De-coannihilation: bound states rouse

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Outline

- Motivations
- Boltzmann equations
- Freeze-out scenario
- Freeze-in scenario
- Conclusions and outlook

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Motivations

- Heavy states always lower the DM density?
- Strong DM-SM interactions with correct DM density?
- Multi-component DM

Bound states!

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Boltzmann equations

$$zHs\frac{dY_\chi}{dz} = -\sum_{a_i,f_j}[\chi a_1\cdots a_n \leftrightarrow f_1\cdots f_m]\,,$$

where $Y \equiv n/s$, $z = m_\chi/T$ and H is the Hubble parameter, while

$$\begin{aligned}[\chi a_1\cdots a_n \leftrightarrow f_1\cdots f_m] =& \frac{n_\chi n_{a_1}\cdots n_{a_n}}{n_\chi^{\rm eq} n_{a_1}^{\rm eq}\cdots n_{a_n}^{\rm eq}}\gamma^{\rm eq}(\chi a_1\cdots a_n \leftrightarrow f_1\cdots f_m)\\ &- \frac{n_{f_1}\cdots n_{f_m}}{n_{f_1}^{\rm eq}\cdots n_{f_m}^{\rm eq}}\gamma^{\rm eq}\left(f_1\cdots f_m \leftrightarrow \chi a_1\cdots a_n\right).\end{aligned}$$

$\gamma^{\rm eq}$ is the decay rate in thermal equilibrium, defined as

$$\begin{aligned}\gamma^{\rm eq}(\chi a_1\cdots a_n \to f_1\cdots f_m) =& \int\frac{{\rm d}^3 p_\chi}{2E_\chi(2\pi)^3}e^{-\frac{E_\chi}{T}}\times\prod_{a_i}\Big[\int\frac{{\rm d}^3 p_{a_i}}{2E_{a_i}(2\pi)^3}e^{-\frac{E_{a_i}}{T}}\Big]\\ &\times(2\pi)^4\delta^4\Big(p_\chi+\sum_{i=1}^n p_{a_i}-\sum_{j=1}^m p_{f_j}\Big)|M|^2\,,\end{aligned}$$

where $|M|^2$ is the squared amplitude summed over *initial* and final spins.

Giudice et al., hep-ph/0310123

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Boltzmann equations

For $2 \leftrightarrow 2$ processes, the thermal rate can be expressed as

$$\gamma^{\mathrm{eq}}\left(a_1 a_2 \leftrightarrow f_1 f_2\right) = \frac{T}{64\pi^4} \int_{s_{\min}}^{\infty} ds \, \sqrt{s}\hat{\sigma}(s) \, K_1\left(\frac{\sqrt{s}}{T}\right),$$

s: square of center-of-mass energy

$s_{\min} = \max\left[(m_{a_1} + m_{a_2})^2, (m_{f_1} + m_{f_2})^2\right].$

$\hat{\sigma}$: reduced cross-section

For a decay of the particle a_1, the thermal rate becomes

$$\gamma^{\mathrm{eq}}\left(a_1 \leftrightarrow f_1 f_2\right) = n_{a_1}^{\mathrm{eq}} \frac{K_1(z)}{K_2(z)} \Gamma_{a_1},$$

where $z = m_{a_1}/T$ and Γ_{a_1} is the decay width of particle a_1 at rest.

Giudice et al., hep-ph/0310123

Freeze-out scenario

$$\mathcal{L} \supset \frac{\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f}{\Lambda_1^2} + \frac{\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f}{\Lambda_2^2} + \left(\frac{\bar{\chi}\gamma^\mu f\bar{f}'\gamma_\mu\psi}{\Lambda_3^2} + h.c.\right) + y\phi\bar{\psi}\psi$$

χ (ψ): DM (heavy state) charged under $U(1)'$, f: SM fermions

ϕ: light scalar mediator for Yukawa potential , $\Lambda_{1,2,3}$: scales of heavy mediators

