

Cosmo probes of DM Energy Injection

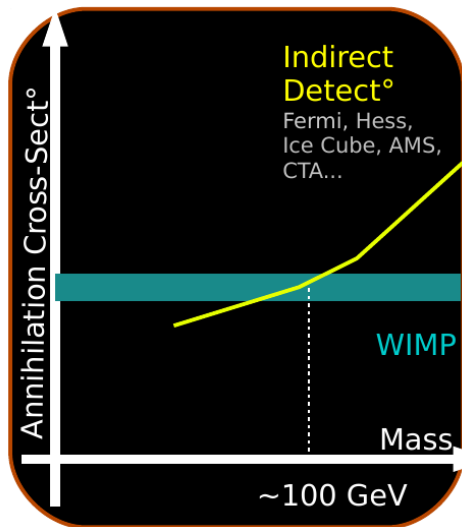
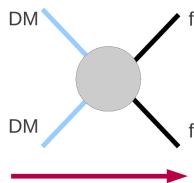
Laura Lopez Honorez



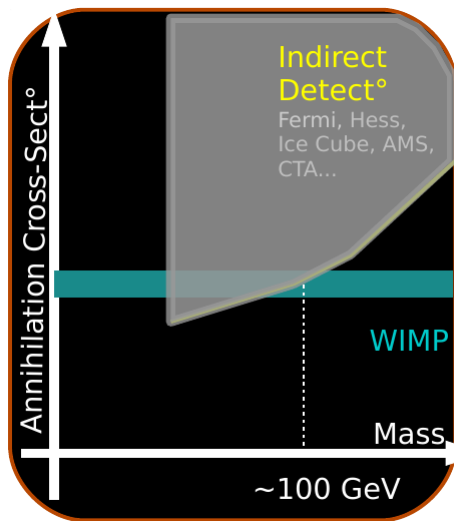
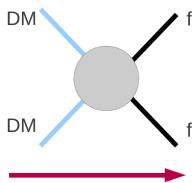
partially based on JCAP 01 (2024) 005 and JCAP 06 (2023) 060,
with F. Capozzi, G. Facchinetti, R.Z. Ferreira, O. Mena, Y. Qin and A. Mesinger

Invisibles 24 Workshop - Bologna
1-7/06/24

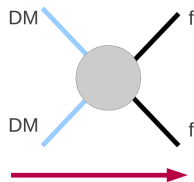
DM searches: Cosmo complementarity



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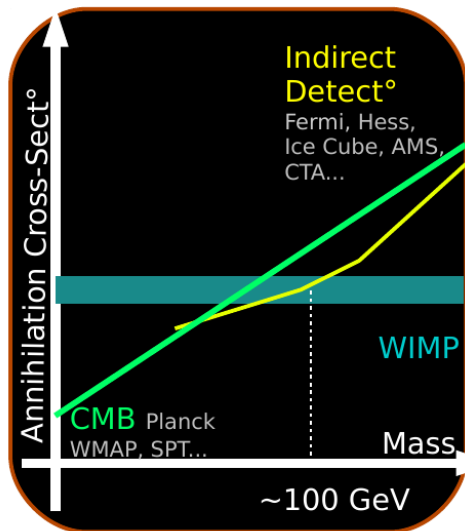


DM searches: Cosmo complementarity

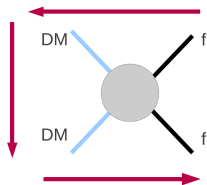


Cosmology probes have already provided stringent constraints on DM energy injection

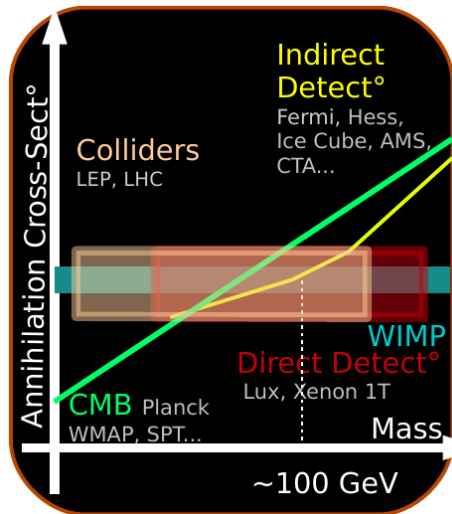
Can we do better with future probes?



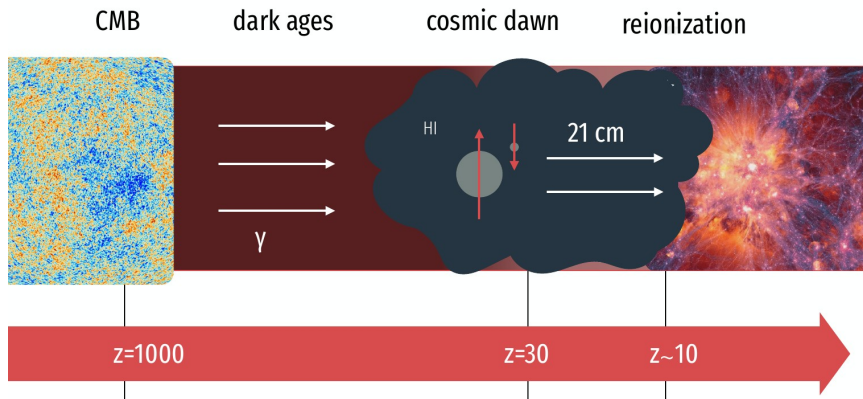
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Cosmology Probes



©G. Facchinetti

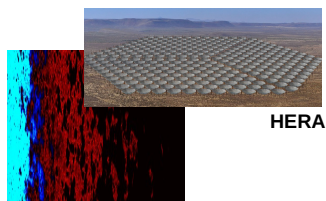
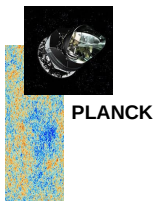
Cosmology Probes

CMB

dark ages

cosmic dawn

reionization



z=1000

z=30

z~10

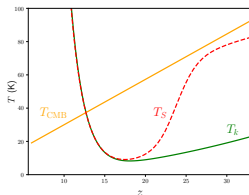
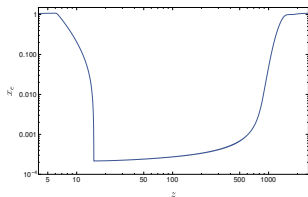
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DM energy injection/deposition in early universe

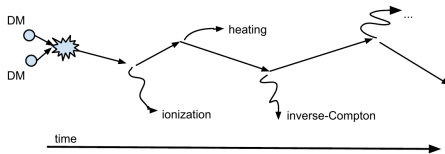
see previous work e.g. [Adams'98, Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05, Slatyer'15, Liu'19] for CMB, [Shchekinov'06, Furlanetto'06, Valdes'07, Chuzhoy'07, Cumberbatch'08, Natarajan'09, Yuan'09, Valdes'12, Evoli'14, LLH'16] for 21cm

- Consider DM injecting SM particles
 - f, γ, W, Z, \dots injected $\rightsquigarrow e^+, e^-, \gamma$
 - neutrinos \rightsquigarrow suppressed depos. but possible via EW corrections

DM energy injection/deposition in early universe

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- Consider DM injecting SM particles
 - f, γ, W, Z, \dots injected $\rightsquigarrow e^+, e^-, \gamma$
 - neutrinos \rightsquigarrow suppressed depos. but possible via EW corrections
- The rate of energy deposition depends on the DM nature



[image from A. Vincent]

decaying DM

s-wave annihilating DM ($\langle \sigma v \rangle \sim \sigma v_0$)

p-wave annihilating DM ($\langle \sigma v \rangle \sim \langle v^2 \rangle$)

accreting Primordial Black Holes (PBH)

$$\frac{dE}{dt dV} \propto \rho_\chi / \tau_\chi \times e^{-t/\tau_\chi}$$

$$\frac{dE}{dt dV} \propto \frac{\rho_\chi^2}{m_\chi} \times \sigma v_0$$

$$\frac{dE}{dt dV} \propto \frac{\rho_\chi^2 \langle v^2 \rangle}{m_\chi} \times \frac{\sigma v_0}{v_0^2}$$

$$\frac{dE}{dt dV} \propto n_{PBH} \times L_{acc}$$

Decaying DM = Later energy injection

Early energy inj. for s-wave ann. DM
(aka **WIMP**):

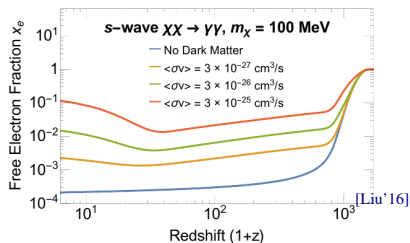
$$\begin{aligned} \frac{dE_{\text{inj/b}}}{dz} &\propto \frac{\rho_{\text{DM}}^2}{n_b(1+z)H} \frac{\sigma v_0}{m_{\text{DM}}} \\ &\propto (1+z)^{1/2} \frac{\sigma v_0}{m_{\text{DM}}} \end{aligned}$$

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$$\frac{dE_{\text{inj/b}}}{dz} \propto \frac{\rho_{\text{DM}}^2}{n_b(1+z)H} \frac{\sigma v_0}{m_{\text{DM}}}$$

$$\propto (1+B(z))(1+z)^{1/2} \frac{\sigma v_0}{m_{\text{DM}}}$$



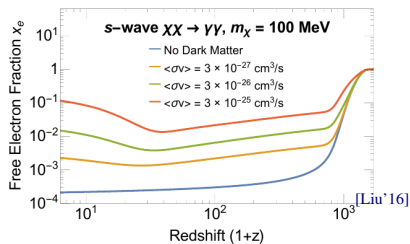
+ later Boost $\sim B(z)$ of $\bar{\rho}_\chi^2$ from
structure formation see e.g. [LLH'13, Liu'16, etc]

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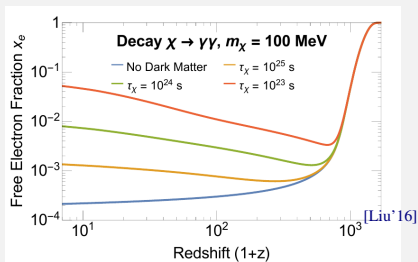


