Multi-Component Dark Matter Systems and Their Observation Prospects

Michael Duerr

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

DESY THEORY WORKSHOP 2012

Based on `arXiv:1207.3318 [hep-ph]`

(accepted for publication in PRD)

with: M. Aoki (MPIK and Kanazawa University),

J. Kubo (Kanazawa University), and

H. Takano (Kanazawa University).

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

MAX-PLANCK-GESELLSCHAFT

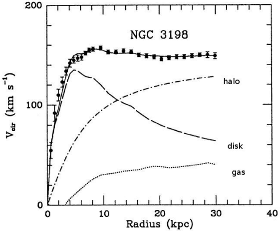
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Hints for DM

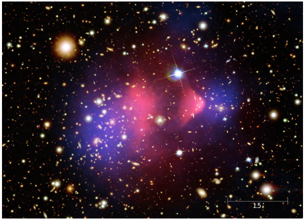
Galaxy rotation curves

Bullet cluster

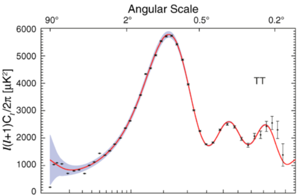
CMB



Begeman et al.,
Mon. Not. R. astr. Soc. (1991) **249**, 523



NASA

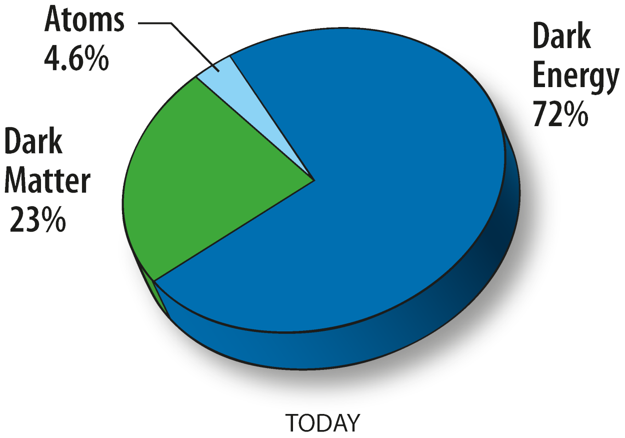


NASA

Consistent hints on all scales.

Content of the Universe

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



Wikipedia

Do you believe there exists only one kind of DM?

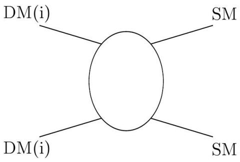
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Multi-component DM systems

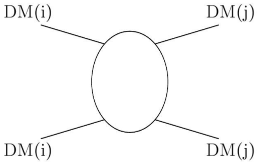
- How can a multi-DM system arise?
  - $Z_N (N \geq 4)$
  - Product of two or more Z_2:
    If $(Z_2)^l$ is unbroken, we have at least $K = l$ stable DM particles. In a kinematically fortunate situation, $2^l - 1$ stable DM particles may exist.
  - ...

- Non-standard annihilations

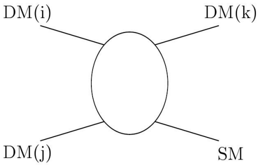
standard annihilation



conversion



semi-annihilation



Coupled Boltzmann equations

- standard annihilation

$$\frac{dY_i}{dx} = -0.264\, g_*^{1/2} \left[\frac{\mu M_{\rm PL}}{x^2}\right] \Big\{ \langle\sigma(ii;X_iX_i')v\rangle \left(Y_iY_i - \bar{Y}_i\bar{Y}_i\right)$$

$$+ \sum_{i>j}\langle\sigma(ii;jj)v\rangle\left(Y_iY_i - \frac{Y_jY_j}{\bar{Y}_j\bar{Y}_j}\bar{Y}_i\bar{Y}_i\right) - \sum_{j>i}\langle\sigma(jj;ii)v\rangle\left(Y_jY_j - \frac{Y_iY_i}{\bar{Y}_i\bar{Y}_i}\bar{Y}_j\bar{Y}_j\right)$$

$$+ \sum_{j,k}\langle\sigma(ij;kX_{ijk})v\rangle\left(Y_iY_j - \frac{Y_k}{\bar{Y}_k}\bar{Y}_i\bar{Y}_j\right) - \sum_{j,k}\langle\sigma(jk;iX_{jki})v\rangle\left(Y_jY_k - \frac{Y_i}{\bar{Y}_i}\bar{Y}_j\bar{Y}_k\right)\Big\}$$

