Dark Meson Dark Matter

Ennio Salvioni

CERN

DESY Zeuthen/Humboldt Theory Seminar

June 18, 2020

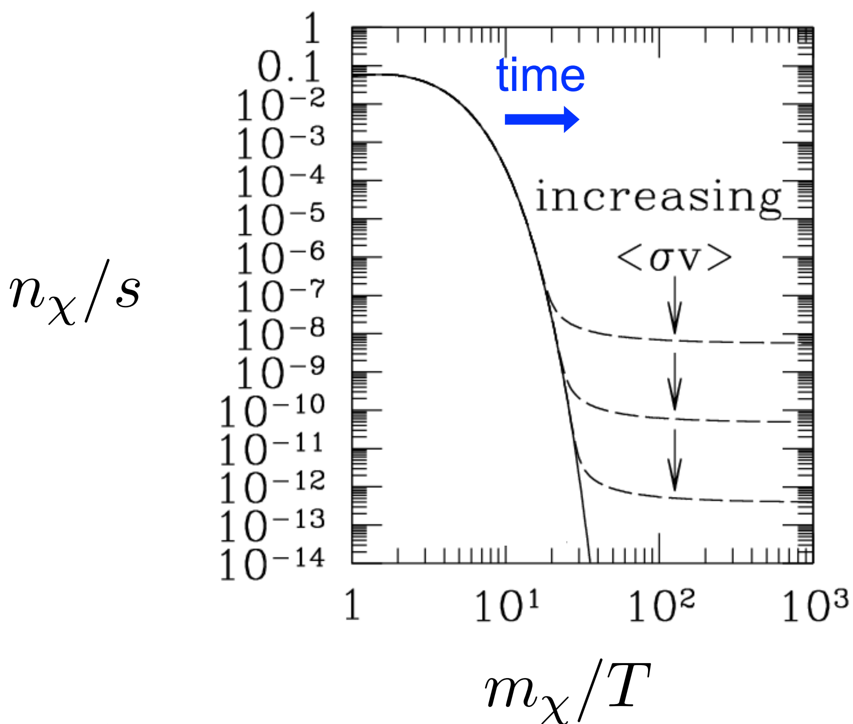
2006.xxxxx with A. Katz, B. Shakya

1809.09106, 1910.04170 + ongoing with A. Weiler, M. Ruhdorfer, R. Balkin, …

Introduction

- Old & compelling idea: the Dark Matter is a weakly interacting massive particle

  The "WIMP paradigm," also strong ties to hierarchy problem



Thermal freeze-out:

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{\pi m_\chi^2}{\lambda^2}$$

$$\frac{\Omega_\chi h^2}{0.1} \sim \left(\frac{0.1}{\lambda}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

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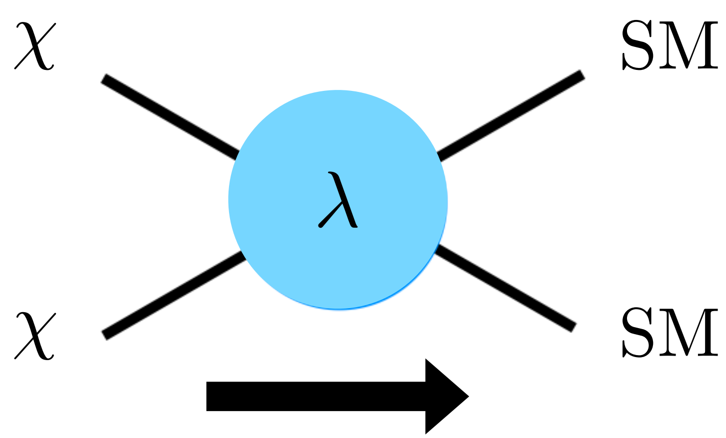

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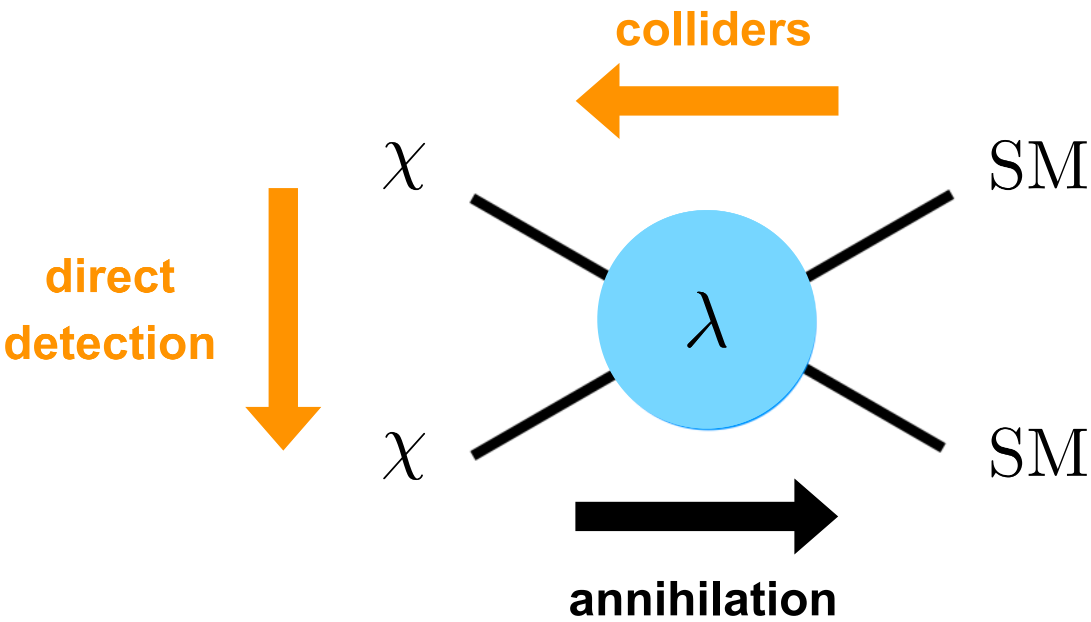

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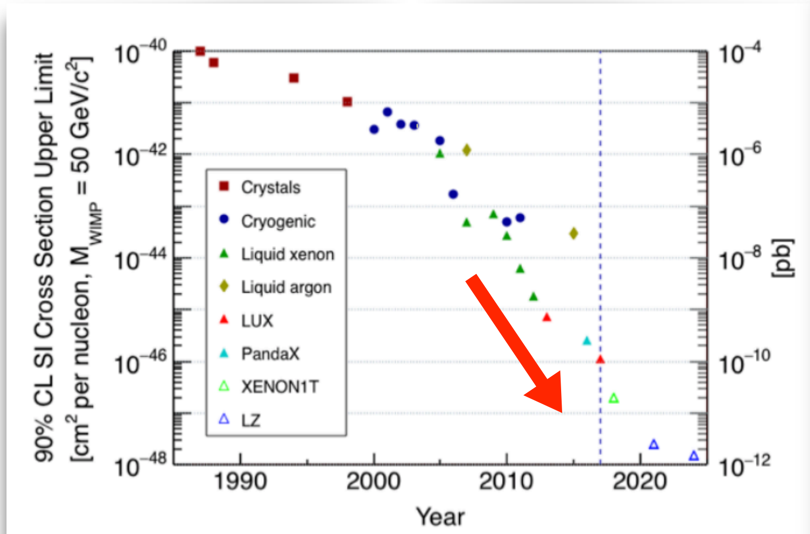
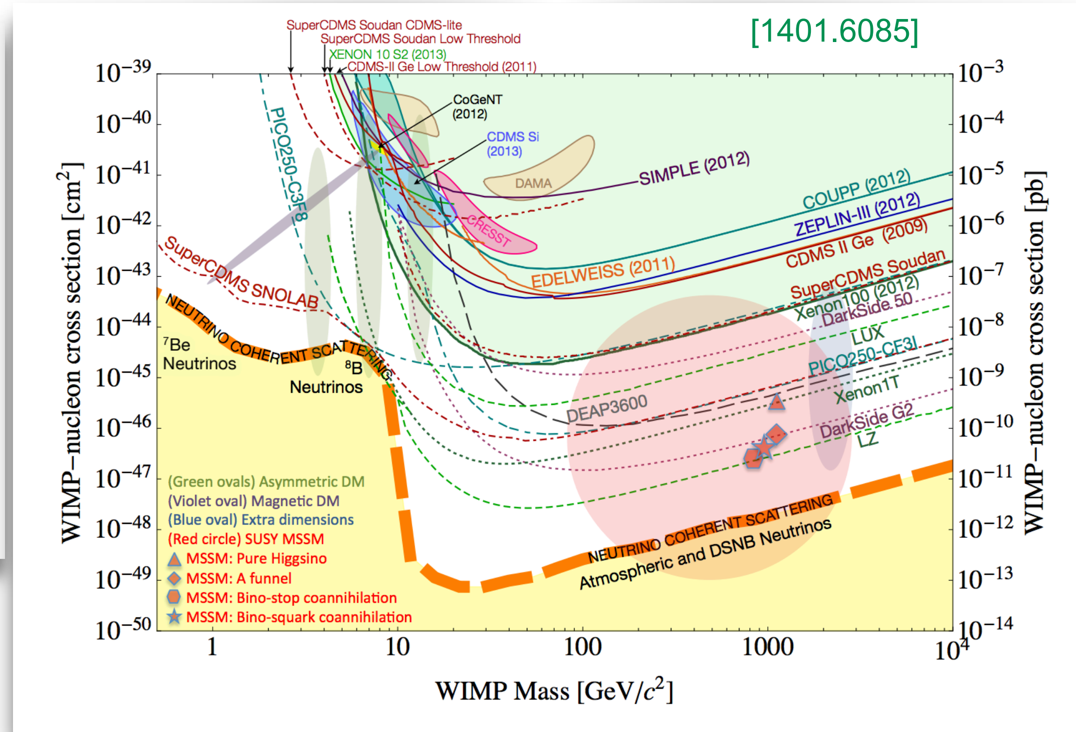
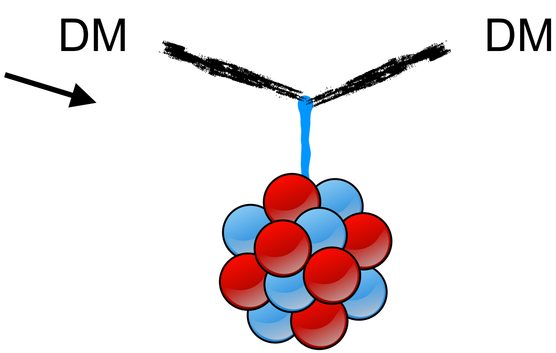
Where have all the WIMPs gone?



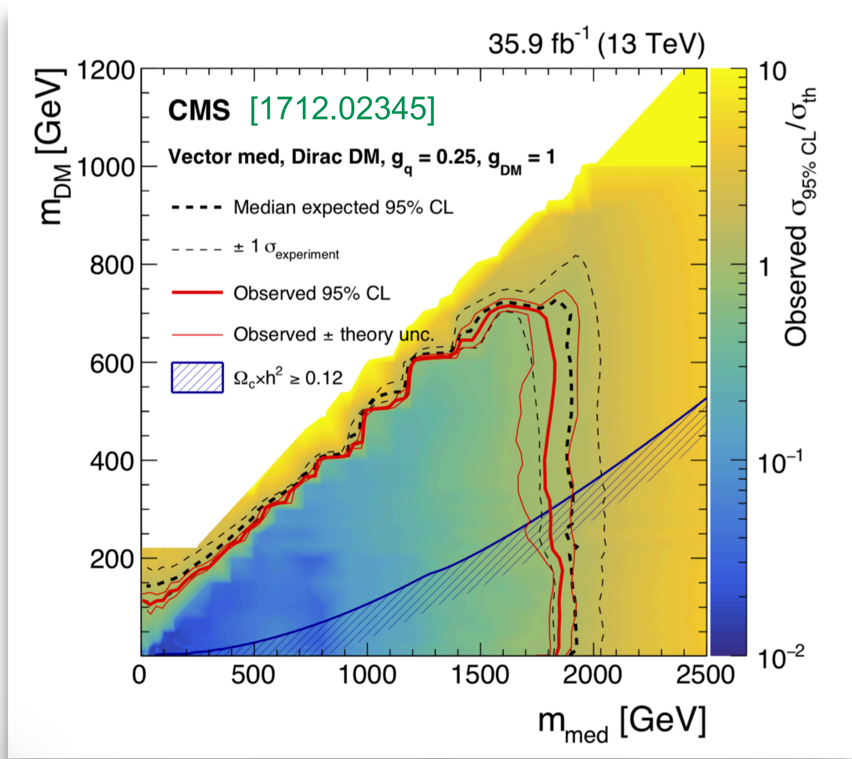




The “neutrino floor” is not so remote anymore

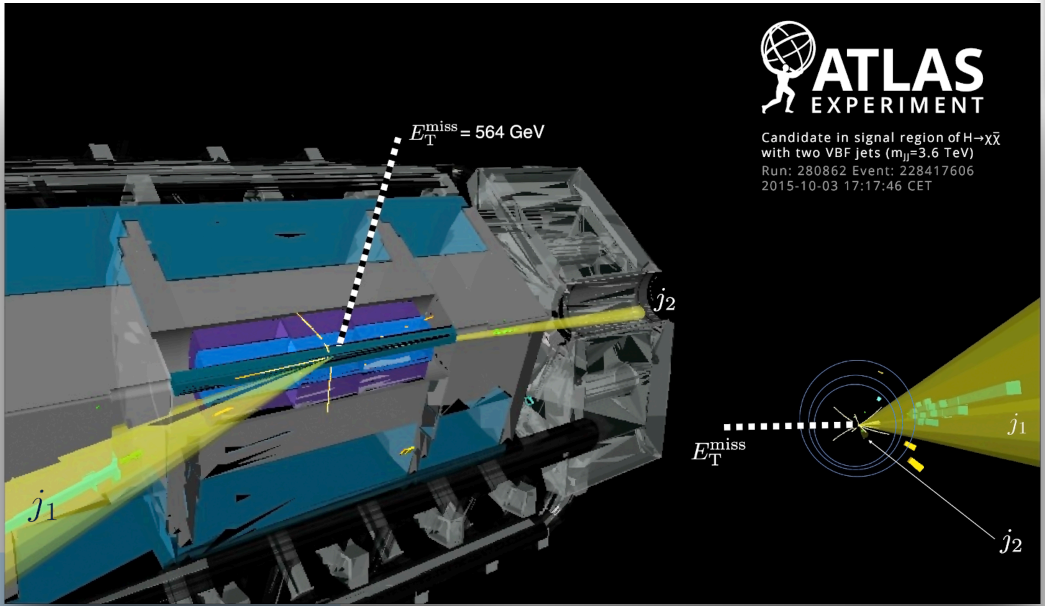
Where have all the WIMPs gone?

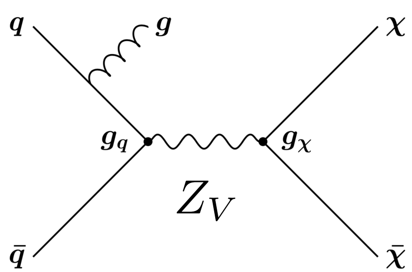
No new physics at the LHC yet,
despite **impressive exploration**



[ATLAS-CONF-2020-008]

$$\mathrm{BR}(\mathrm{Higgs} \to \mathrm{invisible}) < 13\% \quad (95\%\ \mathrm{CL})$$





"mono-jet"

Ways forward

- Vanilla WIMPs may be in trouble, but thermal freeze-out remains powerful guiding principle. Insensitive to initial conditions.

