New results from dark matter minihalos

Limits on the spectrum of cosmological perturbations, reionization and dark stars

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With: Torsten Bringmann, Yashar Akrami, Aparna Venkatesan, Elinore Roebber, Paolo Gondolo, Elena Pierpaoli & Gil Holder

Based on Bringmann, PS, Akrami, arXiv:1110.0xxx.
PS, Venkatesan, Roebber, Gondolo, Pierpaoli & Holder, arXiv:1107.1714, ApJ in press

Slides available from `http://www.physics.mcgill.ca/~patscott`

Outline

1. Introduction
2. Ultracompact minihalos
   - Observational predictions & constraints
   - Primordial power spectrum limits at small scales
3. Dark stars and reionization
   - Impacts on reionization and the CMB
   - Implications for dark stars and reionization models

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WIMPs at a glance

- Dark because no electromagnetic interactions
- Cold because very massive ($\sim$10 GeV to $\sim$10 TeV)
- Non-baryonic and stable - no problems with BBN or CMB
- Weak-scale annihilation cross-sections *naturally* lead to a relic abundance of the right order of magnitude
- Many theoretically well-motivated particle candidates
  - SUSY neutralinos χ if R-parity is conserved - lightest combination of neutral Higgsinos and gauginos
  - Inert Higgses - extra Higgs in the Standard Model
  - Kaluza-Klein photon or Z
  - right-handed neutrinos, sneutrinos, others...
- Weak interaction means scattering with nuclei $\rightarrow$ detection channel
- Many WIMPs are Majorana $\Longrightarrow$ self-annihilation cross-section $\rightarrow$ detection channel

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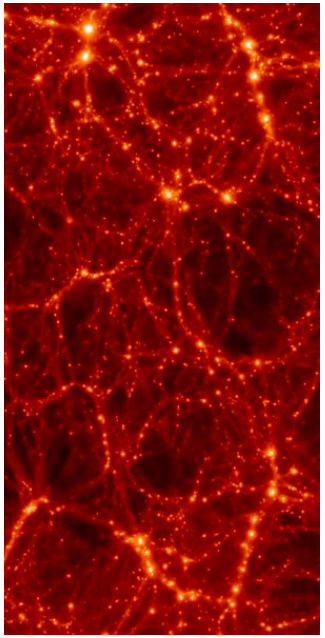
Formation of the smallest dark matter structures

In standard cosmology, inflationary perturbations are weak, Gaussian and scale-free

- Enter horizon during radiation domination (or earlier)
- Grow logarithmically until matter domination, then grow linearly
- Go non-linear and collapse $z \lesssim 30$, seeding star formation
- For WIMPs, lower mass cutoff is approximately set by kinetic decoupling
  $\rightarrow$ free streaming scale, $\sim 10^{-6\pm4}\, M_\odot$ (Bringmann 2009)



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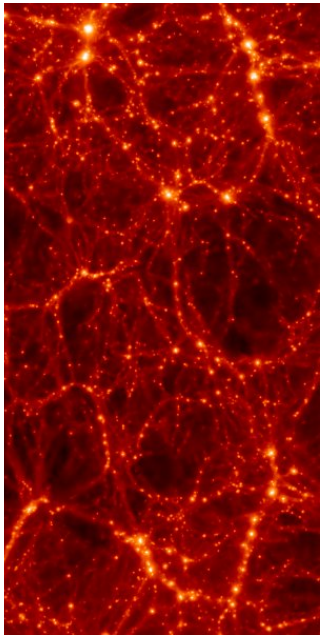

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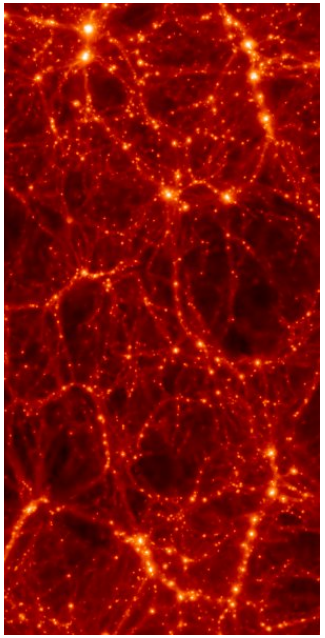

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  $\Longrightarrow$ objects collapse earlier, into ultracompact minihalos

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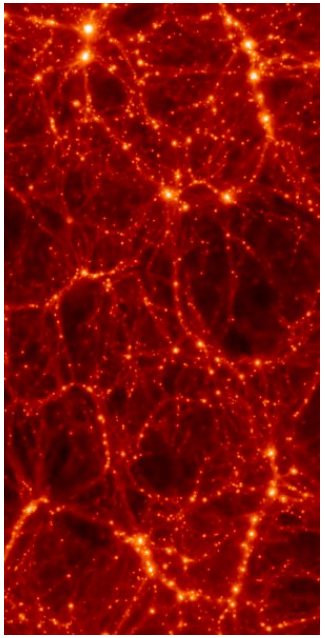

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- WIMP dark matter could feed back on star formation, creating 'dark stars'

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What is an *ultracompact* minihalo?

- Small-scale, large amplitude density perturbations in the early Universe create ultracompact minihalos (UCMHs)
  Ricotti & Gould (2009), Berezinsky et al. (multiple earlier papers)
- 'Failed primordial black holes'
- Very dense dark matter minihalos
- Enhanced perturbations produced by e.g. inflaton potential or phase transitions
- Non-baryonic, diffuse MACHOs
- Also excellent indirect detection targets

UCMH formation

- Formed (or at least 'seeded') well before matter-radiation equality
- Full gravitational collapse before $z = 1000$
- Requires $\delta \gtrsim \mathcal{O}(10^{-3})$
  (compare with normal inflationary perturbations $\delta \sim 10^{-5}$)
- $\longrightarrow$ much more likely than PBH formation ($\delta \gtrsim 0.3$)
- UCMH mass is set by horizon scale at time of transition
- $\Longrightarrow$ specific UCMH mass $\equiv$ specific cosmological scale
- $\Longrightarrow$ limit on abundance of specific mass halo $\equiv$ limit on power on specific scale k

  (Recent limits from Josan & Green (2010), improved analysis here)

UCMH density profiles

- Initially single UCMH per horizon, minimal initial angular momentum
- $\implies$ UCMHs form via radial infall
- $\implies$ Very steep radial density profile

$$\rho_\chi(r) = \frac{3 f_\chi M_{\rm UCMH}}{16\pi R_{\rm UCMH}^{\frac{3}{4}} r^{\frac{9}{4}}}, \tag{1}$$

- Truncated at self-annihilation radius $r_{\rm SA}$, and radius $r_{\rm AM}$ where gas angular momentum violates radial infall approx.

$$\rho(r_{\rm SA}) = \frac{m_\chi}{\langle \sigma v \rangle (t - t_{\rm i})}, \qquad r_{\rm AM} = \frac{\sigma_{\rm DM}^{\frac{8}{7}} R_{\rm UCMH}^{\frac{11}{7}}}{G^{\frac{4}{7}} M_{\rm UCMH}^{\frac{4}{7}}} \tag{2}$$

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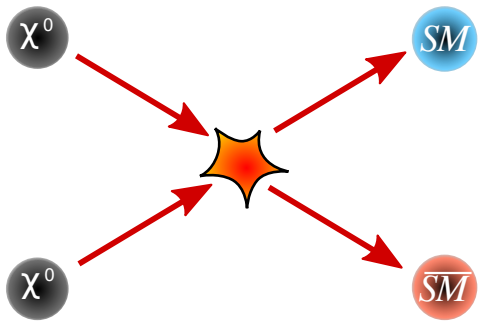
Identifying Dark Matter: Indirect Detection

DM-DM annihilation producing SM particles



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- e^+/e^- – PAMELA, *Fermi*, ATIC, AMS-02
- gamma-rays – *Fermi*, HESS, VERITAS, MAGIC, CTA
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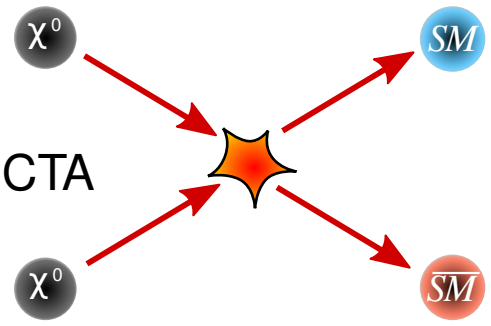

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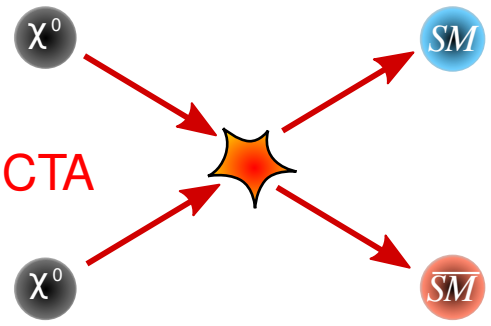
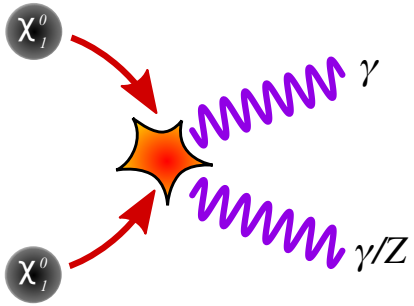


