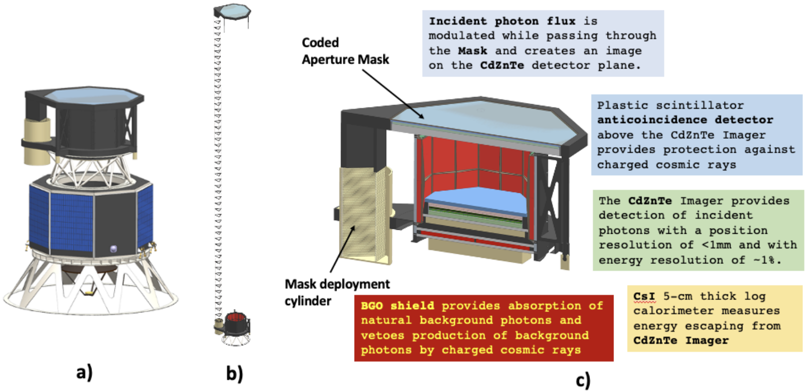
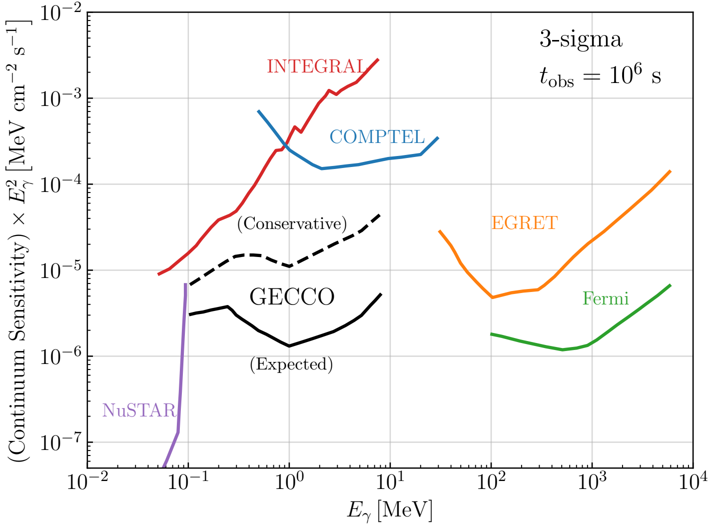
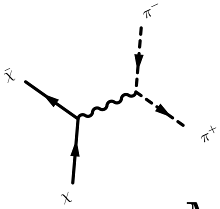
1. No WIMPs $\implies$ Explore different mass ranges/mediators
2. MeV masses much less constrained by current direct and indirect detection experiments
3. **Exciting upcoming oppurtunities to probe MeV DM via indirect detection: AS-Astrogam, AMEGO, GECCO**

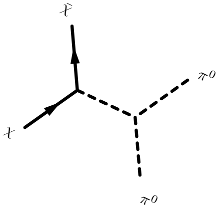
GECCO


Coded
Aperture Mask
Incident photon flux is modulated while passing through the Mask and creates an image on the CdZnTe detector plane.
Plastic scintillator anticoincidence detector above the CdZnTe Imager provides protection against charged cosmic rays
The CdZnTe Imager provides detection of incident photons with a position resolution of <1mm and with energy resolution of ~1%.
Mask deployment cylinder
BGO shield provides absorption of natural background photons and vetoes production of background photons by charged cosmic rays
CsI 5-cm thick log calorimeter measures energy escaping from CdZnTe Imager
a)
b)
c)

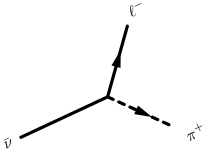
GECCO Sensitivity







MeV Dark Matter: From GeV to MeV



A. Coogan, S. Profumo, LM: arXiv:1907.11846
A. Coogan, S. Profumo, LM: arXiv:2104.06168
A. Coogan, A. Moiseev, S. Profumo, LM: arXiv:2101.10370

Framework

- **Dark Matter models with:**

$$\textbf{Annihilating-DM} : 0.1 \text{ MeV} \lesssim m_\chi \lesssim 250 \text{ MeV}$$
$$\textbf{Decaying-DM} : 0.1 \text{ MeV} \lesssim m_\chi \lesssim 500 \text{ MeV}$$

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(more on this later)

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- **Developed public, open-source python package for comprehensive analysis of MeV DM models**

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- Facilities to compute constraints from CMB and various PHENO constraints

Simplified Models

Models: $\mu \gtrsim$ GeV

- Dark Matter: $[\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y]$-Neutral Dirac Fermion

$$\mathcal{L}_\chi = i\bar{\chi}(\gamma^\mu \partial_\mu - m_\chi)\chi$$

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$$\mathcal{L}_{\chi(\mathrm{int})} \supset \begin{cases} g_{S\chi} S\bar{\chi}\chi & \text{Scalar Mediator} \\ i g_{P\chi} P\bar{\chi}\gamma^5\chi & \text{Pseudo-Scalar Mediator} \\ g_{V\chi} V_\mu \bar{\chi}\gamma^\mu\chi & \text{Vector Mediator} \\ g_{A\chi} A_\mu \bar{\chi}\gamma^\mu\gamma^5\chi & \text{Axial-Vector Mediator} \end{cases}$$

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- Focus on scalar and vector mediator cases
- Also consider RH-neutrino with mixing with a single SM neutrino

$$\begin{pmatrix} \hat{\nu}_k \\ \hat{\bar{\nu}} \end{pmatrix} = \begin{pmatrix} -i\cos\theta & \sin\theta \\ i\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_k \\ \bar{\nu} \end{pmatrix}$$

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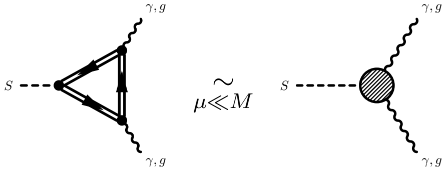

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$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\chi} - \frac{1}{2}(\partial_\mu S)^2 - V(S) - g_{S\chi} S\bar{\chi}\chi \\ &\quad - S\sum_f g_{Sf}\bar{f}f + \frac{S}{\Lambda}\left(g_{SF}\frac{\alpha_{\text{EM}}}{4\pi}F_{\mu\nu}F^{\mu\nu} + g_{SG}\frac{\alpha_s}{4\pi}G^a_{\mu\nu}G^{\mu\nu,a}\right)\end{aligned}$$

Higgs Portal: $\mu \gtrsim \text{GeV}$

- Assume the scalar mediator mixes with SM Higgs

$$\begin{pmatrix} \hat{h} \\ \hat{S} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

Higgs Portal: $\mu \gtrsim$ GeV

- Assume the scalar mediator mixes with SM Higgs

$$\hat{h} = \cos\theta h - \sin\theta S$$

- Induces interactions between SM and S

$$-\frac{h}{v_h}\sum_{\psi} m_{\psi}\bar{\psi}\psi + \cdots \to -\sin\theta\frac{S}{v_h}\sum_{\psi} m_{\psi}\bar{\psi}\psi + \cdots$$

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- Resulting scalar Lagrangian with dimension-5 operators for $\mu \gtrsim$ GeV

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$$g_{Sf} = \frac{m_f}{v_h}\sin\theta, \quad g_{SF} = \frac{5}{6}\sin\theta, \quad g_{SG} = -3\sin\theta, \quad \Lambda = v_h$$

Vector Mediator: $\mu \gtrsim$ GeV

- Add massive U(1) vector V_μ via Stueckelberg (or SSB):

$$
\begin{aligned}
&-\frac{1}{4}V_{\mu\nu}V^{\mu\nu}+\frac{1}{2}(\partial_\mu\sigma+m_V V_\mu)^2-\frac{1}{2\xi}(\partial_\mu V^\mu-\xi m\sigma)^2 \\
&\longrightarrow \frac{1}{2}V_\mu\left[\left(\Box+m_V^2\right)g^{\mu\nu}-\left(1-\frac{1}{\xi}\right)\partial^\mu\partial^\nu\right]V_\nu+\cdots
\end{aligned}
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- Charge SM and DM:

$$
\mathcal{L} \supset V_\mu g_{V\chi} V_\mu \bar{\chi}\gamma^\mu\chi + \sum_f g_{Vf} V_\mu \bar{f}\gamma^\mu f
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- Vector Lagrangian for $\mu \gtrsim$ GeV

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_\chi + \frac{1}{2}V_\mu\left[\left(\Box + m_V^2\right)g^{\mu\nu} - \partial^\mu\partial^\nu\right]V_\nu$$
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Kinetic Mixing: $\mu \gtrsim \text{GeV}$

- Introduce small mixing between new vector and SM photon

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- Induces coupling between charged SM fields and V_μ

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- Result

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_\chi + \frac{1}{2} V_\mu \left[\left(\Box + m_V^2\right) g^{\mu\nu} - \partial^\mu\partial^\nu\right] V_\nu$$
$$+ g_{V\chi} V_\mu \bar{\chi}\gamma^\mu\chi + \sum_f g_{Vf} V_\mu \bar{f}\gamma^\mu f$$

$$g_{Vf} = -\epsilon e Q_f$$

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Charged Currents:

$$J_\mu^+ = \sum_i \nu_i^\dagger \bar{\sigma}_\mu \ell_i + \sum_{i,j} V_{ij}^{\text{CKM}} u_i^\dagger \bar{\sigma}_\mu d_j$$

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- Assume RH-Neutrino mixes with a single active neutrino: ν_k
- Low-energy Lagrangian just 4-Fermi Lagrangian

$$\mathcal{L}_{\bar{\nu}(int)} = -\frac{4G_F}{\sqrt{2}}\left[J^+_\mu J^-_\mu + J^Z_\mu J^Z_\mu\right]\Big|_{\nu_k \to \sin\theta\bar{\nu} - i\cos\theta\nu_k}$$

Neutral Currents:

$$J^Z_\mu = \frac{1}{c_W}\sum_f g^Z_{f,L} f^\dagger\bar{\sigma}_\mu f + \frac{1}{c_W}\sum_{\bar{f}} g^Z_{f,R}\bar{f}^\dagger\bar{\sigma}_\mu\bar{f}$$

$$g^Z_{f,L} = T^3_f - Q_f s^2_W$$

$$g^Z_{f,R} = -Q_f s^2_W$$

Decent to MeV Scale

Moving below 1 GeV

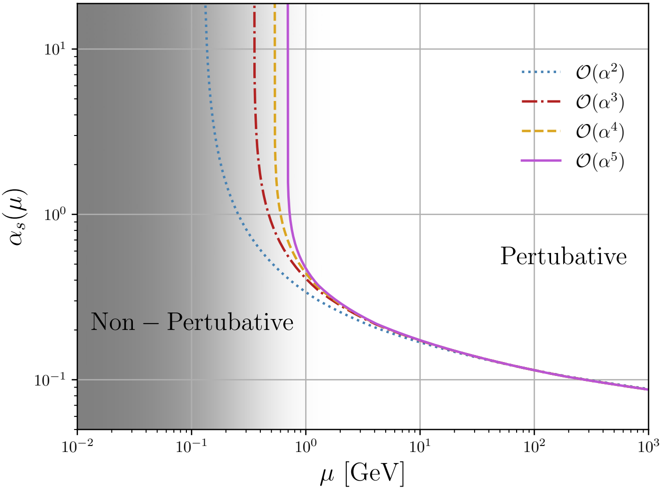
Now that we have the Lagrangians above 1 GeV, we need to determine the Lagrangians below 1 GeV

$$\mathcal{L}_{\mu>1\mathrm{GeV}}$$

$$\downarrow$$

$$\mathcal{L}_{\mu<1\mathrm{GeV}} \sim \mathcal{L}_{\mathrm{ChiPT}}$$

Moving below 1 GeV



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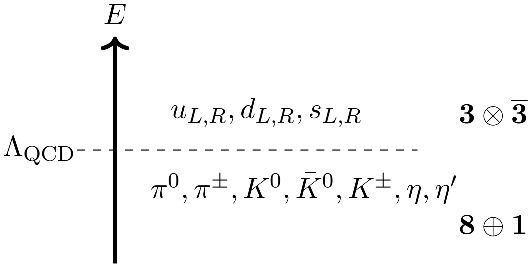

