Neutrinos and Dark Radiation from Large-scale Structure

Marilena Loverde (University of Washington)

Dark Universe Science Center (DUSC) @ University of Washington, Seattle

Tom Quinn

Matt McQuinn

Masha Baryakhtar

Isabel García-García

Bryna Hazelton

me

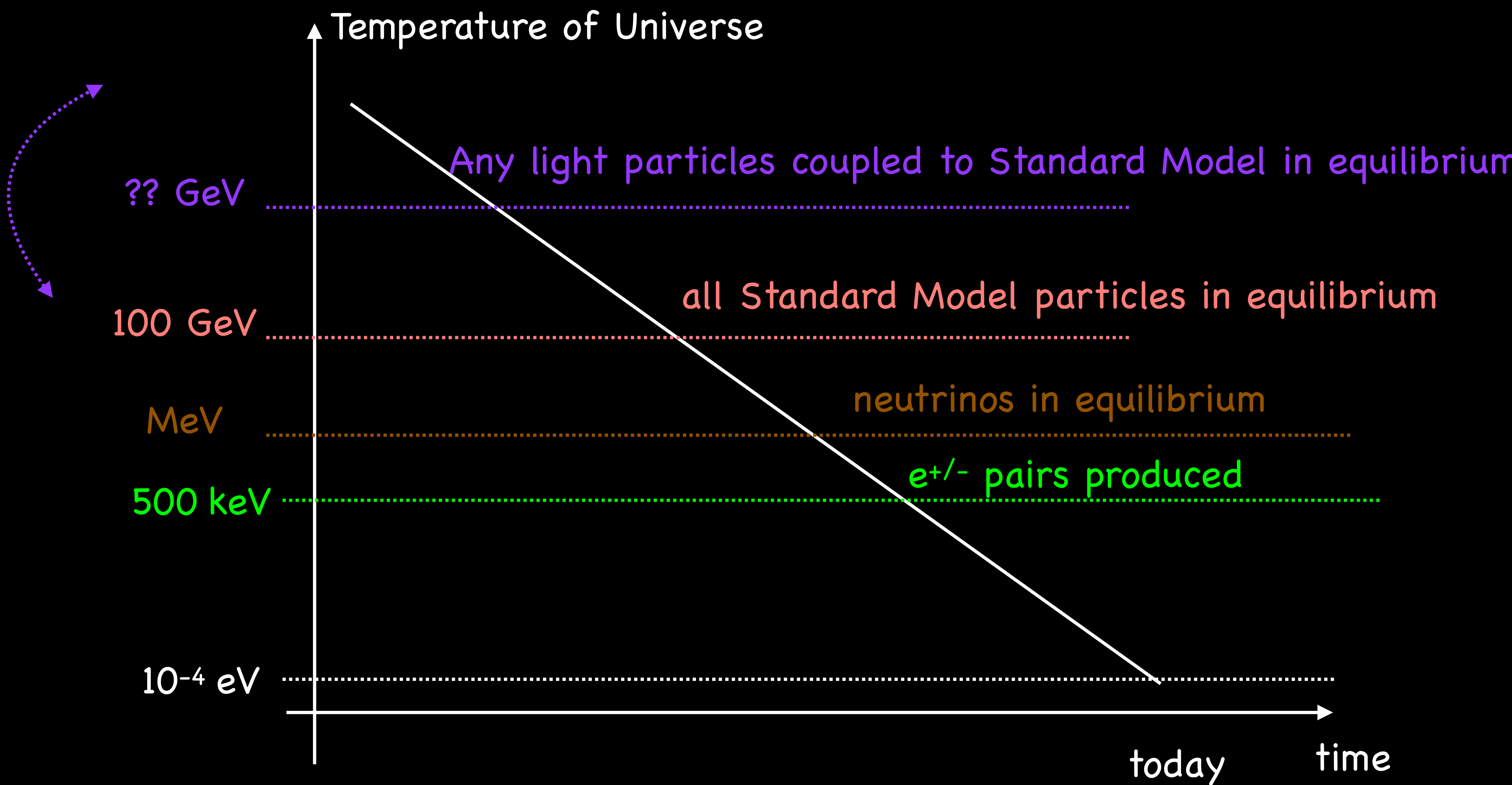
not pictured:
Miguel Morales

- many experimental groups: DAMIC, ADMX, Project 8, . . .
- Institute for Nuclear Theory
- new hires in formal theory: Natalie Paquette, Joaquin Turiaci, . . .

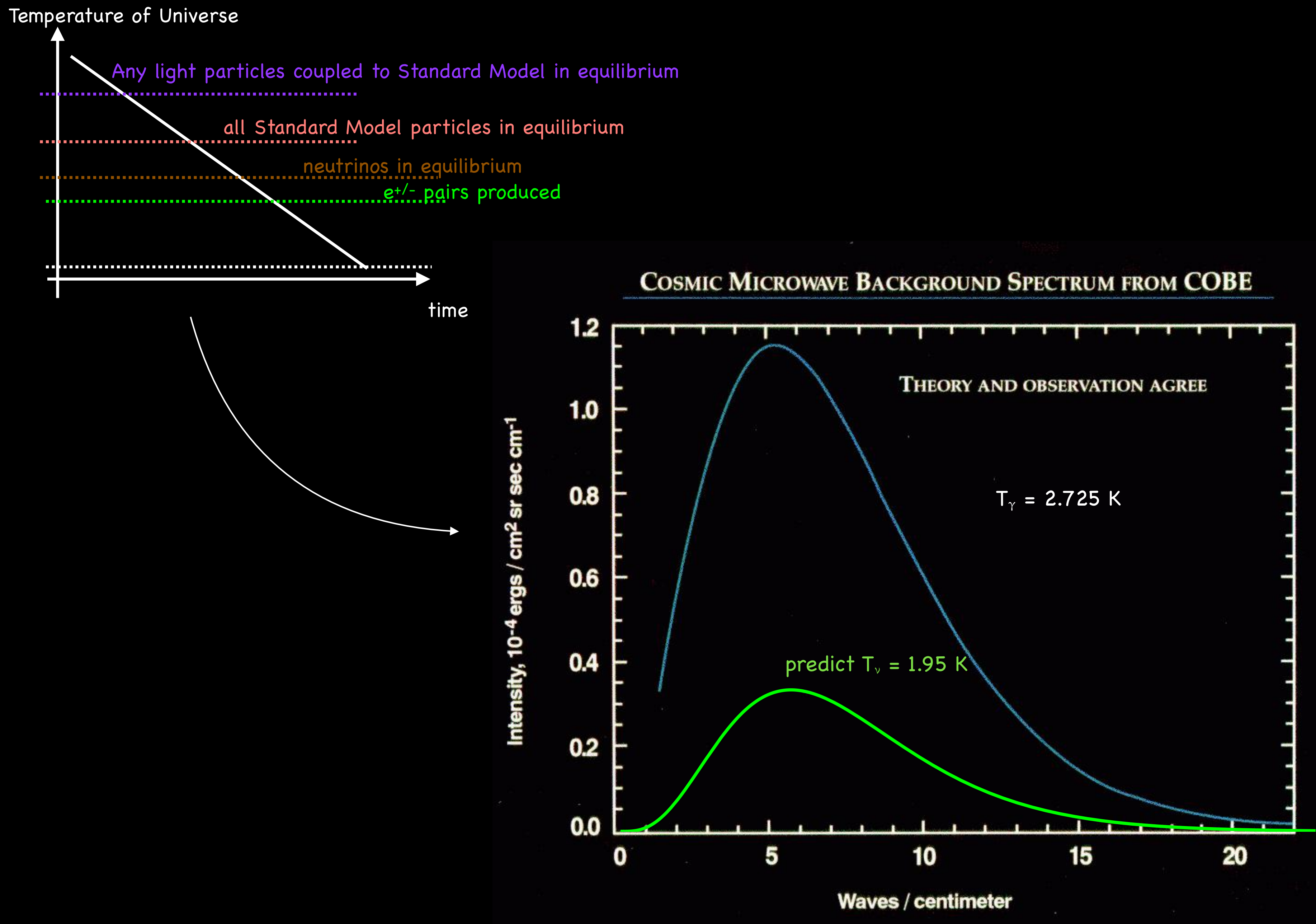
Outline

- Intro to neutrinos and dark radiation
- Signatures in the matter power spectrum
- Signatures in halo bias
- Wakes and higher order statistics

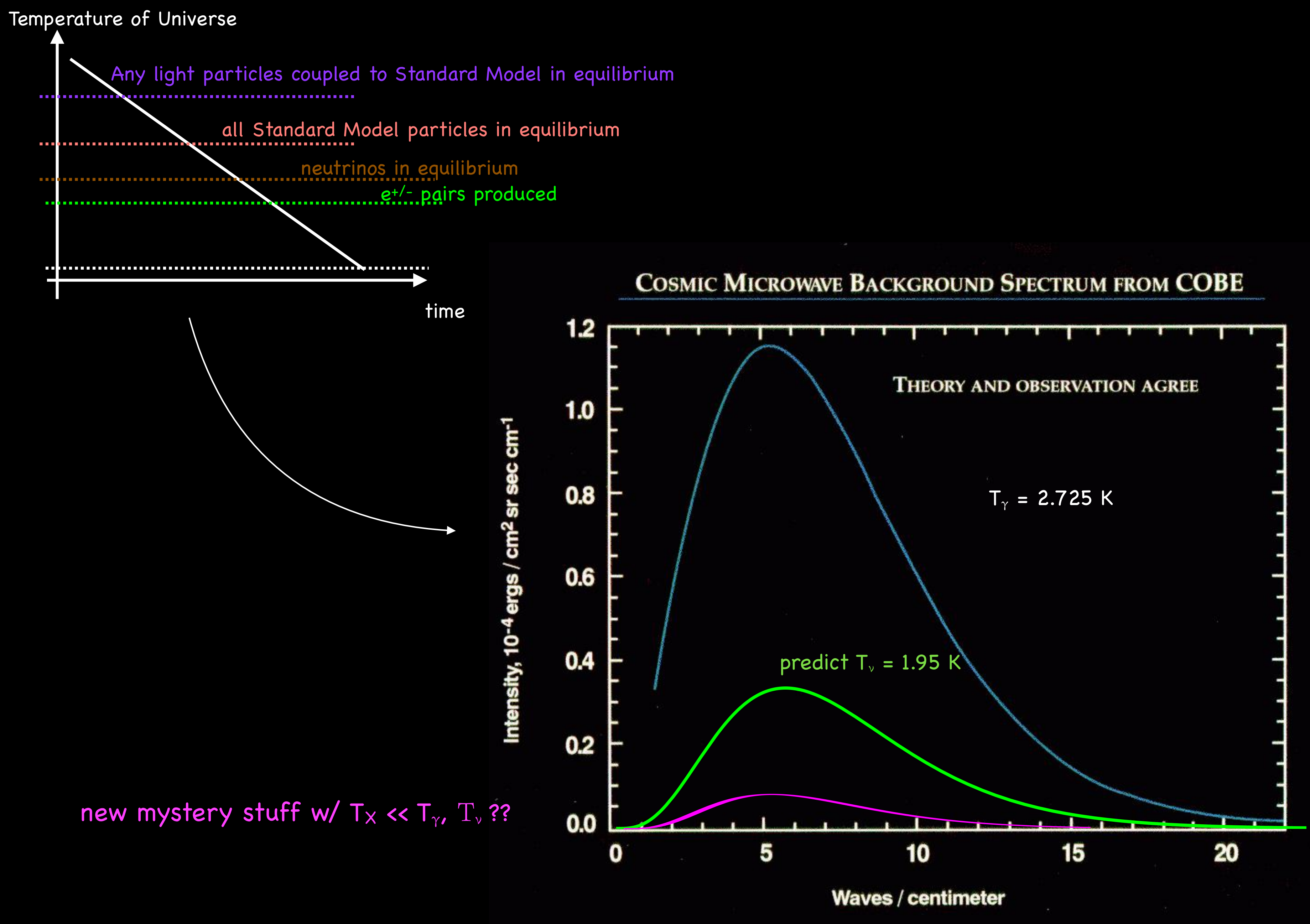
Neutrinos and Dark Radiation



Neutrinos and Dark Radiation



Neutrinos and Dark Radiation



Neutrinos and Dark Radiation

$$N_{eff} = \left(\frac{11}{4}\right)^{4/3} \frac{8}{7} \frac{\rho_{radiation,\ total} - \rho_\gamma}{\rho_\gamma}$$

$$\Delta N_{eff} = N_{eff} - 3.044$$

3.044 = standard model prediction

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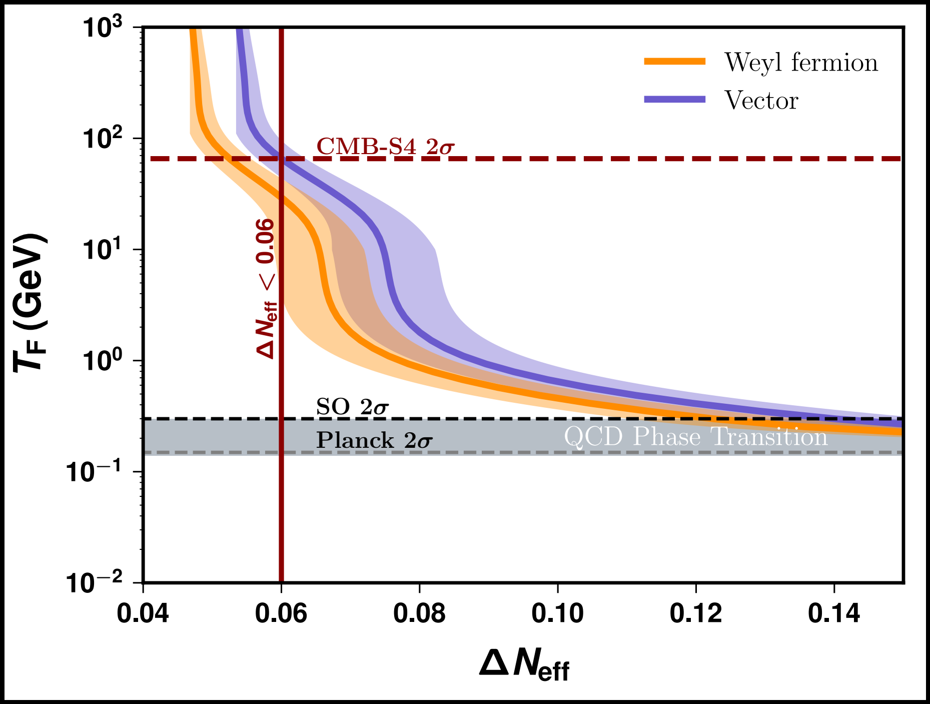
ΔN_{eff} doesn't have to be thermal, but if it is, firm prediction for value from $T_{freeze\text{-}out}$



Neutrinos and Dark Radiation

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$$H^2_{rad\text{-}dom} = \frac{8\pi G}{3} \rho_{rad}$$

