General Constraints on Dark Matter Decay From CMB

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Energy injection in the dark ages

How?

• DM annihilates or decays into SM particles
  → between recombination and reionization (dark age)
  → new sources of energy injection into CMB
  → additional heating and ionization
  → increase optical depth, change CMB power spectrum...
Energy injection in the dark ages

Why?

1. Physics in the dark ages are well understood
2. CMB power spectrum measured precisely
3. **Doe Not** depend on local DM density and distribution nowadays
Energy injection in the dark ages

Why?

1. Physics in the dark ages are well understood
2. CMB power spectrum measured precisely
3. **Do Not** depend on local DM density and distribution nowadays
4. **Strong limit** between MeV – GeV energy for $e^+ e^-$ channel
Energy injection history

- How much energy actually deposit into the CMB by different channel?
Energy injection history

- How much energy actually deposit into the CMB by different channel?

- $p_a (z_f, E_i) = \frac{\text{deposited}}{\text{injected}}$, a: ionization, heating... (by simulation)

- Injection rate: $\propto <\sigma v> (1 + z)^6$ for ann; $\propto e^{-t/\tau} (1 + z)^3$ for decay

- Need time to deposit: delayed deposition
CMB change

- Boltzmann code (ex: CLASS): study specific energy injection profile
- Decaying DM Injecting 30 MeV $e^+ e^-$:

• More information and model-independent way to constrain DM?
Principal component analysis

- Determine numbers of relevant parameters
- PCA:
  - Basis $M_i$ for injection process ex: 10 keV-1TeV photon, find $\delta C_\ell$
  - Construct Fisher matrix, marginalized over standard parameters
  - Eigenvectors $e_i = \sum_j (\alpha_i)_j M_j$ with eigenvalues $\lambda_i$
  - If $\lambda_1 \gg \lambda_i$, $e_1 = \sum_j (\alpha_1)_j M_j$ dominate
  - $2\sigma$ constraint: $\frac{<\sigma v>}{M_x}, \frac{1}{\tau} < \frac{2}{(\alpha_1)_j \sqrt{\lambda_1}}$

* In linear regime, where energy injection is small
* Gaussian likelihood
PCA – Energy

- Basis $M_j$: 10Kev - 1Tev $e^+ e^-$ & 10Kev - 1Tev photon

**Annihilation**

- $e^+ e^- ightarrow$ photons

**Decay**

- $e^+ e^- ightarrow$ photons

**Log$_{10}$[Energy (eV)]**

- WMAP
- PLANCK
- CVL
PCA – Energy

- Basis $M_j$: 10Kev - 1Tev $e^+e^-$ & 10Kev - 1Tev photon

1. $e_1 = \sum_j (\alpha_1)_j M_j$ dominate

2. $\lambda_1$ contributes >99.9% of variance for ann, >97% for decay

3. Upper limit at different energies $E_i$ scales as \[ \frac{2}{(\alpha_1)_j \sqrt{\lambda_1}} \]
PCA – Redshift

- Basis $M_j$: redshift (Delta-like energy injection at each redshift)
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- Basis $M_j$: redshift (Delta-like energy injection at each redshift)

- The weighting function for annihilation peaks at $z \sim 600$ while for decay broadly peaks at $z \sim 300$
- The process can be captured by a single parameter
MCMC

• Go beyond linearity and Gaussian likelihood
• Use MCMC code (ex: Montepython):
  six standard cosmological parameters + DM decay lifetime
• Perform MCMC to check PCA result
Compare with observation

- Constraints from observations of diffuse X-ray or gamma-ray emission
- Depend on the DM local density and distribution in the present day
- Decay to photons (usually stronger) or electrons with FSR
- DM decay to $e^+ e^-$:

![Graph showing DM mass vs. lifetime with data points and lines for different experiments.](image)
Constraint on Decaying DM

- Short-lifetime DM could be a fraction of DM
- Constraint on mass fraction as a function of lifetime:
Summary

