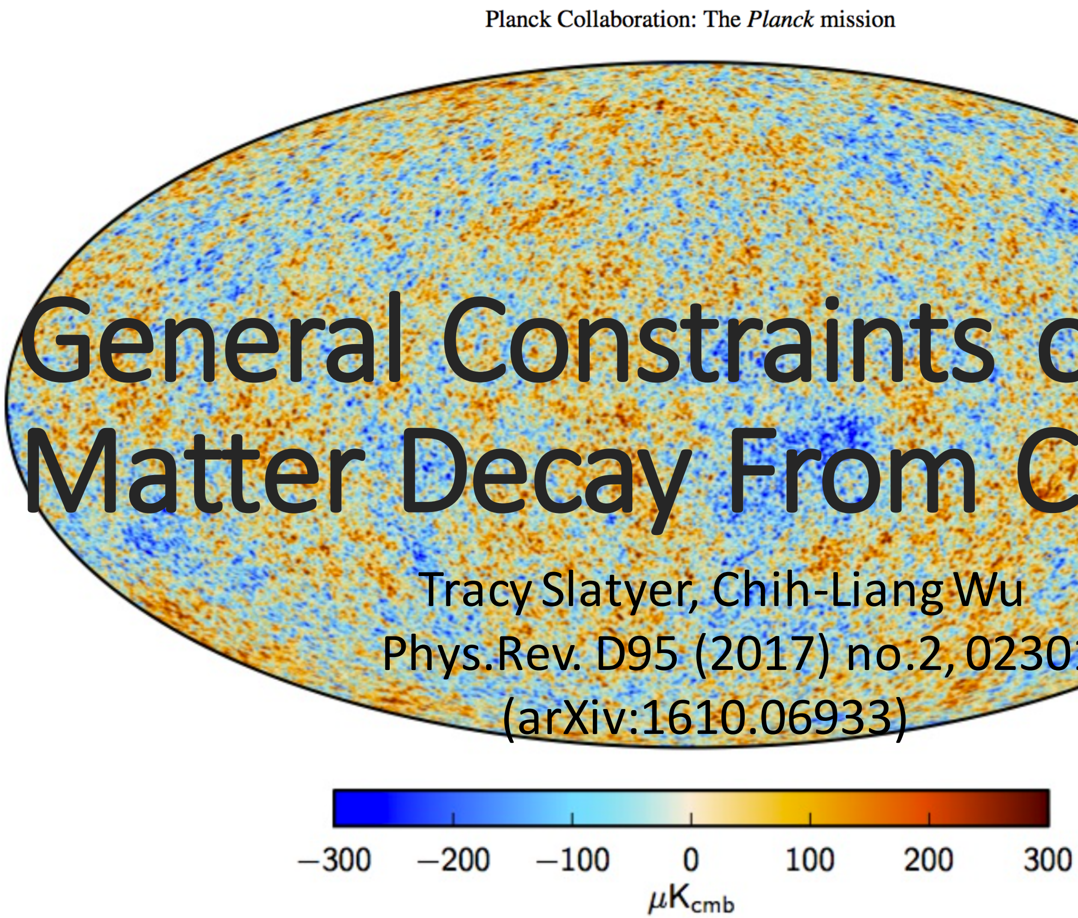

General Constraints on Dark Matter Decay From CMB

Tracy Slatyer, Chih-Liang Wu
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(arXiv:1610.06933)

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Energy injection in the dark ages

How?

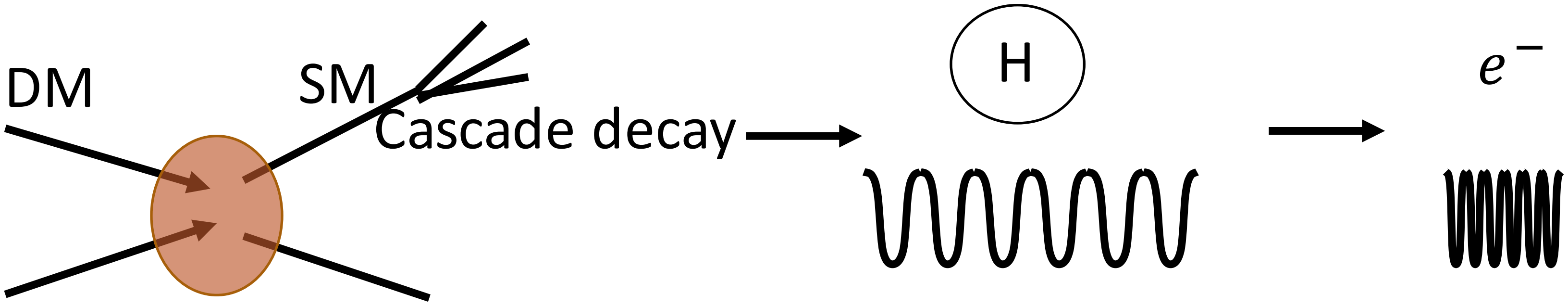
- DM annihilates or decays into SM particles

  →between recombination and reionization (dark age)

  →new sources of energy injection into CMB

  →additional heating and ionization

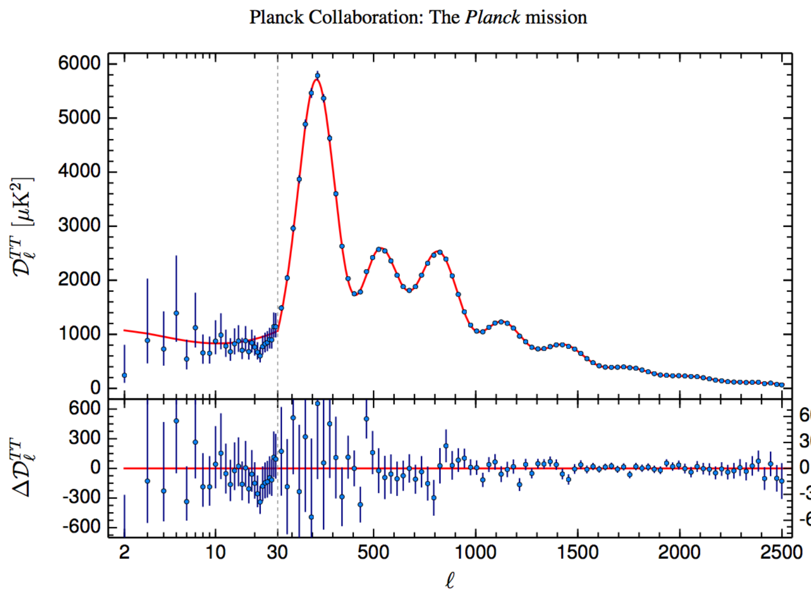
  →**increase optical depth, change CMB power spectrum…**



Energy injection in the dark ages

Why?