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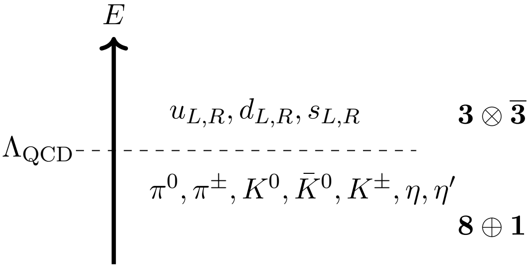

- Use an effective Lagrangian below 1 GeV : Chiral Lagrangian

Chiral Lagrangian

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$$\boldsymbol{q} \equiv \begin{pmatrix} u \\ d \\ s \end{pmatrix} \to e^{i\theta_L^a \lambda^a/2} \begin{pmatrix} u \\ d \\ s \end{pmatrix} \qquad \bar{\boldsymbol{q}} \equiv \begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{s} \end{pmatrix} \to e^{i\theta_R^a \lambda^a/2} \begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{s} \end{pmatrix}$$

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- CCWZ tells us how to construct bottom-up Lagrangian for pseudo-Goldstones generated from symmetry breaking

Chiral Lagrangian

The Chiral Lagrangian is

$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\Big(D_\mu \boldsymbol{\Sigma}^\dagger D^\mu \boldsymbol{\Sigma}\Big) + \frac{f_\pi^2}{4}\,\mathrm{Tr}\Big(\boldsymbol{\chi}\boldsymbol{\Sigma}^\dagger + \boldsymbol{\Sigma}\boldsymbol{\chi}^\dagger\Big)$$

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where

$$\boldsymbol{\Sigma} = \exp\left(\frac{i\sqrt{2}}{f_\pi}\boldsymbol{\Pi}^a\boldsymbol{\lambda}_a\right), \qquad \boldsymbol{\Sigma} \to \boldsymbol{U}_R\boldsymbol{\Sigma}\boldsymbol{U}_L^\dagger$$

$\boldsymbol{\Pi}^a$ are the NBG

$\boldsymbol{\lambda}_a$ Gell-Mann matrices

$$\sqrt{2}\boldsymbol{\Pi}^a\boldsymbol{\lambda}_a = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\overline{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}$$

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where

$$D_\mu \boldsymbol{\Sigma} = \partial_\mu \boldsymbol{\Sigma} - i\boldsymbol{r}_\mu \boldsymbol{\Sigma} + i\boldsymbol{\Sigma}\boldsymbol{\ell}_\mu$$

and $\boldsymbol{\ell}_\mu$ and $\boldsymbol{r}_\mu$ are left- and right-handed currents associated with a local $\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R$ symmetry

$$\boldsymbol{\ell}_\mu \to \boldsymbol{U}_L \boldsymbol{\ell}_\mu \boldsymbol{U}_L^\dagger$$
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where

$$\boldsymbol{\chi} = 2B_0(\boldsymbol{s} + i\boldsymbol{p}), \qquad \boldsymbol{\chi} \to \boldsymbol{U}_R \boldsymbol{\chi} \boldsymbol{U}_L^\dagger$$

and $\boldsymbol{s}, \boldsymbol{p}$ are the scalar and pseudo-scalar current densities and

$$B_0 = \frac{m_\pi^2}{m_u + m_d} \approx 2600 \text{ MeV}$$

Without any external fields,

$$\boldsymbol{s} = \mathrm{diag}(m_u, m_d, m_s)$$

Matching

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- Operators that need to be matched:

$$S\bar{\boldsymbol{q}}\boldsymbol{G}_{Sq}\boldsymbol{q}, \qquad \bar{\boldsymbol{q}}\gamma^\mu(\boldsymbol{\ell}_\mu P_L + \boldsymbol{r}_\mu P_R)\boldsymbol{q}, \qquad SG^a_{\mu\nu}G^{a,\mu\nu}$$

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- Matched onto ChiPT mass term:

$$-\bar{\boldsymbol{q}}(\boldsymbol{M}_q + S\boldsymbol{G}_{Sq})\boldsymbol{q} \to \frac{f_\pi^2}{4}\,\mathrm{Tr}\Big[\boldsymbol{\chi}\boldsymbol{\Sigma}^\dagger + \mathrm{c.c.}\Big], \quad \boldsymbol{\chi} = 2B(\boldsymbol{M}_q + S\boldsymbol{G}_{Sq})$$

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- Additional term from chiral anomaly (Wess-Zumino-Witten):

$$-\frac{e^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}\frac{\pi^0}{f_{\pi}} \to -\frac{e^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}\frac{\pi^0}{f_{\pi}} - \frac{\epsilon e^2}{16\pi^2}F_{\mu\nu}\tilde{V}^{\mu\nu}\frac{\pi^0}{f_{\pi}}$$

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- Scalar interaction is:

$$g_{SG}\frac{\alpha}{4\pi}\frac{S}{\Lambda}G^2 \to -\frac{2g_{SG}}{\beta_0}\frac{S}{\Lambda}\partial_\mu d^\mu + \frac{2g_{SG}}{\beta_0}\frac{S}{\Lambda}\sum_q m_q\bar{q}q + \cdots$$

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- Matched onto ChiPT Lagrangian by computing $\partial_\mu d^\mu$

$$\partial_\mu d^\mu = -\frac{f_\pi^2}{2}\,\mathrm{Tr}\Big[(D_\mu\boldsymbol{\Sigma})^\dagger(D_\mu\boldsymbol{\Sigma})\Big] - f_\pi^2\,\mathrm{Tr}\Big[\boldsymbol{\chi}\boldsymbol{\Sigma}^\dagger + \text{c.c.}\Big]$$

Matching: Dictionary

$$\mathcal{L}_{\mu>\text{GeV}} \supset \bar{\boldsymbol{q}}\boldsymbol{r}_\mu\gamma^\mu P_R\boldsymbol{q} + \bar{\boldsymbol{q}}\boldsymbol{\ell}_\mu\gamma^\mu P_L\boldsymbol{q} + \bar{\boldsymbol{q}}\boldsymbol{s}\boldsymbol{q} + \phi\frac{\alpha}{4\pi}G^a_{\mu\nu}G^{\mu\nu,a}$$

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From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching - **vector**

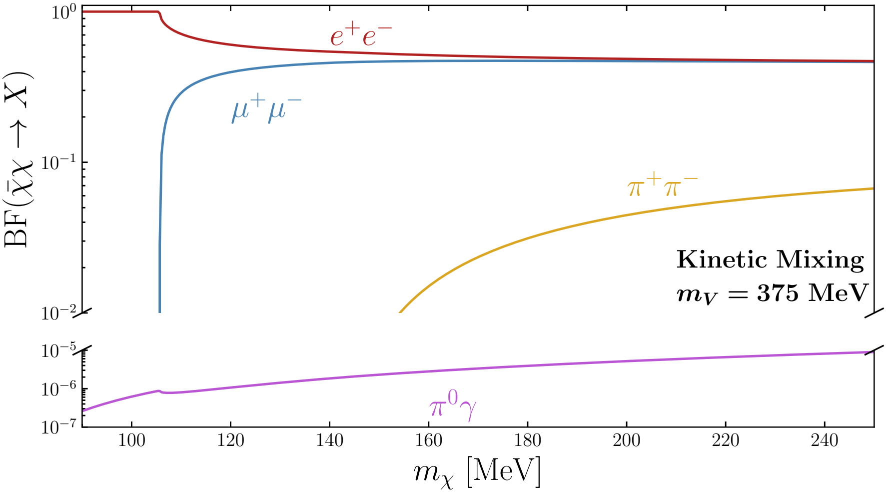
- Below a GeV

$$\mathcal{L}_V \supset g_{V\chi} V_\mu \overline{\chi} \gamma^\mu \chi + \sum_\ell g_{V\ell} V_\mu \overline{\ell} \gamma^\mu \ell + \frac{f_\pi^2}{4} \mathrm{Tr}\Big((D_\mu \Sigma)^\dagger D_\mu \Sigma\Big) + \frac{f_\pi^2}{4} \mathrm{Tr}\Big(\chi \Sigma^\dagger + \Sigma \chi^\dagger\Big)$$

with

$$\begin{aligned} D_\mu \Sigma &= \partial_\mu \Sigma - i r_\mu \Sigma + i \Sigma \ell_\mu \\ \chi &= 2 B_0 s \\ s &= \mathrm{diag}(m_u, m_d, m_s) \\ r_\mu = \ell_\mu &= -e A_\mu \mathrm{diag}\left(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}\right) + V_\mu \mathrm{diag}(g_{Vu}, g_{Vd}, g_{Vs}) \end{aligned}$$

