Title: Dark matter phenomenology across cosmic times

Date: Jun 14, 2016 09:40 AM

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Abstract: The nature of dark matter remains one of the most nagging problems in cosmology. In this talk I will discuss several existing or potential probes of dark matter. I will start with a well known hot dark matter, massive neutrinos, and discuss their effect on large-scale structure in the non-linear regime. I will then talk about the effect of dark matter interactions with standard model particles on the spectrum of the CMB and on 21cm fluctuations. I will conclude by discussing whether LIGO could have detected primordial-black-hole dark matter.

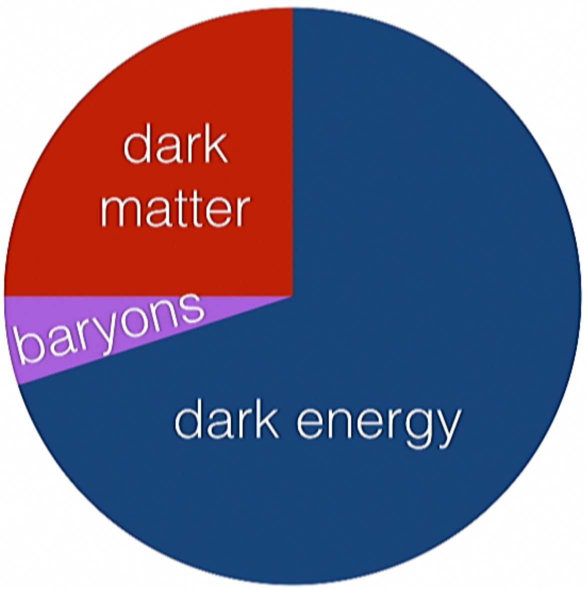
Dark matter phenomenology across cosmic times

Yacine Ali-Haïmoud
Johns Hopkins University

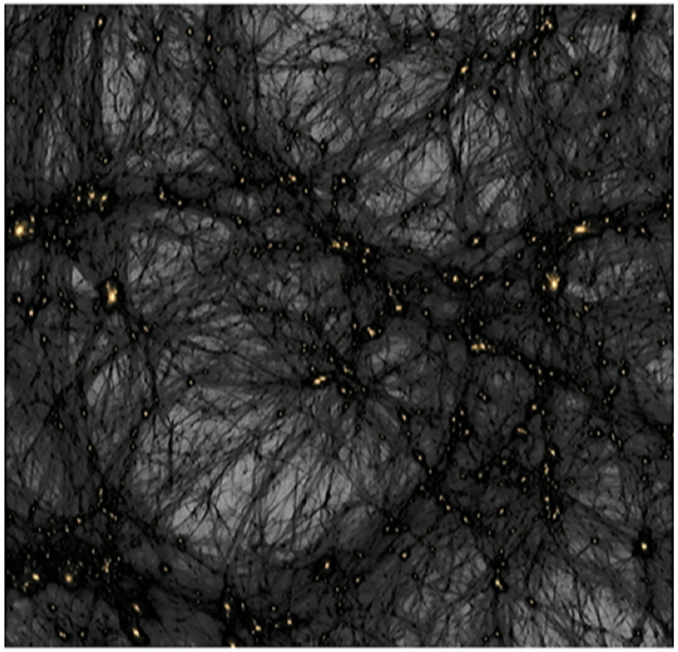
Perimeter Institute, June 14th 2016

Nature of dark matter?

1/4 of the energy budget today
5/6 of the non-relativistic matter



The load-bearing structure for
galaxy formation [Peter 2012]



Outline

1. Massive neutrinos as a hot dark matter: efficient implementation in large-scale-structure simulations

2. Dark matter interactions with standard model particles:

    A. constraints from the CMB spectrum

    B. detection prospects with 21cm fluctuations

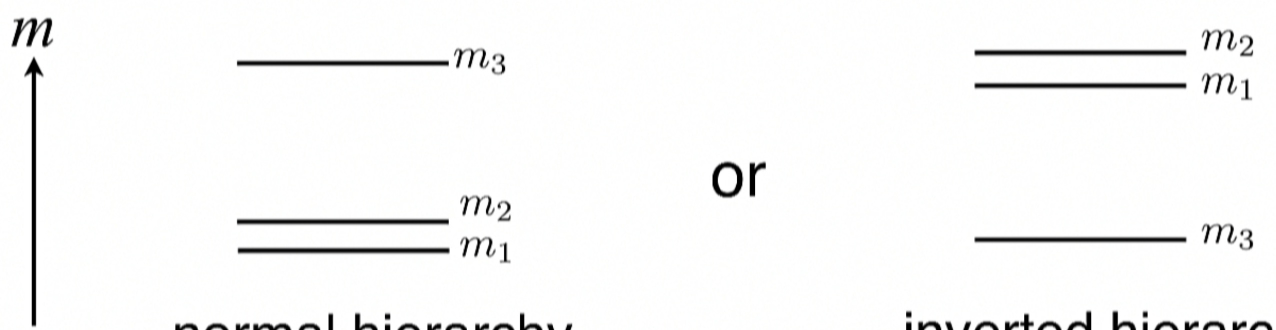
3. Did LIGO detect primordial black hole dark matter?

Neutrinos

Last standard model particle without known mass

From flavor oscillations: neutrinos have mass (Nobel 2015)

$$m_2^2 - m_1^2 \approx (0.009\ \mathrm{eV})^2 \qquad |m_3^2 - m_1^2| \approx (0.047\ \mathrm{eV})^2$$



normal hierarchy inverted hierarchy

Absolute mass scale of neutrinos?

Lower bounds:

normal hierarchy

$$\sum m_\nu \gtrsim 0.06 \text{ eV}$$

inverted hierarchy

$$\sum m_\nu \gtrsim 0.1 \text{ eV}$$

Upper bounds:

Lab experiments (beta decay): $m_{\nu_e} \lesssim 2 \text{ eV}$

From cosmology: $\sum m_\nu \lesssim 0.2 \text{ eV}$ and improving

Basic facts about cosmic neutrinos

- Decouple at $t \sim 1$ s.
  Keep relativistic Fermi-Dirac distribution with $T \sim 2$ K.

- Non-relativistic today, but `hot'

$$v_\nu \approx 800 \ \ \mathrm{km/s} \ (1+z) \frac{0.1 \ \mathrm{eV}}{m_\nu}$$

- Number density (ν + anti-ν): 336 cm^{-3}

- Small fraction of the dark matter

$$f_\nu \equiv \frac{\rho_\nu}{\rho_m} \approx 2\% \left(\frac{\sum m_\nu}{0.3 \mathrm{eV}} \right)$$

Neutrino clustering

Free-streaming scale

$$\lambda_{\rm fs} \sim v_\nu H^{-1}$$

larger scales:

neutrinos cluster
like cold dark matter

contribute
to potentials

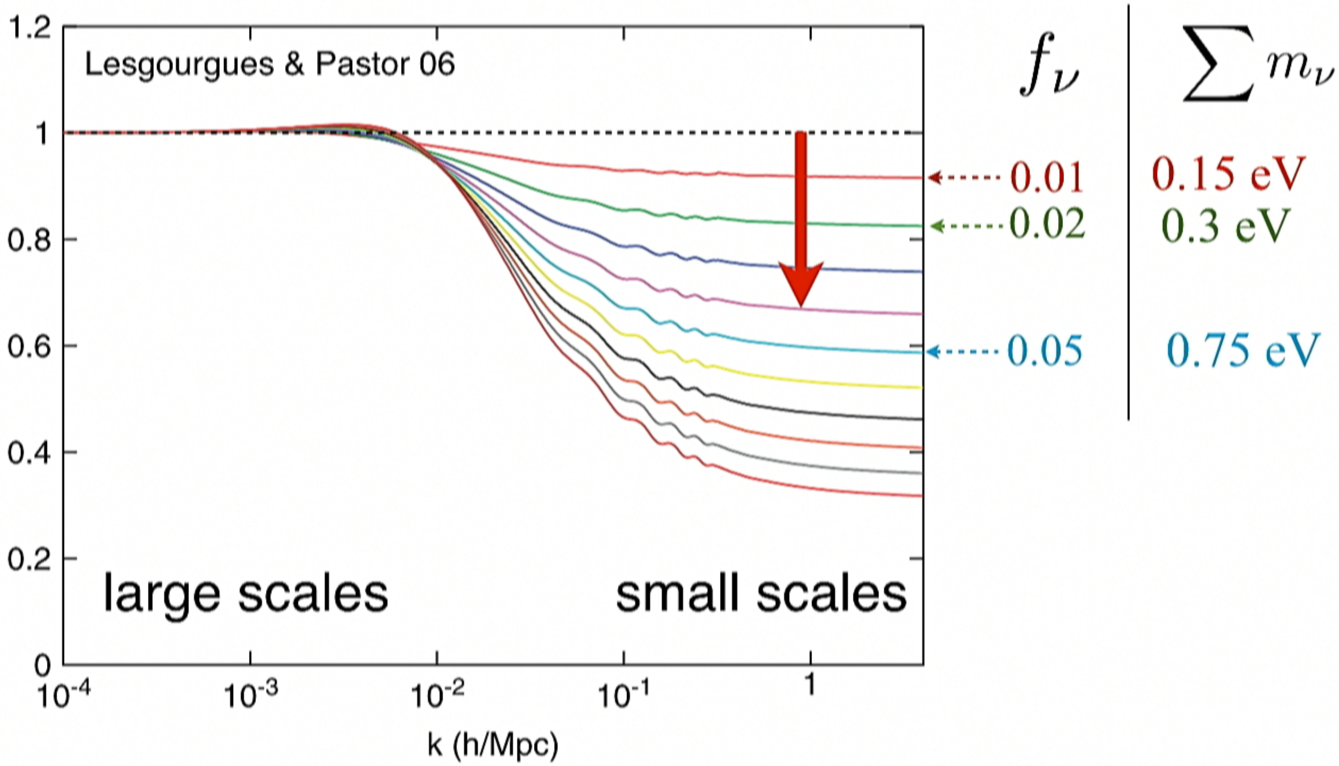
smaller scales:

neutrinos free-stream,
do not cluster

do not contribute
to potentials

slower growth of CDM perturbations

Ratio of power spectrum with massive neutrinos to power spectrum without massive neutrinos