2 photons (or Z+photon): monochromatic lines



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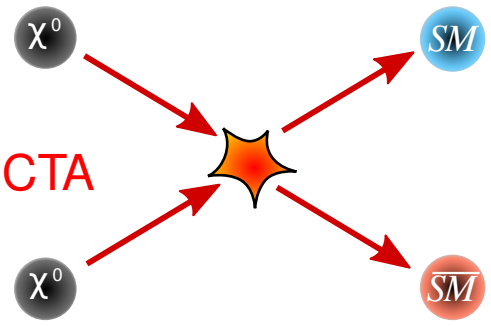

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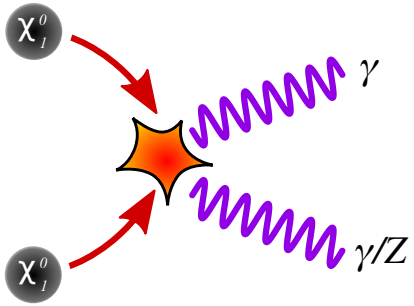
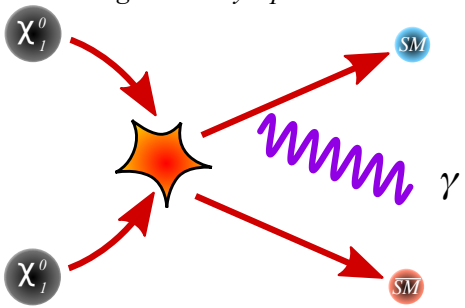


Internal bremsstrahlung: hard gamma-ray spectrum



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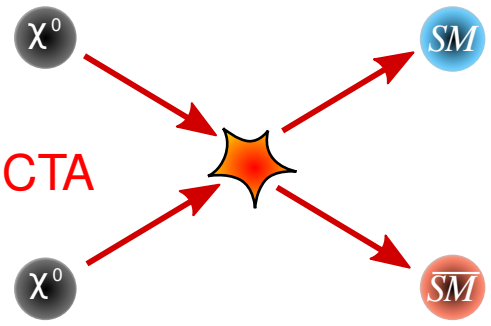

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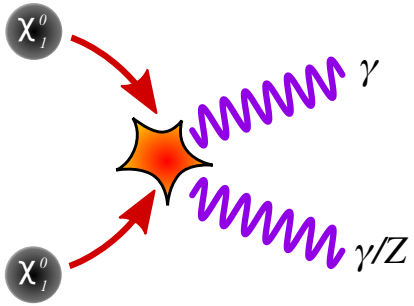

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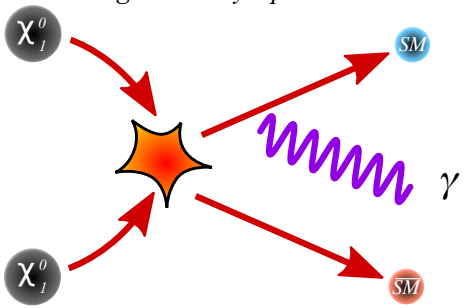
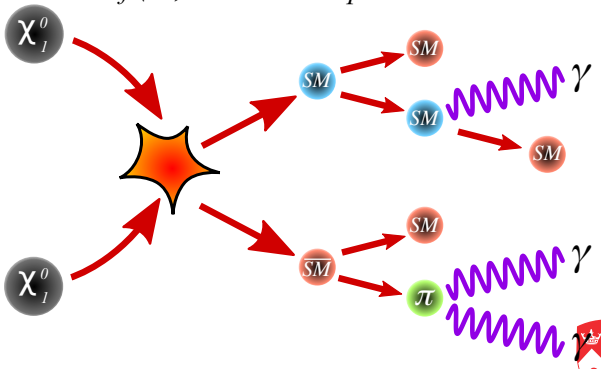
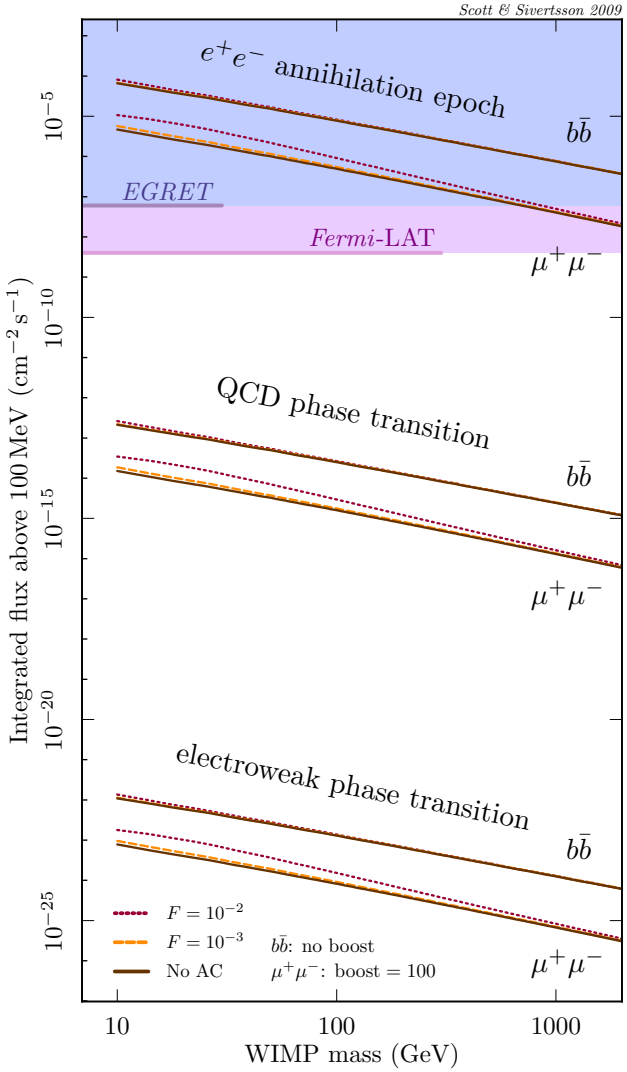


Secondary decay: soft(er) continuum spectrum



Gamma-ray fluxes from UCMHs

- Take e.g. $d = 100\,\mathrm{pc}$
- Minihalos produced at e.g. time of the e^+e^- annihilation epoch should be visible today by *Fermi* or HESS, or even in *EGRET* data
- Strongly constrains spectrum of perturbations formed at time of e^+e^- annihilation phase
- Gravitational contraction of UCMHs makes little difference



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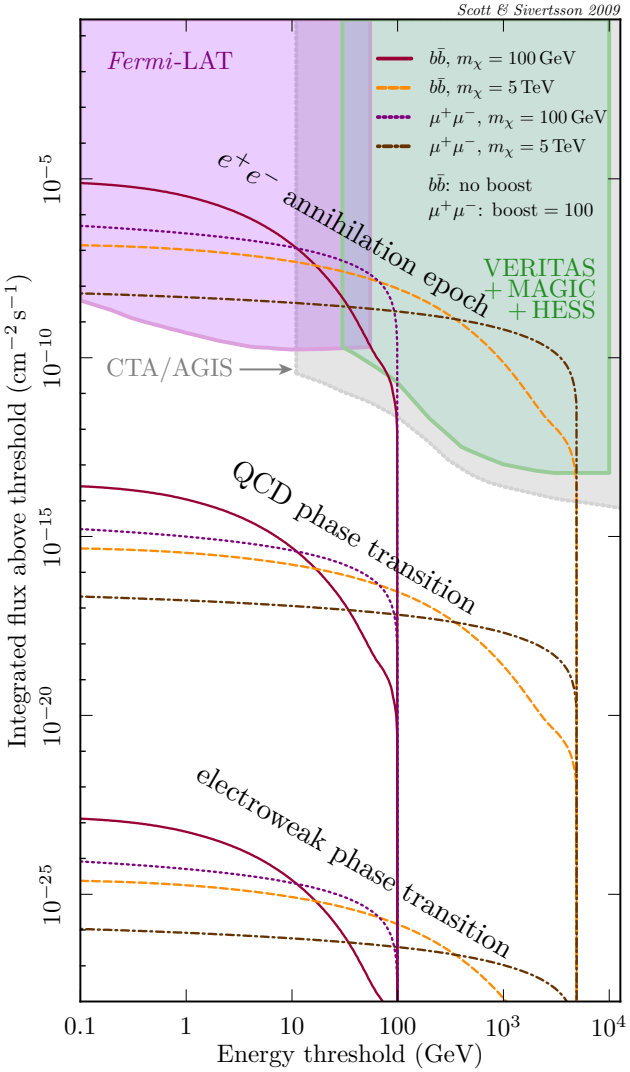
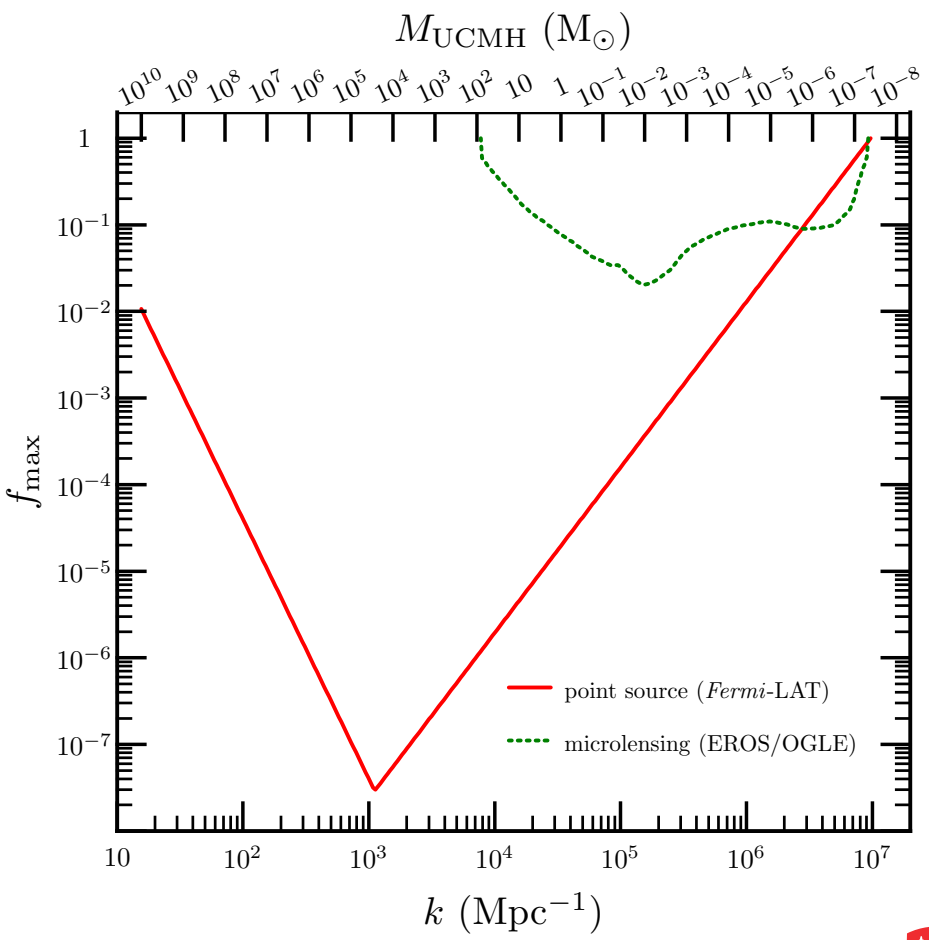