- DM conversion
- DM semi-annihilation

$$Y_i = n_i/s \qquad \mu = \Big(\sum_i m_i^{-1}\Big)^{-1}$$

see also F. D'Eramo, J. Thaler, JHEP **06** (2010) 109, G. Belanger, K. Kannike, A. Pukhov, M. Raidal, JCAP **04** (2012) 010.

A fictive three-component DM system

stand. annihilation: $\langle \sigma(ii; X_i X_i) v \rangle = \sigma_{0,i}$

conversion:

$$\langle \sigma(11;22) v \rangle = \sigma_{0,12}$$
$$\langle \sigma(11;33) v \rangle = \sigma_{0,13}$$
$$\langle \sigma(22;33) v \rangle = \sigma_{0,23}$$

semi-annihilation:

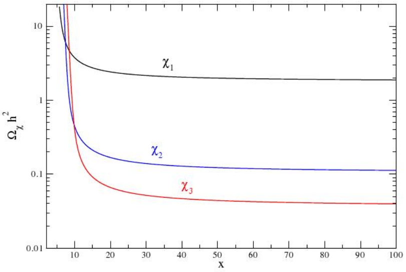
$$\langle \sigma(12;3X_{123}) v \rangle = \sigma_{0,123}$$
$$\langle \sigma(23;1X_{231}) v \rangle = \sigma_{0,231}$$
$$\langle \sigma(31;2X_{312}) v \rangle = \sigma_{0,312}$$

(all of the above) $\times\, 10^{-9}\ \mathrm{GeV}^{-2}$

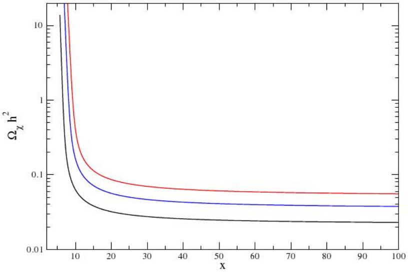
$$m_1 > m_2 > m_3 \quad \text{and} \quad m_2 + m_3 > m_1 .$$

Temperature evolution

only standard



standard + conversion

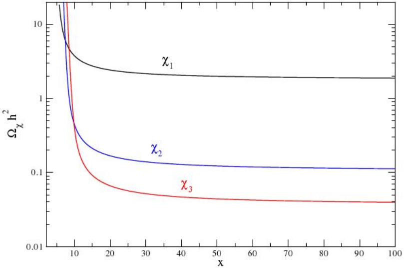


- standard: $\sigma_{0,1} = 0.1\,,\ \sigma_{0,2} = 2\,,\ \sigma_{0,3} = 6$
- conversion: $\sigma_{0,12} = \sigma_{0,13} = \sigma_{0,23} = 5.2$

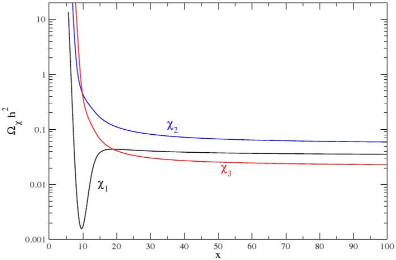
$m_1 = 200\text{ GeV},\ m_2 = 160\text{ GeV},\ m_3 = 140\text{ GeV};\ x = \mu/T.$

Temperature evolution

only standard



standard + semi-annihilation



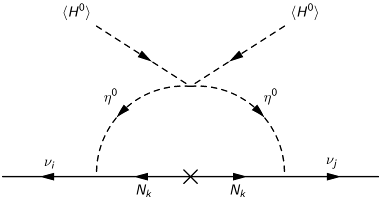
- standard: $\sigma_{0,1} = 0.1\,,\ \sigma_{0,2} = 2\,,\ \sigma_{0,3} = 6$
- conversion: $\sigma_{0,123} = \sigma_{0,312} = \sigma_{0,231} = 5.1$

$m_1 = 200$ GeV, $m_2 = 160$ GeV, $m_3 = 140$ GeV; $x = \mu/T$.