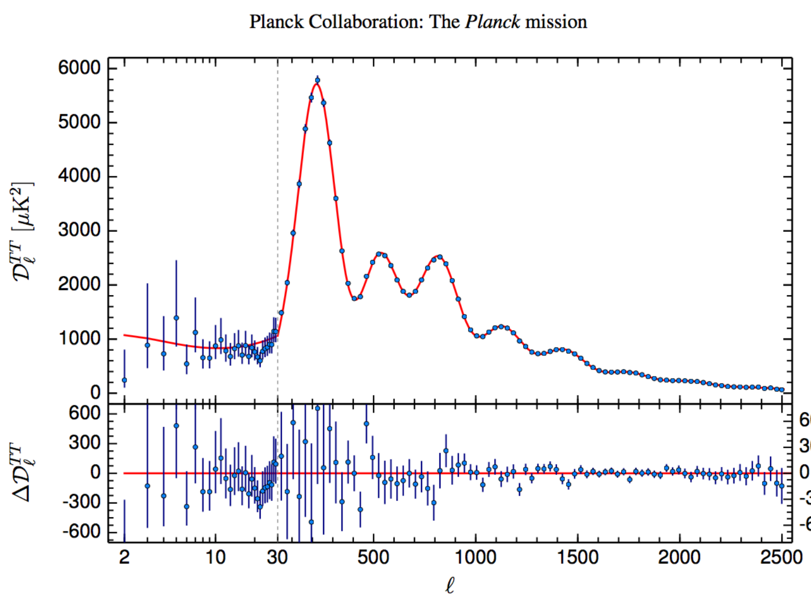
1. Physics in the dark ages are well understood
2. CMB power spectrum measured precisely
3. **Doe Not** depend on local DM density and distribution nowadays

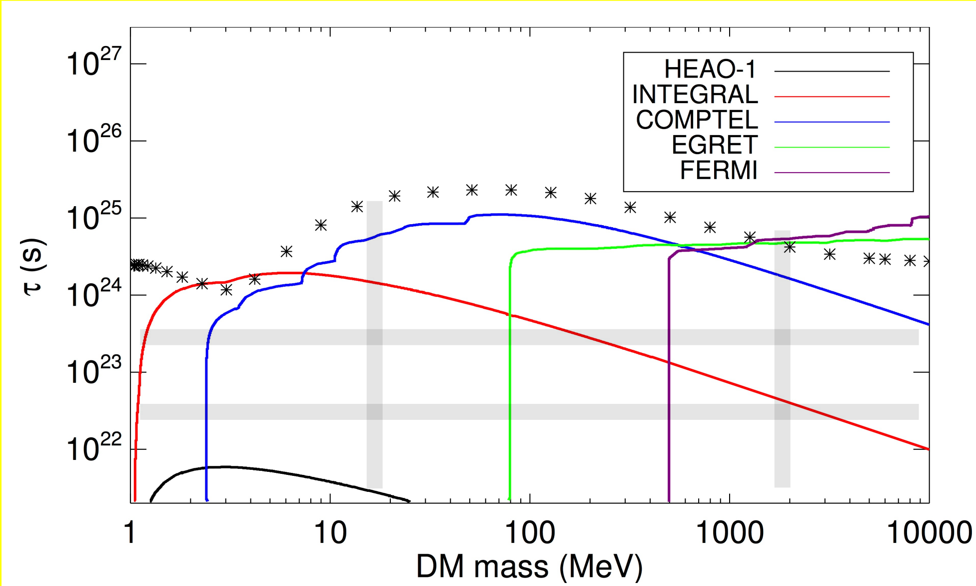


Energy injection in the dark ages

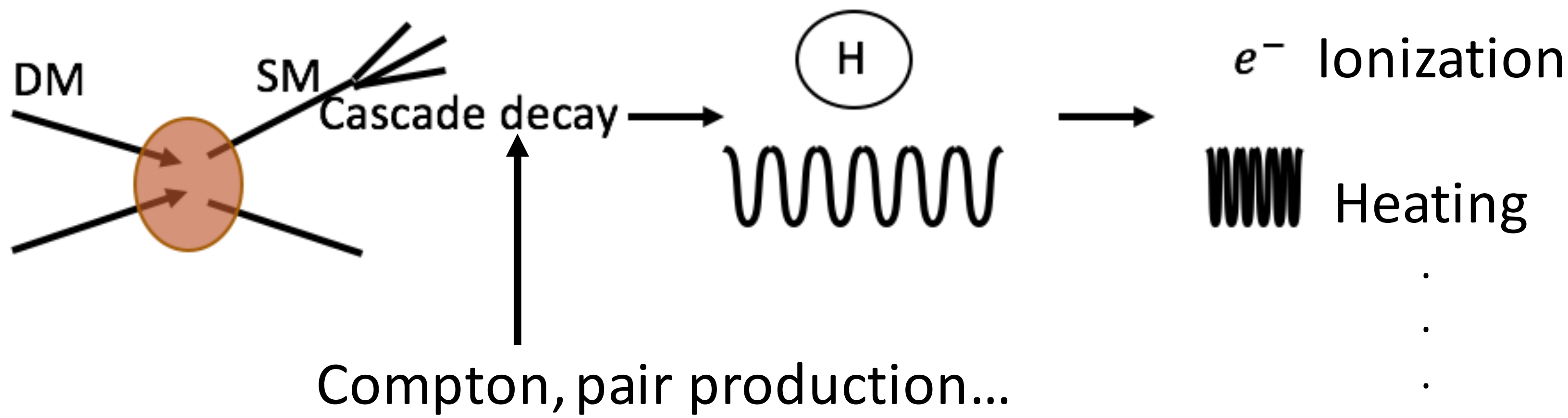
Why?