Limits on present-day UCMH abundance with *Fermi*

- 1-year, 5σ upper limits
- Based on public *Fermi* point source sensitivity
- Proper statistical treatment of observable limit
- Rather conservative assumptions:
  - 100% $b\bar{b}$
  - $\langle \sigma v \rangle = 3\,.\,10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
  - $m_\chi = 5\,\mathrm{TeV}$
  - no DM minihalo detected
- Microlensing limits also competitive at large k



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UCMH relic density calculation

- For some distribution of perturbations $\mathrm{pdf}(\delta)$

$$f_{\mathrm{UCMH}} = \left(\frac{1+z_{\mathrm{eq}}}{1+z_{\mathrm{stop}}}\right)\int_{\delta_{\mathrm{min}}}^{\delta_{\mathrm{PBH}}} \mathrm{pdf}(\delta)\,\mathrm{d}\delta \tag{3}$$

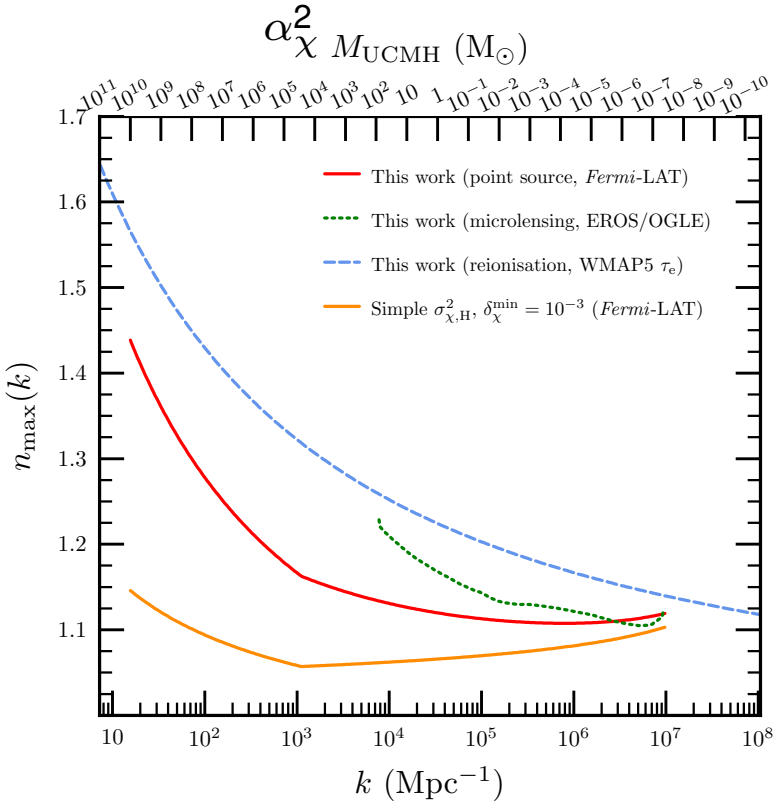
- For Gaussian perturbations,

$$\mathrm{pdf}(\delta) = \frac{1}{\sqrt{2\pi}\sigma^2_{\chi,H}(z_{\mathrm{X}},R)}\exp\left(-\frac{\delta^2}{2\sigma^2_{\chi,H}(z_{\mathrm{X}},R)^2}\right) \tag{4}$$

Scale-free (power law) spectrum

$$\sigma^2_{\chi,H}(R) \approx \delta^2_H(t_{k_0}) \left(\frac{k}{k_0}\right)^{n-1} \underbrace{\int_0^\infty x^{n+2}\, T^2_\chi(x)\, W^2_{\rm TH}(x)/T^2_\chi(1)\, {\rm d}x}_{\alpha^2_\chi} \qquad (5)$$

- Improved $\sigma^2_{\chi,H}$ using top hat window function
- Explicit calculation of $\delta_{\rm min}$ (Solution to linear growth eqs; $\delta = 1.686$ during matter domination in linear approx $\implies \delta \to \infty$ in non-linear regime)



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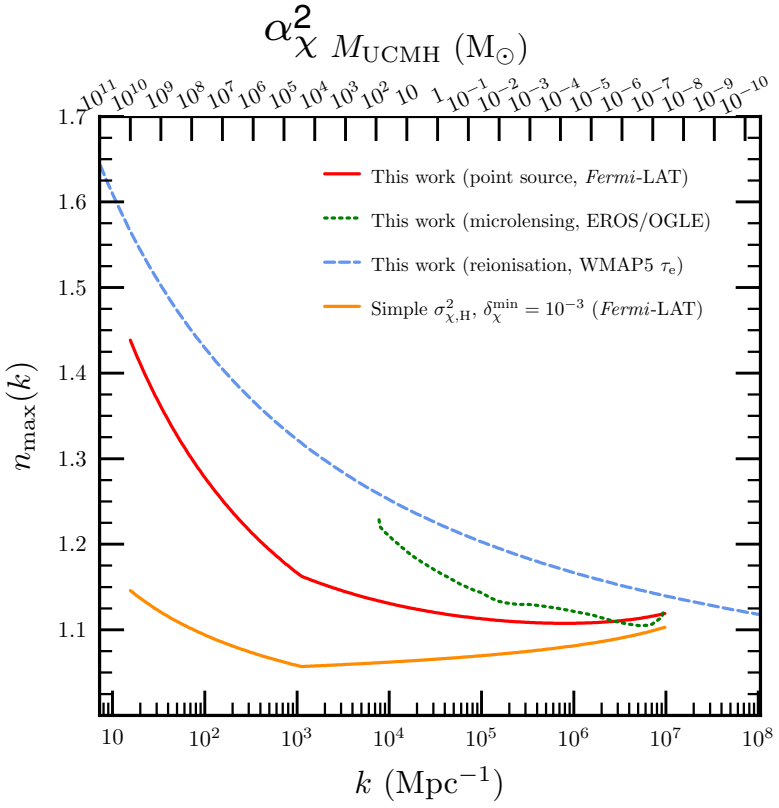
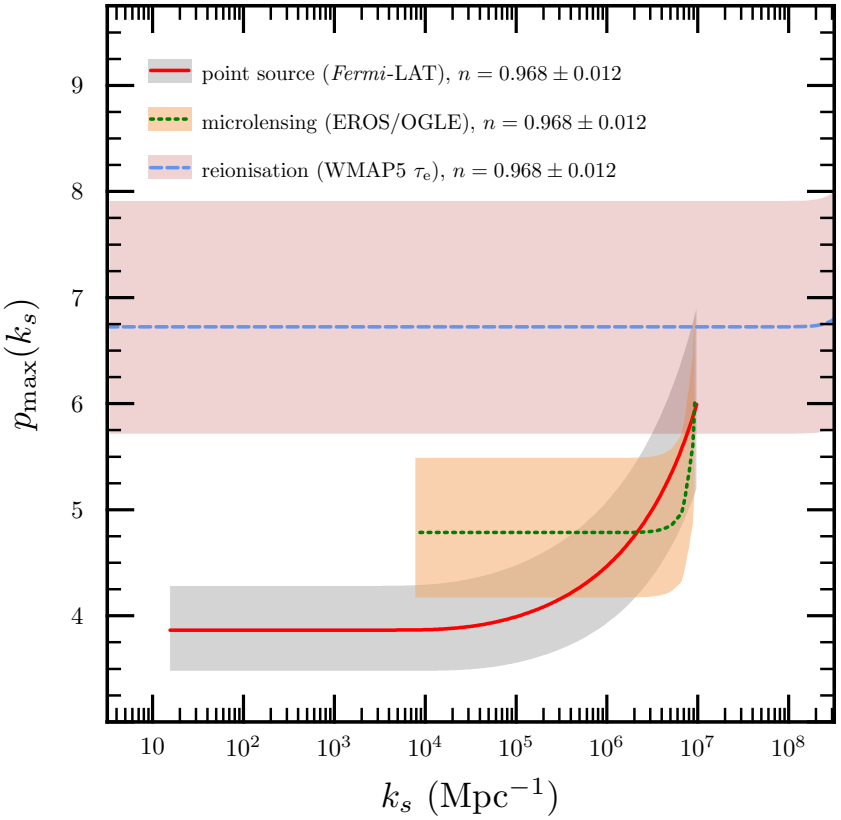
- Early-time ($z \sim 800$) contribution of UCMHs to reionisation is constrained by WMAP τ (Zhang 2010)
- $\rightarrow$ weak, but no mass cutoff, so covers more k than microlensing or gamma-rays



