Particle Physics at Cosmic Dawn - Part I

Focus on Dark Matter imprint

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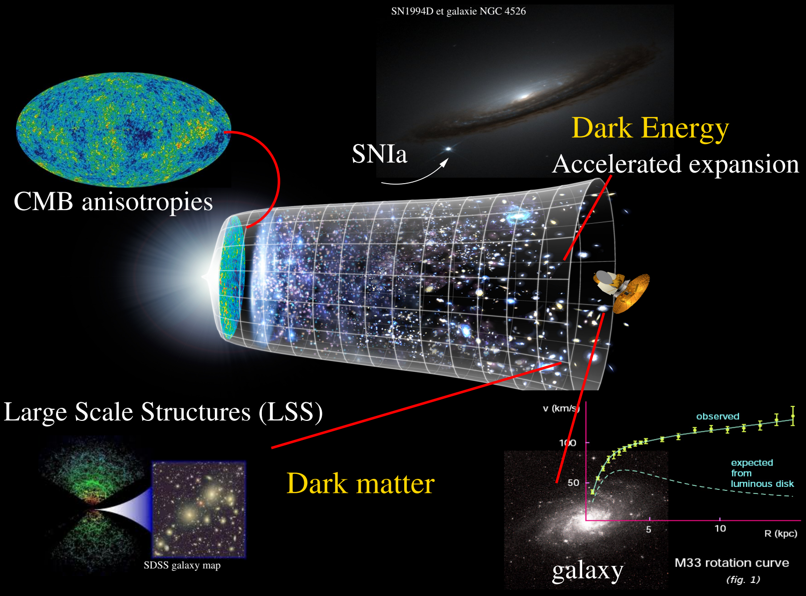


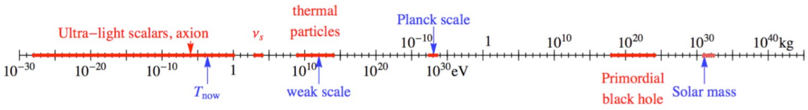
The Quest to determine the Composition of our Universe

80% of the matter content is made of Dark Matter

What is the Nature of Dark Matter?

Dark Matter should be essentially:

- Neutral
- Massive
- Beyond the Standard Model (non baryonic)

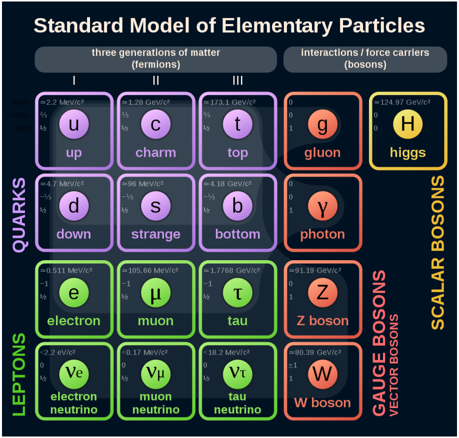


Courtesy of M.Cirelli

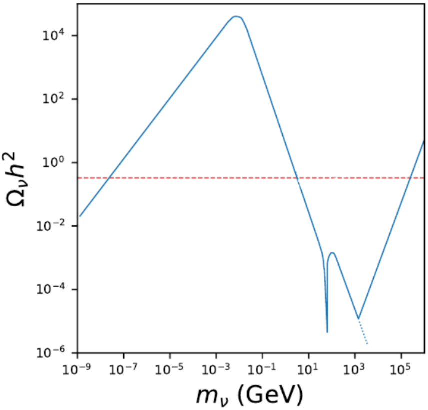
Dark Matter

Illustrative Particle Physics Scenarios

Standard Model of Particle Physics

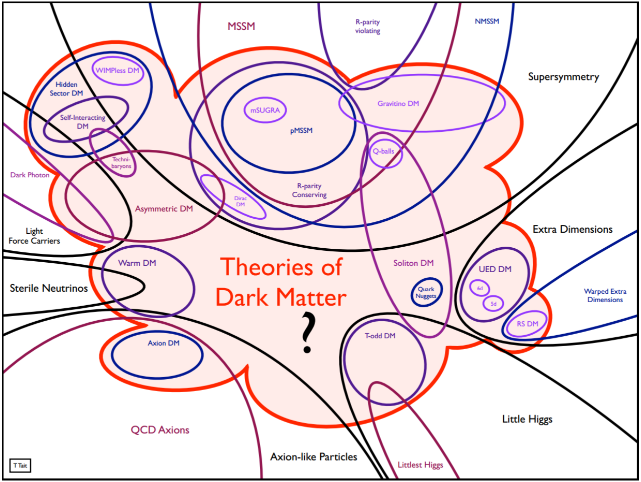


The SM neutrino



Being agnostic about the existing particle physics and Cosmology constraints, the SM neutrino is the perfect example of thermal weakly interacting DM candidate see e.g. [Coy'21,Kanulainen'02].

