Dark matter pions

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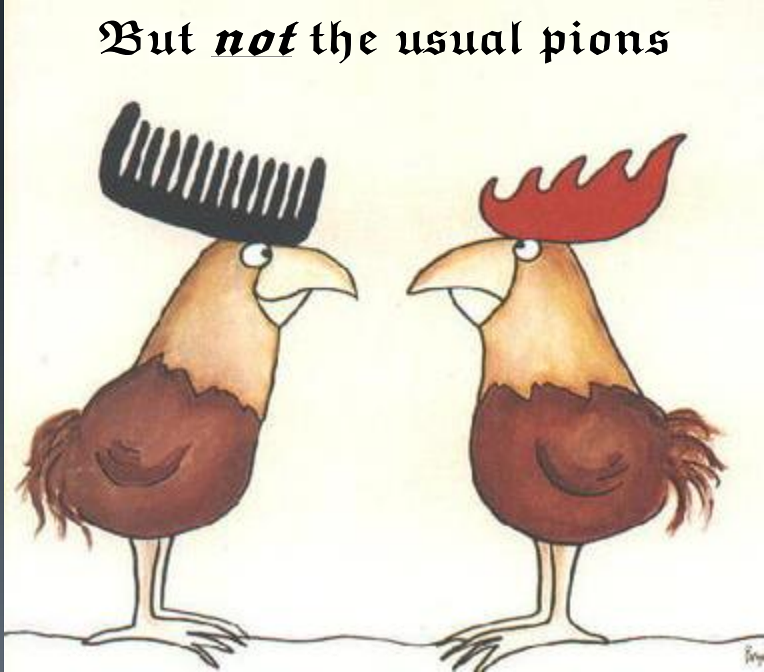
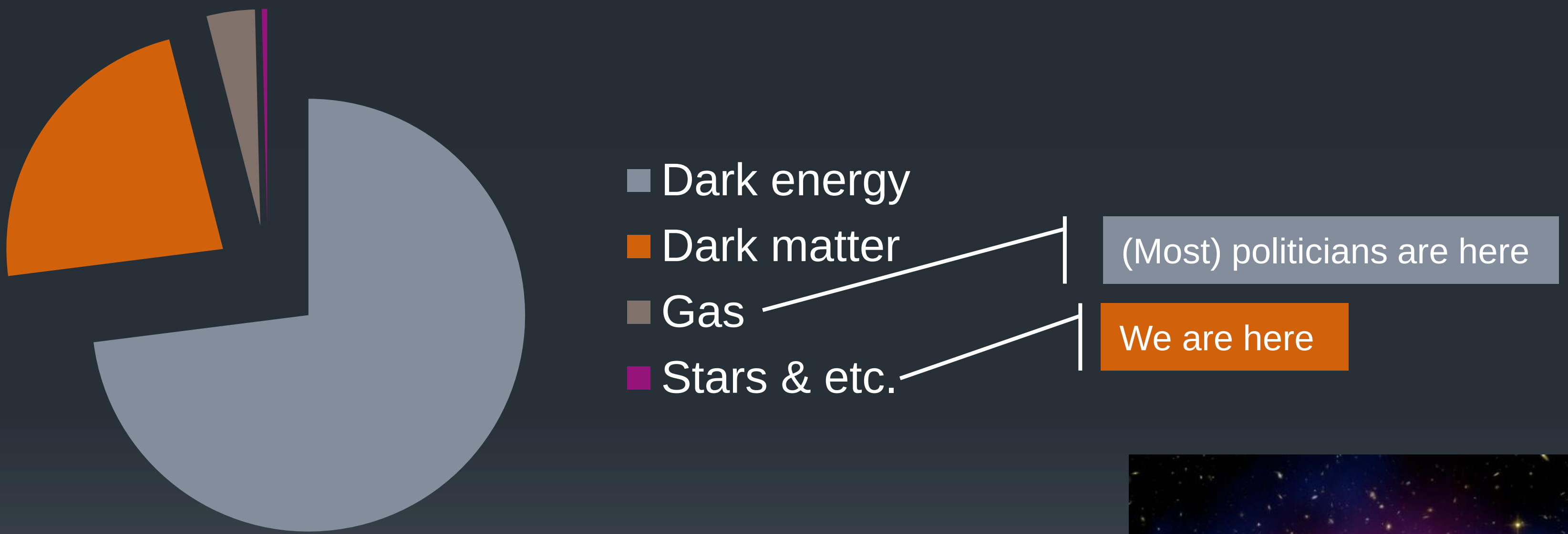


