ALPino cosmology and its detection prospect

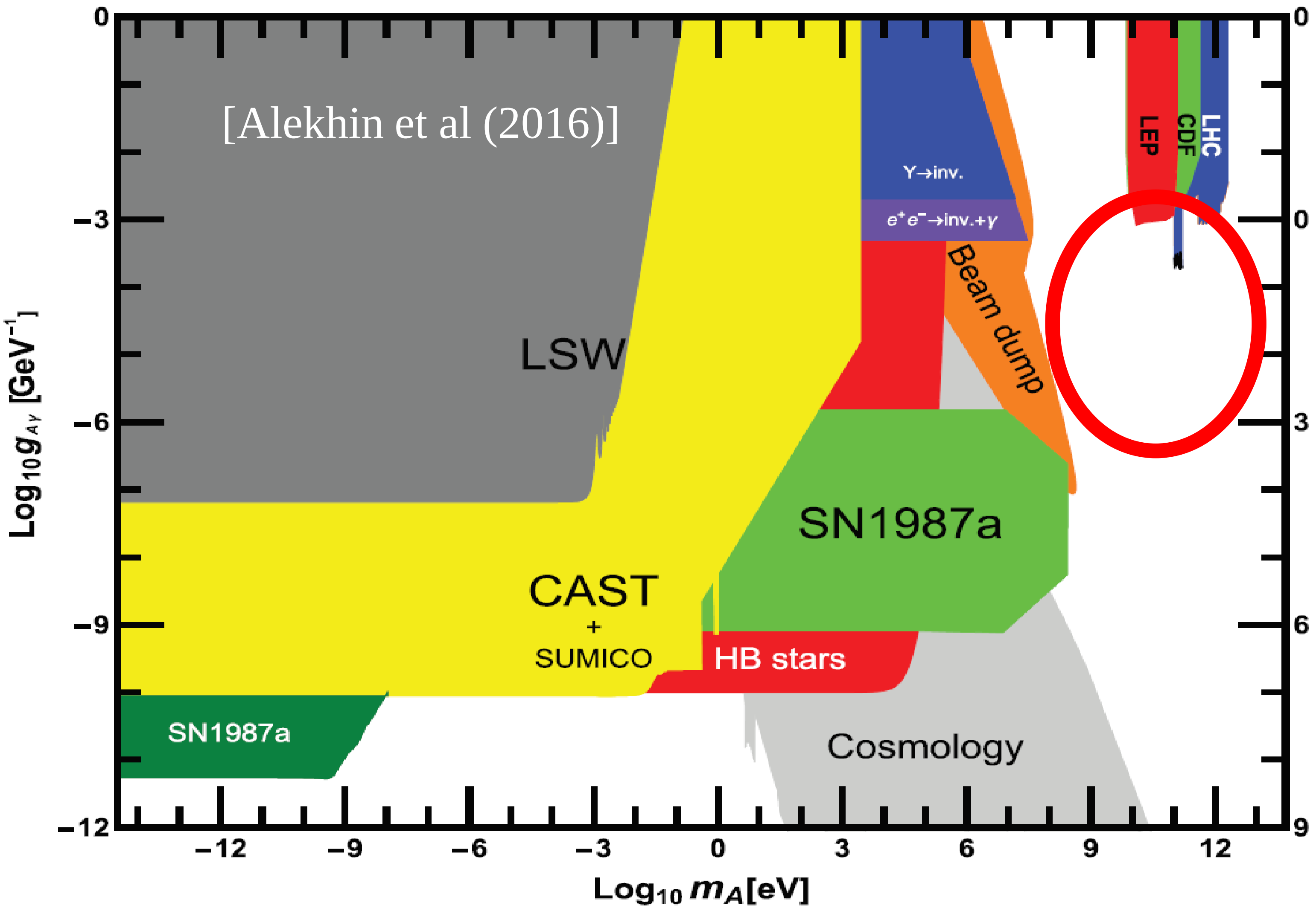
Osamu Seto (Hokkaido Univ.)