3.044 = standard model prediction

->time and distance scales during rad domination probe N_{eff}

Neutrinos and Dark Radiation

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->time and distance scales during rad domination probe N_{eff}

Neutrinos have mass, new dark stuff may too

For a non-interacting species $T \propto 1/a$. Once $T_\nu \ll m_\nu$ $\rho_\nu = \Sigma\, m_\nu\, n_\nu$ and $\rho_\nu \propto 1/a^3$

ρ_ν evolution affects $H(a)$

but free-streaming makes $\delta\rho_\nu \to 0$ for modes with $k \gtrsim v_\nu aH$

-> evolution of $\delta\rho_c$ affected by $\delta\rho_\nu$, growth rate of $\delta\rho_c$ depends on k

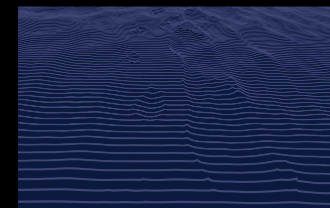
Neutrinos and Dark Radiation

ΔN_{eff} could be:

axions

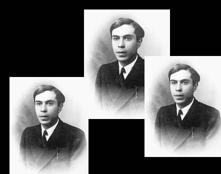
sterile neutrinos?

gravitational waves?



dark gauge bosons?

majorans?



new light fermions?

anything relativistic at CMB times

contributions to ρ_ν could be:

standard model neutrinos

new dark bosons

axions

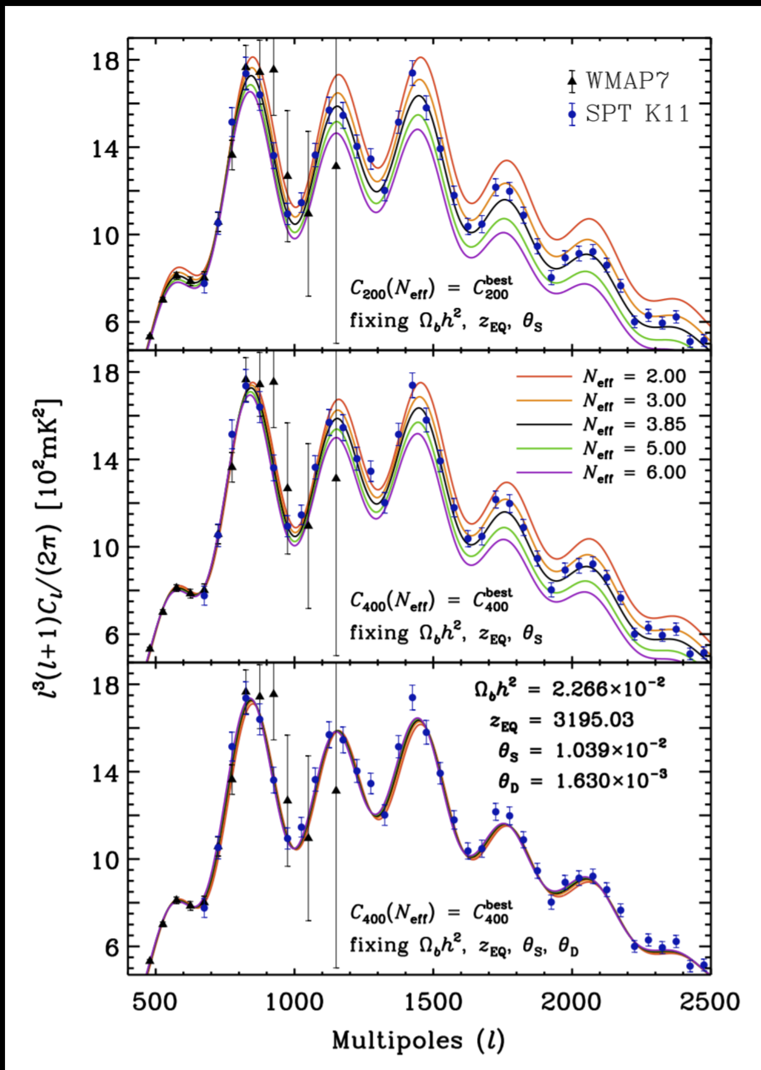
sterile neutrinos

new light fermions

anything cold and smoothly distributed

Probes of relativistic neutrinos and dark radiation

CMB Damping scale



Hou, Keisler, Knox, Millea, Reichardt 2011

$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

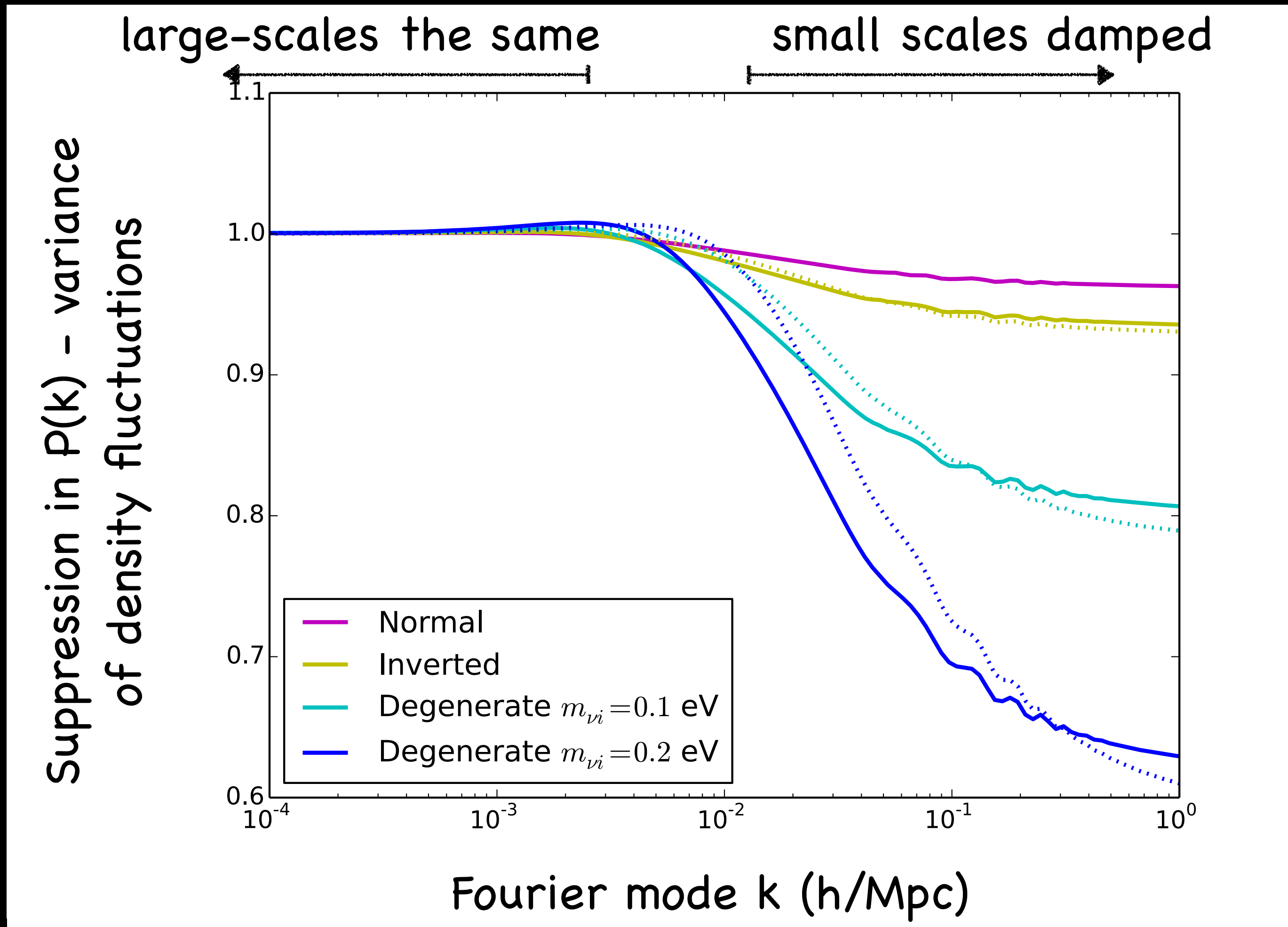
$N_{\rm eff}$

Planck: $N_{\rm eff}$ = 2.99 +/- 0.17

CMB-S4: $\sigma(N_{\rm eff})$ = 0.03

Seljak and Bashinsky 2004

Probes of non-relativistic neutrinos etc



Planck 2018

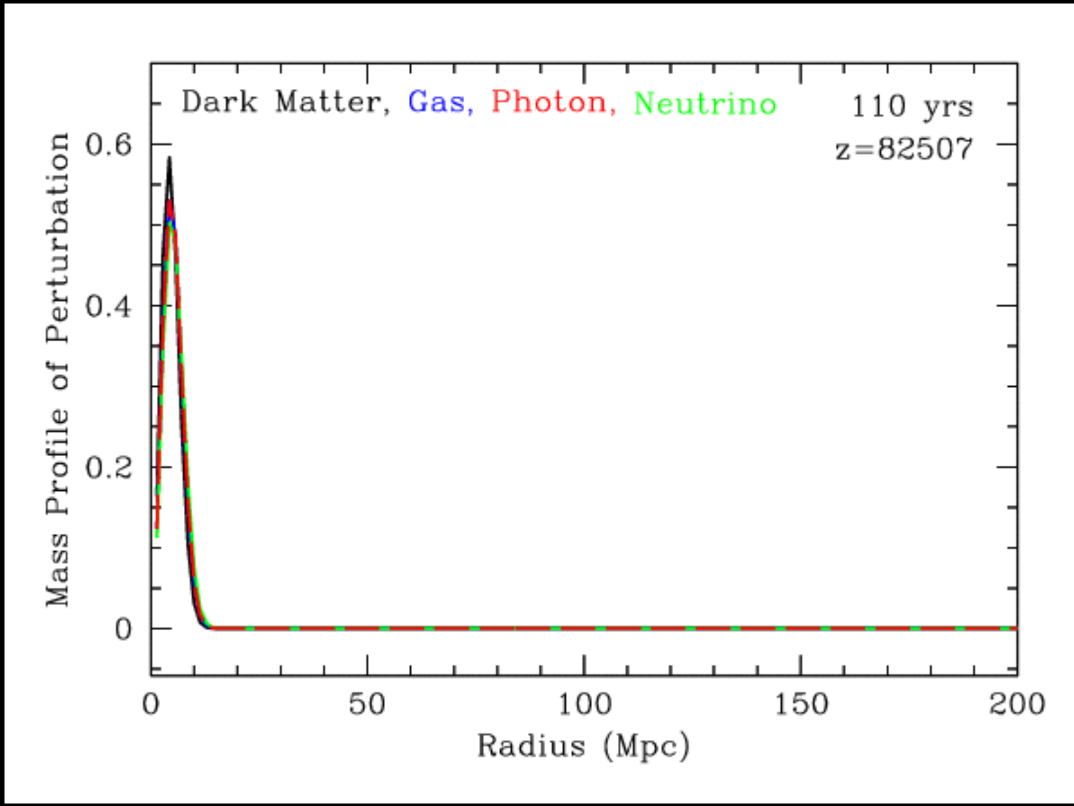
$$\sum m_\nu < 0.24 \text{ eV} \quad (95\,\%, \text{ TT,TE,EE+lowE+lensing}).$$

$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%, \textit{Planck} \text{ TT,TE,EE+lowE+lensing+BAO}).$$

Bond, Efstathiou, Silk 1980
Hu, Eisenstein, Tegmark 1998

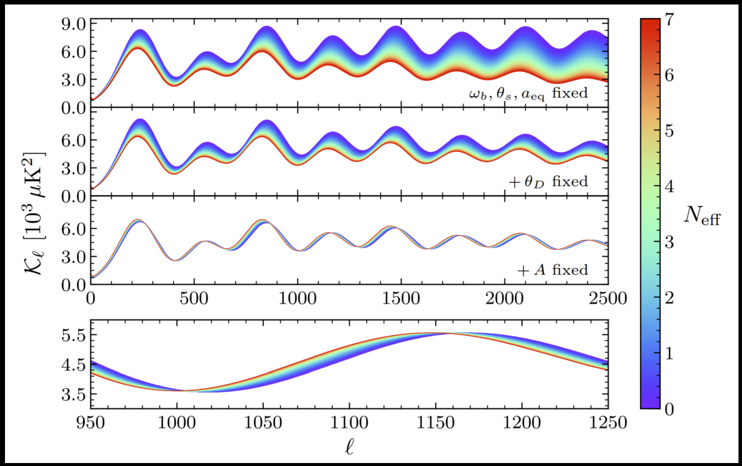
Probes of **free-streaming** neutrinos and dark radiation

