Axinos as Light Dark Matter

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Dark Side of the Universe
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Light Dark Matter - Introduction

- Evidences for Dark Matter – Rotation Curves, SDSS, WMAP, ...
- Nature of DM – Neutral, Weakly Interacting, Stable

  $\Omega_{DM} \simeq 0.2$
- Light Dark Matter (LDM)
  - Mass 1 – 20 MeV
  - Decay or Annihilation

    511 keV γ-rays from the galactic bulge

    γ-ray background in 1 – 20 MeV range
  - Particle physics models

    Annihilation – ?

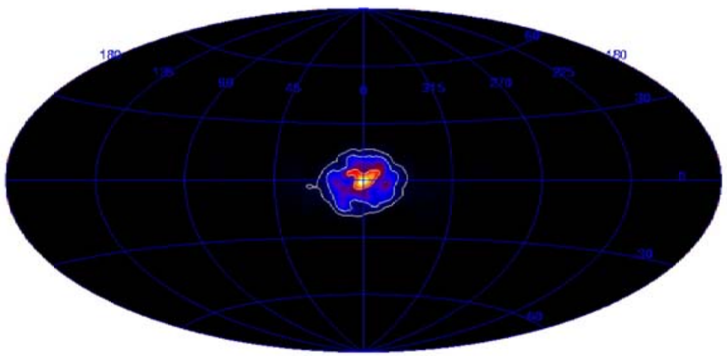
    Decay – Axino, Moduli

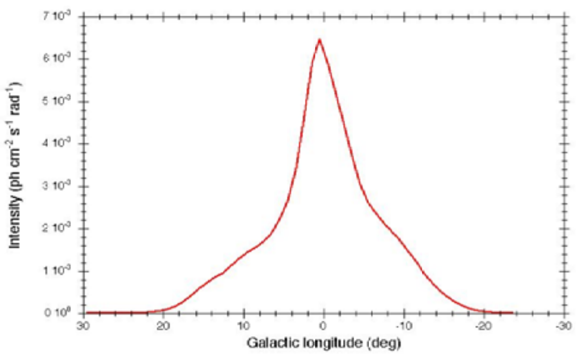
511 keV γ rays from the galactic center

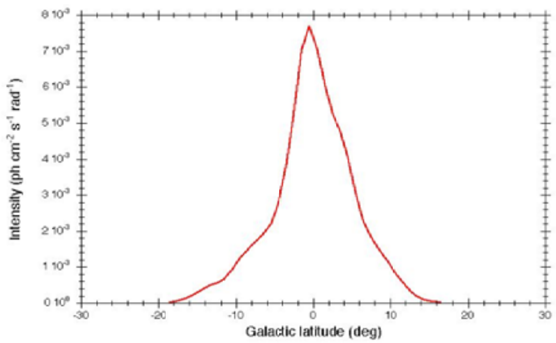
- Discovery : Johnson, Harnden, Haymes, ApJ 172, L1 (1972)
- Identification: Leventhal, MacCallum, Stang ApJ 225, L11 (1978)

  e^+e^- annihilation

- Mystery – the origin of low energy galactic positrons
- the Latest observation – SPI aboad in INTEGRAL
  - total flux $\approx 10^{-3}$ photons / $cm^2 \cdot s$
  - morphology of galactic bulge emission
    - $\sim$ Gaussian with $\sim 10°$ FWHM
  - disc component : large B/D luminorsity ratio, 3–9
    (cf. B/D mass ratio 0.3–1.0)







Astrophysical Sources — proposed so far

- Massive stars
- Hypernova
- Cosmic ray interactions, $N + p \to \pi^+ + e^+$
- X-ray binaries — HMXB, $\boxed{\text{LMXB}}$
- $\boxed{\text{Thermonuclear SNIa}}$

high B/D ratio

Light dark matter annihilation /decay

- The galactic halo profile can explain the high B/D ratio

$$\begin{cases} \text{annihilation}, & \Phi \propto \rho^2 \\ \text{decay}, & \Phi \propto \rho \end{cases}$$

- Energy budget — easy to give enough flux

LDM as the source for galactic 511 keV γ-rays

Boehm, Hooper, Silk, Casse, Paul, PRL 92, 101301 (2004)

Hooper, Wang, PRD 70, 063506 (2004)