With: Ki-Young Choi, Takeo Inami, Kenji Kadota , Inwoo Park

Ref : 1902.10475

§ Introduction

- Axion (a) is interesting.
  - A solution to the Strong CP problem
  - Astrophysical and cosmological constraints
  - Good DM candidate
- General axion: Axion-like Particles (ALPs)
  - Universal : e.g., String Compactification, Axiverse, …
  - Mass and decay constant as free parameters
    - Today, we consider ALP mass larger than QCD axion's.



- Today, we consider ALP mass larger than QCD axion’s.

Heavy ALPs is an interesting to explore

§ Introduction

- Axion (a) is interesting.
  - A solution to the Strong CP problem
  - Astrophysical and cosmological constraints
  - Good DM candidate
- General axion: Axion-like Particles (ALPs)
  - Universal : e.g., String Compactification, Axiverse, …
  - Mass and decay constant as free parameters
    - Today, we consider ALP mass larger than QCD axion’s.
- Supersymmetry
  - Superparticle

§ Supersymmetric model with ALPs

Model

- Superpartner of ALP: ALPino $\tilde{a}$
  - Analogus to Axino
    - F_a suppressed interaction
    - Could be the lightest supersymmetric particle, LSP, which is stable for a R-parity conserving model.
    - Dark matter candidate
  - axion decay constant as a free parameter
    - Free f_a suppression
- Interaction (ALPino-photino-photon)

$$\mathcal{L}_{\mathrm{int}} = \frac{\alpha_{\mathrm{em}} C_{a\gamma\gamma}}{16\pi f_a} \tilde{a}\gamma_5[\gamma^\mu, \gamma^\nu]\tilde{\gamma} F_{\mu\nu}$$

Model

- Superpartner of ALP: ALPino $\tilde{a}$
- Interaction (ALPino-photino-photon)

$$\mathcal{L}_{\rm int} = \frac{\alpha_{\rm em} C_{a\gamma\gamma}}{16\pi f_a} \tilde{a}\gamma_5[\gamma^\mu, \gamma^\nu]\tilde{\gamma} F_{\mu\nu}$$

- Mass spectrum
  - ALPino LSP (good DM candidate too)
  - Bino-like neutralino NLSP
- Free parameter
  - ALPino mass [Chun, Kim, and Nilles (1992), Chun and Lukas (1992)], ALPs decay constant, Neutralino mass

§ ALPino cosmology : ALPino as dark matter

Review of axino dark matter

- ALPino : a variant of axino
- Axino dark matter [Covi et al (1999)]
  - Interaction

$$\mathcal{L}_{\rm int} = \frac{\alpha_{\rm em} C_{a\gamma\gamma}}{16\pi f_a} \tilde{a}\gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{\gamma} F_{\mu\nu}$$

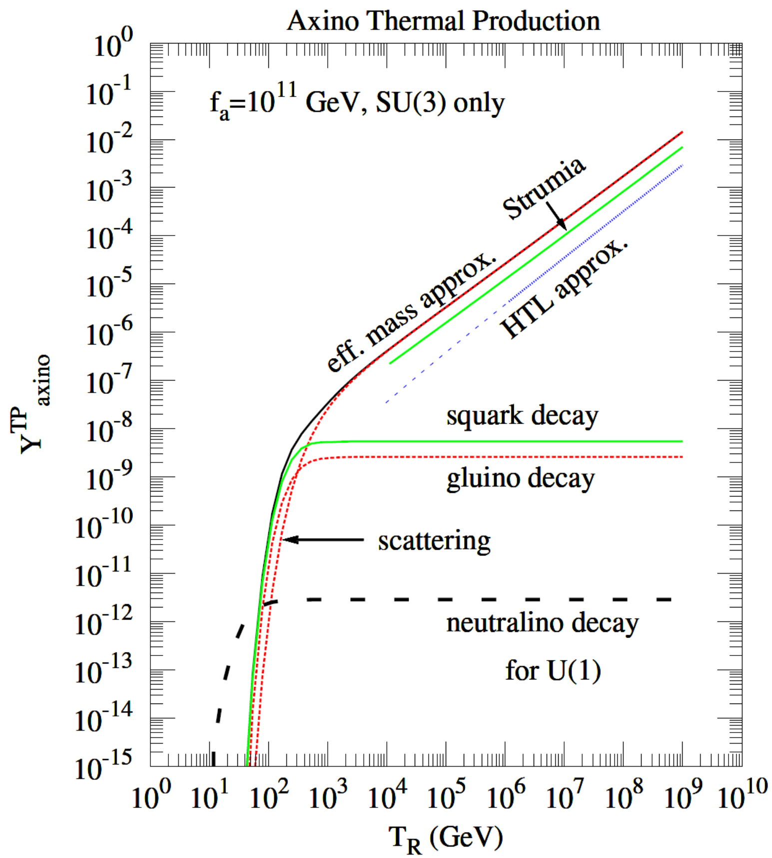
  - Production
    - Scattering and decay in thermal plasma