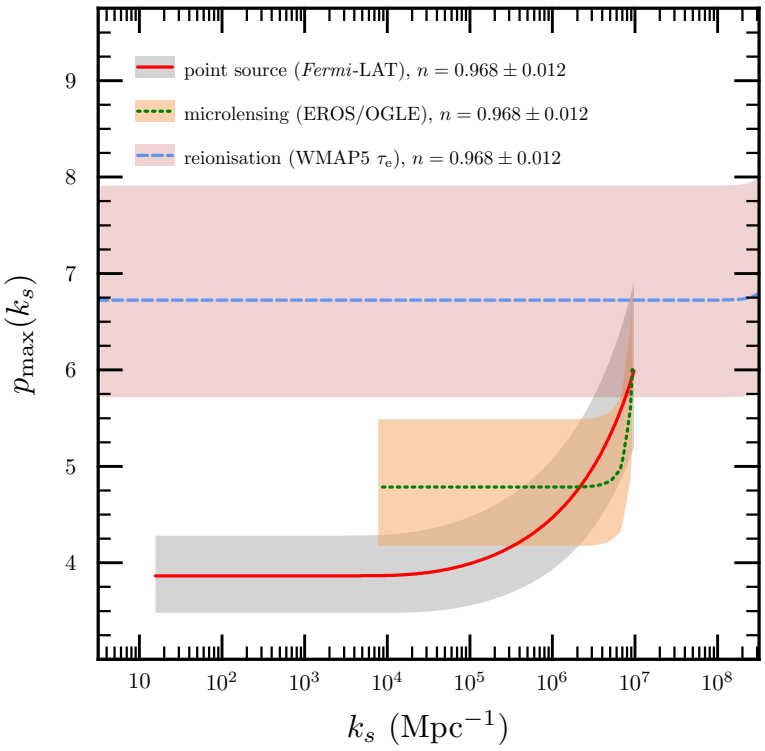
Spectrum with a step

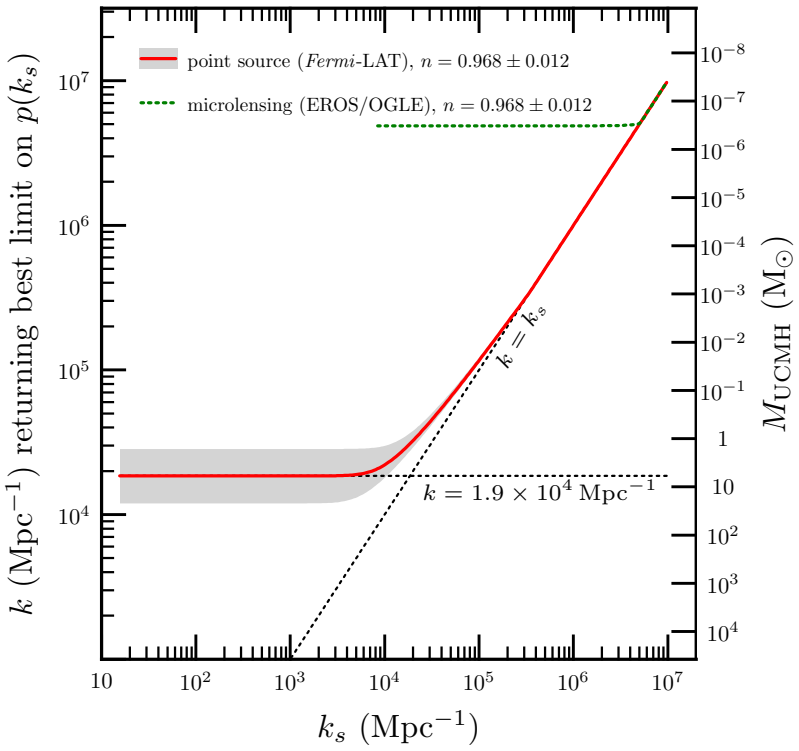
$$\alpha_\chi^2 \to \alpha_\chi^2 \left\{ \theta\left(\frac{k_s}{k} - x\right) + p^2\theta\left(x - \frac{k_s}{k}\right) \right\} \mathrm{d}x \tag{6}$$



Best scale for limits on step spectrum

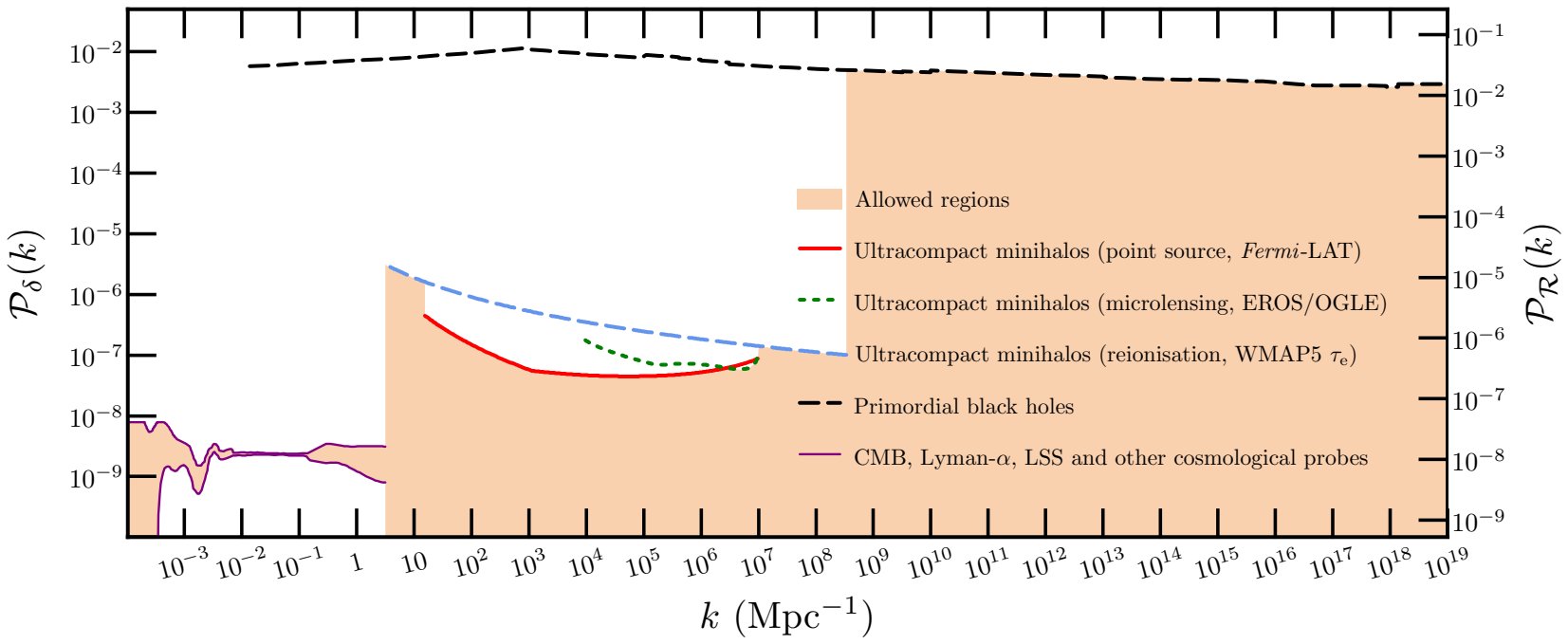
$$\alpha_\chi^2 \to \alpha_\chi^2 \left\{ \theta\left(\frac{k_s}{k} - x\right) + p^2\theta\left(x - \frac{k_s}{k}\right) \right\} \mathrm{d}x \tag{7}$$





