Clustering with Light (but Massive) Relics

Jason Kumar

University of Hawaii

w/ Pearl Sandick, Shuting Xu

2512.14672

LiMRs

- Light (but Massive) Relics are a general class of new particles which are light enough to be relativistic after BBN …
- … but are non-relativistic today

- so today they contribute to the matter density …
- … and may even have done so at recombination

- but they are not necessarily cold dark matter
  - even when non-relativistic, they may be fast enough to free-stream out of gravitational potentials
  - could lead to deviations from standard ΛCDM cosmology

- similar to neutrinos, warm/hot dark matter

eV-scale LiMRs and N_{eff}

- eV-scale LiMRs are interesting because they can reconcile energy injection in the early Universe with CMB constraints on ΔN_{eff}
- what's the issue?
  - consider a process which injects dark radiation in the early Universe (near or after BBN)
  - decay of dark sector matter, first-order phase transition, etc.
  - there are tight constraints on the amount of dark radiation at the time of recombination from CMB observations
  - for dark sector FOPT, constraints on latent heat also limit the amplitude of GW waves, making them hard to detect

- can avoid ΔN_{eff} constraints if dark radiation starts to redshift like matter before recombination

why eV-scale?

- for this purpose, we're most interested in LiMRs near eV-scale … why?
- for $m_X \ll$ eV, likely relativistic at recomb. → constrained by ΔN_{eff}
- for $m_X \gg$ eV, likely redshifting as matter well before matter-radiation equality ($T_{MRE} \sim 1$ eV), in radiation-dominated epoch
  - density fraction then grows rapidly until around MRE
  - would end up with too much matter, unless injected radiation was very small
  - defeats the purpose

- eV-scale LiMRs are at the sweet spot
  - if eV-scale LiMRs are an $\mathcal{O}(1)$ fraction of radiation at the time on injection, remain so until about MRE
  - at MRE, they start to redshift like matter, and can be an $\mathcal{O}(1)$ fraction of matter
  - avoid constraints from ΔN_{eff}

but what's the catch?

- the catch is that even if eV-scale LiMRs are non-relativistic at recombination, they still may not be cold dark matter

- if LiMRs are fast enough, will free-stream out of small gravitational potentials
- this essentially erases matter structures

- this effect is constrained by weak lensing of the CMB, for example
- one of the ways we know that all dark matter can't be warm/hot

- so what can we add to this story?

goal

- this strategy has been considered before … (Xu, Munoz Dvorkin 2107.09664, etc.)
- … but under specific assumptions about the LiMR cosmological history
  - assumptions about LiMR temperature, coupling to SM, clustering
  - often lead to very tight constraints on LiMR mass, abundance

- we will loosen assumptions on LiMR cosmological history
- will find that LiMRs can be an $O(1)$ fraction of the DM without erasing structure in conflict with observation

- at some level, this is obvious → if you make the LiMR cold enough, it can't free-stream
- but we will quantify this, using some approximations

what we do and don’t do

- we don’t perform a global analysis of any model
- only focusing on constraints arising from the growth of structure, parameterized by the mass and effective temperature of the LiMRs
- for any particular model, there are a variety of other constraints which depend on the properties and initial conditions of all other sectors
  - precise values of Ω_m, Ω_{cdm}, m_ν, etc.
- we instead perform an analytic analysis of how LiMRs affect the structure growth, illustrating degeneracy between LiMRs and other unknowns

overview of how matter clusters

- assume LiMR is a spin-0 particle
  - mass = m_X
  - effective temperature $T_X = r\, T_\gamma$
- decoupled while relativistic
- T_X determines occupancy of momentum modes
- redshifts like matter today