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



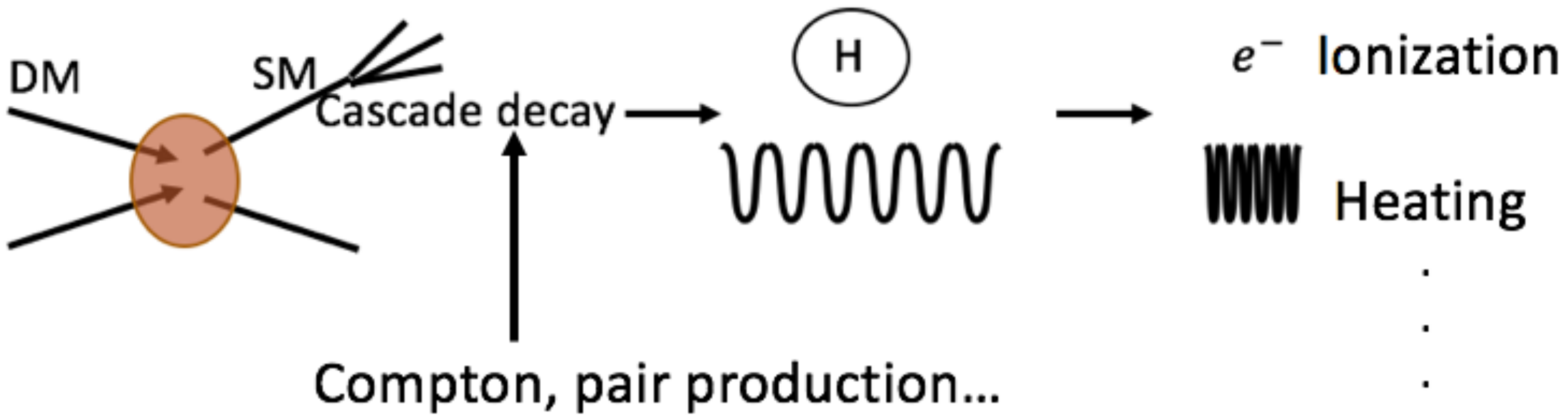


Energy injection history



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

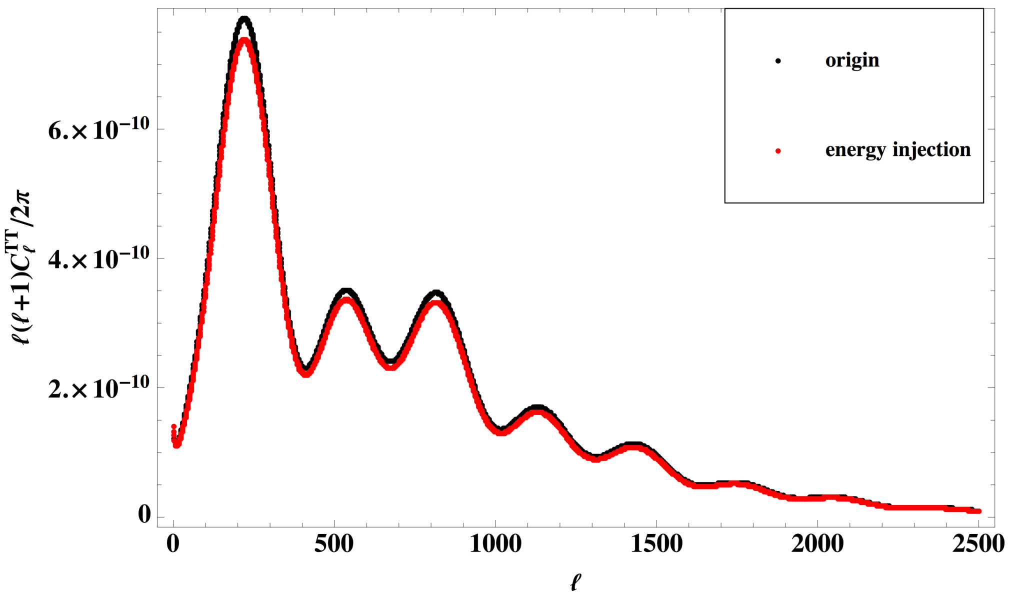
Energy injection history



- 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 ; $\propto e^{-t/\tau}/_{\tau}\,(1+z)^3$ for decay
- Need time to deposit: delayed deposition

CMB change

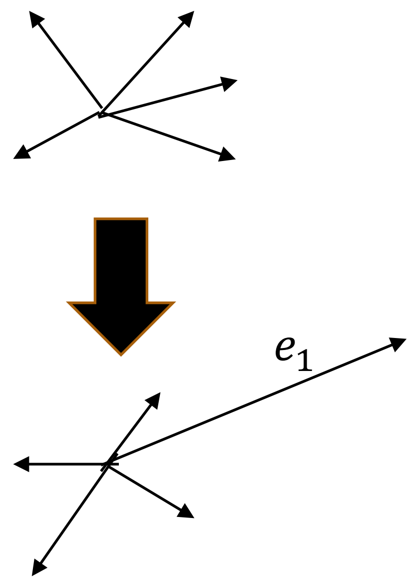
- Boltzmann code (ex: **CLASS)**: study specific energy injection profile
- Decaying DM Injecting 30 MeV e^+e^- :



- **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 δC_ℓ
  - Construct Fisher matrix, marginalized over standard parameters
  - Eigenvectors $e_i = \sum_j (\alpha_i)_j \; M_j$ with eigenvalues λ_i
  - If $\lambda_1 >> \lambda_i$, $e_1 = \sum_j (\alpha_1)_j \; M_j$ dominate
  - 2σ constraint: $\frac{<\sigma v>}{M_x}$, $\frac{1}{\tau} < \frac{2}{(\alpha_1)_j \sqrt{\lambda_1}}$