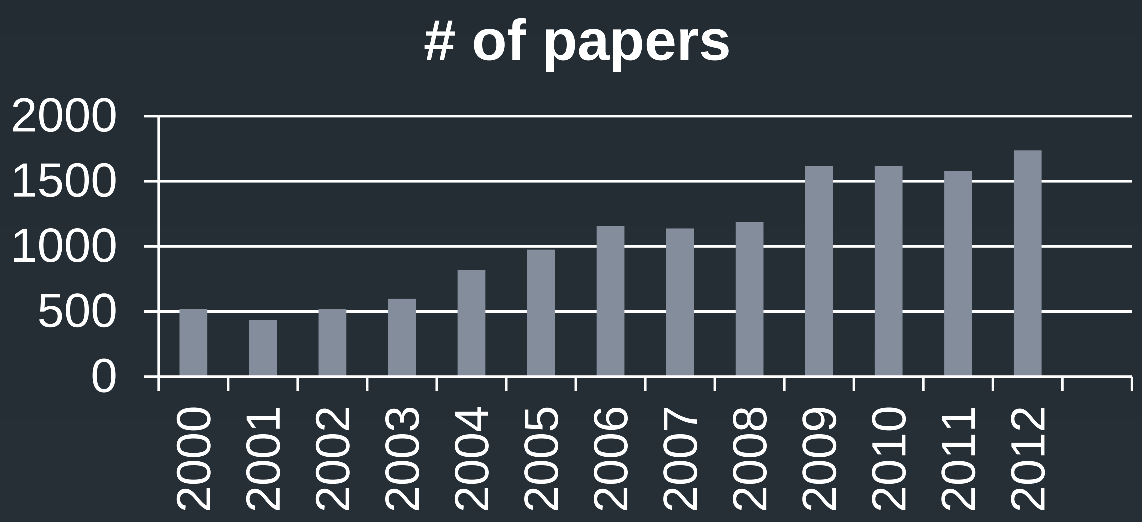
Introduction

- DM makes ~ 23% of the mass-energy content of the universe



- No direct evidence, only gravitational footprints

- Enormous interest in the community:



- Many models:
  - SUSY based (DM = LSP)
  - Higher dimensional models (a first KK mode)
  - SM extensions (anything stabilized by a symmetry)

- Also: a phenomenological approach:

$$\mathcal{L}_{\mathrm{DM}\times\mathrm{SM}} \sim \mathcal{O}_{\mathrm{DM}} \times \mathcal{O}_{\mathrm{SM}}$$

The model

Dark sector

mediators

SM sector

Many particles

Assumptions:

- DM = the lightest dark particle
- **DM = a (pseudo) Goldstone boson (a scalar for simplicity)**
- All dark particles are SM-gauge singlets

Assumed heavy & not observed

$$\mathcal{L}_{\mathrm{DM}\times\mathrm{SM}} \sim \mathcal{O}_{\mathrm{DM}} \times \mathcal{O}_{\mathrm{SM}}$$

- Construct the lowest dimensional operators using the DM bosons
- Construct the lowest dimensional operators using the SM fields

Lowest-dimensional SM operators: **$|\phi|^2$** **$B_{\mu\nu}$**

$\Rightarrow$ Effective Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm DM} + |\phi|^2 \mathcal{O}_{\rm DM} + B_{\mu\nu} \mathcal{O}_{\rm DM}^{\mu\nu}$$

Non-linear σ model
For simplicity:
$SU(N)_L \times SU(N)_R$

- Need a mass term for the DM pions:
  (dark chiral symmetry explicitly broken) to $SU(N)_V$
- $\Rightarrow$ Require the dark effective operators to be $SU(N)_V$ invariant

- Dark pion field:

$$\Sigma = \exp(i\pi_a T^a/f).$$

- Conventions
  - $\mathrm{tr}\{T_a T_b\} = \delta_{ab}$.
  - $[T_a, T_b] = i f_{ab}{}^c T_c$.
  - f = dark-pion decay constant (units of mass).