+ later Boost $\sim B(z)$ of $\bar{\rho}_\chi^2$ from
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Late energy inj. for decaying DM
(beyond **WIMP**):

$$\frac{dE_{\text{inj/b}}}{dz} \propto \frac{\rho_{\text{DM}}}{n_b(1+z)H} \frac{1}{\tau_{\text{DM}}}$$

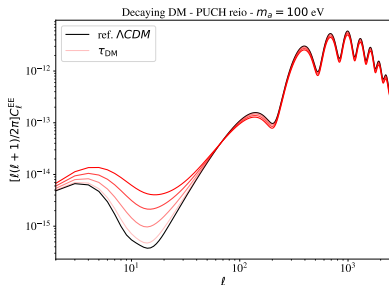
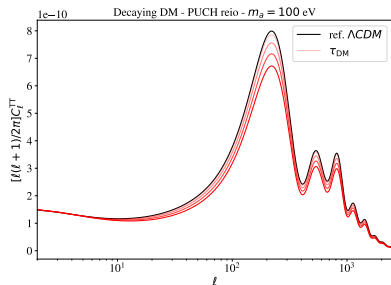
$$\propto (1+z)^{-5/2} \frac{1}{\tau_{\text{DM}}}$$



focus on $\tau_{\text{DM}} > t_u$

Existing CMB constraints

DM energy injection on CMB anisotropy spectra

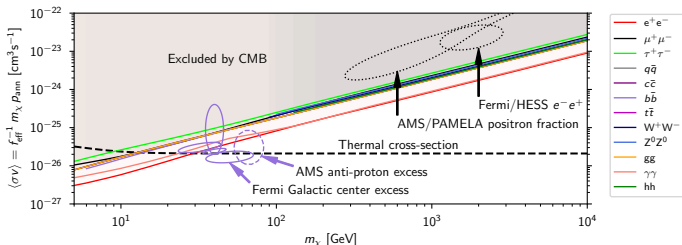


- **increased residual ionization** after recombination
- increased the optical depth to reionization $\tau_{\text{reio}} = \int dt x_e n_b \sigma_T$
- **attenuates correlations** at small scales (large ℓ) and **enhances low- ℓ polarisation power**.

The low- ℓ data are important to discriminate energy injection from other cosmo params such as n_s, A_s affecting the amplitude of the CMB peaks.

Stringent CMB constraints on DM s-wave annihilation

see e.g. [Chen'03, Padmanabhan'05, Cirelli'09, Slatyer'09, Galli'11, Giesen'12, LLH'13, Galli'13, Madhavacheril'13, Poulin'15,...]

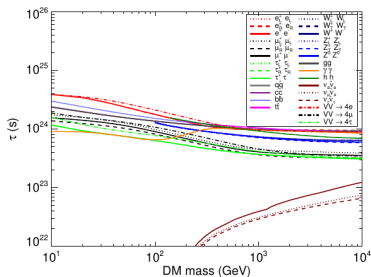
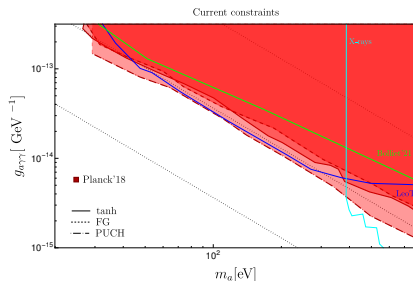


$$\rightsquigarrow p_{\text{ann}} = f_{\text{eff}} \langle\sigma v\rangle / m_{\text{DM}} < 3.2 \cdot 10^{-28} \text{ cm}^3/\text{s}/\text{GeV} \text{ at } 95\% \text{ CL [Planck'18]}$$

- CMB data most sensitive to annihilating DM energy injections at $z \simeq 600$ [Finkbeiner'12].
- **Advantage** of CMB compared to other DM annihilation probes: **do not suffer astrophysics uncertainties** (such as ρ_{DM}) and **no contributions from halos** for σv independent of v (s-wave annihilation) [LLH'13, Poulin'15, Hongwan'16].

CMB constraints on DM decay

see also [LLH'13, Liu'16, Slatyer'16, Capozzi'23,... + M. Cirelli's talk]

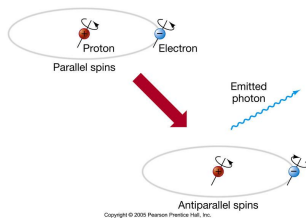


- CMB data most sensitive to decaying DM energy injections at $z \simeq 300$ [Slatyer'16].
- CMB bounds: $\tau_{\text{DM}} > \text{few} \times 10^{24} \text{ s}$ at 95% CL [Slatyer'16]. Usually weaker than indirect DM searches probing up to $\tau \sim 10^{27-30} \text{ s}$.
- Stronger sensitivity for MeV-GeV DM decaying to e^+e^- and <MeV DM decaying to $\gamma\gamma$ reaching $\tau_{\text{DM}} > \text{few} \times 10^{26} \text{ s}$ at 95% CL see [Capozzi'23& Liu'23].

21cm Cosmology : near future late time probe

Cosmic Dawn and 21 cm signal

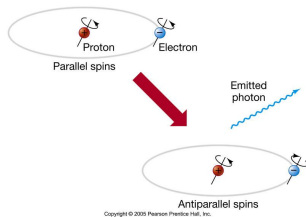
The Cosmic Dawn \equiv period where first galaxies started to shine up until reionization (EoR). The most powerful probe is 21 cm spin flip line of HI :



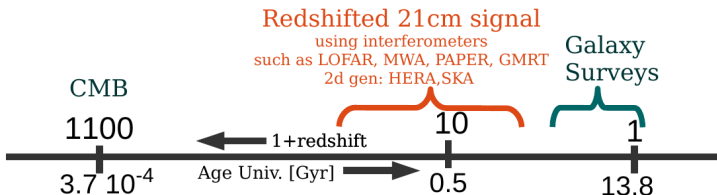
- Transitions between the two ground state energy levels of neutral hydrogen HI
 \rightsquigarrow 21 cm photon ($\nu_0 = 1420$ MHz)

Cosmic Dawn and 21 cm signal

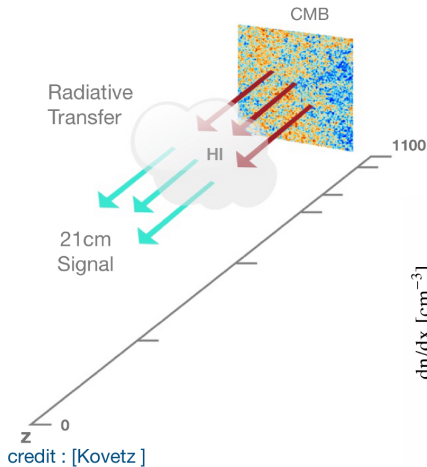
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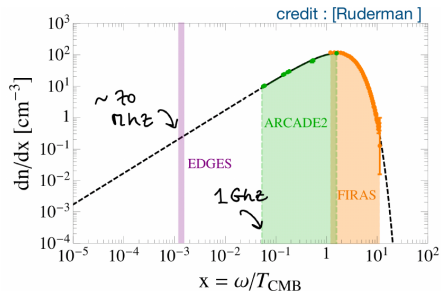
- Transitions between the two ground state energy levels of neutral hydrogen HI \rightsquigarrow 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during **Cosmic Dawn & EoR** redshifted to $\nu \sim 100$ MHz \rightsquigarrow **new cosmology probe**



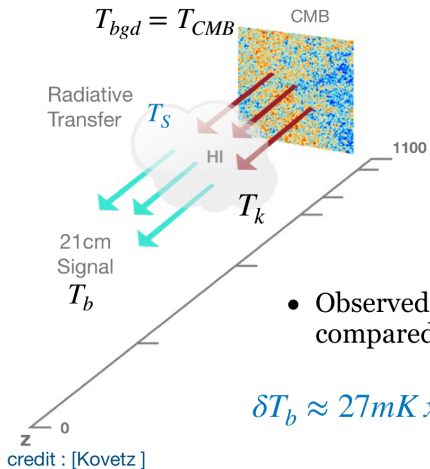
21 cm in practice



- 21cm signal observed as CMB spectral distortions



21 cm in practice



- 21cm signal observed as CMB spectral distortions

- The spin temperature (= excitation T of HI) characterises the relative occupancy of HI ground state

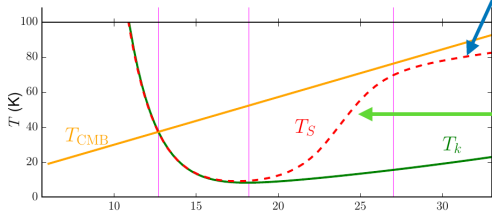
$$n_1/n_0 = 3 \exp(-h\nu_0/k_B T_S)$$

- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

$$\delta T_b \approx 27 \text{mK} x_{HI} (1 + \delta) \sqrt{\frac{1+z}{10}} \left(1 - \frac{T_{CMB}}{T_S} \right)$$

The spin temperature

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$



Emmission/
absorption of CMB
photons

$$T_S \rightarrow T_{CMB}$$

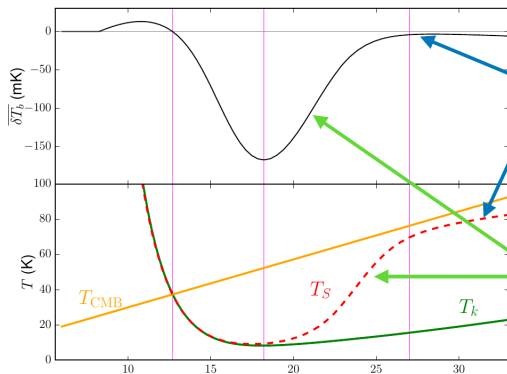
- Collisions with H, e
- Scattering of Ly- α photons (Wouthuysen-Field effect)

$$T_S \rightarrow T_k$$

$T(K)$ and δT_b obtained using 21cm Fast [Mesinger'10]