General spectrum and curvature perturbation limits

$$\sigma^2_{\chi,\mathrm{H}}(R) = \frac{1}{9}\mathcal{P}_{\mathcal{R}}(k_{\mathrm{R}}) \int_0^\infty x^{n_{\mathrm{R}}+2} W^2_{\mathrm{TH}}(x) W^2_{\mathrm{TH}}(x/\sqrt{3})\,\mathrm{d}x \qquad (8)$$



UCMHs – Conclusions

- Ultracompact minihalos are promising indirect detection targets
- Could be visible by *Fermi*/VERITAS/HESS/CTA
- Assuming DM annihilates, non-observation places limits on primordial perturbations at small scales
- Derived limits are much tighter than existing ones from primordial black holes
- . . . but weakened slightly by careful treatment of mass variance, radial profile and minimum density contrast required for formation

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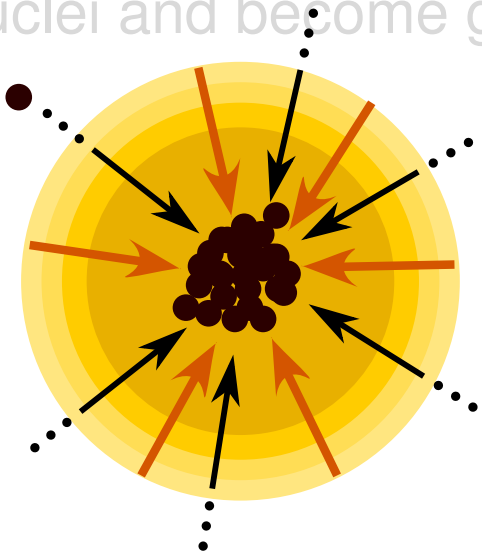
A Dark-Star Spotter's Guide to the Universe

(My preferred definition of) a '**dark star**': any star whose structure or evolution has been affected by WIMP annihilation

2 main ways to get the DM into the star:

- **gravitational contraction:** baryons collapse, change the gravitational potential, taking the DM along for the ride
- **nuclear scattering:** WIMPy passers-by scatter off stellar nuclei and become gravitationally bound



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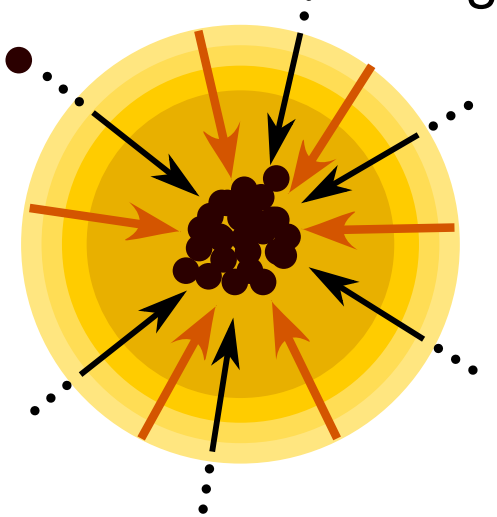

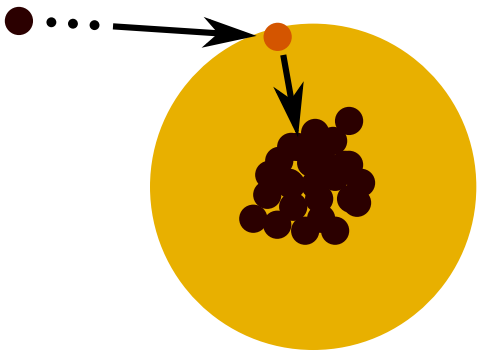

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$\Longrightarrow$ **There are many kinds of dark stars...**

- Main sequence stars in the Milky Way - fed by scattering, maybe interesting (Salati, PS, Fairbairn, et al.)
- White dwarfs in the Milky Way - fed by scattering, maybe interesting (Moskalenko, Wai, Fairbairn, et al.)
- Neutron stars in the Milky Way - fed by scattering, probably not interesting (Bertone, Fairbairn, et al.)
- Pop III stars in the early Universe - fed by grav. contraction and *maybe* scattering, maybe interesting (Spolyar, Freese, Gondolo, Iocco, et al.)

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- White dwarfs in the Milky Way - fed by scattering, maybe interesting (Moskalenko, Wai, Fairbairn, et al.)
- Neutron stars in the Milky Way - fed by scattering, probably not interesting (Bertone, Fairbairn, et al.)
- Pop III stars in the early Universe - fed by grav. contraction and *maybe* scattering, maybe interesting (Spolyar, Freese, Gondolo, Iocco, et al.)

However they got there, effects are similar

WIMPs congregate in the star and self-annihilate

$\Longrightarrow$ standard model particles (= heat) are injected into the gas

Stars end up looking larger, puffier and cooler than normal Pop III

…and live longer?

Reionization models with dark stars

Standard reionisation code: semianalytical models of Venkatesan, Tumlinson & Shull (2003), Venkatesan (2000)

- Press-Schechter-based
- Follows temperature and collapse of each halo, mergers of halos
- Tracks halo history, including stellar populations and ionisation fronts
- Assume 10-140 $M_\odot$ Salpeter IMF for normal Pop III stars (Tumlinson 2004), in a 10 Myr starburst
- Followed by Pop II

Reionization models with dark stars

Additional population of 800 $M_\odot$ dark stars (following 100 GeV track from Spolyar et al, 2009) with

$$Q_{\rm tot}(t) = f_{\rm DS} Q_{\rm DS}(t) + (1 - f_{\rm DS}) Q_{\rm normal}(t). \tag{9}$$

$Q_{\rm DS}$ calculated from dark star stellar atmospheres (a la Zackrisson, Scott, et al 2010a, 2010b)

2 phases:

- Dark star proper (DSP – cool, dark matter dominated – $Q_{\rm DS} = 0$)
- Dark star near the main sequence (DSNMS – hot, small amount of annihilation – resembles main sequence but slightly cooler)

3 scenarios:

- NC – No capture; no nuclear scattering, dark stars die quickly and are replaced by Pop III/II
- MC – Meagre capture; enough nuclear scattering that the DSNMS phase is extended, DSP is not
- EC – Extreme capture; enough nuclear scattering that the DSP phase is extended, DSNMS is not