- Within standard cosmology, several possibilities to reconcile thermal DM with experimental constraints:

  - ✓ DM lighter than a few GeV
  - ✓ Structural suppression of elastic scattering on nuclei
  - ✓ DM annihilating to a hidden sector
  - ✓ …

The role of Higgs naturalness

The role of Higgs naturalness

- Still a useful motivation. But rather than razor-sharp predictions, helps to identify broad scenarios, and scales of special interest

- Prominent case are **strongly-interacting hidden sectors**
  - At **~ GeV**: neutral naturalness models (for example, Twin Higgs)
  - At **~ TeV**: Higgs as a pseudo Nambu-Goldstone boson

- **Dark mesons as DM**

  Broadly inspired by naturalness, but focus on DM problem (and phenomenology)

[Katz, Salvioni, Shakya 2006.xxxxx]

[Balkin, Ruhdorfer, Salvioni, Weiler 2017, 2018]
[Ruhdorfer, Salvioni, Weiler 2019]
[Haisch, Ruhdorfer, Salvioni, Venturini, Weiler, in progress]

[Cheng, Li, Salvioni, Verhaaren 2019 + in progress]

This talk

- Introduction

- Dark mesons at the strong scale
  - Mini-review of SIMP dark matter
  - Our setup and cosmology
  - Constraints and signatures

- Dark mesons at the weak scale

Dark mesons at the strong scale

- **SIMPs** (strongly interacting massive particles) as dark matter

  Dark mesons at ~ 100 MeV scale, $3 \to 2$ annihilations set relic density

  [Hochberg, Kuflik, Volansky, Wacker 2014]
  [Hochberg, Kuflik, Murayama, Volansky, Wacker 2014]

- Minimal setup: **hidden copy of QCD** with $N_f = N_c = 3$

  New questions: [Katz, Salvioni, Shakya, to appear]

  - Some mesons are unstable. Are their decays cosmologically viable?
  - If meson mass splittings are sizeable, is SIMP mechanism still effective?
  - Requirements for DM stability? Lessons for phenomenology (DM decays) and model building

also: [Berlin, Blinov, Gori, Schuster, Toro 2018]
[Hochberg, Kuflik, Murayama 2018]

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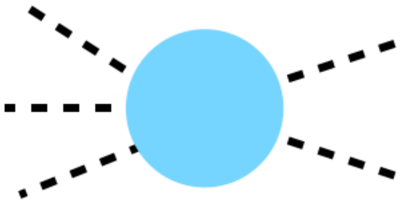
A dark copy of QCD

- $SU(N_c)$ gauge theory
- N_f light quark flavors $\rightarrow$ $N_f^2 - 1$ (pseudo-) Goldstone bosons
- Can these light mesons be thermal DM?

  Need a number-changing interaction to freeze out.

For $N_f \geq 3$, **Wess-Zumino-Witten action** contains just that:



$$\frac{N_c}{240\pi^2 f_\pi^5}\,\epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\left(\Pi\partial_\mu\Pi\partial_\nu\Pi\partial_\rho\Pi\partial_\sigma\Pi\right) \subset \mathcal{L}_{\mathrm{WZW}}$$

[Wess, Zumino 1971]
[Witten 1983]

$$U = e^{i\Pi/f_\pi}, \quad \Pi = \pi^a \lambda^a$$

SM: e.g. $K^+K^- \rightarrow \pi^+\pi^-\pi^0$

WIMP parametrics

Freeze-out happens when:

credit: Eric Kuflik

$$\Gamma_{\text{annihilation}} \sim H$$

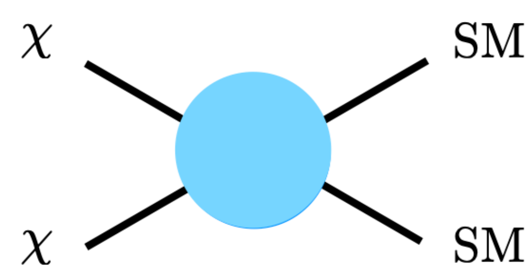
$$= n_{\text{DM}} \langle \sigma v \rangle_{2\to 2}$$

$$H \sim \frac{T^2}{M_{\text{Pl}}}$$

$$m_{\text{DM}} n_{\text{DM}} \sim m_p n_b$$

$$\langle \sigma v \rangle_{2\to 2} \sim \frac{\alpha^2}{m_{\text{DM}}^2}$$

$$n_b \sim s\,\eta_b \sim s\,\frac{T_{\text{eq}}}{m_p}$$



$$\Gamma_{\text{annihilation}} \sim \frac{\alpha^2 T^3 T_{\text{eq}}}{m_{\text{DM}}^3}$$

$$m_{\text{DM}} \sim \alpha \left(\frac{T_{\text{eq}} M_{\text{Pl}}}{x_{\text{fo}}} \right)^{1/2} \sim \alpha \times 10 \text{ TeV}$$

$$\left(x_{\text{fo}} = \frac{m_{\text{DM}}}{T_{\text{fo}}} \approx 20 \right)$$

weak coupling → weak scale

SIMP parametrics

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[Hochberg, Kuflik, Volansky, Wacker 2014]

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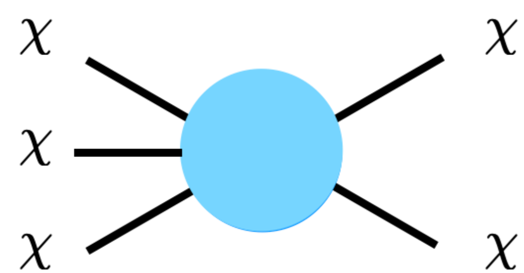

$$\Gamma_{\text{annihilation}} \sim \frac{\alpha^3 T^6 T_{\text{eq}}^2}{m_{\text{DM}}^7}$$

$$m_{\text{DM}} \sim \alpha \left(\frac{T_{\text{eq}}^2 M_{\text{Pl}}}{x_{\text{fo}}^4} \right)^{1/3} \sim \alpha \times 100 \text{ MeV}$$

$$\left(x_{\text{fo}} = \frac{m_{\text{DM}}}{T_{\text{fo}}} \approx 20 \right)$$

strong coupling → strong scale

SIMP parametrics

credit: Eric Kuflik

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$$\parallel$$

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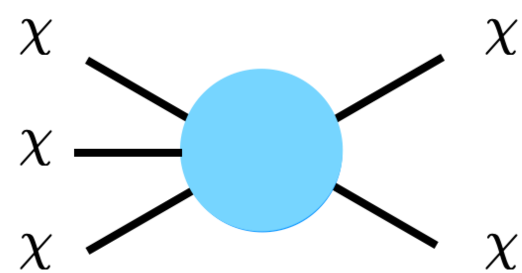


$N_f = 3$ QCD, degenerate mesons:

$$\langle \sigma v^2 \rangle_{3\to 2} = \left(\frac{\sqrt{5}}{8\pi} \right)^5 \frac{N_c^2 m_\pi^5}{f_\pi^{10} x^2}$$

[Hochberg, Kuflik, Murayama Volansky, Wacker 2014]

$$\left(\quad T_{\text{fo}} \right)$$

$$\sim \alpha \times 100\ \text{MeV}$$

strong coupling → strong scale

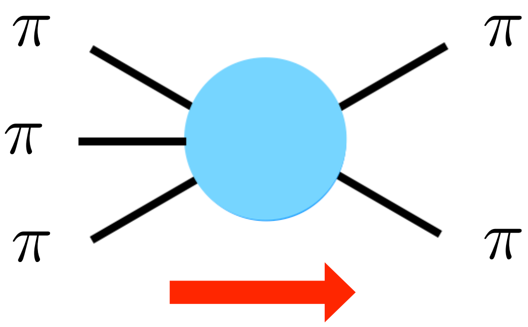
The need for a mediator

- Hidden pions with SM-like mass (~ 100 MeV) obtain relic density through freeze out of $3 \to 2$ annihilations

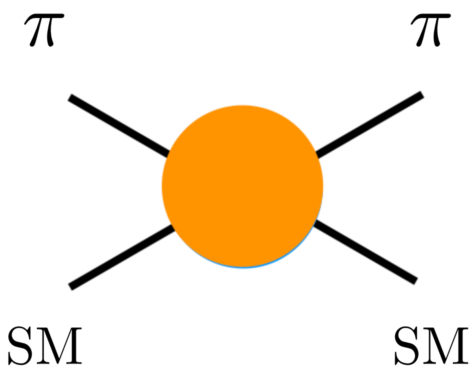
- However, if hidden sector is isolated the DM stays **too warm**

  Too high T during structure formation, ruled out

[Carlson, Machacek, Hall 1992]
[de Laix, Scherrer, Schaefer 1995]



- Need mediation mechanism



keeps hidden & SM sectors
in kinetic equilibrium until freezeout

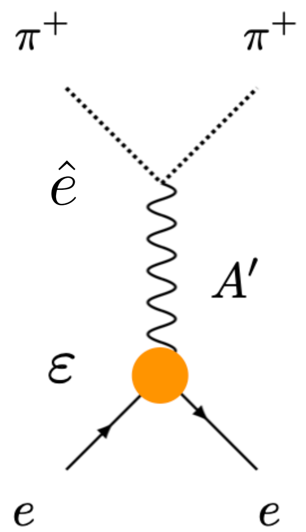
[Hochberg, Kuflik, Volansky, Wacker 2014]

Simplest mediator: dark photon

- Introduce dark electromagnetism, kinetically mixed with SM hypercharge

$$\mathcal{L} \supset \frac{1}{2} m_{\hat{A}}^2 \hat{A}_\mu \hat{A}^\mu + \frac{\varepsilon}{2} \hat{F}^{\mu\nu} B_{\mu\nu}$$

- Physical dark photon couples to SM EM current, $\varepsilon e c_w Q_f \bar{f} \gamma^\mu f A'_\mu$



Scattering on light (abundant) SM fermions keeps kinetic equilibrium down to $T_{\rm fo} \sim \frac{m_\pi}{20} \sim \text{few MeV}$

lower bound on $\frac{\varepsilon\, \hat{e}}{m_{A'}^2}$

[Lee, Seo 2015]
[Hochberg, Kuflik, Murayama 2015]

- Bonus: annihilation is *p*-wave, CMB bounds are very weak

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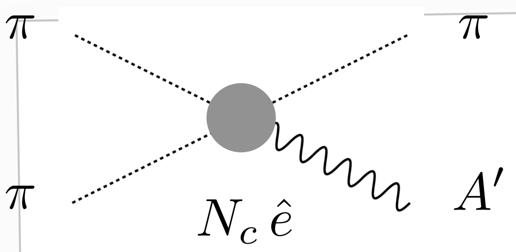
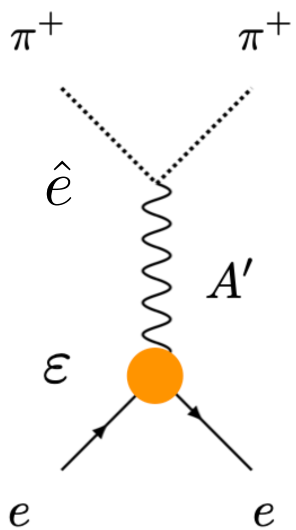


subleading if $Y_{A'} Y_\pi \lesssim Y_\pi^3$

$m_{A'} \gtrsim 2 m_\pi$

(from gauged WZW action)



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Dark matter self-interactions

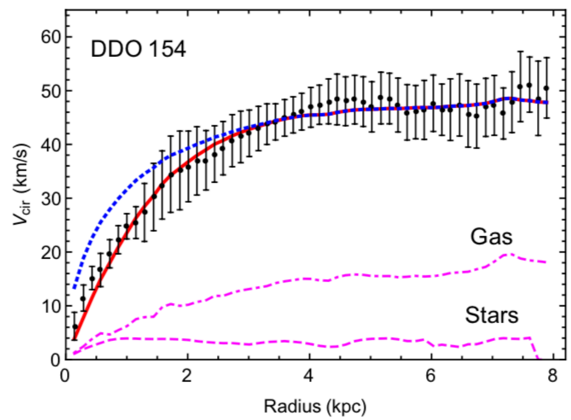
- Mesons undergo $2 \to 2$ scattering in DM halos

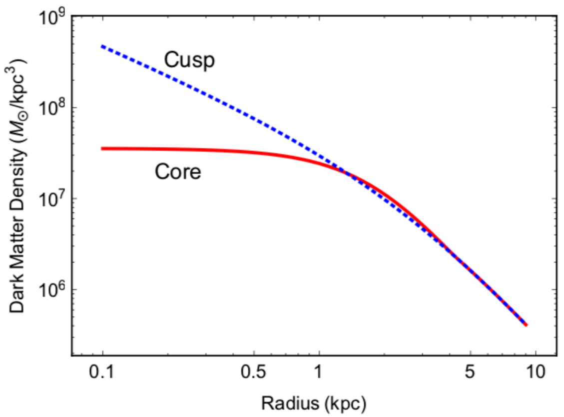
$$\frac{f_\pi^2}{4}\mathrm{Tr}[(D_\mu U)^\dagger D^\mu U] \supset -\frac{r_{abcd}}{24 f_\pi^2}\pi^a \pi^b \partial_\mu \pi^c \partial^\mu \pi^d$$

- Cross section $$\frac{\sigma}{m_\pi} \sim \frac{m_\pi}{16\pi f_\pi^4} \sim (0.1 - 10)\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

Interesting order of magnitude for small-scale structure "puzzles" [Spergel, Steinhardt 1999]

Maybe baryonic effects?





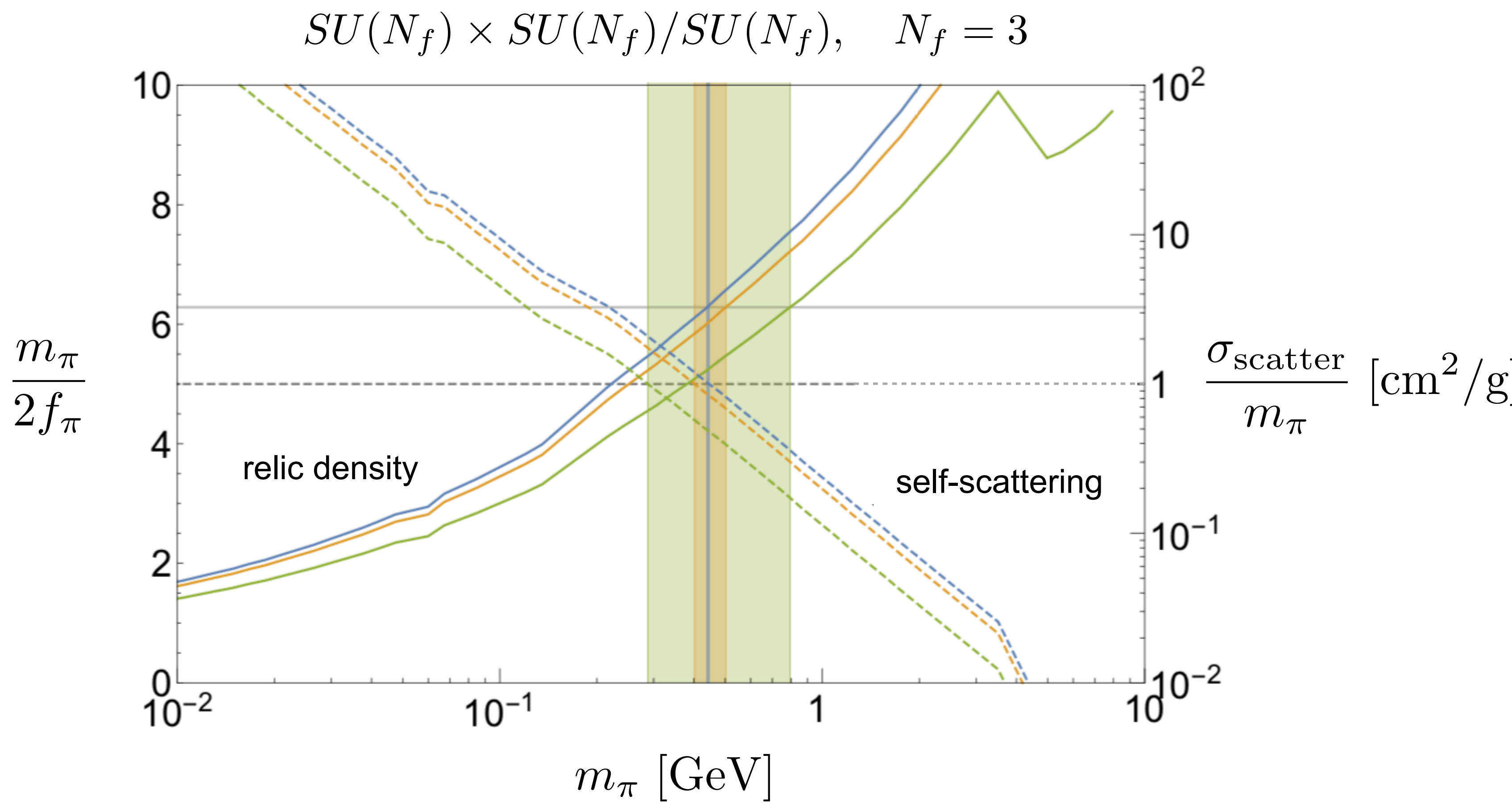
- Bullet cluster and halo shape constraints [review by Tulin and Yu, 2017]

$$\frac{\sigma}{m_\pi} \lesssim O(1)\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

Not-so-light pNGBs

adapted from: [Hochberg, Kuflik, Murayama, Volansky, Wacker 2014]

(colors: different choices of N_c)



$$\left[\frac{\sigma}{m_\pi} \sim \frac{1}{m_\pi^3} \left(\frac{m_\pi}{2 f_\pi} \right)^4 \right]$$

Not-so-light pNGBs

adapted from: [Hochberg, Kuflik, Murayama, Volansky, Wacker 2014]