Free streaming radiation introduces a phase shift in acoustic oscillations

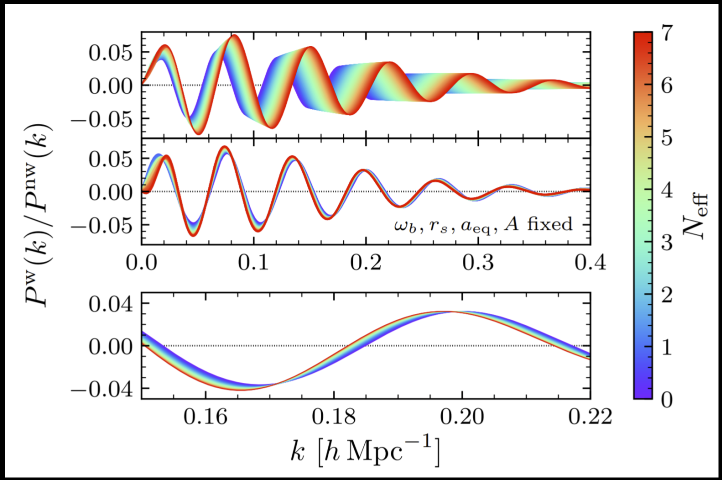


Eisenstein, Seo, White 2007

CMB



BAO



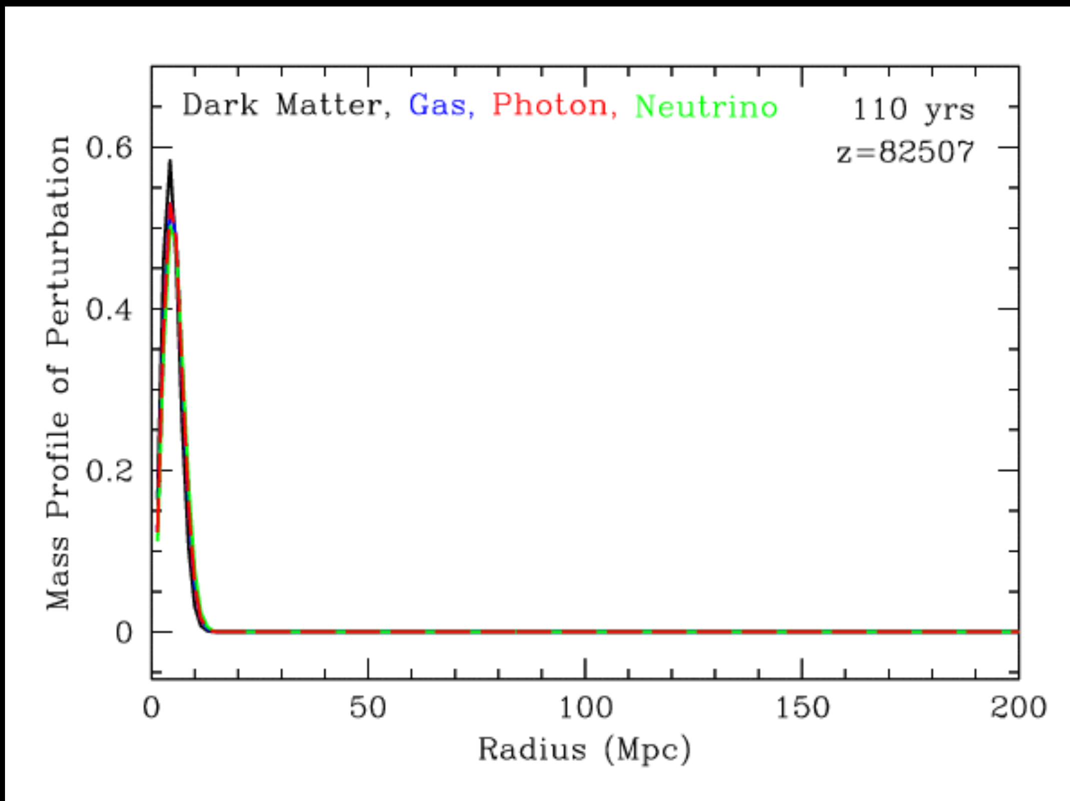
Wallisch 2018

Seljak and Bashinsky 2004 Baumann, Green, Meyers, Wallisch 2016

Probes of **interacting** neutrinos and dark radiation

Free-streaming neutrinos and dark radiation

Free streaming radiation introduces a phase shift in acoustic oscillations



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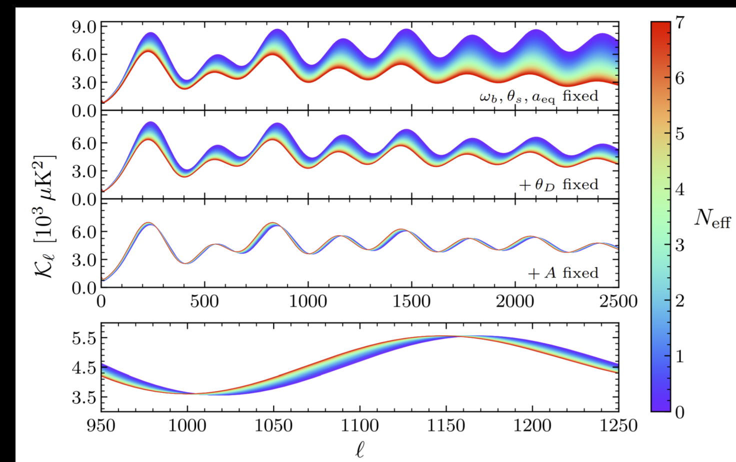
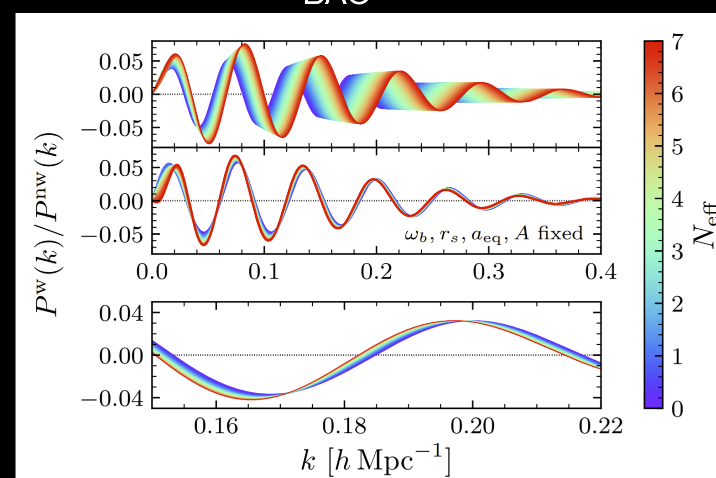


BAO



Wallisch 2018

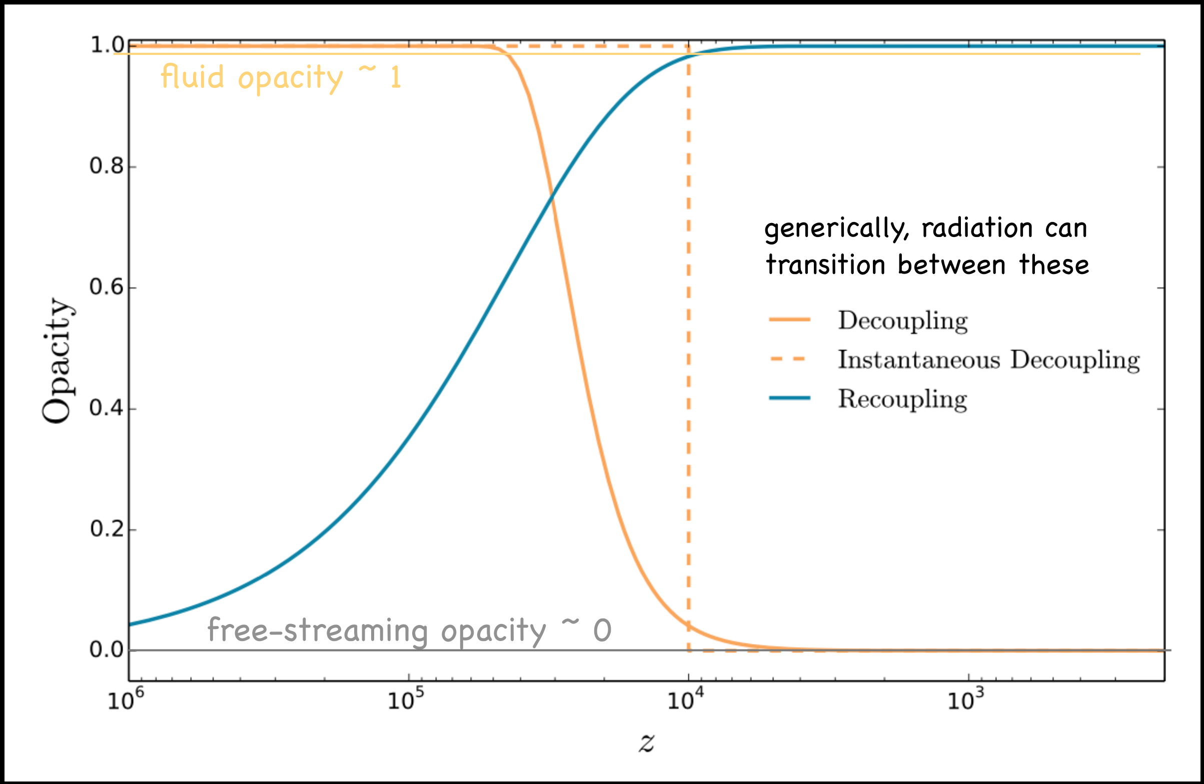
Usual N_{eff} constraints assume free-streaming

Seljak and Bashinsky 2004 Baumann, Green, Meyers, Wallisch 2016

Probes of **interacting** neutrinos and dark radiation

Probes of **interacting** neutrinos and dark radiation

$$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$$



Brinckmann, Chang, Du, ML 2022

Cyr-Racine, Sigurdson 2014; Lancaster, Cyr-Racine, Knox, Pan 2017 + . . .

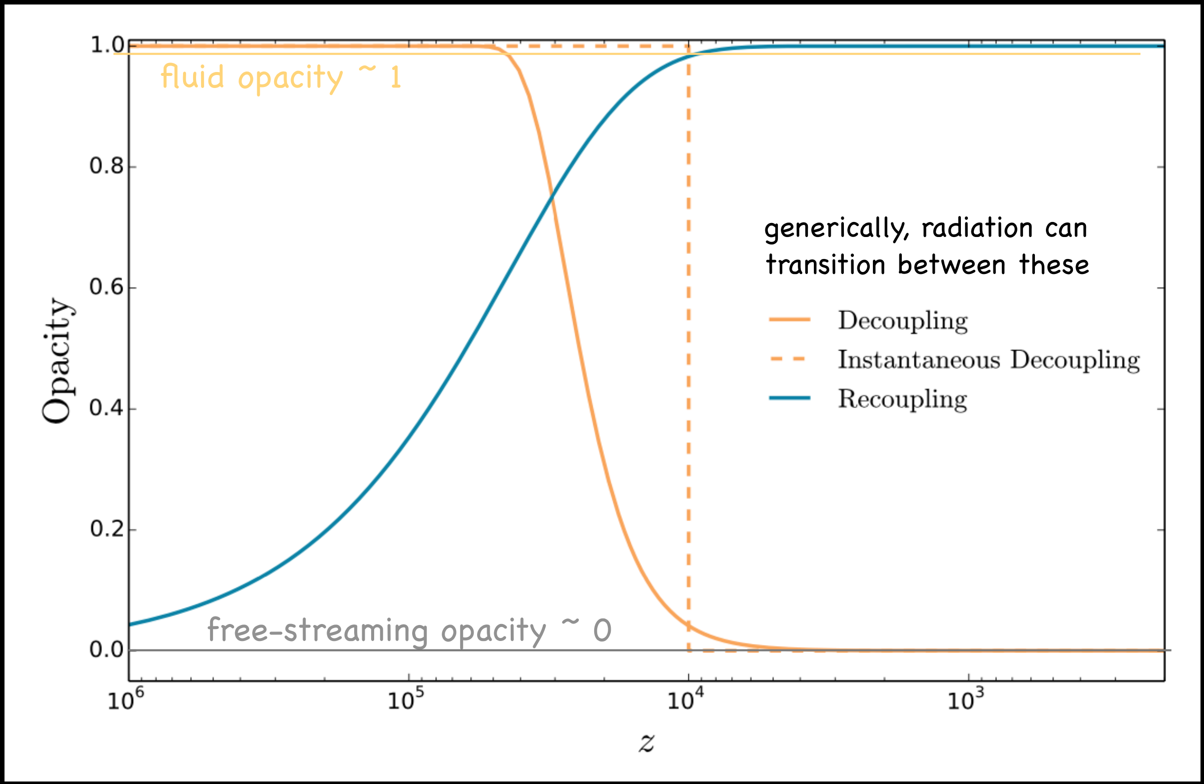
Probes of **interacting** neutrinos and dark radiation

$$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$$

- standard model neutrinos since z ~ 10^9
- gravitational waves
- . . . .

- dark photons scattering off dark atoms
- anything that continues to scatter off itself until z~2000
- . . . .

- dark photons that decouple at z ≳ 2000
- neutrino with new self-interactions
- dark gauge bosons
- majorans that recouple
- . . . .



Brinckmann, Chang, Du, ML 2022

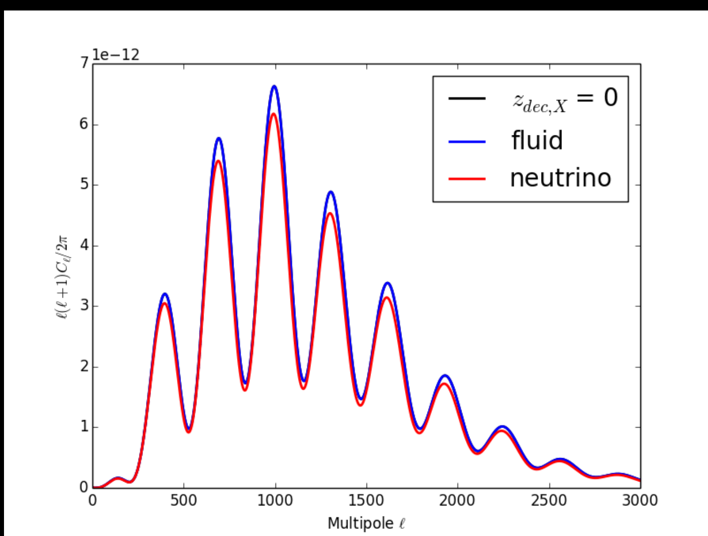
Cyr-Racine, Sigurdson 2014; Lancaster, Cyr-Racine, Knox, Pan 2017 + . . .

Probes of **interacting** neutrinos and dark radiation

$$N_{\mathrm{eff}} = N_{\mathrm{free\text{-}streaming}} + N_{\mathrm{fluid}} + N_{\mathrm{interacting}}$$

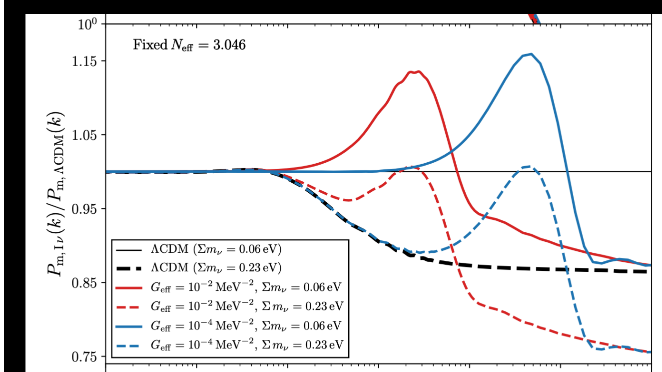
These different constituents leave imprints in many datasets

CMB



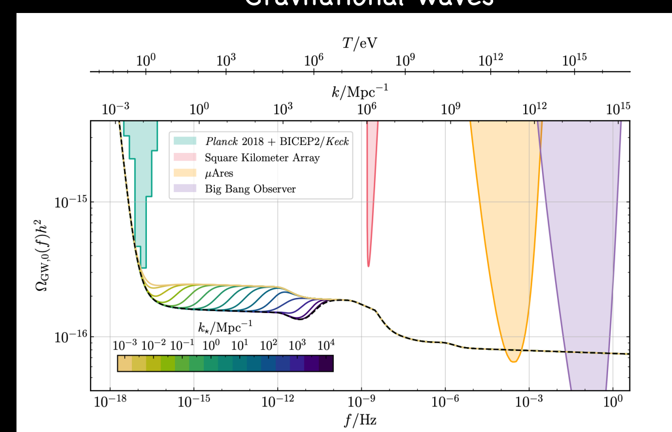
Choi, Chiang, ML 2018

Large-scale structure



Kreisch, Cyr-Racine, Dore 2019

Gravitational waves



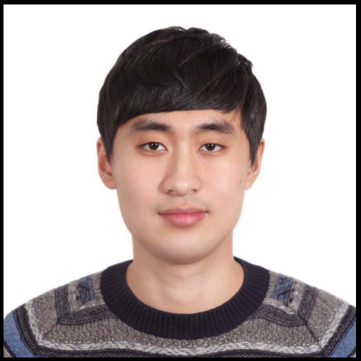
Weiner, ML 2022

Cyr-Racine, Sigurdson 2014; Lancaster, Cyr-Racine, Knox, Pan 2017 + . . .