- c_i = propagation speed of i^{th} species $\sim [\delta p_i/\delta\rho_i]^{1/2}$
- δ_i = Fourier trans. of matter density contrast $(\delta\rho_i/\bar{\rho}_i)$

$$f(p) = \frac{1}{\exp\left[p/rT_\gamma\right] - 1}$$

$$f_X \equiv \frac{\rho_X}{\rho_M} = 10^{-2}\,\frac{m_X}{0.075\ \mathrm{eV}}\,r^3$$

$$c_X \sim \frac{\langle p_X \rangle}{m_X} = 3T_\gamma\,\frac{r}{m_X}$$

following Green (TASI), 2212.08685; Craig, et al. 2405.00836

growth of structure

- starting point is continuity and Euler eqns.
- perturbations grow due to grav. pot. from all matter overdensities
- perturbations damped by Hubble expansion and pressure
- assume matter-dominated era
  - $a \propto t^{2/3}$, $H = 2/3t$
- define $\alpha_i = (3/2)(kc_i t/a)^2 = (k/k_{fs})^2$
- k_{fs} = comoving free-streaming wavenumber
- determines k for which pressure matters

$$\frac{d^2\delta_i}{dt^2} + 2H\frac{d\delta_i}{dt} = -\frac{k^2}{a^2}c_i^2\delta_i + \frac{3}{2}H^2\sum_j f_j\delta_j$$

Hubble pressure gravity

$$\frac{d^2\delta_i}{dt^2} + \frac{4}{3t}\frac{d\delta_i}{dt} = -\frac{2}{3t^2}\alpha_i\delta_i + \frac{2}{3t^2}\sum_j f_j\delta_j$$

erasing structure

- say $\alpha \gg 1$
  - pressure dominates over grav.
  - approximate α as constant
- density contrast has damped oscillation

$$\frac{d^2\delta_i}{dt^2} + \frac{4}{3t}\frac{d\delta_i}{dt} \approx -\frac{2}{3t^2}\alpha_i\delta_i$$

- intuition → particles stream out of potentials
  - suppresses structure

$$\delta_i \propto t^\gamma$$

$$\gamma = -\frac{1}{6} \pm \frac{i}{6}\sqrt{24\alpha - 1}$$

- α is time-dep., but won't need the details of how δ damps out

clustering, and its suppression

- consider species for which $\alpha \ll 1$
- collectively, contrast is δ_{cl}
- f_{fs} = free-streaming matter frac.
  - doesn't source grav. pot.

$$\frac{d^2\delta_{cl}}{dt^2} + \frac{4}{3t}\frac{d\delta_{cl}}{dt} \approx \frac{2}{3t^2}\left(1 - f_{fs}\right)\delta_{cl}$$

- if $f_{fs} = 0$ (all matter clusters), density grows as $\delta \propto t^{2/3} \propto a$
- free-streaming has two effects
  - reduces fraction of matter which clusters
  - suppresses the grav. pot which causes structures to grow

$$\delta_{cl} \propto t^{\gamma}$$

$$\gamma_{+} = \frac{2}{3} - \frac{2}{5} f_{fs} + O\left(f_{fs}^2\right)$$

weak lensing power spectrum

- growth of matter structures can be probed by lensing of the CMB
- we are interested in the CMB lensing convergence power spectrum $C^{\kappa\kappa}_{\ell}$
- integrated effect over all conformal times from recomb. (η_*) to now (η_0)
  - $d\eta/dt = 1/a \rightarrow ds^2 = a^2\,[d\eta^2 - d\mathbf{x}^2]$
- so at fixed angular scale (ℓ), we are interested in all comoving scales which could subtend the angular scale at some conformal time
- at large ℓ which obs. probe, dominated by transverse wave numbers (Limber approximation)
  - $k = \ell / (\eta_0 - \eta)$ = comoving wavenumber
- $P(k;\eta)$ = matter power spectrum = $\langle\delta\delta\rangle \propto k^{-3}\, t^{4/3}$ (if no free-streaming)

$$C_\ell^{\kappa\kappa} \cong 2\pi^2 \ell \int_{\eta_*}^{\eta_0} d\eta\, \eta \left[\frac{9\Omega_m^2(\eta)(aH)^4}{8\pi^2}\,\frac{P(\ell/(\eta_0-\eta);\eta)}{\ell/(\eta_0-\eta)}\right]\left(\frac{\eta_*-\eta}{(\eta_0-\eta_*)(\eta_0-\eta)}\right)^2$$

analytic result

- if matter free-streams, power spectrum suppressed → suppresses $C^{\kappa\kappa}_\ell$
- two effects
  - only a fraction of matter clusters, …
  - and structures grow more slowly