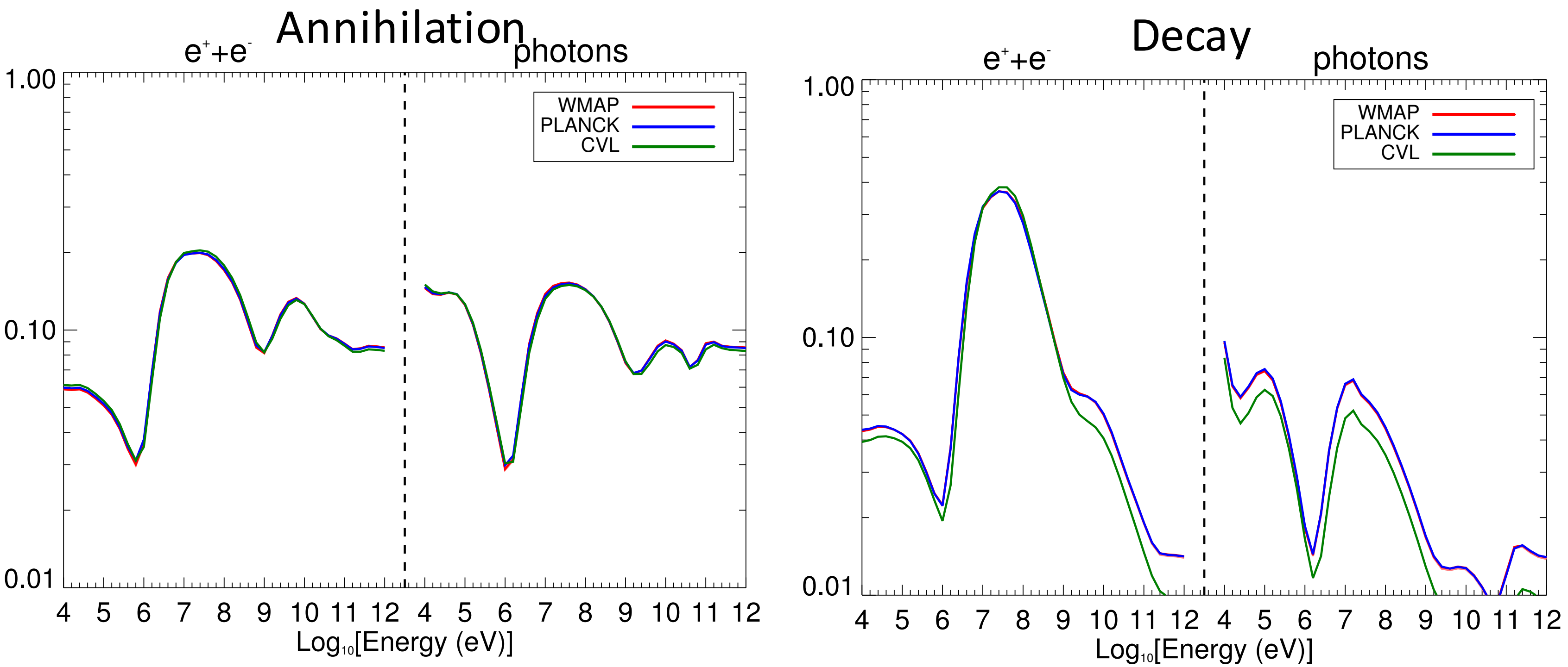


* In linear regime, where energy injection is small

* Gaussian likelihood

PCA – Energy

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



PCA – Energy

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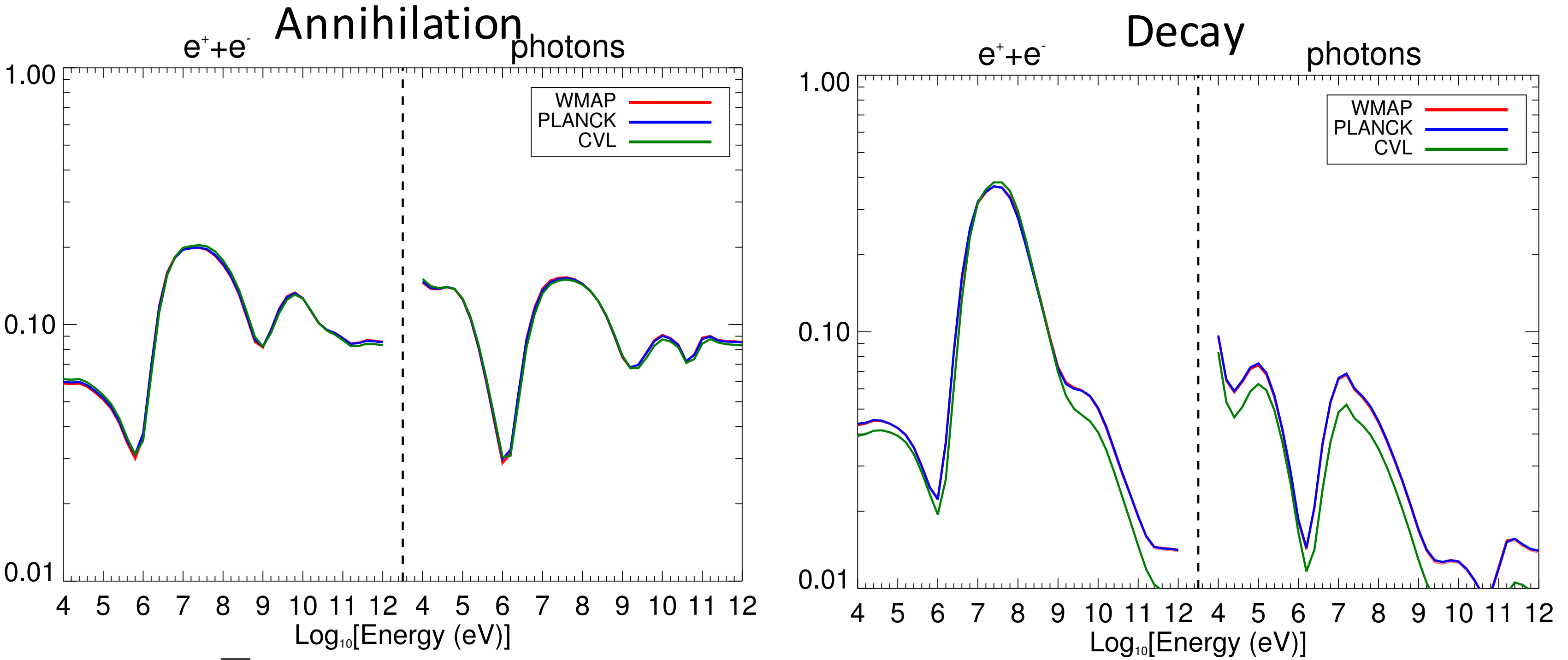


1. $e_1 = \sum_j (\alpha_1)_j \; M_j$ dominate

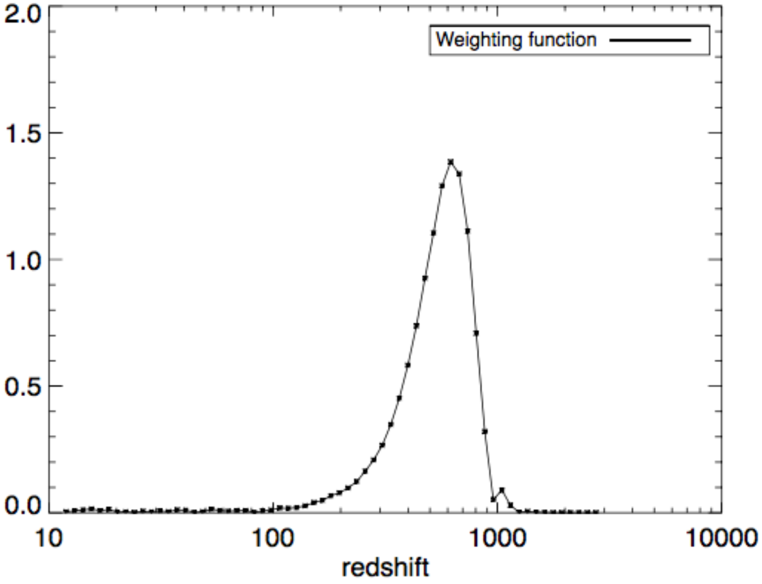
2. λ_1 contributes >99.9% of variance for ann, >97% for decay

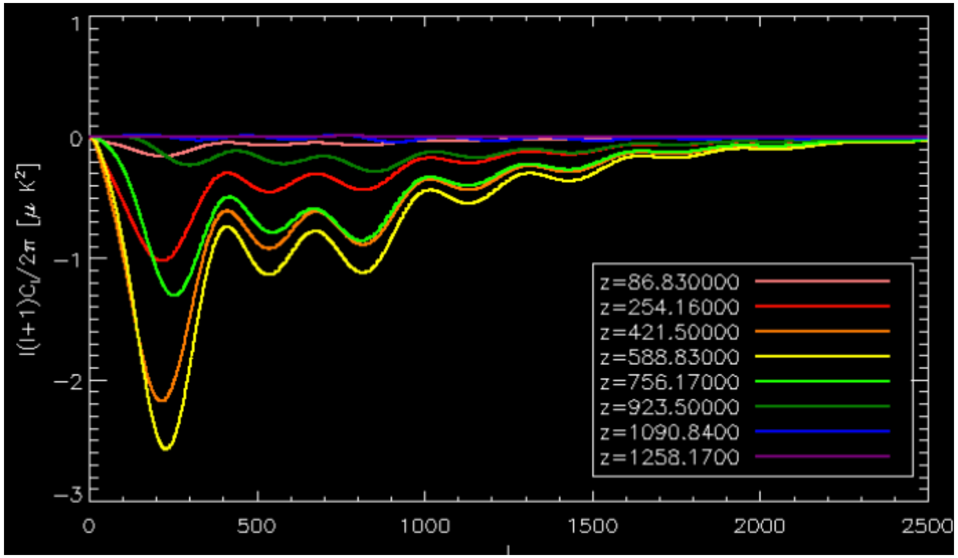
3. Upper limit at different energies E_i scales as $\frac{2}{(\alpha_1)_j\sqrt{\lambda_1}}$

PCA – Redshift

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

Annihilation





PCA – Redshift

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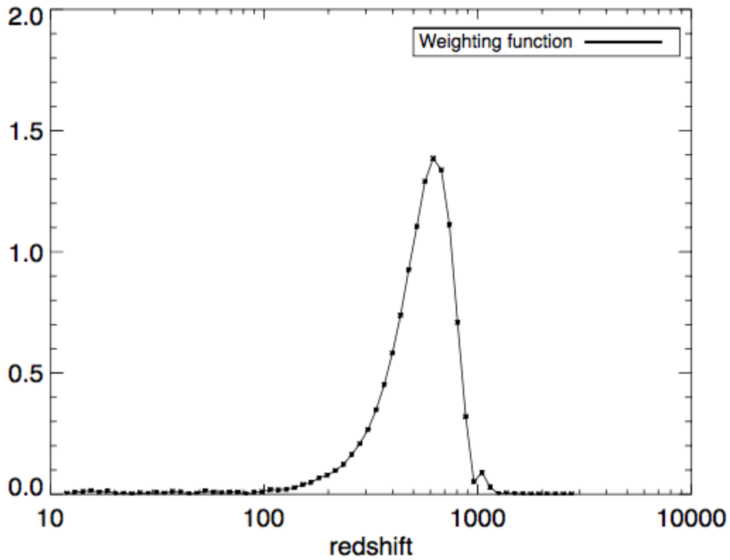
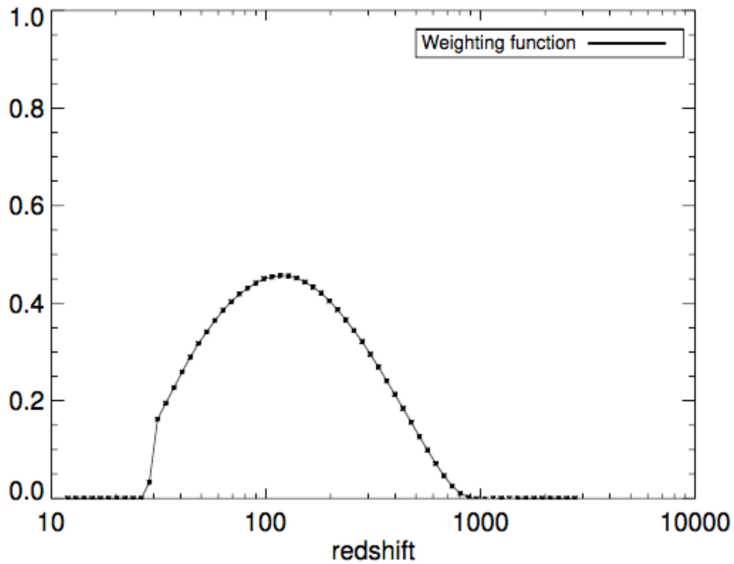