LSS probes of **interacting** neutrinos and dark radiation

Peizhi Du
(Rutgers)

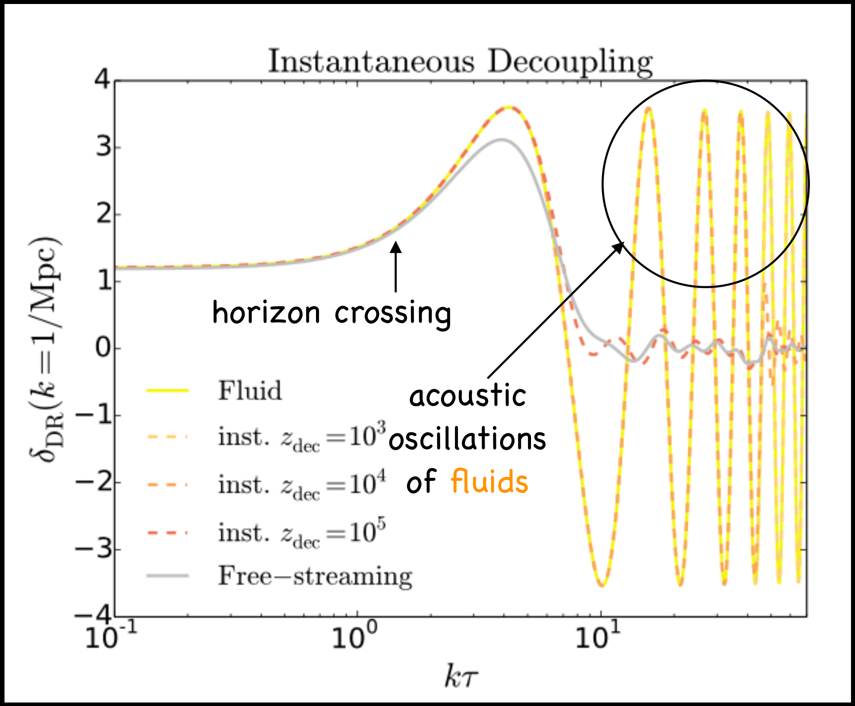
Thejs Brinckmann (University of Ferrara)



Jae-Hyeok Chang
(Fermilab/UIC)

LSS probes of **interacting** neutrinos and dark radiation

Perturbations in different types of dark radiation evolve differently



Brinckmann, Chang, Du, Loverde 2022

LSS probes of **interacting** neutrinos and dark radiation

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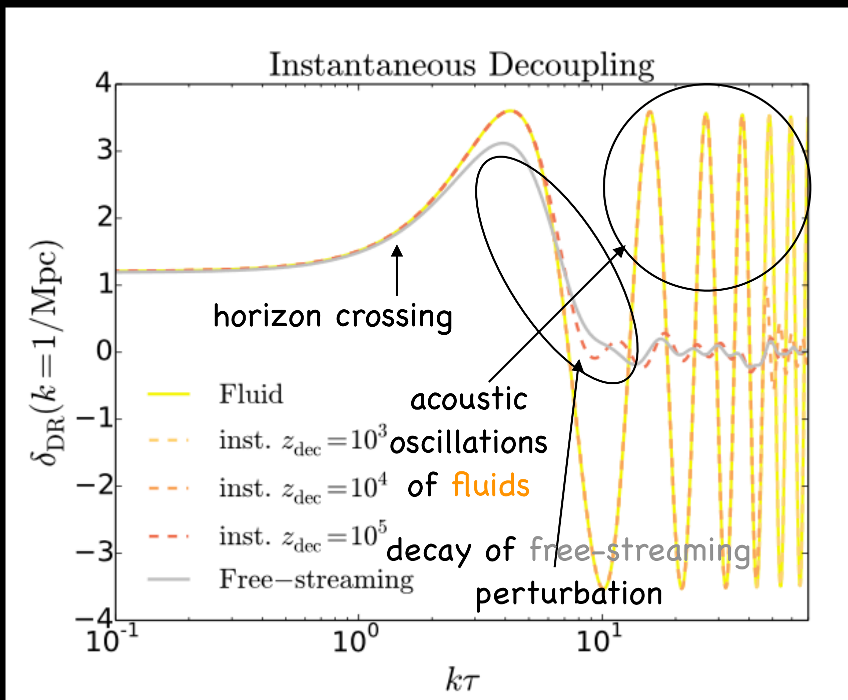

Brinckmann, Chang, Du, Loverde 2022

LSS probes of **interacting** neutrinos and dark radiation

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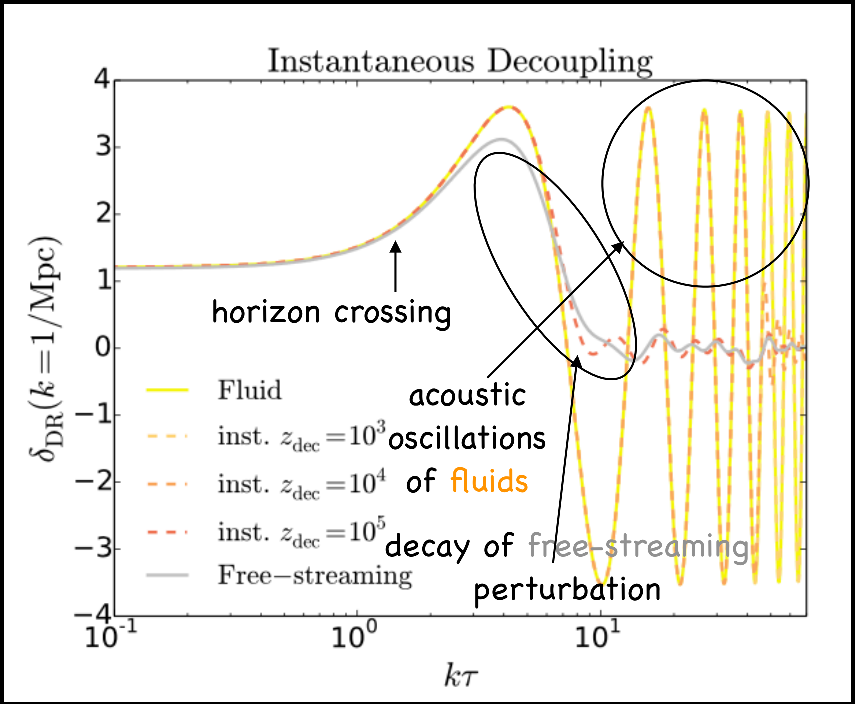
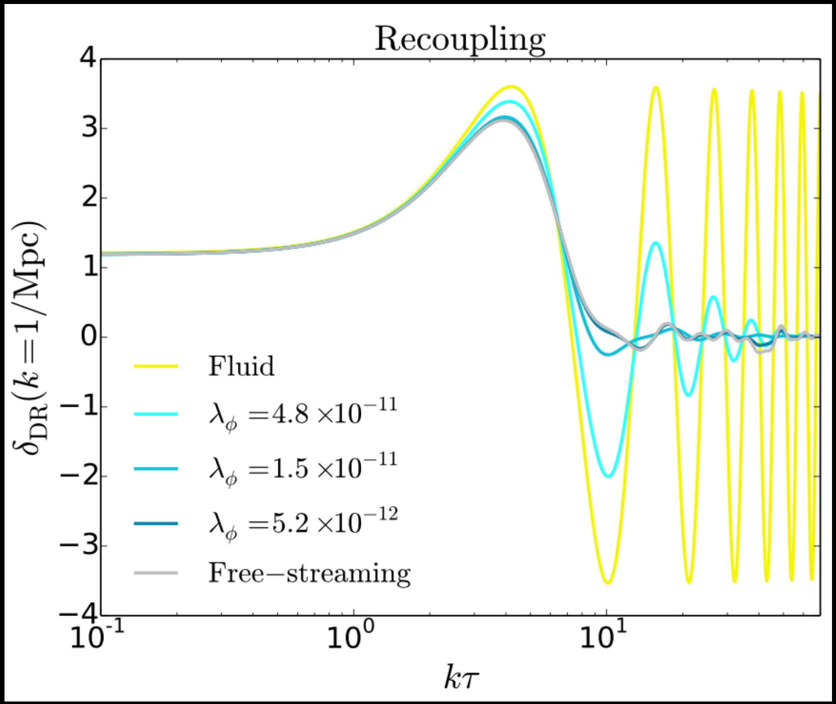


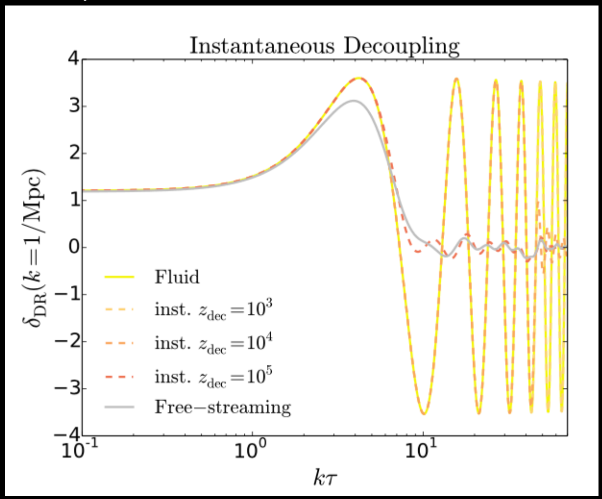


Brinckmann, Chang, Du, Loverde 2022

LSS probes of **interacting** neutrinos and dark radiation

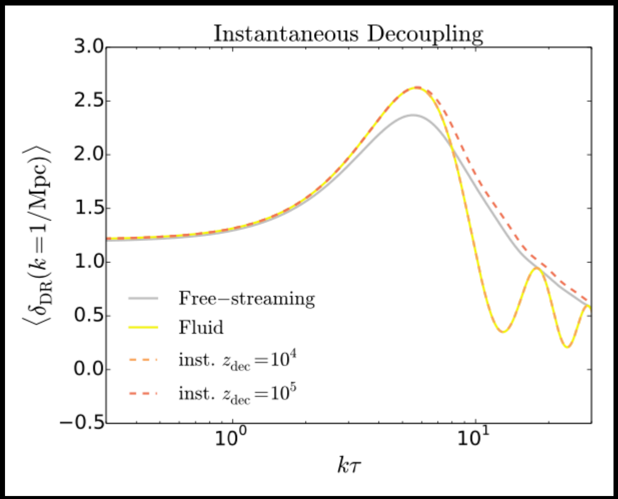
$\delta_{\text{dark radiation}}$ ←gravity→ δ_{cdm}

perturbations in DR



→

time average of δ_{DR}
better captures source to $\nabla^2\,\Phi$

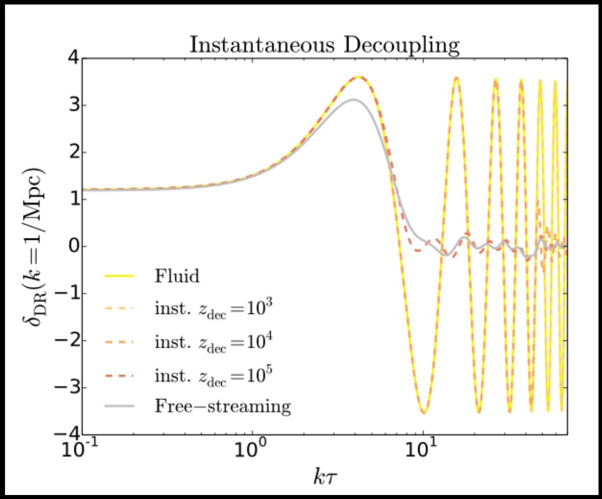


Brinckmann, Chang, Du, Loverde 2022

LSS probes of **interacting** neutrinos and dark radiation

$\delta_{\text{dark radiation}} \xleftrightarrow{\text{gravity}} \delta_{\text{cdm}}$

perturbations in DR



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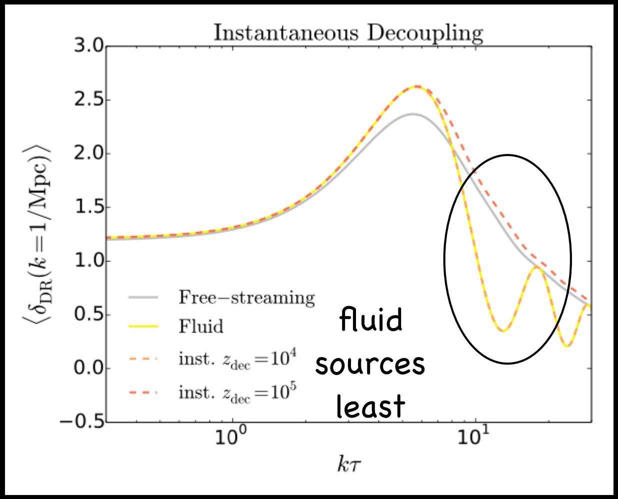

Brinckmann, Chang, Du, Loverde 2022

LSS probes of **interacting** neutrinos and dark radiation

$\delta_{\text{dark radiation}}$ ←— gravity —→ δ_{cdm}

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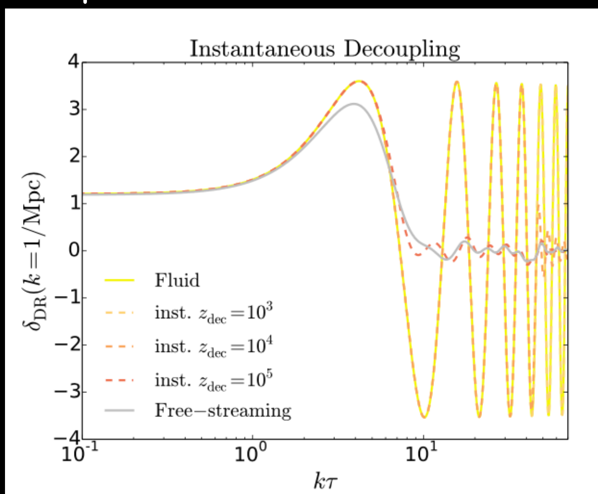