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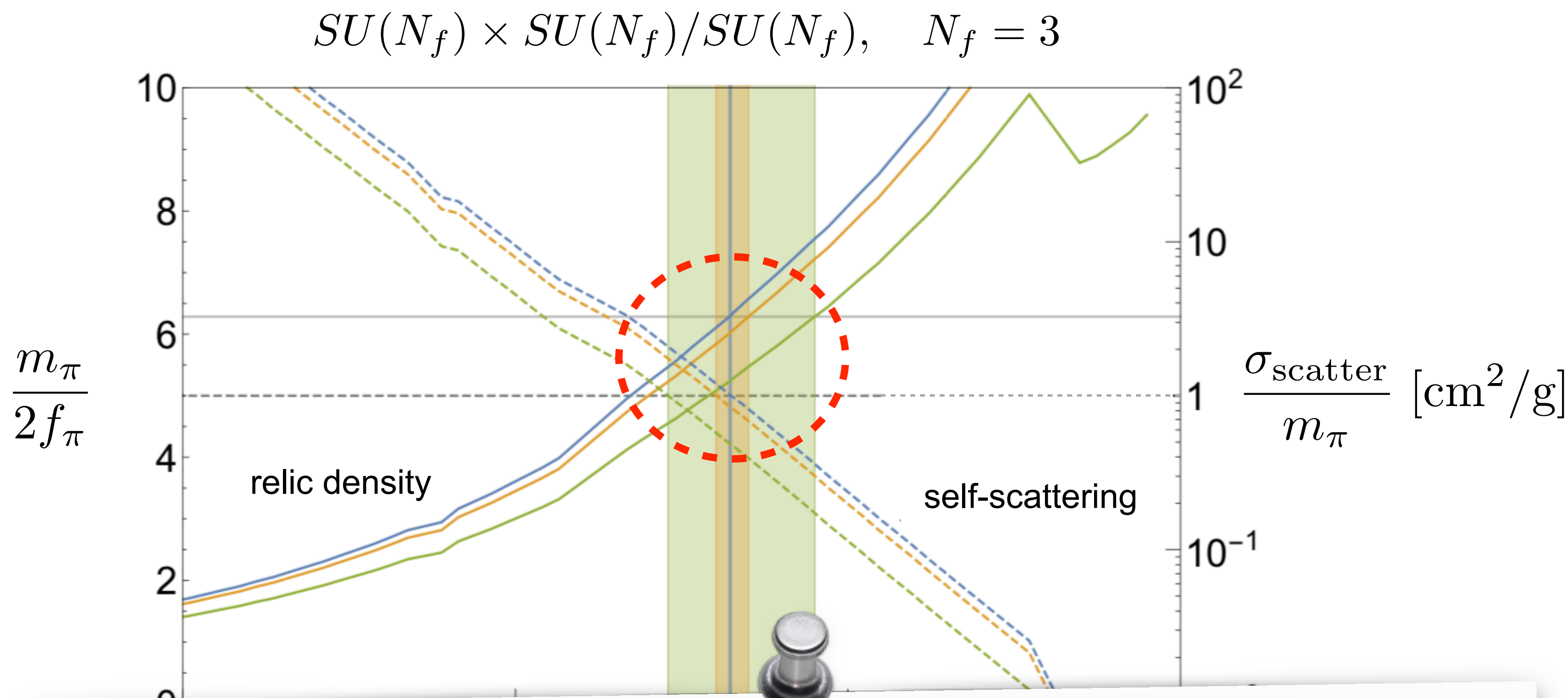

Viable parameter space has **heavy pNGBs,** $m_\pi / f_\pi \sim 8 - 10$

Expect important corrections to chiral perturbation theory

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A minimal SIMP model

- $SU(N_c)$ confining gauge theory, 3 light flavors $(u, d, s) \to$ octet of GBs
- EM is gauged by dark photon
- Explicit breaking parametrized by

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

$$Q = \mathrm{diag}\,(2/3, -1/3, -1/3)$$

- Stability of DM mesons? Which spectra allow viable cosmology?

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Minimal choice: $m_u > m_d = m_s$

singlet is unstable

exact $SU(2)_U \times U(1)_Q$

"U-spin" in the SM

η

$\mathbf{1}_0$

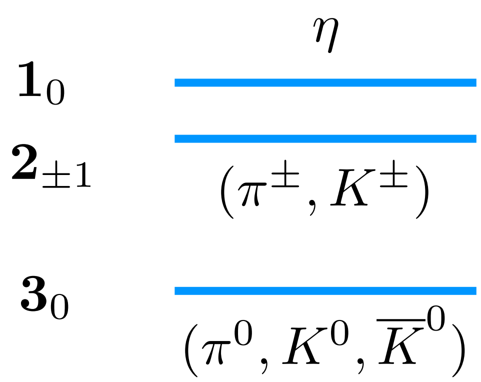
$\mathbf{2}_{\pm 1}$ $(\pi^{\pm}, K^{\pm})$

$\mathbf{3}_0$ $(\pi^0, K^0, \overline{K}^0)$

"the U-symmetric Standard Model"

Questions

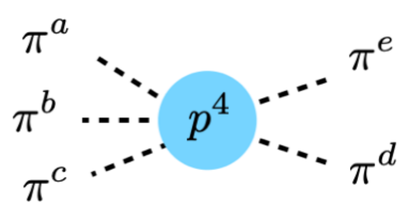
$$m_d = m_s = m$$
$$m_u = m + \Delta m$$



- How suppressed must singlet density be, for viable cosmology?

- **DM is light triplet** of neutral pion + kaons. Does $3 \to 2$ still work?

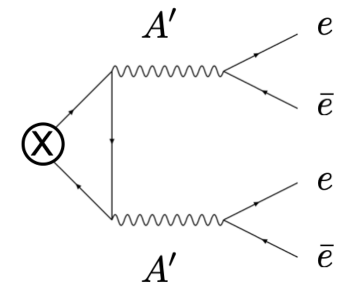
  5-meson interaction requires $a \neq b \neq c \neq d \neq e$



- How accurate does $SU(2)_U$ need to be?

  Introduce explicit breaking, study quantitatively

Singlet η decays



- Decay through chiral anomaly, $\mathrm{Tr}\,(Q^2\lambda^\eta) \neq 0$

$$\Gamma(\eta \to 4f) = \frac{2048}{6301}\left(\frac{8\sqrt{3}N_c Q_{f_1} Q_{f_2}}{9}\right)^2 \frac{\varepsilon^4 \hat{\alpha}^2 \alpha^2 c_w^4}{8\pi(4\pi)^4} \frac{(m_\eta/2)^{11}}{f_\pi^2 m_{A'}^8}$$

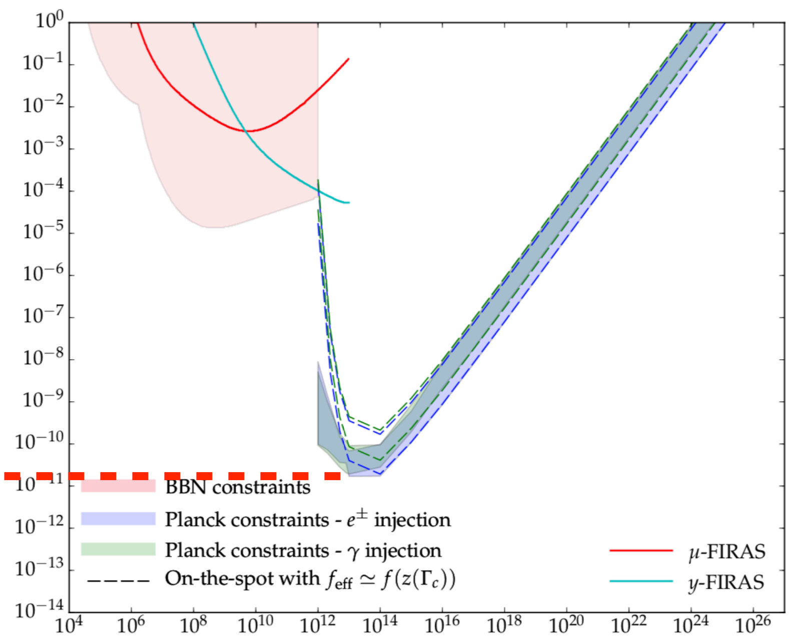
$$\tau_{\eta\to 4e}^{(\text{anomaly})} \approx 1.9 \times 10^{14}\ \text{s} \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{\alpha}{\hat{\alpha}}\right)^2 \left(\frac{m_{A'}}{0.4\ \text{GeV}}\right)^8 \left(\frac{200\ \text{MeV}}{m_\eta}\right)^9 \left(\frac{10}{m_\eta/f_\pi}\right)^2$$

(FeynRules+MG5)

Comparable to timescale of recombination:
EM injection impacts CMB anisotropies,
strongly constrained

density of decaying species
norm. to CDM

$\sim 10^{-11}$

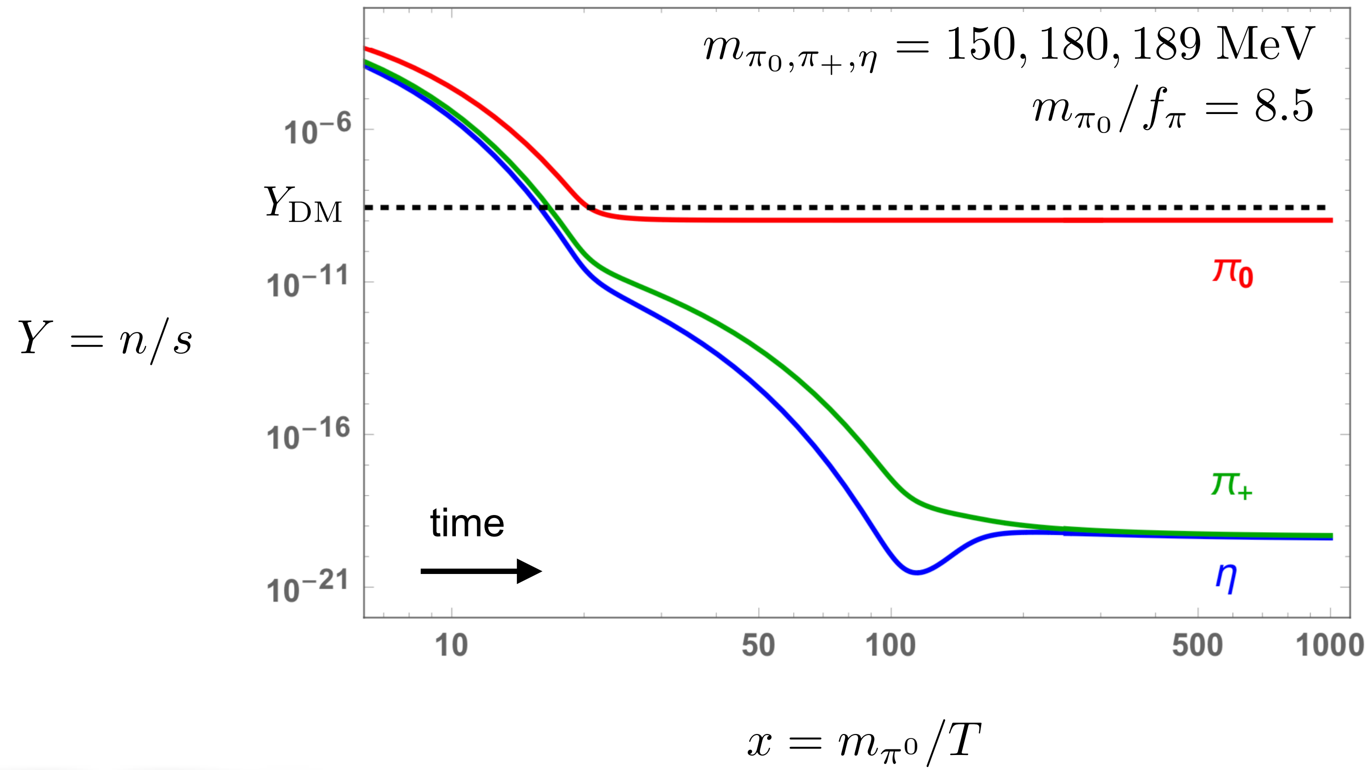


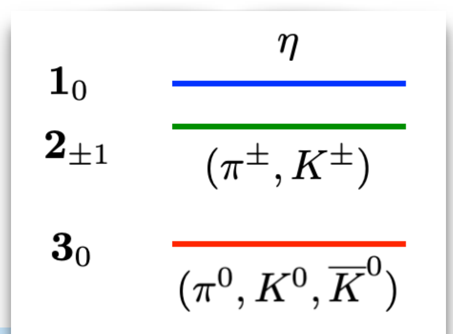
[Poulin, Serpico 2016]

τ[seconds]

Cosmological history

20% mass splitting $\gg T_{\rm fo}^{3\to 2} \sim m_\pi/20$. Realized for $m \sim 2m_{d,s}$





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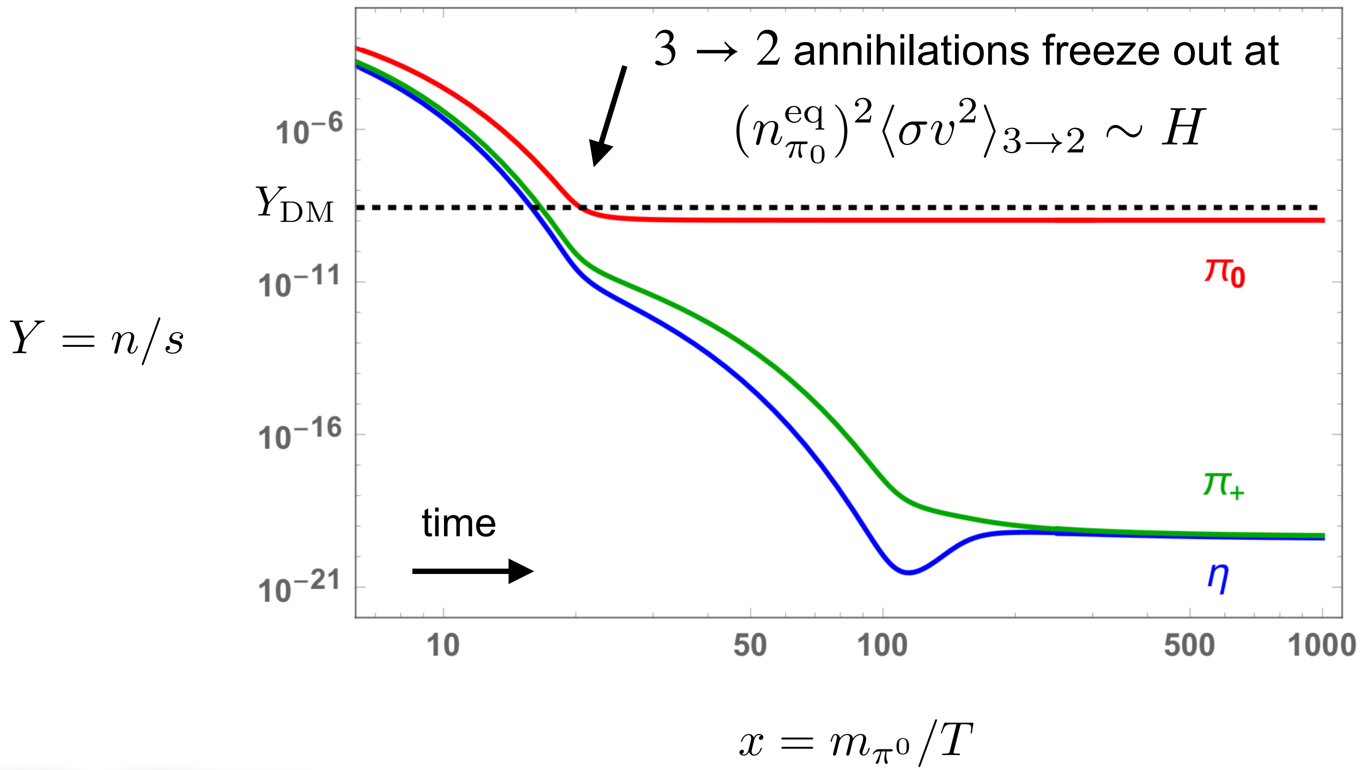
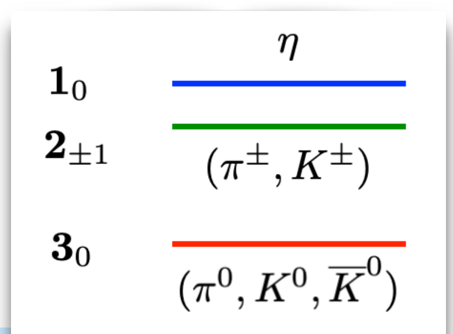
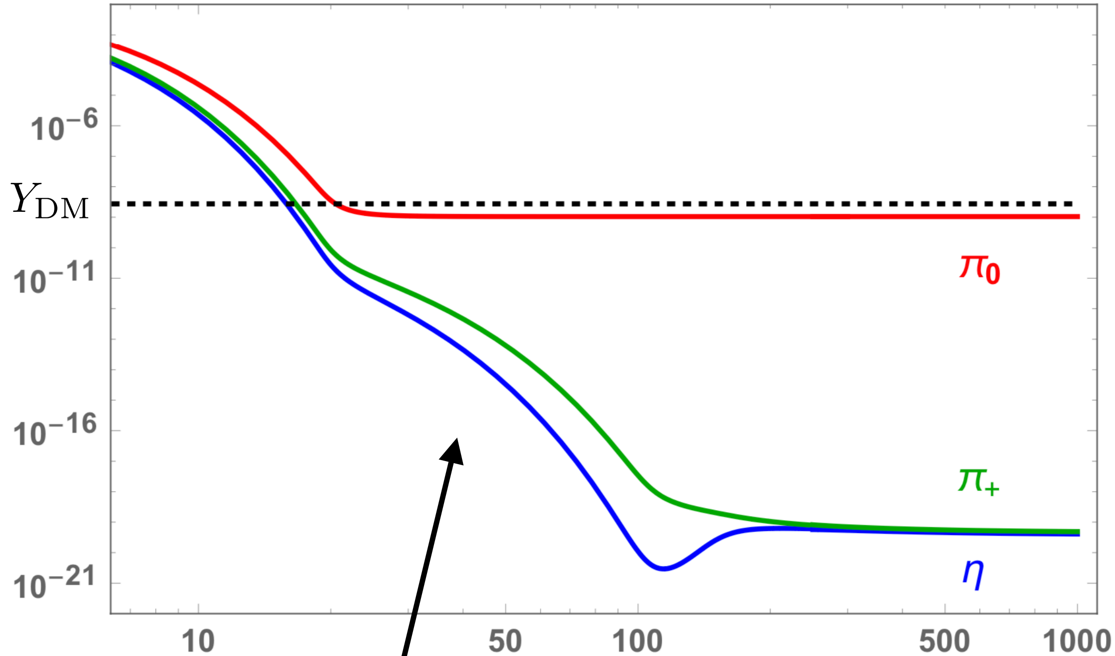