- Dark-pion Lagrangian

$$\mathcal{L}_{\mathrm{DM}} = f^2\,\mathrm{tr}\{\partial_\mu \Sigma^\dagger\,\partial^\mu \Sigma\} + \frac{1}{2} f^2\left(M^2 \mathrm{tr}\Sigma + \mathrm{H.c.}\right).$$

- DM-SM interactions

$$\begin{aligned}\mathcal{L}_{\rm int} &= \frac{1}{2}\lambda_h \left(|\phi|^2 - v^2\right) {\rm tr}\left\{\partial_\mu \Sigma^\dagger \, \partial^\mu \Sigma\right\} \\ &\quad + B^{\mu\nu}\left(\lambda_V {\rm tr}\left\{\Sigma^\dagger \partial_\mu \Sigma \, \partial_\nu \Sigma^\dagger\right\} + {\rm H.c.}\right) . \\ &\quad + \frac{1}{2} f^2 \lambda_h' \left(|\phi|^2 - v^2\right)\left({\rm tr}\Sigma + {\rm H.c.}\right)\end{aligned}$$

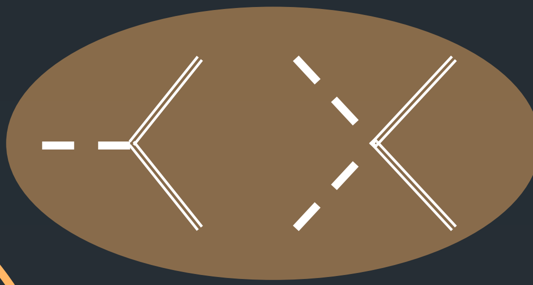
where $v = \langle \phi \rangle \sim 174$ GeV

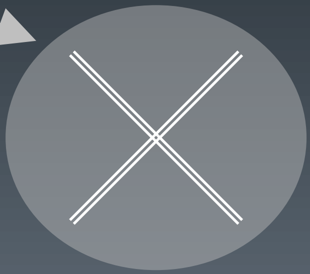
- The first term: full $SU(N)_L \times SU(N)_R$ invariant
- The other two terms invariant under the diagonal $SU(N)_V$
- The π_a are triplets under $SU(N)_V$

- Expansion in powers of the π:
  - π-h interactions
  - π-Z/γ interactions
  - π-π interactions

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial\boldsymbol{\pi})^2 - \frac{1}{2}M^2\boldsymbol{\pi}^2 \\ &+\frac{\lambda_h}{f^2}\left(\frac{vh}{\sqrt{2}}(\partial\boldsymbol{\pi})^2 + \frac{1}{4}h^2(\partial\boldsymbol{\pi})^2\right) \\ &+\lambda_h'\left(\frac{vh}{\sqrt{2}}\boldsymbol{\pi}^2 + \frac{1}{4}h^2\boldsymbol{\pi}^2\right) \\ &-\frac{\lambda_V}{f^3}B^{\mu\nu}f_{abc}\partial_\mu\pi_a\,\partial_\nu\pi_b\,\pi_c \\ &+\frac{N}{16f^2(N^2-2)}\left[(\partial\boldsymbol{\pi}^2)^2 - \mu^2(\boldsymbol{\pi}^2)^2\right]\end{aligned}$$

Usual Higgs portal coupling





$$\mu^2 = \frac{6N^2-4}{N^2(N^2+1)}M^2$$

Thermal History

- Boltzmann equation

$$\begin{aligned} \dot{n}_a + 3Hn_a &= -\mathcal{C}_a\,, \\ \mathcal{C}_a &= \sum_{b,c,d} \int d\Phi |\mathcal{A}_{a+b\to c+d}|^2 (f_a f_b - f_c f_d)\,, \\ d\Phi &= d\Pi_a\, d\Pi_b\, d\Pi_c\, d\Pi_d (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d)\,, \end{aligned}$$

- Neglect quantum statistics
- Assume SM remains in equilibrium
- Write the BE in terms of: **Y = n/s (s = entropy density)**
- Simplify to the case N=2: $\pi_\pm$, π_o
  - One conserved charge: **$q = Y_- - Y_+$**