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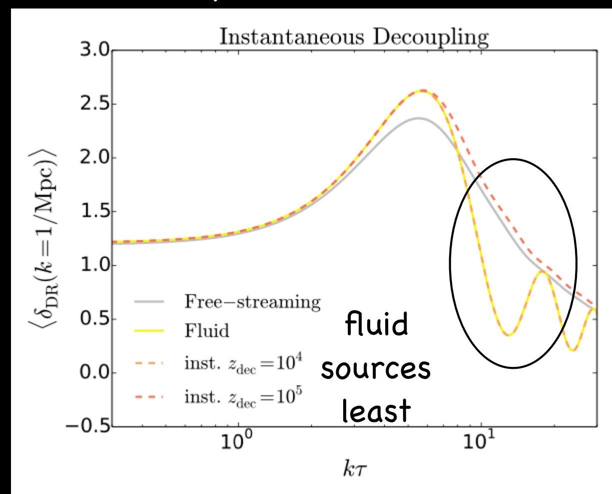
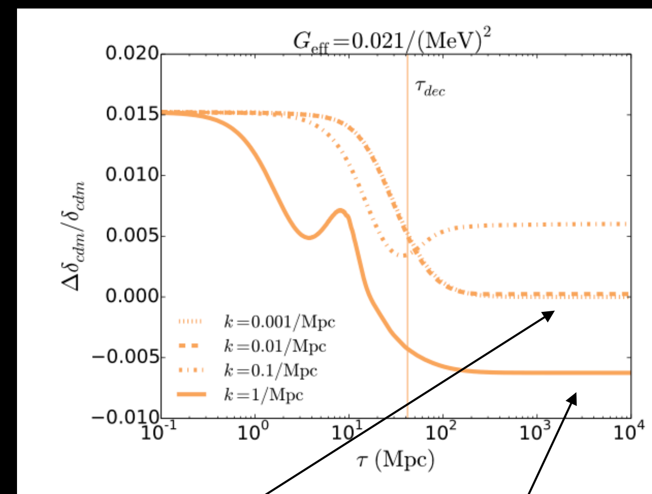


→

change in δ_{cdm} relative to free-streaming



slight bump for mode that decouples just after horizon crossing

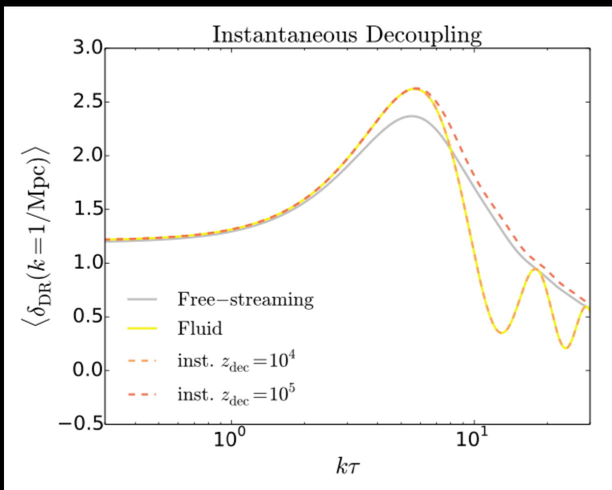
CDM perturbations suppressed in fluid-limit

Brinckmann, Chang, Du, Loverde 2022

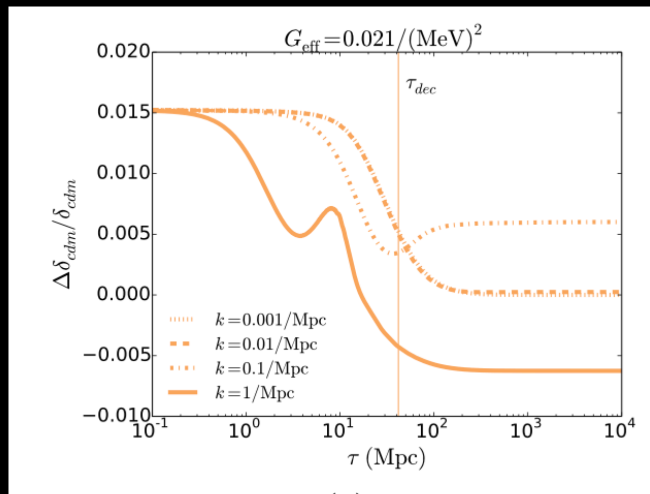
LSS probes of **interacting** neutrinos and dark radiation

$\delta_{\text{dark radiation}}$ ←gravity→ δ_{cdm}

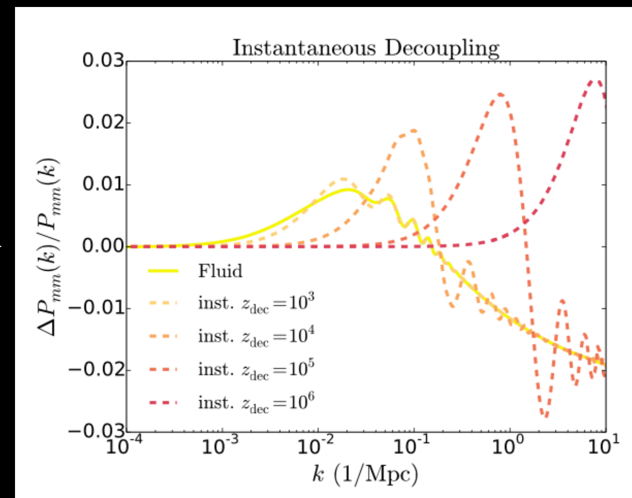
time average of δ_{DR} better captures source to $\nabla^2 \Phi$



change in δ_{cdm} relative to free-streaming



change in P(k) relative to free-streaming



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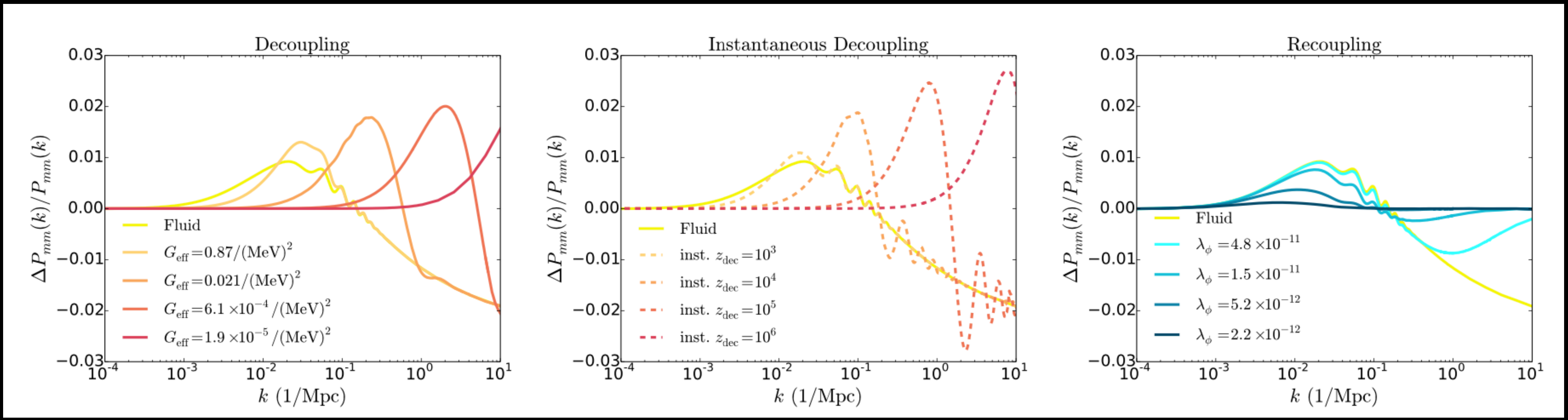
Interacting neutrinos and dark radiation in the matter power spectrum

change in P(k) relative to free-streaming varies with decoupling/recoupling process



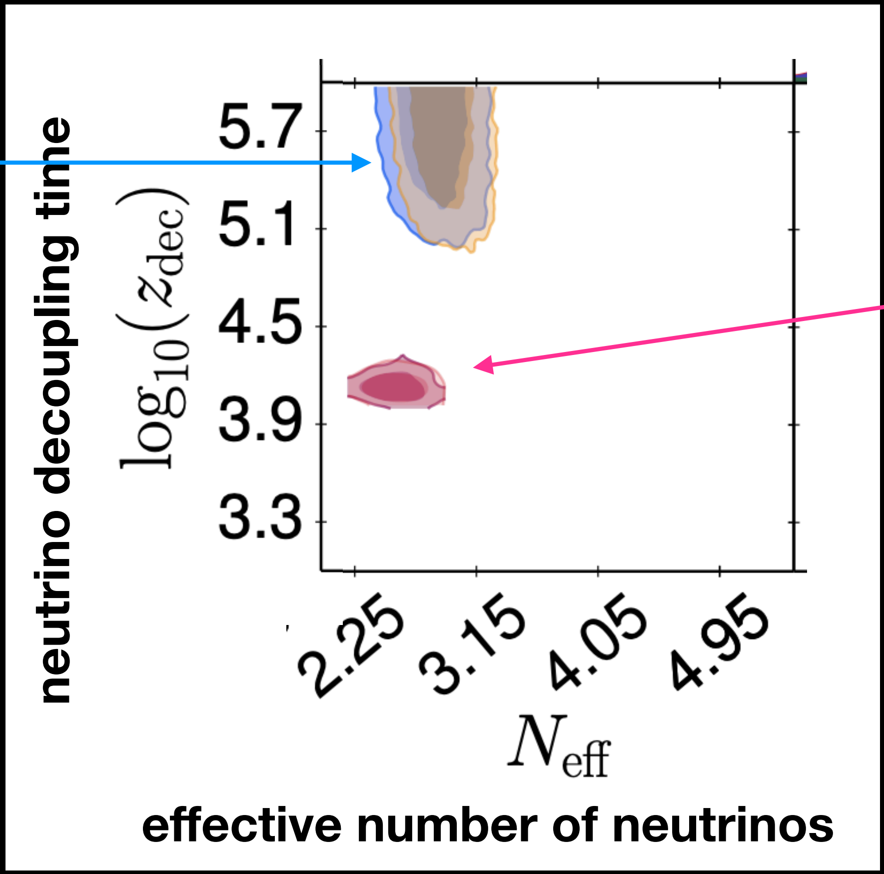
each plot above assumes $N_{\text{free-streaming}}$ = 3.044 , $N_{\text{interacting}}$ = 0.5

Brinckmann, Chang, Du, Loverde 2022

Constraints on new neutrino interactions

Planck 2018 TT, TE, EE, low -E, lensing + BAO

Allows neutrino interactions as late as z~10⁵, t~ 50 years, w/ no change in values of other cosmological parameters



Also permits a second mode w/neutrinos interacting until z~10⁴, t~ 4000 years and different values of other cosmological parameters!

(this second mode disappears when H0 data added)

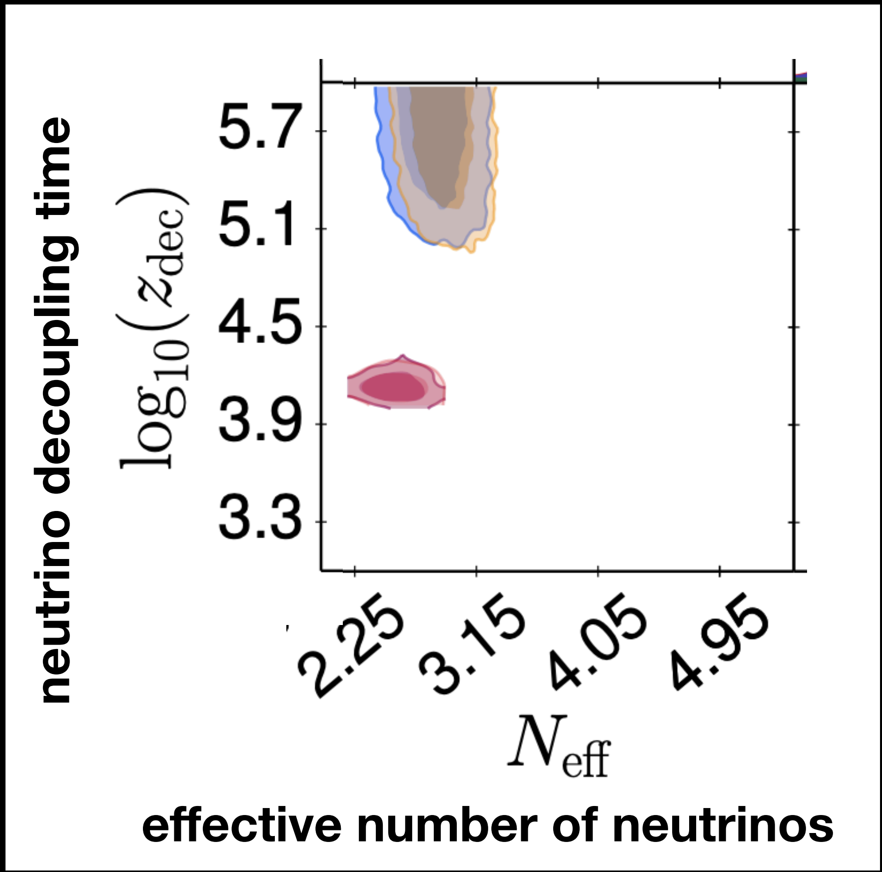
(standard neutrinos decouple at z ~10⁹, t ~ 1s)

also many papers by Francis-Yan!

Brinckmann, Chang, ML 2020

Constraints on new neutrino interactions

Planck 2018 TT, TE, EE, low -E, lensing + BAO



Full shape P(k) analyses: He, An, **Ivanov**, Gluscevic 2023; Camarena, **Cyr-Racine**, Houghteling 2023

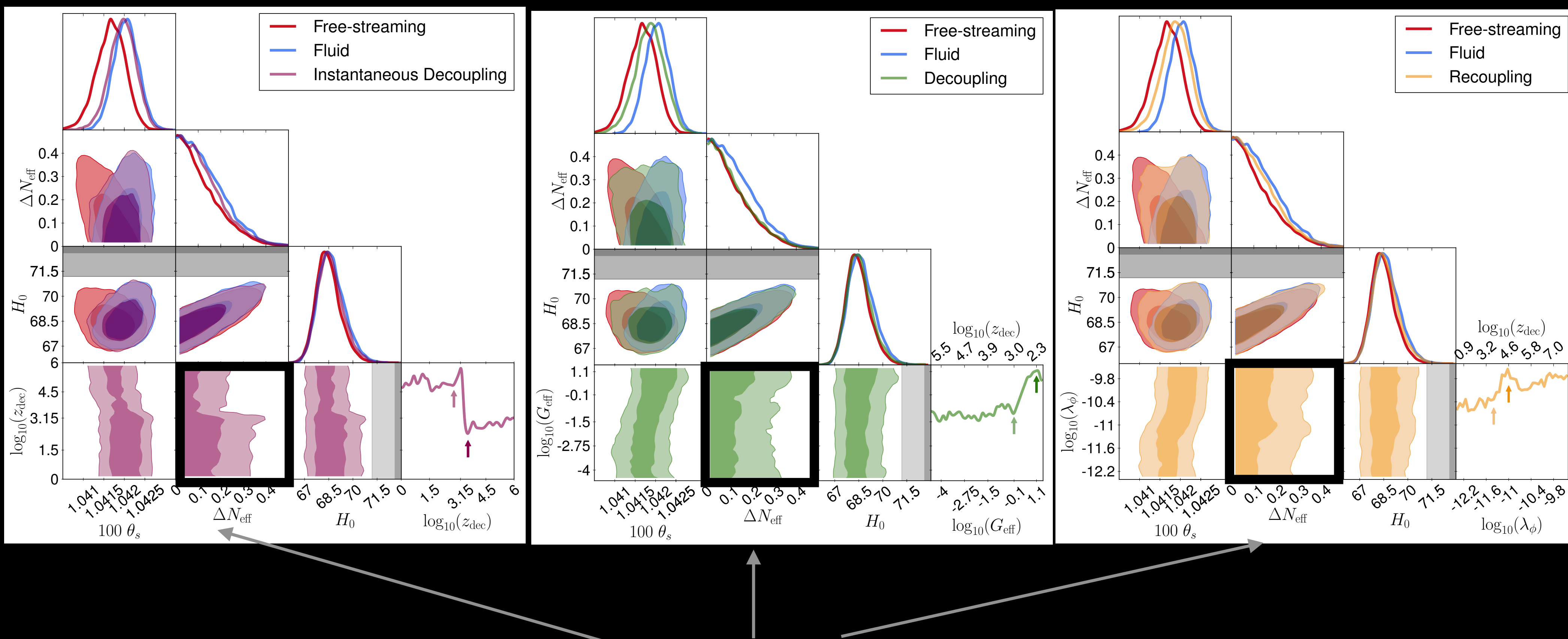
Second mode also appears in matter power spectrum? See Francis-Yan's talk!

also many papers by Francis-Yan!