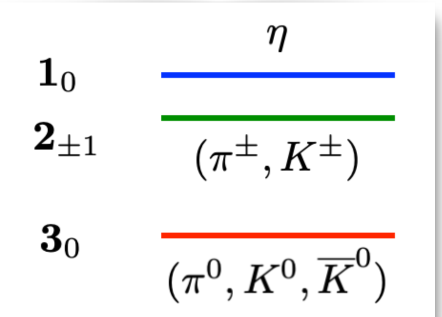
As long as $\pi^0 K^0 \overline{K}^0 \to \pi^+\pi^-$ is kinem. open,
$3 \to 2$ freeze-out **remains efficient**

Cosmological history/2



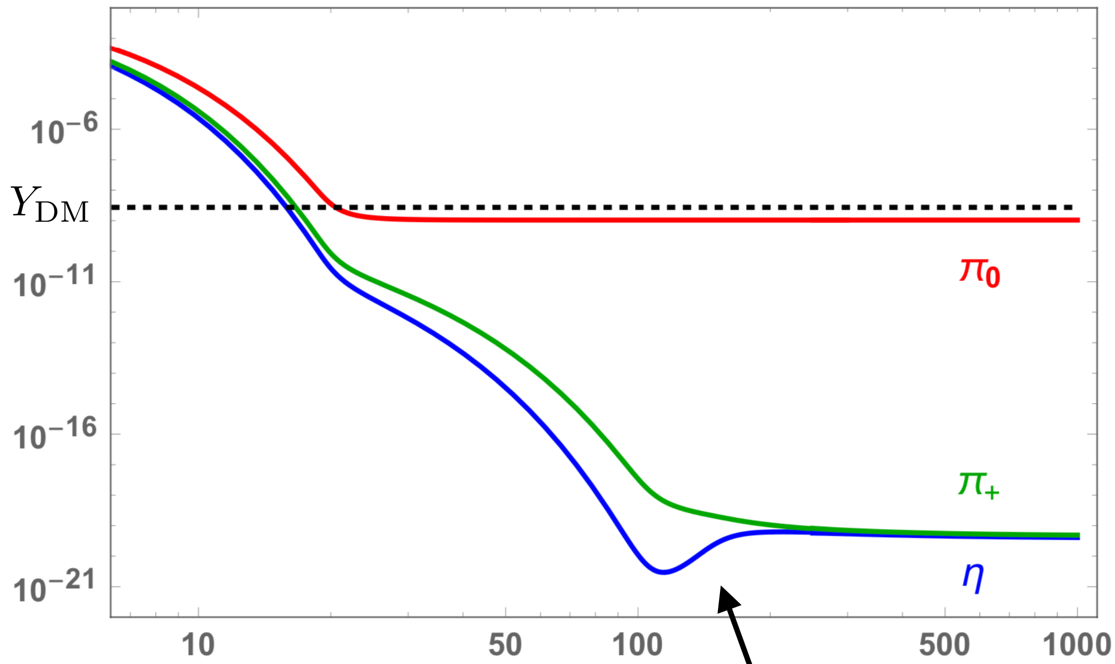
$Y = n/s$

$x = m_{\pi^0}/T$



$2 \to 2$ scattering, e.g. $\pi^+\pi^- \to \pi^0\pi^0$, keeps heavier multiplet on $\quad Y^{\rm eq}_{\pi^+}\dfrac{Y_{\pi^0}}{Y^{\rm eq}_{\pi^0}} \simeq Y_{\pi^0}\exp\left(-\dfrac{m_{\pi^+}-m_{\pi^0}}{T}\right)$

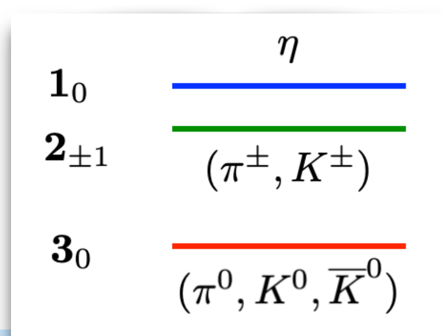
Cosmological history/3



$Y = n/s$

$x = m_{\pi^0}/T$

$$2m_{\pi^+} > m_{\pi^0} + m_\eta$$

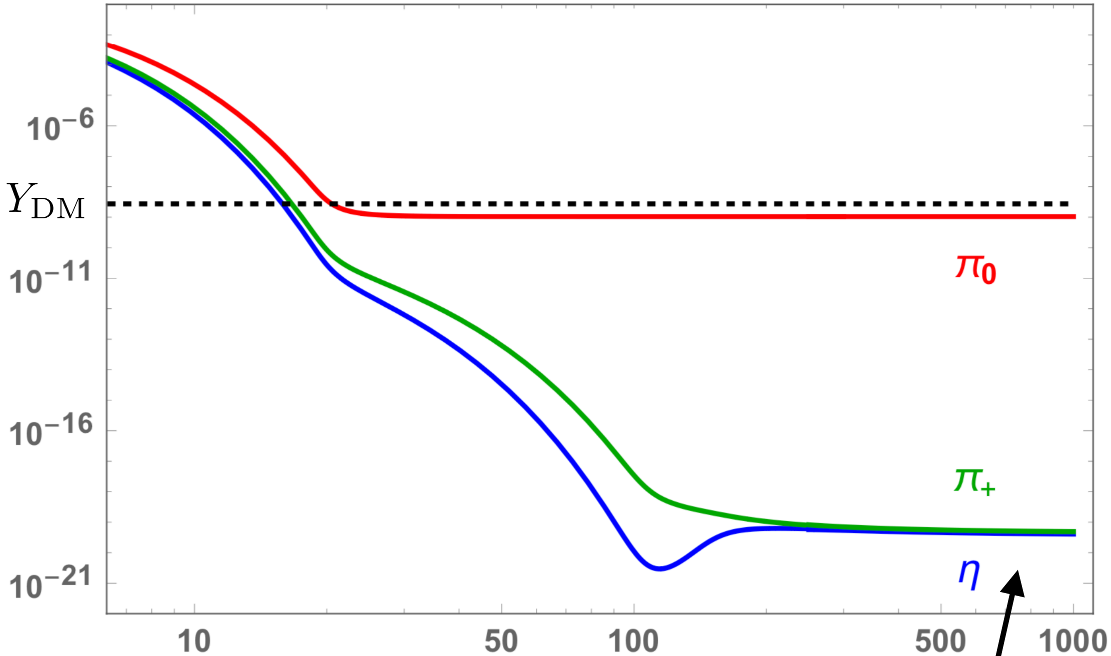


$\pi^+\pi^- \to \pi^0\pi^0$ and $\eta\,\pi_0 \to \pi^+\pi^-$ become inefficient

$\pi^+\pi^- \to \eta\,\pi^0$ makes η density **increase**

Cosmological history/4

$$Y = n/s$$



$$x = m_{\pi^0}/T$$

$$\frac{Y_\eta^{\rm fo}}{Y_{\rm DM}} \approx 10^{-11}$$

CMB ✓

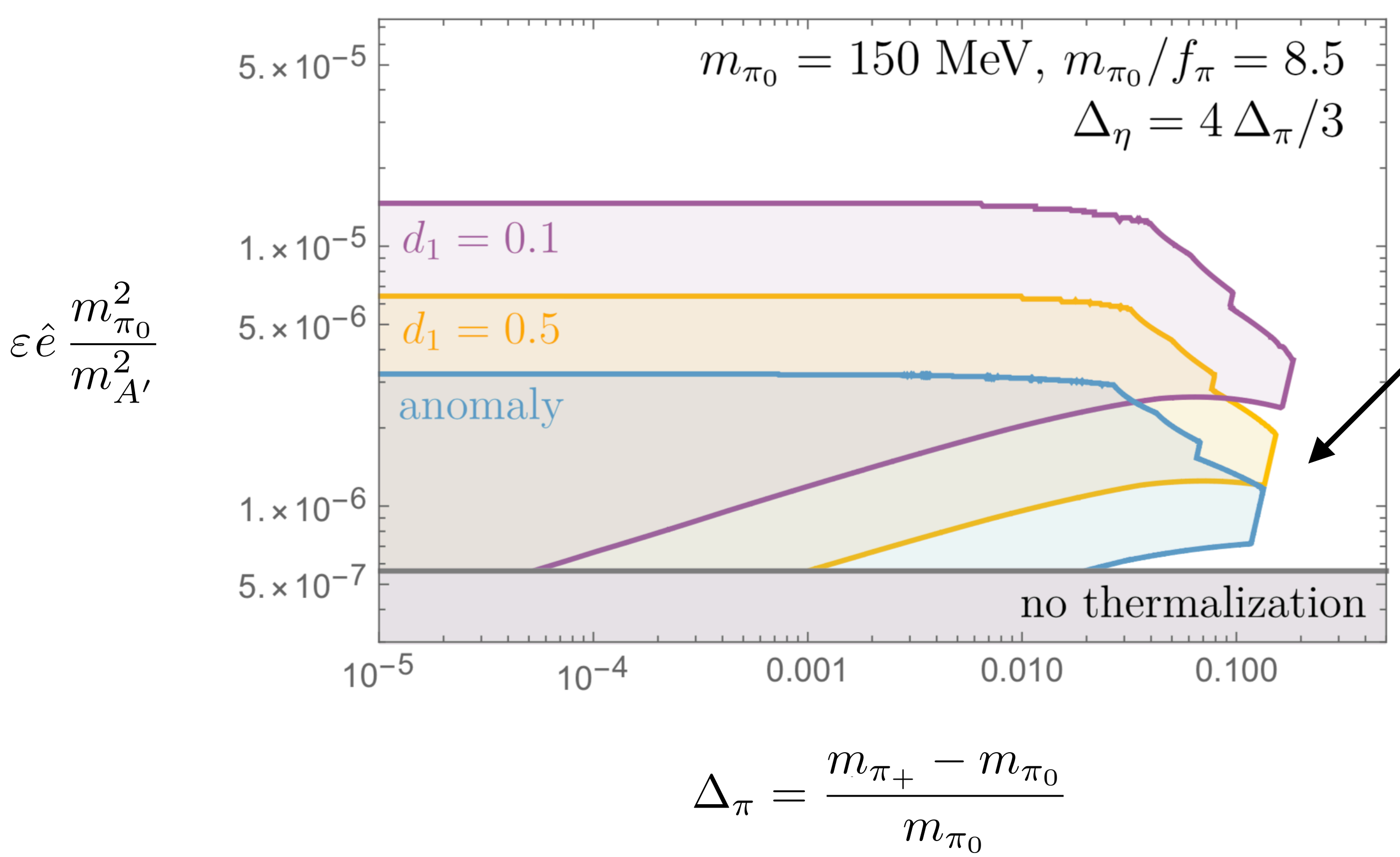
$\mathbf{1}_0$	η (blue)
$\mathbf{2}_{\pm 1}$	$(\pi^\pm, K^\pm)$ (green)
$\mathbf{3}_0$	$(\pi^0, K^0, \overline{K}^0)$ (red)

η and π^+ densities settle on

$$\left.\frac{Y_\eta}{Y_{\pi^+}}\right|_{\rm fo} \sim \sqrt{\frac{\langle\sigma v\rangle_{\pi^+\pi^-\to\eta\pi^0}}{\langle\sigma v\rangle_{\eta\eta\to\pi^+\pi^-}}} \sim O(1)$$

CMB constraints on η decay

- η lifetime + relic density $\rightarrow$ exclusion on parameter space



no bounds for splitting $\gtrsim 10$ - $20\,\%$

Breaking isospin

- Introduce small breaking of isospin $SU(2)$ by $m_s = m_d + dm$

DM triplet $(\pi_0, K_0, \overline{K}_0)$

decays by mixing with η

stable due to residual $U(1)$

$$\tau_{\pi^0} \sim \frac{\tau_\eta}{\delta^2} \qquad \left(\frac{dm}{\Delta m} \equiv \delta\right)$$

$$\tau^{(\text{anomaly})}_{\pi_0 \to 4e} \sim 1.0 \times 10^{25}\ \text{s} \left(\frac{10^{-5}}{\delta}\right)^2 \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{\alpha}{\hat{\alpha}}\right)^2 \left(\frac{m_{A'}}{0.4\ \text{GeV}}\right)^8 \left(\frac{200\ \text{MeV}}{m_{\pi_0}}\right)^9 \left(\frac{10}{m_{\pi_0}/f_\pi}\right)^2$$

- Constraints/ future reach on δ ?