Suppression on small scales $\sim 8 \times f_\nu$

Current and future probes require understanding the effect of massive neutrinos on non-linear scales

i.e. scales where $\frac{\delta\rho_{\rm cdm}}{\rho_{\rm cdm}} \gtrsim 1$

Standard approach: include neutrino `particles' in simulations, i.e. same approach as for cold dark matter

e.g. Klypin+ 93, Brandbyge+ 08, 09,10, Viel+ 10, Bird+ 12, Hannestad+ 12, Rossi+ 14

Challenges of simulating massive neutrinos

- Neutrinos are very fast at early times.
  In principle need a very small time step.
  Start later? ⇒ May not get the cold DM right

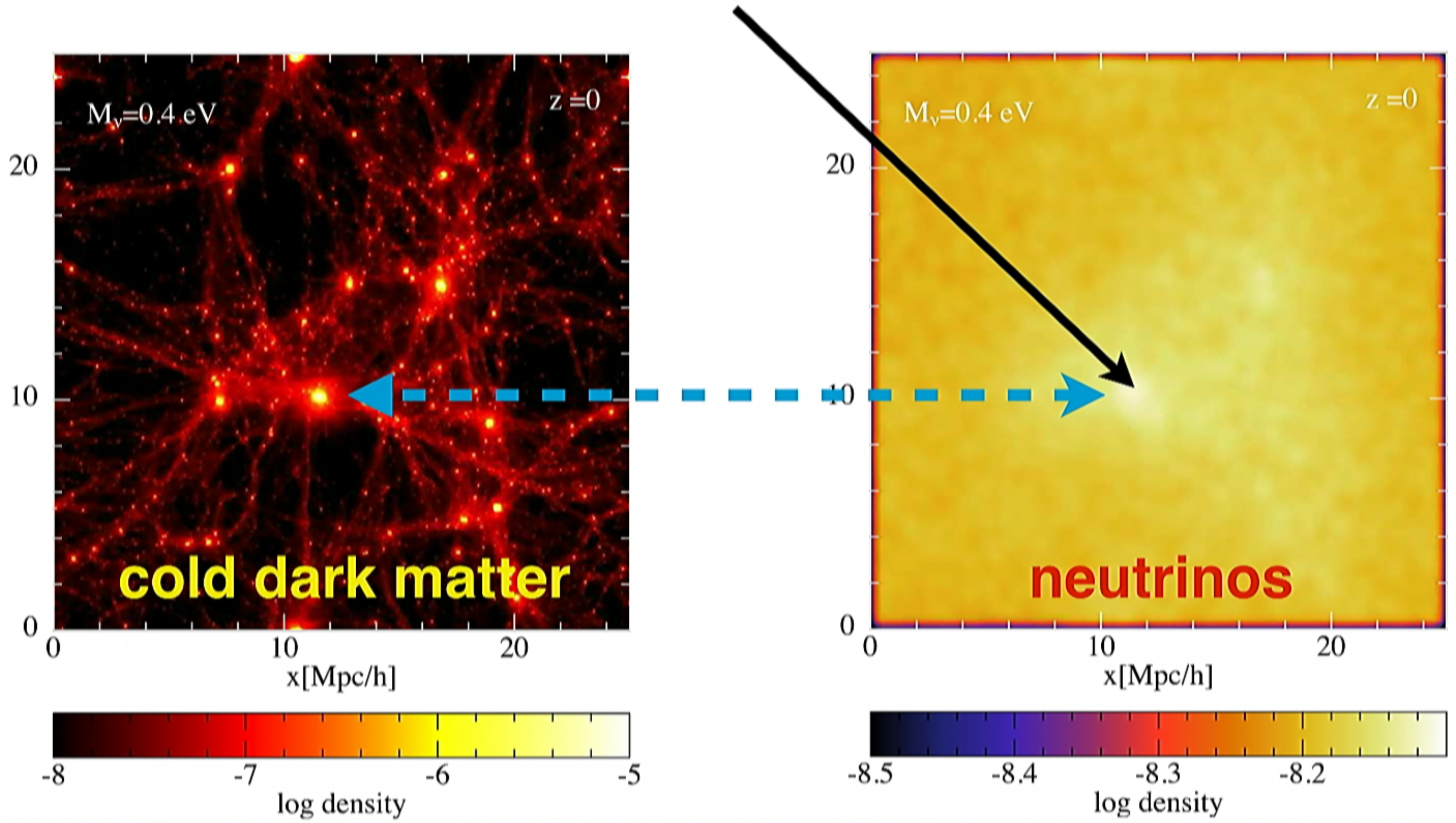
- Neutrino phase-space of neutrinos is 6D
  (vs 3D sheet for cold DM)