- but clustering only suppressed while X redshifts as matter
- and only suppressed if $k > k_{fs}$, which depends on η

- we will approximate break as sharp → either $\alpha \ll 1$ or $\alpha \gg 1$
  - at any η and k, either X clusters or doesn't

- how is lensing affected by LiMRs which don't always free-stream?

suppression of lensing

- dimensionless variables
  - $\tilde{\eta} = \eta / (3t_0)$, $\tilde{k} = k\,(3t_0)$
  - X redshifts as matter after $\tilde{\eta}_X$
- F encodes suppression of clustering ($O(f_X)$)
  - if all matter clusters, F=1
- X free-streams at sufficiently late times, but may not at early times

$$C_\ell^{\kappa\kappa} \propto \int_{\tilde{\eta}_*}^{\tilde{\eta}_0} d\tilde{\eta}\; \tilde{\eta}\left(\tilde{\eta}_* - \tilde{\eta}\right)^2 \left(\tilde{\eta}_0 - \tilde{\eta}\right)^2 \times F(\tilde{\eta};\ell)$$

$$\tilde{\eta}_X = \left[71.4\left(\frac{m_X / r}{0.05\mathrm{eV}}\right)\right]^{-1/2}$$

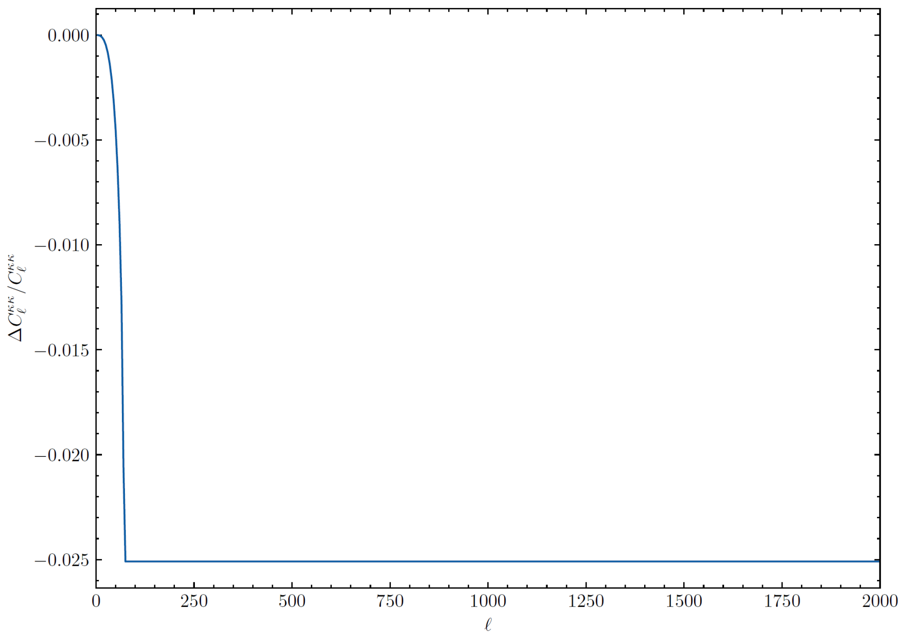
$$\tilde{k}_{fs} = 174\,\frac{m_X / r}{0.05\mathrm{eV}}\,\tilde{\eta}$$

$$F = \exp\left[\ln\left(1 - 2f_X - \frac{12}{5} f_X \ln\frac{\tilde{\eta}}{\max\left[\tilde{\eta}_X, \tilde{\eta}_*\right]}\right) \times \theta\left(\tilde{\eta} - \tilde{\eta}_X\right) \times \theta\left(\frac{\tilde{\ell}}{\tilde{\eta}_0 - \tilde{\eta}} - \tilde{k}_{fs}\right)\right]$$