- Yukawa interactions are always attractive regardless of particles or antiparticles
- $\psi - \psi$ ($R_{\psi\psi}$), $\bar{\psi} - \bar{\psi}$ ($R_{\bar{\psi}\bar{\psi}}$) and $\psi - \bar{\psi}$ ($R_{\psi\bar{\psi}}$)
- $R_{\psi\bar{\psi}} \leftrightarrow \bar{f}f$ is induced by $\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f/\Lambda_2^2$
- $R_{\psi\psi}$ ($R_{\bar{\psi}\bar{\psi}}$) $\leftrightarrow ff$ is forbidden by $U(1)'$ and/or $U(1)_Q$
- $R_{\psi\psi}$ ($R_{\bar{\psi}\bar{\psi}}$) can decay back to $DM + f + f'$ via $\bar{\chi}\gamma^\mu f\bar{f}'\gamma_\mu\psi/\Lambda_3^2$ if $(m_\psi - m_\chi) > E_B(\simeq y^4 m_\psi/(64\pi^2))$

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Bound state dissociation

$$R_{\psi\psi} + \phi \to \psi + \psi$$

$$V_{\text{potential}}(r) = -\frac{y^2}{4\pi}\frac{\exp(-m_\phi r)}{r} \sim -\frac{y^2}{4\pi}\frac{1}{r} \quad \text{if } m_\phi \ll m_\psi$$

$$\frac{d\sigma}{d\Omega} = \frac{|V_{fi}|^2}{(2\pi)^2}\mu_\psi|\mathbf{p}|$$

$$|\mathbf{p}| = \sqrt{2\mu_\psi(E_B + E_\phi)}$$

$$V_{fi} = y\sqrt{\frac{2\pi}{E_\phi}}\int d^3r\,\Psi_i^*\exp(ikr)\,\Psi_f$$

$$\sigma = \frac{y^{12}m_\psi^{\frac{5}{2}}\sqrt{E_B + E_\Phi}}{2\pi^3 E_\Phi^5}\frac{v\exp\left(4v\arctan\left[v^{-1}\right]\right)}{1-\exp(-2\pi v)}$$

$$v = \frac{my^2}{8\pi|\mathbf{p}|}$$

Lifshitz, Quantum Electrodynamics

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Freeze-out scenario

	$\bar{\chi}\chi \leftrightarrow \bar{f}f$	$\bar{\psi}\psi \leftrightarrow \bar{f}f$	$\chi f' \leftrightarrow \psi f$	$R_{\psi\psi}\phi \leftrightarrow \psi\psi$	$R_{\psi\bar{\psi}}\phi \leftrightarrow \bar{\psi}\psi$	$R_{\psi\bar{\psi}} \leftrightarrow \bar{f}f$
χ	$\surd$		$\surd$			
ψ		$\surd$ (S)	$\surd$	$\surd$	$\surd$	
$R_{\psi\psi}$				$\surd$		
$R_{\psi\bar{\psi}}$					$\surd$	$\surd$

All relevant interactions for χ, ψ, $R_{\psi\psi}$ (bound state of $\psi - \psi$), $R_{\psi\bar{\psi}}$ (bound state of $\bar{\psi} - \psi$), where S denotes the Sommerfeld enhancement.

$$zHs\frac{dY_\chi}{dz} = -\left(\frac{n_\chi n_{\bar{\chi}}}{n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}}} - \frac{n_f n_{\bar{f}}}{n_f^{\mathrm{eq}} n_{\bar{f}}^{\mathrm{eq}}}\right)\gamma^{\mathrm{eq}}\left(\chi\bar{\chi} \leftrightarrow f\bar{f}\right) - \left(\frac{n_\chi n_{\bar{f}}}{n_\chi^{\mathrm{eq}} n_{\bar{f}}^{\mathrm{eq}}} - \frac{n_\psi n_{\bar{f}'}}{n_\psi^{\mathrm{eq}} n_{\bar{f}'}^{\mathrm{eq}}}\right)\gamma^{\mathrm{eq}}\left(\chi\bar{f} \leftrightarrow \psi\bar{f}'\right)$$