⇒ In principle need much more numerical particles

- Neutrinos do not cluster very much

⇒ Large shot noise with finite number of particles

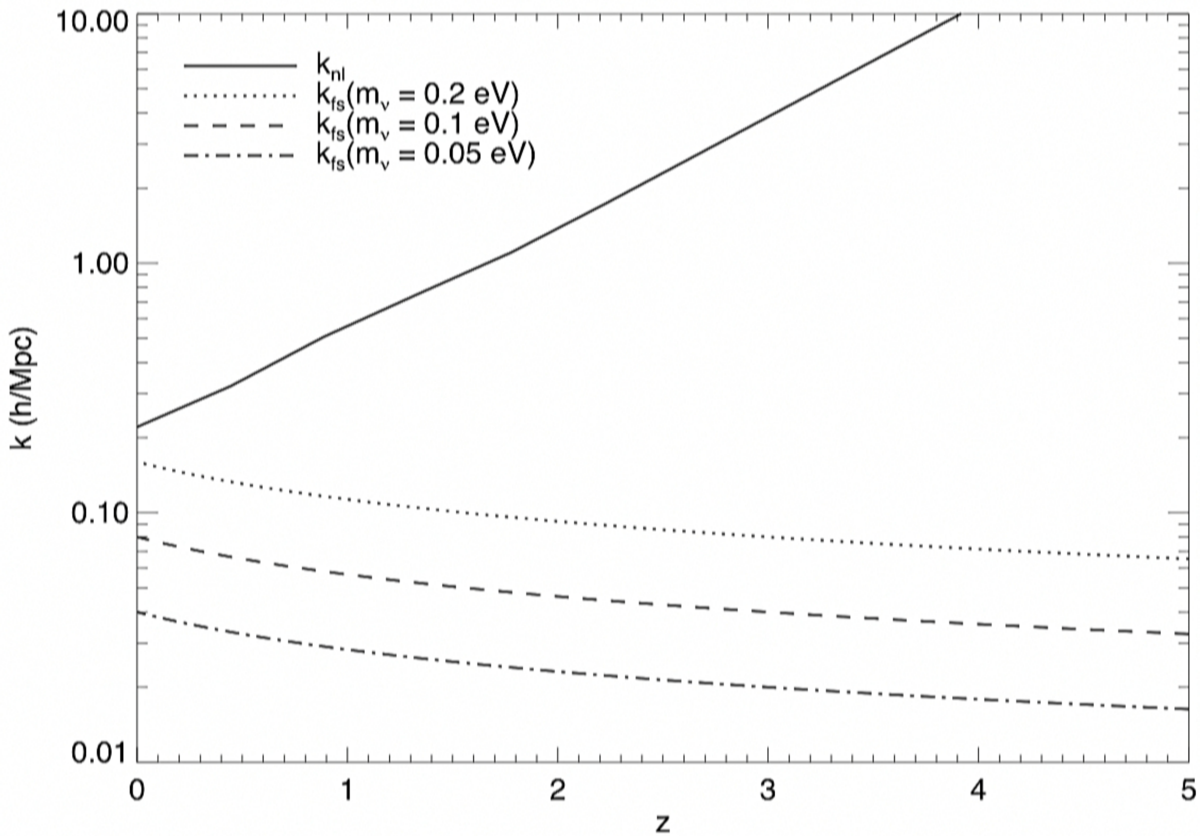
real structure



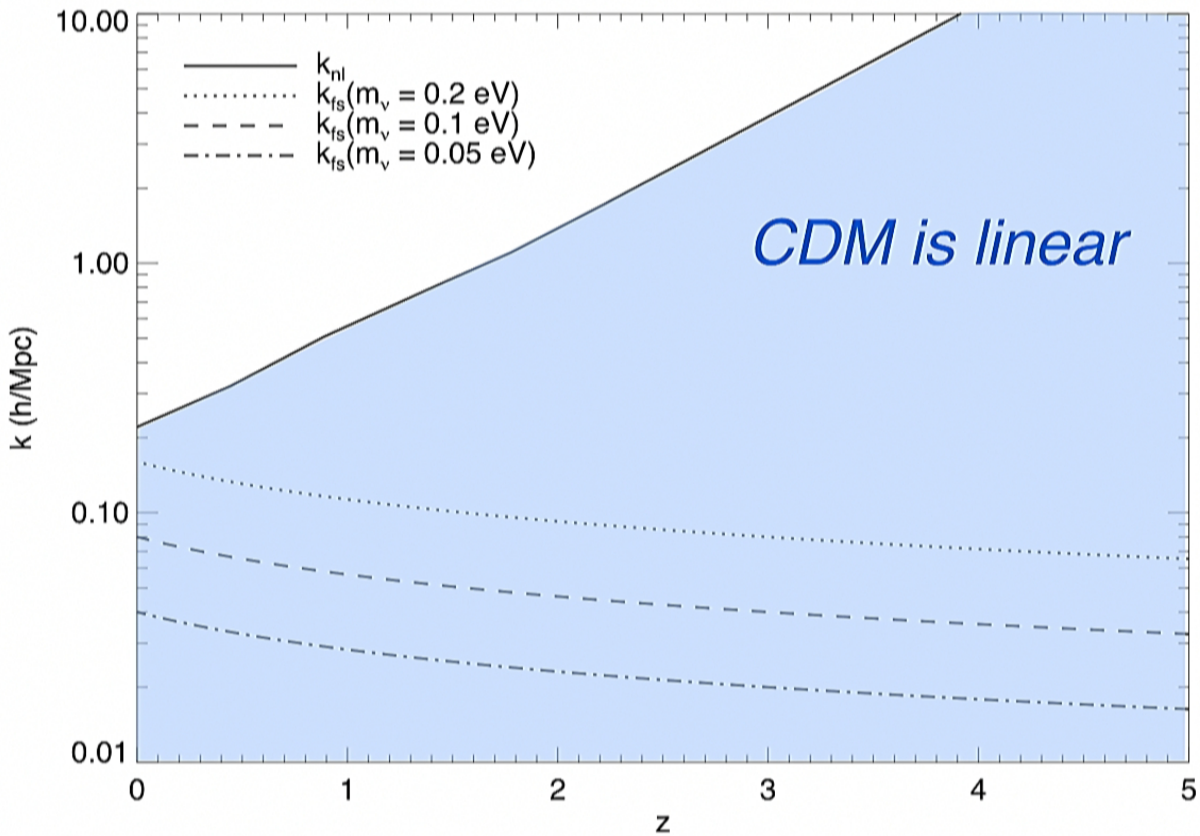
simulations by Rossi et al. 14

$$\sum m_\nu = 0.4 \text{ eV}$$

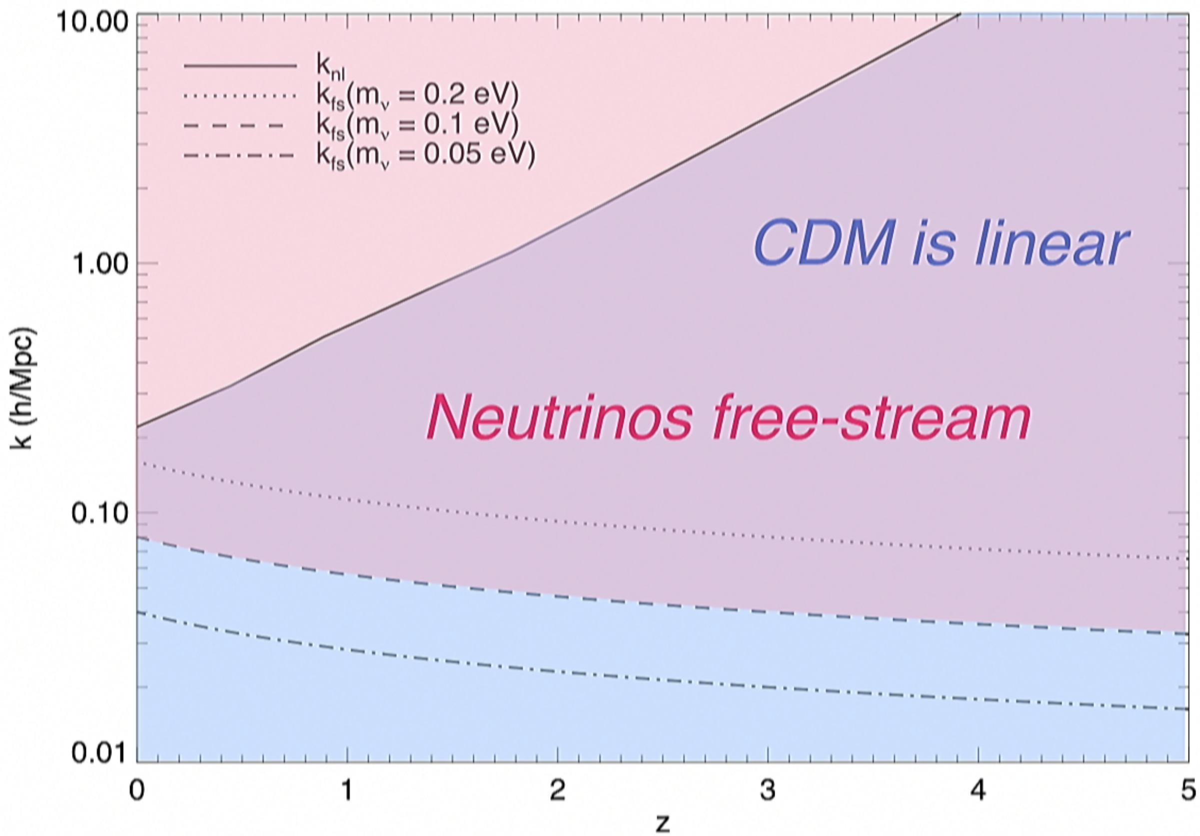
Characteristic scales



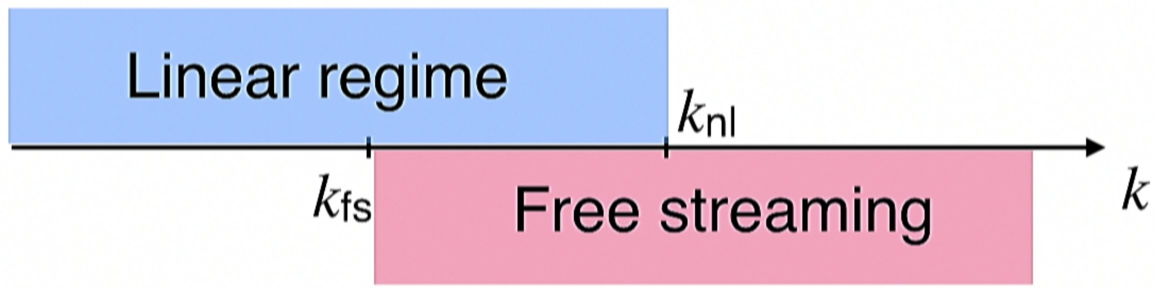
Characteristic scales



Characteristic scales



Characteristic scales



$$\delta_\nu \approx (k_{\rm fs}/k)^2 \delta_m, \text{ for } k \gg k_{\rm fs}$$

Neutrinos should be unclustered
at all scales

Efficient implementation of neutrinos in non-linear structure formation simulations

YAH & Bird, MNRAS 2013

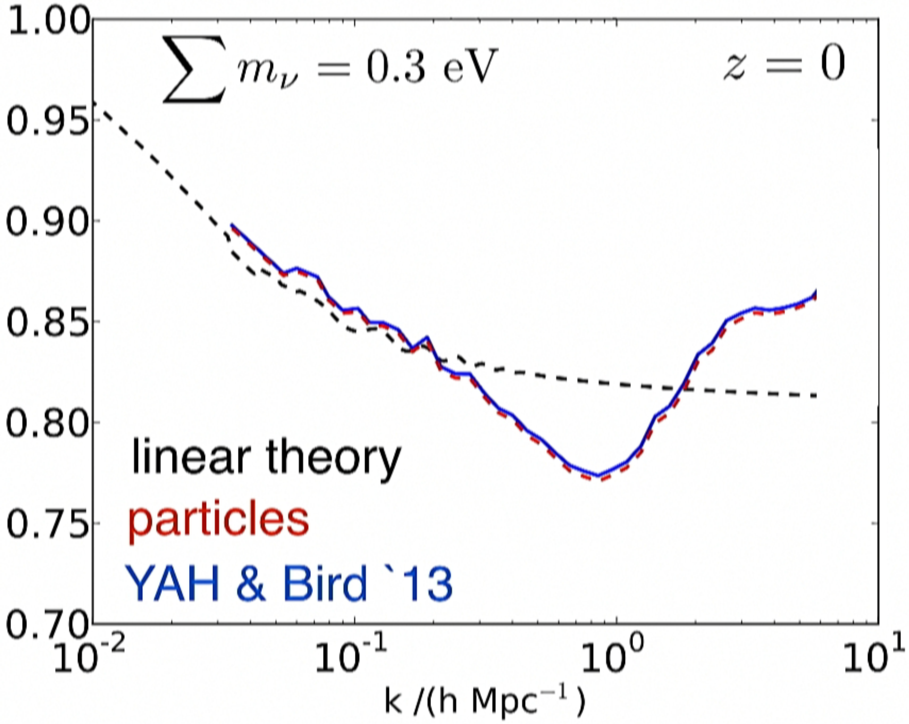
- Use numerical solver to evolve CDM and gas
- Solve analytically for neutrino phase-space density in the limit of small deflections. Linear response to ϕ:

$$\delta_\nu(\vec{k},t) = \int^t dt' G(t,t',\vec{k})\phi(t',\vec{k})$$

← Full non-linear ϕ

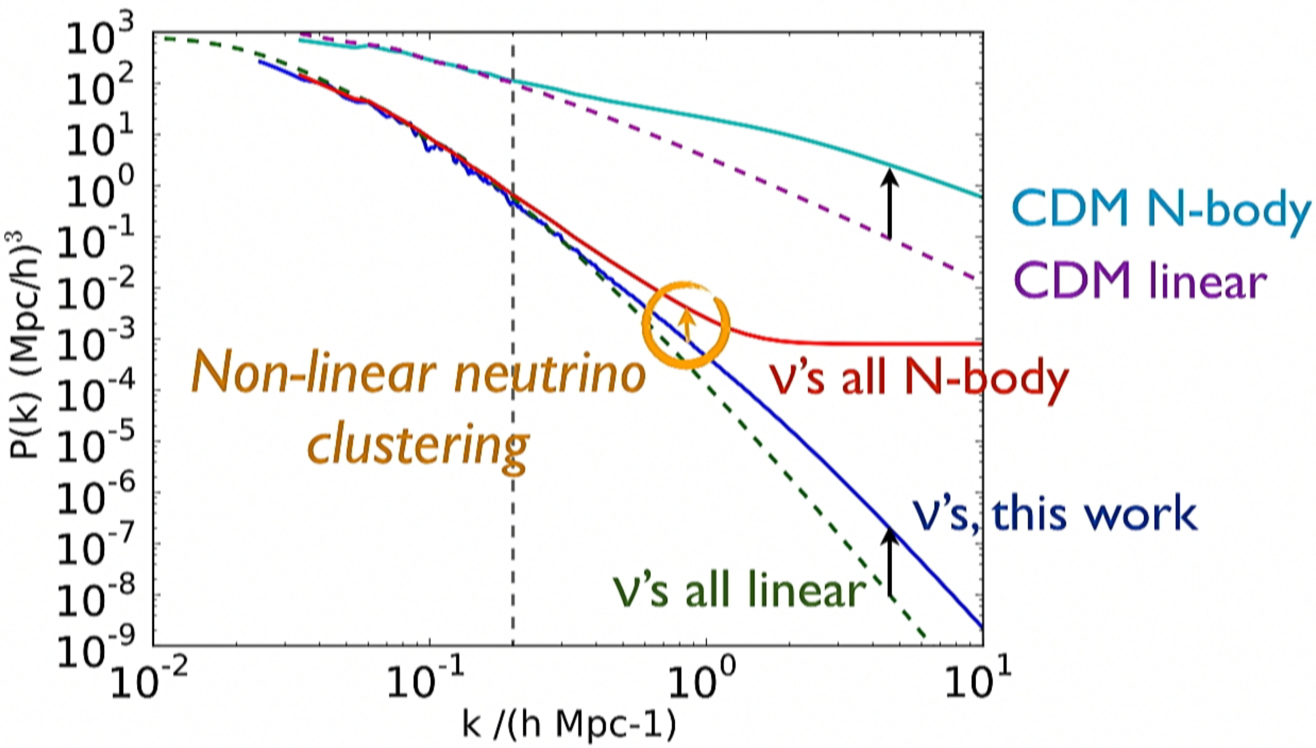
- Update ϕ from neutrino and CDM/baryon densities

Ratio of power spectrum with massive neutrinos to power spectrum without massive neutrinos

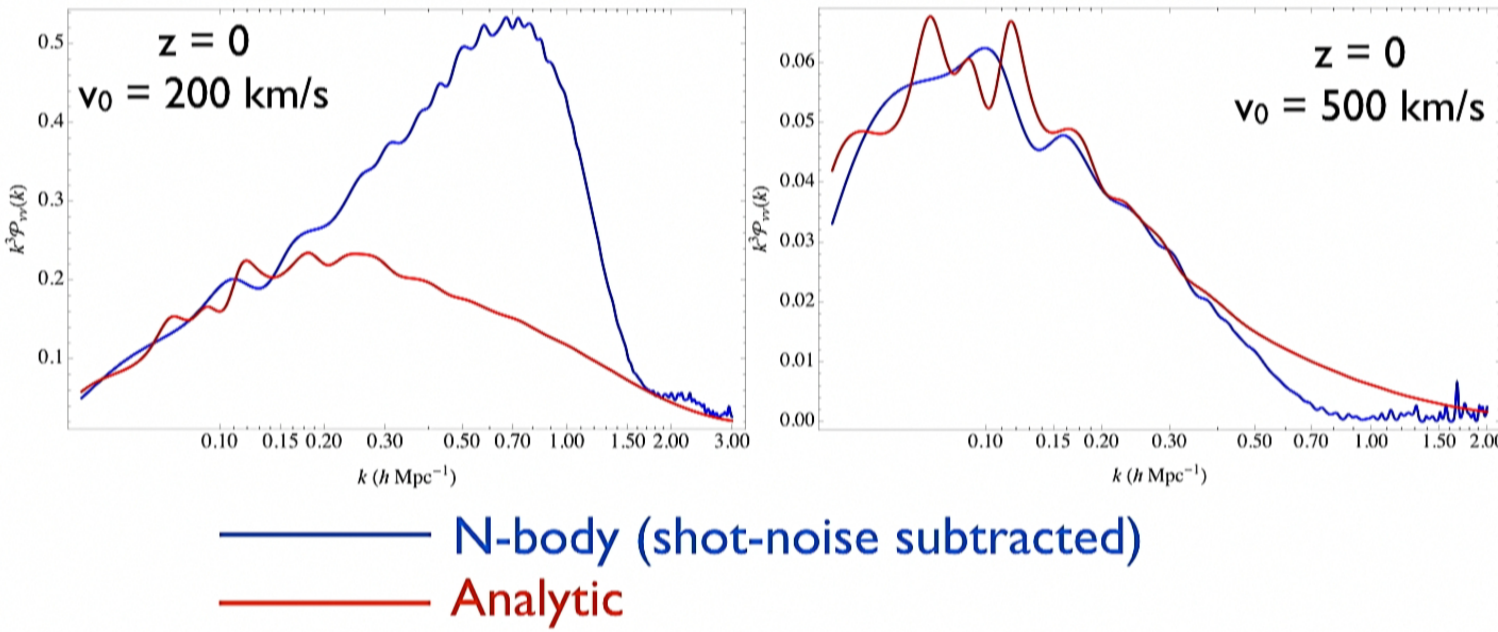


Limitation (in principle)

This method does not account for the non-linear clustering of neutrinos in massive clusters at z = 0

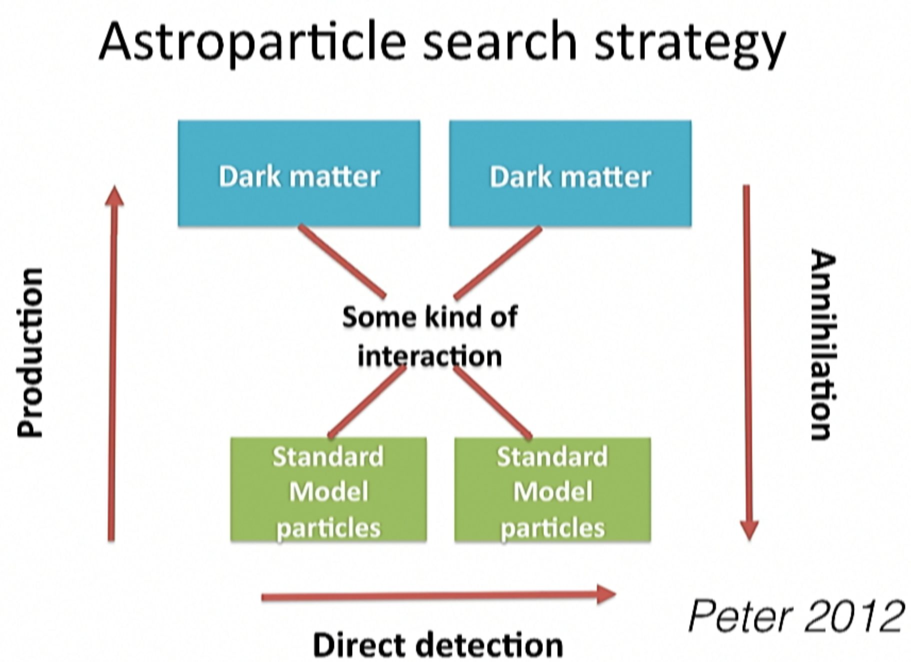


Explanation: while the bulk of neutrinos are unclustered, the slowest ones do get captured in massive haloes