Brinckmann, Chang, ML 2020

Constraints on dark radiation

Idea: keep neutrinos fixed to Standard Model, search for additional (possibly self-interacting) radiation



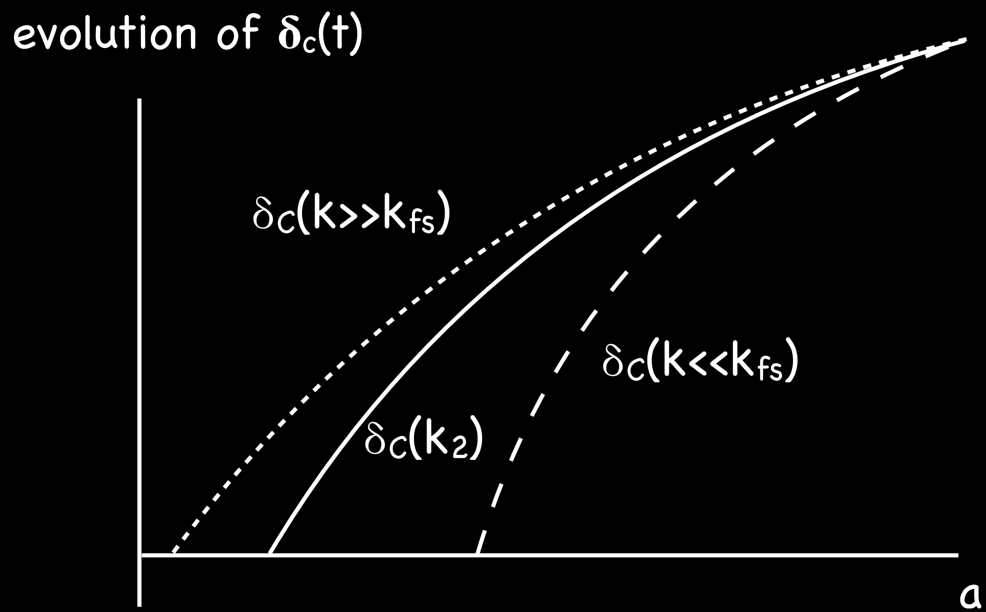
No detections, but data allows more dark radiation if that radiation is interacting

Brinckmann, Chang, Du, ML 2022

Halo Bias as a probe of neutrinos and dark radiation

Halo Bias as a probe of neutrinos and dark radiation

Scale-dependent growth from neutrinos (or other particles with Jeans or free-streaming scale)



ML 2014   Chiang, Hu, Li, ML 2017

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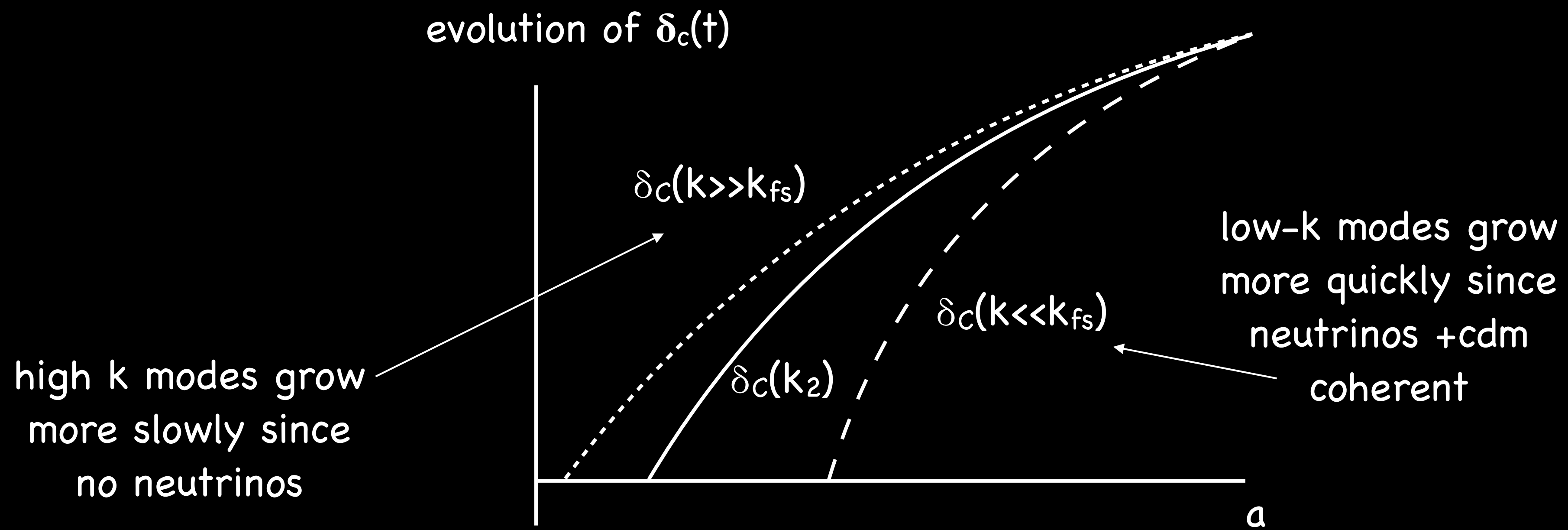

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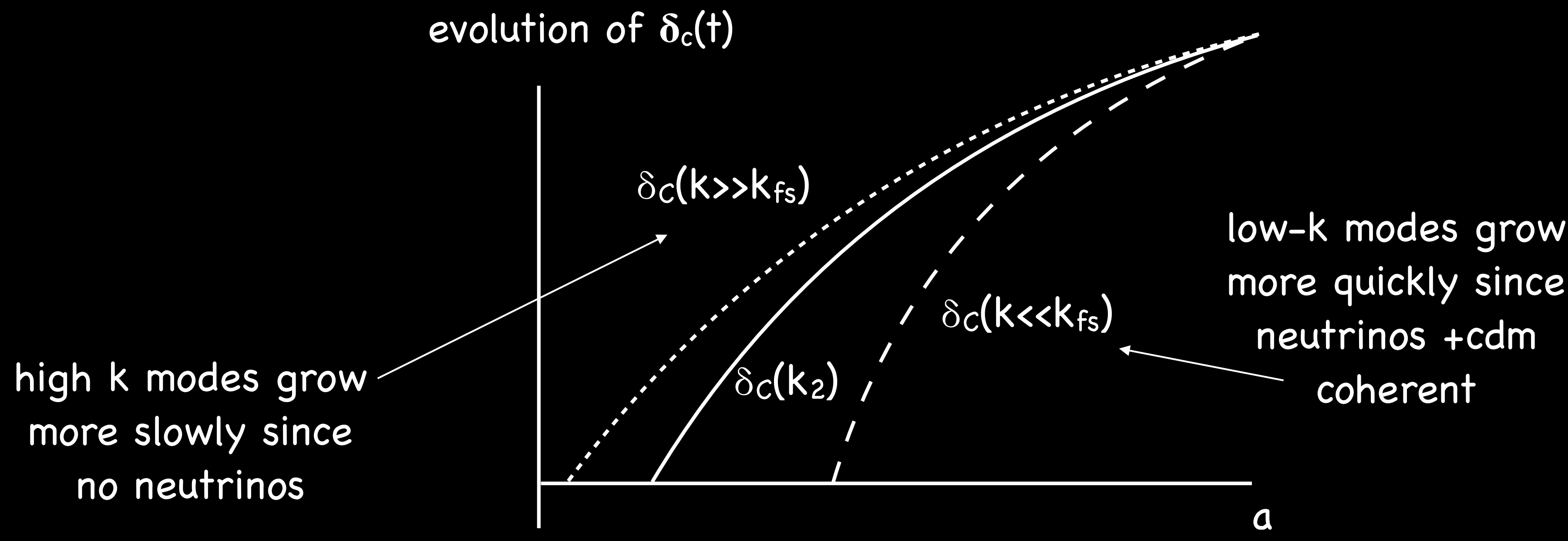
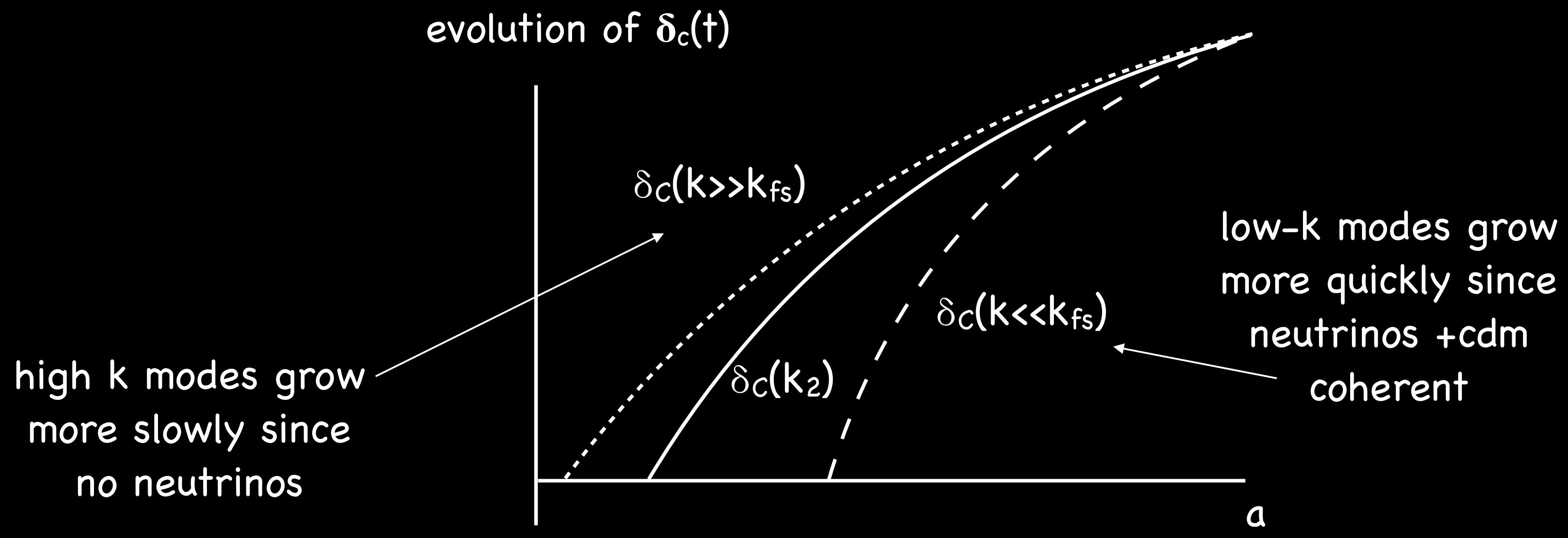


halos forming in region with $\delta_c(k \gg k_{fs})$ will have had more of an "assist" from the background mode $\delta_C(k \gg k_{fs})$, relative to halos in a region with $\delta_c(k \ll k_{fs})$

ML 2014   Chiang, Hu, Li, ML 2017

Halo Bias as a probe of neutrinos and dark radiation

Scale-dependent growth from neutrinos (or other particles with Jeans or free-streaming scale)



halos forming in region with $\delta_c(k>>k_{fs})$ will have had more of an "assist" from the background mode $\delta_C(k>>k_{fs})$, relative to halos in a region with $\delta_c(k<<k_{fs})$

$\Longrightarrow$ $b_L(k>>k_{fs}) > b_L(k<<k_{fs})$

Bias becomes scale-dependent (i.e. $b_1 \rightarrow b_1(k)$)

ML 2014 Chiang, Hu, Li, ML 2017

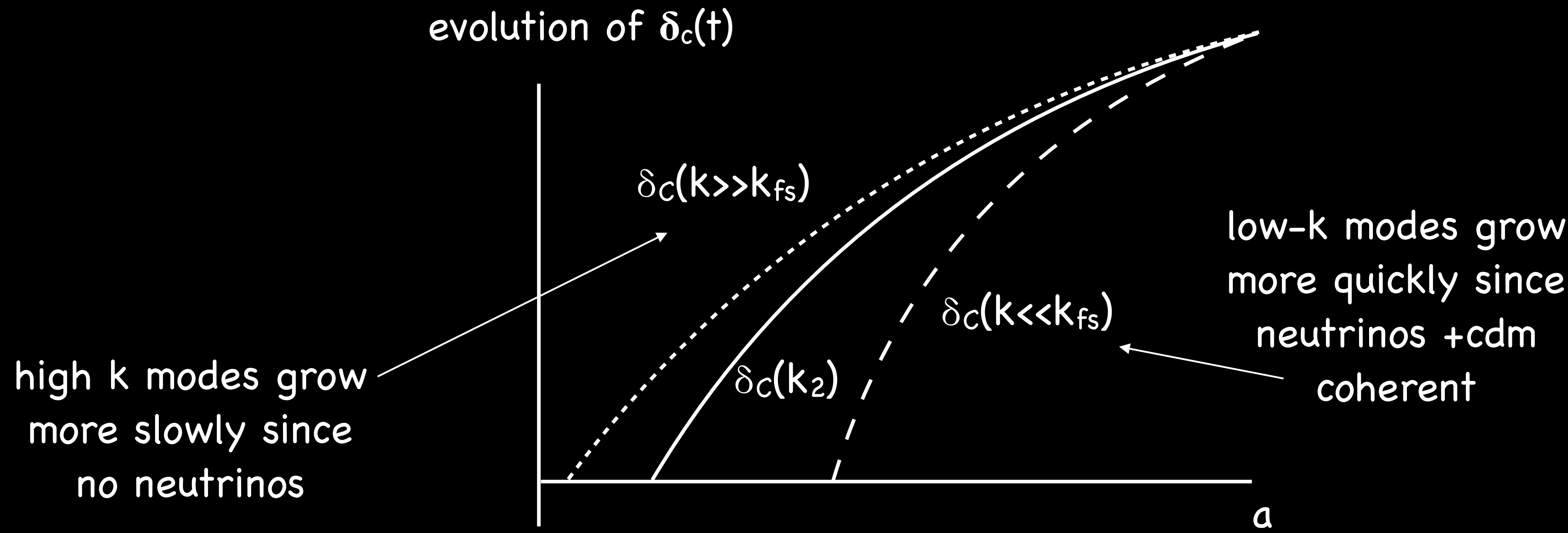
Halo Bias as a probe of neutrinos and dark radiation