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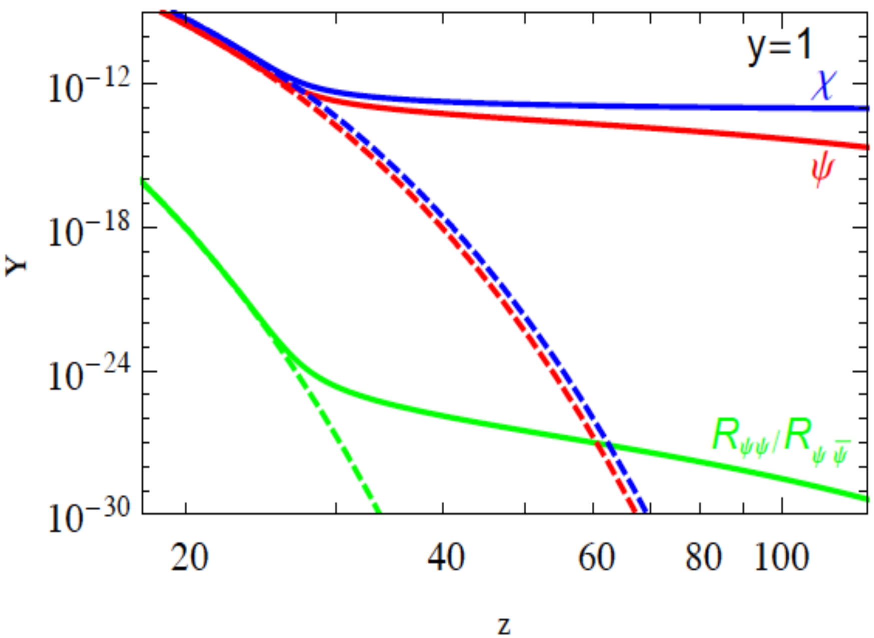
Freeze-out scenario

$(m_\chi,\, m_\psi) = (1,\, 1.03)$ TeV with $\Lambda_1 = \Lambda_2 = \Lambda_3 = 2.2$ TeV

$\Longrightarrow \Omega_\chi < \Omega_{\rm DM}^{\rm obs}$ without bound states



$Y \equiv n/s,\; z = m_\chi/T$

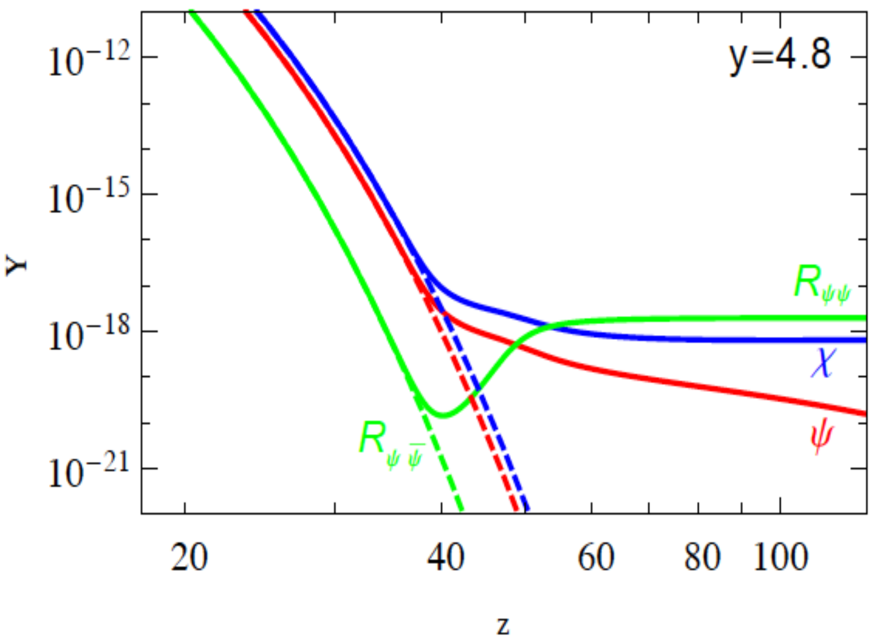
- Freeze-out of χ and ψ is determined by operators of $\Lambda_{1,2,3}$
- $E_B \sim 10^{-3} m_\psi \ll m_\psi \Longrightarrow$ bound state formation is still active for $T \ll m_\psi$
- Freeze-out of $R_{\psi\psi}$ takes place too late to have any significant impact on the DM density

Preliminary results!!