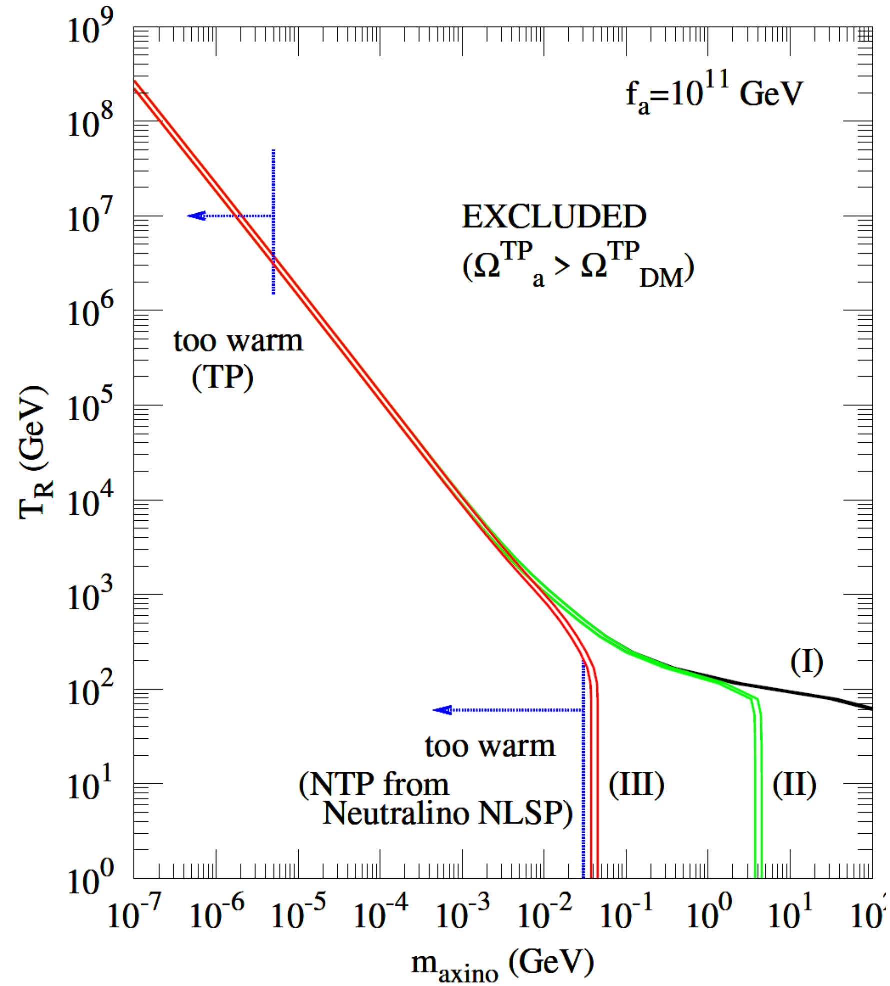
n	Process	$\overline{\sigma}_N$	$n_{\rm spin}$	$n_{\rm F}$	$\eta_1\eta_2$
A	$g^a + g^b \to \tilde{a} + \tilde{g}^c$	$\frac{1}{8}\|f^{abc}\|^2$	4	1	1
B	$g^a + \tilde{g}^b \to \tilde{a} + g^c$	$\frac{5}{16}\|f^{abc}\|^2 \left[\log\left(s/m_{\rm eff}^2\right) - \frac{15}{8}\right]$	4	1	$\frac{3}{4}$
C	$g^a + \tilde{q}_k \to \tilde{a} + q_j$	$\frac{1}{8}\|T^a_{jk}\|^2$	2	$N_F \times 2$	1
D	$g^a + q_k \to \tilde{a} + \tilde{q}_j$	$\frac{1}{32}\|T^a_{jk}\|^2$	4	$N_F \times 2$	$\frac{3}{4}$
E	$\tilde{q}_j + q_k \to \tilde{a} + g^a$	$\frac{1}{16}\|T^a_{jk}\|^2$	2	$N_F \times 2$	$\frac{3}{4}$
F	$\tilde{g}^a + \tilde{g}^b \to \tilde{a} + \tilde{g}^c$	$\frac{1}{2}\|f^{abc}\|^2 \left[\log\left(s/m_{\rm eff}^2\right) - \frac{29}{12}\right]$	4	1	$\frac{3}{4}\ \frac{3}{4}$