Beyond the Standard Model?



Beyond the Standard Model: Minimal Models

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Minimal Models: 3 extra parameters $m_\chi, m_B, \lambda_\chi$

Dark matter χ coupled to dark B and SM A through Yukawa-like interactions

$$\mathcal{L} \subset \lambda_\chi \, \chi \, A_{SM} B$$

- Dark sector (Z_2 odd): $m_B > m_\chi$
- B is $SU(3) \times SU(2) \times U(1)$ charged
  - fast $B^\dagger B \leftrightarrow$ SM SM through gauge interactions at early time
  - B can be produced at particle physics experiments

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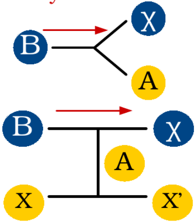
  - B can be produced at particle physics experiments
- Minimal scenarios:

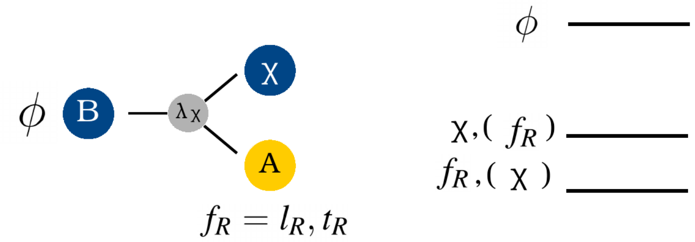
$A_{\rm SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\bar{\psi}_{\rm SM} \Psi_B \phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\bar{\psi}_{\rm SM} \chi \Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B \sigma_{\mu\nu} \chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$H^\dagger \Phi_B \phi$	$\mathcal{S}_{H\phi}$
	1/2	1/2	$\bar{\Psi}_B \chi H$	$\mathcal{F}_{H\chi}$

[Calibbi, D'Eramo, Junius, LLH,Mariotti 21]

Production in the early universe



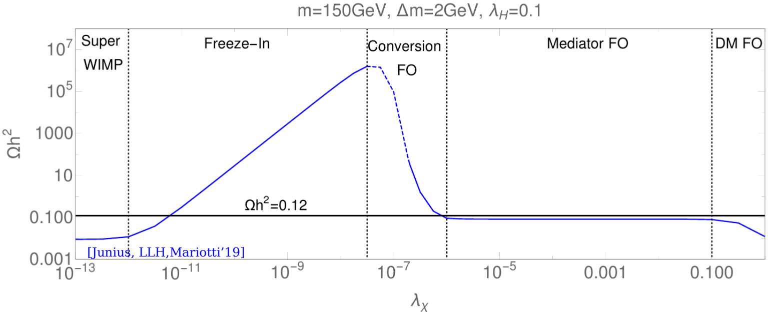
Fermionic DM coupling to $f_R = l_R$ or t_R



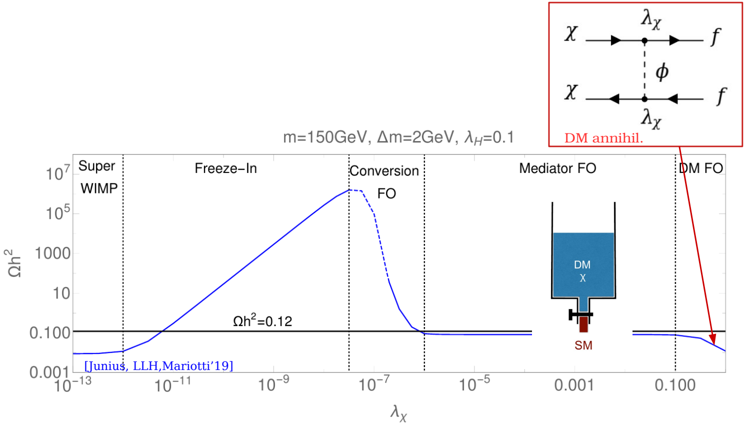
$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} f_R \; + \; h.c.$$

- SM + 1 charged/colored dark scalar ϕ + 1 Majorana dark fermions χ (Z_2 symmetry for DM stability)
- We can explore a large range of couplings say $10^{-14} \lesssim \lambda_\chi \lesssim 1$
- Here we will consider $f_R = l_R, t_R$ for illustrative purposes.