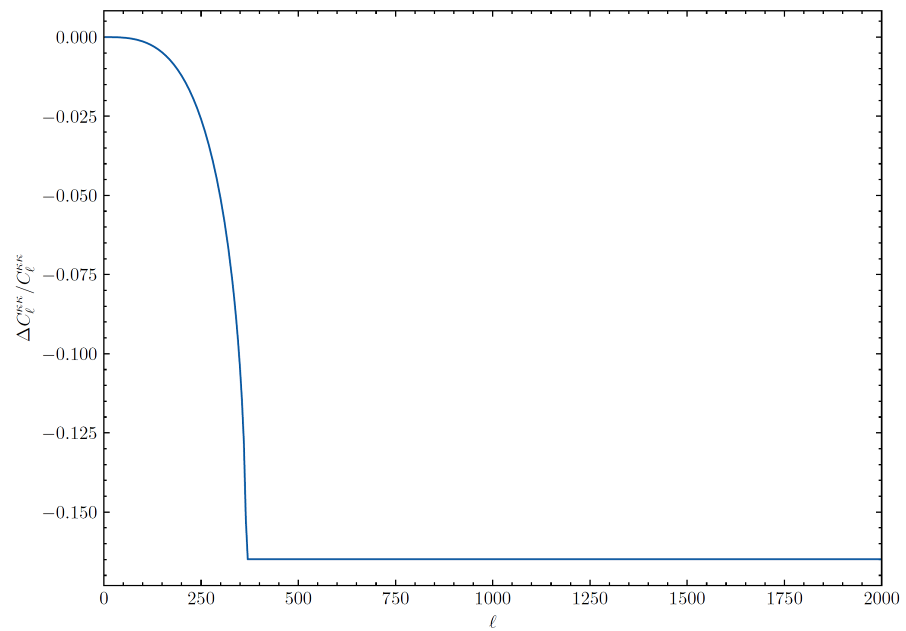
fraction which clusters

growth suppression

let’s apply to neutrinos



Σm_ν = 58 meV

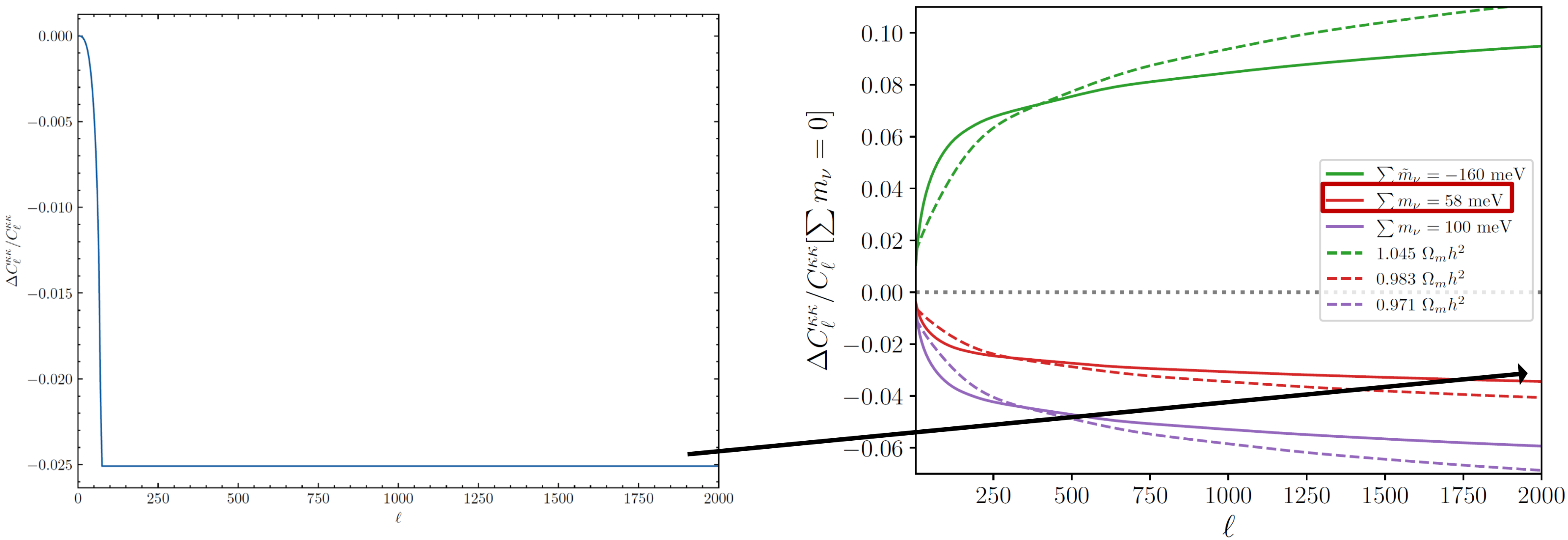


Σm_ν = 300 meV

plotting [$C^{\kappa\kappa}_\ell$ - $C^{\kappa\kappa}_\ell$(F=1)] / $C^{\kappa\kappa}_\ell$(F=1) as a function of ℓ; observ. probe $\ell \sim 2000$

curve flattens at large ℓ, since ν free-streams at all relevant k → never clusters

comparison to full numeric result



$\Sigma m_\nu = 58$ meV

Craig, Green, Meyers, Ragendran
2405.00836

caveats

- shape of lensing power spectrum does not match full numerical calculation of Boltzmann equations, but asymptotic value does
- we essentially took $\Omega_M = 1$, which fails at late times
  - doesn't matter much at large ℓ, but for smaller ℓ, late times more relevant
- for a complete analysis, need to make many model/cosmology choices
  - Ω_{cdm}, Ω_b, etc.
  - but we want to estimate the effect of X free-streaming on clustering, without fixing other choices
- in fact, both X and neutrinos will free-stream, so we should include both
  - we are computing to linear order in f, so contributions add