Decay

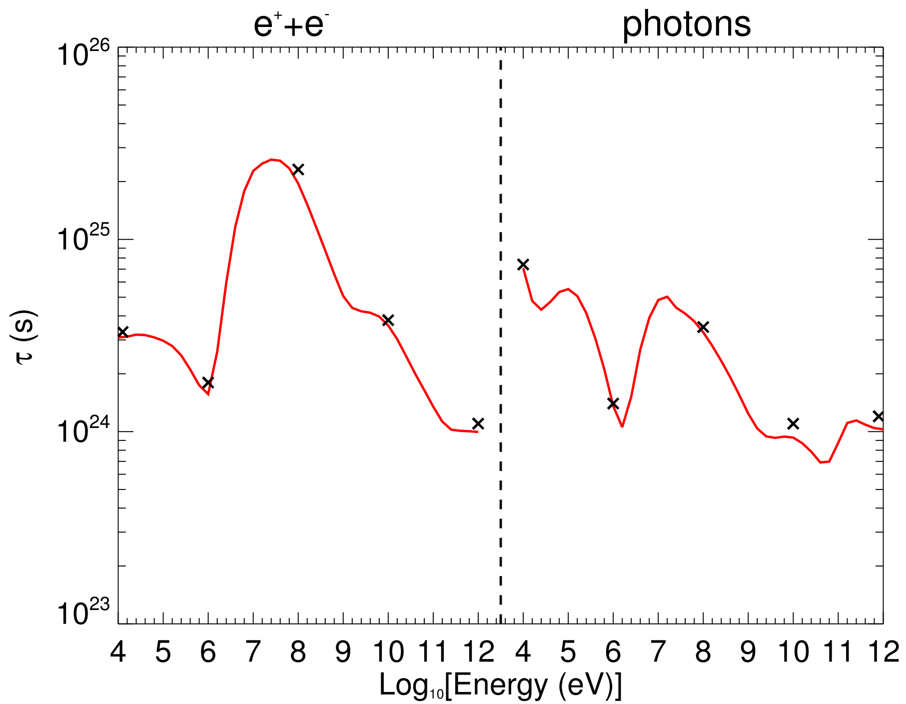


- The weighting function for annihilation peaks at z∼600 while for decay broadly peaks at z∼300
- The process can be captured by a single parameter

MCMC

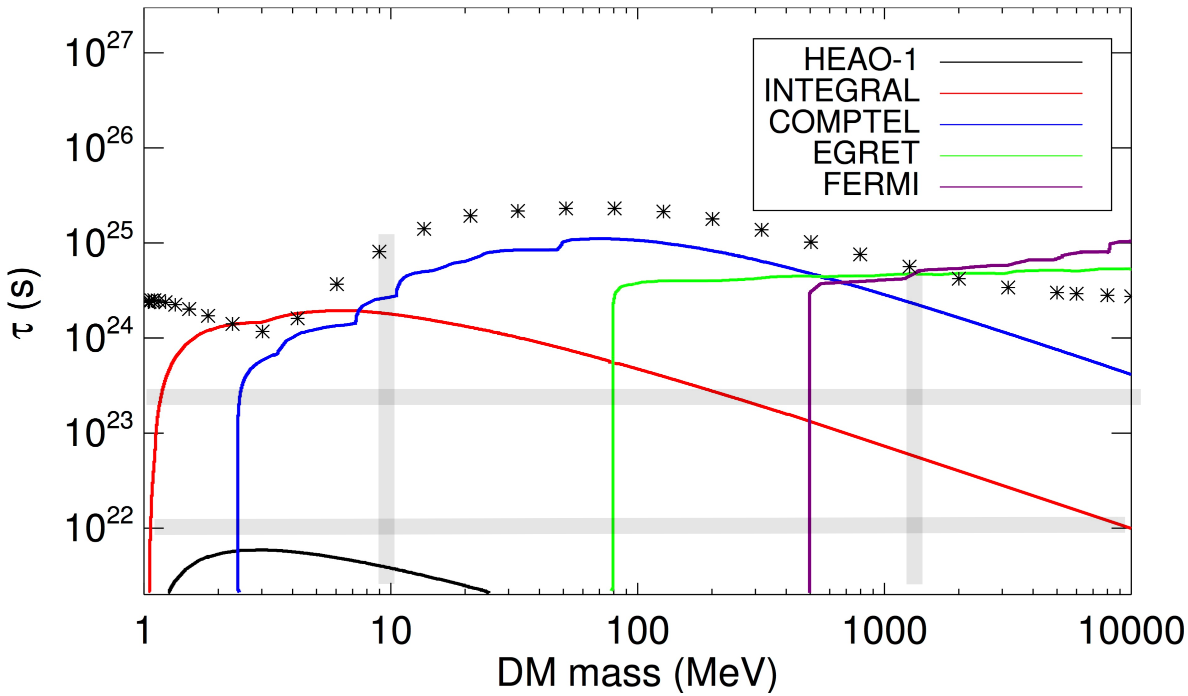
- Go beyond linearity and Gaussian likelihood
- Use MCMC code (ex: **Montepython**):

  six standard cosmological parameters + DM decay lifetime
- Perform MCMC to check PCA result