    - Nonthermal production: decay of NLSP

Review of axino dark matter

- Abundance
  - Proportional to T_R/f_a^2



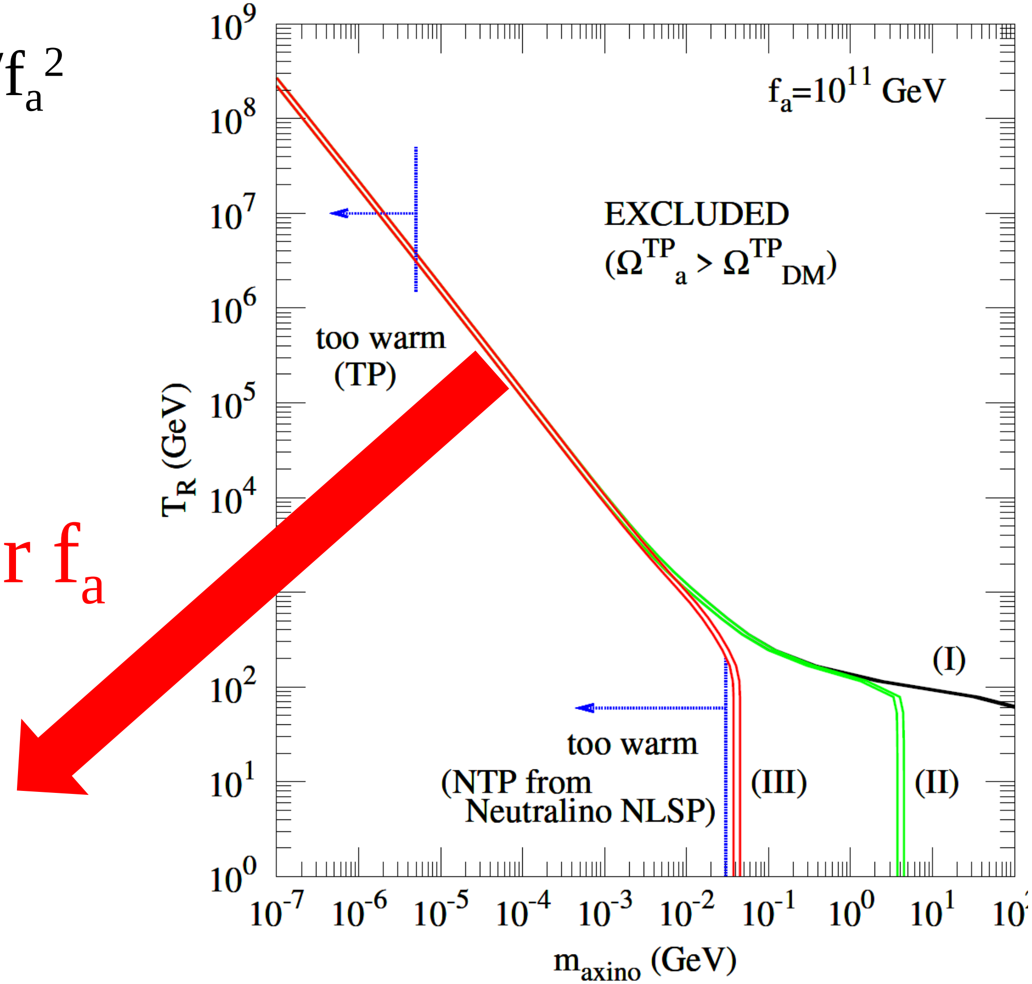


[Choi et al (2012)]