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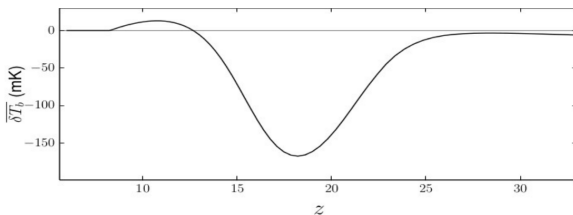
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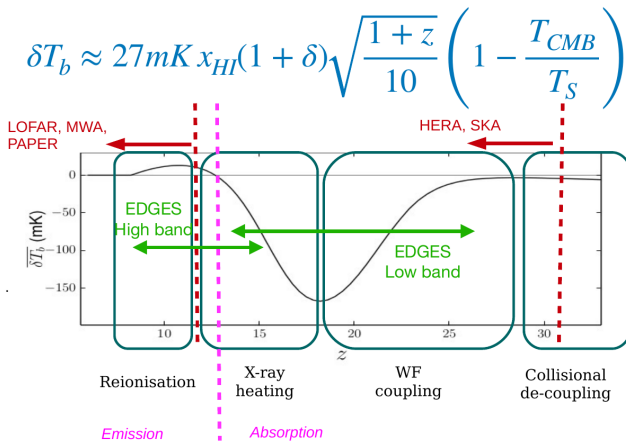
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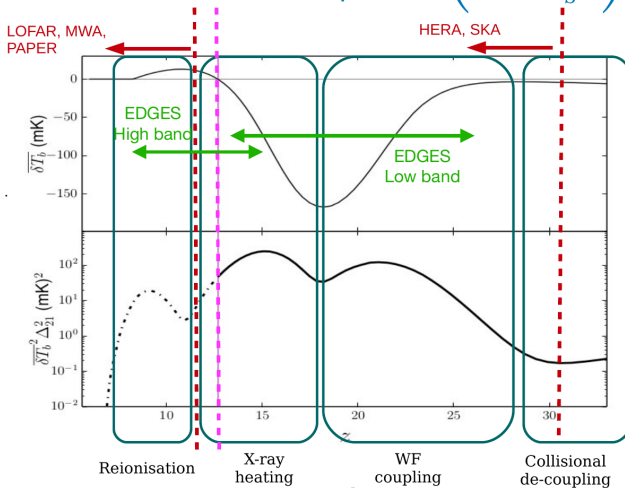


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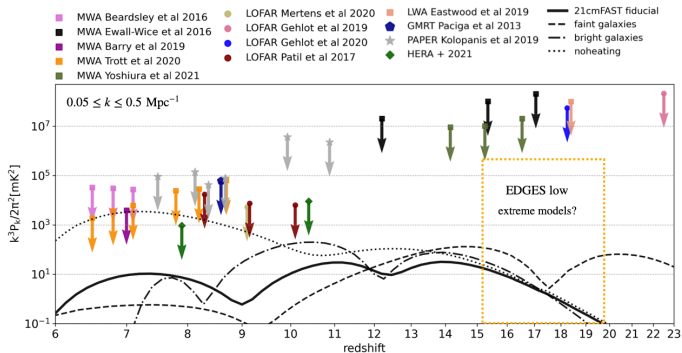
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$$\langle \tilde{\delta}_{21}(\mathbf{k}, z) \tilde{\delta}_{21}^*(\mathbf{k}', z) \rangle \equiv (2\pi)^3 \delta^D(\mathbf{k} - \mathbf{k}') P_{21}(k, z) \quad \Delta_{21}^2(k, z) = \frac{k^3}{2\pi^2} P_{21}(k, z)$$

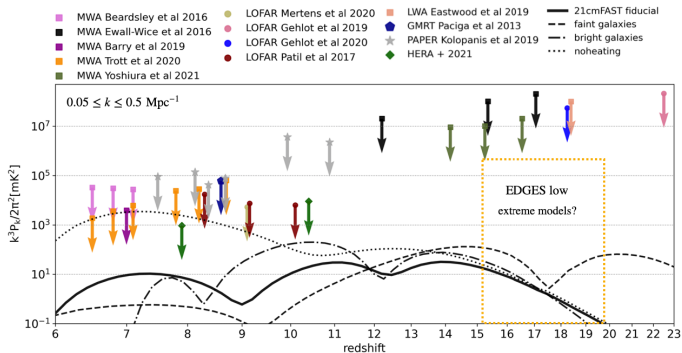
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Constraints on 21cm Power spectrum?



[Shimabukuro'23]

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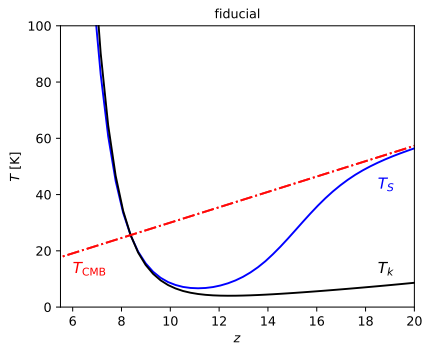


[Shimabukuro'23]

- We will consider **HERA interferometer** in South Africa with 331 antennas (14m dishes) under deployment (=SKA precursor).
- First data from **HERA phase I** probed $z \sim 8 - 10$ with only ~ 70 ant. **already set a lower bound on X-ray heating** [HERA'21& 22]. Actually the full set of 331 antennas is already build and soon taking data.

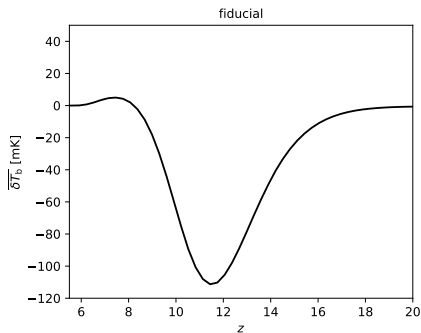
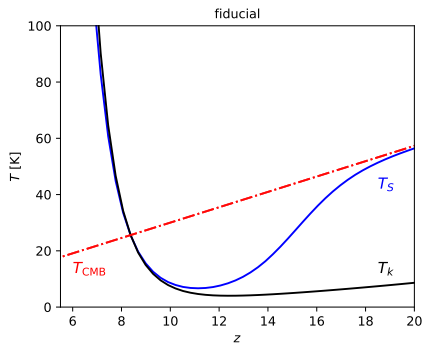
Decaying DM and 21cm power spectrum

Impact of decaying DM on T_k and δT_b



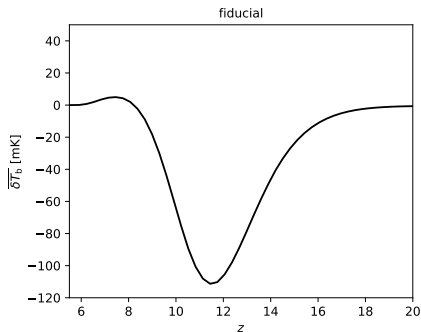
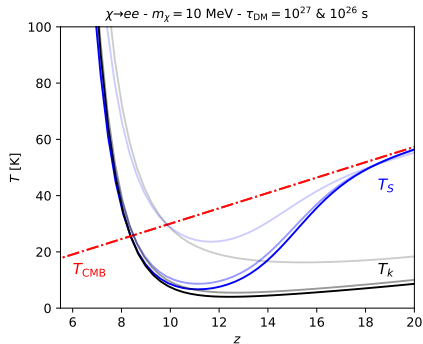
plots made using exo21cmFast developed by G. Facchinetti merging 21cmFast and DarkHistory

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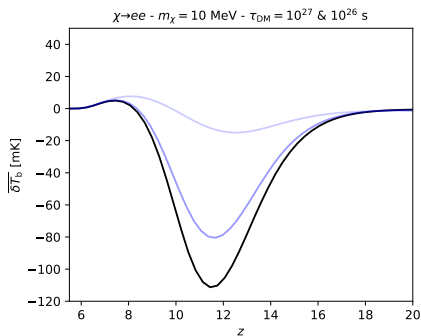
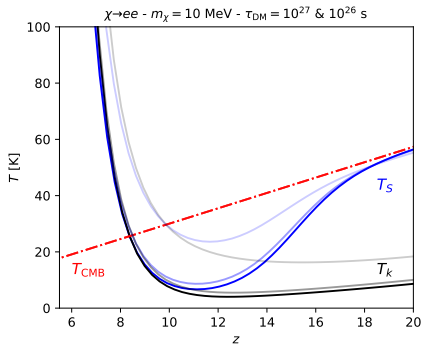


DM energy injection implies

- new **source of heating**, earlier than X-rays from stars

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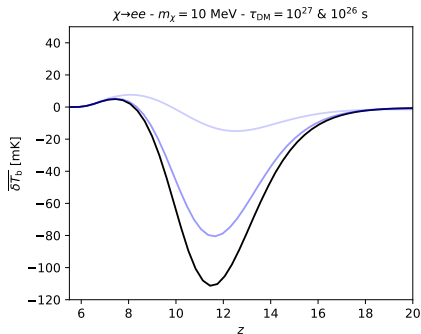
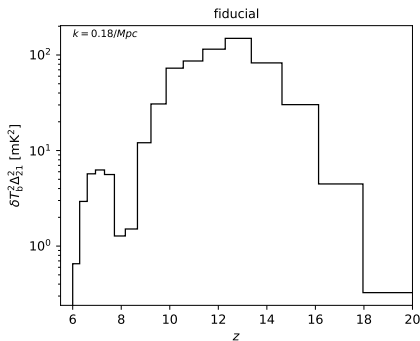


DM energy injection implies

- new **source of heating**, earlier than X-rays from stars
- **suppressed absorption** in δT_b

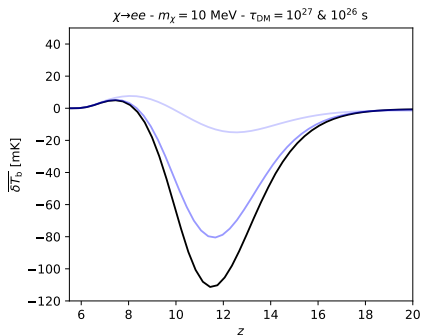
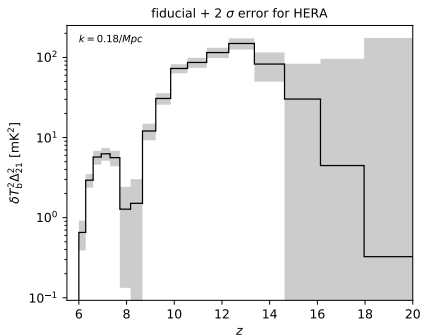
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Impact of decaying DM on δT_b and Δ_{21}



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 $k = 0.18/\text{Mpc}$ is relatively free from foregrounds.