Indirect detection bounds are relatively weak for $m_{\text{DM}} \sim 100\ \text{MeV}$

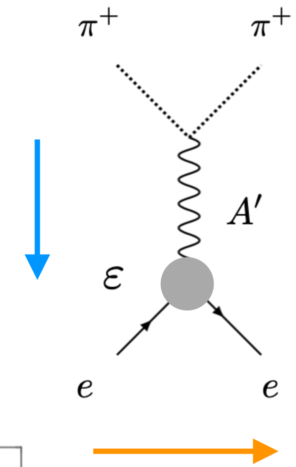
"MeV gap" of gamma-ray astronomy

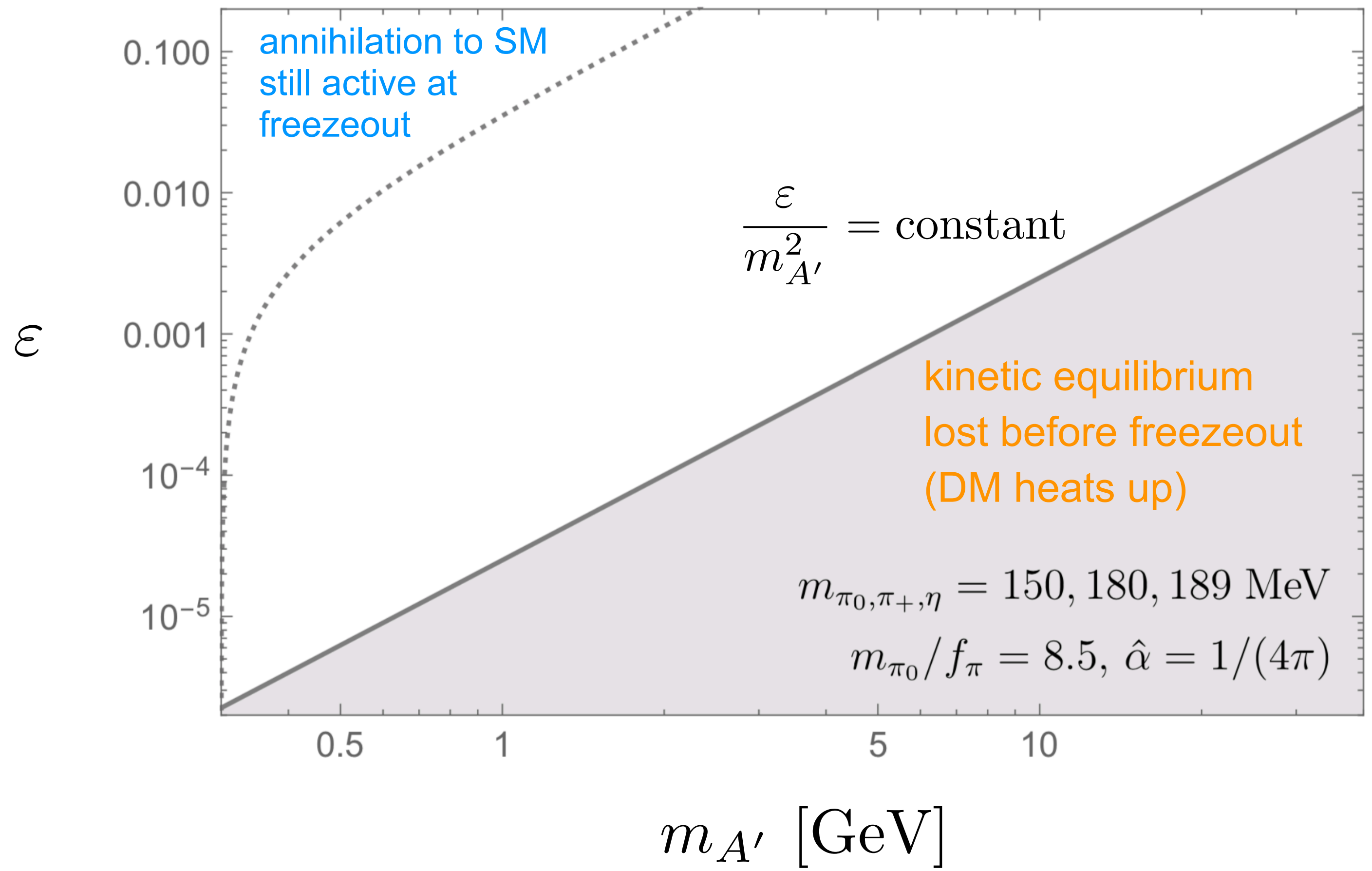
[Bartels, Gaggero, Weniger 2017]

This talk

- Introduction
- Dark mesons at the strong scale
  - Mini-review of SIMP dark matter
  - Our setup and cosmology
  - Constraints and signatures
- Dark mesons at the weak scale

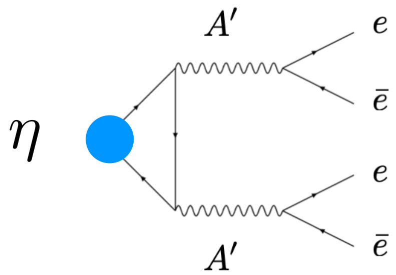
Building the full picture



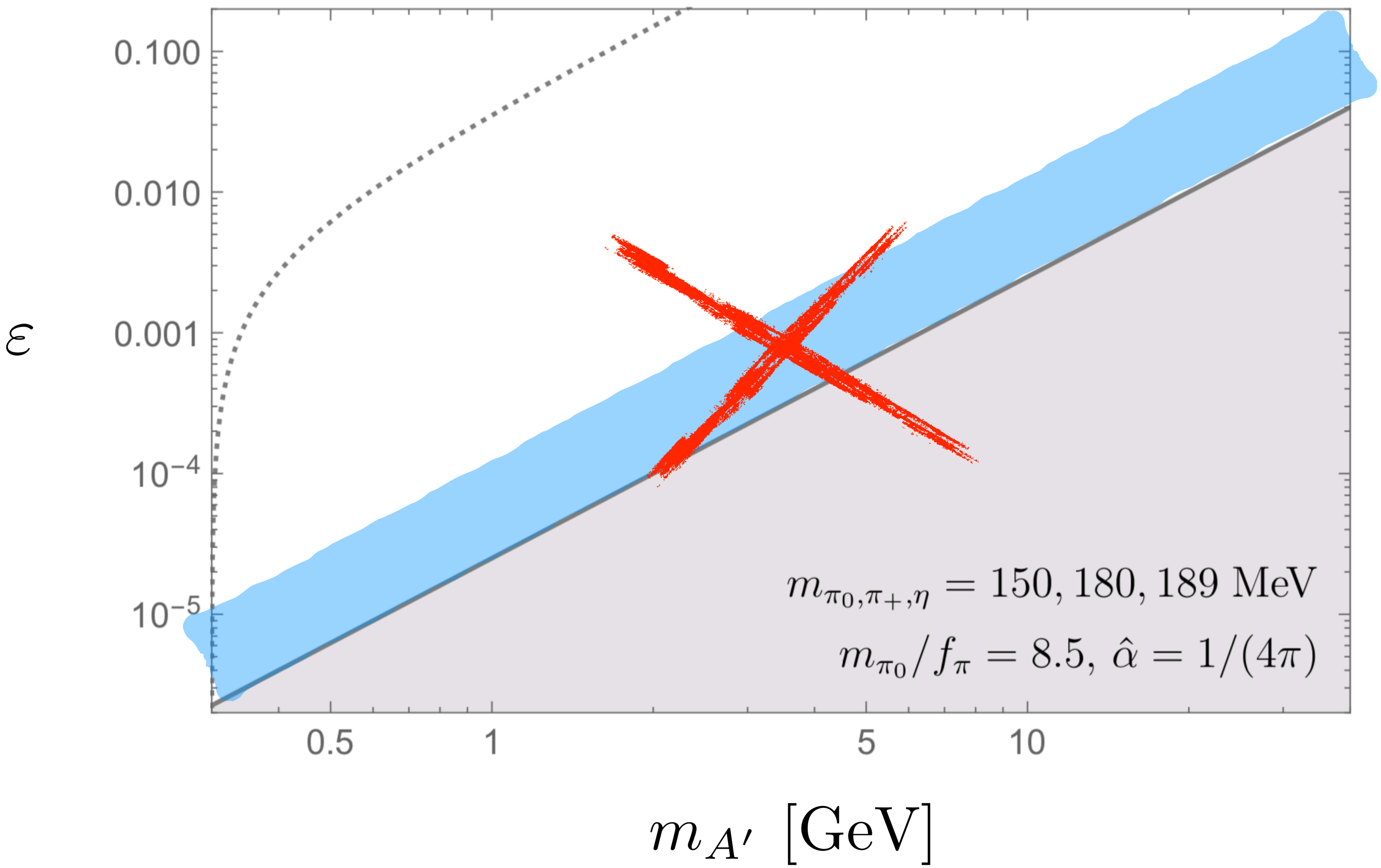


[Hochberg, Kuflik, Murayama 2015]

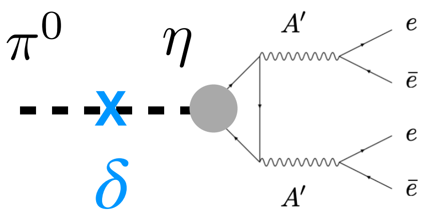
Building the full picture



would be ruled out by CMB anisotropies, if mesons were more degenerate

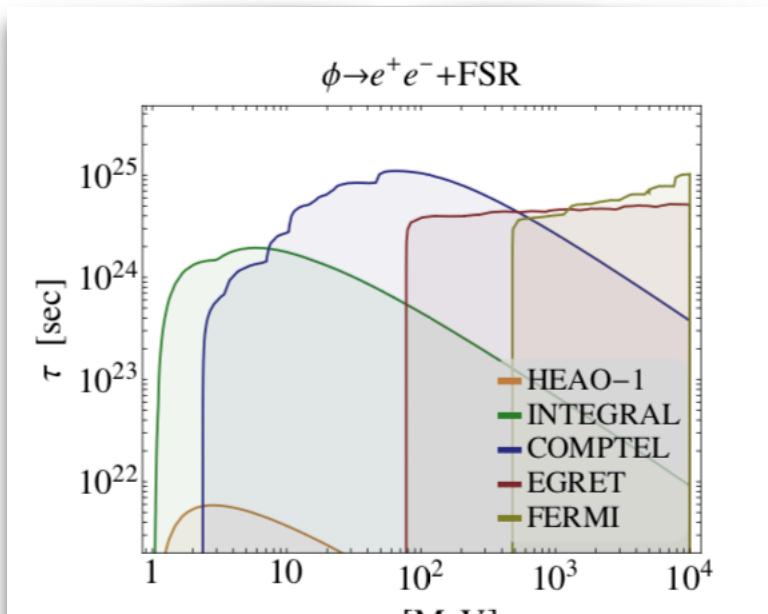


Dark matter decays



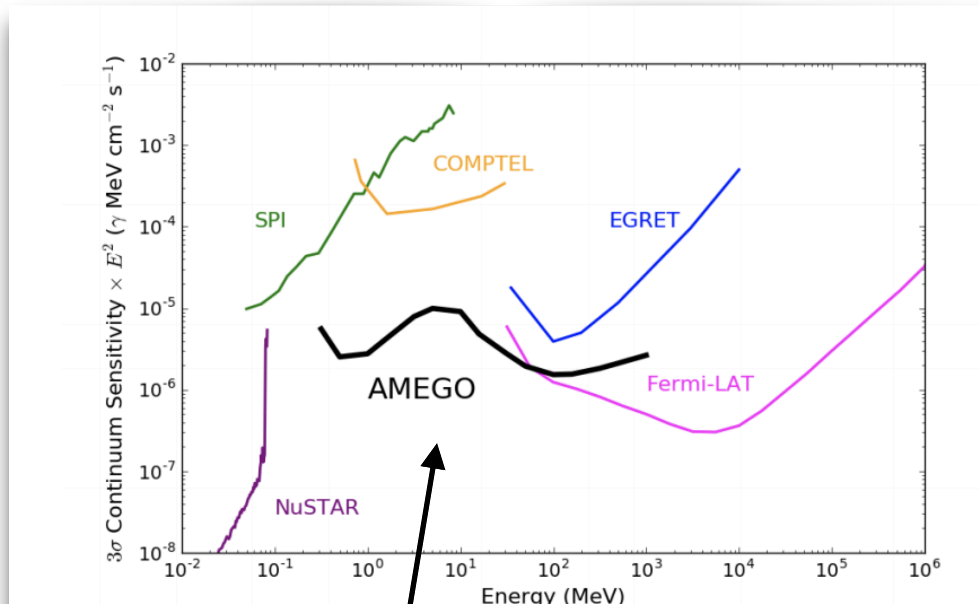
$$\tau_{\pi_0 \to 4e}^{(\mathrm{anomaly})} \approx 1.6 \times 10^{25}\ \mathrm{s} \left(\frac{10^{-6}}{\delta}\right)^2 \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{m_{A'}}{0.3\ \mathrm{GeV}}\right)^8$$

~ 1/3 of DM in Milky Way halo decays. Final state radiation produces gamma rays



[Essig, Kuflik, McDermott, Volansky, Zurek 2013]

COMPTEL on Compton Observatory (1990s)

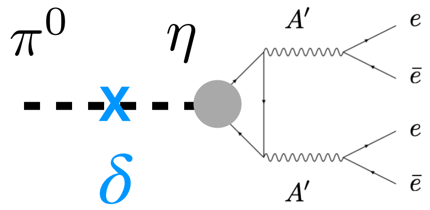


[McEnery et al. 2019]

Proposed new observatory

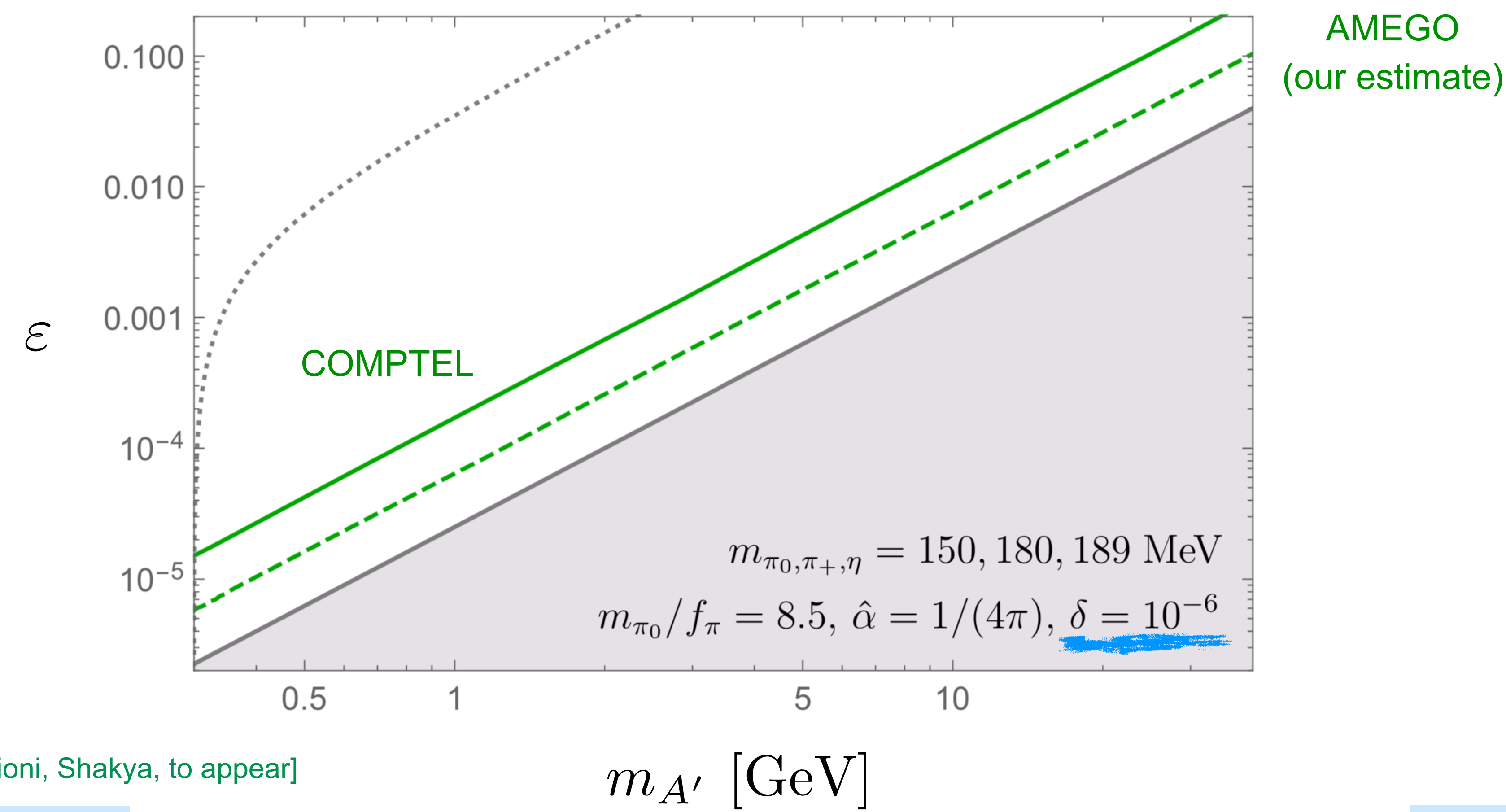
Improve sensitivity to MeV gammas by factor 20-50

Dark matter decays



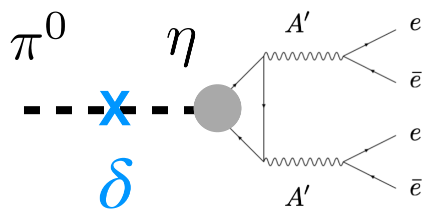
$$\tau_{\pi_0 \to 4e}^{(\text{anomaly})} \approx 1.6 \times 10^{25}\ \text{s} \left(\frac{10^{-6}}{\delta}\right)^2 \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{m_{A'}}{0.3\ \text{GeV}}\right)^8$$

DM indirect detection (gammas)



[Katz, Salvioni, Shakya, to appear]

Dark matter decays/2



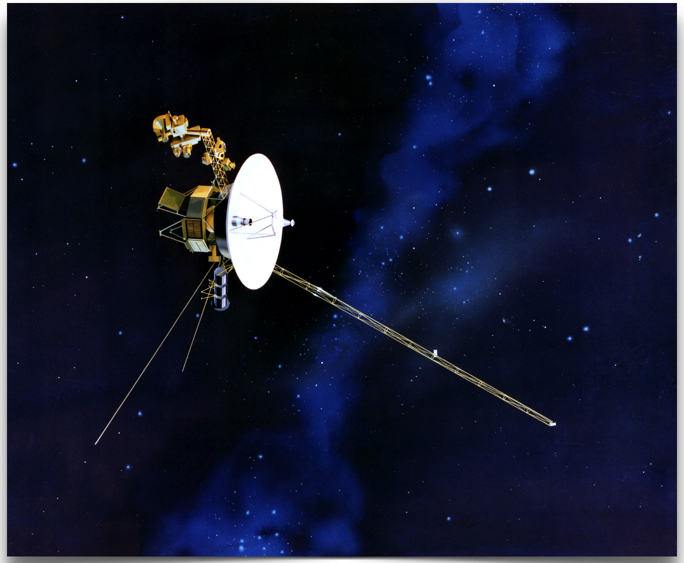
$$\tau_{\pi_0 \to 4e}^{(\text{anomaly})} \approx 1.6 \times 10^{25}\ \text{s} \left(\frac{10^{-6}}{\delta}\right)^2 \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{m_{A'}}{0.3\ \text{GeV}}\right)^8$$