Freeze-out scenario

$(m_\chi, m_\psi) = (1, 1.03)$ TeV with $\Lambda_1 = \Lambda_2 = \Lambda_3 = 2.2$ TeV

$\Longrightarrow \Omega_\chi < \Omega_{\rm DM}^{\rm obs}$ without bound states



$Y \equiv n/s$, $z = m_\chi/T$

Preliminary results!!

- $E_B \sim 0.8 m_\psi \Longrightarrow$ stable $R_{\psi\psi}$
- $R_{\psi\psi}\phi \to \psi\psi$ becomes ineffective at $z \sim 35$
- $\psi\psi$ $(\chi\chi) \to R_{\psi\psi}\phi$ becomes ineffective at $z \sim 55$
- Freeze-out of χ and ψ is driven by that of $R_{\psi\psi}$
- $2(\Omega_\chi + \Omega_{R_{\psi\psi}}) \ll \Omega_{\rm DM}^{\rm obs}$
- $R_{\psi\bar{\psi}}$ always follows the equilibrium density

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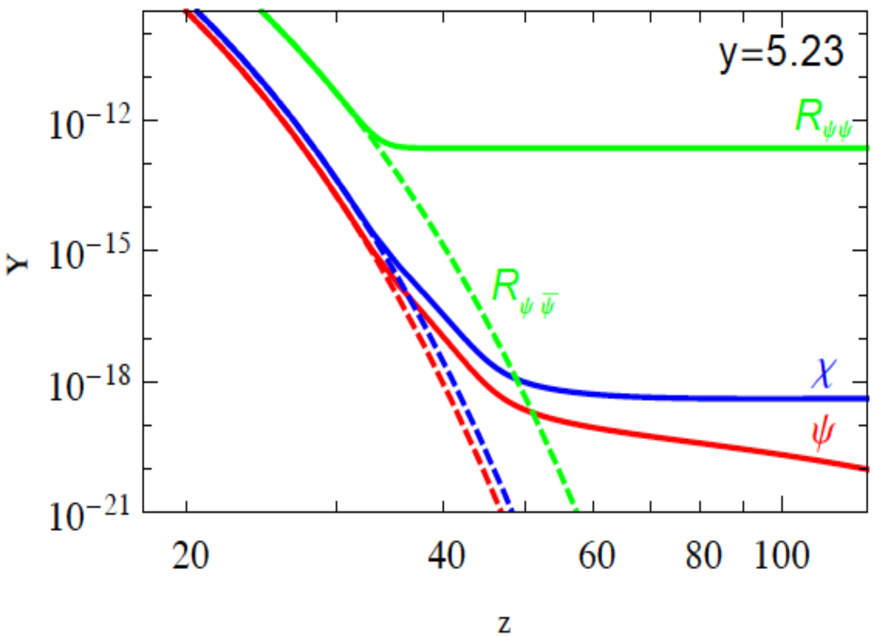
Freeze-out scenario

$(m_\chi,\, m_\psi) = (1,\, 1.03)$ TeV with $\Lambda_1 = \Lambda_2 = \Lambda_3 = 2.2$ TeV

$\Longrightarrow \Omega_\chi < \Omega_{\rm DM}^{\rm obs}$ without bound states



$Y \equiv n/s,\; z = m_\chi/T$

Preliminary results!!