  $\Rightarrow$ need only equation for Y_+ and Y_o

- Explicitly:

$$\frac{dY_r}{dx} = -\sqrt{\frac{\pi g(T)}{45G}}\frac{M}{x^2}C_r(Y)\,, \qquad C_r(Y) = \frac{1}{s^2}\mathcal{C}_r\,, \qquad (r = o, \pm)$$

with **x = M/T**

- Collision terms

$$\begin{aligned} C_o(Y) &= \left(Y_o^2 - {Y_o^{(\mathrm{eq})}}^2\right)\langle\sigma v\rangle_{\pi_o\pi_o\to SM} + \left(Y_o^2 - Y_+Y_-\right)\langle\sigma v\rangle_{\pi_o\pi_o\to\pi_+\pi_-} \\ &\quad + \left[Y_oY_o^{(\mathrm{eq})} - Y_+Y_- + (Y_+ + Y_-)(Y_o - Y_o^{(\mathrm{eq})})\right]\langle\sigma v\rangle_{\pi_+\pi_-\to\pi_oV}\,, \end{aligned}$$

$$\begin{aligned} C_\pm(Y) &= \left(Y_+Y_- - {Y_o^{(\mathrm{eq})}}^2\right)\langle\sigma v\rangle_{\pi_o\pi_o\to SM} + \left(Y_+Y_- - Y_o^2\right)\langle\sigma v\rangle_{\pi_+\pi_-\to\pi_o\pi_o} \\ &\quad + \left(Y_+Y_- - Y_oY_o^{(\mathrm{eq})}\right)\langle\sigma v\rangle_{\pi_+\pi_-\to\pi_oV}\,, \end{aligned}$$

- Boundary conditions: $Y \to Y^{eq}$ as $x \to 1$
- For $q \neq 0$ use

$$\begin{aligned} Y_t &= Y_o + Y_+ + Y_- \,, \\ Y_d &= \frac{Y_+ + Y_-}{2} - Y_o \,, \\ q &= Y_- - Y_+ \end{aligned}$$

- Abundance: given by Y_t; its BE is even under $q \leftrightarrow -q$ and

$$\left.\left(\frac{\partial Y_t}{\partial q^2}\right)_{q=0}\right|_{x=x_i} > 0 \quad \text{and} \quad \frac{d}{dx}\left(\frac{\partial Y_t}{\partial q^2}\right)_{q=0} > 0$$

$$\Rightarrow \quad Y_t(q=0,x) < Y_t(q \neq 0, x)$$

$$\Rightarrow \Omega_{\rm DM}(f, M, \lambda_h, \lambda_V; q=0) < \Omega_{\rm DM}(f, M, \lambda_h, \lambda_V; q) \,.$$