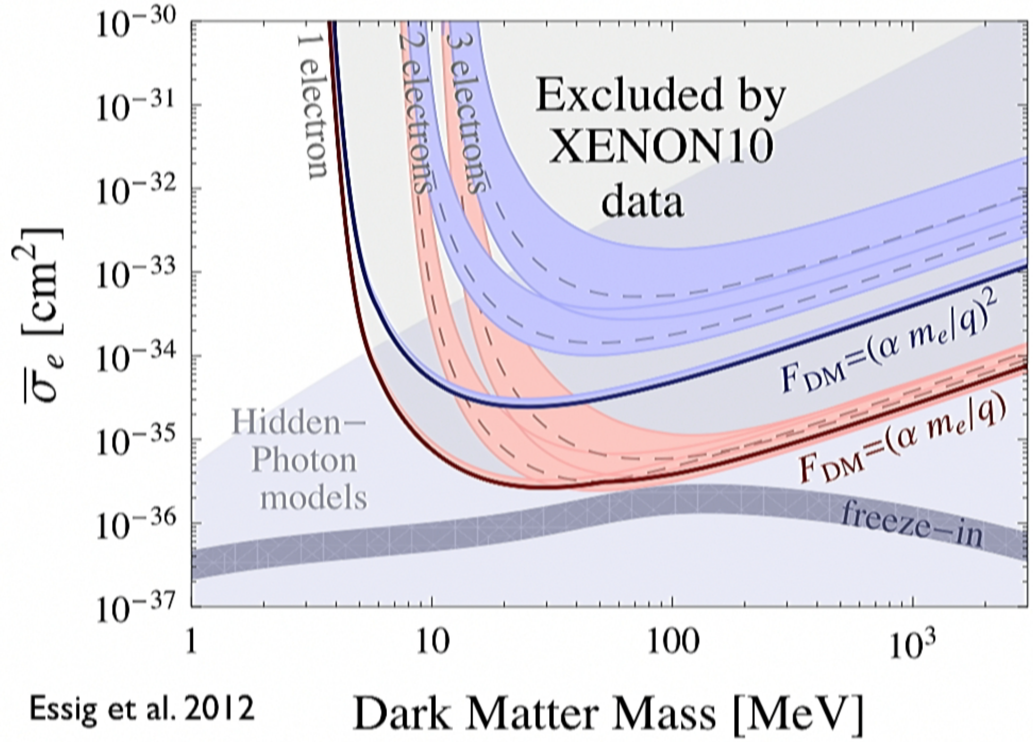
II-Dark matter interactions with standard model particles: prospects for CMB spectral distortions and 21cm

Dark matter may have some kind of weak interaction with standard model particles (hopefully…)



Direct detection constraints

DM-electron: constraints only for $m_{DM} \gtrsim$ MeV



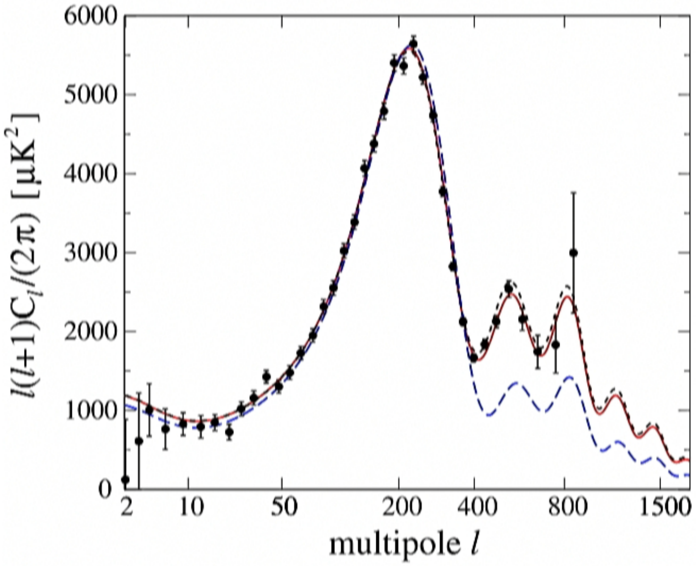
Essig et al. 2012

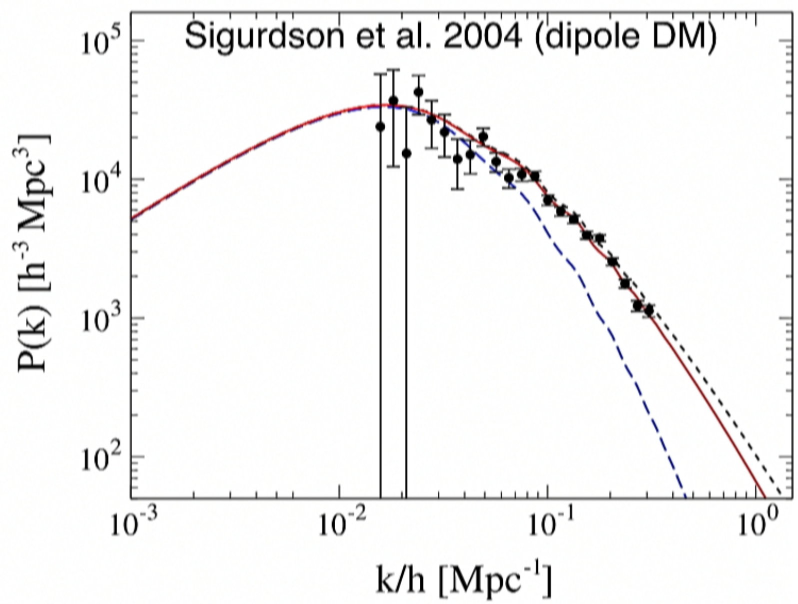
In both cases: rely on assumptions about local DM distribution

Limits from CMB anisotropy /LSS

Momentum exchange ⇒ friction between DM and baryons

Used to set constraints on DM-baryon scattering from CMB anisotropies and LSS :
Chen et al. '02, Sigurdson et al. '04, Dubovsky et al. '04, Dvorkin et al. '14.





Limits from CMB anisotropy /LSS

- CMB anisotropy probes $k \lesssim 0.2$ Mpc^{-1} i.e. modes that entered Horizon at $z \lesssim$ 6e4
- Lyman-alpha probes $k \lesssim 1$ Mpc^{-1} i.e. $z \lesssim$ 3e5
- Not sensitive to DM-SM interactions at higher *z*.

Limits from CMB anisotropy /LSS

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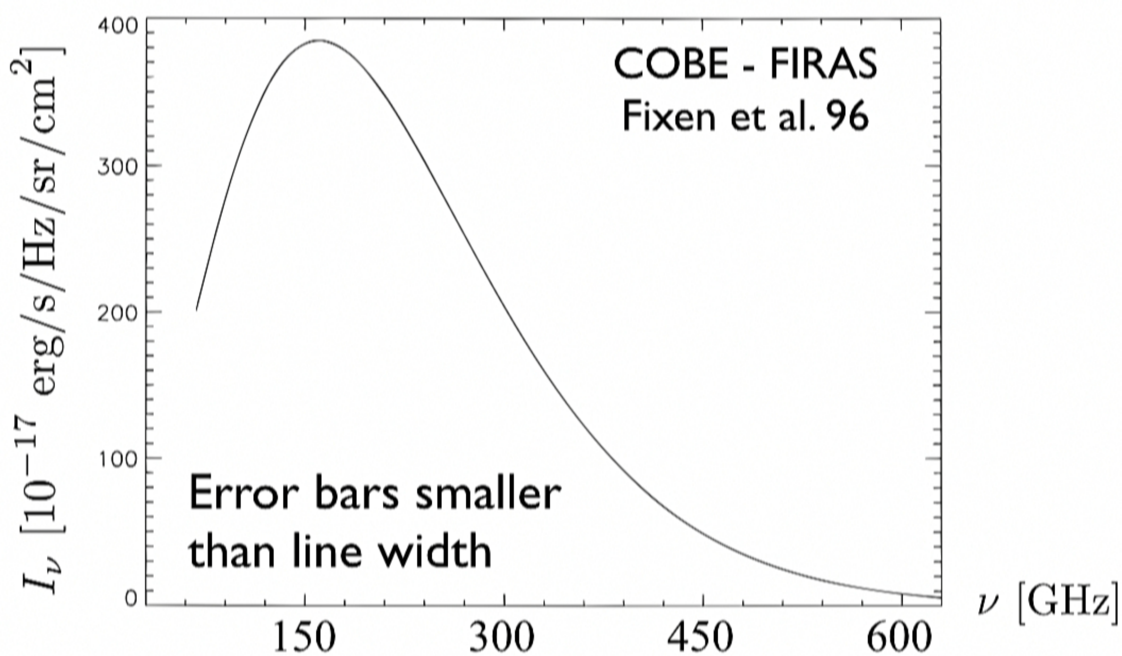
- Lyman-alpha probes $k \lesssim 1$ Mpc^{-1} i.e. $z \lesssim 3e5$
- Not sensitive to DM-SM interactions at higher *z*.