- $E_B \sim 1.2 m_\psi \Longrightarrow m_{R_{\psi\psi}} < m_\chi$
- $R_{\psi\psi}\phi \to \psi\psi$ becomes inefficient early enough such that $2\Omega_{R_{\psi\psi}} \approx \Omega_{\rm DM}^{\rm obs}$
- Conversions among χ, ψ and $R_{\psi\psi}$ are similar to the case of $y = 4.8$

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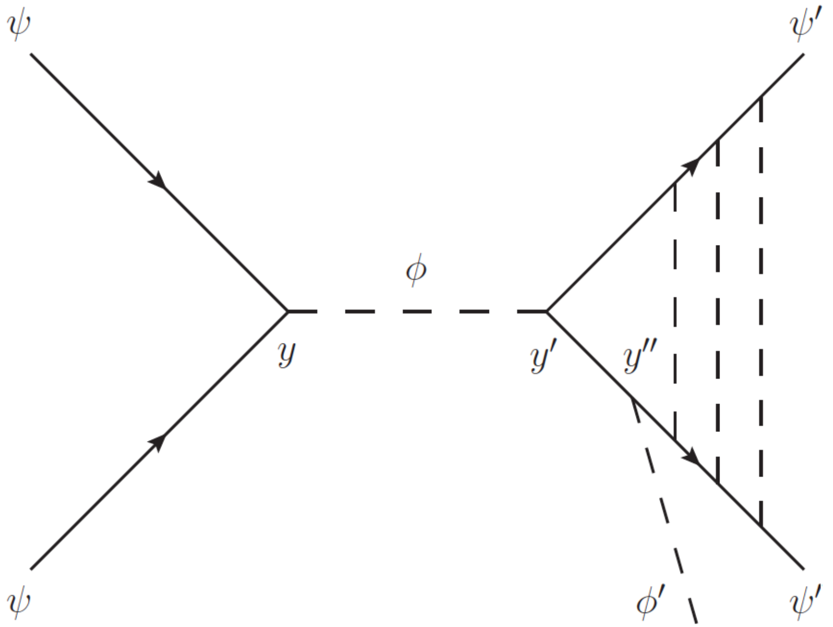
Freeze-in scenario

$$\mathcal{L} \supset \frac{1}{2}\phi\left(y\,\bar{\psi}\psi^c + y'\,\bar{\psi}'\psi'^c\right) + \frac{y''}{2}\phi'\,\bar{\psi}'\psi'^c,$$

χ (ψ) and ψ' are odd under $Z_2 \Longrightarrow$ multi-component DM



Freeze-in mechanism was proposed by Hall et al., 0911.1120

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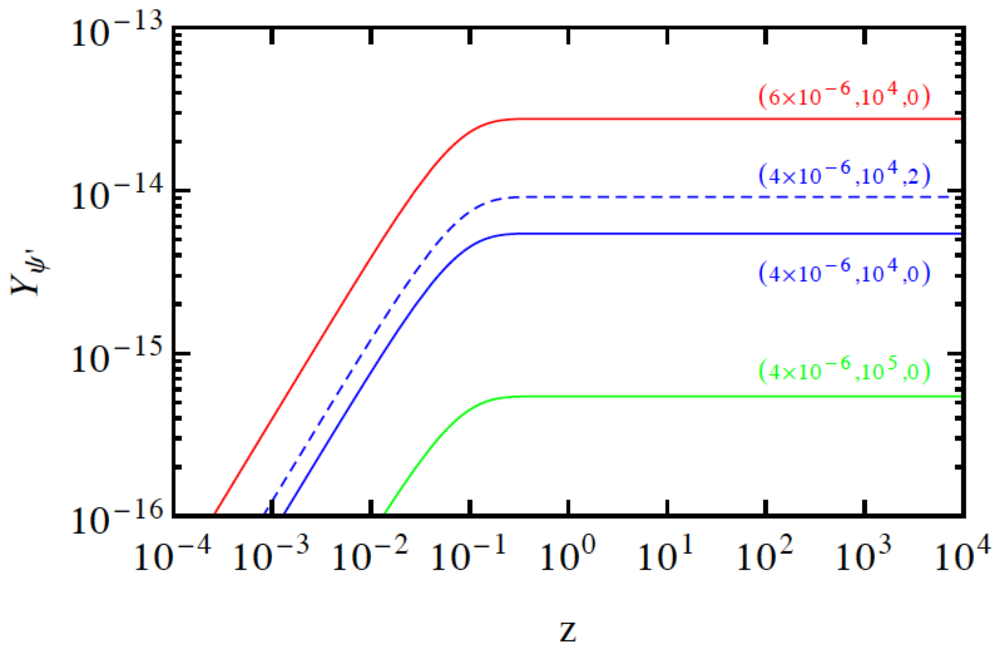
Freeze-in scenario