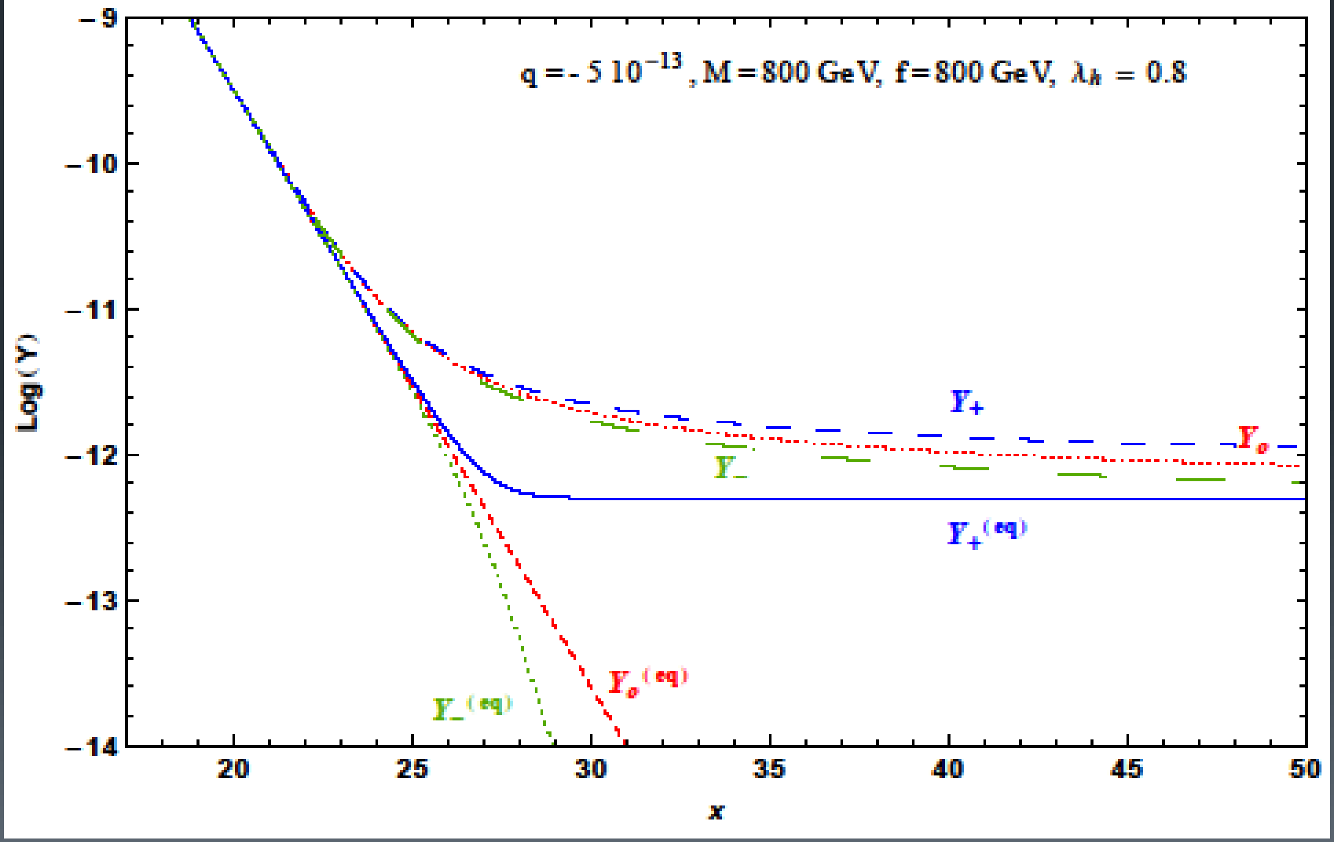
- The WMAP/PLANCK constraint is then

$$\Omega_{DM}(f, M, \lambda_h, \lambda_V; q=0) < \Omega_{\rm CDM} \,.$$

- Numerically
  - q < 10^{-13} : irrelevant
  - q > 10^{-12} : dominates Ω_{DMP}:

$$\frac{3.4\times 10^{-10}}{M/\mathrm{GeV}} < |q| < \frac{4.7\times 10^{-10}}{M/\mathrm{GeV}} \qquad M < 100\mathrm{GeV}$$

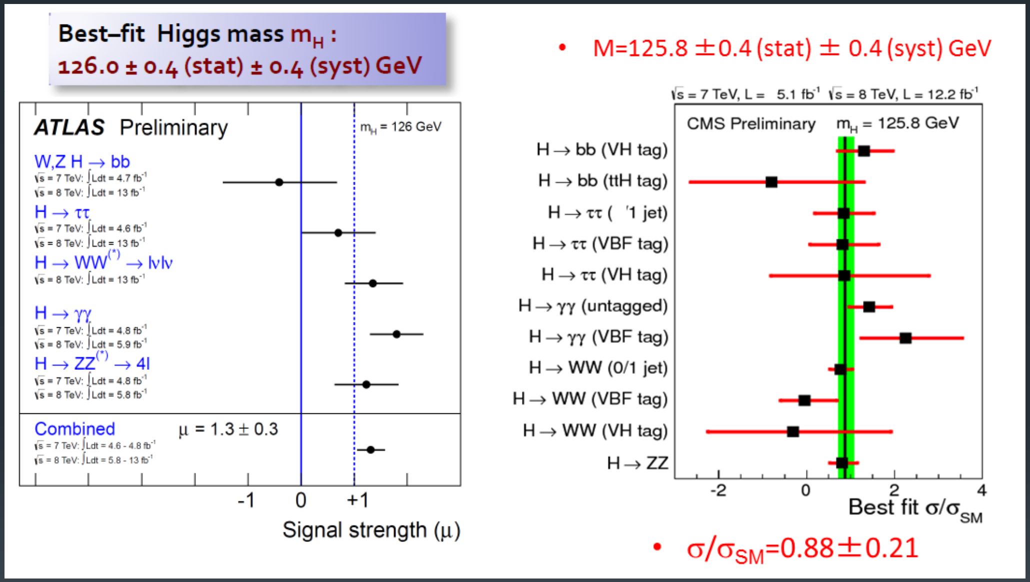
  - q: 10^{-12} to 10^{-13} : same order as Y