- we are computing one piece of several

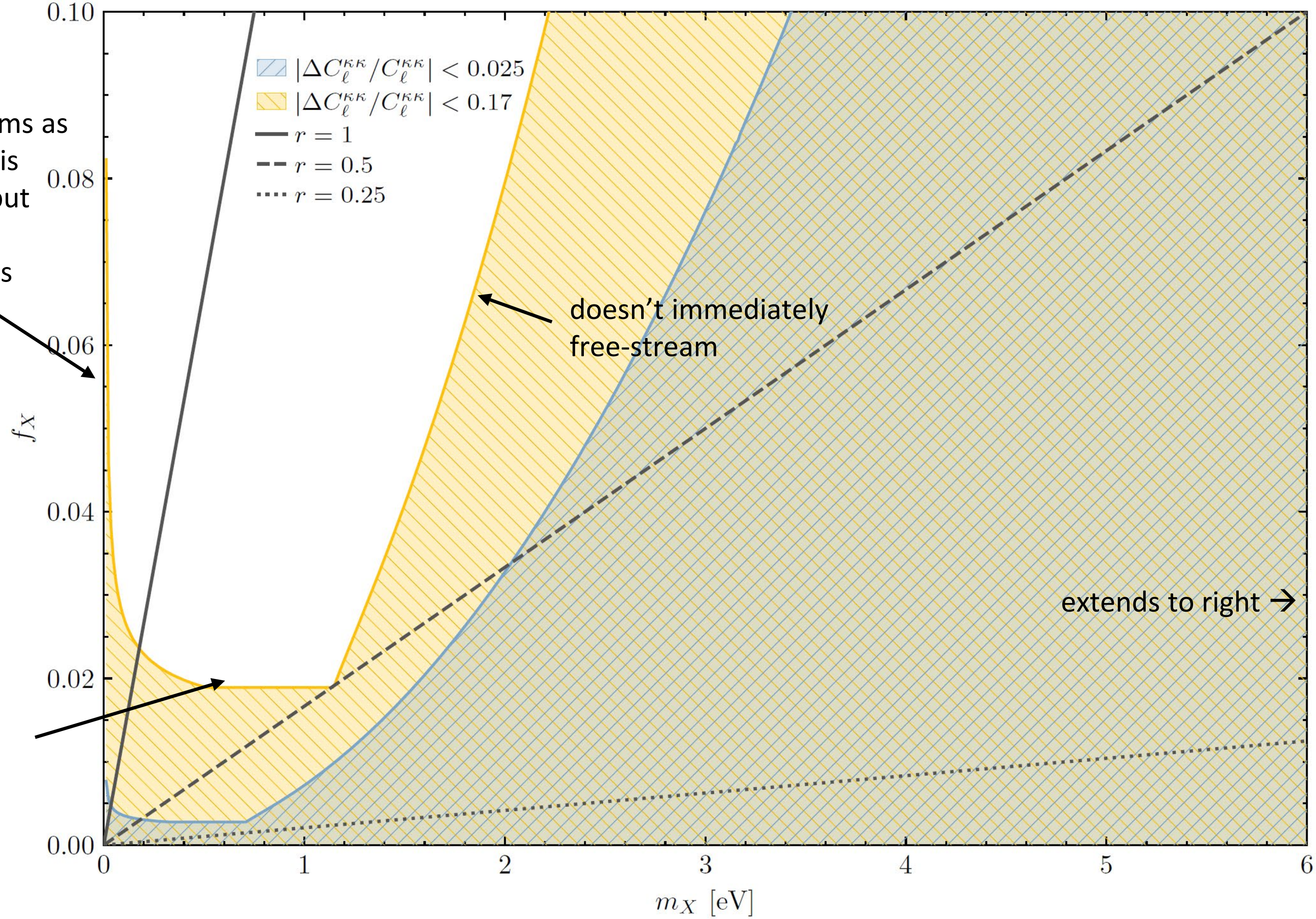
our approach

- in some sense, that is one lesson from the DESI preference for "negative neutrino mass" in ΛCDM (DESI 2404.03002)
- really a preference for additional CMB lensing beyond expectation
  - interpreted as a preference for negative m_ν in a cosmology in which that contribution is least constrained by cosmology
  - but the lensing power spectrum is a sum of several contributions, and one of them has to give
- that's the approach we will take here
- if the contribution of X to CMB lensing lies in the range of neutrino models which are largely allowed by current constraints …
- … then this contribution can be hidden within neutrino slop which we don't know, so is likely allowed by lensing

result

take ℓ = 2000

free-streams as soon as it is non-rel., but has ΔN_{eff} constraints



doesn't immediately free-stream

extends to right →

non-rel. at recomb.

upshot

- eV-scale LiMRs can be consistent with lensing constraints
  - intuitively sensible … no matter how light, if LiMR is slow enough, it will cluster
- early deposition of relativistic particles may not be constrained by ΔN_{eff}
- if they are LiMRs, then main constraint will be from clustering, which can be satisfied