- 511 keV γ-rays from the galactic bulge
  - coming from e^+e^- annihilations (at rest)
- The sources of galactic positrons
  - annihilations/decays of LDM particles with mass 1-100 MeV
- Positron propagation and annihilation within the galaxy
  - Propagation

No. density of Hydrogen positron's Lorentz factor

Ionization losses $\frac{dE}{dt} \simeq 2\times10^{-9}\left(\frac{N_H}{10^5\,m^{-3}}\right)(\ln\Gamma + 6.6)\ \mathrm{eV/s}$

Stopping distance $R_{stop} \simeq 10^{24} - 10^{26}$ cm (1-100 MeV)

Positron's Larmor radius $R_{Larm} \simeq \frac{mv}{Bq} \sim 10^{11} - 10^{9}$ cm (100 - 1 MeV)

Confining distance (assuming simple random walk) $R_c \sim \sqrt{R_{stop}\times R_{Larm}} \lesssim 1\,\mathrm{pc}$ 3.1×10^{18} cm

Positrons are easily confined to the galactic bulge.

— Annihilation of e^+e^-

Cross section for pair annihilation of e^+ with e^- at rest

$\sigma_{pa} \simeq 1\ \mathrm{barn}/\Gamma$

positron mean free path $d \sim \frac{1}{N_e \sigma_{pa}} \sim \Gamma \left(\frac{10^5\,\mathrm{m}^{-3}}{N_e} \right) \times 10^{25}\,\mathrm{cm}$

$d \gg R_{stop}$: Annihilations do not occur while positrons are losing energy.

Annihilation after thermalization

$\to$ 511 keV γ-rays

<u>e^+e^- annihilation</u>

direct annihilation 7%

positronium formation 93%

(orthopositronium : $\frac{3}{4}$ $\longrightarrow$ 3γ

(parapositronium : $\frac{1}{4}$ $\longrightarrow$ 2γ

$2\left(0.07 + 0.93 \times \frac{1}{4}\right) = 0.6$ photon per annihilation

- Photon flux

- positron production $\dot{n}_{e^+} = n_{DM}\Gamma$

$$\Gamma = \begin{cases} \Gamma_d & \text{decay} \\ (a + b v_{DM}^2)\, n_{DM*} & \text{annihilation} \end{cases}$$

- photon production $\dot{n}_\gamma = 0.605\, \dot{n}_{e^+}$

- Intensity $I(l,b) = \frac{1}{4\pi}\int_0^\infty \dot{n}_\gamma(\vec{r})\, ds$

galactic coordinates   line-of-sight integration

- Total photon flux $\Phi = \int I(l,b)\, d\Omega$

- Density profile of the galactic dark matter halo

$$n_{DM}(r) = \frac{\rho_{DM}(r)}{2 m_{DM}}$$

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_0}\right)^\gamma \left[1 + \left(\frac{r}{r_0}\right)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}}$$

Normalization $\rho(r_\odot = 8.5\,\text{kpc}) = 0.3\,\text{GeV}\cdot\text{cm}^{-3}$

	α	β	γ	r_0 (kpc)	ρ_0 ($\text{GeV}\cdot\text{cm}^{-3}$)
ISO	2	2	0	4.0	1.655
NFW	1	3	1	16.7	0.347
M99	1.5	3	1.5	29.5	0.0536

- Annihilation of LDM

DM with mass $m_{DM} < m_\mu, m_\pi$

Annihilation channel $\chi + \bar{\chi} \rightarrow \underbrace{e^+e^-}_{\text{dominant}}, \gamma\gamma, \nu\bar{\nu}$

- 511 keV γ-ray flux

$$\Phi \simeq 1.4 \left(\frac{\langle\sigma v\rangle}{\text{pb}}\right)\left(\frac{1\,\text{MeV}}{m_{DM}}\right)^2 \bar{J}(\Delta\Omega)\Delta\Omega \ \text{cm}^{-2}\text{s}^{-1}$$

annihilation cross section

mass of LDM

$\Delta\Omega$: 0.02 sr (9° diameter circle)

$\bar{J}(\Delta\Omega)$: integration over the galactic bulge direction depending on the DM halo profile, $\sim 10 - 100$

$$\simeq 10^{-3}\ \text{ph}\cdot\text{cm}^{-2}\text{s}^{-1} \ \text{(observed value)}$$

$$\left(\frac{\langle\sigma v\rangle}{\text{pb}}\right)\left(\frac{1\,\text{MeV}}{m_{DM}}\right)^2 \simeq 10^{-4} - 10^{-5}$$