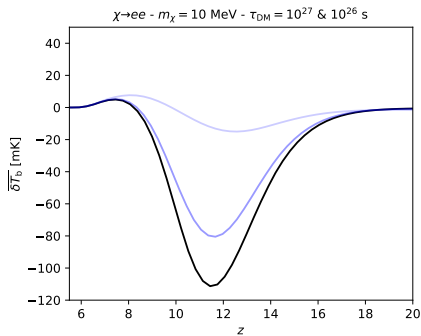
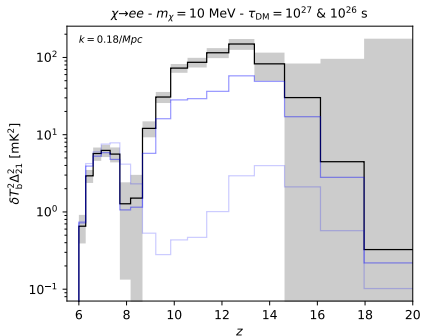
Impact of decaying DM on δT_b and Δ_{21}



- 2 σ error bands from 21cmSense for HERA.

plots made using exo21cmFast developed by G. Facchinetti merging 21cmFast and DarkHistory.
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Impact of decaying DM on δT_b and Δ_{21}

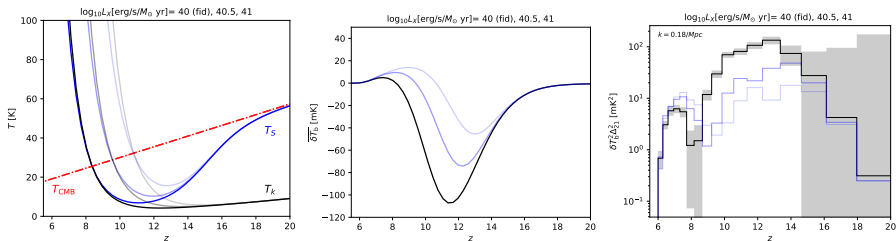


- 2σ error bands from 21cmSense for HERA.
- DM decays give **suppressed power** around X-ray heating - Lyman- α coupling time
- Lifetimes as large as $\tau_{DM} = 10^{27}$ s shall leave a measurable imprint

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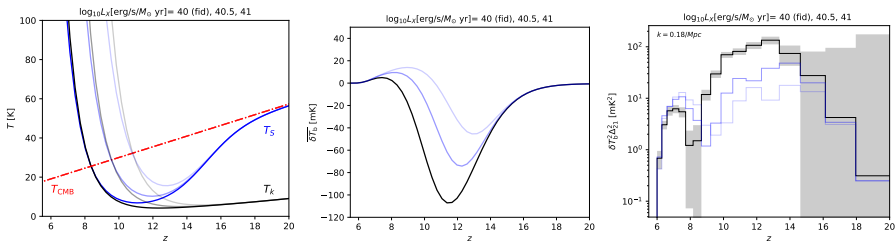
Degeneracies with astro parameters

For example, X-ray heating from stars parametrized with a normalisation of soft-band X-ray luminosity per unit SFR: $L_X \sim 10^{40}$ [erg/s/ M_\odot yr].



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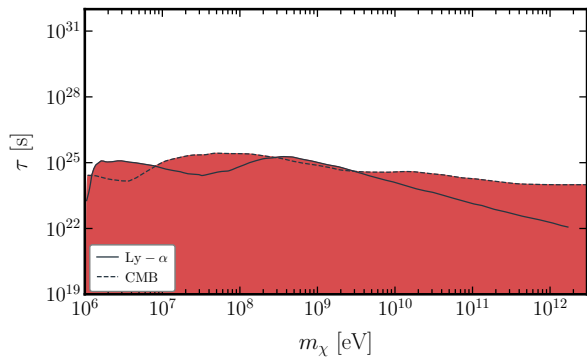
- Increasing L_X also gives rise to a **suppression of the PS at large z**
- X-rays from stars drive a 21cm signal saturated earlier
 \rightsquigarrow **stronger contrast at low z .**

It is possible to **disentangle** L_X effect from τ_{DM}

plots with exo21cmFast developed by G. Facchinetti merging 21cmFast and DarkHistory

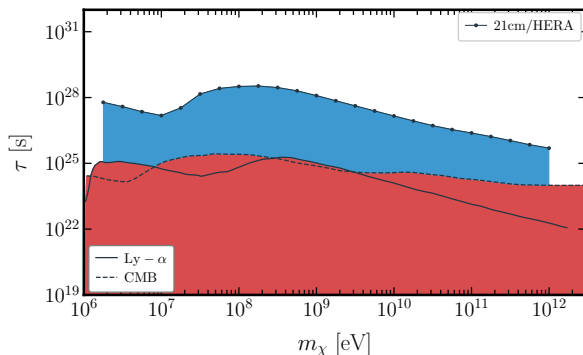
Encouraging forecasts of 21cm bounds on $\chi \rightarrow ee$

$$\chi \rightarrow e^+e^-$$



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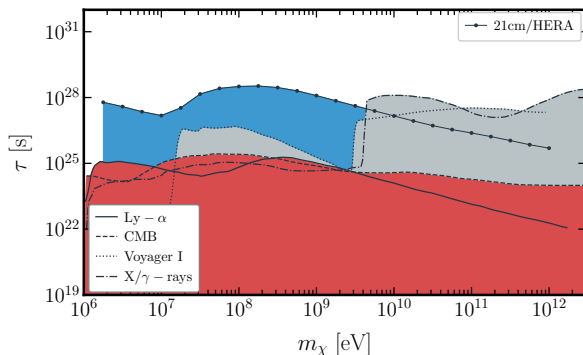


- (optimistic) Fisher Matrix forecasts for HERA 331 antennas and $t_{obs} = 1000$ h
- $\tau_{DM} \gtrsim 10^{27-28} s$

- Future redshifted 21cm signal power-spectrum measurements can **surpass** current CMB and/or Lyman- α sensitivity by 2-3 orders of magnitude.

Encouraging forecasts of 21cm bounds on $\chi \rightarrow ee$

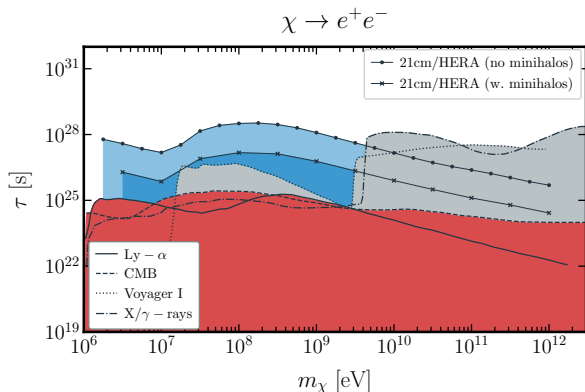
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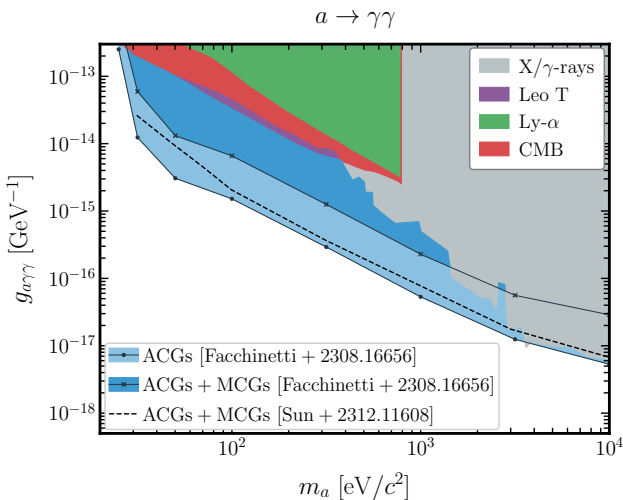
- Future redshifted 21cm signal power-spectrum measurements can **surpass** current CMB and/or Lyman- α sensitivity by 2-3 orders of magnitude.
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Encouraging forecasts of 21cm bounds on $\chi \rightarrow ee$



- (optimistic) Fisher Matrix forecasts for HERA 331 antennas and $t_{obs} = 1000$ h
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- Future redshifted 21cm signal power-spectrum measurements can **surpass** current CMB and/or Lyman- α sensitivity by 2-3 orders of magnitude.
- Can put **more stringent** bounds than **indirect DM** searches bounds...
- ...even when considering an early second population of stars (POPIII)

and forecasts of 21cm bounds on $a \rightarrow \gamma\gamma$ 

NB: we have implemented homogeneous energy injection. Inhomogeneous injection was studied in details by [Sun'231](#). Similar sensitivity prospects! But δT_b can differ.

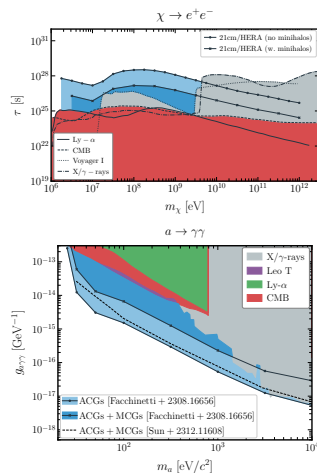
Conclusions

Dark matter energy injection in SM particles affect ionization and IGM temperature.