From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching - **vector**



From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching- **scalar**

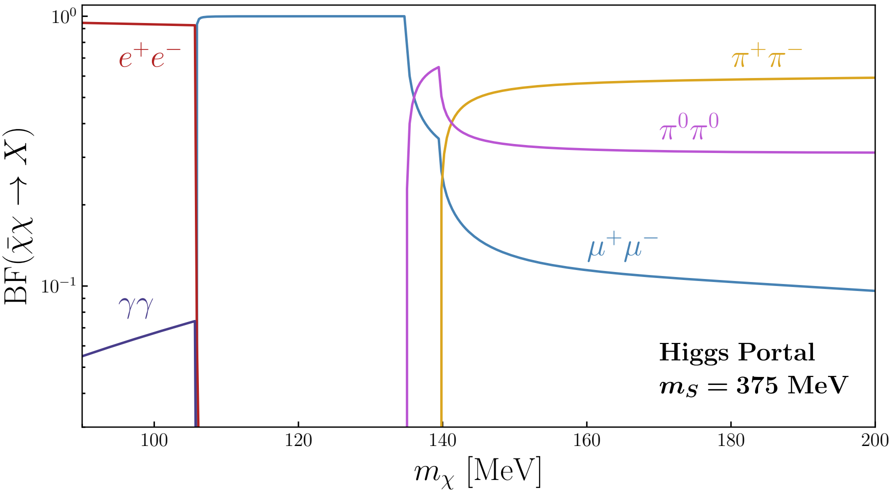
- Below 1 GeV, we have

$$\mathcal{L}_S \supset g_{S\chi} S\overline{\chi}\chi + g_{fV}\frac{S}{v}\sum_{\ell} m_\ell \overline{\ell}\ell + \frac{\alpha_{\text{EM}}}{4\pi\Lambda} g_{SF} S F^2$$
$$+ \frac{f_\pi^2}{4}\text{Tr}\Big((D_\mu\Sigma)^\dagger D_\mu\Sigma\Big) + \frac{f_\pi^2}{4}\text{Tr}\Big(\chi\Sigma^\dagger + \Sigma\chi^\dagger\Big)$$
$$+ \frac{2g_G}{9v} S\left(\frac{f_\pi^2}{2}\text{Tr}\Big((D_\mu\Sigma)^\dagger(D^\mu\Sigma)\Big) + f_\pi^2\,\text{Tr}\Big(\chi\Sigma^\dagger + \Sigma\chi^\dagger\Big)\right)$$

with

$$D_\mu\Sigma = \partial_\mu\Sigma - ir_\mu\Sigma + i\Sigma\ell_\mu$$
$$\chi = 2B_0 s$$
$$s = \text{diag}(m_u, m_d, m_s)\left(1 + g_{Sf}\frac{S}{v}\right)$$
$$r_\mu = \ell_\mu = -eA_\mu \text{diag}\left(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}\right)$$

From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching- **scalar**



From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching- **RHN**

$$\mathcal{L}_{\bar{\nu}(\text{int})} = \frac{f_\pi^2}{4}\,\text{Tr}\left[\left|\partial_\mu \boldsymbol{\Sigma} - i\boldsymbol{r}_\mu \boldsymbol{\Sigma} + i\boldsymbol{\Sigma}\boldsymbol{\ell}_\mu\right|^2\right]$$

Currents:

$$\boldsymbol{r}_\mu = -\frac{8G_F}{\sqrt{2}}\boldsymbol{G}_R R_\mu^0, \qquad \boldsymbol{\ell}_\mu = -\frac{4G_F}{\sqrt{2}}\left(2\boldsymbol{G}_L L_\mu^0 + \boldsymbol{V}^\dagger L_\mu^-\right)$$

$$L_\mu^0 = \frac{\sin(2\theta)}{4c_W}\delta_{ik}\left(\nu_i^\dagger\bar{\sigma}_\mu\bar{\nu} + \text{c.c.}\right) + \frac{1}{2c_W}\left(-1 + 2s_W^2\right)\ell_i^\dagger\bar{\sigma}_\mu\ell_i$$

$$L_\mu^- = \sin\theta\delta_{ik}\ell_i^\dagger\bar{\sigma}_\mu\bar{\nu}$$

$$R_\mu^0 = \frac{s_W^2}{c_W}\bar{\ell}_i^\dagger\bar{\sigma}_\mu\bar{\ell}_i$$

From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching- **RHN**

$$\mathcal{L}_{\bar{\nu}(\text{int})} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\Big[\left|\partial_\mu \boldsymbol{\Sigma} - i\boldsymbol{r}_\mu \boldsymbol{\Sigma} + i\boldsymbol{\Sigma}\boldsymbol{\ell}_\mu\right|^2\Big]$$

Currents:

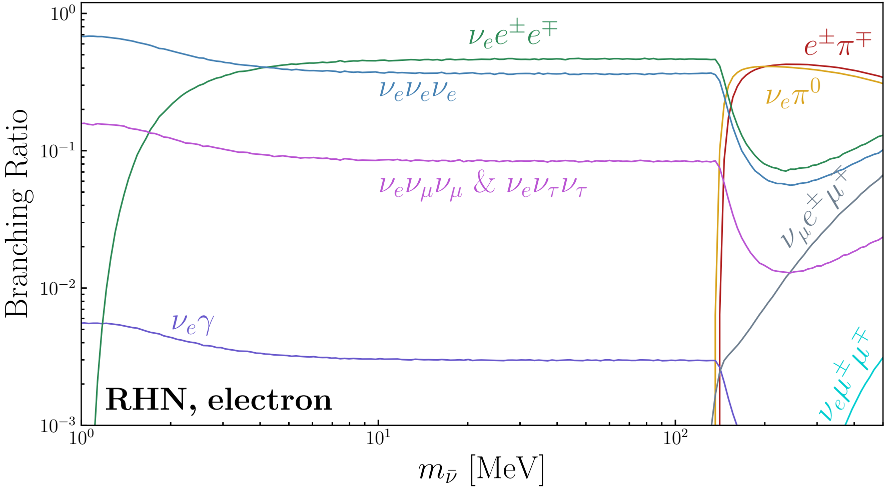
$$\boldsymbol{r}_\mu = 2\boldsymbol{G}_R R^0_\mu, \qquad \boldsymbol{\ell}_\mu = 2\boldsymbol{G}_L L^0_\mu + \boldsymbol{V}^\dagger L^-_\mu$$

$$\boldsymbol{G}_R = -\frac{s_W^2}{3c_W}\mathrm{diag}(2,-1,-1)$$

$$\boldsymbol{G}_L = \frac{1}{2c_W}\mathrm{diag}(1,-1,-1) + \boldsymbol{G}_R$$

$$\boldsymbol{V} = \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

From $\mu > 1\text{GeV}$ to $\mu < 1\text{GeV}$: Matching- **RHN**



Validity of ChiPT

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- Chiral perturbation theory has a limited range of validity

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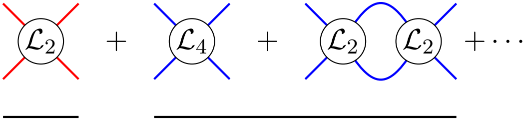
- Chiral perturbation theory has a limited range of validity
- The chiral expansion is

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \cdots$$

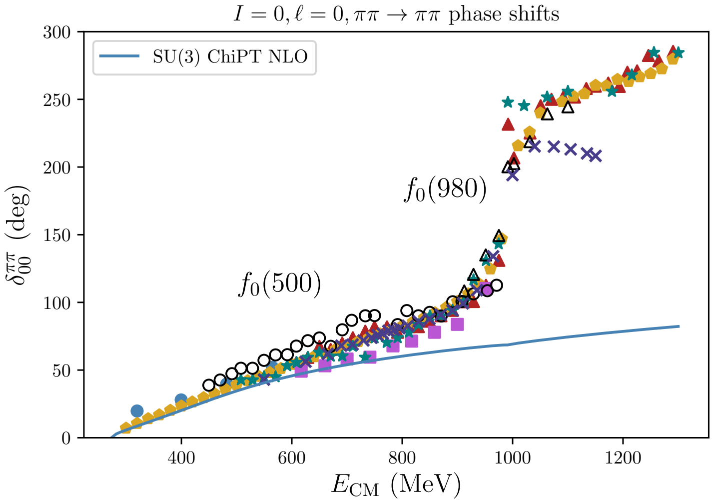
$$\mathcal{M} \sim \left(\frac{p^2}{\Lambda_\chi^2}\right)\mathcal{M}^{(2)} + \left(\frac{p^2}{\Lambda_\chi^2}\right)^2 \mathcal{M}^{(4)} + \cdots$$



$\mathcal{O}(p^2/\Lambda_\chi^2)$ $\mathcal{O}(p^4/\Lambda_\chi^4)$

where $\Lambda_\chi \approx 4\pi f_\pi \approx 1.2$ GeV

Validity of ChiPT



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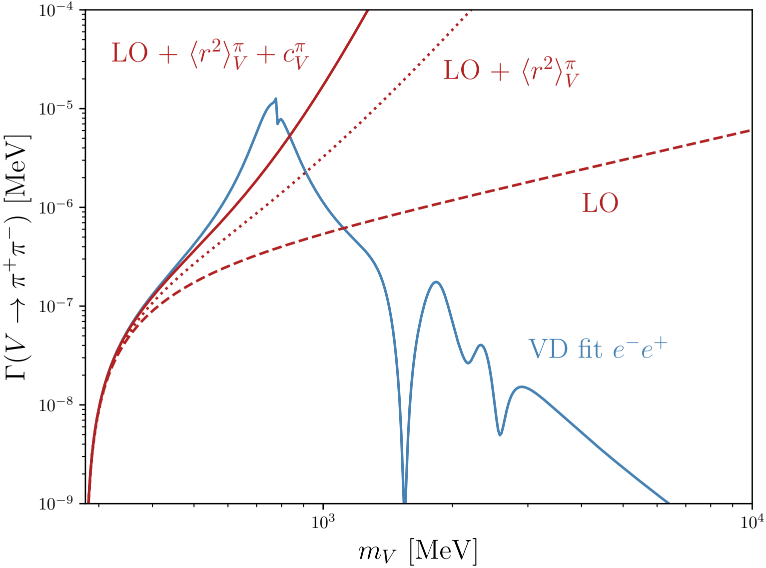

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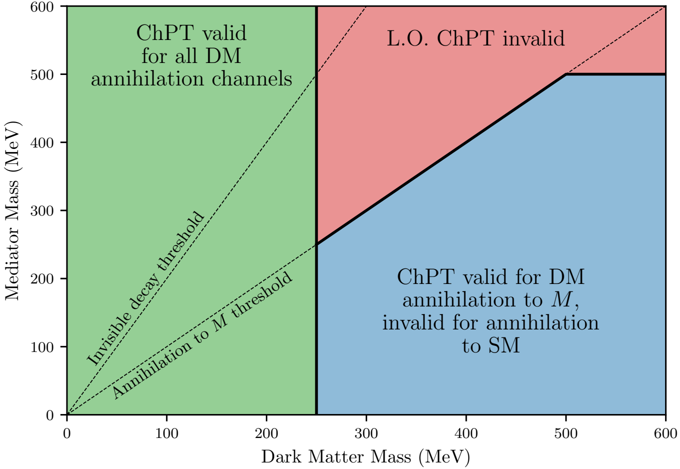

Indirect Detection

- Gamma ray flux observed by detector

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{\Delta\Omega}{4\pi m_\chi^a} \cdot \left[\frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{LOS}} \mathrm{d}\ell\, \rho_\chi^a\right] \cdot \Gamma \cdot \frac{\mathrm{d}N}{\mathrm{d}E_\gamma}$$

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Integral along detector's "Line-of-sight" of dark matter density of target with angular size $\Delta\Omega$

$a = 2$ for annhilating DM

$a = 1$ for decaying DM

	$[\mathrm{MeV}^2\mathrm{cm}^{-5}\mathrm{sr}^{-1}]$		$[\mathrm{MeV}\mathrm{cm}^{-2}\mathrm{sr}^{-1}]$	
Target	$J(1')$	$J(5^\circ)$	$D(1')$	$D(5^\circ)$
Galactic Center (NFW)	6.972×10^{32}	1.782×10^{30}	4.84×10^{26}	1.597×10^{26}
Galactic Center (Einasto)	5.987×10^{34}	4.965×10^{31}	4.179×10^{27}	2.058×10^{26}
Draco (NFW)	3.418×10^{30}	8.058×10^{26}	5.949×10^{25}	1.986×10^{24}
M31 (NFW)	1.496×10^{31}	1.479×10^{27}	3.297×10^{26}	4.017×10^{24}