- the annihilation cross section required for (cold) thermal relic

$$\frac{\langle\sigma v\rangle}{\text{pb}} \simeq 0.2 \times \frac{x_F}{\sqrt{g_*}}\left(\frac{\Omega_{DM}h^2}{0.11}\right)^{-1}$$

x_F: freeze-out temperature

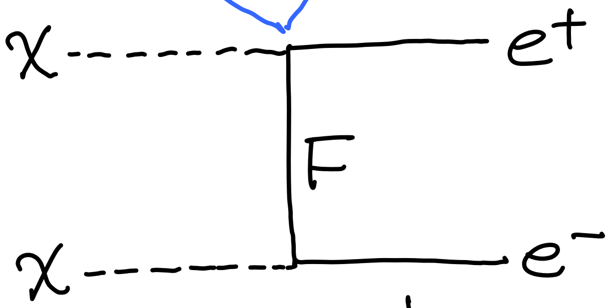
$$x_F \equiv \frac{m_{DM}}{T_F} \simeq 17.2 + \ln\left(\frac{g}{g_*}\right) + \ln\left(\frac{m_D}{\text{GeV}}\right) + \ln\sqrt{x_F}$$

Apparent Discrepancy!

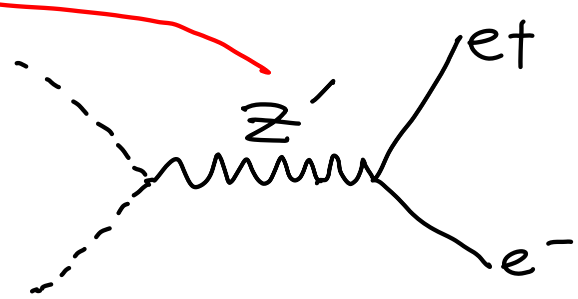
– Possible solution for LDM annihilation

- $m_{DM} \gtrsim 100\,\mathrm{MeV}$, not good
- thermal-averaged cross section
  $\langle \sigma v \rangle$ is small now, but large in the early universe

$$\sigma v \simeq a + b v^2 \quad \text{with} \quad a \ll b$$



fermion exchange



massive gauge boson exchange

$$a \lesssim 10^{-31} \left(\frac{m_{DM}}{\mathrm{MeV}} \right)^2 \mathrm{cm}^3 \mathrm{s}^{-1} , \quad b \sim 10^{-25} \left(\frac{m_{DM}}{\mathrm{MeV}} \right)^2 \mathrm{cm}^3 \mathrm{s}^{-1}$$

Boehm, Ascasibar, PRD 70, 115013 (2004)
Ascasibar, Jean, Boehm, Knödlseder, astro-ph/0507142

* To explain the morphology of 511 keV γ-rays
a-term should be included.

- signature of F-particle
  * muon & electron anomalous magnetic moment, $a_{\mu,e} = (g-2)_{\mu,e}$

$$\delta a_{\mu,e} \sim \frac{f_e f_r}{16\pi^2} \frac{m_{\mu,e}}{m_{F_{\mu,e}}}$$

may explain small discrepancy

$$\delta a_e = a_e^{exp} - a_e^{th} \simeq (3.44 - 3.49) \times 10^{-11}$$

  * production at LHC

$$e^+e^- \longrightarrow F + X$$
$$\hookrightarrow e^- + \chi$$

∘ Decay of LDM

- 511 keV γ-ray flux

$$\Phi_\gamma \simeq \frac{3.0\times10^{66}\,\mathrm{GeV}}{m_{DM}\tau_{DM}}\cdot\frac{1}{4\pi R_{GC}^2}$$

mass within the galactic bulge depends on the DM halo profile

$$\tau_{DM}\left(\frac{m_{DM}}{\mathrm{MeV}}\right) \simeq 4\times10^{26}\,s$$

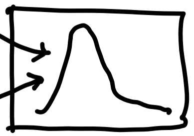
- particle physics models
  * Axino
  * Moduli

* abundance & lifetime are not related in the decay model.

- Morphology of 511 keV γ-rays requires very curspy DM halo profile.