CMB is already providing robust constraints for s-wave DM annihilations while it can only compete wrt to indirect searches at $m_{\text{DM}} < \text{few } 100 \text{ eV}$.

Low z data such as 21cm power spectrum measurements might improve on existing Cosmo bounds:

- We forecast HERA sensitivity with 331 antennas under deployment in South Africa and taking data.
- Expected to surpass CMB/ Lyman- α sensitivity and reach $\tau_{\text{DM}} > 10^{27-28} \text{ s}$.
- DM annihilation is the next step, checking the impact of the $B(z)$.

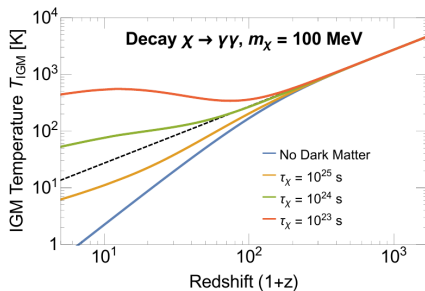


Thank you for your attention!!

Backup

DM energy injection implies earlier heating

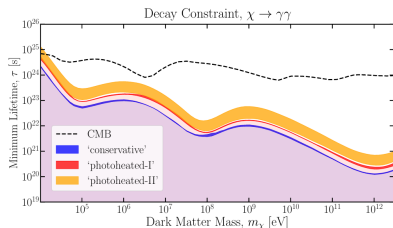
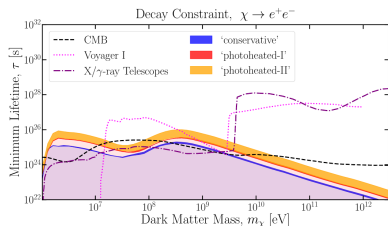
DM decays heats the IGM before astro sources light-on.



[Liu'16]

DM energy injection implies earlier heating

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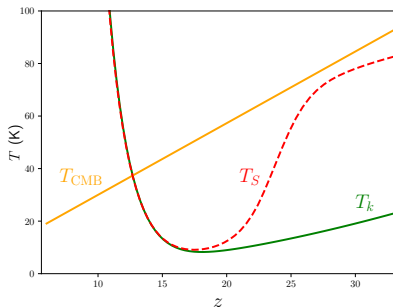
[Liu'20]

The IGM temperature T_k can be probed **at low z** by using:

- **Lyman- α forest** data at $2 \lesssim z \lesssim 6$ with $T_k \sim 10^4$ K [Liu'20,Capozzi'23]

DM energy injection implies earlier heating

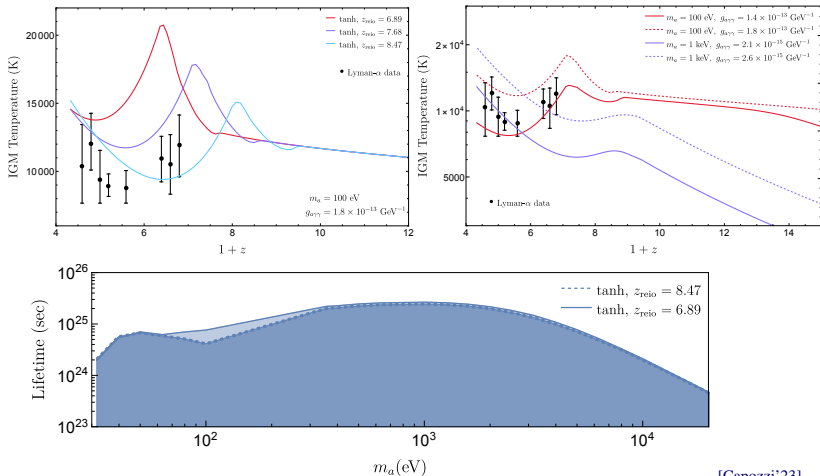
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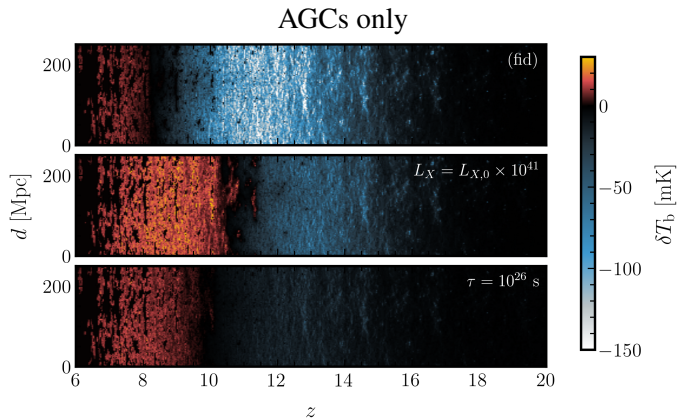
- **Lyman- α forest** data at $2 \lesssim z \lesssim 6$ with $T_k \sim 10^4$ K [Liu'20, Capozzi'23]
- **Redshifted 21cm signal** detected by radio telescope arrays that will measure $|\Delta_{21}(k, z)|^2$ at $z \in [6, 25]$ with $T_k \sim 10$ K [Furlaneto'06, Evoli'14, Liu'18]

T_k for $a \rightarrow \gamma\gamma$

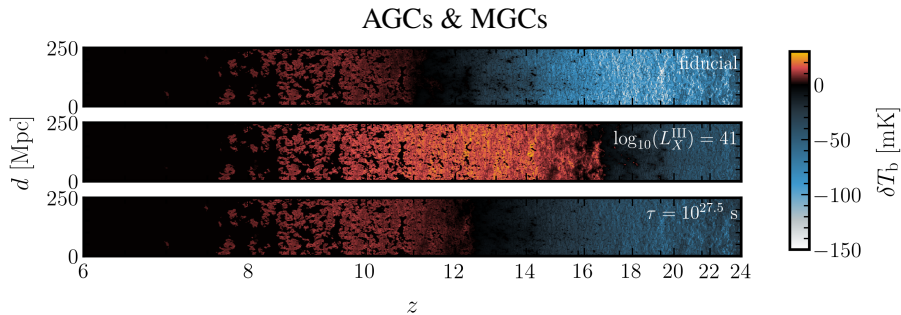


[Capozzi'23]

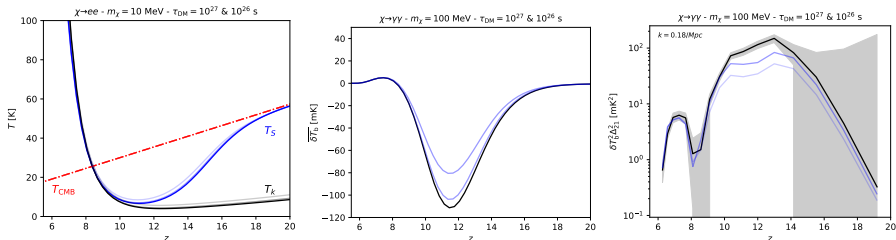
DM decay and earlier heating



DM decay and earlier heating



Impact of $\text{DM} \rightarrow \gamma\gamma$ on T_k , δT_b and Δ_{21}



DM energy injection implies

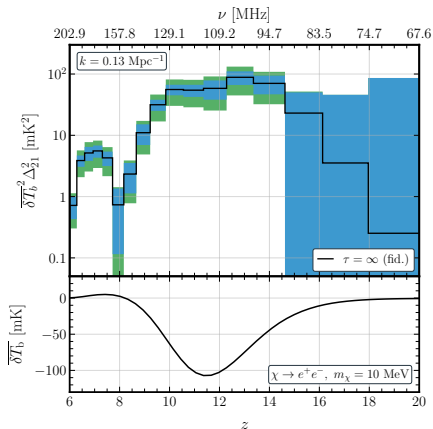
- new **source of heating**, earlier than X-rays from stars
- **suppressed absorption** in δT_b
- **suppressed power** at large z

plots made using exo21cmFast developed by G. Facchinetti merging 21cmFast and DarkHistory

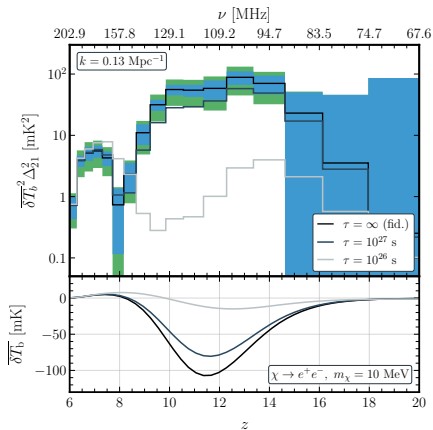
Fisher matrix analysis

- Fisher matrix can be used to estimate the minimum uncertainties of parameters given observations $\sigma_{Fisher} \lesssim \sigma_{true}$ [Albrecht et al. 2009] (= optimistic estimate of the errors) (e.g. using 21cmFISH by C. Mason'22, they show that $\sigma_{Fisher,i}$ are within 40% of the those obtained with MCMC for Λ CDM)
- The Fisher formalism assumes that the likelihood is Gaussian within the parameter range under consideration and $F_{ij} = \sum_{k,z} \frac{\partial \Delta_{21}}{\partial \theta_i} \frac{\partial \Delta_{21}}{\partial \theta_j} (\sigma_{\Delta}^2(k,z))^{-1}$ where σ_{Δ}^2 measurement error in Δ_{21} at a given k, z bin. Forecasted uncertainty in the i -th parameter is $\sigma(\theta_i) = \sqrt{C_{ii}}$ where the covariance matrix $C = F^{-1}$.
- $\sigma_{\Delta}^2(k, z)$ is obtained w/ 21cmSense considering HERA thermal noise plus the cosmic variance plus 20% 'modelling uncertainty'. The noise assumes 1000 hours of obs. (~ 167 days for 6h/day with max 180 effective days of obs/year) using 331 antennae.
- **foregrounds** are taken into account by putting a cut neglecting $k_{\parallel} < 0.1/Mpc$
- boxes have a comoving volume of $(250Mpc)^3$ on a grid of $z = 6 - 30$ ($\sim \nu = 50 - 250$ Mhz). We use $BW = \Delta\nu_{max} = 8$ Mhz which sets $k_{\parallel,min}$ at a given z . Notice that given HERA config, the available $k_{\parallel} > k_{\perp}$.