- $e^\pm$ with sub-GeV energies are shielded by solar magnetic field, do not reach observatories orbiting Earth

- However, Voyager1 (launched 1977!) is traveling in interstellar space since 2012

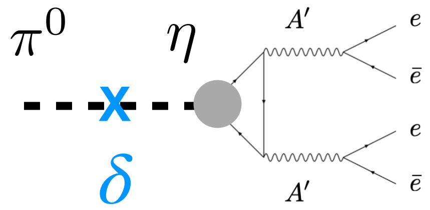
➡ complementary probe, subject to very different systematic uncertainties (CR propagation)

[Boudaud, Lavalle, Salati 2016]



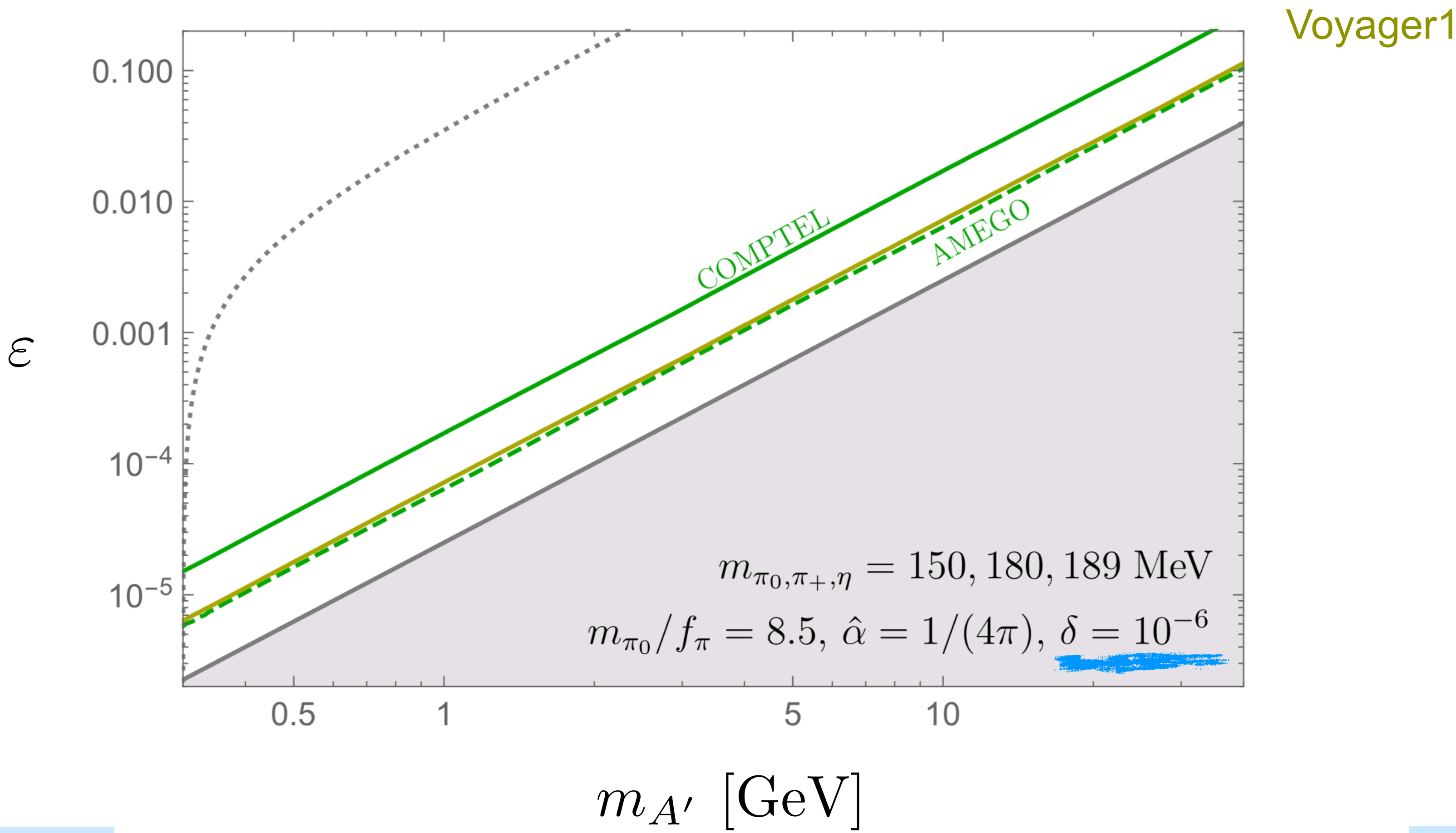
NASA

Dark matter decays/2



$$\tau^{(\text{anomaly})}_{\pi_0 \to 4e} \approx 1.6 \times 10^{25}\ \text{s} \left(\frac{10^{-6}}{\delta}\right)^2 \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{m_{A'}}{0.3\ \text{GeV}}\right)^8$$

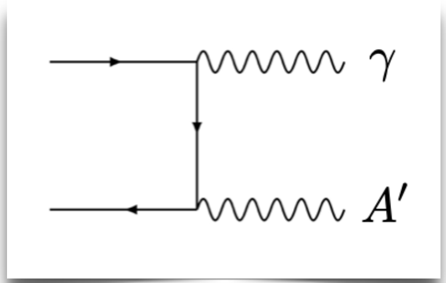
DM indirect detection (electrons/positrons)



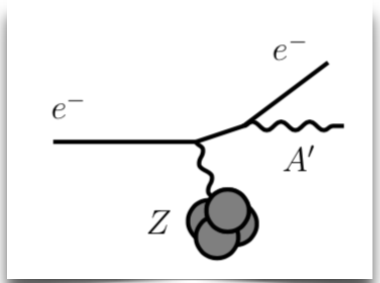
Dark photon at lab experiments

- Dark photon has ε coupling to SM electromagnetic current, $\varepsilon e c_w Q_f \bar{f} \gamma^\mu f A'_\mu$
- Dominant decay mode is **invisible** (dark quarks/hadrons, $\hat{\alpha} \gg \alpha\, \varepsilon^2$)
- Mass range $100\ \mathrm{MeV} \lesssim m_{A'} \lesssim 100\ \mathrm{GeV}$

- Monophoton @ e^+e^- colliders (BaBar, Belle II, LEP) $\longrightarrow$
- Electroweak precision tests
- Monojet @ hadron colliders
- Fixed-target experiments (NA64, LDMX)

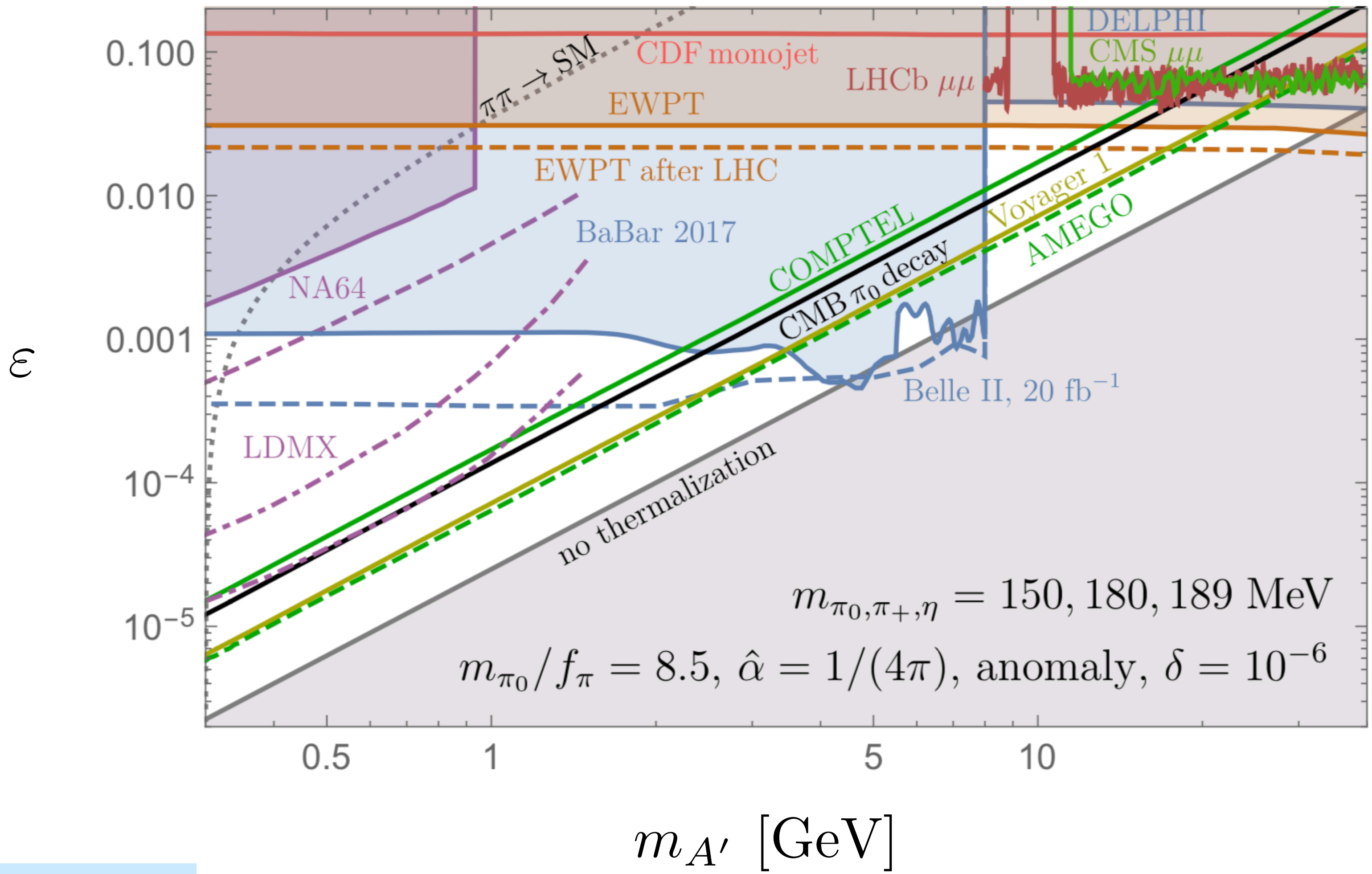


[Izaguirre et al., Essig et al. 2013]
[Fox, Harnik, Kopp, Tsai 2011]
[Shoemaker, Vecchi 2011]
[Curtin, Essig, Gori, Shelton 2014]
[LDMX 2018]
…



[Katz, Salvioni, Shakya, to appear]

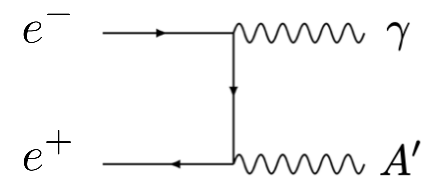
Summary

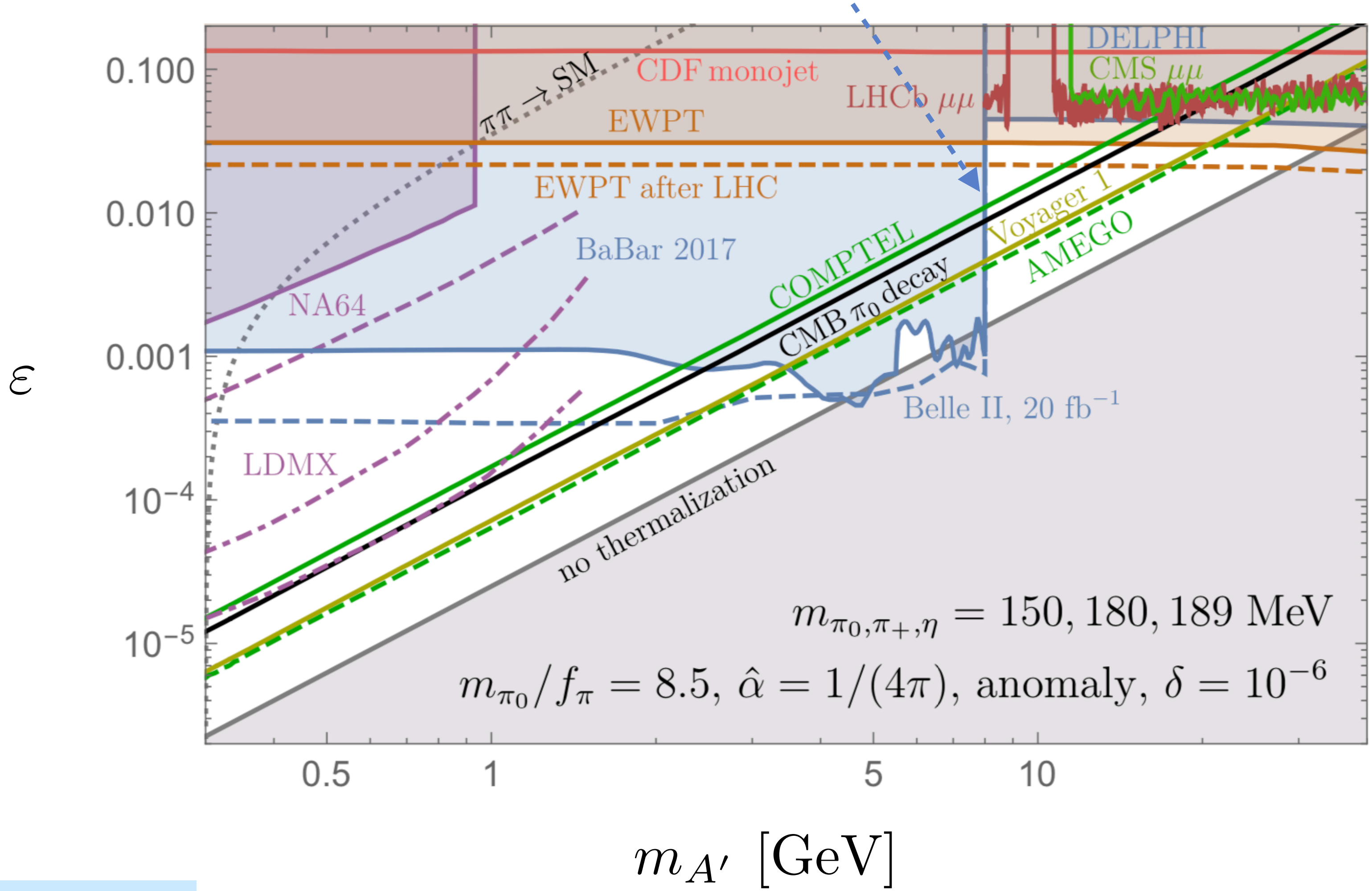


[Katz, Salvioni, Shakya, to appear]

Summary

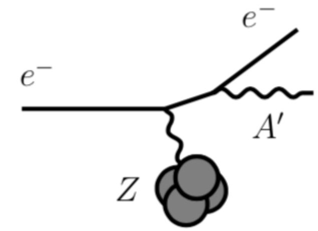
$$m_{A'}^2 = s - 2\sqrt{s}\, E_\gamma^*$$
$$\sqrt{s} \sim 10 \text{ GeV}, E_\gamma^* \gtrsim 1.8 \text{ GeV}$$