Annihilation $\Phi \propto \rho^2$

Decay $\Phi \propto \rho$



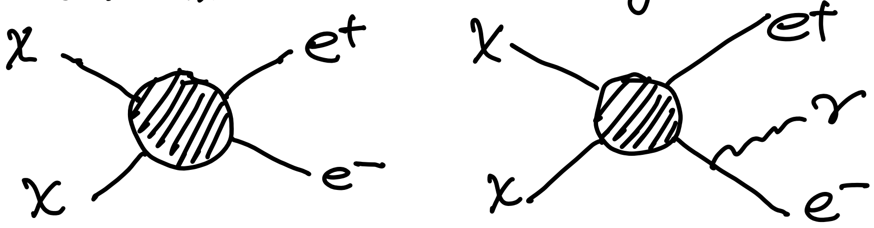
NFW profile does not work for the decay model.

Direct γ ray production from LDM annihilation/decay

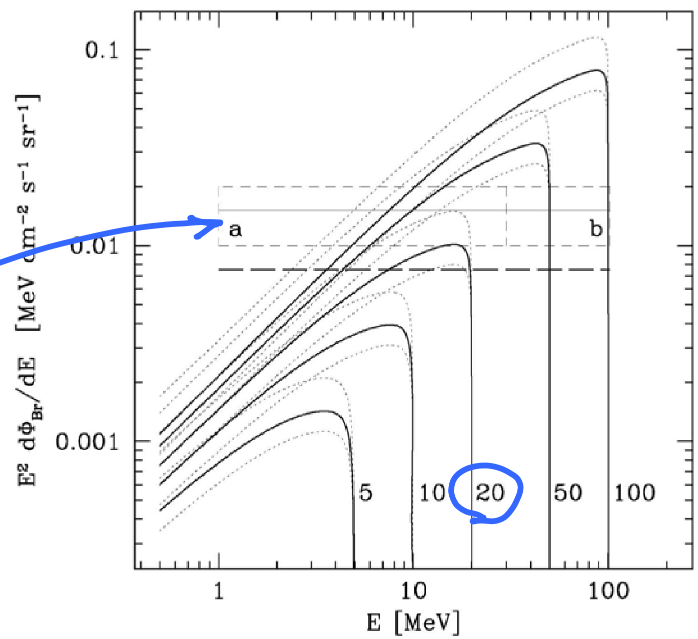
Beacom, Bell, Bertone, PRL 94, 171301 (2005)

The dark matter annihilation process $\chi\chi \to e^+e^-$ is necessarily accompanied by the process $\chi\chi \to e^+e^-\gamma$.

"Internal Bremsstrahlung"



COMPTEL & EGRET measurements of diffuse radiation from the galactic center



$m_{DM} \lesssim 20\,\text{MeV}$

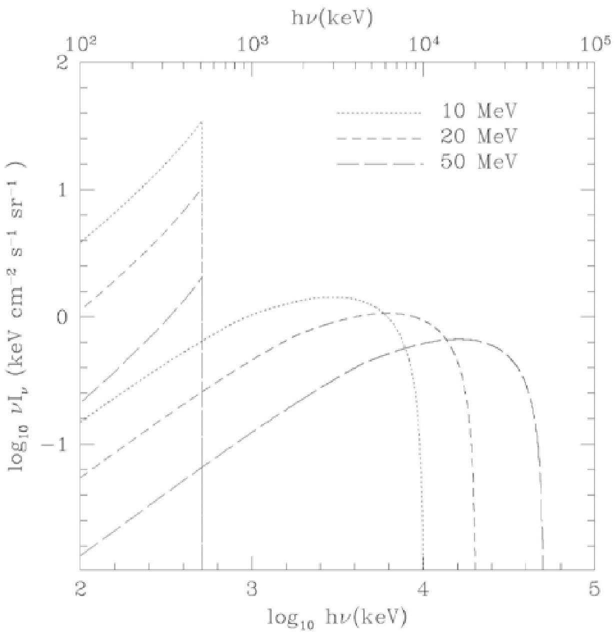
LDM as the origin of cosmic γ-ray background at 1-20MeV