Constraints on the model

- No large deviations in Higgs decays: $\Gamma(h \to \pi\,\pi) < 4$ MeV

$$f > 5.9|\lambda_h|^{1/2}|7812.5 - M^2|^{1/2}\left[1-(M/62.5)^2\right]^{1/8} \qquad (M < 62.5\ [\mathrm{GeV}])$$



- Perturbativity (consistency of the model)

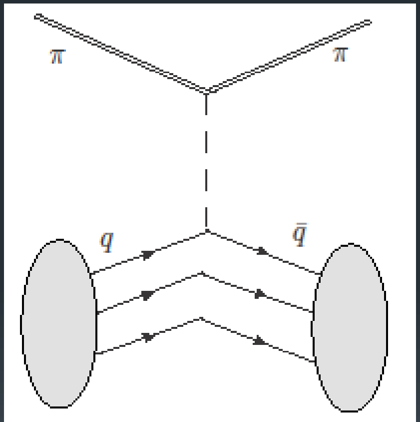
$$f \geq \max\{\sqrt{4\pi\lambda_V}\,,\,1\}\frac{M}{4\pi}$$

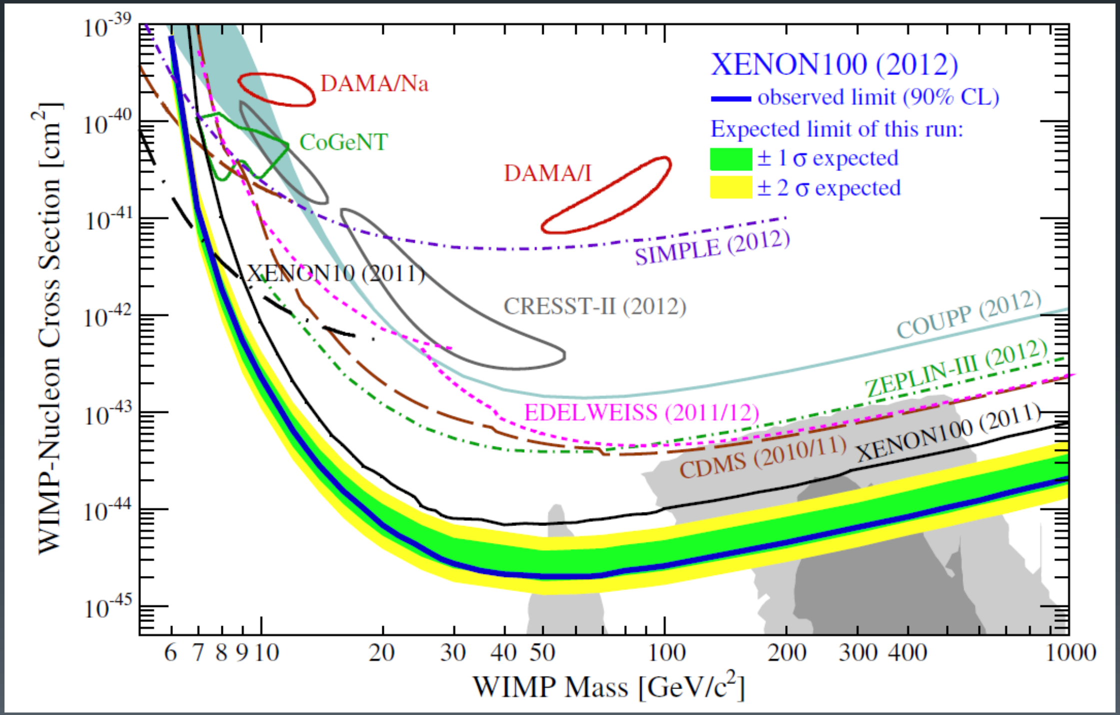
- CMD: $0.094 \leq \Omega_{DM} h^2 \leq 0.130$

$$4.04 \times 10^{-7} \cdot \left(\frac{\lambda_h M}{f^2}\right)^2 + 0.93 \left(\frac{\lambda_V M^2}{f^3}\right)^2 \cdot 5.59 \times 10^{-7} \delta_{q,0}$$