Variety of DM production mechanisms



Variety of DM production mechanisms



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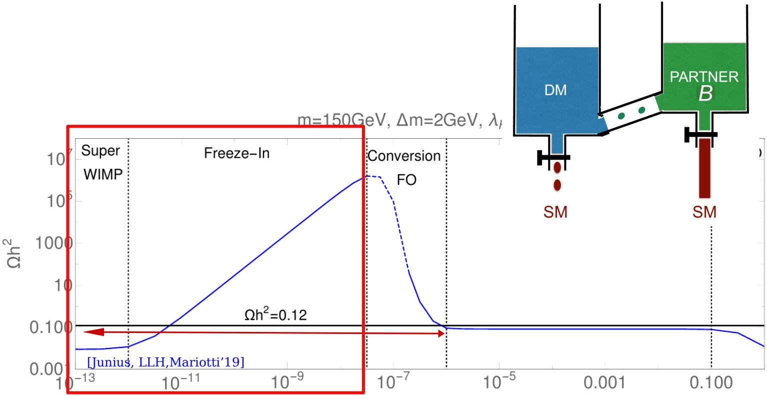
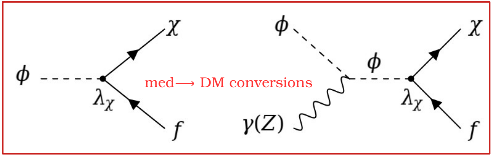




WIMP versus FIMP

Cosmology

Particle Physics

$$\boxed{\frac{df_\chi(t,p)}{dt}} = \boxed{\mathcal{C}[f_\chi]}$$

WIMP versus FIMP

Cosmology

$$\frac{df_\chi(t,p)}{dt} = \mathcal{C}[f_\chi]$$

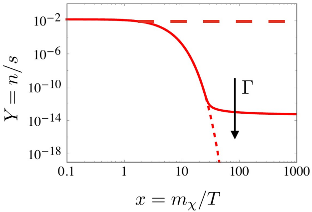
Particle Physics

Weak coupling
to SM

$\Gamma_{\chi\leftrightarrow \rm SM} > H$

"Thermal DM" (incl. WIMP)

$f_\chi(t,p) = f_\chi(t,p)^{fD,BE}$



WIMP versus FIMP

Cosmology

Particle Physics

$$\frac{df_\chi(t,p)}{dt} = \mathcal{C}[f_\chi]$$

Weak coupling to SM

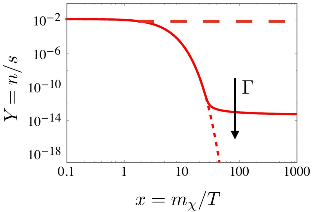
$\Gamma_{\chi\leftrightarrow \mathrm{SM}} > H$

Feeble coupling to SM

$\Gamma_{\chi\leftrightarrow \mathrm{SM}} < H$

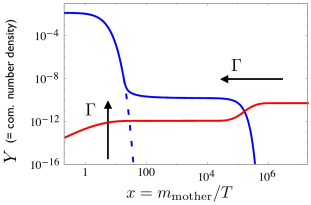
“Thermal DM” (incl. WIMP)

$f_\chi(t,p) = f_\chi(t,p)^{fD,BE}$



“Non-Thermal” FIMP

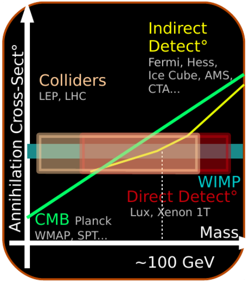
$f_\chi(t,p) \neq f_\chi(t,p)^{fD,BE}$



Why do we care?

DM fundamental properties can give rise to distinctive signatures in particle physics experiments and in Cosmology.

- Thermal WIMP
  - Annihilating DM
  - Energy injection affect indirect DM searches, CMB, 21cm etc
  - similar imprint from decaying DM, accreting PBH, etc



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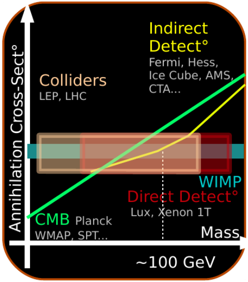
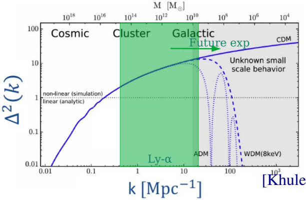


- Thermal WDM, FIMPs
  - Non Cold Dark Matter: free-streeming, collisional damping
  - Erase small scale structures: impact on Lyman-α forest observation, 21cm etc
  - similar effect for DM interacting with light dofs



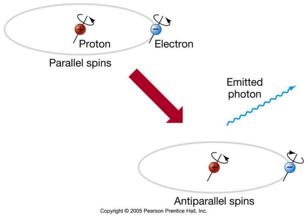
[Khulen'12]