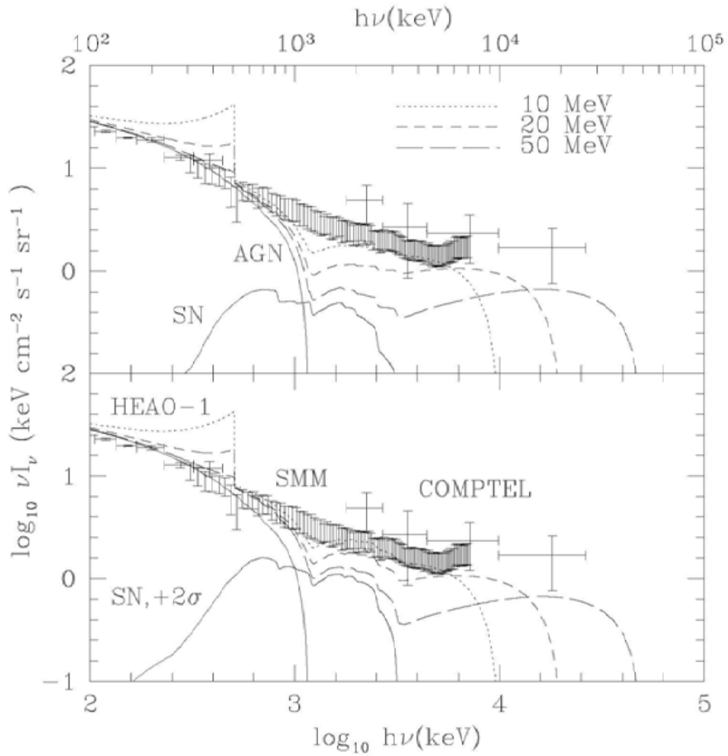
Ahn, Komatsu, PRD 72, 061301 (2005)

The origin of the cosmic γ-ray background is the superposition of unresolved astronomical γ-ray sources distributed in the universe.

* AGNs (ordinary AGNs – low energy ($\lesssim 0.5$MeV)
  beamed AGNs – high energy ($\gtrsim 20$MeV)
* SNs
* 4-20MeV unexplained

LDM
~20MeV





Axinos as LDM

- PQ mechanism + Supersymmetry

Strong CP problem

KSVZ, DFSZ

f_a, PQ scale

axion – pseudo-Goldstone boson of PQ sym.

$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim 10^{-2} - 10^{-5}\,\text{eV}$$

$$\underbrace{10^9\,\text{GeV} \lesssim}_{\text{astrophysical bound}} f_a \underbrace{\lesssim 10^{12}\,\text{GeV}}_{\Omega_a \text{ from initial misalignment}}$$

→ DM axion

Gauge hierachy problem

axion supermultiplet

$$A = \frac{1}{\sqrt{2}}(s + i a) + \sqrt{2}\,\tilde{a}\,\theta + F_A \theta\theta$$

saxion (s), axion (a), axino ($\tilde{a}$)

SUSY breaking

Gravity mediation

Gauge mediation

⋮

Anomaly mediation

Mirrage mediation

- The Axino Mass

The axino mass depends crucially on the way of ~~SUSY~~.

- SUGRA model

  generically $m_{\tilde{a}} \sim m_{3/2} \sim 100\,\mathrm{GeV}$

  special arrangement — No scale model

  $m_{\tilde{a}} \sim 1\,\mathrm{keV} - 10\,\mathrm{GeV}$

- Gauge mediated ~~SUSY~~ (GMSB)

  hidden sector field X, F_X : $\Lambda \equiv \frac{F_X}{X} = 10^4 - 10^5\,\mathrm{GeV}$

  $m_{\tilde{a}} \approx \frac{X F_X}{f_a^2}$ $\quad m_s^2 = \frac{F_X^2}{f_a^2} \Rightarrow m_s^2 = m_{\tilde{a}} \Lambda$

  $m_s \simeq 3\text{–}30\,\mathrm{GeV}$ for $m_{\tilde{a}} = 1\text{–}10\,\mathrm{MeV}$

* Working in DFSZ + GMSB for illustration

- The origin of cosmic axinos
  - the reheat temperature T_R
  - the axino decoupling temperature

$$T_{aD} \approx 10^{10}\,\text{GeV}\left(\frac{f_a}{10^{11}\,\text{GeV}}\right)\left(\frac{\alpha_s}{0.1}\right)^3$$