Scale-dependent growth from neutrinos (or other particles with Jeans or free-streaming scale)

Important point: different histories for different modes gives rise to scale-dependent bias

also happens for e.g., isocurvature (evolution depends on composition of mode)

Hu, Chiang, Li, ML 2016; Chiang, Li, Hu, ML 2016; Chiang, Hu, Li, ML 2017; Jamieson & ML 2018; Shiveshwarkar, Jamieson, ML 2020



halos forming in region with $\delta_c(k>>k_{fs})$ will have had more of an "assist" from the background mode $\delta_C(k>>k_{fs})$, relative to halos in a region with $\delta_c(k<<k_{fs})$

→ $b_L(k>>k_{fs}) > b_L(k<<k_{fs})$

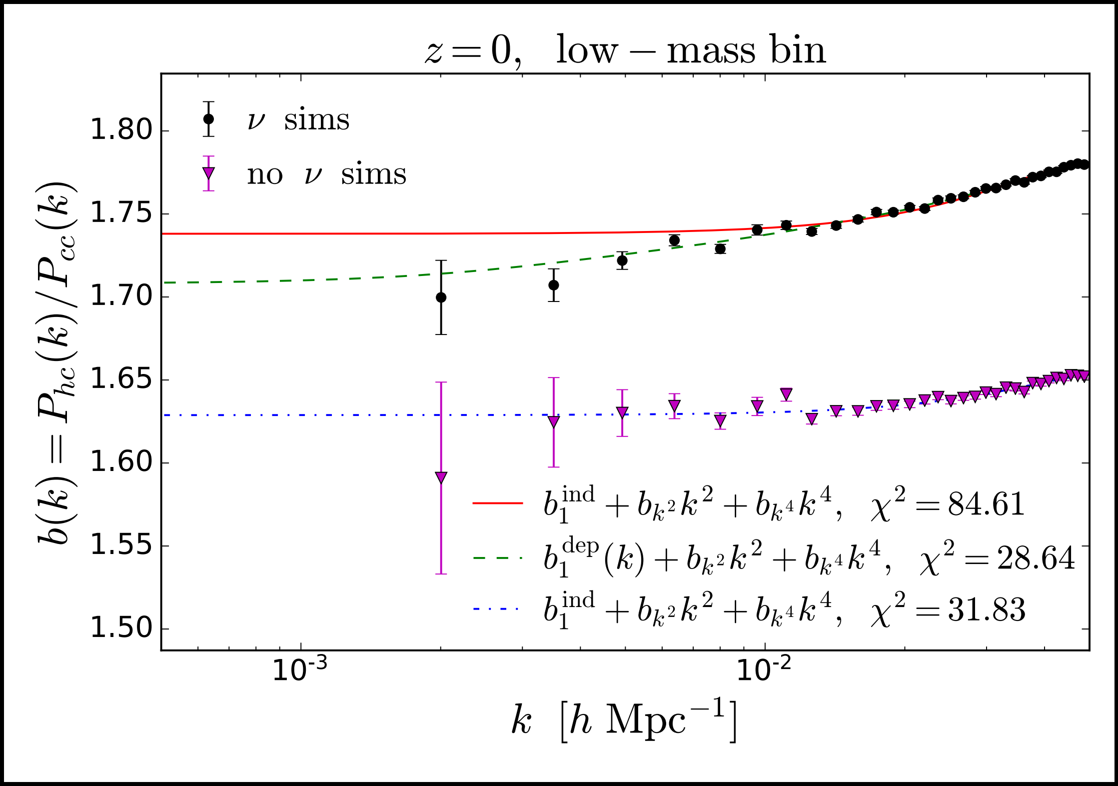
ML 2014

Bias becomes scale-dependent (i.e. $b_1 \rightarrow b_1(k)$)

Halo Bias as a probe of neutrinos and dark radiation

Scale-dependent growth from neutrinos (or other particles with Jeans or free-streaming scale)

Bias (w.r.t δ_c) becomes scale-dependent (i.e. b_1 —> $b_1(k)$)



Chiang, Loverde, Villaescusa-Navarro 2018

$b_L(k>>k_{fs}) \sim (1+f_\nu)\ b_L(k<<k_{fs})$

ML 2014 Chiang, Hu, Li, ML 2017

Neutrino Wakes: Higher -Order statistics of halos and matter

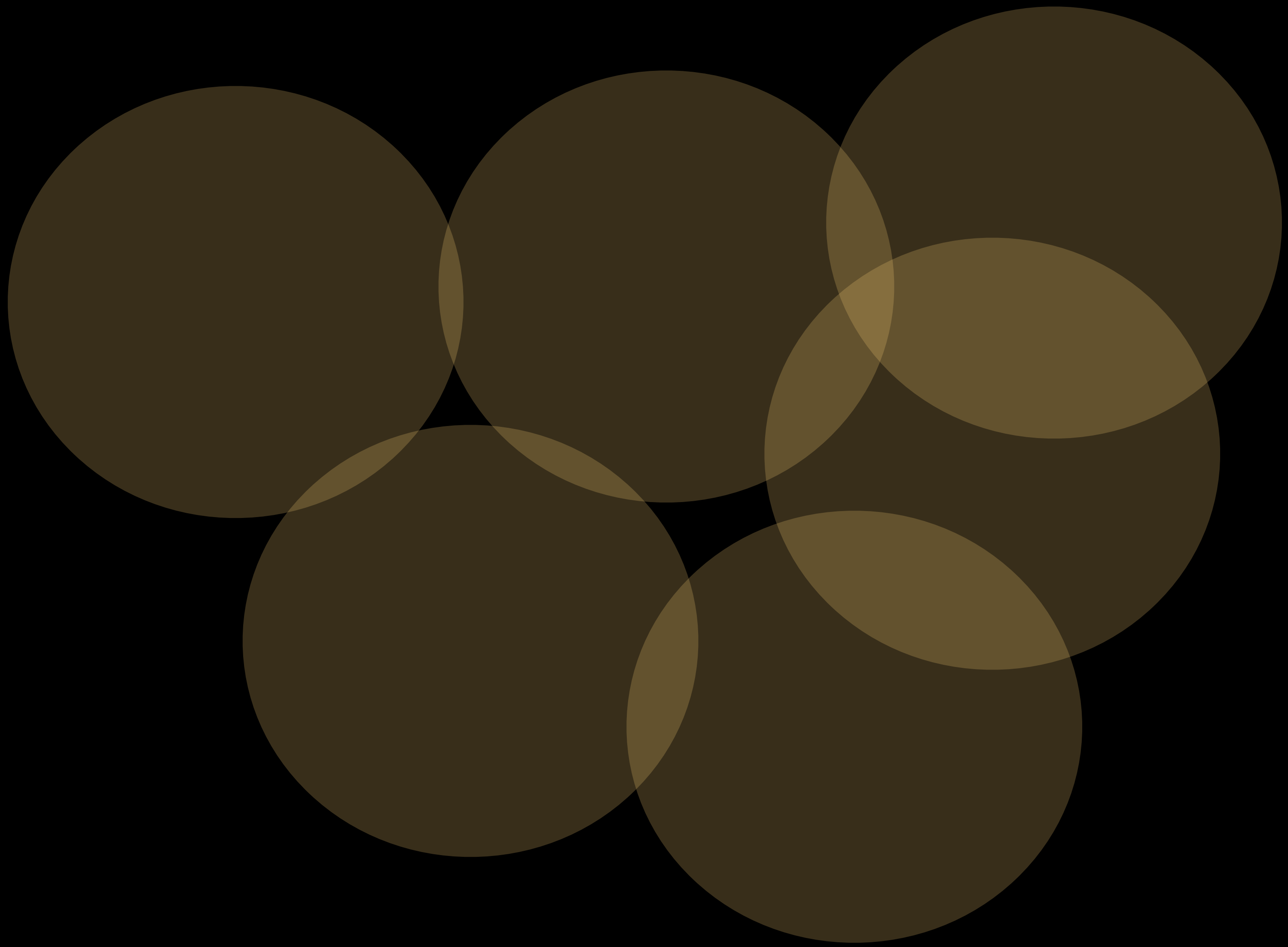
Neutrino Wakes: Higher -Order statistics of halos and matter

Caio Nascimento & ML 2023

related: Fry 1980; Zhu, Pen, Chen, Inman, Yu 2013; Inman, Emberson, Pen, Farchi, Yu, Harnois-Deraps 2015; Okoli, Scrimgeour, Afshordi, Hudson 2017; Zhu & Castorina 2019

Neutrino Wakes: Higher -Order statistics of halos and matter

On scales smaller than k_{fs}, neutrinos are smooth



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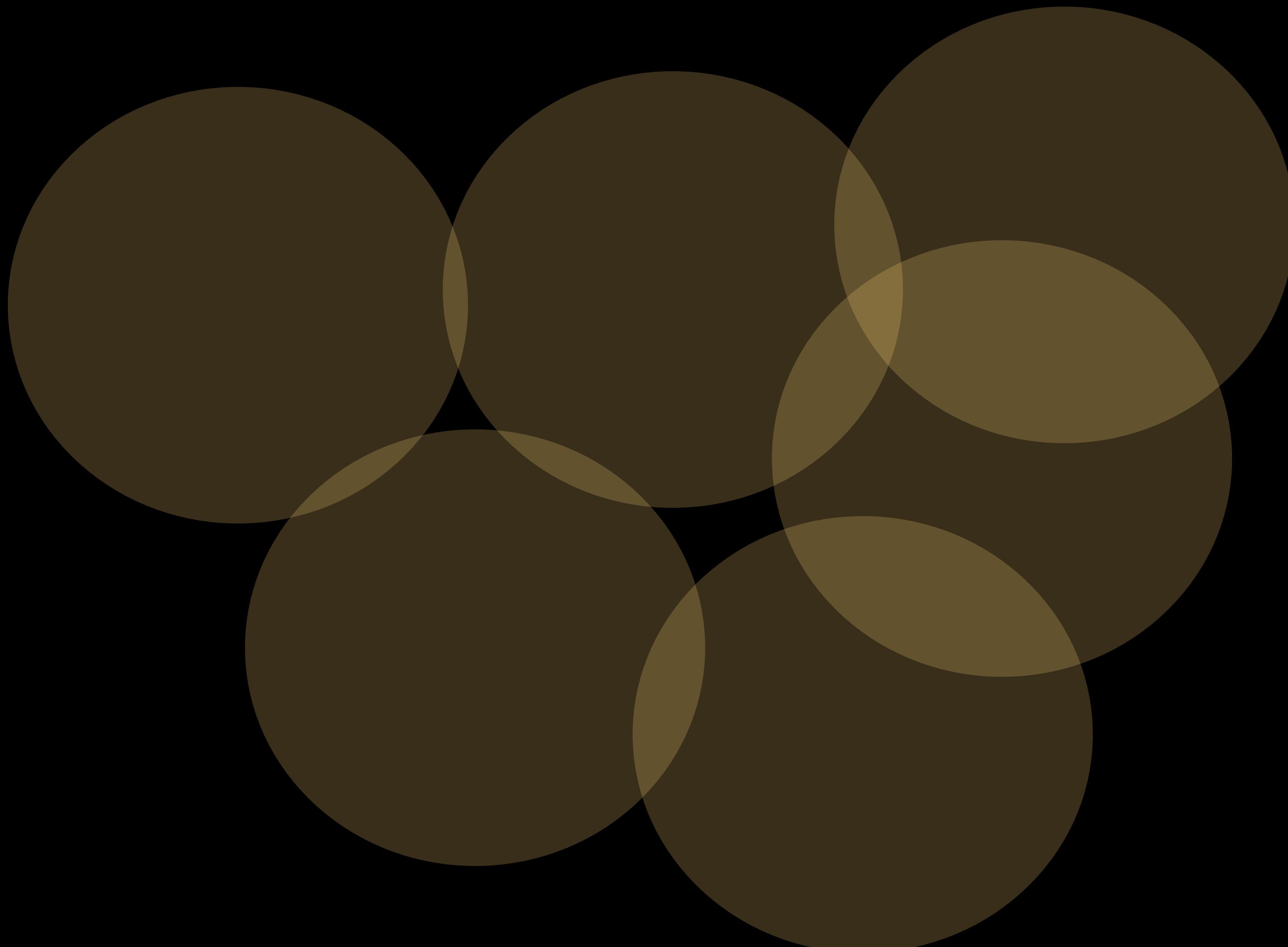

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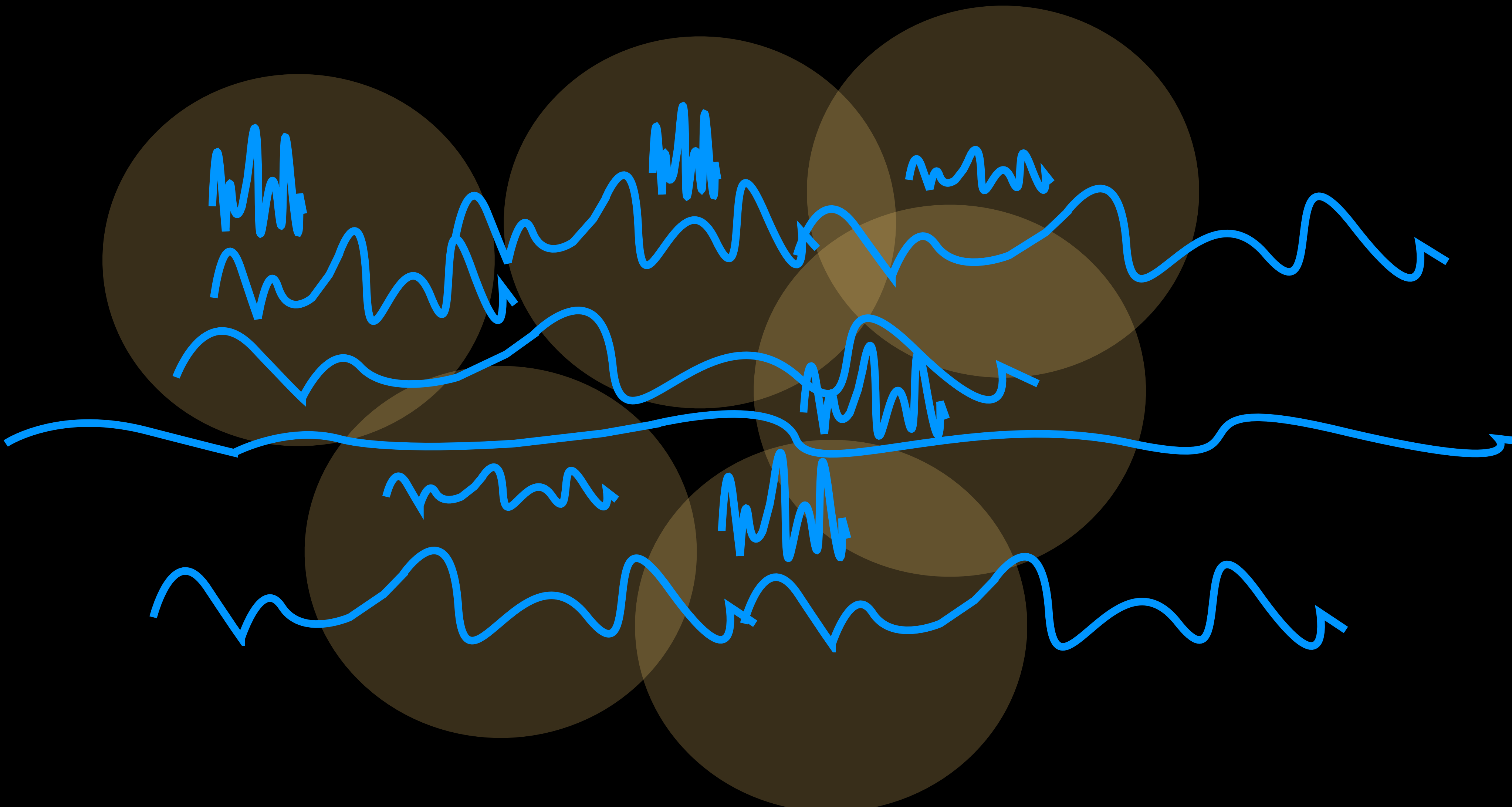
On scales smaller than k_{fs}, neutrinos are smooth
CDM and baryons are clumpy on all scales