Dark Matter at Cosmic Dawn

Possible Imprints

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)

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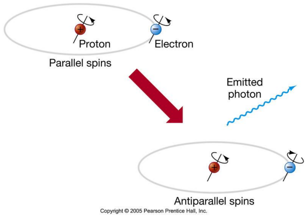
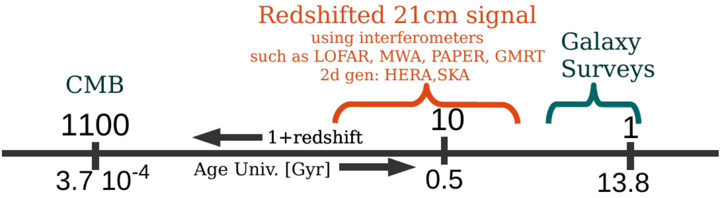
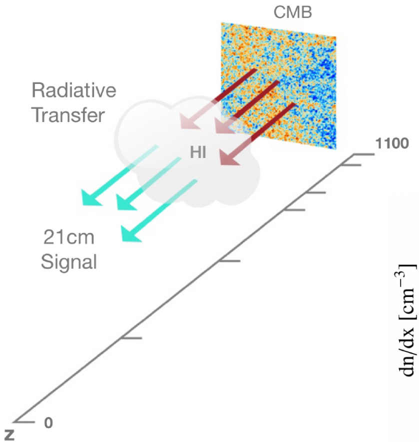


- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during Cosmic Dawn & EoR redshifted to $\nu \sim 100$ MHz $\rightsquigarrow$ new cosmology probe

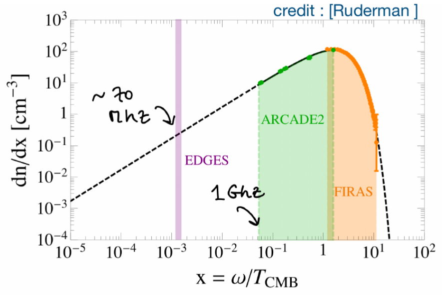


21 cm in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions



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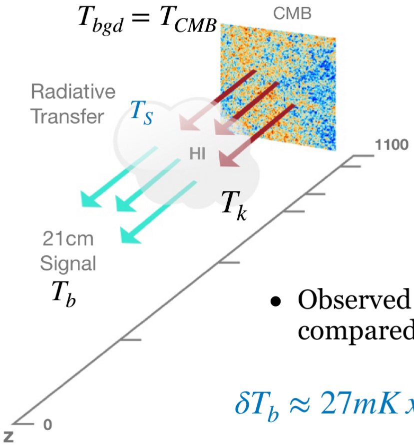


credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions
- The spin temperature (= excitation T of HI) charaterises the relative occupancy of HI gnd state

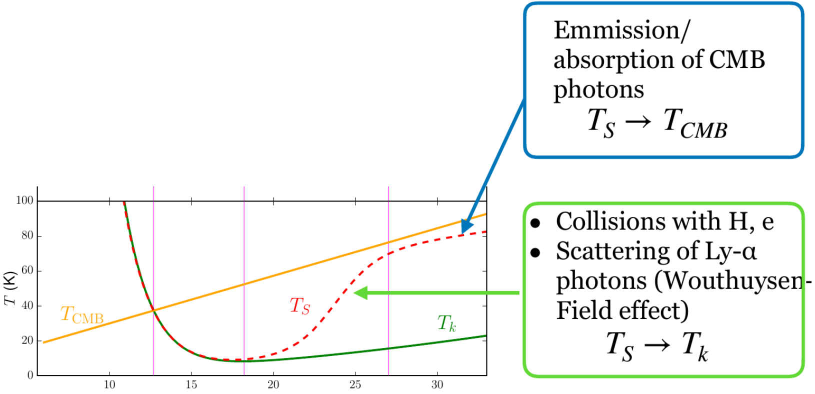
$$n_1/n_0 = 3\exp(-h\nu_0/k_B T_S)$$

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

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

The spin temperature

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



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

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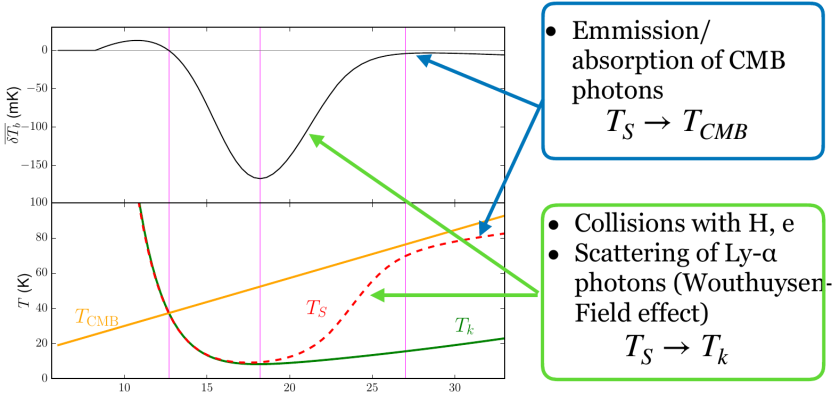