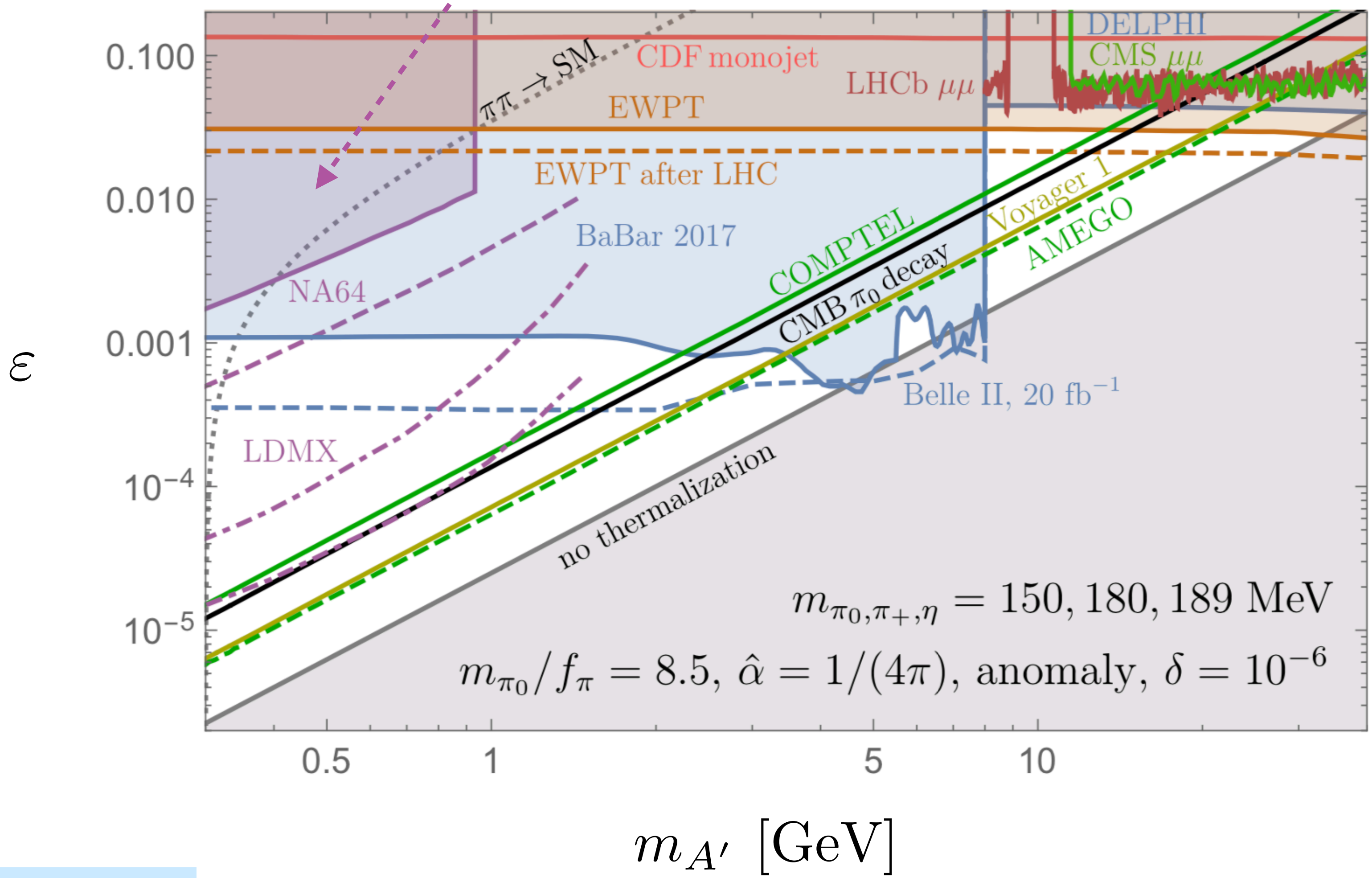


Summary

[Katz, Salvioni, Shakya, to appear]



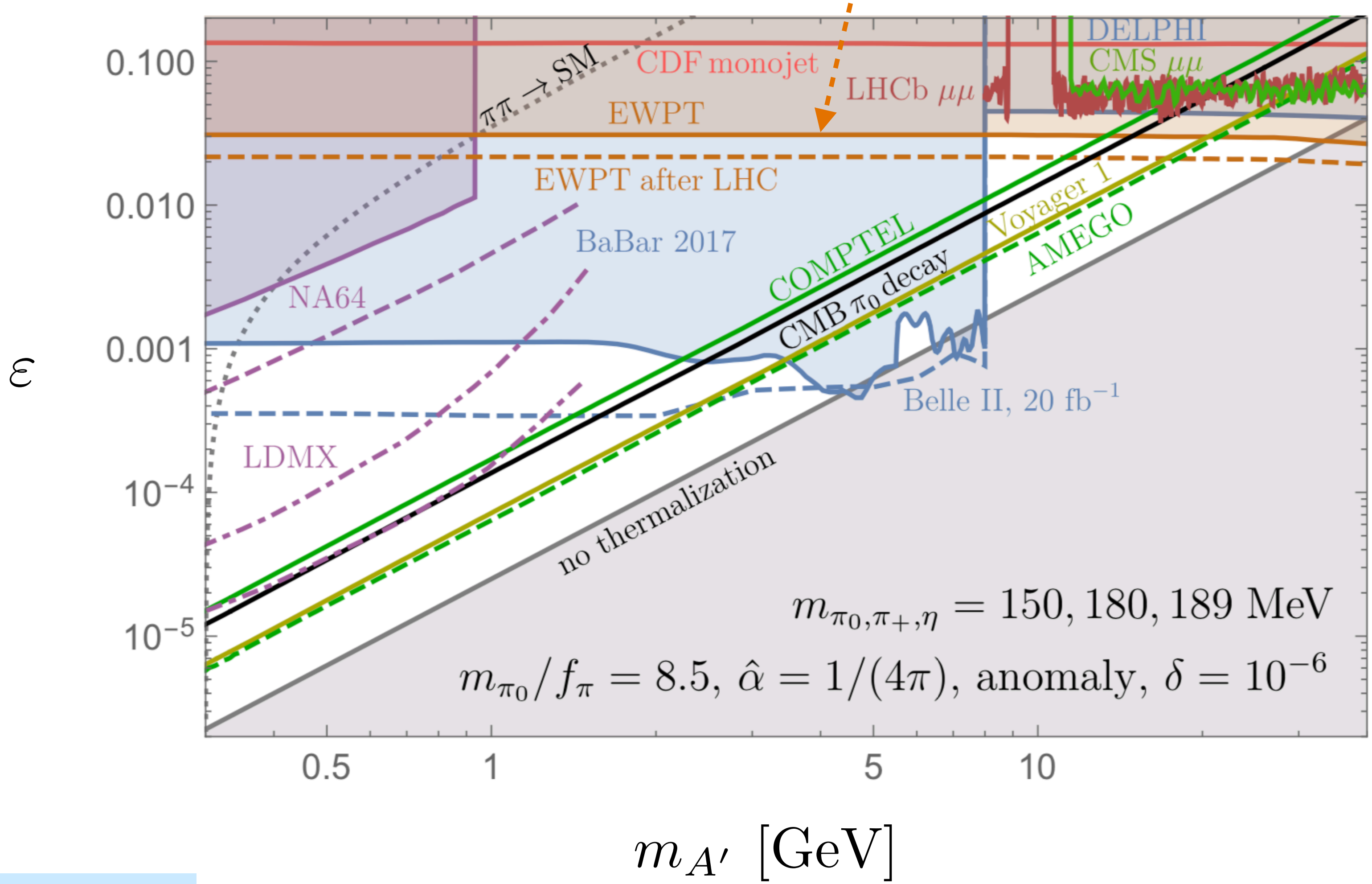
fixed-target experiments



[Katz, Salvioni, Shakya, to appear]

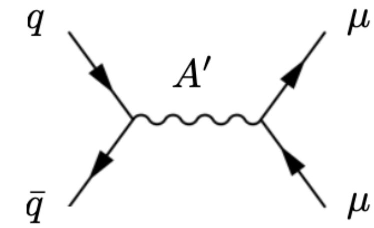
Summary

Z-pole observables $m_Z^2 \approx m_{Z^0}^2(1 + \varepsilon^2 \sin^2 \theta_w)$



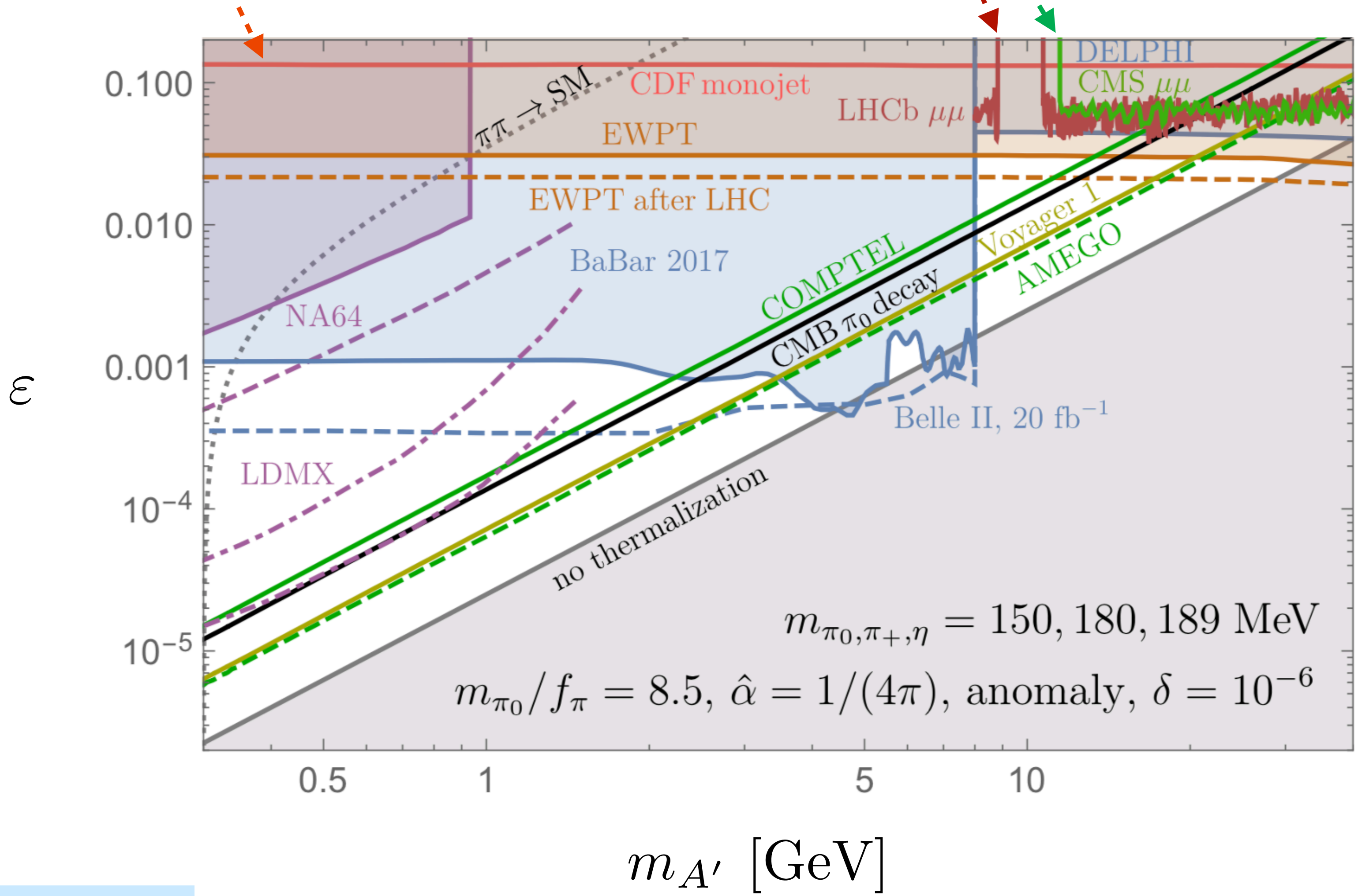
[Katz, Salvioni, Shakya, to appear]

Summary



current ATLAS/CMS monojet bounds are *weaker* than CDF

searches for *visible* decays @ hadron colliders



DM self-interactions

- DM self-scattering

mass term

$$\sigma_{\text{average}} = \frac{m_\pi^2}{256 f_\pi^4} \frac{c^2 + r^2/9}{2N_\pi^2}$$

kinetic term

[Hochberg, Kuflik, Murayama Volansky, Wacker 2014]

$$\Rightarrow \quad \frac{\sigma_{\text{average}}}{m_{\pi_0}} \approx 4.2 \, \frac{\text{cm}^2}{\text{g}} \left(\frac{200 \text{ MeV}}{m_{\pi_0}}\right)^3 \left(\frac{m_{\pi_0}/f_\pi}{9.5}\right)^4$$

- For our parameters, 2 to 6 cm^2/g

  Right size for “puzzles” on small scales (e.g. dwarf galaxies)

[Randall et al. 2007]
[Rocha et al. 2012]
[Peter, Rocha, Bullock, Kaplinghat 2012]

- In some tension with limits from Bullet cluster/halo shapes, $O(1)\ \text{cm}^2/\text{g}$

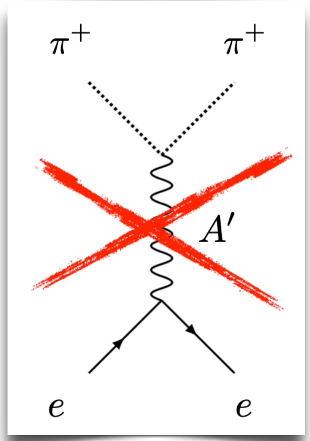
- If π_0 and K_0 masses are split by $\Delta_K \gtrsim v_0^2$, dark matter is only made of π_0

  & cross section ~ 8 times smaller

  But here requires $\delta \gtrsim 10^{-2}$, ruled out by DM decay. Open question

Wrap up

- DM as a triplet of dark mesons, with mass ~ SM pions
- One heavier meson is unstable, but cosmologically viable for sizable mass splittings. $3 \to 2$ freezeout remains effective
- Phenomenology: no DM direct or indirect detection, but plenty of astrophysical and laboratory probes. Interesting “holes” in coverage exist



- Theory: new insight on viable spectra and required accuracy of symmetry stabilizing DM

This talk

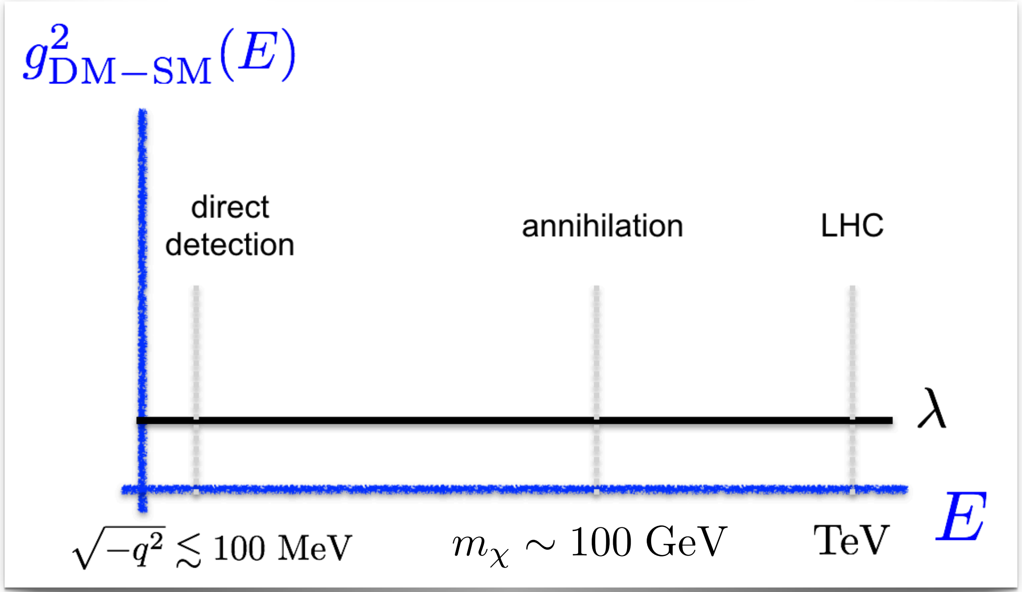
- Introduction

- Dark mesons at the strong scale
  - Mini-review of SIMP dark matter
  - Our setup and cosmology
  - Constraints and signatures