- Thermal production

  $T_R > T_D$: axinos overpopulated if $m_{\tilde{a}}$ > a few keV

  $T_R < T_D$: Regeneration from the thermal bath

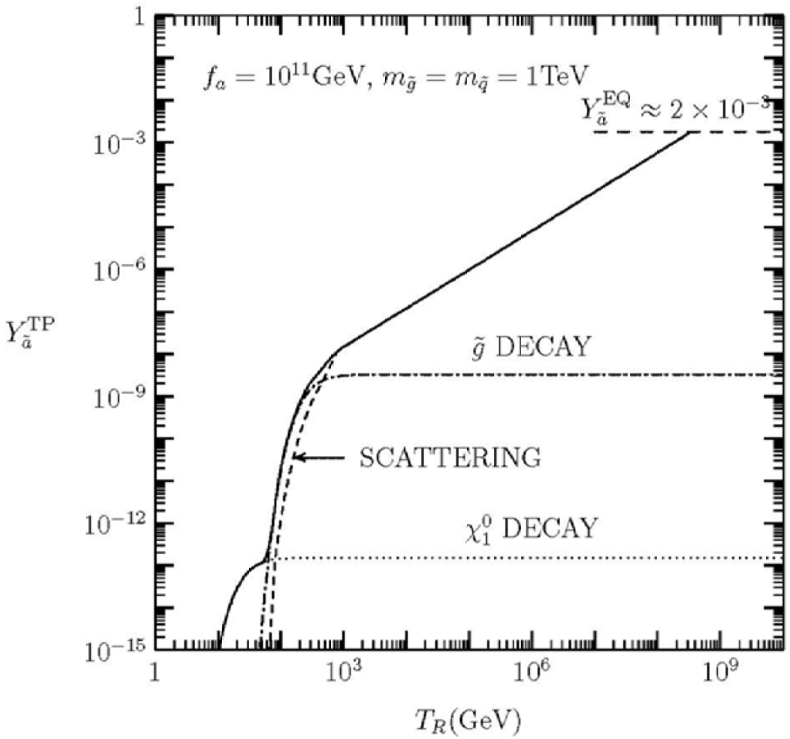
$$\Omega_{\tilde{a}} h^2 = 0.28\left(\frac{m_{\tilde{a}}}{\text{MeV}}\right)\left(\frac{T_R}{10^5\,\text{GeV}}\right)\left(\frac{f_a}{10^{11}\,\text{GeV}}\right)^{-2}$$

$$T_R \simeq 10-100\,\text{TeV} \text{ for } m_{\tilde{a}} = 1-20\,\text{MeV}$$

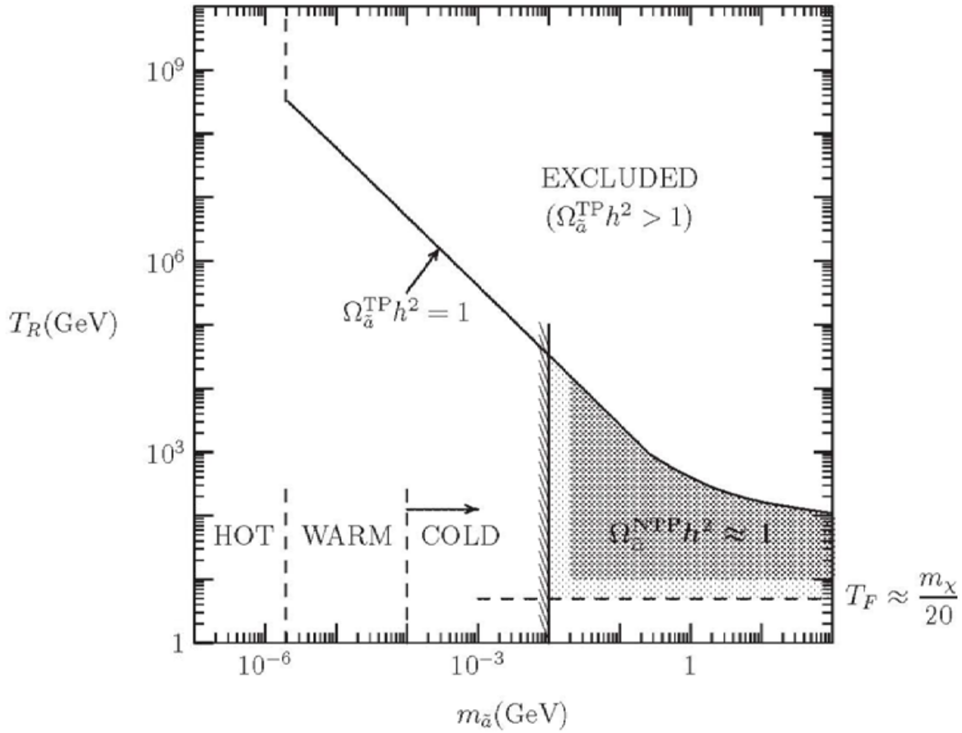
- Non-thermal production

  Decays of LOSP (lightest ordinary SUSY particle)