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DM interaction rate:

$$\text{Annhilating DM} : \Gamma = \frac{\langle\sigma v\rangle}{2 f_\chi}$$

$$\text{Decaying DM} : \Gamma = \frac{1}{\tau}$$

Indirect Detection

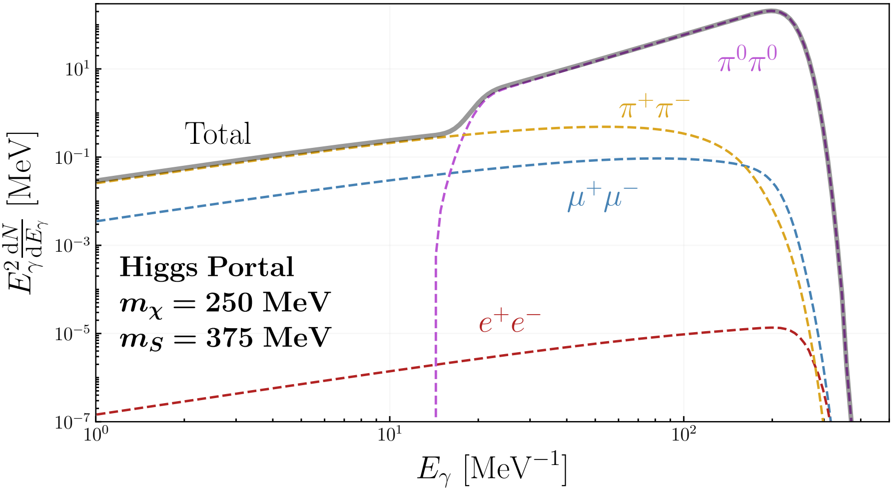
- Gamma ray flux observed by detector

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_{\gamma}} = \frac{\Delta\Omega}{4\pi m_{\chi}^{a}} \cdot \left[\frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{LOS}} \mathrm{d}\ell\, \rho_{\chi}^{a}\right] \cdot \Gamma \cdot \frac{\mathrm{d}N}{\mathrm{d}E_{\gamma}}$$

Photon spectrum per annhilation/decay:

$$\frac{\mathrm{d}N}{\mathrm{d}E_{\gamma}} = \sum_{X} \mathrm{BR}(\bar{\chi}\chi \to \gamma + X)\frac{\mathrm{d}N_{\bar{\chi}\chi\to\gamma+X}}{\mathrm{d}E_{\gamma}}$$

Indirect Detection



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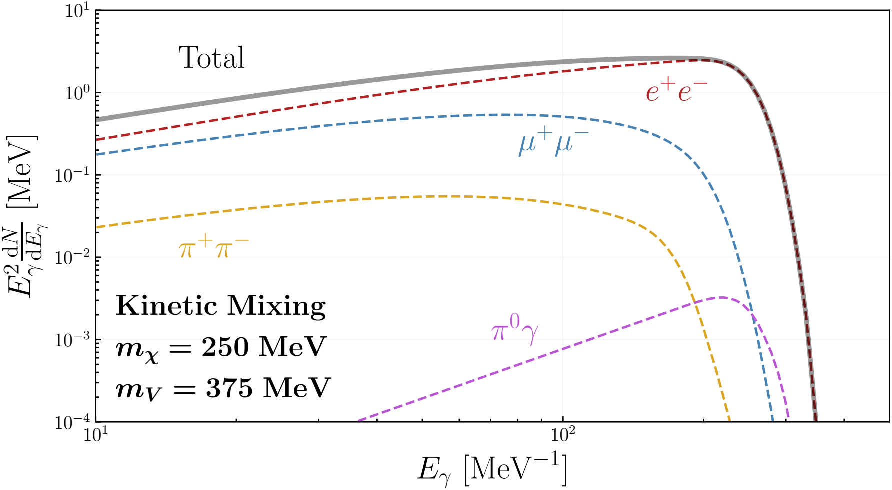

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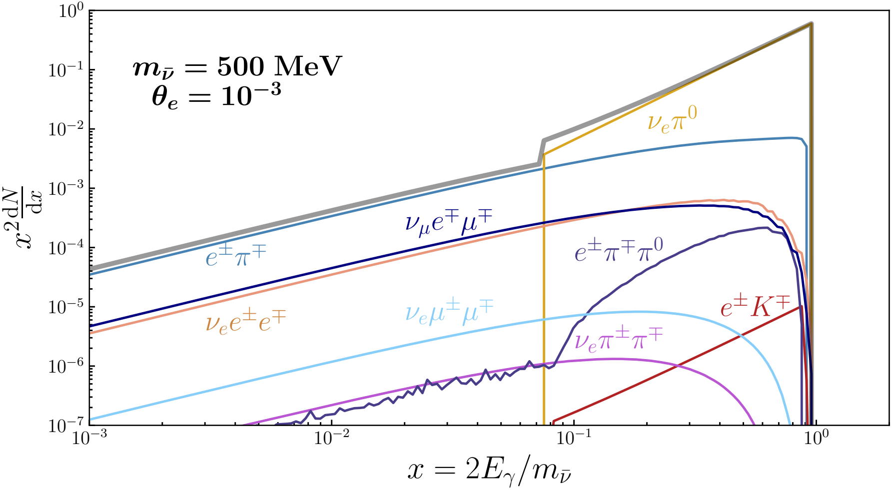

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- Including detector energy resolution

$$\frac{\mathrm{d}\bar{\Phi}}{\mathrm{d}E_{\gamma}} = \int \mathrm{d}\tilde{E}_{\gamma}\, R_{\epsilon}(E_{\gamma}|\tilde{E}_{\gamma}) \frac{\mathrm{d}\bar{\Phi}}{\mathrm{d}E_{\gamma}}$$

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Detector energy resolution $\sim$ Gaussian:

$$R_{\epsilon}(E_{\gamma}|\tilde{E}_{\gamma}) \sim \frac{1}{\sqrt{2\pi}}\frac{1}{\epsilon\tilde{E}} \exp\left(-\frac{1}{2}\left(\frac{\tilde{E}-E}{\epsilon\tilde{E}}\right)^{2}\right)$$

Indirect Detection

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- Observed photon count in energy bin $(E_{\mathrm{min}}^{(i)}, E_{\mathrm{max}}^{(i)})$

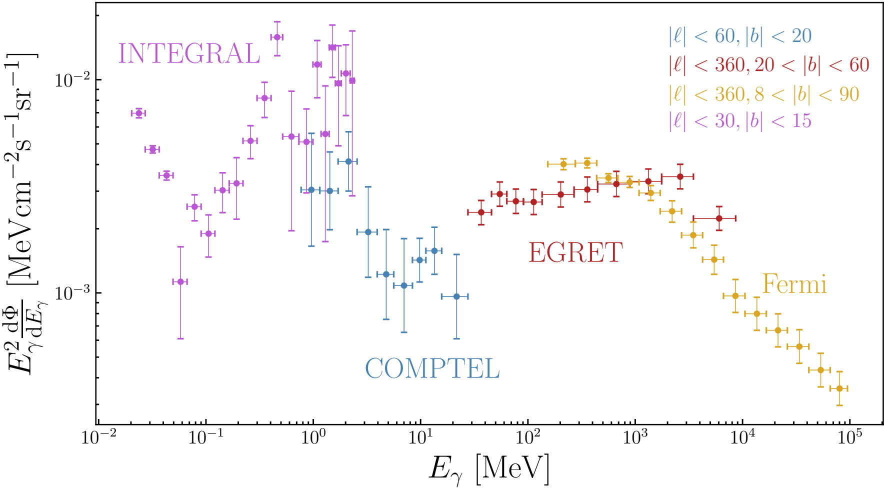
$$N_\gamma = \int_{E_{\mathrm{min}}^{(i)}}^{E_{\mathrm{max}}^{(i)}} \mathrm{d}E_\gamma\, T_{\mathrm{obs}} A_{\mathrm{eff}}(E_\gamma)\frac{\mathrm{d}\bar{\Phi}}{\mathrm{d}E_\gamma}$$

Constrianing

- For telescopes with reported data, constrain by asserting DM signal no greater that twice the upper error

$$\left[\int_{E_{\mathrm{low}}^{(i)}}^{E_{\mathrm{high}}^{(i)}} \mathrm{d}E_{\gamma}\, \frac{\mathrm{d}\Phi_{\gamma}}{\mathrm{d}E_{\gamma}}\right] \leq \Phi_{\gamma}^{(i)} + 2\delta\Phi_{\gamma}^{(i)}, \qquad i \in 1, \ldots, N_{\mathrm{bins}}$$

Constrianing



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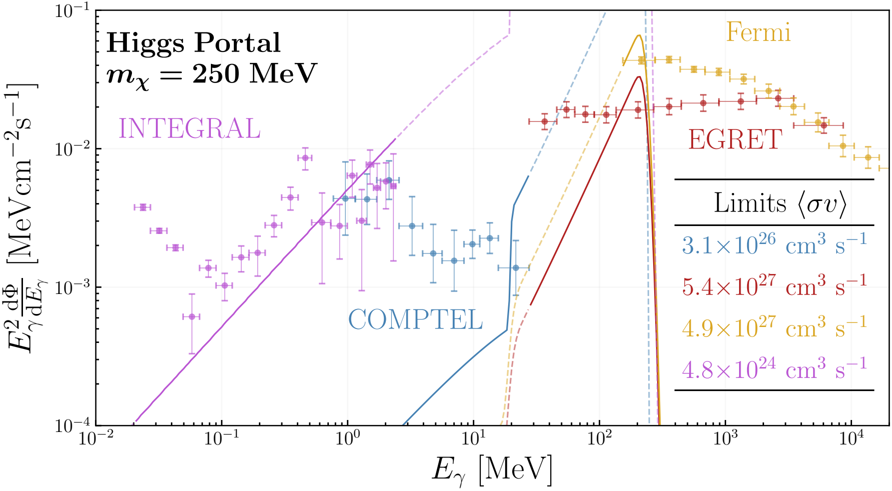

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$$N_{S,\mathrm{bkg}}(a,b) = \int_{a}^{b} \mathrm{d}E_{\gamma}\, \frac{\mathrm{d}\Phi_{\gamma}^{S,\mathrm{bkg}}}{\mathrm{d}E_{\gamma}}$$

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- For targets away from Galactic center we use empirical power-law background fit to COMPTEL

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_{\gamma}} = 2.74 \times 10^{-3} \left(\frac{E_{\gamma}}{\text{MeV}}\right)^{-2} \text{MeV}^{-1}\text{cm}^{-1}\text{s}^{-1}\text{sr}^{-1}$$