CMB spectral distortions: lightning review

The CMB spectrum is a blackbody within ~5 ×10^{-5} [Nobel 2006]



Distortions tell us about thermal history

See e.g. Hu & Silk 1993, Chluba & Sunyaev 2012

Effect of heat injection as a function of time:

full thermalization

unobservable

blackbody with different T

partial / no thermalization

⇒ distorted blackbody spectrum

$z \approx 2\times10^6$

$t \approx 2$ months

time

What can generate spectral distortions

Dissipation of acoustic waves [e.g. Hu+ 94]

Adiabatic cooling of baryons [e.g. Chluba & Sunyaev 11]

At low-redshift, clusters (Sunyaev-Zeldovich effect)

Hydrogen and Helium recombination [e.g. Chluba & YAH 16]

Dissipation of primordial magnetic fields [e.g. Kunze & Komatsu 13]

Annihilating or decaying dark matter particle [e.g. Hu & Silk 93]

......

How can scattering DM particles distort the CMB?

Adiabatic cooling of photon-baryon plasma:

$$T_{\rm cmb}\Big|_{\rm adiabatic} \propto p \propto 1/a$$

Adiabatic cooling of non-relativistic DM is faster:

$$T_{\rm DM}\Big|_{\rm adiabatic} \propto p^2 \propto 1/a^2$$

If DM + $\gamma \leftrightarrow$ DM + γ $\Rightarrow$ heat flows from photons to DM

$\Rightarrow$ CMB cools slightly faster than adiabatically

$$T_{\rm cmb} \propto 1/a^{1+\epsilon} \qquad \epsilon \sim \frac{n_{\rm DM}}{n_\gamma}$$

- What if DM scatters with electrons?
- Same story: indirect thermal coupling to photons through Compton scattering:

$$\mathrm{DM} + e \leftrightarrow \mathrm{DM} + e$$
$$e + \gamma \leftrightarrow e + \gamma$$

- What if DM scatters with nuclei?
- Same story: indirect thermal coupling to photons through Coulomb and Compton scattering:

$$\mathrm{DM} + p \leftrightarrow \mathrm{DM} + p$$
$$p + e \leftrightarrow p + e$$
$$e + \gamma \leftrightarrow e + \gamma$$

Fractional energy extracted from CMB

$$\frac{\Delta U_{\rm cmb}}{U_{\rm cmb}} \approx -\frac{n_{\rm DM}}{n_\gamma} \log\left(\frac{1+z_{\rm max}}{1+z_{\rm dec}}\right)$$

Fractional energy extracted from CMB

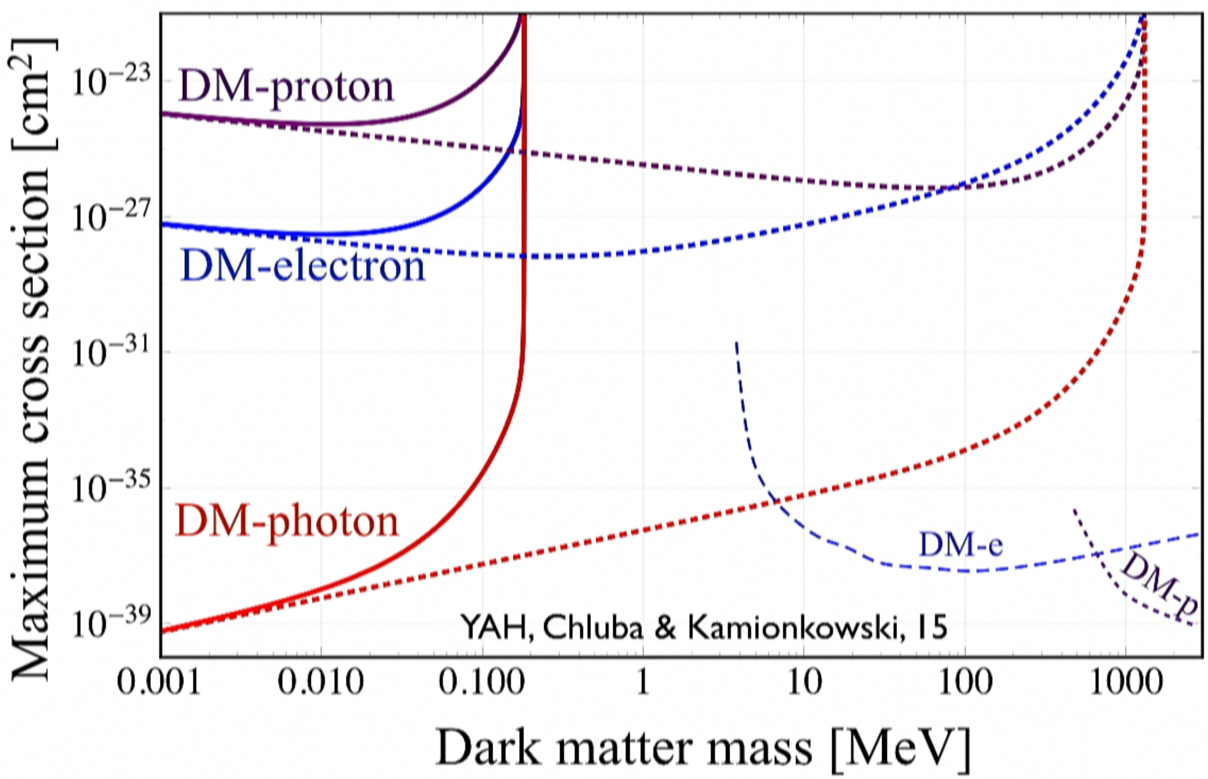
z_{max} = 2e6
otherwise no distortion

$$\frac{\Delta U_{\mathrm{cmb}}}{U_{\mathrm{cmb}}} \approx -\frac{n_{\mathrm{DM}}}{n_\gamma} \log\left(\frac{1+z_{\mathrm{max}}}{1+z_{\mathrm{dec}}}\right)$$

$$n_{\mathrm{DM}} = \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}$$

redshift at which DM and photons thermally decouple depends on σ and m_{DM}

Forecasts for PIXIE [proposed, Kogut et al 2011]
sensitivity $\Delta U/U \sim 10^{-8}$



Fractional energy extracted from CMB

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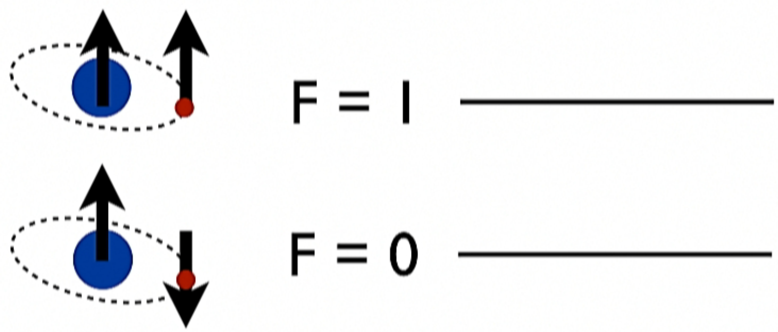
II-B-Detection prospects for DM-baryon interactions from high-redshift 21cm fluctuations

with Muñoz & Kovetz, PRD 2015

$$\sigma_{\chi b} \propto v^{-4}$$

21-cm fluctuations: lightning review

Hyperfine splitting of ground state of neutral hydrogen

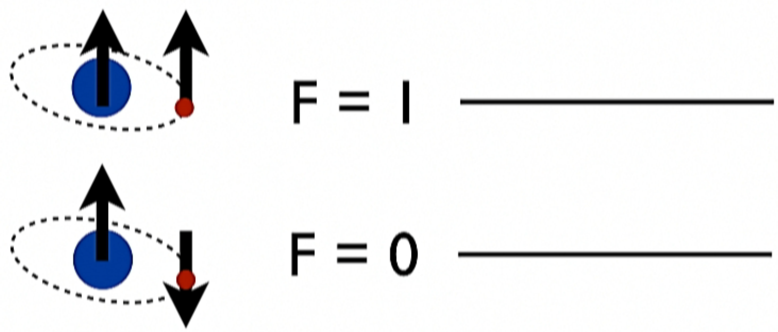


$E_{10} = 6\ \mu eV$

$\lambda_{10} = 21.1cm$

21-cm fluctuations: lightning review

Hyperfine splitting of ground state of neutral hydrogen



$E_{10} = 6\ \mu eV$

$\lambda_{10} = 21.1\text{cm}$

$z \lesssim 200$

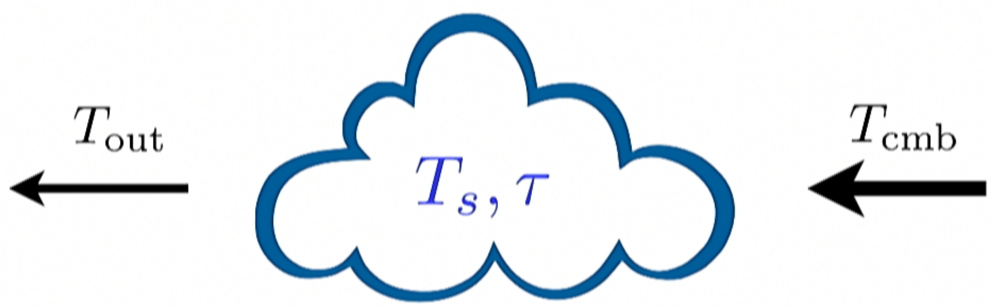
Spin temperature:

$$\frac{n_1}{3n_0} \equiv \exp\left[-\frac{E_{10}}{T_s}\right]$$

$$T_{\text{gas}} < T_s < T_{\text{cmb}}$$

collisions ← - - - - - - - - - - → radiative transitions

21-cm fluctuations: lightning review



$$T_b \equiv T_{\rm out} - T_{\rm cmb} = \tau(T_s - T_{\rm cmb})$$

Effect of DM-baryon collisions

- Heat exchange modifies gas hence spin temperature [Tashiro et al. 2014]

$$\dot{T}_b + 2\mathcal{H}T_b = \Gamma_\gamma(T_\gamma - T_b) + \Gamma_{\chi b}(T_\chi - T_b)$$

$$\dot{T}_\chi + 2\mathcal{H}T_\chi = (n_b/n_\chi)\Gamma_{\chi b}(T_b - T_\chi)$$