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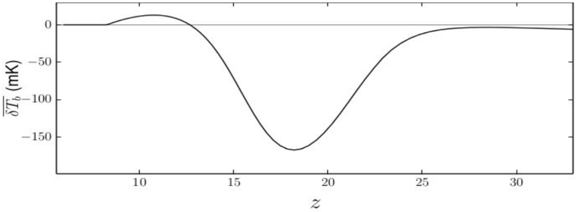

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

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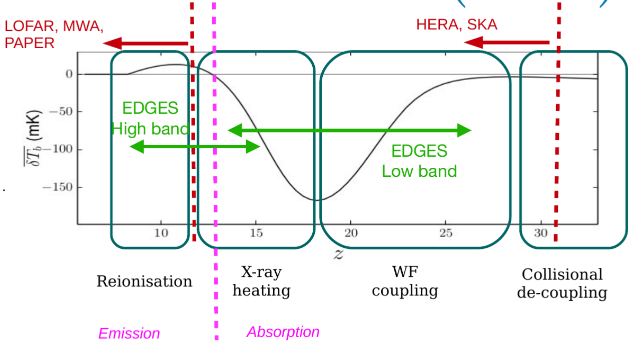

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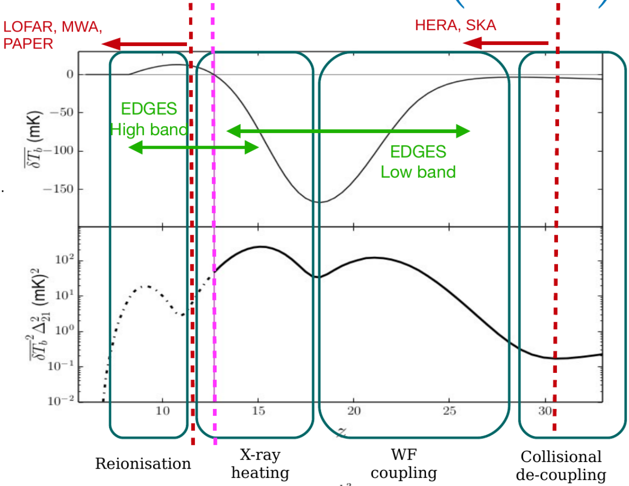
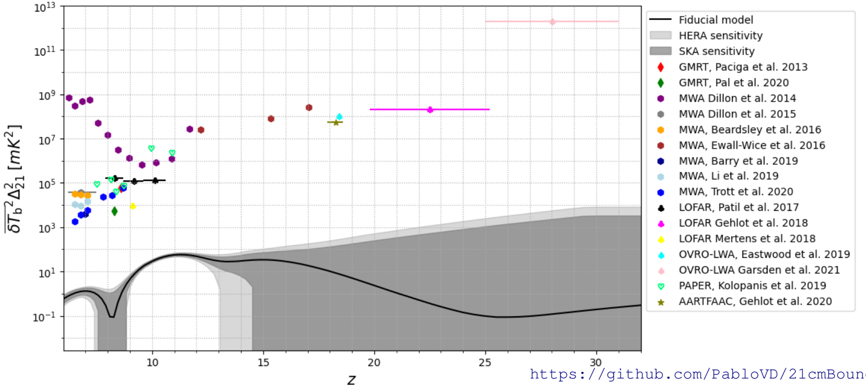


$$\langle\widetilde{\delta}_{21}(\mathbf{k},z)\widetilde{\delta}^*_{21}(\mathbf{k}',z)\rangle \equiv (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z) \qquad \Delta^2_{21}(k,z)=\frac{k^3}{2\pi^2}P_{21}(k,z)$$

δT_b and Δ_{21} obtained using `21cm Fast` [Mesinger'10]