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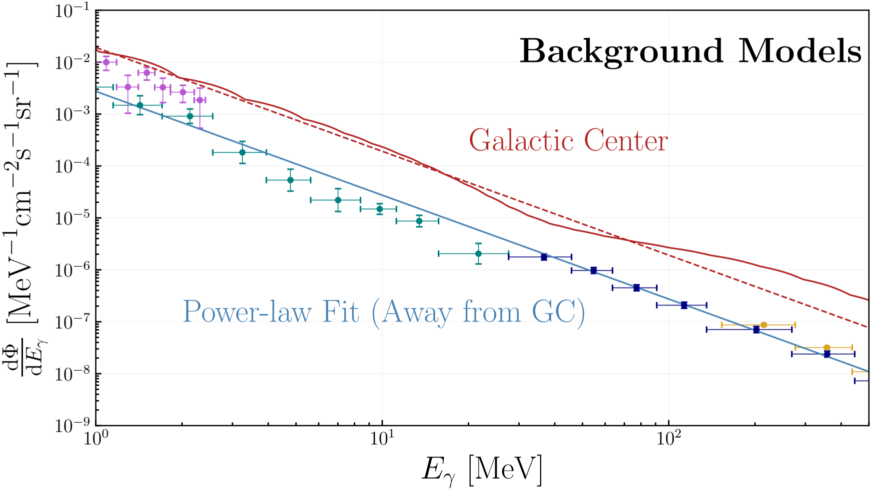
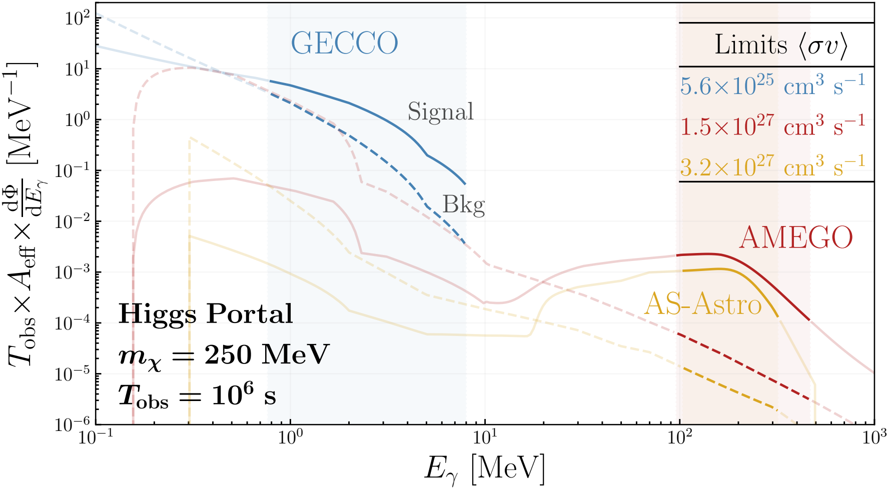
- Use more sophisticated model for Galactic center with bremsstrahlung, π^0 and inverse-Compton computed with GALPROP

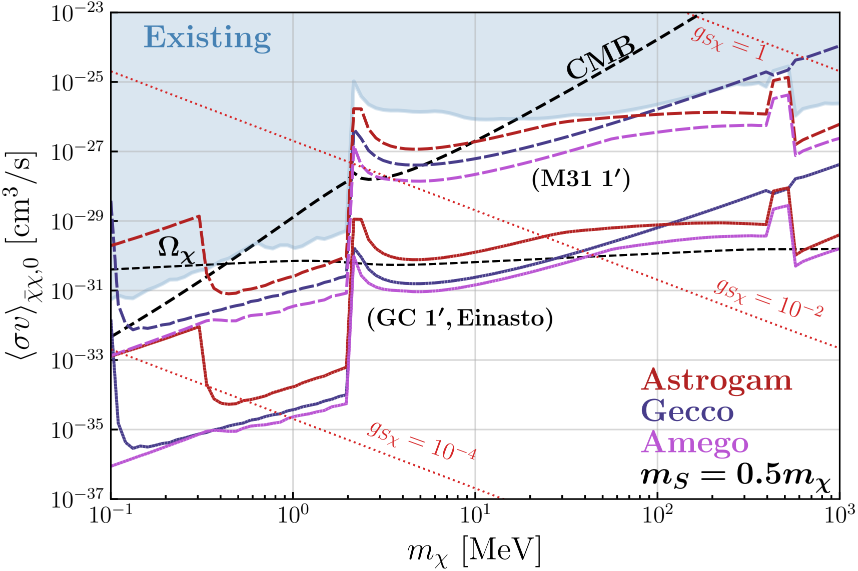
Constrianing



Constriangle



Higgs Portal Constraints



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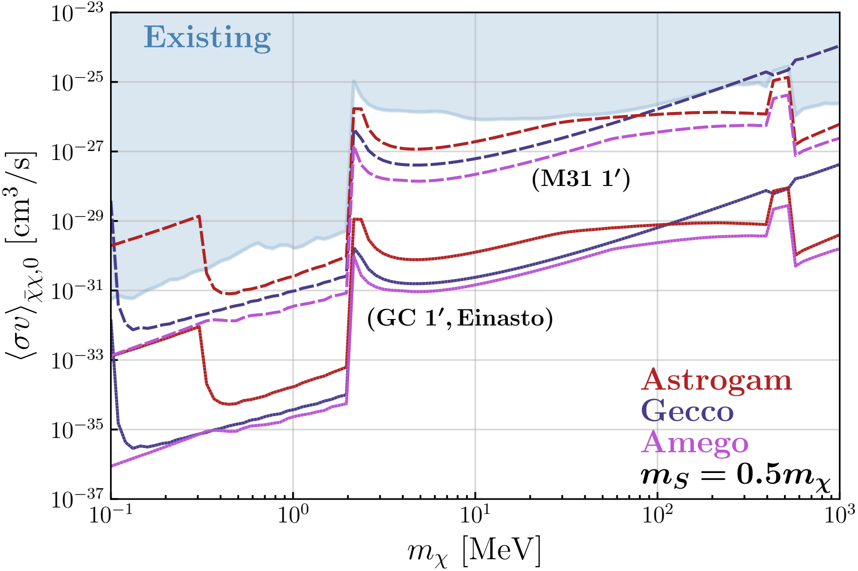

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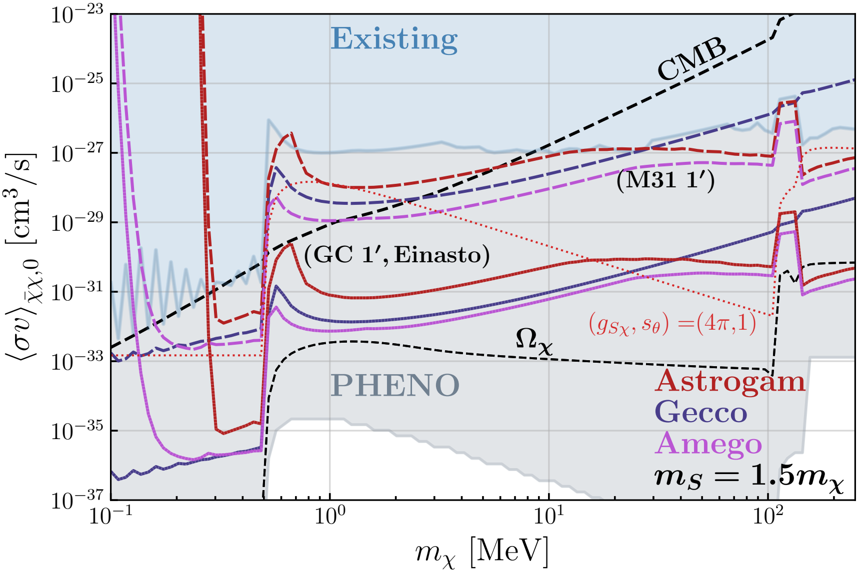
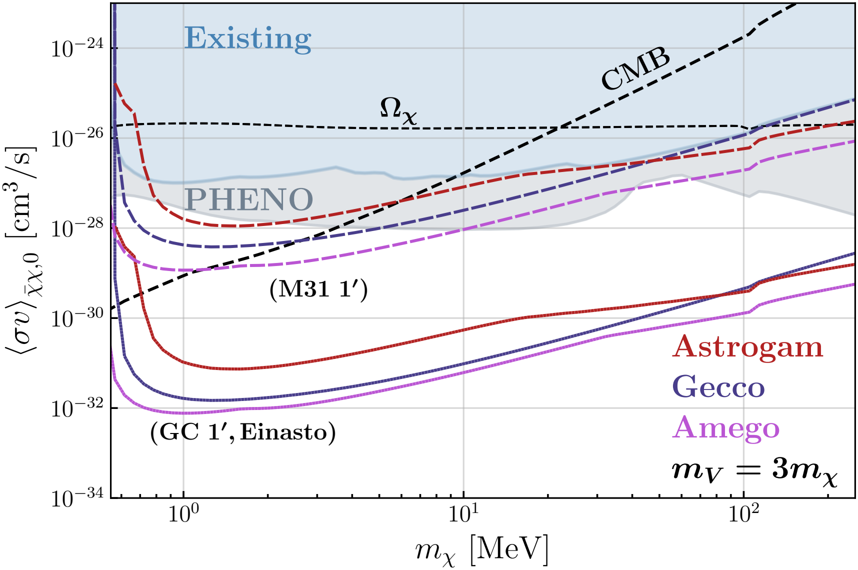
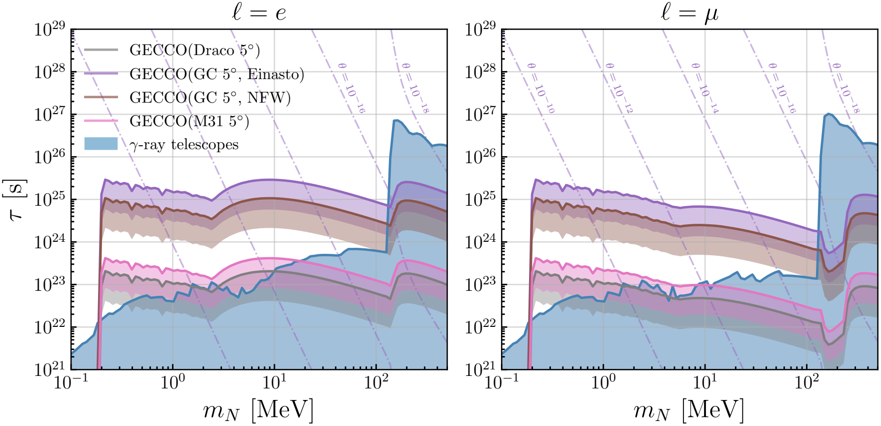