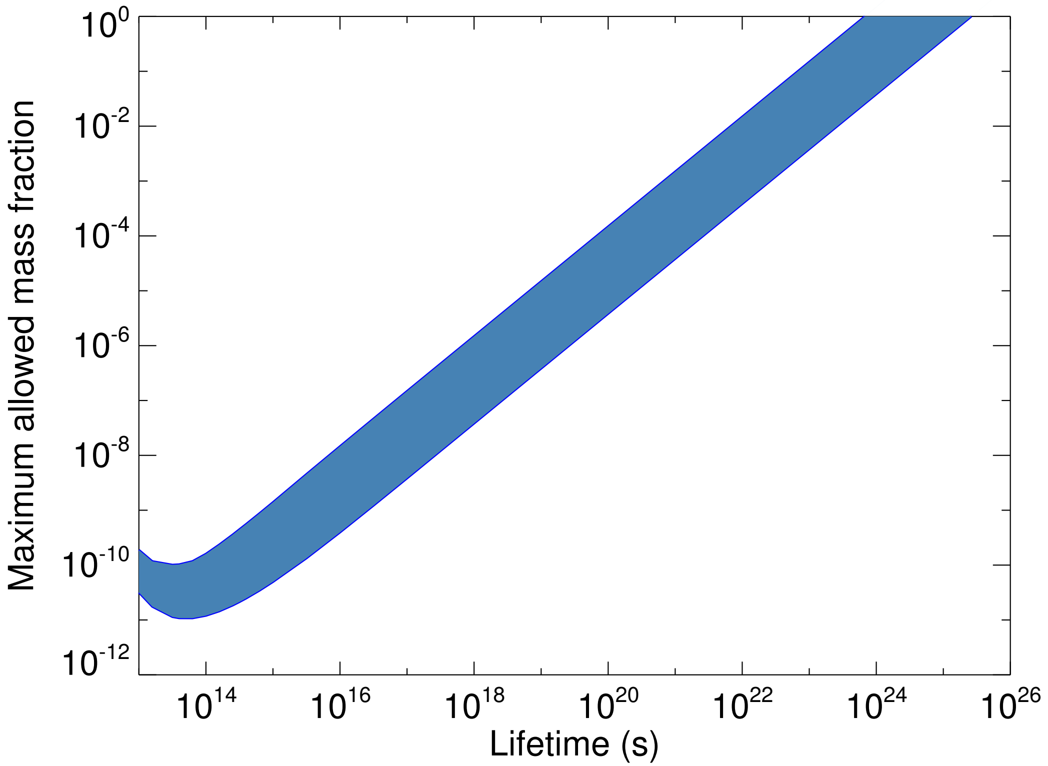
Compare with observation

- 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^-:



Constraint on Decaying DM

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

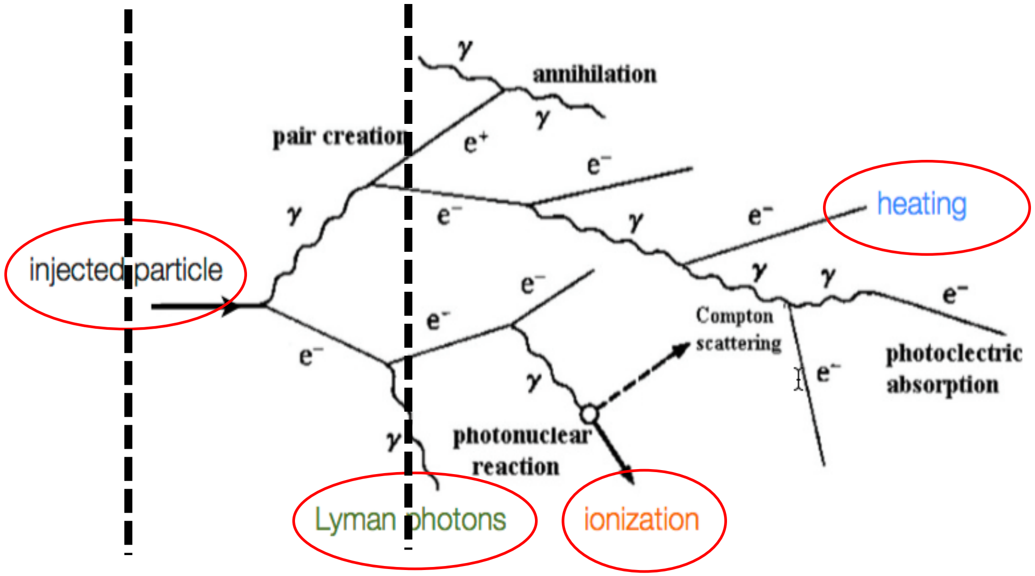


Summary

- 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 MeV – 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

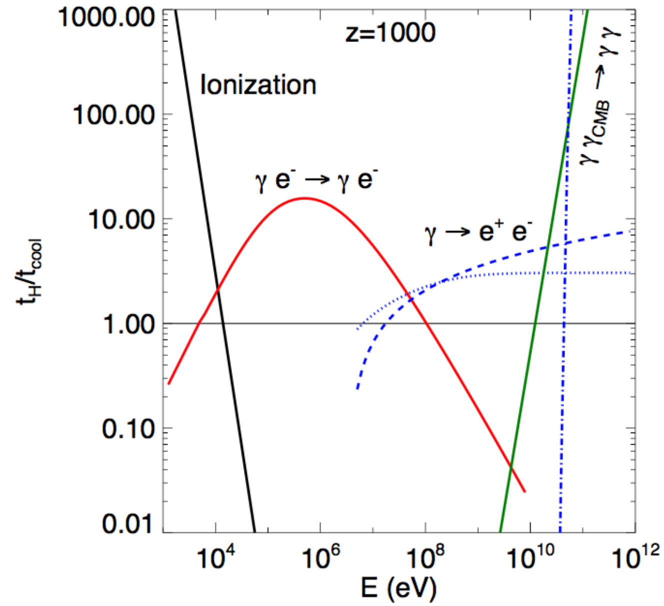
Bonus Slides

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:
  - $p_a(z_f, E_i) \sim \sum_i f_a(z_i, z_f, E_i) \times$ injection rate(z_i)
- Injection rate:
  - $\propto < \sigma v > (1+z)^6$ for annihilation
  - $\propto e^{-t/\tau}/_{\tau}\,(1+z)^3$ for decay

$p_{\text{ionization}}(z_f, E_i)$

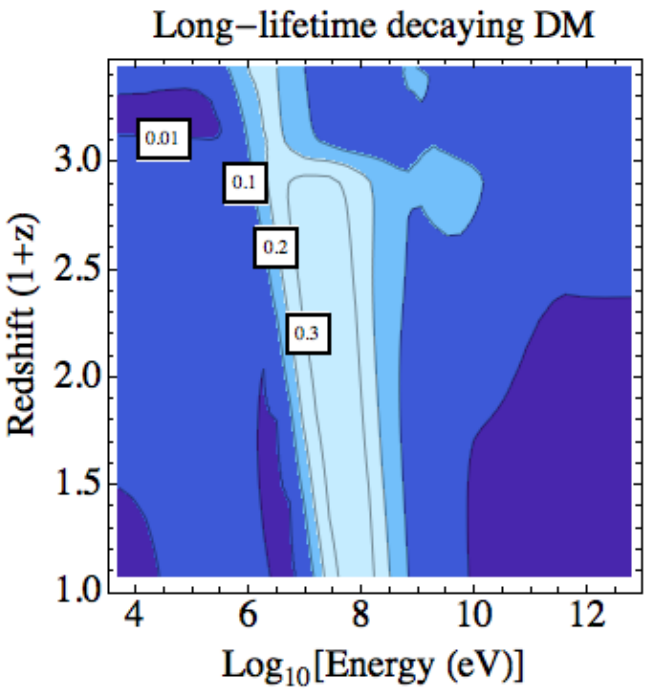


Tracy Slatyer et. al arXiv:0906.197

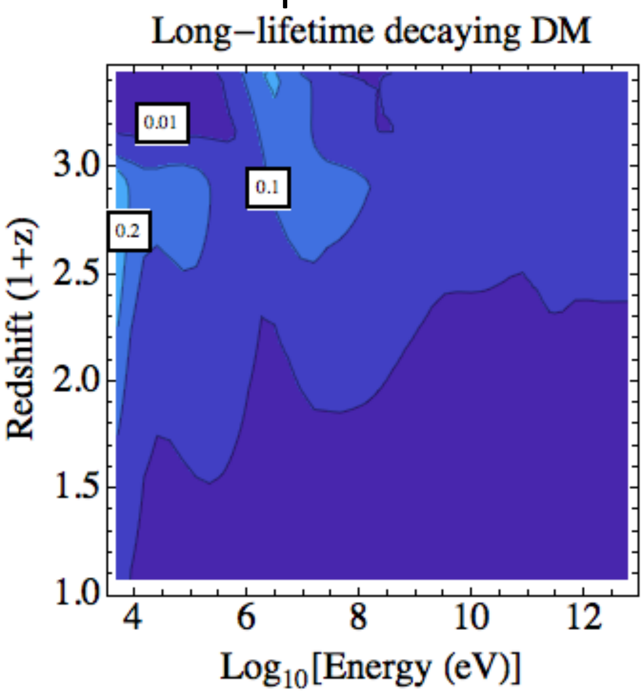
- Photon: ionization efficiency is high for low energy photon
- Electron: 30 MeV upscatter CMB by Compton scattering, produce low energy photon