The Ma model

Extend SM to $SU(2)_L \times U(1)_Y \times Z_2$, introducing $N_i \sim (1, 0; -)$ and $(\eta^+, \eta^0) \sim (2, 1/2; -)$.

Z_2 is exact $\rightarrow \langle\eta\rangle = 0$.



Higgs potential

$$V = m_1^2 H^\dagger H + m_2^2 \eta^\dagger \eta + \frac{1}{2}\lambda_1 (H^\dagger H)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{1}{2}\lambda_5 [(H^\dagger \eta)^2 + \text{H.c.}]$$

Neutrino mass

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik} h_{jk} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right]$$

E. Ma, Phys. Rev. **D73** (2006) 077301, `arXiv:hep-ph/0601225`

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The Ma model – DM

N_R DM studied by

- Krauss, Nasri, Trodden, Phys. Rev. **D67** (2003) 085002
- Kubo, Ma, Suematsu, Phys. Lett. **B642** (2006) 18 ...

η DM studied by

- Barbieri, Hall, Rychkov, Phys. Rev. **D74** (2006) 015007
- Lopez Honorez, Nezri, Oliver, Tytgat, JCAP **02** (2007) 028
- Dolle, Su, Phys. Rev. **D80** (2009) 055012 ...

Promotion of Z_2 to $Z_2 \times Z_2'$

$\rightarrow$ Promotion to a three-component DM system.

Extension of the Ma model

New particles

Add Majorana fermion χ and scalar ϕ with interaction $Y_k^\chi \chi N_k \phi$.

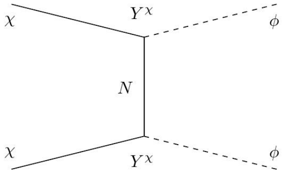
DM candidates

field	$SU(2)_L$	$U(1)_Y$	Z_2	Z_2'
N_i^c	1	0	$-$	$+$
$\eta = (\eta^+, \eta^0)$	2	1/2	$-$	$+$
χ	1	0	$+$	$-$
ϕ	1	0	$-$	$-$

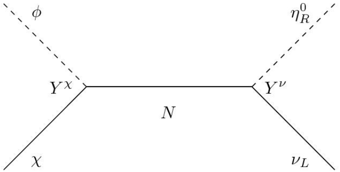
Our DM particles

η_R^0, χ, ϕ.