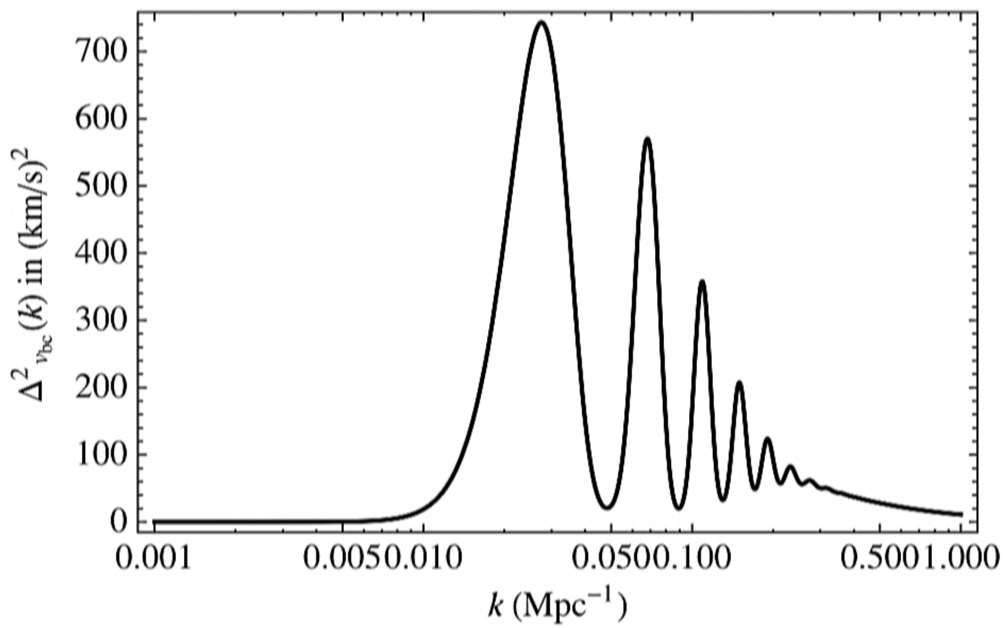
- **Bulk flows** are dissipated into heat:

$$\frac{1}{2}\frac{\rho_\chi \rho_b}{\rho_m} v_{\chi b}^2 + \frac{3}{2} n_\chi T_\chi + \frac{3}{2} n_b T_b = \text{constant}$$

$$\dot{T}_b + 2\mathcal{H}T_b = \Gamma_\gamma(T_\gamma - T_b) + \Gamma_{\chi b}(v_{\chi b}^2) \times [T_\chi - T_b] + F(v_{\chi b}^2)$$

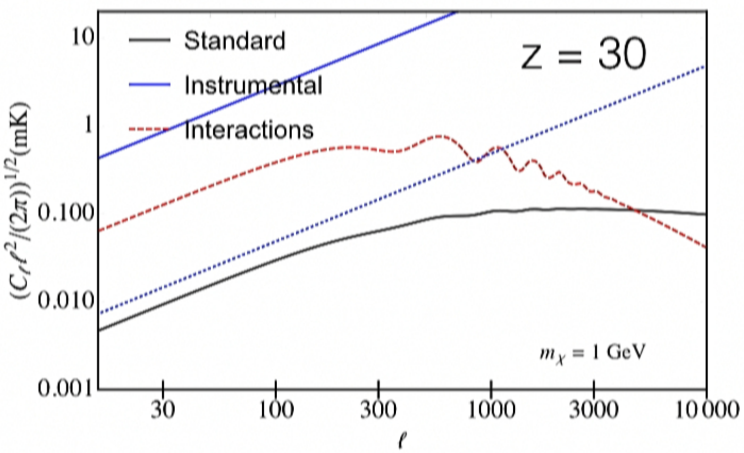
$v_{\chi b}$: local baryon-DM relative velocity

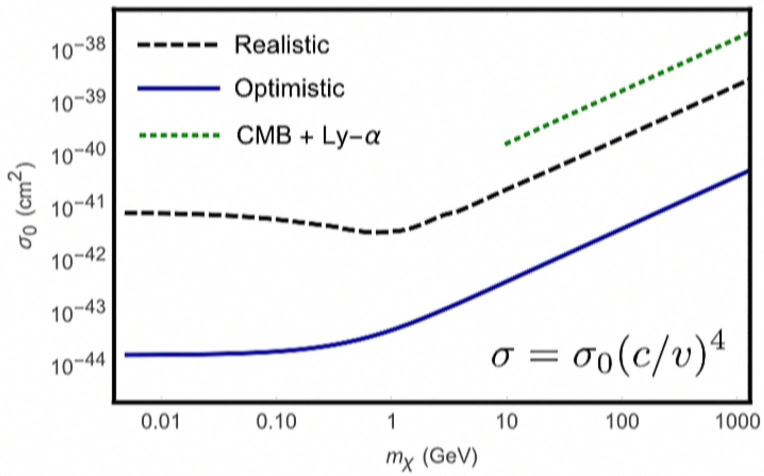
DM and baryons have large-scale relative velocities [e.g. Tseliakhovich & Hirata 2010]



see YAH et al. 2014 for effect of relative velocities on standard 21cm signal, without DM-baryon scattering

⇒The 21-cm signal gets modulated on large scales by relative velocity fluctuations





Realistic: SKA-like: 6-km baseline, 2% cover fraction
Optimistic: 50-km baseline, 10% cover fraction

Take-home message: future 21-cm surveys will improve on CMB anisotropy limits by 1-2 oom

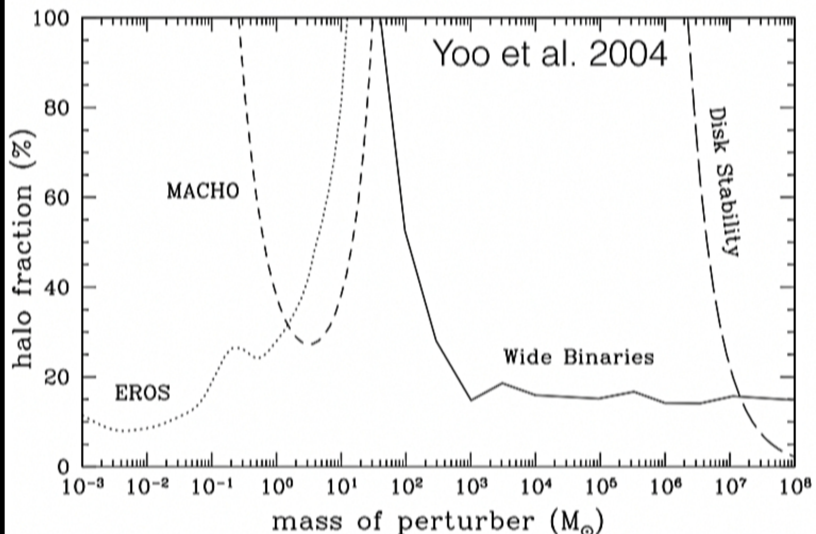
IV-Did LIGO detect dark matter?

Bird, Cholis, Muñoz, YAH, Kamionkowski, Kovetz, Raccanelli & Riess (PRL 2016)