Review of axino dark matter

- Abundance
  - Proportional to T_R/f_a^2

ALPino: Smaller f_a



[Choi et al (2012)]

ALPino abundance

- Freeze out temperature

$$T_f \simeq 1\,\mathrm{GeV}\left(\frac{f_a}{10^5\,\mathrm{GeV}}\right)^2\left(\frac{0.01}{\alpha_{\mathrm{em}}}\right)^3$$

- Thermal relic?
  - For $T_f > m_{\tilde{a}}$, hot relic
  - For $T_f < m_{\tilde{a}}$, $f_a > 10^4$ GeV leads to overabundance

- A way out
  - Non-thermal production with a low reheating temperature ($T_R \ll m_{\chi}$)

ALPino abundance

- A way out
  - Non-thermal production with a low reheating temperature ($T_R \ll m_\chi$)

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = C_{\rm coll.}(f\bar{f} \to \tilde{\chi}_1^0 \tilde{a}) + C_{\rm decay}(\tilde{\chi}_1^0 \to \tilde{a} + \gamma),$$

- $\longrightarrow$ Integrated to T_R
- $\longrightarrow$ $$\Omega_{\tilde{a}} h^2 \simeq 6.8 \times 10^{28} \frac{\alpha \sum_f Q^2}{8\pi^{13/2} g_*^{3/2}} \left(\frac{\alpha m_{\tilde{\chi}_1^0}}{8\pi f_a} \right)^2 \times \left(\frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1^0}} \right) \left(\frac{m_{\tilde{\chi}_1^0}}{T_R} \right)^{3/2} e^{-m_{\tilde{\chi}_1^0}/T_R},$$
- Problem of baryogenesis… (as in Axino DM…)

§ ALPino detection : as a long-lived particle

Model

- Superpartner of ALP: ALPino $\tilde{a}$
- Interaction (ALPino-photino-photon)

$$\mathcal{L}_{\rm int} = \frac{\alpha_{\rm em} C_{a\gamma\gamma}}{16\pi f_a} \tilde{a}\gamma_5[\gamma^\mu, \gamma^\nu]\tilde{\gamma} F_{\mu\nu}$$

- Process

$$pp \to M + X \quad \text{with} \quad M \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X'$$

$$\tilde{\chi}_1^0 \to \begin{cases} \tilde{a} + \gamma \\ \tilde{a} + l^+ + l^- \end{cases}$$

- Detection
  - CHARM, NOMAD, SHiP
  - $c\tau \sim 100$ m

§ § Production

- in SHiP
  - SPS: energy = 400 GeV ($\sqrt{s}$ ~27.4 GeV)
  - N_{proton} ~ 2 ×10^{20} for 5 years [Alekhin et al (2016)]
- The number of produced mesons
  - Multiplicity

$$N_M = N_{\rm pot} \times N_{M,multi}$$

Meson	π^+	π^0	π^-	K^+	K^-
$N_{M,multi}$	4.10	3.87	3.34	0.331	0.224
Meson	K_S^0	η	ρ^0	ω	ϕ
$N_{M,multi}$	0.232	0.30	0.385	0.390	0.019

[Becattini and Heinz (1997)]

  - For J/Ψ and B

$$N_M = N_{\rm pot} \frac{\sigma_M}{\sigma_{pN}}$$

σ_M : meson production per nucleon

$\sigma_{J/\Psi}$ ~ 200 nb, σ_B ~ 3.6 nb

§ § ALPino in the fixed target

- The decay rate of the neutralino

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{a} + \gamma) = \frac{\alpha_{\rm em}^2 C_{a\chi\gamma}^2}{128\pi^3} \frac{m_{\tilde{\chi}_1^0}^3}{f_a^2} \left(1 - \frac{m_{\tilde{a}}{}^2}{m_\chi^2}\right)^3$$

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{a} + l^+ + l^-) \simeq \frac{\alpha_{\rm em}^3 C_{a\chi\gamma}^2}{512\pi^4} \frac{m_\chi^3}{f_a^2} \left(4 \ln \frac{m_{\tilde{\chi}_1^0}}{m_l} - 6\right),$$