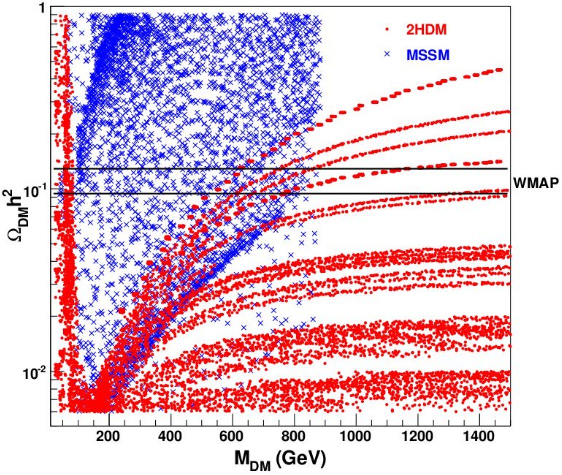
Conversion



Semi-annihilation

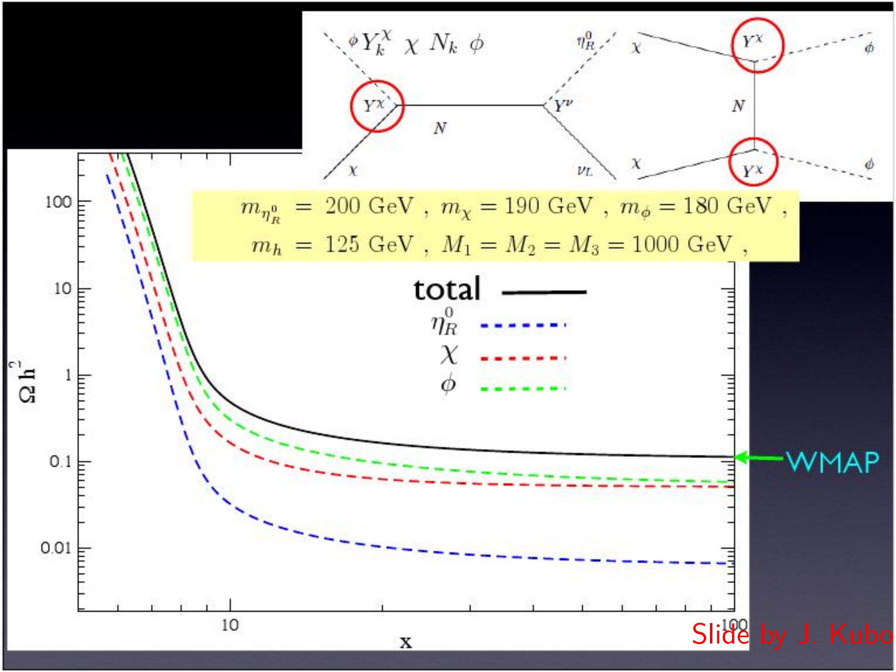


Inert Doublet Model



L. Lopez Honorez, E. Nezri, J. Oliver, M. Tytgat, JCAP **02** (2007) 028

Only low and high mass regimes are allowed.



Slide by J. Kubo.

Including all constraints

IDM (only η_R^0 is DM):

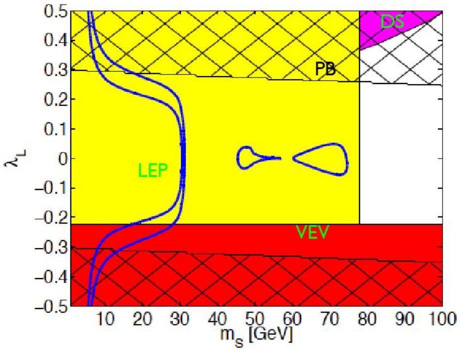
E. Dolle, S. Su, Phys. Rev. **D80** (2009) 055012

$$60\text{ GeV} \leq m_{\eta_R^0} \leq 80\text{ GeV or } m_{\eta_R^0} > 500\text{ GeV}$$