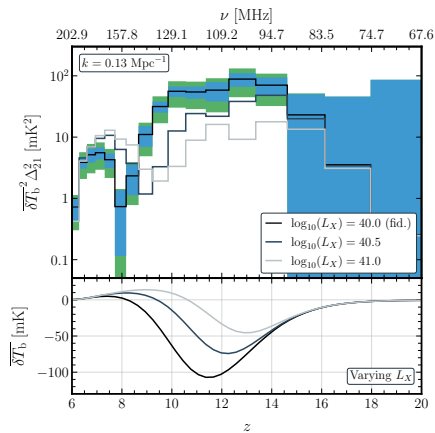
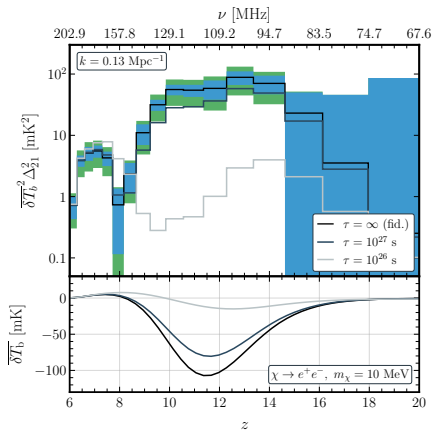
DM vs X rays with POPII stars only



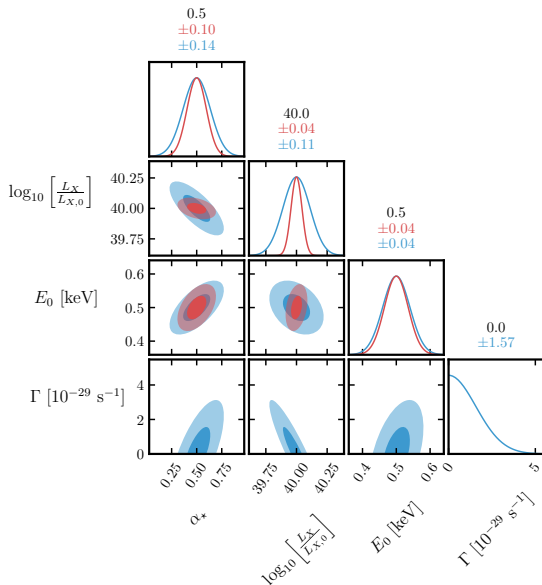
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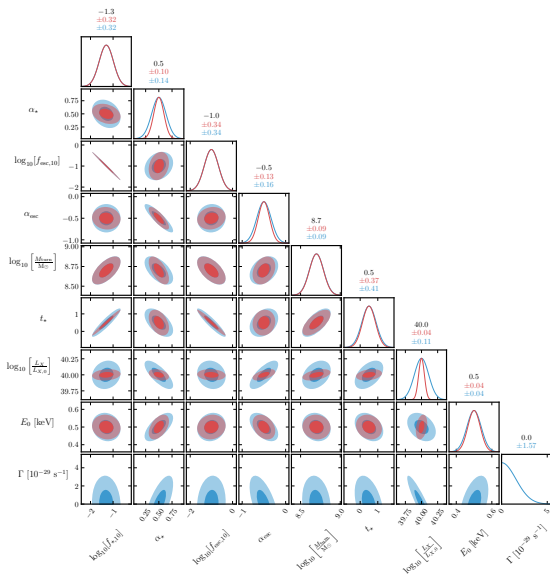


21cm Fisher results for $\chi \rightarrow ee$ $m_\chi = 100$ MeV



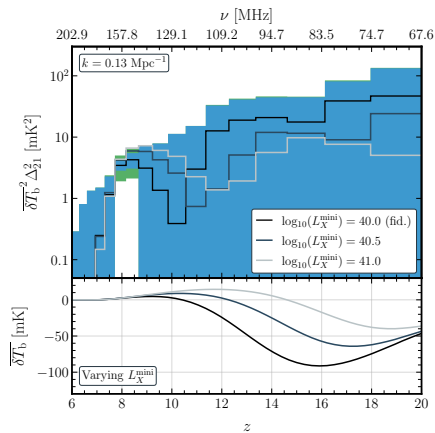
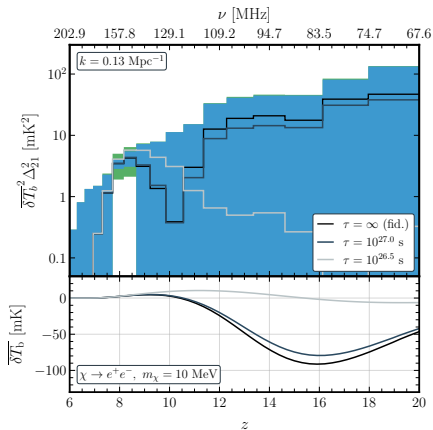
- L_X normalisation of soft-band X-ray (< 2 keV which efficiently heat IGM) luminosity per unit SFR. E_0 minimum in X-ray energies which can escape galaxies.
- stellar mass (M_*) to halo mass ratio is described by a power law: $\alpha_*, f_{*,10} =$ low mass slope, normalisation for galaxies forming pop II stars

21cm Fisher results for $\chi \rightarrow ee$ $m_\chi = 100$ MeV

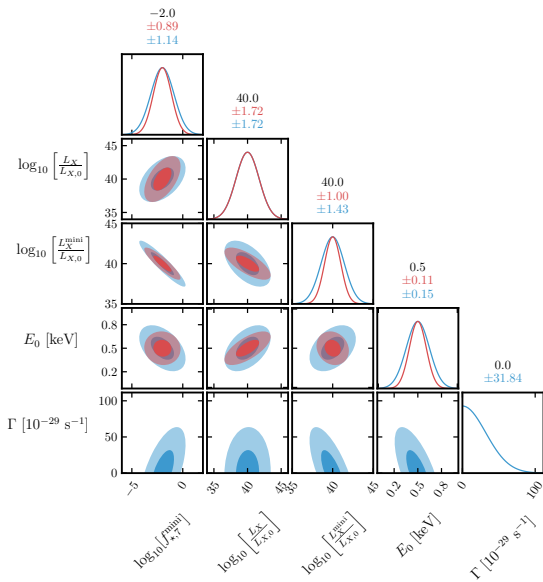


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DM vs X rays with POPII&III stars only

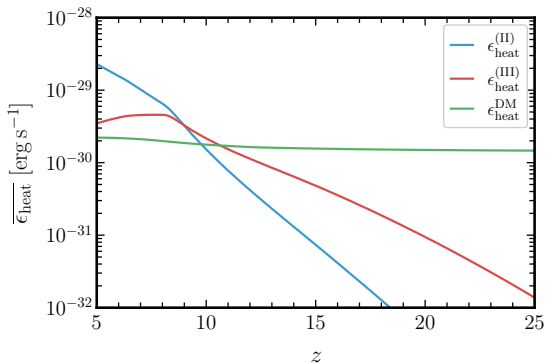


21cm Fisher for $\chi \rightarrow ee$, $m_\chi = 100$ MeV+ POPIII stars



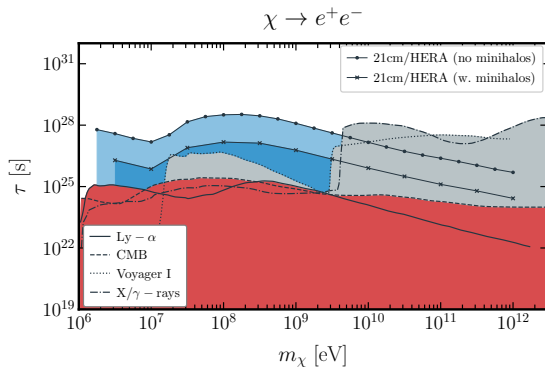
- L_X^{mini} normalisation of soft-band X-ray (< 2 keV which efficiently heat IGM) luminosity per unit SFR from minihalos,
- E_0 minimum in X-ray energies which can escape galaxies,
- $f_{*,7}$ is the normalisation of the stellar mass to halo mass for galaxies forming pop III stars

Rates of energy injection into heat



- DM heats the IGM well before POPII stars but is less efficient at low z
- POPIII stars give rise to heating rate “more similar” to DM than POPII.

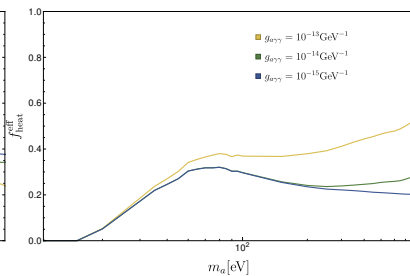
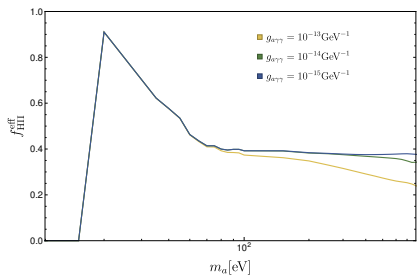
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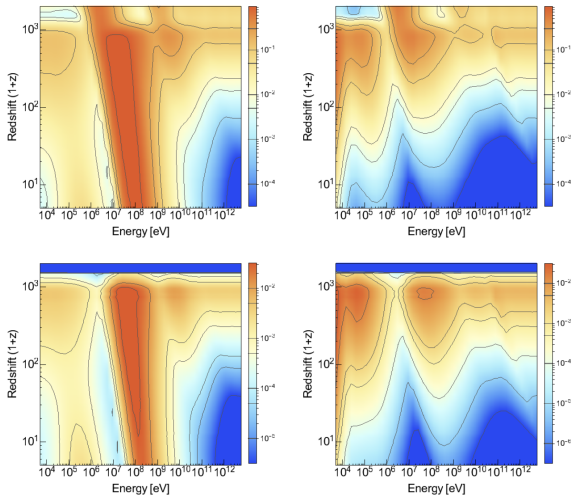
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Stronger degeneracy with POPIII star heating parameters
 \rightsquigarrow **less stringent** constraints on DM decay width
 when **POPIII** stars are taken into account.