- Lifetime

$$\tau(\tilde{\chi}_1^0 \to \tilde{a} + \gamma)$$

$$= 0.49 \times 10^{-9} \sec \left(\frac{1/128}{\alpha_{\rm em}}\right)^2 \left(\frac{f_a}{10^5\,\text{GeV}}\right)^2 \left(\frac{10\,\text{GeV}}{m_{\tilde{\chi}_1^0}}\right)^3$$

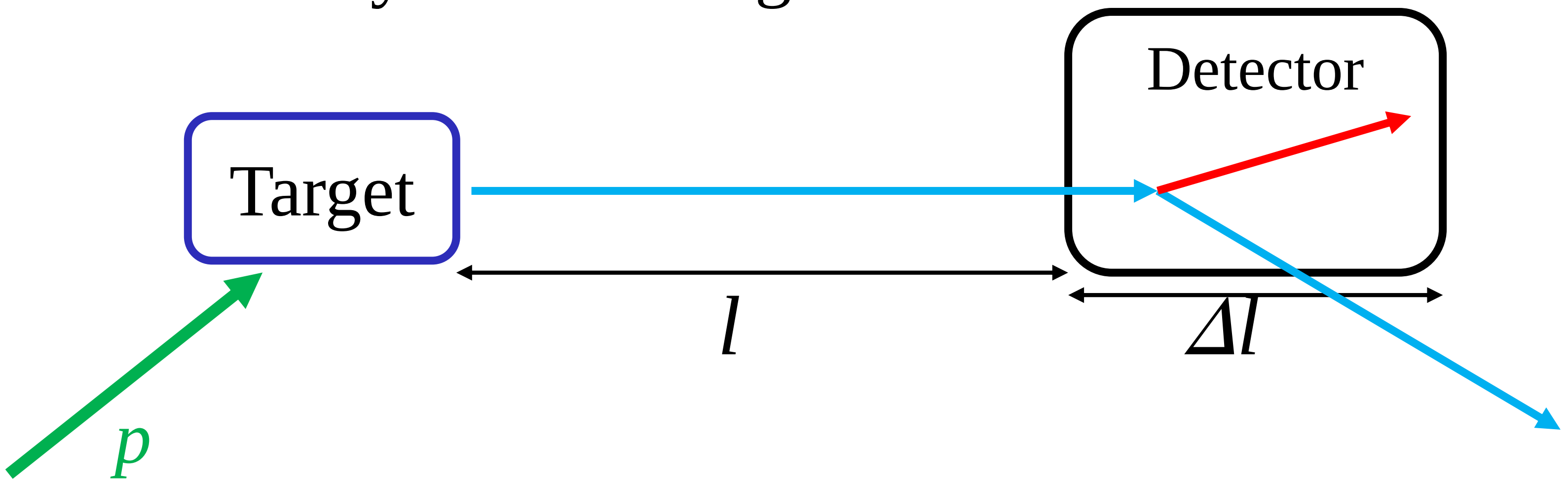
- Reference scale: for $c\tau$ ~100 m

§ § ALPino in the fixed target

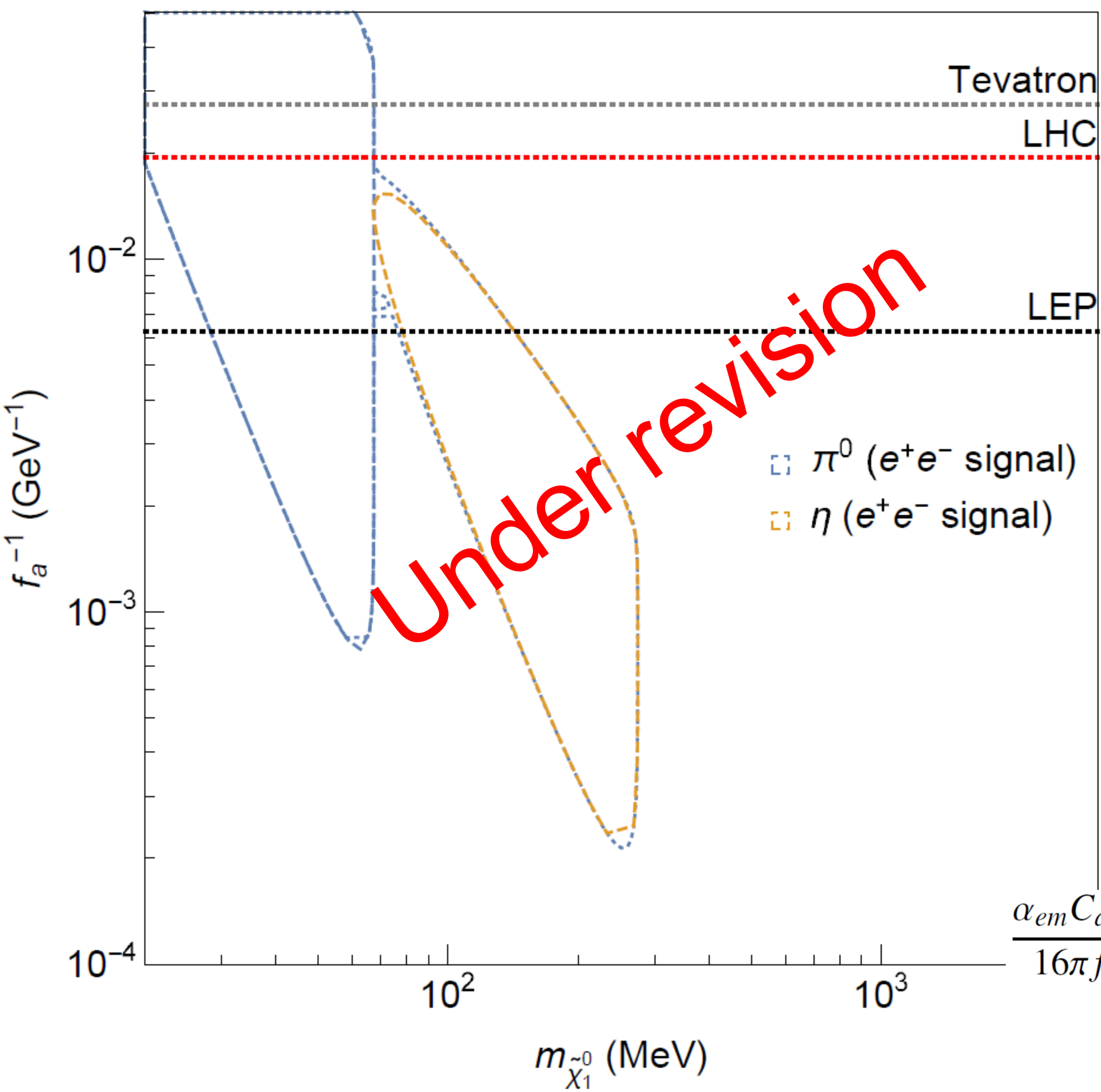
- The number of neutralino decay events

$$N_{\rm det} \simeq N_{\tilde{\chi}_1^0}\left[\exp\left(-\frac{l}{\gamma\beta c\tau}\right)-\exp\left(-\frac{l+\Delta l}{\gamma\beta c\tau}\right)\right]$$

  - *l* : distance from the target = 70 m
  - *Δl* : decay volume length = 55 m



§ § Constraints and Prospect 1



$m_{\tilde{a}} = 10$ MeV

$\tan\beta = 10$

$\mu = 100$ TeV

$m_{squark} = 10$ TeV

CAHRM, NOMAD

$$N_{\tilde{\chi}_1^0 \to \tilde{a}+l^+ + l^-} < N^{90\%}_{e^+e^-}$$

with N_{ee}~2

N>3 for SHiP

Mono-X by dipole

$$\frac{\alpha_{em} C_{a\gamma\gamma}}{16\pi f_a} \bar{\tilde{a}} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{\gamma} F_{\mu\nu} = -\frac{\alpha_{em} C_{a\gamma\gamma}}{8\pi f_a} \bar{\tilde{a}} \sigma_{\mu\nu} \tilde{\gamma} \tilde{F}^{\mu\nu}$$

for Tevatron, LHC, LEP

§ Summary

- ALPino: super-partner of ALPs
- $c\tau$ of the neutralino decay is $\mathcal{O}(100)$ m

- Range of search
  - Light neutralino < GeV
  - Decay constant $f \sim 10^5$ GeV