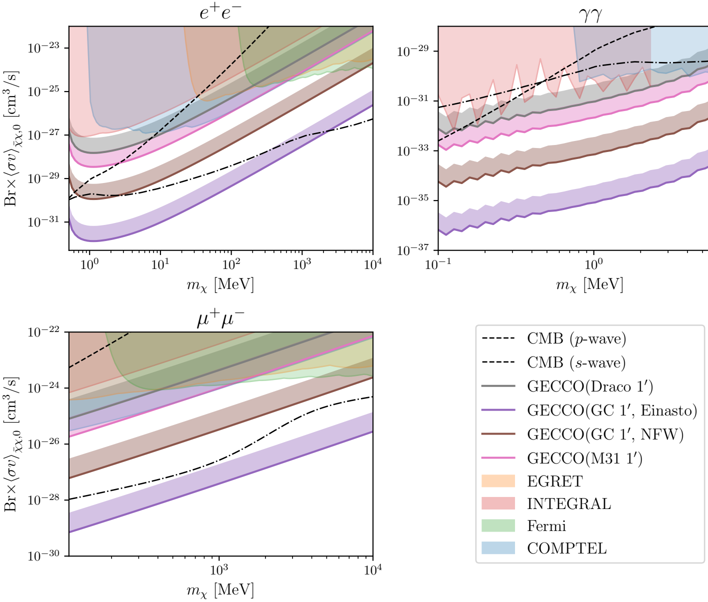
Kinetic Mixing Constraints



RH Neutrino Constraints



Model Independent Constraints



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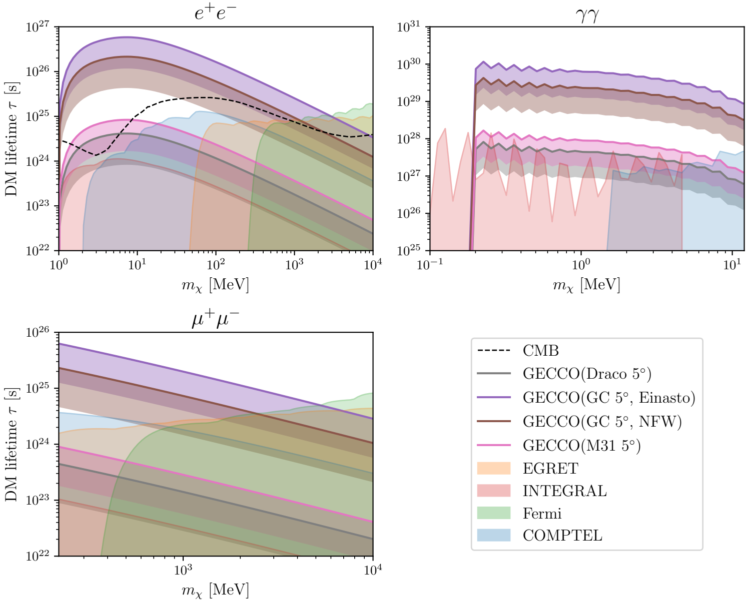

Primodial Black Holes

A. Coogan, S. Profumo, LM: arXiv:2010.04797
A. Coogan, S. Profumo, LM: arXiv:2101.10370

Hawking Radiation

1. Can MeV telescopes be used to probe Hawking radiation for PBH?

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$$\frac{\partial^2 N}{\partial E_i \partial t} = \frac{1}{2\pi}\frac{\Gamma(E_i, M)}{e^{E_i/T_H} - (-1)^{2s}}, \qquad T_H = \frac{M_{\text{pl}}^2}{8\pi M_H}$$

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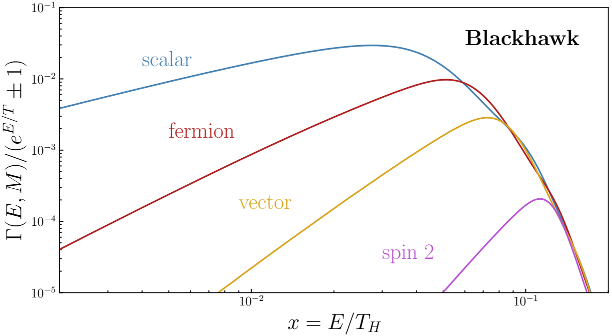

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3. Total photon spectrum

$$\frac{\partial^2 N}{\partial E_\gamma \partial t} = \frac{\partial^2 N_{\gamma,\text{primary}}}{\partial E_\gamma \partial t} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \int \mathrm{d}E_i \, \frac{\partial^2 N_{i,\text{primary}}}{\partial E_i \partial t} \frac{\mathrm{d}N_\gamma^{\text{FSR}}}{\mathrm{d}E_\gamma} + \sum_{i=\mu^\pm,\pi^0,\pi^\pm} \int \mathrm{d}E_i \, \frac{\partial^2 N_{i,\text{primary}}}{\partial E_i \partial t} \frac{\mathrm{d}N_\gamma^{\text{decay}}}{\mathrm{d}E_\gamma}$$

Hawking Radiation: Photon Spectrum

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Primary spectra:

$$\frac{\partial^2 N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t} = \frac{1}{2\pi} \frac{\Gamma(E_\gamma, M)}{e^{E_\gamma/T_H} - 1}$$

Hawking Radiation: Photon Spectrum

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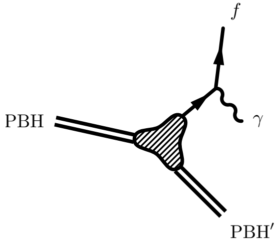
FSR: $(x = E_\gamma / E_i)$

$$\frac{\partial N_\gamma^{\text{FSR}}}{\partial E_\gamma} = \frac{\alpha_{\text{EM}}}{2\pi E_i} P_{\gamma \leftarrow i}(x) \left[\log\left(\frac{1-x}{\mu_i^2} \right) - 1 \right]$$

$$P_{\gamma \leftarrow i} = \begin{cases} \frac{2(1-x)}{x}, & i = \pi^\pm, \\ \frac{1+(1-x)^2}{x}, & i = e^\pm, \mu^\pm, \end{cases}$$



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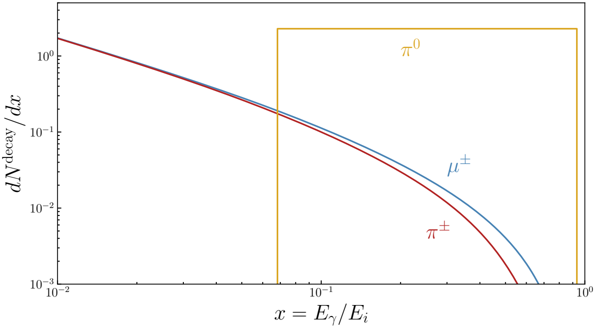
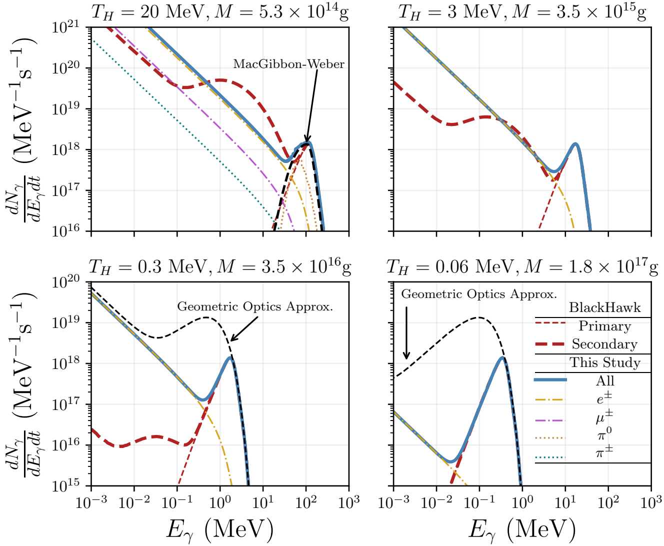
$$+ \sum_{i=\mu^\pm,\pi^0,\pi^\pm} \int \mathrm{d}E_i \, \frac{\partial^2 N_{i,\text{primary}}}{\partial E_i \partial t} \frac{\mathrm{d}N_\gamma^{\text{decay}}}{\mathrm{d}E_\gamma}$$



Hawking Radiation: Photon Spectrum



Constraining f_{PBH}

- Given a fraction of DM in the form of (monochromatic) PBHs $f_{\mathrm{PBH}} = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{CDM}}$ observed gamma-ray spectrum is:

$$\frac{\mathrm{d}\Phi_{\gamma}}{\mathrm{d}E_{\gamma}} = \frac{1}{4\pi}\int_{\mathrm{LOS}} \mathrm{d}\ell \, \frac{\partial^2 N_{\gamma}}{\partial E_{\gamma}\partial t} f_{\mathrm{PBH}} \frac{\rho_{\mathrm{DM}}}{M}$$

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- As with decaying DM, number of observed photons:

$$N_\gamma = T_{\mathrm{obs}} \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \mathrm{d}E_\gamma \, A_{\mathrm{eff}} \int \mathrm{d}\tilde{E}_\gamma \, R_\epsilon(E_\gamma, \tilde{E}_\gamma) \frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}$$

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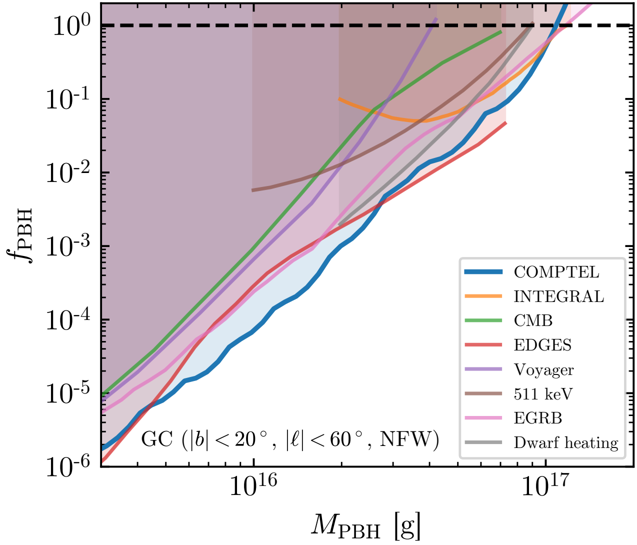
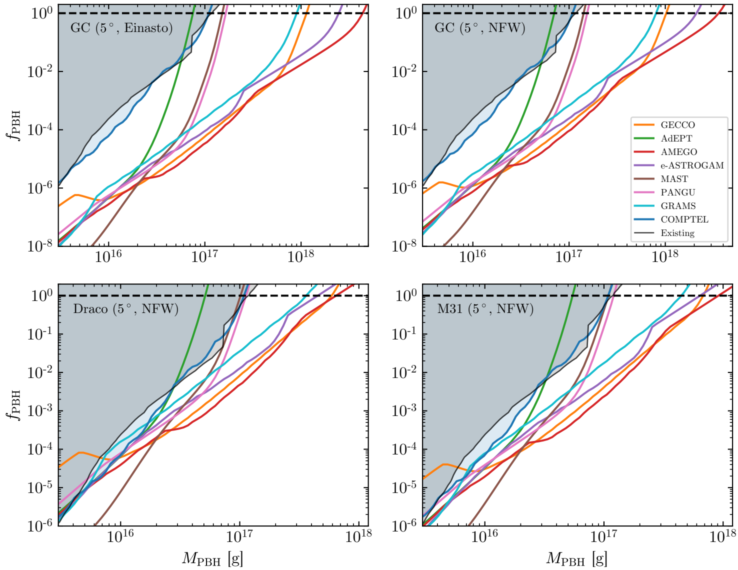


Constraining $f_{\rm PBH}$



Future Work

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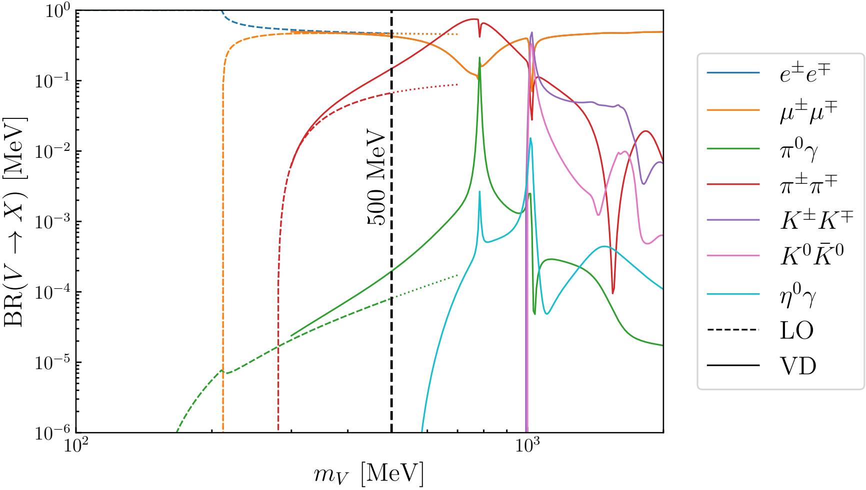
- How much does this change?