$f_{ionH,eff}$ & $f_{heat,eff}$ for $a \rightarrow \gamma\gamma$

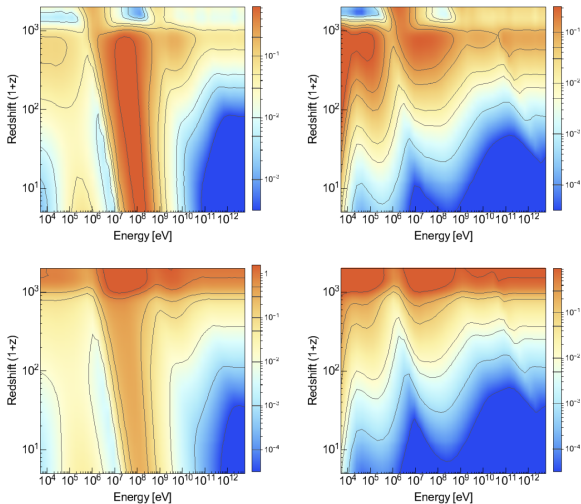


f_{ionH} & f_{ionHe} for $\chi \rightarrow ee, \gamma\gamma$



[Liu'16]

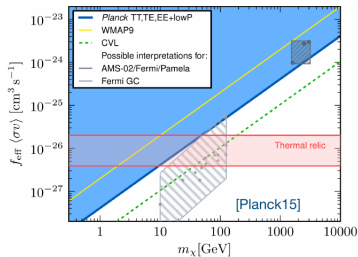
f_{exc} & f_{heat} for $\chi \rightarrow ee, \gamma\gamma$



[Liu' 16]

DM annihilation and earlier heating

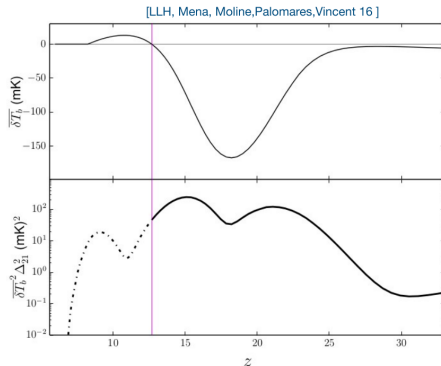
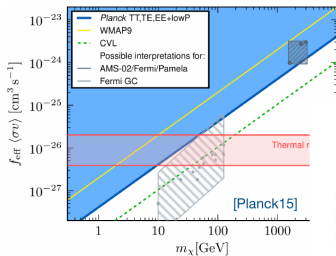
see also [Hansen'04, Pierpaoli'04, Bierman'06, Mapelli'06, Valdes'07, Natarajan'08, Evoli'14, etc]



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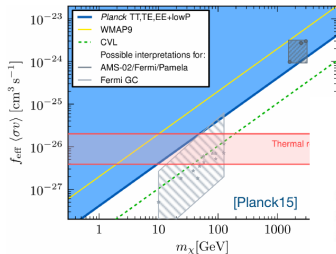
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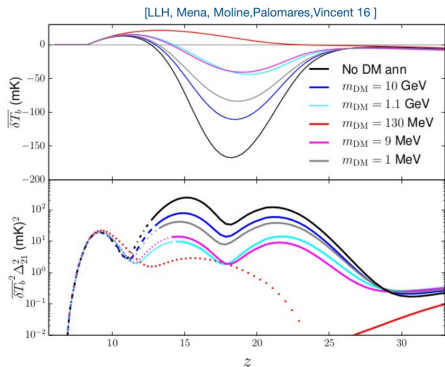
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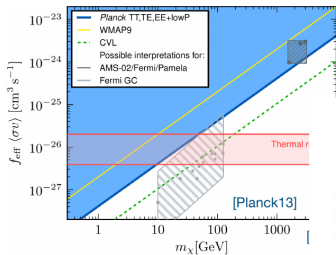
- Suppressed absorption
- Imposing some maximal δT_b could **constrain DM annihilation**



see also [Valdes13, Evoli14, D'Amico18, Liu18]

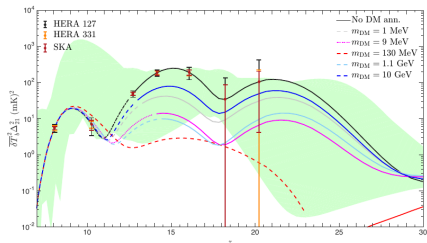
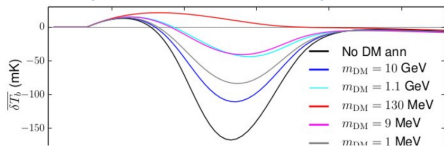
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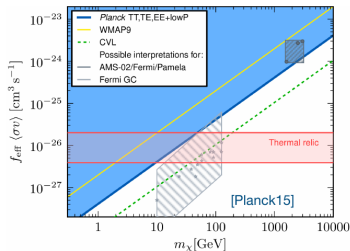
Beware!
large astrophysics
uncertainties

[LLH, Mena, Moline, Palomares, Vincent 13]

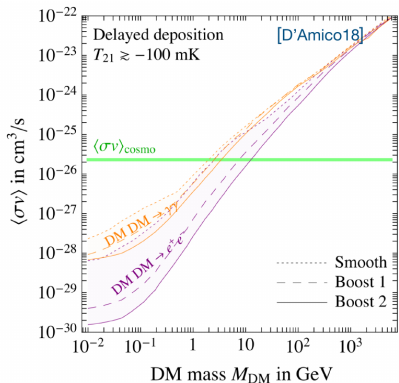


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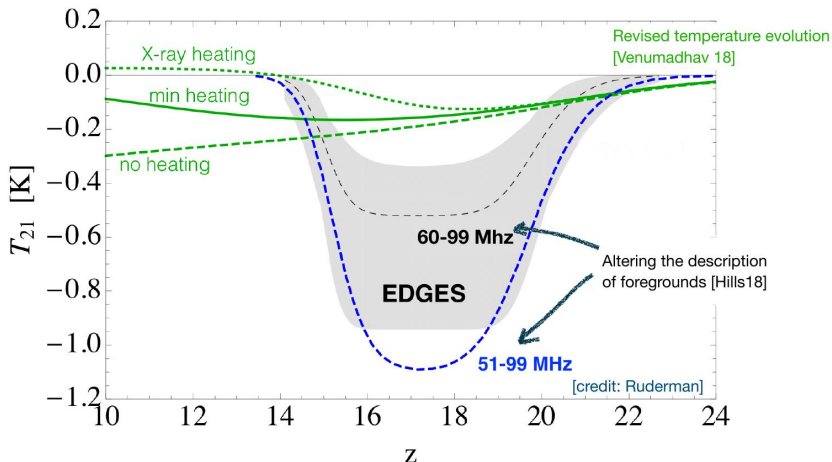


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see also [Valdes13, Evoli14,LLH16, Liu18]

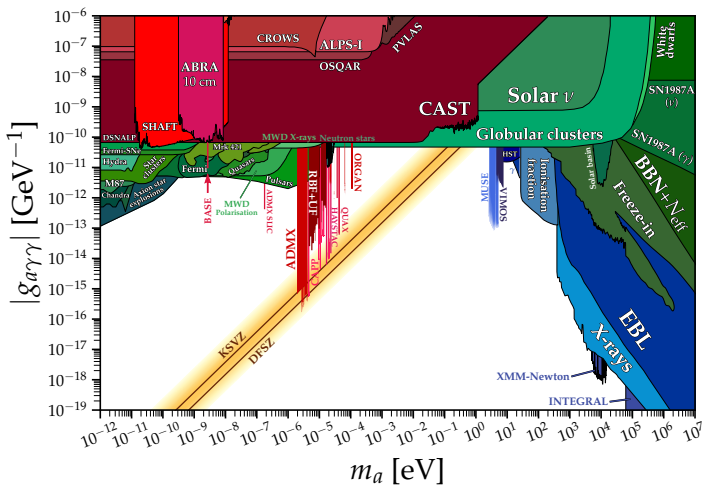
Constraints on 21cm Global signal?



Why bothering more??

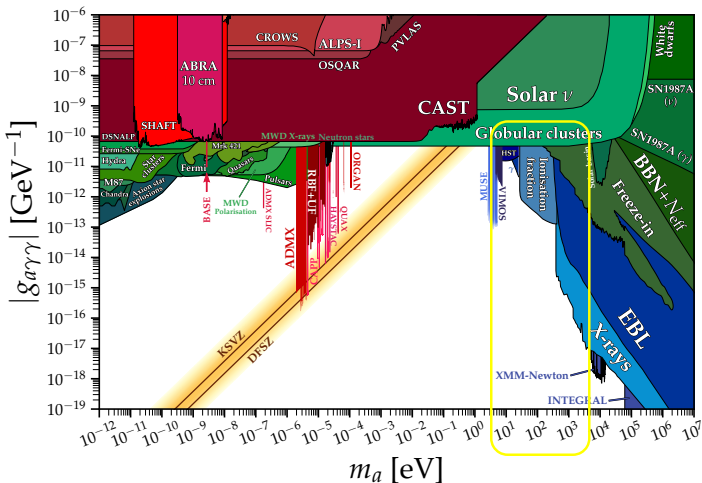
ALP decays into 2 photons

$$\Gamma_{DM} = \frac{g_{a\gamma\gamma}^2}{64\pi} m_a^3$$



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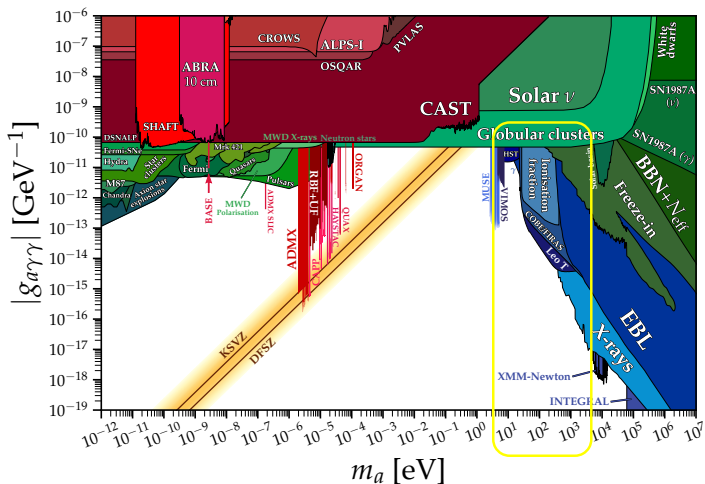
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Between 10 and 100 eV relatively poorly constrained with old CMB data