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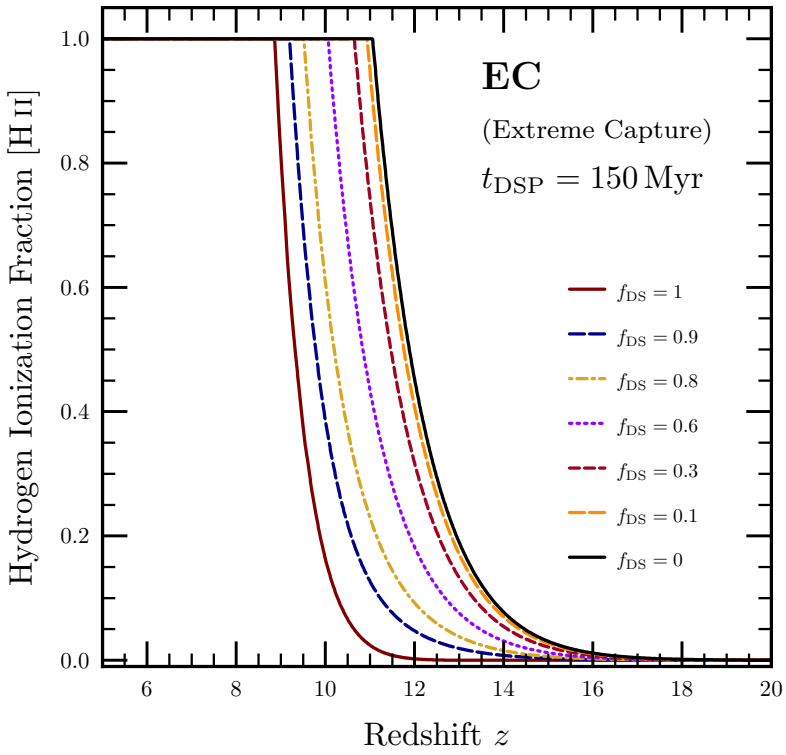
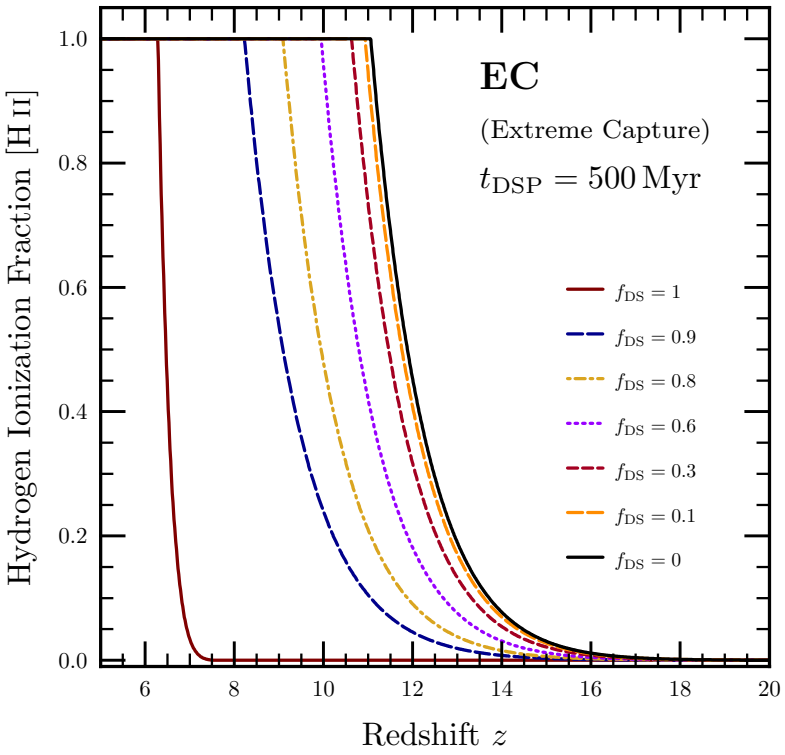
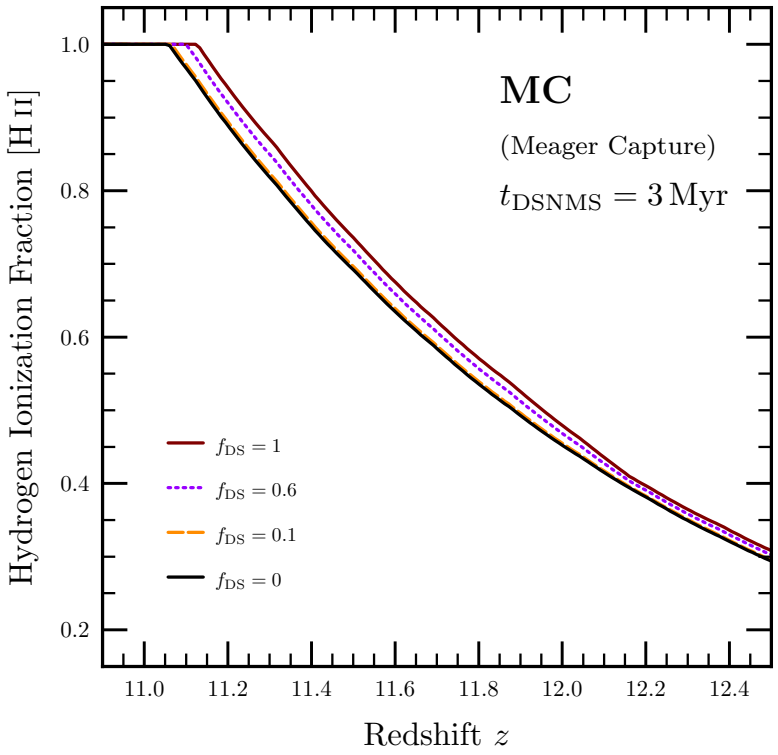
2. Ultracompact minihalos
   - Observational predictions & constraints
   - Primordial power spectrum limits at small scales
3. Dark stars and reionization
   - Impacts on reionization and the CMB
   - Implications for dark stars and reionization models