- but a detailed model and cosmology are needed to test all CMB constraints
  - need to specify neutrino sector, Ω_{cdm}, etc.
  - with a complete model, can go beyond linear approx. to a full numerical calculation, but main result should be robust

conclusion

- a non-negligible fraction of dark matter could be eV-scale LiMRs, consistent with constraints on clustering
- if cold enough, don’t free-stream until very late
- can avoid tight constraints on dark radiation by hiding it as LiMRs

- prospects for direct and indirect detection of eV-scale DM?

Mahalo!

Backup Slides

clustering matter

$$f_{cl} = 1 - f_{fs} = \sum_{i \in cl} f_i$$

$$f_{cl}\delta_{cl} = \sum_{i \in cl} f_i \delta_i$$

$$\frac{d^2\delta_i}{dt^2} + 2H\frac{d\delta_i}{dt} \approx \frac{3}{2}H^2 \sum_{j \in cl} f_j \delta_j$$

$$\frac{d^2\left(\sum_{i \in cl} f_i\delta_i\right)}{dt^2} + 2H\frac{d\left(\sum_{i \in cl} f_i\delta_i\right)}{dt} \approx \frac{3}{2}H^2\left(\sum_{i \in cl} f_i\right)\sum_{j \in cl} f_j\delta_j$$

$$f_{cl}\frac{d^2\delta_{cl}}{dt^2} + 2Hf_{cl}\frac{d\delta_{cl}}{dt} \approx \frac{3}{2}H^2 f_{cl}\left(f_{cl}\delta_{cl}\right)$$

$$\frac{d^2\delta_{cl}}{dt^2} + 2H\frac{d\delta_{cl}}{dt} \approx \frac{3}{2}H^2\left(1 - f_{fs}\right)\delta_{cl}$$