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CMB analysis for $a \rightarrow \gamma\gamma$

Goals of our analysis:

- Up to date **MCMC analysis using Planck'18** data with $f_{\text{eff}} = f_c(z = 300)$.
The few $\times 10$ eV energy photons are very good at ionizing the medium!
We modified CLASS to account for $f_{\text{eff}} = f_c(z = 300, m_a, g_a)$ from DarkHistory.
- **Check the impact of reionization history**

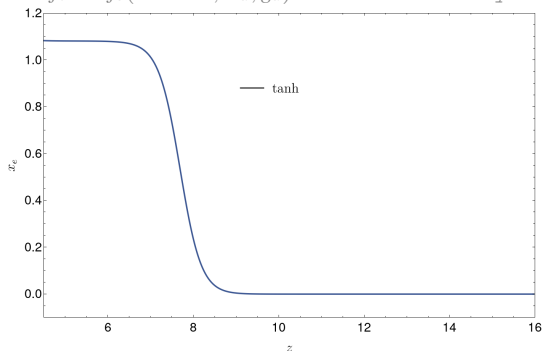
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all shown reio agree with
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$$\tau_{\text{reio}} = 0.054 \pm 0.007$$



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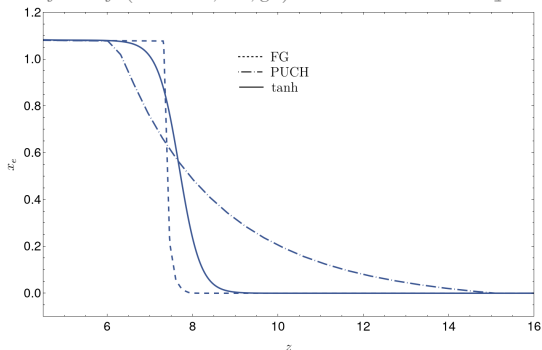
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[Puchwein'18,

Fauchère-Giguère'19]

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Without DM, PUCH reio model gives larger $\tau_{\text{reio}} = \int dt x_e n_b \sigma_T$

\rightsquigarrow **Stronger CMB bounds for PUCH-like model expected**

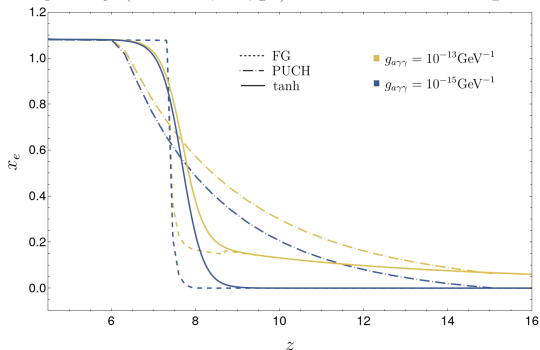
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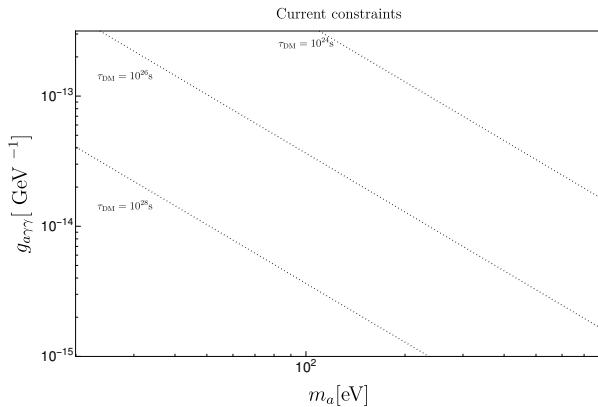
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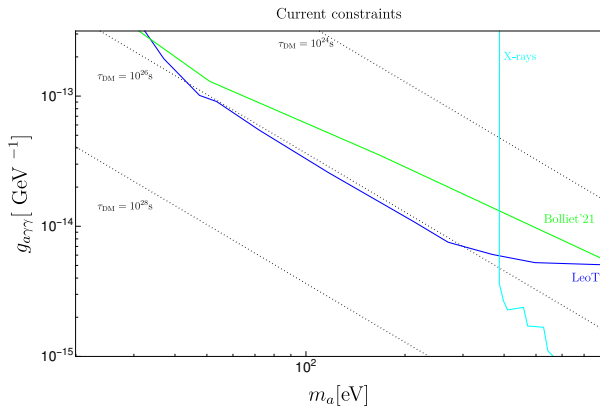
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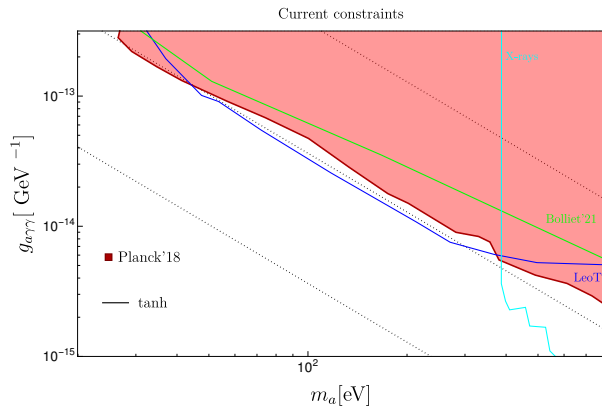
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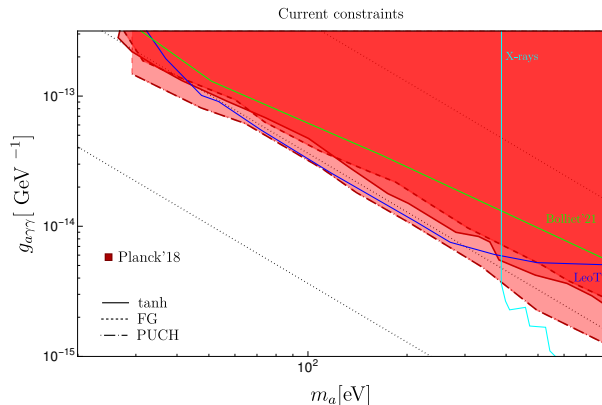
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- $\tau_{DM} \gtrsim 10^{26} \text{s}$

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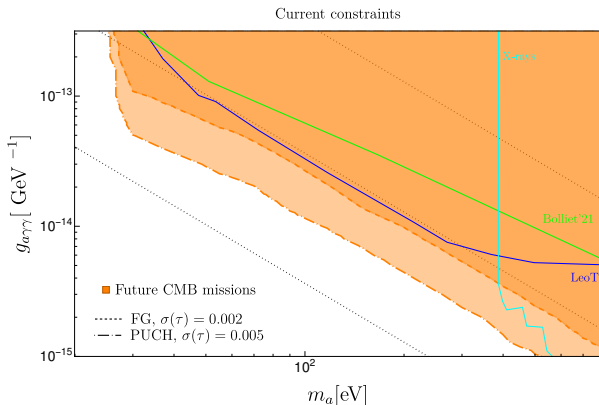


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- CMB bounds are of the same order as astro bound from Leo-T

- Currently, fixing $x_e(z)$ to a reionization history in agreement with Planck does not significantly change the bounds

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- $\tau_{DM} \gtrsim 10^{26} \text{s}$
- CMB bounds are of the same order as astro bound from Leo-T

- Currently, fixing $x_e(z)$ to a reionization history in agreement with Planck does not significantly change the bounds
- Future CMB variance limited Experiments will definitely give more stringent bounds. In the latter case, the reionization history from stars will matter.

DM energy injection/deposition in early universe

see previous work e.g. [Adams'98, Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05, Slatyer'15, Liu'19] for CMB, [Shchekinov'06, Furlanetto'06, Valdes'07, Chuzhoy'07, Cumberbatch'08, Natarajan'09, Yuan'09, Valdes'12, Evoli'14, LLH'16] for 21cm

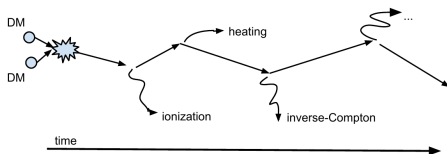
- **DM particles can annihilate/decay into:**

- f, γ, W, Z, \dots injected $\rightsquigarrow e^+, e^-, \gamma$
- neutrinos \rightsquigarrow suppressed depos. but possible via EW corrections

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- DM particles can annihilate/decay into:
 - f, γ, W, Z, \dots injected $\rightsquigarrow e^+, e^-, \gamma$
 - neutrinos \rightsquigarrow suppressed depos. but possible via EW corrections
- Effectively DM deposit energy in the early Universe



[image from A. Vincent]

Rate of energy injection/deposition into $c =$ heat, ionization, excitation

$$\left(\frac{dE_c(\mathbf{x}, z)}{dt dV} \right)_{\text{deposited}} \equiv f_c(z) \left(\frac{dE(\mathbf{x}, z)}{dt dV} \right)_{\text{injected}} \equiv f_c(z) \times \begin{cases} \rho_{DM}^2 \langle \sigma v \rangle / m_{DM} & \text{annihil} \\ \rho_{DM} / \tau_{DM} e^{-t/\tau_{DM}} & \text{decay} \end{cases}$$

$f_c(z) =$ energy deposition efficiency per channel

(can be obtained using DarkHistory [Liu'19, Liu'23])

bla

This is really the end