- **Dark mesons at the weak scale**

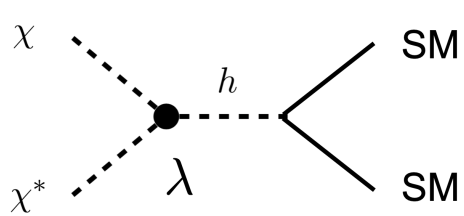
Vanilla WIMP

- The tension with WIMPs, in a nutshell



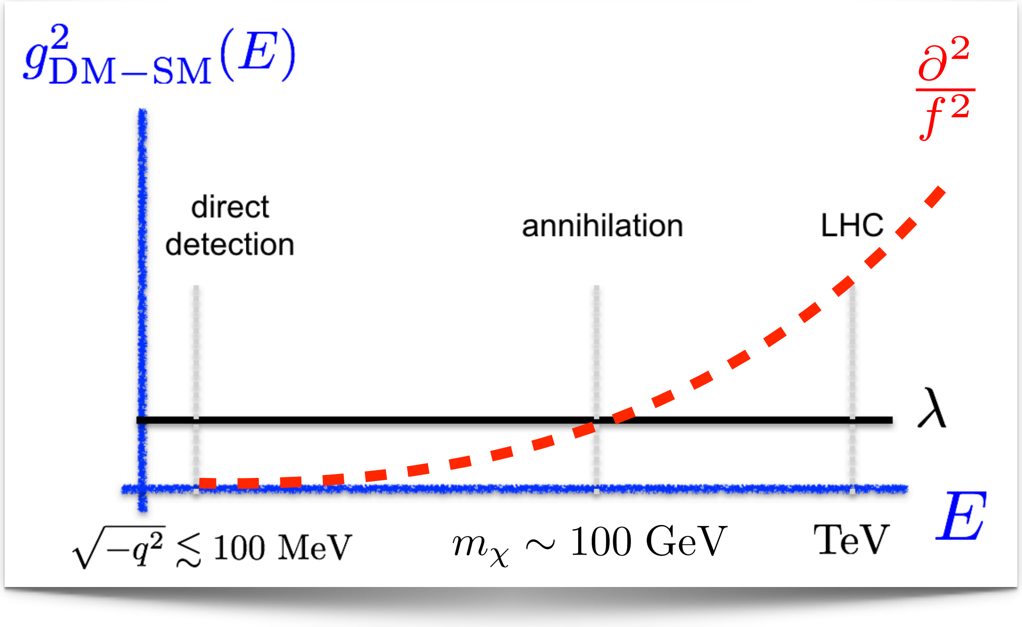
"Higgs portal dark matter"

$$\mathcal{L} \ni \lambda |H|^2 |\chi|^2$$



Pseudo-Goldstone WIMP

- The tension with WIMPs, in a nutshell

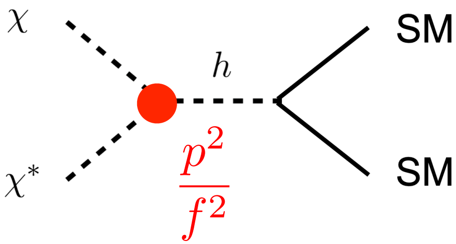


[Frigerio, Pomarol, Riva, Urbano 2012]
[Bruggisser, Urbano, Riva 2016]

Goldstone shift symmetry

$$\chi \to \chi + \epsilon$$

leading coupling $\mathcal{L} \ni \frac{1}{f^2}\partial_\mu |H|^2 \partial^\mu |\chi|^2$



pNGB Dark Matter

- Scalar DM candidate χ

$$\mathcal{L}_{\rm BSM} = |\partial_\mu \chi|^2 + \frac{1}{f^2}\partial_\mu |\chi|^2 \partial^\mu |H|^2 - m_\chi^2 |\chi|^2 - \cancel{\lambda |\chi|^2 |H|^2} + \ldots$$

pNGB Dark Matter

- Scalar DM candidate χ

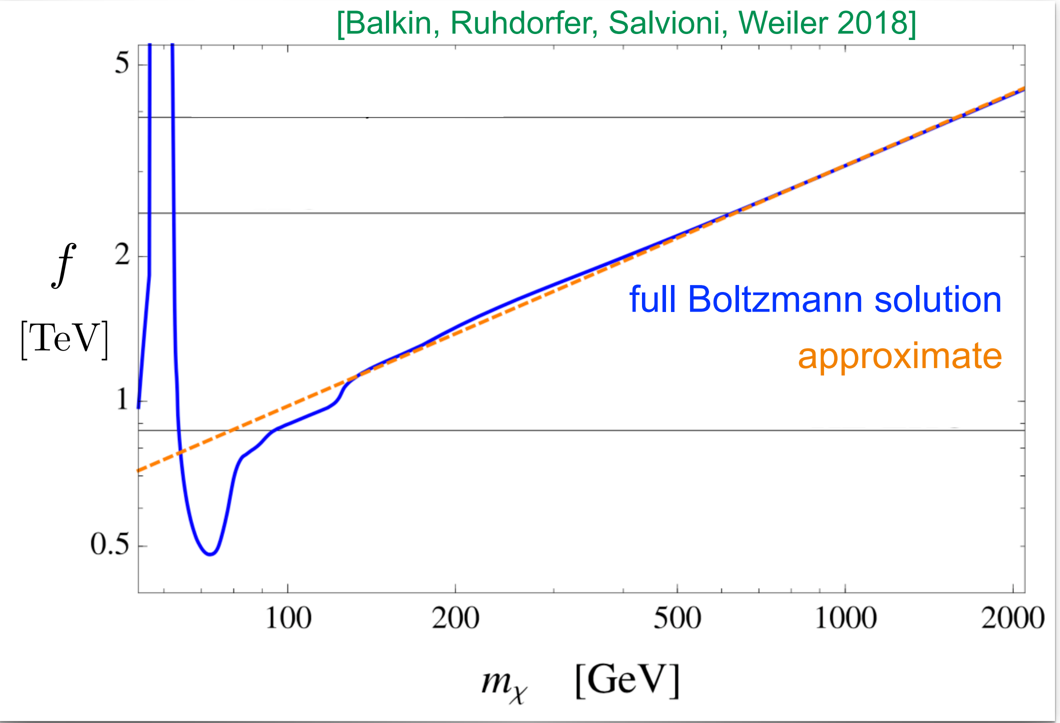
$$\mathcal{L}_{\rm BSM} = |\partial_\mu \chi|^2 + \frac{1}{f^2}\partial_\mu |\chi|^2 \partial^\mu |H|^2 - m_\chi^2 |\chi|^2 - \cancel{\lambda |\chi|^2 |H|^2} + \dots$$

- Freeze-out reproduces relic density for $f \sim \mathrm{TeV}$ and $m_\chi \sim m_h$

$$\langle \sigma v \rangle \simeq \frac{m_\chi^2}{\pi f^4}$$

$$\Downarrow$$

$$f \simeq 1.1\ \mathrm{TeV} \left(\frac{m_\chi}{130\ \mathrm{GeV}}\right)^{1/2}$$

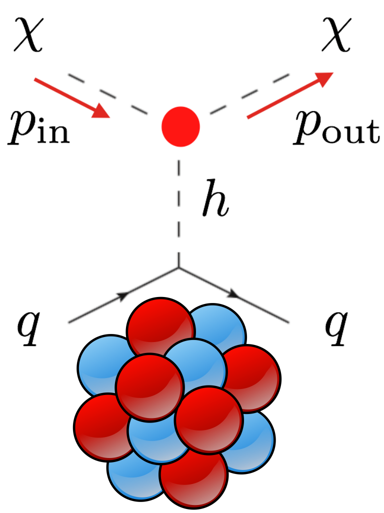


pNGB Dark Matter

- Scalar DM candidate χ

$$\mathcal{L}_{\rm BSM} = |\partial_\mu \chi|^2 + \tfrac{1}{f^2}\partial_\mu |\chi|^2 \partial^\mu |H|^2 - m_\chi^2 |\chi|^2 - \cancel{\lambda |\chi|^2 |H|^2} + \dots$$

- Direct detection extremely suppressed (below “neutrino floor”)

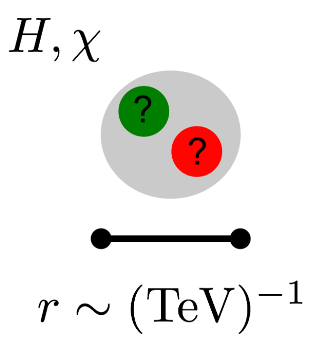


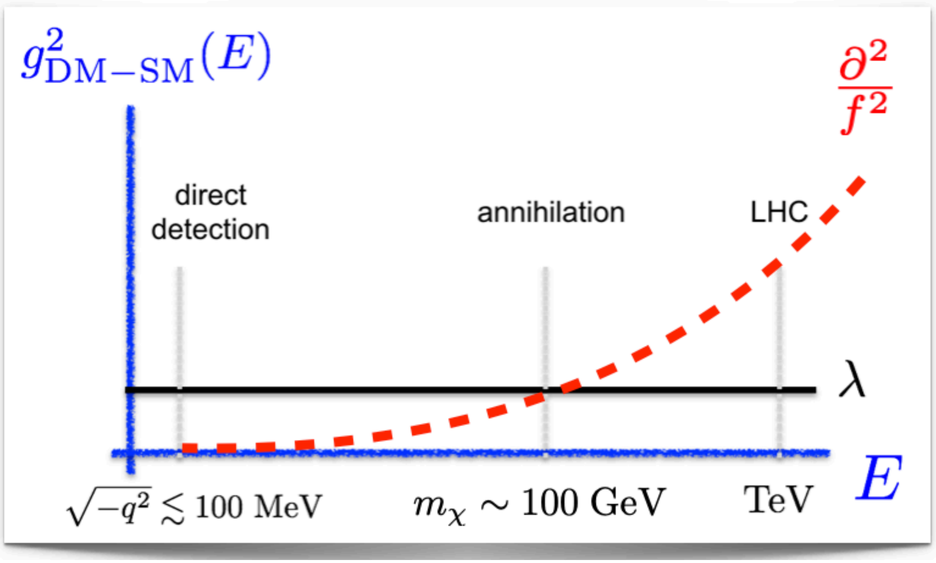
$$\propto \frac{(p_{\rm in} - p_{\rm out})^2}{f^2} = \frac{q^2}{f^2} \sim \frac{m_\chi^2 v_{\rm DM}^2}{f^2} \sim 10^{-8}$$

$$(v_{\rm DM} \sim 10^{-3})$$

pNGB Dark Matter

- This picture can arise if **both Higgs and DM** are composite pNGBs, with decay constant $f \sim \mathrm{TeV}$





- Appealing solution to Higgs naturalness problem
- Dark matter stabilized by discrete or continuous symmetry
- Naturally light (and weakly coupled) at low energies

[Frigerio, Pomarol, Riva, Urbano 2012]
[Balkin, Ruhdorfer, Salvioni, Weiler 2017]

pNGB Dark Matter

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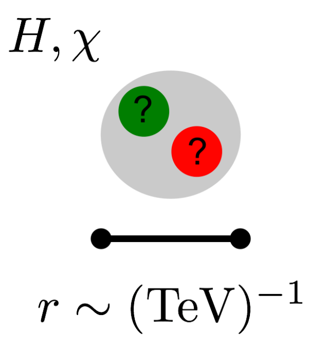
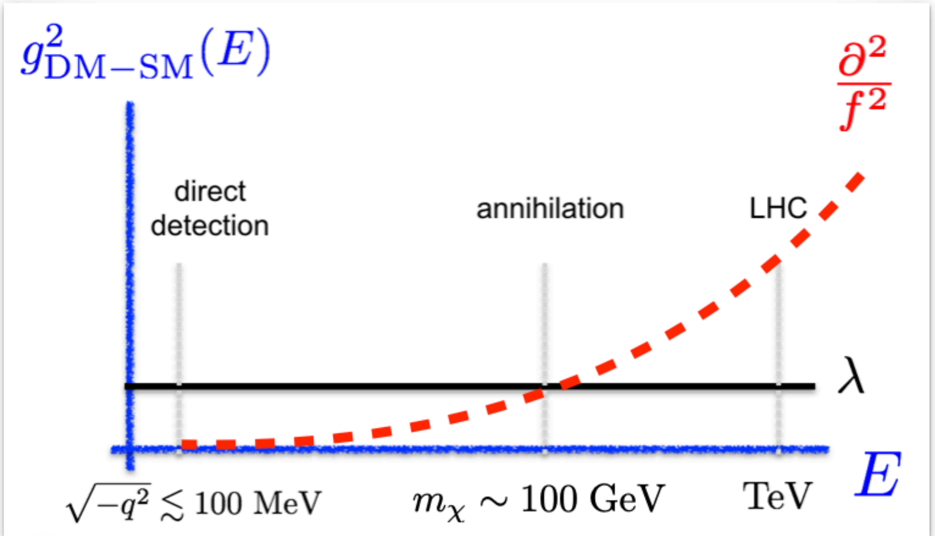
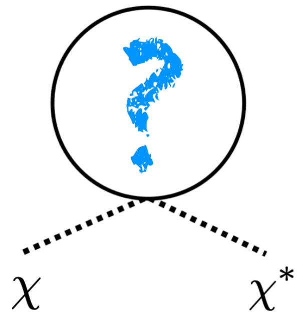




- λ is dangerous even @1 loop. Generate m_χ without spoiling picture?
- Which other probes? Reach at colliders?

[Balkin, Ruhdorfer, Salvioni, Weiler 2017, 2018]

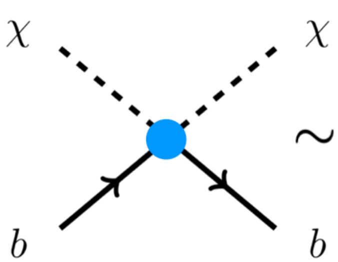
Origin of dark matter mass



- Higgs doublet + complex scalar DM as pNGBs of $SO(7)/SO(6)$
- DM mass arises from largest breaking of its shift symmetry

✓ Top quark couplings: already ruled out by XENON1T

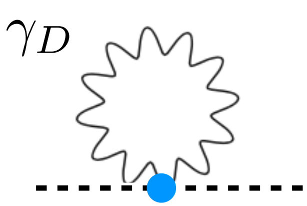
✓ Bottom quark couplings: signal @LZ (next generation direct detection)



$\sim \frac{m_b}{f^2}$

$$\sigma_{\mathrm{SI}}^{\chi N} \approx 1.0 - 5.6 \times 10^{-47}\ \mathrm{cm}^2 \left(\frac{1\ \mathrm{TeV}}{f}\right)^4 \left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2$$

✓ Dark sector couplings: gauge *U*(1) symmetry that stabilizes χ,



$$m_\chi \simeq \sqrt{\frac{3\alpha_D}{2\pi}}\, m_\rho \approx 100\ \mathrm{GeV} \left(\frac{\alpha_D}{10^{-3}}\right)^{1/2} \left(\frac{m_\rho}{5\ \mathrm{TeV}}\right)$$

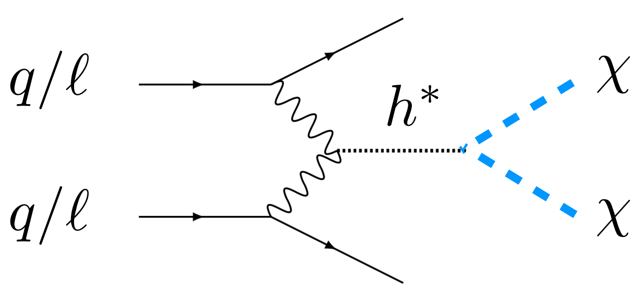
$\lambda |H|^2 |\chi|^2$ @2 loops, below neutrino floor

[Balkin, Ruhdorfer, Salvioni, Weiler 2018]

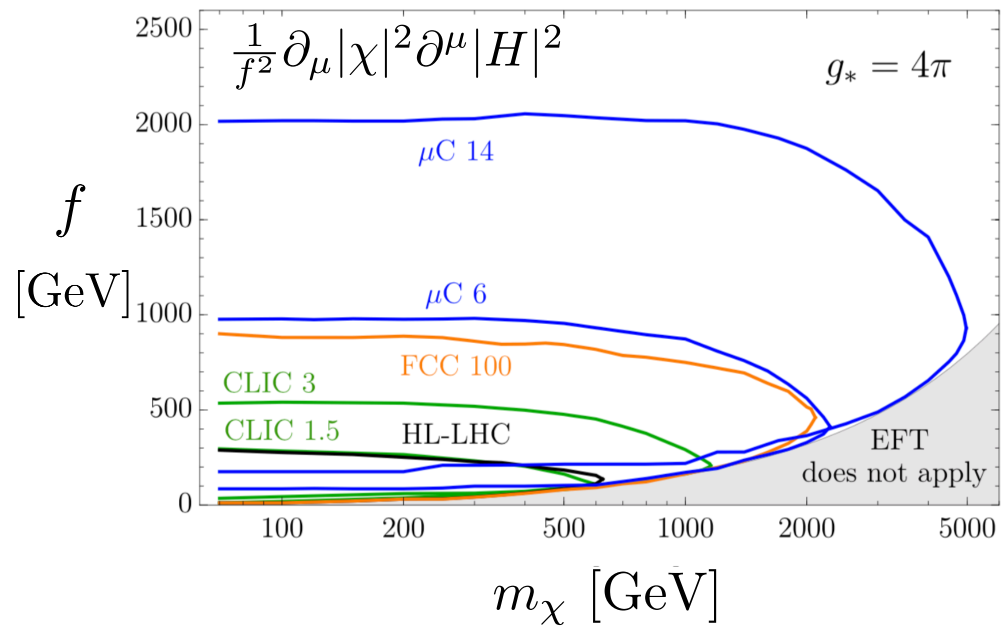
Indirect & laboratory probes

- Indirect detection similar to “vanilla” WIMPs (*s*-wave annihilation)
- Collider sensitivity is being explored

Vector boson fusion



[Ruhdorfer, Salvioni, Weiler 2019]



Off-shell Higgs production

[Haisch, Ruhdorfer, Salvioni, Venturini, Weiler, in progress]