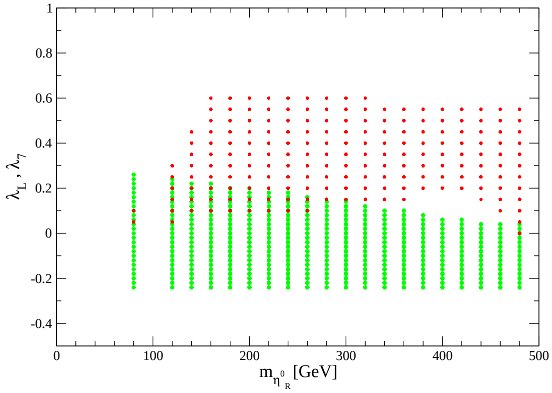
Parameters

$$\delta_1 = m_{\eta^\pm} - m_{\eta_R^0} = 10\text{ GeV}$$

$$\delta_2 = m_{\eta_I^0} - m_{\eta_R^0} = 10\text{ GeV}$$



With χ and ϕ



Parameters

green: λ_L and red: λ_7

$\delta_1 = m_{\eta^\pm} - m_{\eta_R^0} = 10$ GeV

$\delta_2 = m_{\eta_I^0} - m_{\eta_R^0} = 10$ GeV

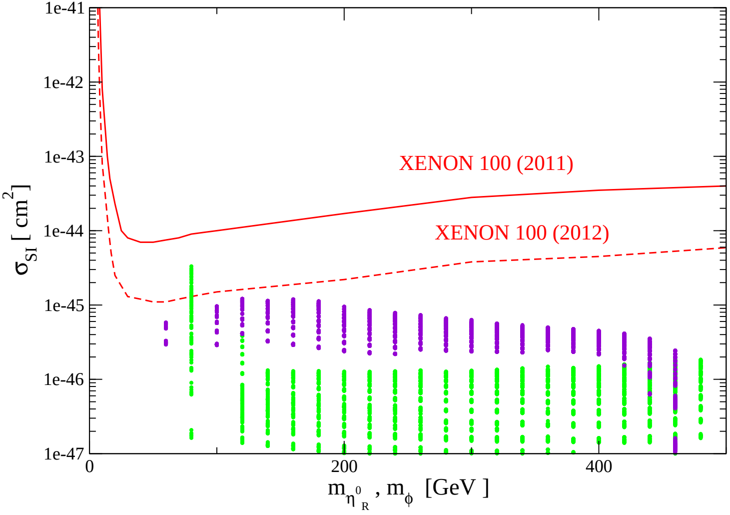
$m_\chi = m_{\eta_R^0} - 10$ GeV

$m_\phi = m_{\eta_R^0} - 20$ GeV

$M_k = 1000$ GeV

Max-Planck-Institut für Kernphysik Heidelberg

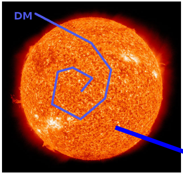
Direct detection

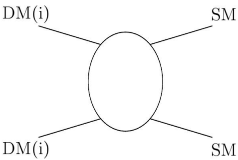


green: η_R^0 and violet: ϕ

Indirect search at neutrino telescopes

DM can be captured and annihilated in the Sun, producing neutrinos that can escape from the Sun.

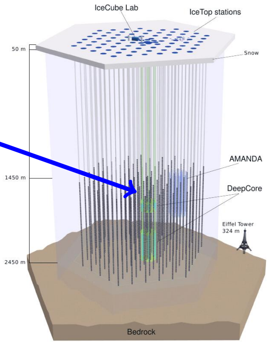




produces diffuse ν's

ν

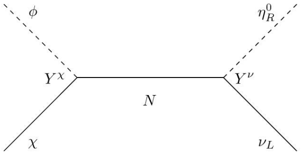
IceCube detector

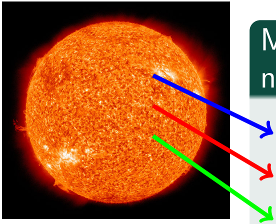


Max-Planck-Institut für Kernphysik Heidelberg

Monochromatic ν's from the Sun

Semi-annihilations





NASA

Monochromatic neutrinos:

$$E_\nu = m_\eta + m_\phi - m_\chi$$
$$E_\nu = m_\eta + m_\chi - m_\phi$$
$$E_\nu = m_\chi + m_\phi - m_\eta$$

Time evolution of the numbers of DM in the Sun:

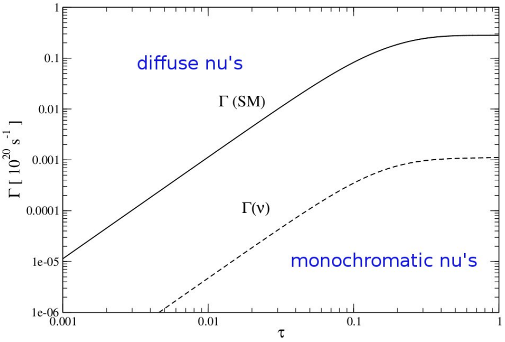
$$\dot{N}_\eta = C_\eta - C_A(\eta\eta \leftrightarrow \mathrm{SM})N_\eta^2 - C_A(\eta\eta \leftrightarrow \phi\phi)N_\eta^2 - C_A(\eta\chi \leftrightarrow \phi\nu_L)N_\eta N_\chi$$
$$- C_A(\eta\phi \leftrightarrow \chi\nu_L)N_\eta N_\phi + C_A(\phi\chi \leftrightarrow \eta\nu_L)N_\chi N_\phi \ ,$$