$p_{ionization}(z_f, E_i)$ - Decay

e^+e^-



photons



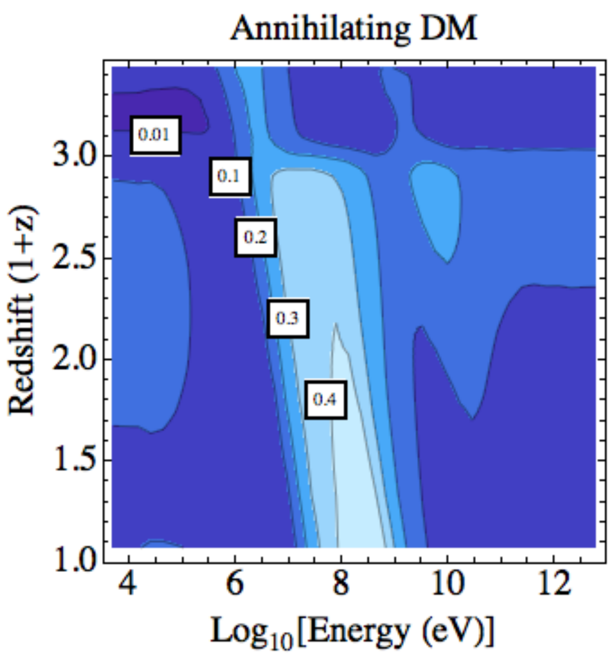
- transparent at low redshift?

  need time to deposit (delayed deposition)
- High efficiency window:

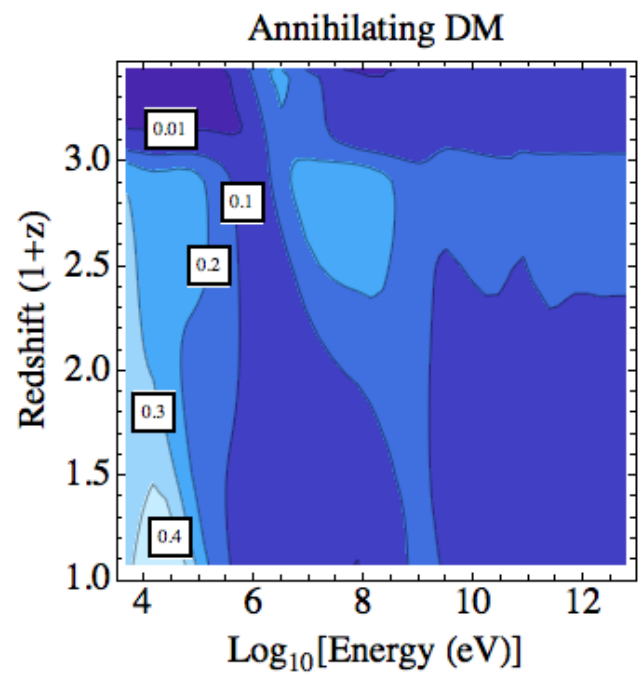
  30 MeV for e^+e^- and 10 keV for photon

$p_{ionization}(z_f, E_i)$ - Annihilation

e^+e^-



photons

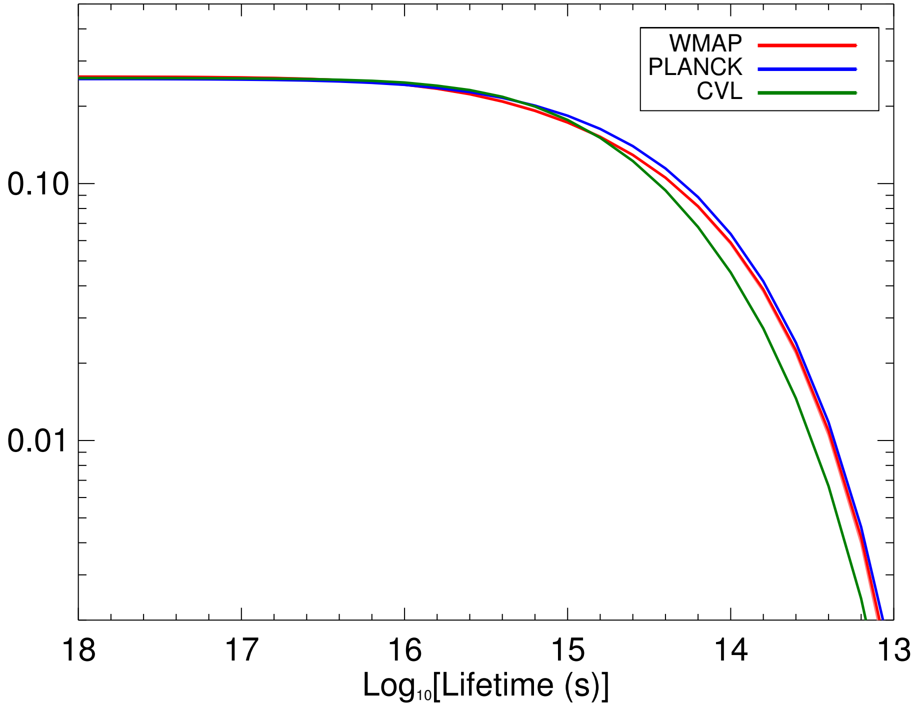


- transparent at low redshift? -> delayed deposition
- High efficiency window:
  - 30 MeV for electron and 10 keV for photon