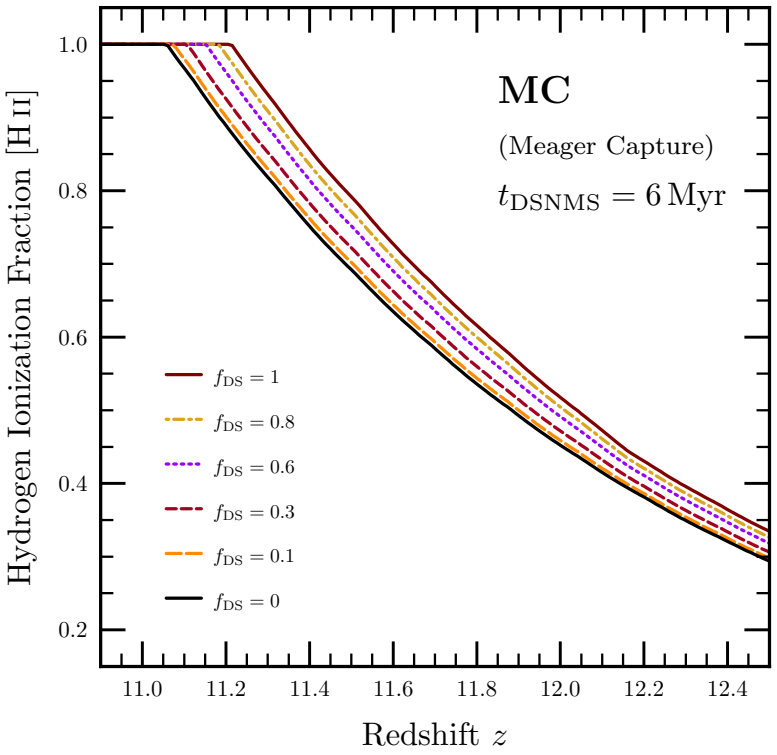
Reionization history of the Universe



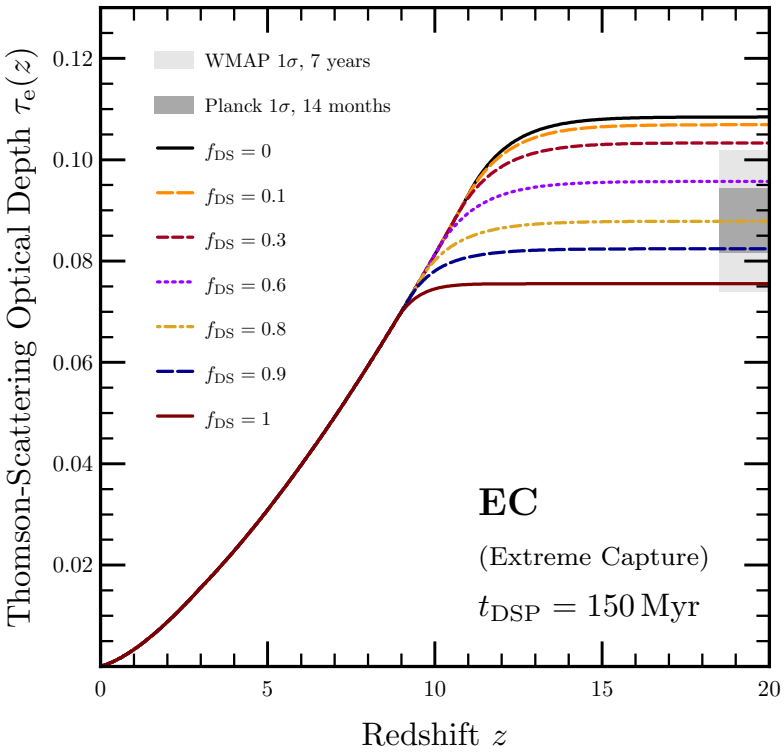


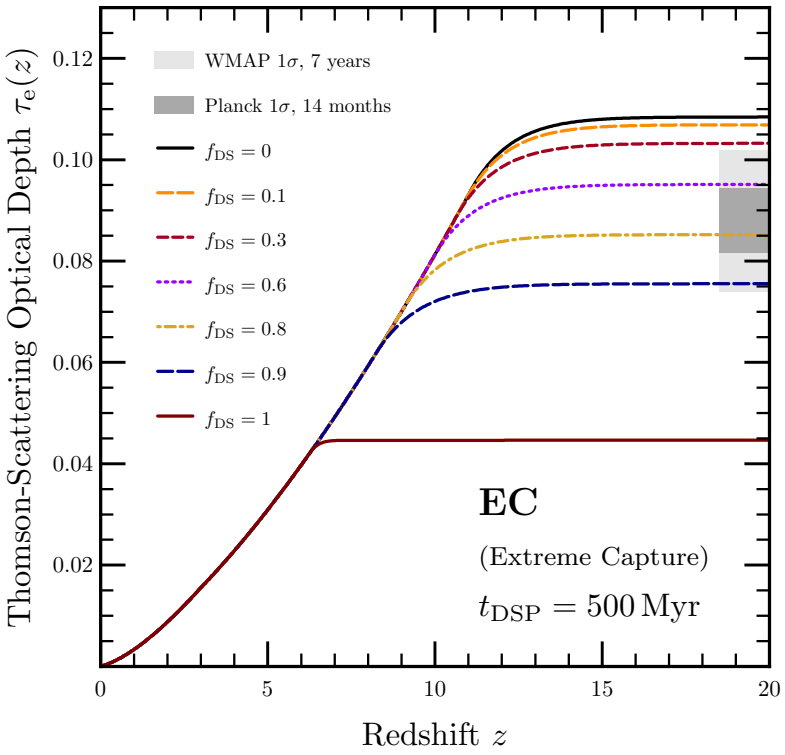
Reionization history of the Universe



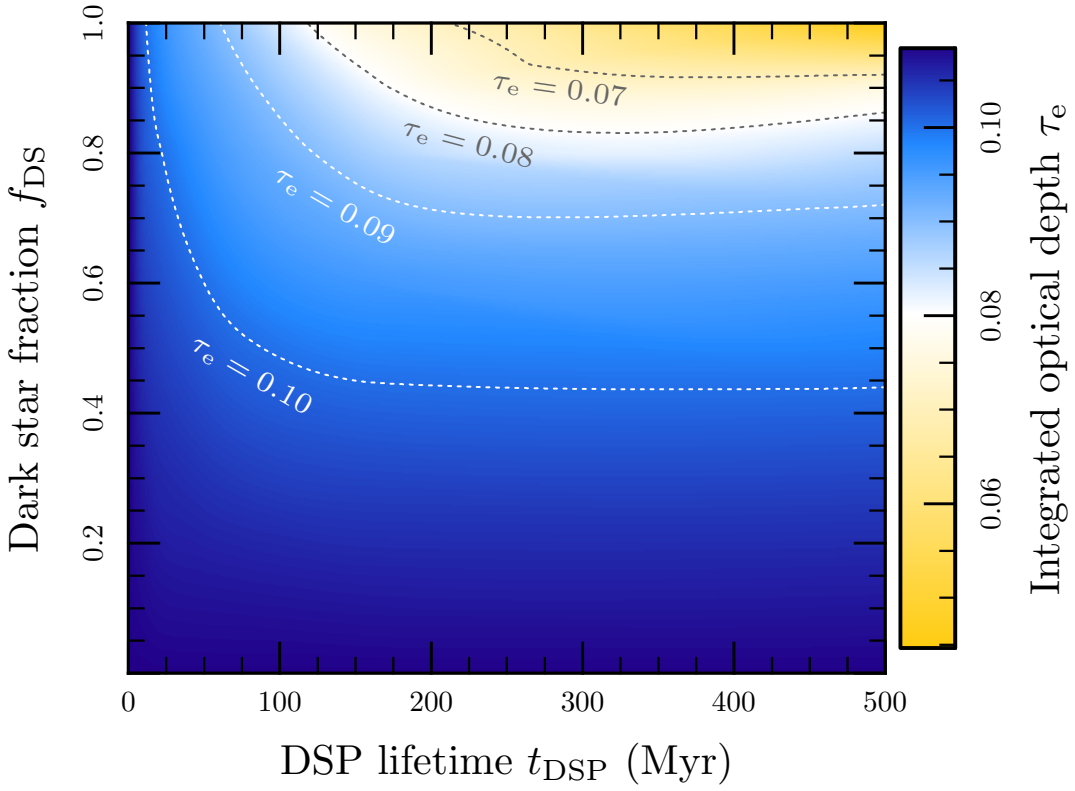


Evolution of CMB optical depth

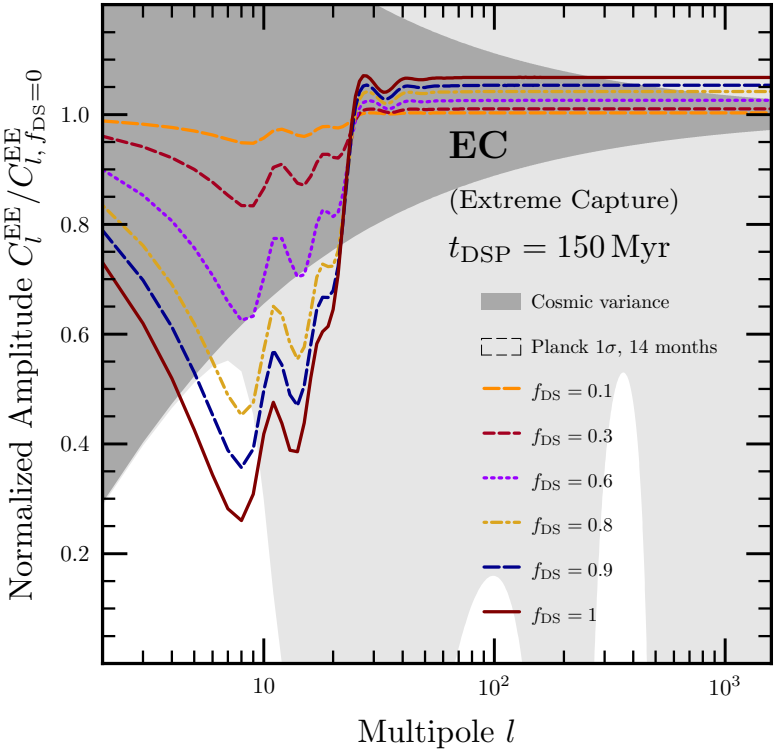


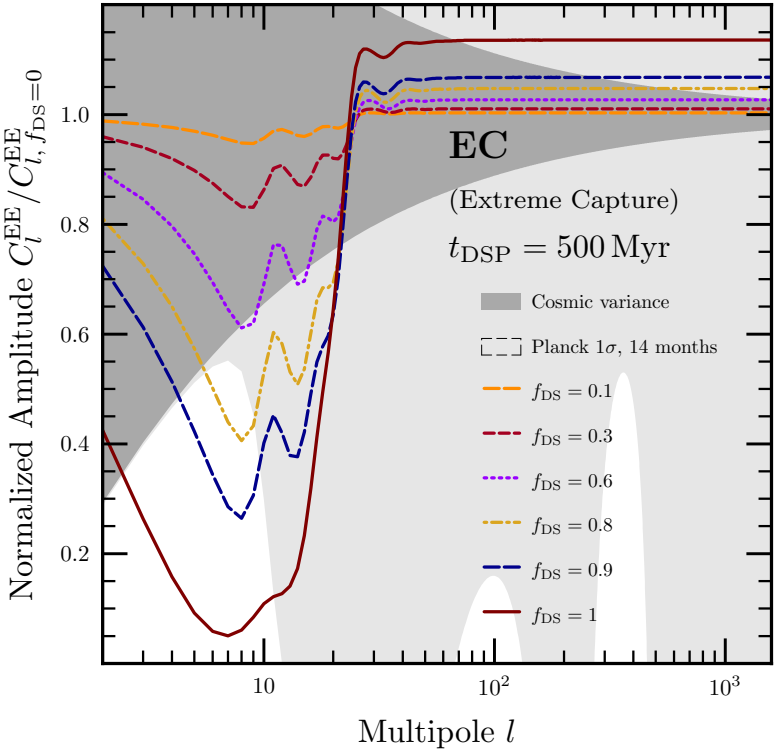


Integrated CMB optical depth



Signatures in CMB polarisation power spectrum





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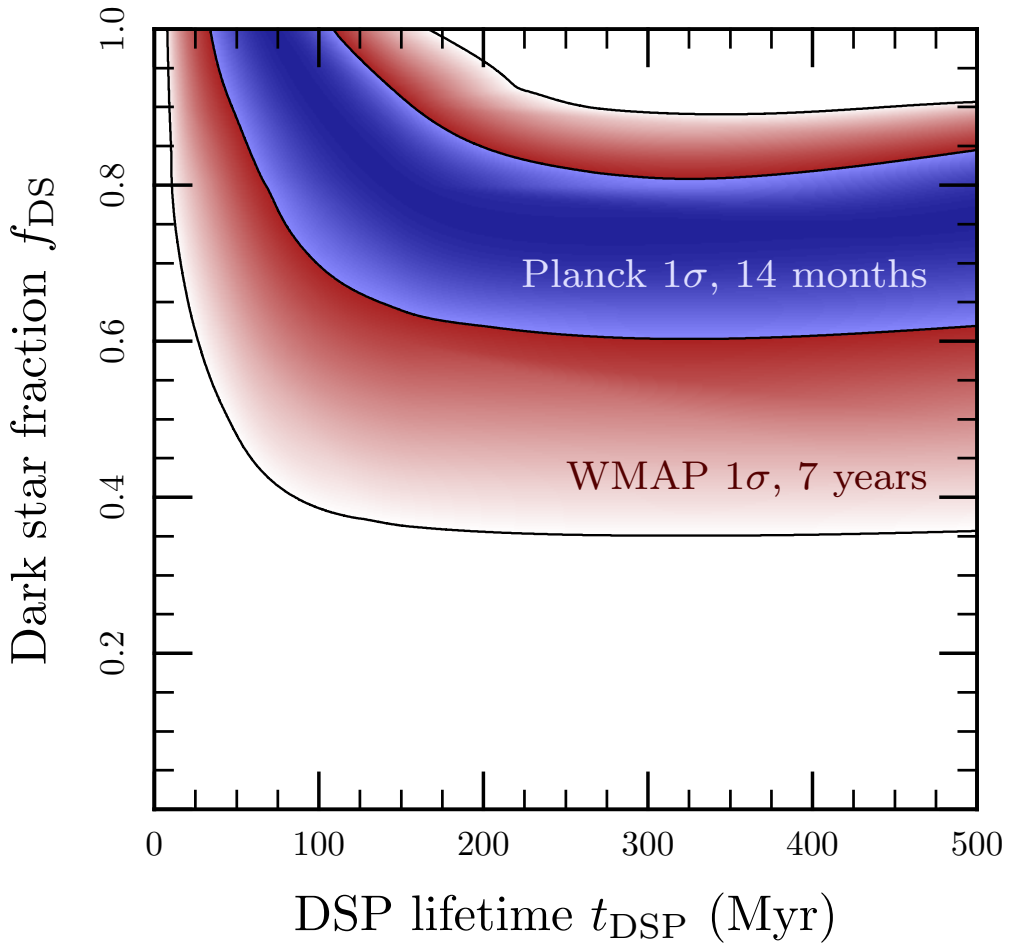
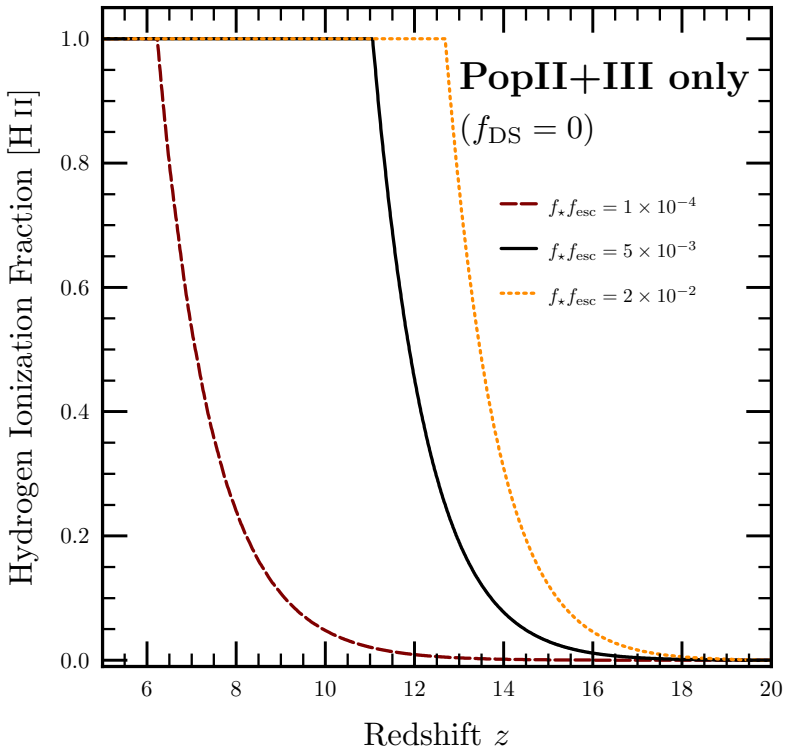
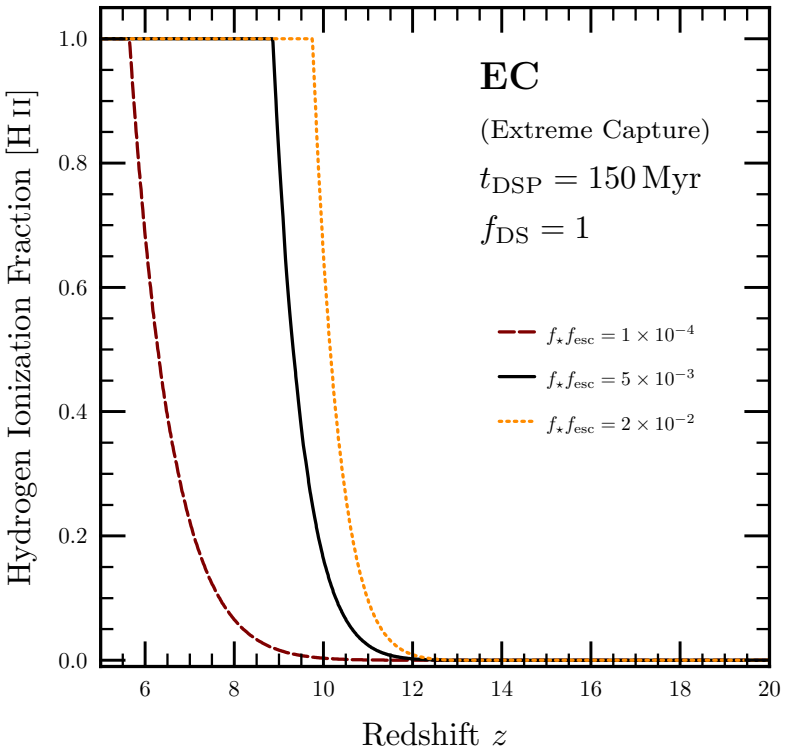
Limits on dark star parameters

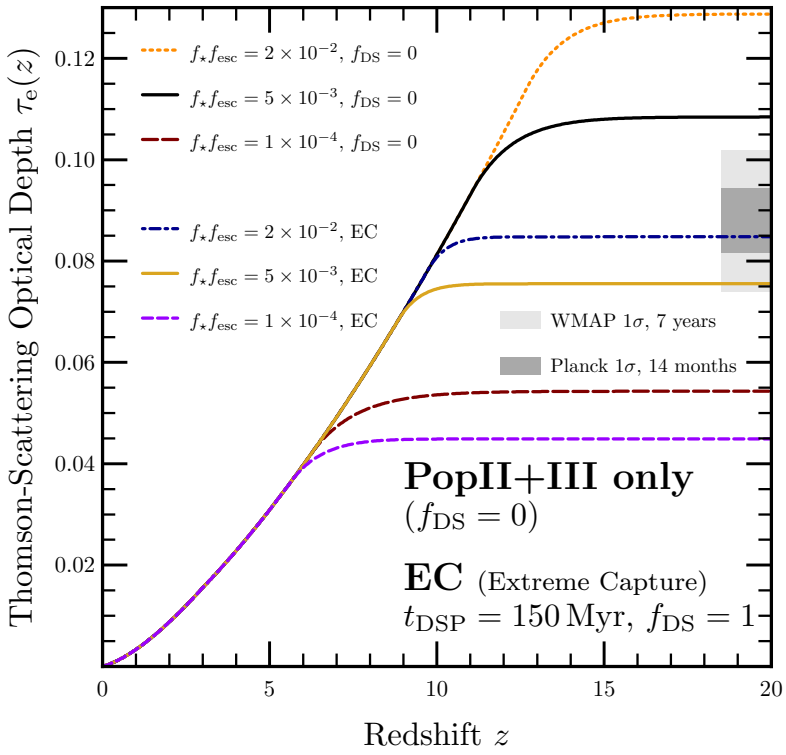


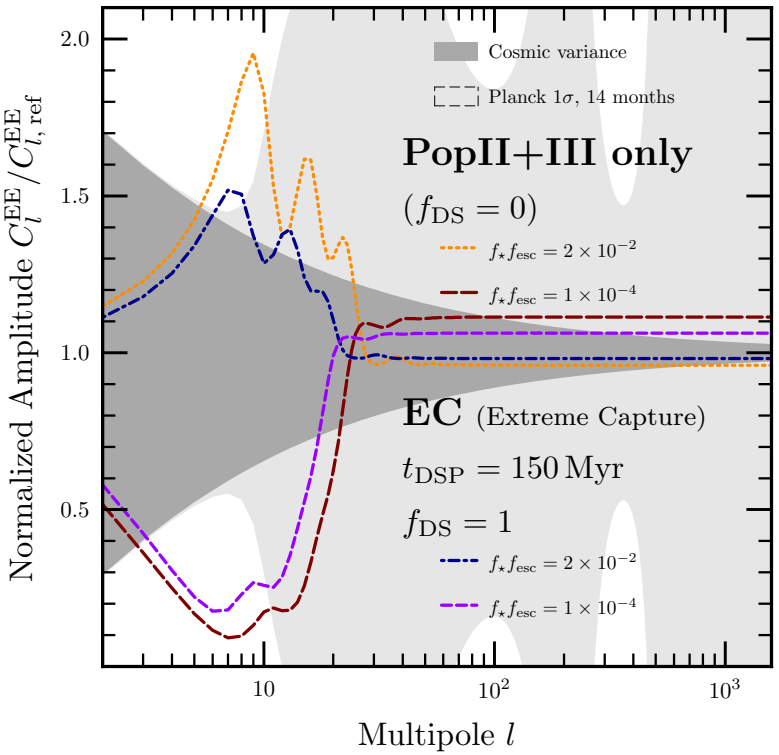
Implications for reionization parameters





Implications for reionization parameters





Dark stars & reionization – Conclusions

Impacts on the reionization history of the Universe

- EC dark stars could substantially delay reionization
- MC dark stars could slightly hasten reionization
- Without capture, dark stars have no impact on reionization

Signatures in the CMB

- EC dark stars decrease CMB optical depth, MC dark stars increase it slightly
- $\implies$ constrains dark star lifetimes to $\lesssim 250\,\mathrm{Myr}$, abundance to $\lesssim 90\%$ by mass
- Produces characteristic signatures in EE polarisation power spectrum

Final Summary

- The smallest dark matter halos are arguably the most interesting
- Could be UCMHs
  - $\Longrightarrow$ good indirect detection prospects
  - $\Longrightarrow$ strong limits on amplitude of primordial density perturbations on small scales
- Could harbour dark stars
  - would delay reionization if WIMP capture by nuclear scattering is important
  - changes CMB optical depth, CMB power spectra, EE polarisation especially
  - constrains dark star parameters
  - has implications for standard reionization parameters also