Extending Hazma to GeV



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Conclusions

- Without including non-pertubative effects, it is crucial to restrict use of chiral Lagrangian to $\sqrt{s} \lesssim 500$
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- **Hazma**: New open-source, user-friendly python package to explore/constrain MeV DM models
- Upcoming MeV telescopes could increase sensitivity to MeV DM models by factor ~ 100
- MeV telescopes could also detect Hawking radiation for $M_{\mathrm{PBH}} \sim 10^{15} - 10^{18}$ g

Thanks

Thanks to everyone who has helped and encouraged me throughout Graduate School...






Happy Holidays!

Honorable Mentions

Large-Nightmare
One-Loop Charge Breaking 2HDM
Asymptotic Analysis of Boltzmann Equation

Large-Nightmare Dark Matter

Stefano Profumo, Dean J. Robinson, LM: arXiv:2010.03586

Theory

- Consider an SU(N) gauge theory with a single dark (effectively massless, $m_{\tilde{q}} \ll \Lambda$) "quark"
- We take $N \gg 1$ and assume $g_{\text{dark}} \sim 1/\sqrt{N}$ (large-N limit)
- Two stable states: $\tilde{\eta}'$ ($\bar{q}q$) and $\tilde{\Delta}$ ($N\tilde{q}$)
- The $\tilde{\eta}'$ is very light while the $\tilde{\Delta}$ very heavy

State	Mass	Lifetime	$\mathrm{U}(1)_V$
$\tilde{\eta}'$	$\sim \Lambda/\sqrt{N}$	stable	0
$\tilde{\Delta}$	$\sim N\Lambda$	stable	N
$\tilde{\omega}$	$\sim \Lambda$	N^2/Λ	0
$\tilde{G}$	$\sim$ few Λ	N^2/Λ	0

Interactions

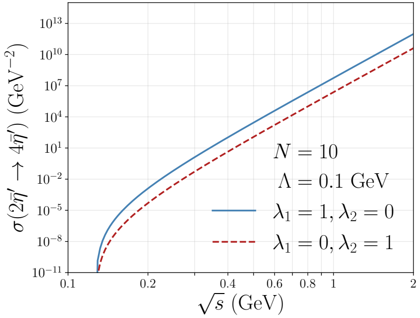
- Interactions for the $\tilde{\eta}$ are roughly:

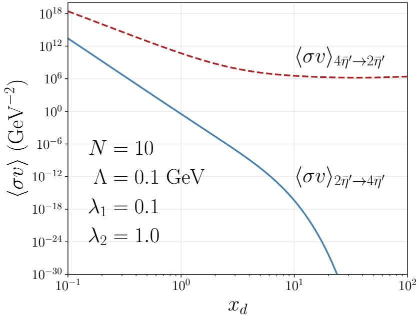
$$\sigma_{2\tilde{\eta}\to 2\tilde{\eta}}(s) \sim \frac{\pi^3 s^3 |\lambda_1|^2}{4\Lambda^8 N^2}, \qquad \sigma_{2\tilde{\eta}\to 4\tilde{\eta}}(s) \sim \frac{\pi^3 s^7}{48\Lambda^{16} N^4}\left|10\lambda_1^2 + \lambda_2\right|^2$$

- Interactions for the $\tilde{\Delta}$:

$$\sigma_{\tilde{\eta}\tilde{\eta}\to\bar{\tilde{\Delta}}\tilde{\Delta}}(s) \sim \frac{e^{-2cN}}{64\pi N^2 \Lambda^2}, \qquad \sigma_{\tilde{\Delta}\tilde{\Delta}\to\tilde{\Delta}\tilde{\Delta}}(s) \sim \frac{4\pi^3}{\Lambda^2}$$

Interactions





Thermal Evolution of Dark Sector

- If a theory is thermally decoupled from the SM, it may have a different temperature
- Total entropy in dark and SM sector will be conserved
- Ratios of entropies densities are then constant:

$$\text{const} = \frac{s_d}{s_{\text{SM}}} = \frac{h_d(T_d)T_d^3}{h_{\text{SM}}(T_{\text{SM}})T_{\text{SM}}^3}$$

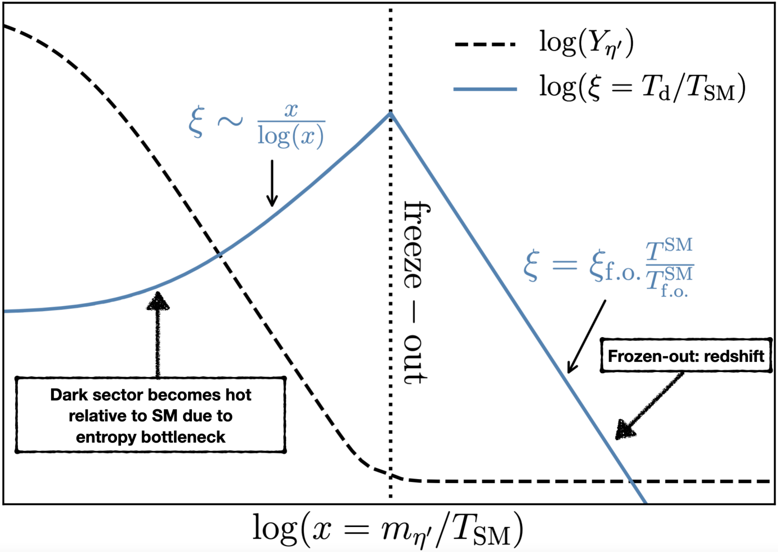
- We can determine dark temperature at late times if we know ratio at some early time

$$\xi(T_{\text{SM}}) \equiv \frac{T_d}{T_{\text{SM}}} = \left(\frac{h_{\text{SM}}}{h_{\text{SM}}^{\infty}} \frac{h_d^{\infty}}{h_d(\xi T_{\text{SM}})}\right)^{1/3} \xi^{\infty}$$

- As long as dark sector is in thermal equillibrium, it becomes exponetially hot relative to SM bath

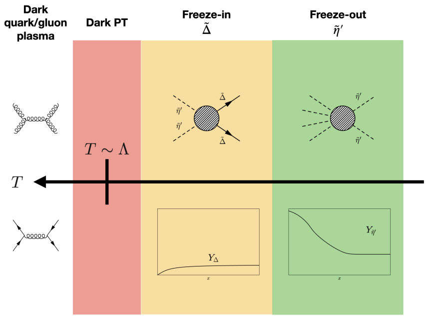
$$h(x = m/T) \sim x^3 K_3(x) \sim x^{5/2} x^{-x}, \qquad (x \to \infty)$$

Thermal Evolution of Dark Sector



Cosmic Evolution

1. High temperatures: dark quark-gluon plasma
2. $T \sim \Lambda$: dark quark and gluons confine to $\tilde{\eta}'$ and $\tilde{\Delta}$
3. n_{Δ} initially suppress due to difficulty in forming
4. $\tilde{\Delta}$s are frozen in via $2\tilde{\eta}' \to \bar{\tilde{\Delta}}\tilde{\Delta}$
5. $\tilde{\eta}'$ annihilate via $4\tilde{\eta}' \to 2\tilde{\eta}'$



Experimental Handels

- Measurements from bullet cluster and shapes of halos put tight constraints on self-interaction cross section

$$\sigma_{\mathrm{SI}} \lesssim \frac{\mathrm{barn}}{\mathrm{GeV}}$$

- BBN and CMB constrain the effective number of neutrino constraints:

$$\Delta N_{\mathrm{eff}} < 0.3$$

- If the $\tilde{\eta}'$ is in equilibrium for too long, we affect N_{eff}

$$N_{\mathrm{eff}}^{\mathrm{CMB}} \sim 3.046 + \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g_d^{\mathrm{CMB}} \xi_{\mathrm{CMB}}^4, \quad N_{\mathrm{eff}}^{\mathrm{BBN}} \sim 3 + \frac{4}{7} g_d^{\mathrm{BBN}} \xi_{\mathrm{BBN}}^4$$

Relic Densities

- $\tilde{\eta}'$ relic density can be approximated using entropy conservation and instantaneous freeze-out

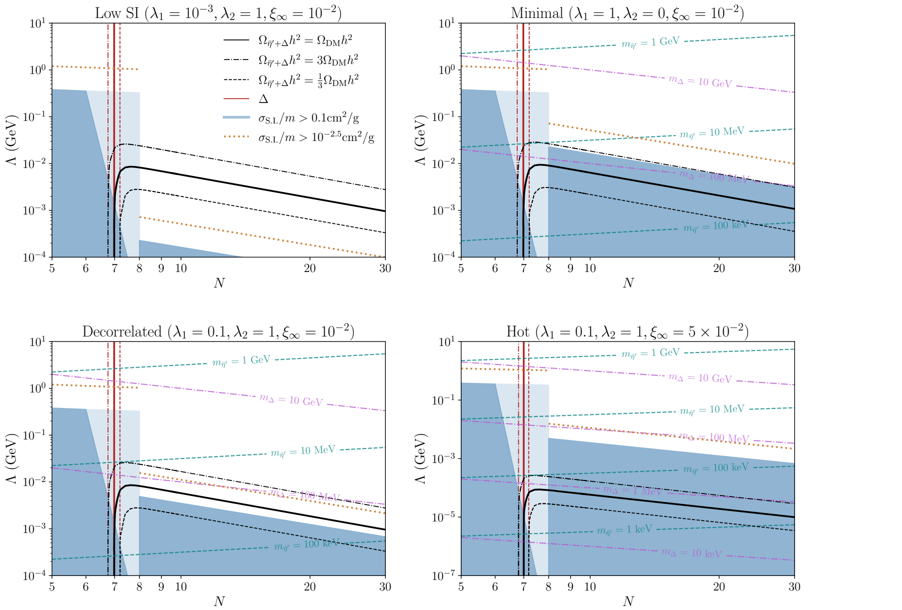
$$r_s = \frac{h_d}{h_{\mathrm{SM}}}\xi^3 \sim \frac{N^2}{100}\xi_\infty^3, \qquad Y_{\tilde{\eta}'} \sim \frac{n_{\tilde{\eta}'}}{s_{\mathrm{SM}}} = \frac{r_s}{x^{d,f}}$$