$$m_\psi = 1 \text{ TeV with } y = y' \text{ and } z \equiv m_\psi / T$$

$$\psi\psi \leftrightarrow \psi'\psi'$$



- Density of ψ' for different values of (y, $m_{\psi'}$ (GeV), y'')
- Sommerfeld enhancement when switching on y'' (blue lines)
- Larger y'', larger density $Y_{\psi'}$
- Lighter $m_{\psi'}$, larger density $Y_{\psi'}$

Preliminary results!!

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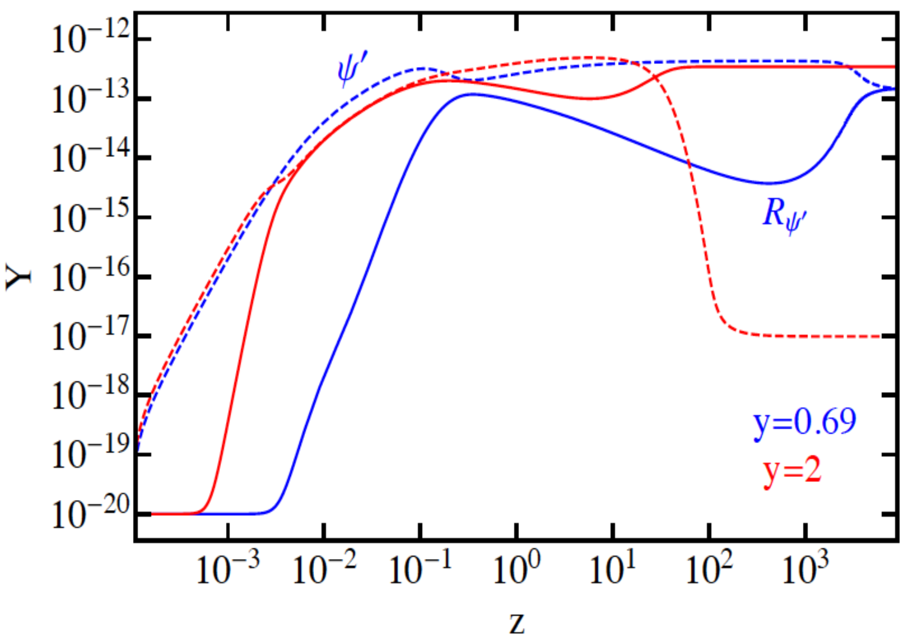
Freeze-in scenario

$$(m_\psi, m_{\psi'}) = (1, 10) \text{ TeV with } y = y' \text{ and } z \equiv m_\psi/T$$



$$\psi\psi \leftrightarrow \psi'\psi' \leftrightarrow \phi' R_{\psi'}$$

Preliminary results!!

- Densities of $Y_{R_{\psi'}}$ and $Y_{\psi'}$
- Larger y'', earlier $Y_{R_{\psi'}}$ catches up with $Y_{\psi'}$
- After freeze-in, the correlation between $Y_{R_{\psi'}}$ and $Y_{\psi'}$ is determined by chemical potentials
- for $y'' \sim 0.69$, one has multi-component DM with $\Omega_\chi \sim \Omega_{\psi'}$ after $R_{\psi'} \to 2\chi + f \cdots$
- No need for Yukawa coupling $\gtrsim 5$ as before

Conclusions and outlook

- We provide two examples where heavy states increase the DM density
- DM abundance is stored at the bound state which is free from annihilating into SM particles
- The existence of bound states can yield the correct DM density regardless of DM-SM interactions
- Multi-component DM can be naturally realized
- In the freeze-in scenario, long-range interactions (m_{ϕ}~0) between ψ' might solve small scale problems of ΛCDM (L. G. van den Aarssen et al. 1205.5809)