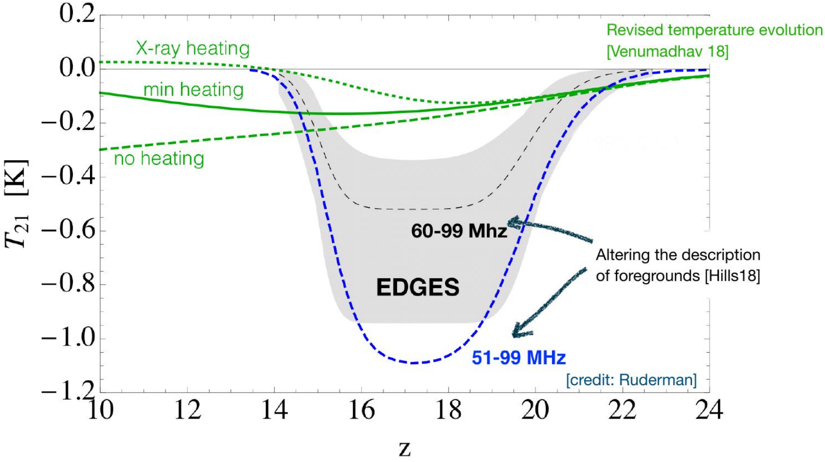
Observations/constraints on 21cm signal at large z?



https://github.com/PabloVD/21cmBounds

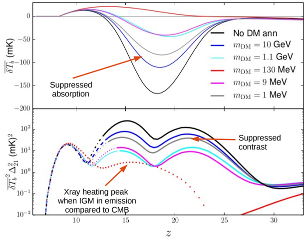
data mostly for 0.1 h/Mpc $< k <$ 0.5 h/Mpc, fiducial for $k = 0.2$ Mpc/h

Observations/constraints on 21cm signal at large z?



In these seminar-lectures

- Extra energy injection
  - Annihilating DM
  - Energy injection affect e.g. CMB
  - further constraints from imprint at cosmic dawn?



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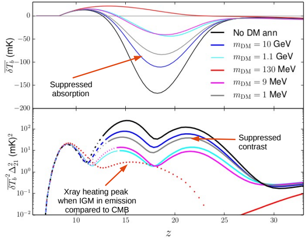
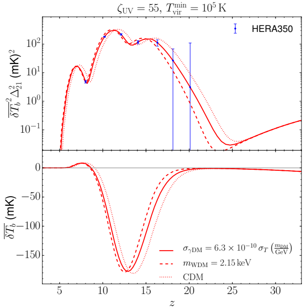


- Delay of structure formation
  - Non Cold Dark Matter: free-streeming, collisional damping
  - also delay in 21cm features
  - can help to disentangle NCDMs?



Description of the 21 cm signal

Relevant Astro/DM Parameters

Ionized fraction, IGM temperature and Lyman-α flux

see e.g. [Pritchard & Loeb '11]

- IGM mostly neutral phase (as e.g. at early times) :

$$\begin{aligned} \dot{x}_e &= \Lambda_{ion,e} - \Lambda_{rec,e} \\ \dot{T}_k &= Q_{adia} + \sum_\alpha Q_\alpha \end{aligned}$$

with x_e, ionized fraction in neutral IGM, T_k gaz temperature.

- When galaxies begin to form, energetic UV $\gamma \rightsquigarrow$ ionized HII regions surrounding galaxies:

$$\dot{Q}_i = \Lambda_{ion,i} - \Lambda_{rec,i}$$

with Q_i=volume filling fraction of HII regions= $\langle x_{HII} \rangle$.

- Galaxies are also responsible of Lyman-α flux J_α:

$$J_\alpha = J_{\alpha,*} + J_{\alpha,X}$$

$J_{\alpha,*} = \gamma$ between Ly-α and Lyman limit;
$J_{\alpha,X} =$ X-rays excited $e \rightsquigarrow$ Ly-α γ through desexcitation + redshift.

X-rays and stellar sources depend on f_{coll}

Ionization, heating and excitation critically depend on the fraction of mass collapsed in halos:

$$f_{\rm coll}(> M_{\rm vir}) = \int_{M_{\rm vir}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM} dM \,,$$

where dn/dM is the halo mass function and $M_{\rm vir}$ is the min virial halo M for star forming galaxies. Indeed:

- $\Lambda_{ion,e}$, $J_{\alpha,X}$ and Q_X depend on the comoving emissivity for X ray sources:

$$\epsilon_X \sim \frac{L_X}{\rm SFR} \times f_* \times \dot{f}_{coll}$$

- $\Lambda_{ion,i}$, $J_{\alpha,*}$ depend on the comoving emissivity for stellar sources:

$$\epsilon_* \sim N_{\gamma/b} \times f_* f_{esc} \times \dot{f}_{coll}$$

The halo mass function

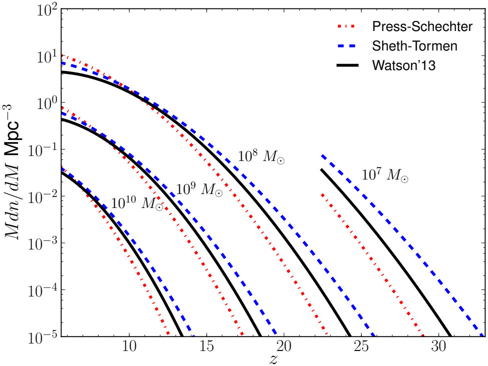
see A. Schneider lectures

Using Press-Schechter (PS) formalism [PS'74, Bond'91] to match N-body simu.:

$$\frac{dn(M,z)}{dM} = \frac{\rho_{m,0}}{M^2}\frac{d\ln\sigma^{-1}}{d\ln M}f(\sigma)$$

For CDM (e.g. WIMPs):

- first crossing distribution $f(\sigma)$ of e.g. Press Schechter [PS], Sheth & Tormen [ST], Watson [W'13].



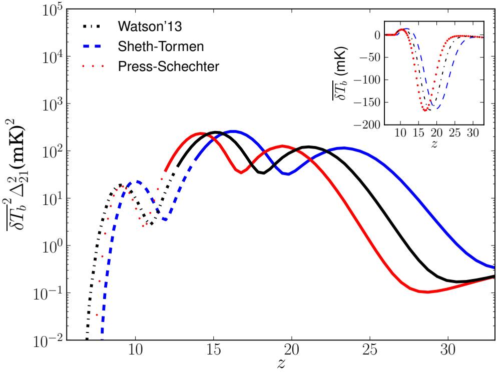
- $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ is the variance of linear perturb. smoothed over $R(\leftrightarrow M)$ using a top hat window fn. W in real space.

$\rightsquigarrow$ PS $\rightarrow$ W13 $\rightarrow$ ST: larger number of fixed mass halo at fixed z at early time

Halo mass function impact on 21cm signal

Using semi-numerical tools such as 21cmfast [Mesinger'10]: δT_b and Δ_{21} depends on halo mass function as the ionization, heating and excitation critically depend on the fraction of mass collapsed in halos

$$f_{\rm coll}(> M_{\rm vir}) = \int_{M_{\rm vir}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM} dM \,,$$



- W13: our default for CDM annihilation analysis
- PS: underpredicts $\frac{dn(M,z)}{dM}$ at large M and z and overpredicts $\frac{dn(M,z)}{dM}$ at low M and z
- ST: default 21cmFast: slight overestimation compared to simu. at large z see e.g. Watson'13

$\rightsquigarrow$ PS $\rightarrow$ W13 $\rightarrow$ ST: astro sources switch on earlier

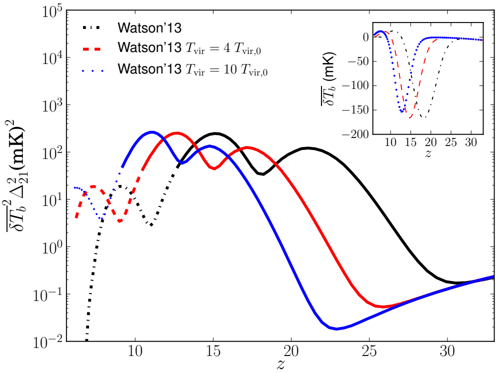
Threshold for star formation impact on 21cm signal

$$f_{\rm coll}(> M_{\rm vir}) = \int_{M_{\rm vir}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM}\, dM\ ,$$

Threshold for efficient star formation: $T_{\rm vir} > T_{\rm vir\,,0} = 10^4$ K

($\equiv M_{\rm vir\,,0}(z=10) = 3\;10^7\, M_\odot$) [Evrard'90, Blanchard'92, Tegmark'96, Haiman'99, Ciardi'99]

$$M_{\rm vir} \simeq 10^8 \left(\frac{T_{\rm vir}}{2\;10^4\;{\rm K}}\, \frac{10}{1+z}\right)^{3/2} M_\odot$$



⇝ larger $M_{\rm vir}$ threshold implies a delay in the X-ray and UV sources.

Take Home Message Part I

- Particle Physics beyond the SM (BSM) give us a large variety of DM candidates/models/production mechanisms
- Depending on DM fundatmental properties specific imprints on Cosmology are expected
- DM can affect IGM at Cosmic Dawn and the 21cm signal arising from this epoch through e.g. extra heating, specific DM distribution
- Ionization/heating/excitation sources depend on f_{coll}. Our understanding of DM imprint might depend on how well we can extract/model this quantity.

Thank you for your attention!!