Short-lifetime decaying DM

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

  basis: fixed 30 MeV electrons but different lifetimes

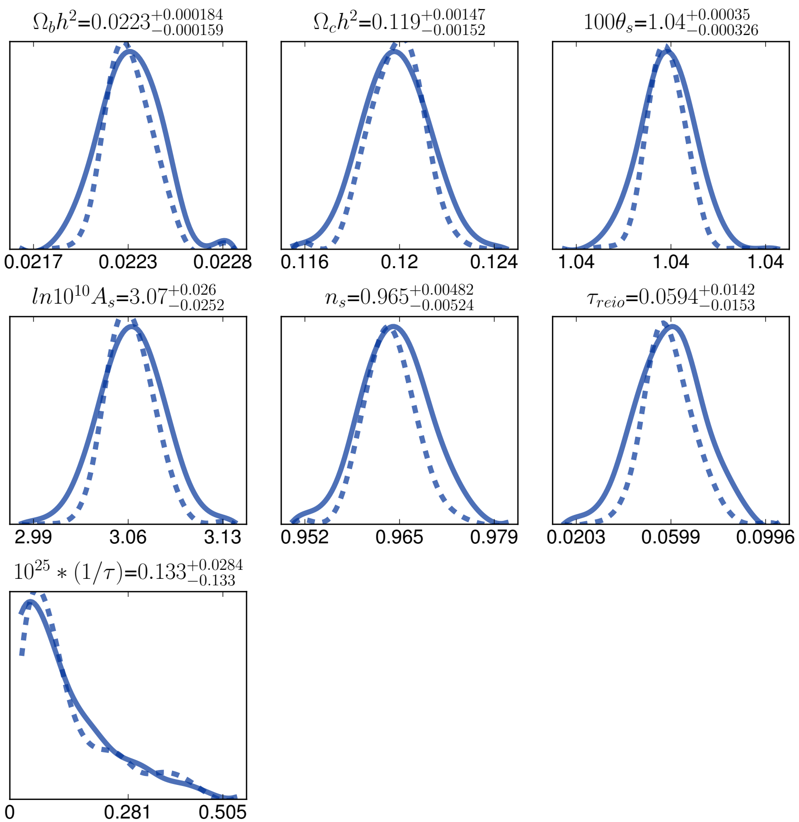


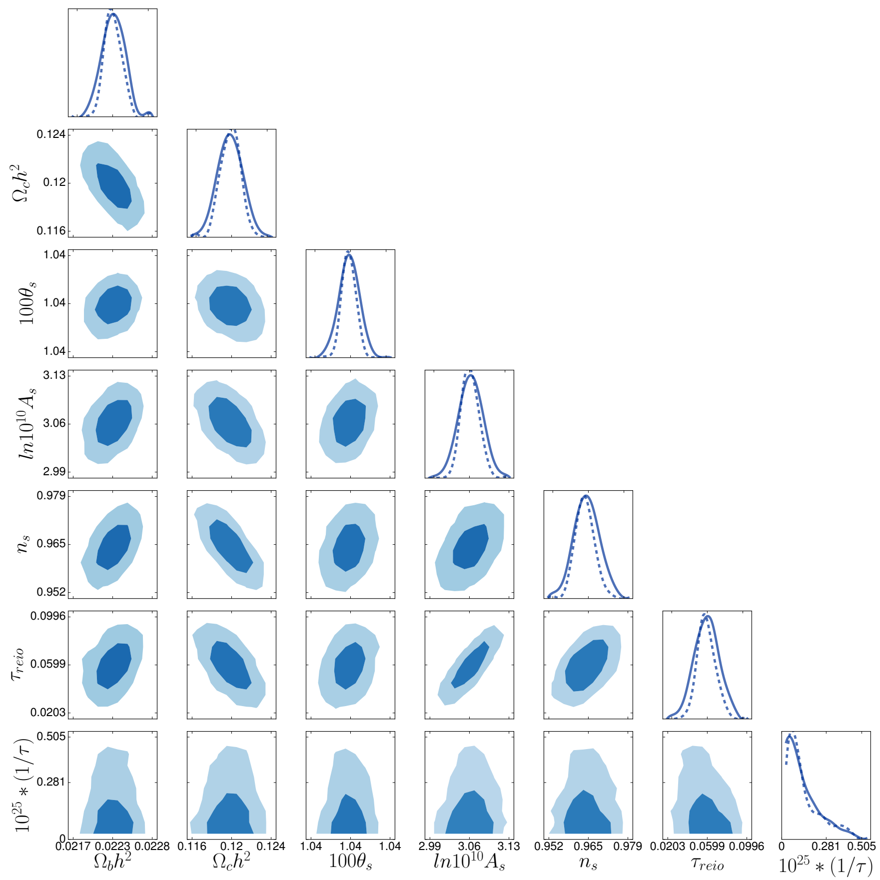
1. λ_1 (first PC) dominate > 98%
2. Short-lifetime DM has little weight

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

MCMC

- For example: decaying DM, 30MeV electron injection



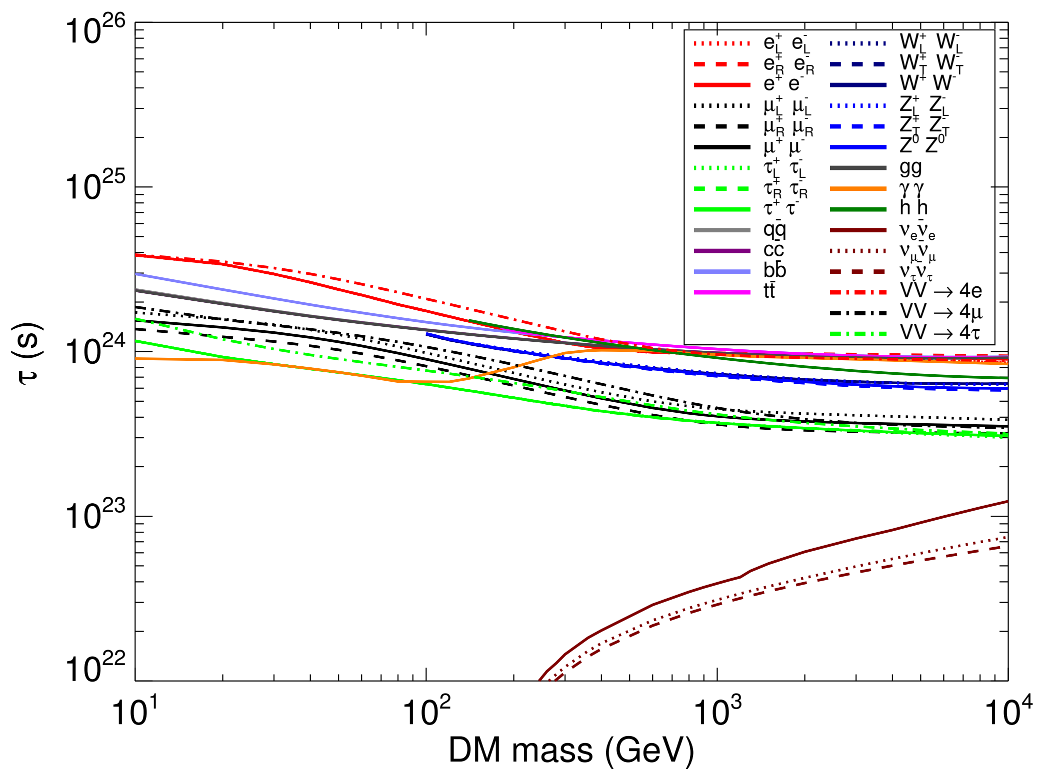


General constraint

- DM decay to Standard Model particles:

  PPPC4DMID package:

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



Fisher Matrix

$$\Sigma_\ell = \frac{2}{2\ell+1}\times$$

$$\begin{pmatrix} \left(C_\ell^{TT}\right)^2 & \left(C_\ell^{TE}\right)^2 & C_\ell^{TT}C_\ell^{TE} \\ \left(C_\ell^{TE}\right)^2 & \left(C_\ell^{EE}\right)^2 & C_\ell^{EE}C_\ell^{TE} \\ C_\ell^{TT}C_\ell^{TE} & C_\ell^{EE}C_\ell^{TE} & \left[\left(C_\ell^{TE}\right)^2 + C_\ell^{TT}C_\ell^{EE}\right] \end{pmatrix}$$

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

- 6 cosmological parameter: baryon density, ωb, CDM density, ωc, the primordial scalar spectral index ns, the normalization As (k = 0.002/Mpc), the optical depth to reionization τ and the Hubble parameter H0

$$F = F_e - F_v F_c^{-1} F_v^T$$

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