• PCA provides a method to quickly estimate the CMB limit for arbitrary energy injection spectra, consistent with MCMC

• For annihilating DM and DM decaying with a long lifetime, the effect on the CMB can be approximately described by a single parameter

• Constraints on decay to $e^+ e^-$ are strong between $\text{MeV} – \text{GeV}$

• The limit would improve by a factor of $\sim 5$ with an experiment that is cosmic variance limited up to $l = 2500$

• An Example of Mathematica notebook is given at http://nebel.rc.fas.harvard.edu/epsilon/

• Future: explore more general energy injection models, with different redshift dependence
Bonus Slides
Energy injection history

- $f_a(z_i, z_f, E_i) = \frac{\text{deposited}}{\text{injected}}$, $a =$ excitation, ionization, heating...
  - injection time ($z_i$), deposit time ($z_f$), injection species & energy ($E_i$)

- Energy deposited into CMB:
  - $p_a(z_f, E_i) \sim \sum_i f_a(z_i, z_f, E_i) \times \text{injection rate}(z_i)$

- Injection rate:
  - $\propto <\sigma v> (1 + z)^6$ for annihilation
  - $\propto e^{-t/\tau} (1 + z)^3$ for decay
\( p_{\text{ionization}}(z_f, E_i) \)

- **Photon:** ionization efficiency is high for low energy photon
- **Electron:** 30 MeV upscatter CMB by Compton scattering, produce low energy photon

Tracy Slatyer et. al arXiv:0906.197
\( p_{\text{ionization}}(z_f, E_i) - \text{Decay} \)

- transparent at low redshift?
  need time to deposit (delayed deposition)
- High efficiency window:
  30 MeV for \( e^+ e^- \) and 10 keV for photon
\[ p_{\text{ionization}}(z_f, E_i) - \text{Annihilation} \]

- transparent at low redshift? -> delayed deposition
- High efficiency window:
  - 30 MeV for electron and 10 keV for photon
Short-lifetime decaying DM

- Short-lifetime decaying DM could also be a fraction of DM
- PCA:

  basis: fixed 30 MeV electrons but different lifetimes

1. $\lambda_1$ (first PC) dominate $> 98$

2. Short-lifetime DM has little weight

Injection rate $\propto \frac{e^{-t/\tau}}{\tau} (1 + z)^3$
MCMC

- For example: decaying DM, 30MeV electron injection
General constraint

- DM decay to Standard Model particles:

  PPPC4DMID package:

  28 decay channels in the galaxy, electron & photon energy spectra
Fisher Matrix

\[
\Sigma_\ell = \frac{2}{2\ell + 1} \times \\
\begin{pmatrix}
(C_\ell^{TT})^2 & (C_\ell^{TE})^2 & C_\ell^{TT} C_\ell^{TE} \\
(C_\ell^{TE})^2 & (C_\ell^{EE})^2 & C_\ell^{EE} C_\ell^{TE} \\
C_\ell^{TT} C_\ell^{TE} & C_\ell^{EE} C_\ell^{TE} & [(C_\ell^{TE})^2 + C_\ell^{TT} C_\ell^{EE}] \\
\end{pmatrix}
\]

\[
(F_e)_{ij} = \sum_\ell \left( \frac{\partial C_\ell}{\partial \alpha_i} \right)^T \Sigma_\ell^{-1} \cdot \frac{\partial C_\ell}{\partial \alpha_j}.
\]

- 6 cosmological parameter: baryon density, \( \omega_b \), CDM density, \( \omega_c \), the primordial scalar spectral index \( n_s \), the normalization \( A_s \) (\( k = 0.002/\text{Mpc} \)), the optical depth to reionization \( \tau \) and the Hubble parameter \( H_0 \)

\[
F = F_e - F_v F_c^{-1} F_v^T
\]
Reionization

- Studied by Hongwan Liu et al. (arXiv: 1604.02457)
- Using different reionization models, including structure formation
- Less than 10% to the ionization fraction at reionization is from annihilating DM