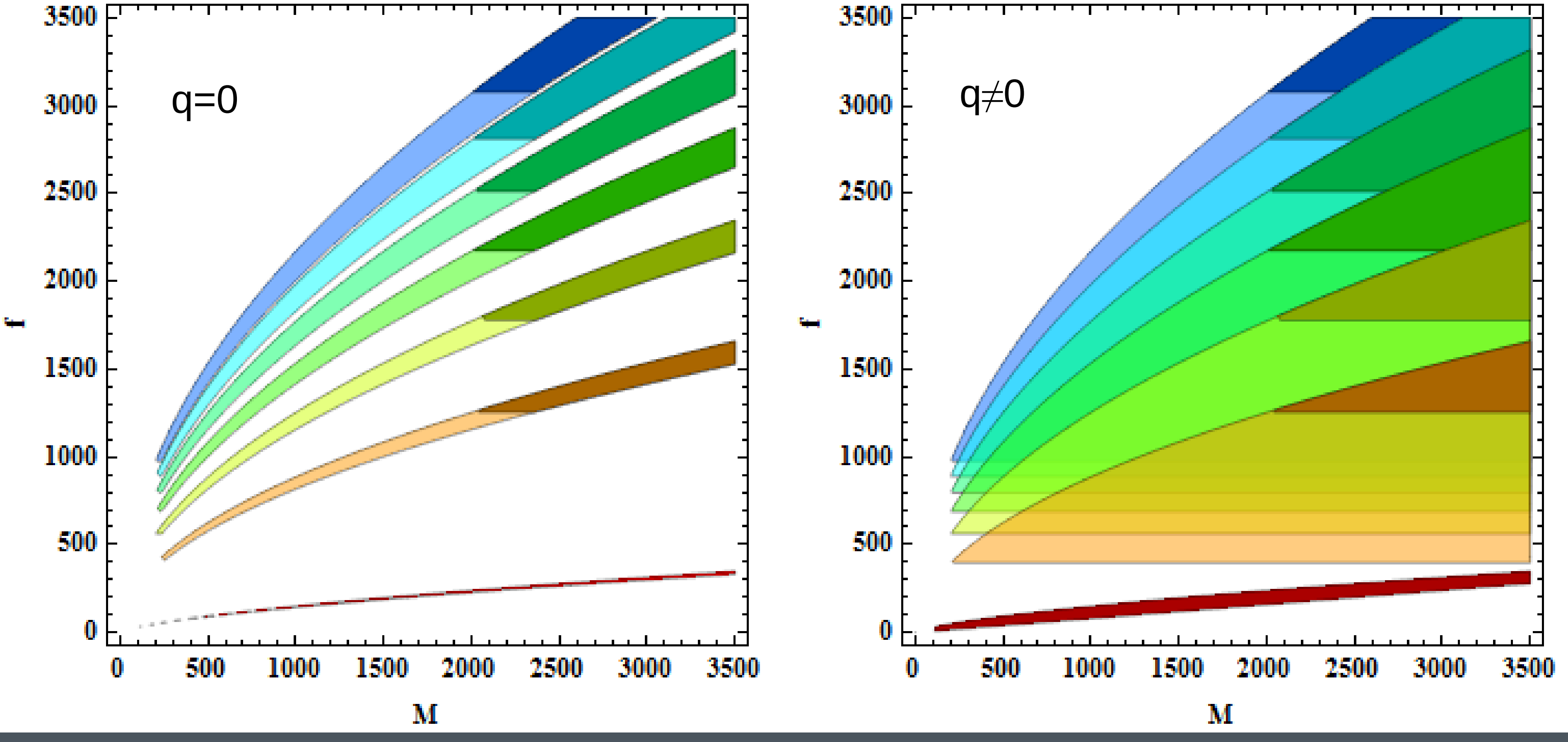
- Direct detection:XENON100 sees nothing (no explanation for DAMA/LIBRA)

$$f > 562.3 |\lambda_h|^{1/2}$$





Combined results: colored regions allowed by XENON100 (darker: XENON1T projected allowed regions)