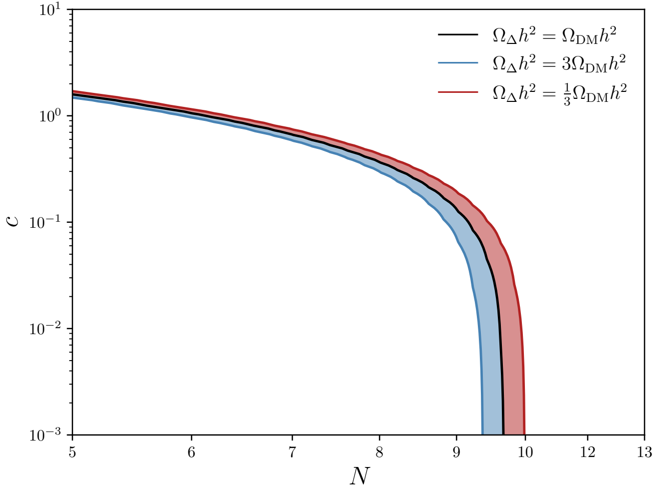
- Putting together:

$$\Omega_{\tilde{\eta}'} h^2 \sim 0.12 \left(\frac{10}{x_{d,f}+1}\right)\left(\frac{\xi_\infty}{10^{-2}}\right)^3 \left(\frac{\Lambda}{20\ \mathrm{MeV}}\right)\left(\frac{N}{10}\right)^{3/2}$$

- $\tilde{\Delta}$ relic density from direct integration of Boltzmann equation:

$$\Omega_{\tilde{\Delta}} h^2 \sim (\text{const.}) N^{3/2} e^{-2(c+1)N}$$


Low SI ($\lambda_1 = 10^{-3}, \lambda_2 = 1, \xi_\infty = 10^{-2}$)
$\Omega_{\bar{\eta}'+\Delta}h^2 = \Omega_{\mathrm{DM}}h^2$
$\Omega_{\bar{\eta}'+\Delta}h^2 = 3\Omega_{\mathrm{DM}}h^2$
$\Omega_{\bar{\eta}'+\Delta}h^2 = \frac{1}{3}\Omega_{\mathrm{DM}}h^2$
Δ
$\sigma_{\mathrm{S.I.}}/m > 0.1\mathrm{cm}^2/\mathrm{g}$
$\sigma_{\mathrm{S.I.}}/m > 10^{-2.5}\mathrm{cm}^2/\mathrm{g}$
Λ (GeV)
N
Minimal ($\lambda_1 = 1, \lambda_2 = 0, \xi_\infty = 10^{-2}$)
$m_{\bar{\eta}'} = 1$ GeV
$m_\Delta = 10$ GeV
$m_{\bar{\eta}'} = 10$ MeV
$m_\Delta = 100$ MeV
$m_{\bar{\eta}'} = 100$ keV
Decorrelated ($\lambda_1 = 0.1, \lambda_2 = 1, \xi_\infty = 10^{-2}$)
Hot ($\lambda_1 = 0.1, \lambda_2 = 1, \xi_\infty = 5 \times 10^{-2}$)
$m_\Delta = 1$ MeV
$m_{\bar{\eta}'} = 1$ keV
$m_\Delta = 10$ keV



10^1
10^0
10^{-1}
10^{-2}
10^{-3}
c
5
6
7
8
9
10
12
13
N
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One-Loop Charge-Breaking Minima in the Two-Higgs Doublet Model

Pedro Ferreira, Stefano Profumo, LM: arXiv:1910.08662

Tree-Level Charge-Breaking Minima in the THDM

- Possible to show that tree-level THDM potential with softly broken $\mathbb{Z}_2$ yeilds either an EW or CB minimum, **but not both**

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&+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
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$$

$$
\text{CB}: \qquad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}\alpha\\ \bar{v}_1\end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \bar{v}_2\end{pmatrix}
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- Does this hold at 1-loop?

One-Loop Corrections

- One-loop corrections are included using the effective potential:

$$
\begin{aligned}
V_{\mathrm{eff}}(\bar{\phi}) &= V_{\mathrm{tree}}(\bar{\phi}) \\
&\quad + \frac{\hbar}{64\pi^2}\sum_i (-1)^{2s_i} n_i \left[M_i^2(\bar{\phi})\right]^2 \left[\log\left(\frac{M_i^2(\bar{\phi})}{\mu^2}\right) - c_i\right]
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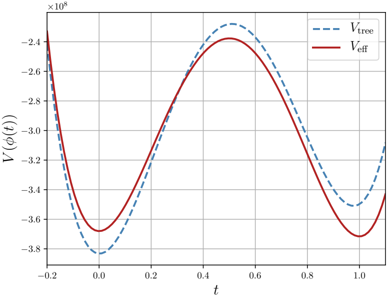
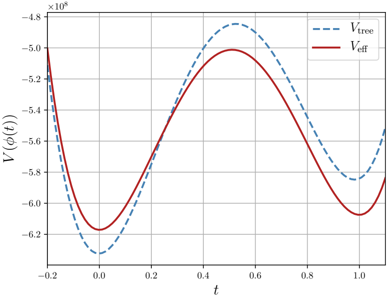
- Results: **there exists parameters with simultaneous CB and EW minima**
- Tend to occur when $V_{\text{CB}} \sim V_{\text{EW}}$

One dimensional slices of the effective scalar potential

$$\phi(t) = (1-t)\phi_{\text{EW}} + t\phi_{\text{CB}}$$
$$\phi(0) = \phi_{\text{EW}}, \quad \phi(1) = \phi_{\text{CB}}$$

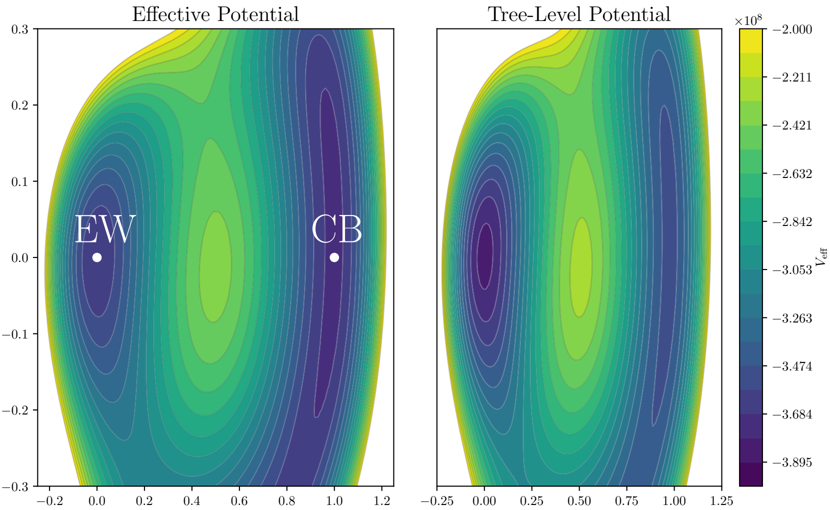


(a) $V_{\text{eff}}(\phi_{\text{EW}}) < V_{\text{eff}}(\phi_{\text{CB}})$



(b) $V_{\text{eff}}(\phi_{\text{CB}}) < V_{\text{eff}}(\phi_{\text{EW}})$

$V_{\text{eff}}(\phi_{CB}) < V_{\text{eff}}(\phi_{EW})$



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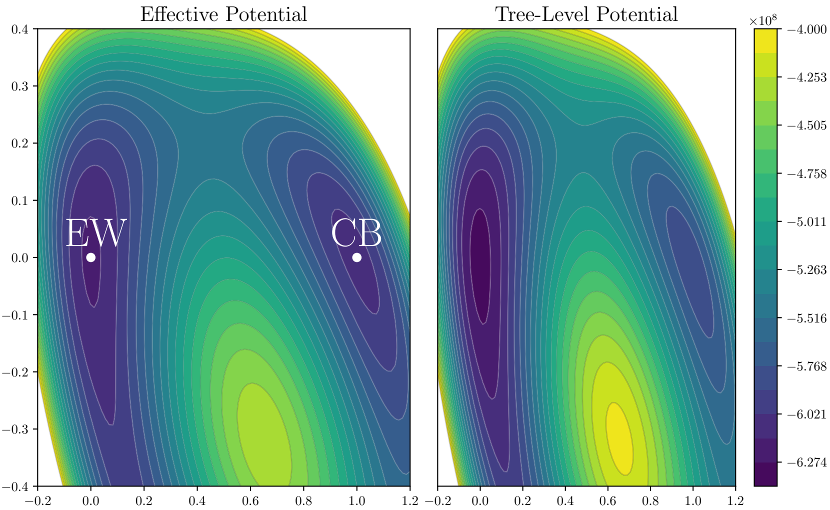

Asymptotic analysis of the Boltzmann equation for dark matter relic abundance

Hiren H. Patel, Jaryd F. Ulbricht, LM: arXiv:2009.04012

Asymptotic Analysis of the Boltzmann Equation

1. Dark Matter relic abundance determined using first moment of Boltzmann equation

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = -\lambda f(x)\left[Y^2 - Y_{\mathrm{eq}}\right],$$
$$\lambda f(x) = \sqrt{\frac{\pi}{45}}\frac{m_\chi M_{\mathrm{pl}}}{x^2}\frac{h}{\sqrt{g}}\left(1 + \frac{1}{3h}\frac{\mathrm{d}h}{\mathrm{d}x}\right)\langle\sigma v_{\mathrm{M\o l}}\rangle$$

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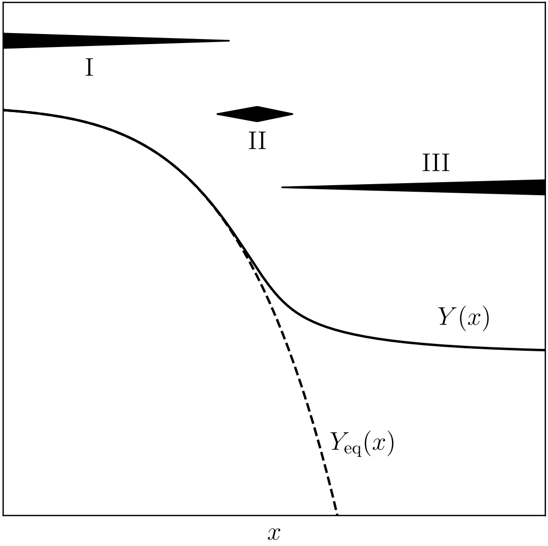
3. Standard analysis of Gondolo, Gemini makes estimating errors in appoximations difficult
4. Asymptotic analysis gives method for arbitrary accurate results with error estimates

Asymptotic Analysis of the Boltzmann Equation



Asymptotic Analysis of the Boltzmann Equation