analog for $\dot{N}_\chi$ and $\dot{N}_\phi$

Time evolution of the annihilation rates

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

$$\Gamma(\mathrm{SM}) = C_A(\eta\eta \leftrightarrow \mathrm{SM}) N_\eta^2/2 + C_A(\phi\phi \leftrightarrow \mathrm{SM}) N_\phi^2/2$$



$$\Gamma(\nu) = C_A(\eta\phi \leftrightarrow \chi\nu) N_\eta N_\phi + C_A(\eta\chi \leftrightarrow \phi\nu) N_\eta N_\chi + C_A(\chi\phi \leftrightarrow \eta\nu) N_\chi N_\phi$$

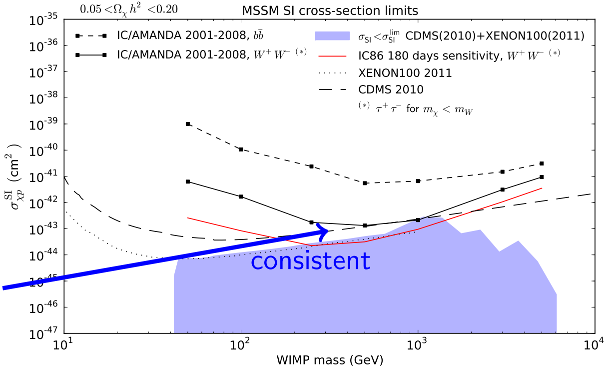
Input parameters: $m_{\eta_R^0} = 200$ GeV, $m_\chi = 190$ GeV, $m_\phi = 180$ GeV, $m_h = 125$ GeV, $M_k = 1000$ GeV $\rightarrow E_\nu \approx 200$ GeV.

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Limits from neutrino telescopes

- IceCube/Amanda
- ANTARES
- Super-K

$\Gamma(\mathrm{SM}) \approx 0.3 \times 10^{20}/\mathrm{sec}$



$\Gamma(\text{monochromatic}\,\nu) \approx 0.001 \times 10^{20}$ sec
$\rightarrow$ 0.05 events per year at Ice Cube

Conclusions

- Non-standard annihilations of DM can play an important role for the relic abundance of DM and for indirect observation of DM.
- The detection of monochromatic neutrinos from the Sun may give a hint for multi-component DM in the Universe.

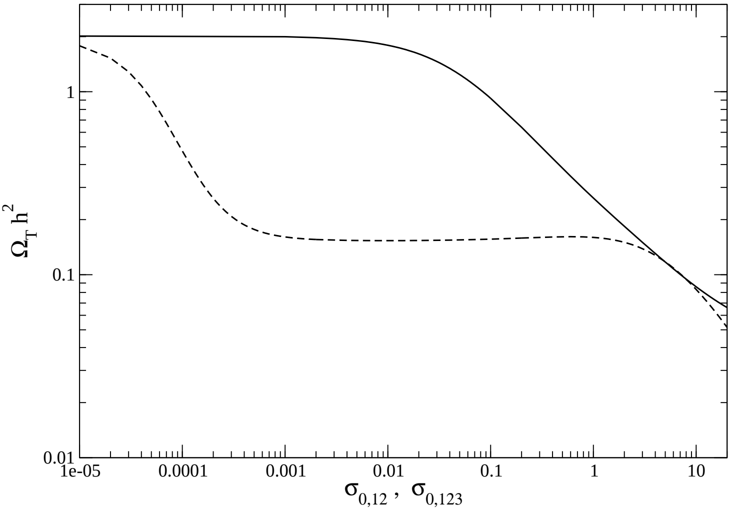
Conclusions

- Non-standard annihilations of DM can play an important role for the relic abundance of DM and for indirect observation of DM.
- The detection of monochromatic neutrinos from the Sun may give a hint for multi-component DM in the Universe.

Thanks for your attention!

Backup slides

Dependence on the non-standard annihilations



dashed = semi-annihilation, full = conversion.