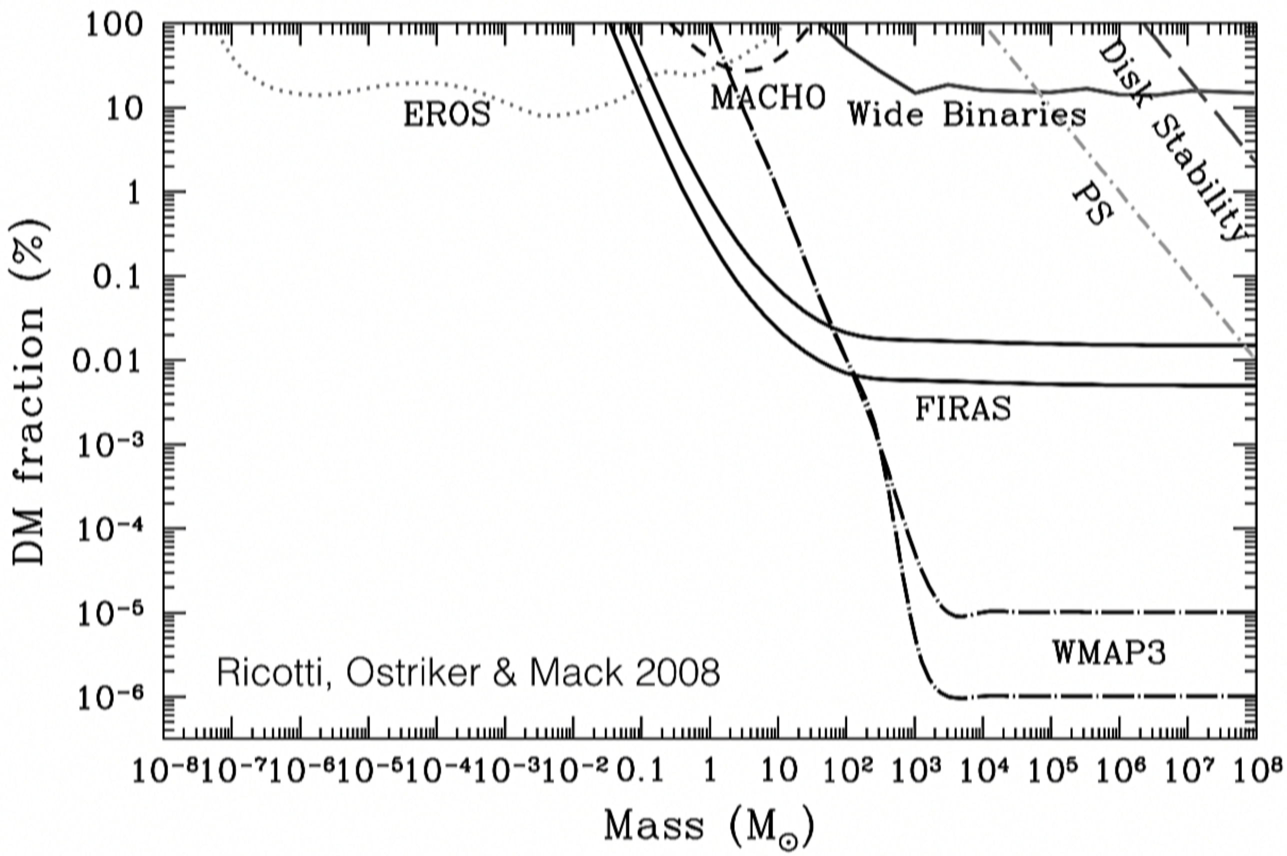
+ work in prep.

Motivations

- Primordial black holes (PBHs) are a dark matter candidate [e.g. Carr et al 2010]
- There is a window where they are not excluded by microlensing and wide binary constraints



CMB Limits on PBH abundance



Ingredients

- PBHs accrete gas. Bondi-Hoyle accretion rate

$$\dot{M} \approx 4\pi \rho_b \frac{(GM_\bullet)^2}{(c_s^2 + v^2)^{3/2}}$$

- A fraction of the accreted mass is re-radiated:

$$L = \min[\epsilon \dot{M} c^2, L_{\rm Edd}]$$

- A fraction of this energy is deposited in the plasma as heat and ionizations

$$\frac{dE}{dtdV} \sim f_{\rm pbh} \frac{\rho_{\rm cdm}}{M_\bullet} L$$

Ingredients

- Heating leads to distortions of the CMB spectrum:

$$\frac{\Delta I_\nu}{I_\nu} \sim \int dt \frac{1}{\rho_{\rm cmb}} \frac{dE}{dtdV}$$

- Ionizations affect the recombination history:

$$\Delta \dot{x}_e \sim \frac{1}{n_b E_{\rm I}} \frac{dE}{dtdV}$$

In progress: revisiting CMB limits

- There seems to be a numerical error in CMB spectrum bounds
- Baryon-CDM relative velocity largely under-estimated, leading to significant over-estimate of accretion rate $\sim 1/v^3$.
- Expect bound to significantly loosen. Work in progress.

In progress: revisiting CMB limits

- There seems to be a numerical error in CMB spectrum bounds
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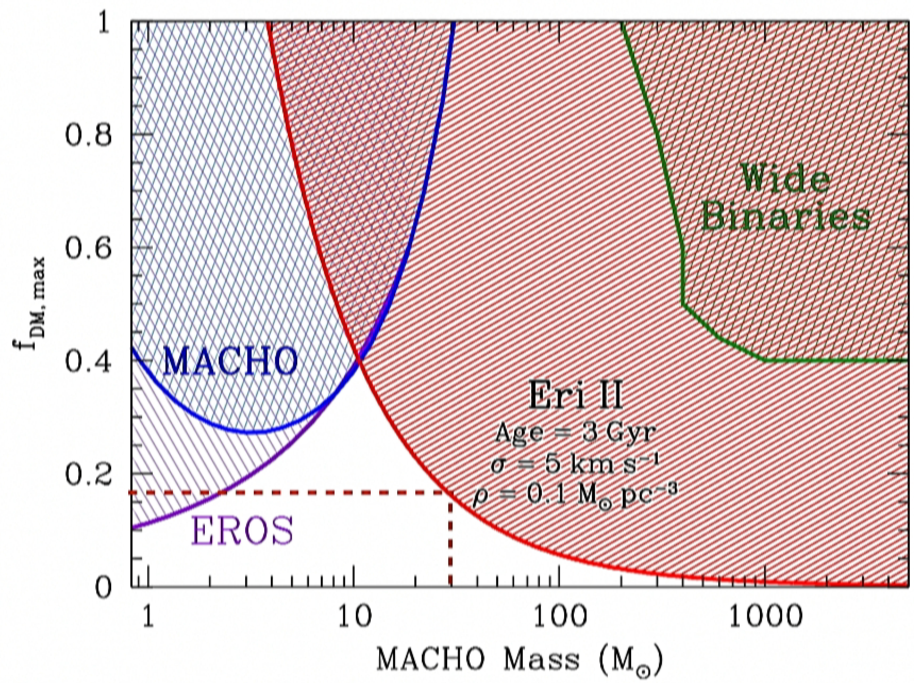
- Expect bound to significantly loosen. Work in progress.
- Future work: quantify impact of astrophysical uncertainties on the bounds.

Other recent limit

Brandt, 2016

MACHO dark matter would heat up the star cluster in Eridanus II.



GWs from PBHs: Basic idea

Bird et al. 2016

- If 2 PBHs pass close by, they may lose enough energy through GW emission to become bound.
- Cross section: $\sigma(v) \approx 45\ M_\bullet^2\ v^{-18/7}$
- This is a lower bound on the rate of capture: there are also 3-body captures, neglected here.

— work in preparation —

- At the smallest scales (dominating the rate), Poisson fluctuations dominate

$$\sigma(M_{\rm h}, a) \approx \frac{3}{2}\left(\frac{a}{a_{\rm eq}}\right)\sqrt{M_\bullet/M_{\rm h}}$$

(e.g. Afshordi, McDonald & Spergel 2003)

- Collapse time: $\sigma(M_{\rm h}, a_{\rm coll}) \approx 1.69$

- For simplicity I will assume $\rho_{\rm h} \approx 200\ \overline{\rho}_{\rm dm}(a_{\rm coll})$

- Very dense haloes quickly evaporate (cf Binney & Tremaine)

$$t_{\rm evap} \approx \frac{14N}{\log(N)} \left(\frac{4\pi\rho_{\rm h}}{3}\right)^{-1/2}$$

$$\approx 0.5\ H_0^{-1} \left(\frac{M_{\rm h}}{10^3 M_\bullet}\right)^{7/4} \frac{\log(10^3)}{\log(M_{\rm h}/M_\bullet)}$$

- So haloes containing <~ 10^3 PBHs evaporate in Hubble time

  (see also Afshordi, McDonald & Spergel 2003)

- For the lowest-mass haloes, merger rate per halo:

$$\Gamma \approx 10^{-13}\ \mathrm{yr}^{-1} \left(\frac{M_\bullet}{30 M_\odot}\right)^{10/21} \left(\frac{M_\mathrm{h}}{10^3 M_\bullet}\right)^{-53/84}.$$

- Press-Schechter halo mass function:

$$\frac{dn_\mathrm{h}}{d\log(M_\mathrm{h})} \approx 0.5 \times 10^{13}\ \mathrm{Gpc}^{-3}\ \frac{30 M_\odot}{M_\bullet} \left(\frac{M_\mathrm{h}}{10^3 M_\bullet}\right)^{-1/2}$$

- Final result:

$$\frac{d\Gamma_{\rm pbh}}{dV} \approx 0.5\ {\rm Gpc}^{-3}{\rm yr}^{-1} \left(\frac{M_\bullet}{30M_\odot}\right)^{-11/21}$$

- Broadly consistent with LIGO's estimated rate

$$\frac{d\Gamma_{\rm LIGO}}{dV} \approx 2 - 53\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

- An interesting observable, to quantify in more detail…

Fan mail…

from M., 63, in Prescott, AZ

“I'M SO HAPPY!! PRIMORDIAL BLACK HOLES = BLACK MATTER/BLACK ENERGY”

Recap

- Massive neutrinos as a hot dark matter. Future work: understand better non-linear clustering of neutrinos.
- Spectral distortions can probe DM-SM interactions. In general, a window into the pre-recombination Universe.
- 21-cm fluctuations can probe DM-baryon scattering. In general, high-z 21cm fluctuations will be the ultimate cosmological probe.
- If the DM is made of ~30 $M_{\rm sun}$ PBHs, the merger rate is broadly consistent with LIGO results. Future work: revisit CMB limits and quantify uncertainties.

Thanks!