$$\Omega_{\tilde{a}} = \frac{m_{\tilde{a}}}{m_{\chi^0}}\,\Omega_{\chi^0}$$



$f_a = 10^{11}\mathrm{GeV},\ m_{\tilde{g}} = m_{\tilde{q}} = 1\mathrm{TeV}$
$Y_{\tilde{a}}^{\mathrm{EQ}} \approx 2 \times 10^{-3}$
$\tilde{g}$ DECAY
SCATTERING
χ_1^0 DECAY
$Y_{\tilde{a}}^{\mathrm{TP}}$
$T_R(\mathrm{GeV})$
1
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
1
10^3
10^6
10^9



EXCLUDED
$(\Omega_{\tilde{a}}^{\mathrm{TP}} h^2 > 1)$
$\Omega_{\tilde{a}}^{\mathrm{TP}} h^2 = 1$
HOT
WARM
COLD
$\Omega_{\tilde{a}}^{\mathrm{NTP}} h^2 \approx 1$
$T_F \approx \frac{m_\chi}{20}$
$T_R(\mathrm{GeV})$
$m_{\tilde{a}}(\mathrm{GeV})$
10^9
10^6
10^3
1
10^{-6}
10^{-3}
1

- Cosmological constraints

  * LOSP (neutralino) decays during or after BBN
    Hadronic shower spoils the standard BBN result.

    $m_\chi \gtrsim 150\,\mathrm{GeV} \longrightarrow \tau_\chi \lesssim 0.1\,\mathrm{sec}$

  * saxion problem
    The same number of saxions are produced.
    Saxion decays, $s \to f\bar{f}$, coupling $\propto \frac{m_f}{f_a}$

    $\underline{m_s > 2m_b} \Longrightarrow s \to b\bar{b}$

    $$\tau_s \simeq \left[\frac{1}{8\pi}\frac{m_b^2}{f_a} m_s\right]^{-1} \simeq 10^{-3}\,\mathrm{sec}$$

∘ The Decay of Axino

– R-parity, $R_p \equiv (-1)^{3B+L-2S}$

stability of proton, LSP, light $\tilde{a}\,(\longrightarrow \tilde{G} + a)$

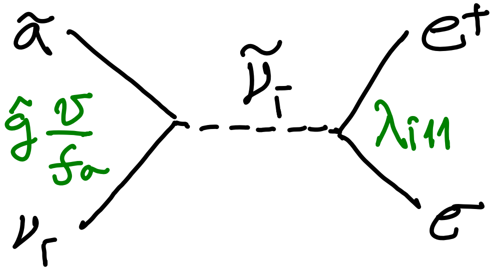
R-parity is not dictated from any deep theoretical principle.

– R_p violation

$$W_{\cancel{R_p}} = \epsilon_i \mu L_i H_2 + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \cdots$$

– Axino decay

* Trilinear $\cancel{R_p}$



$$\tau_a = 10^{20}\,\mathrm{sec}\left(\frac{10\,\mathrm{MeV}}{m_{\tilde{a}}}\right)^5\left(\frac{m_{\tilde{\ell}}}{\mathrm{TeV}}\right)^4 \times\left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^2\left(\frac{0.1}{\lambda}\right)^2 \hat{g}^{-2}$$

$$\lambda_{i11} \lesssim 0.1\left(\frac{m_{\tilde{e}}}{200\,\mathrm{GeV}}\right)$$