$\lambda_V = 0.0023$ and $\lambda_h = 0, 0.5, \ldots 3$

Conclusions

- The model works in wide ranges of parameter space
- Y_∞ is M-dependent
- Nice scaling behavior in Ω: depends on only on the combinations:

$$\lambda_h M / f^2 \qquad \text{and} \qquad \lambda_V M^2 / f^3$$

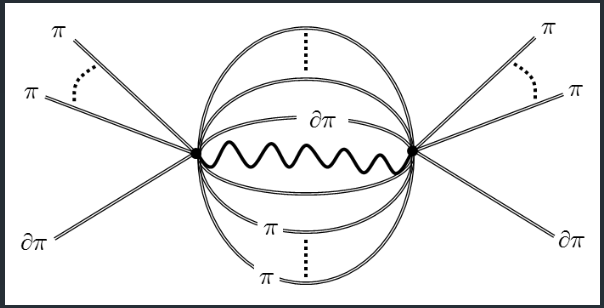
- Low M region require $\lambda_h \ll 1$ (and there is a $Z \to 3\pi$ constraint)
- No easy explanation for the DAMA/LIBRA effects

Thank you!

Extra slides

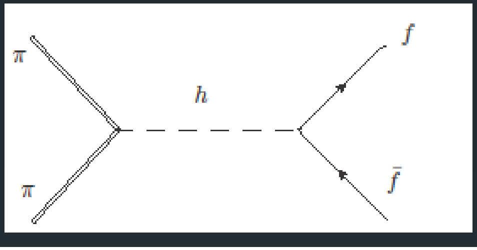
Some details

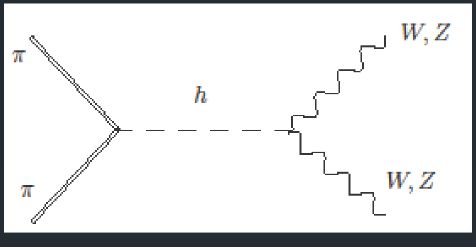
- χ pert theory: 4 π f $\geq$ [max{ 4 π λ_V , 1 }]$^{1/2}$ M

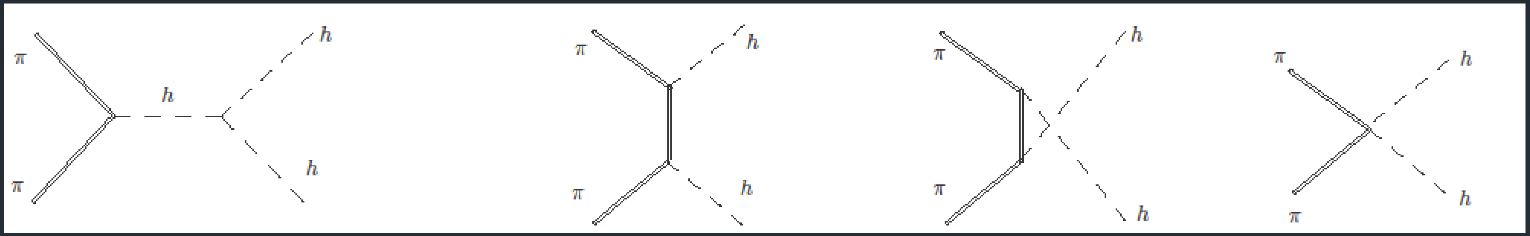


- Mild constraints from h $\to \pi\pi$ and Z $\to \pi\pi\pi$
- Ineractions w/SM via
  - **π Z $\leftrightarrow \pi\pi$**
  - **$\pi\pi \leftrightarrow$ h* $\to$ WW, ZZ, hh, ff**
  - **$\pi\pi \leftrightarrow$ hh** (via t-channel π and contact interactions)
- We ignore the portal interaction (well studied already)
- Exact chiral symmetry $\to$ N conserved currents

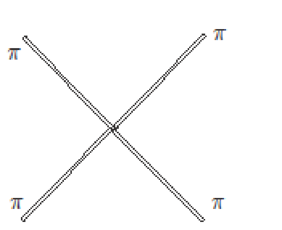
- $\pi\ \pi \to$ SM reactions







- $\pi\pi \to \pi\ \pi$ reactions



- $\pi\pi \to$ Z/γ π reactions