Backup

fraction of mass collapsed into halos

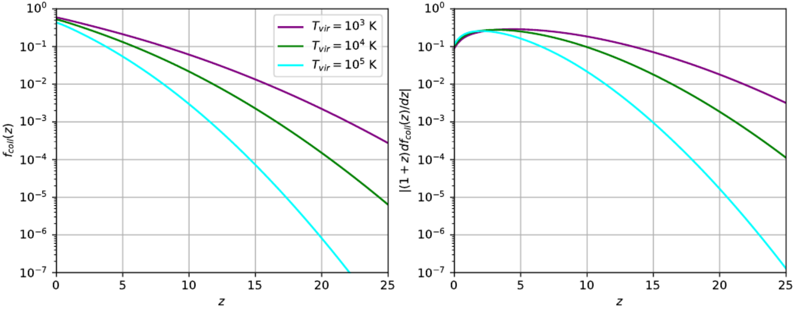


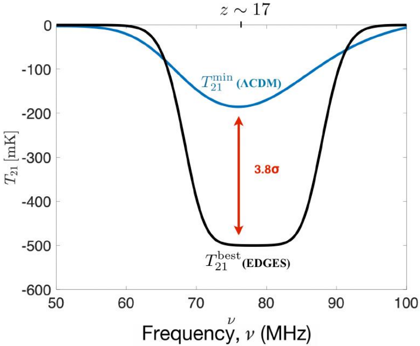
Figure 2.1: *Left:* evolution of the fraction of mass collapsed in halos above a mass corresponding to a virial temperature $T_{\rm vir}$ via Eq. (2.17), assuming a ST prescription. *Right:* derivative of the same quantity than in the left panel times $1 + z$.

see [P. Villanueva'21]

DM at the origin of EDGES signal?

- First detection of an absorption trough at 78+/-1 Mhz (z~17) with amplitude $0.5^{+0.2}_{-0.5}$K at 99% CL
- Stronger absorption than predicted

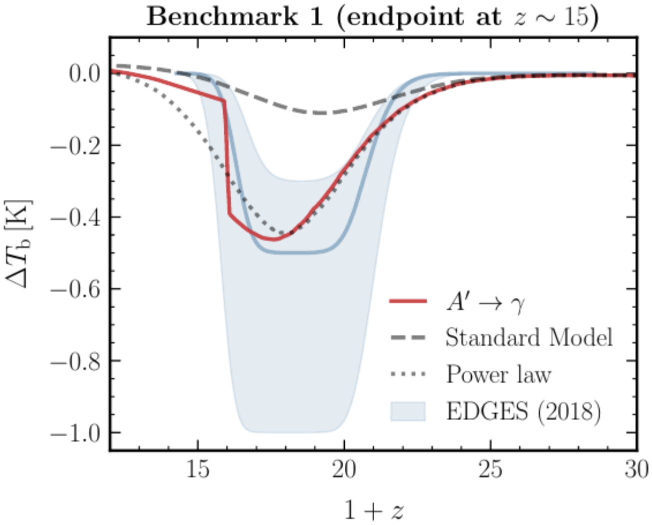
  $T_{CMB}/T_S > 15$ instead of 7
- Needs a larger bgd radiation temperature or a lower gas temperature as $T_S^{min} \sim T_K$



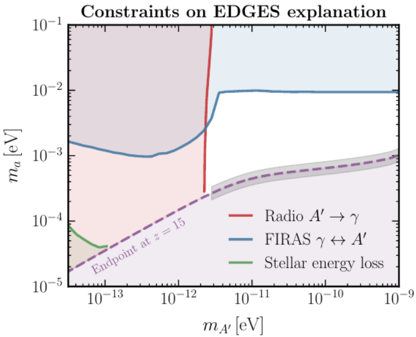
[credit: Kovetz] see also [Bowman18, Barkana18]

Not the topic of these lectures: Some DM scenarios could address EDGES signal. e.g. DM-B scatterings lowering T_k due to CDM velo. [Bowman'18, Barkana'18] or increase of T_{radio} from $a \to A'A' \to \gamma\gamma$ [Pospelov'18, Caputo'20]

ALP-dark photon-photon EDGES-like signal



ALP-dark photon-photon EDGES-like signal



Parameter space that could explain EDGES anomalous absorption feature. Constraints from stellar energy loss (green), spectral distortion constraints from COBE/FIRAS (blue), and $A' \to \gamma$ saturating radio obs. (red); Purple region: produced photons too soft to contribute to the EDGES obs.; Grey band: can simultaneously explain the anomalous depth and sharp endpoint at $z \sim 15$. Mixing parameter values $\epsilon \sim 10^{-6} - 10^{-8}$ can explain the putative depth of the EDGES observation in the unconstrained part (white region) of parameter space.

see [Caputo'20]

bla

This is really the end