$\hat{g} \simeq 10^{-2}$ for DFSZ

$*$ Bilinear $\not{R}_p$

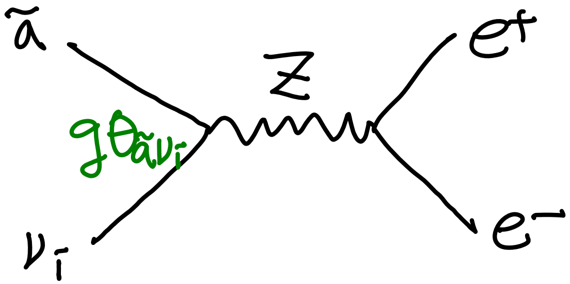
axino-Higgsino, axino-neutrino mixing

$$K_{eff} = e^{x_i \frac{A+\bar{A}}{f_a}} \bar{\Phi}_i \Phi_i \,, \quad x_i = \text{PQ charge of } \Phi_i$$

$$= \frac{A}{f_a}\left[x_{H_i} \bar{H}_i H_i + x_{L_j} L_j L_j + \cdots\right] + \cdots$$

$$\to \mathcal{L}_{mixing} = x_{H_1} \frac{\mu v_2}{f_a} \tilde{a} \tilde{H}_1 + x_{H_2} \frac{\mu v_1}{f_a} \tilde{a} \tilde{H}_2 + x_{L_i} \frac{\mu_i v_2}{f_a} \tilde{a} \nu_i + \text{h.c.}$$

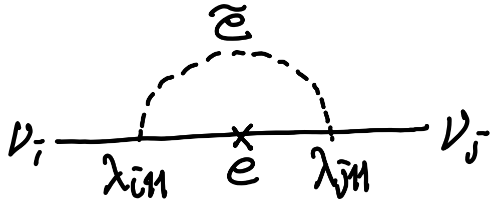
For $\frac{\mu v}{f_a} \ll m_{\tilde{H}}$, $\frac{\mu_i v_2}{f} \ll m_{\tilde{a}}$, $\theta_{\tilde{a}\tilde{H}} \sim \frac{v}{f_a}$, $\theta_{\tilde{a}\nu_i} = x_{L_i} \frac{\mu_i v_2}{f_a m_{\tilde{a}}}$



$$\tau_a = 2\times 10^{23}\,\text{sec} \left(\frac{10\,\text{MeV}}{m_{\tilde{a}}}\right)^3 \left(\frac{f_a}{10^{11}\,\text{GeV}}\right)^2 \left(\frac{10^{-7}}{x_{L_i}\epsilon_i}\right)^2 \left(\frac{\mu}{100\,\text{GeV}}\right)^{-2}$$

– $\not{R}_p$ and Neutrino Masses

* Trilinear $\not{R}_p$



$$M^\nu_{ij} \simeq \frac{1}{8\pi^2}\lambda_{i11}\lambda_{j11}\frac{m_e^2\,\mu\tan\beta}{m_{\tilde{e}}^2}$$

↳ $m_\nu \simeq 0.05\,\text{eV}$ for boundary values

$\lambda_{i11} = 0.05$, $m_{\tilde{e}} = 100\,\text{GeV}$, $\mu\tan\beta = 50\,\text{TeV}$

* Bilinear $\not{R}_p$

neutrino–Higgsino mixing

$$M^\nu_{ij} = -\frac{M_Z^2}{F_N}\xi_i\xi_j\cos^2\beta$$

sneutrino VEVs

$$\frac{\langle\tilde{\nu}_i\rangle}{v_1} = -\frac{m^2_{L_iH_1} + B_i\tan\beta}{m^2_{\tilde{\nu}_i}}, \quad F_N = \frac{M_1M_2}{M_{\tilde{\gamma}}} + \frac{M_Z^2\cos 2\beta}{\mu}, \quad \xi_i \equiv \epsilon_i - \frac{\langle\tilde{\nu}_i\rangle}{v_1}$$

→ one neutrino mass, say m_{ν_3}, from $\xi = \sqrt{\sum_i|\xi_i|^2}$

$$|\xi| = 0.7\times10^{-6}\,\frac{1}{\cos\beta}\left(\frac{F_N}{M_Z}\right)^{1/2}\left(\frac{m_{\nu_3}}{0.05\,\text{eV}}\right)^{1/2}$$

other neutrino masses – from trilinear $\not{R}_p$

Conclusion & Outlook

- LDM provides an explanation for
  - Dark matter
  - 511 keV γ-rays from the galactic bulge
  - Diffuse background γ-rays in 1–20 MeV range

  * If it turns out true, LDM provides a good probe of the galactic DM halo profile through the morphology of 511 keV γ-rays.
  * Distinction from astrophysical sources
    e.g. 511 keV γ-rays from Dwarf Spheroidals

- Particle physics model for LDM is needed
  - ~10 MeV axino is a good candidate.
  - The same $\not{R}_p$ can provide the axino lifetime and neutrino masses.