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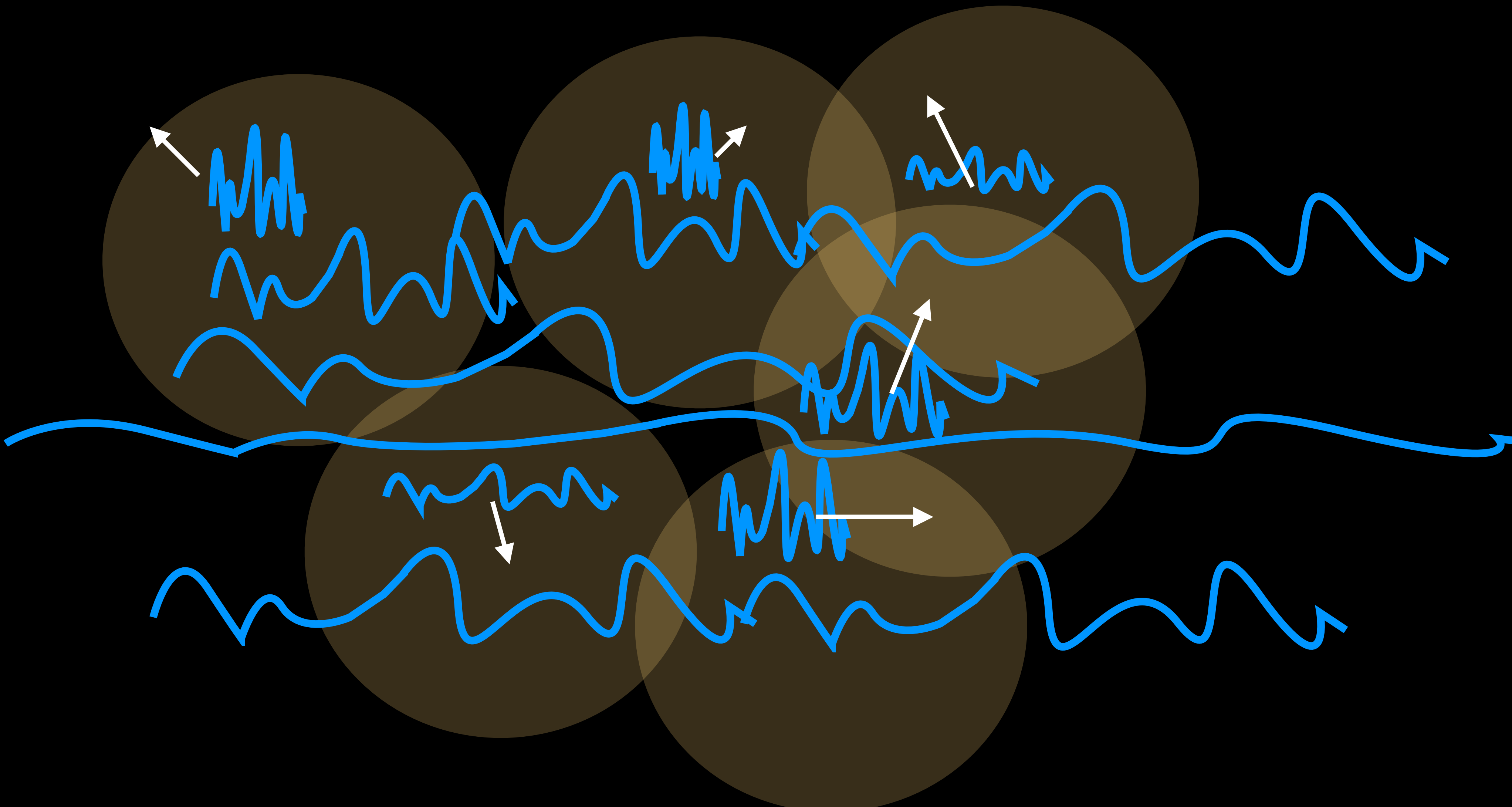
On scales smaller than k_{fs}, neutrinos are smooth, and at rest in the cosmic frame

CDM and baryons are clumpy on all scales, and typically have large peculiar **velocities**



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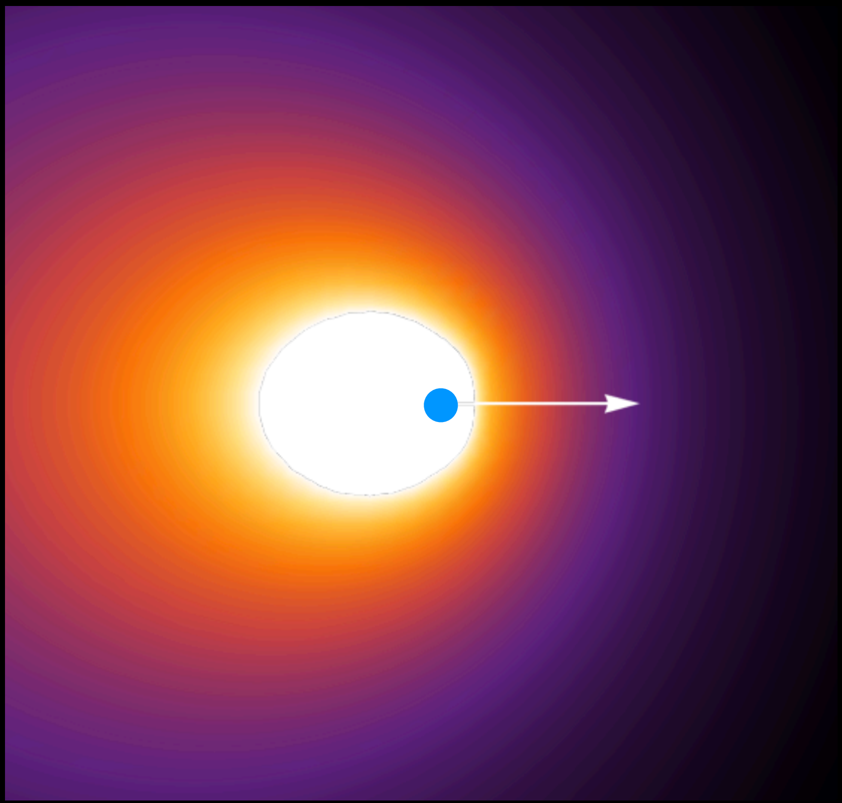
CDM structure moving through the smooth neutrino field generates a neutrino wake



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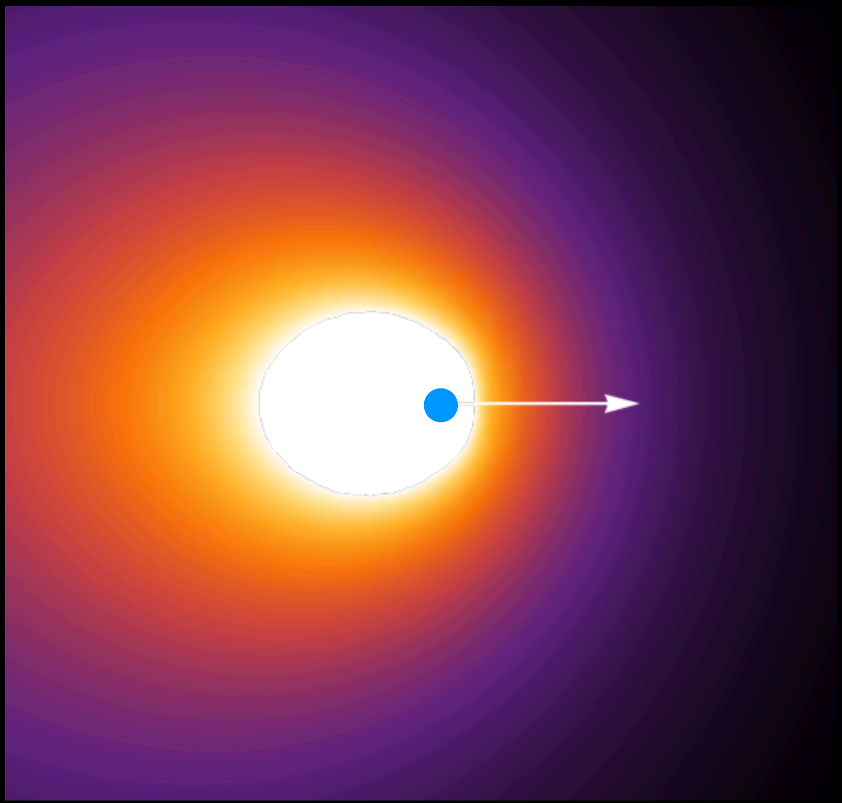

in a region with coherent velocity field, CDM and baryons overdensity will always be in front of the neutrino overdensity

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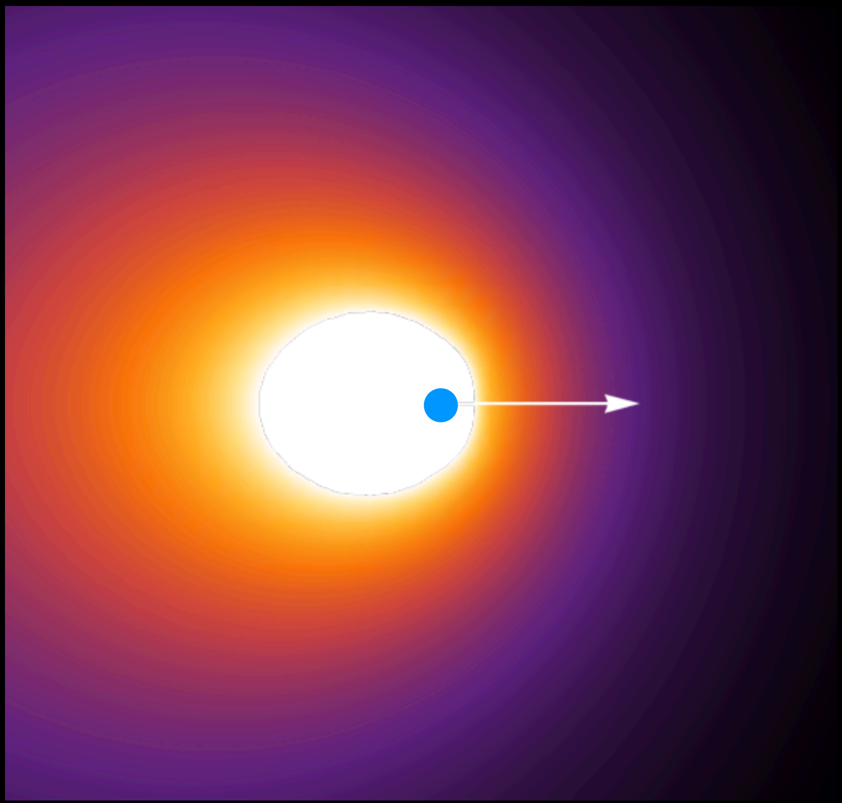

CDM + baryons   nonlinear momentum p(x) = δ(x)v(x)

more concretely,

$$\delta_\nu(\vec{k}) \approx \frac{\left(\frac{k_{\rm fs}}{k}\right)^2}{(1+\frac{k_{\rm fs}}{k})^2}\delta(\vec{k}) + \gamma \frac{\left(\frac{k_{\rm fs}}{k}\right)^2}{(1+\frac{k_{\rm fs}}{k})^3}\frac{p(\vec{k})}{\sigma_\nu}$$

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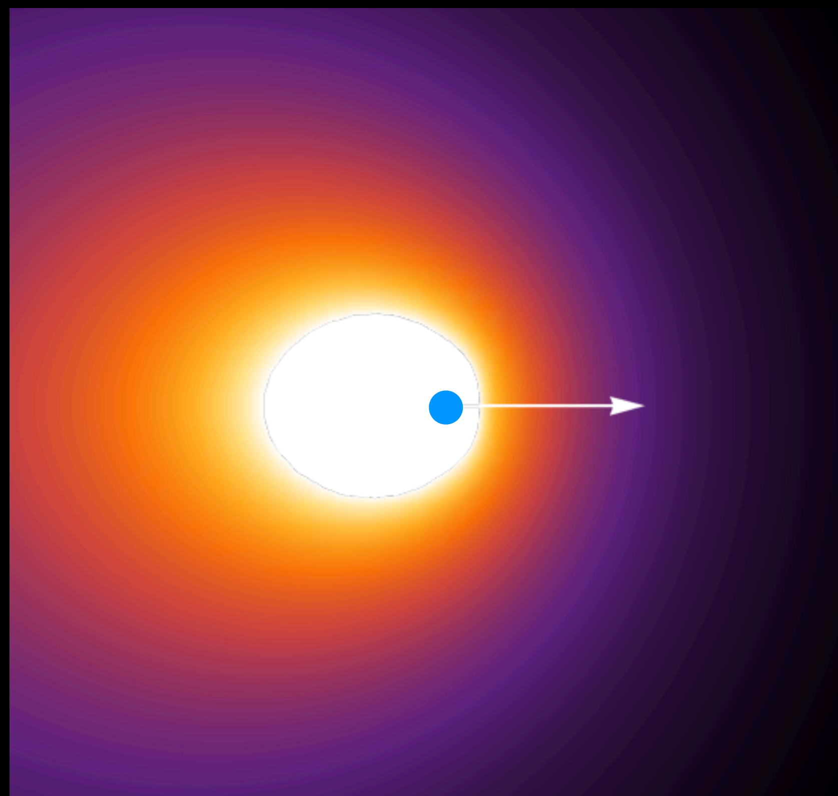

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expression does not depend on realization of δ, p or on theory/nonlinear modeling of δ, p

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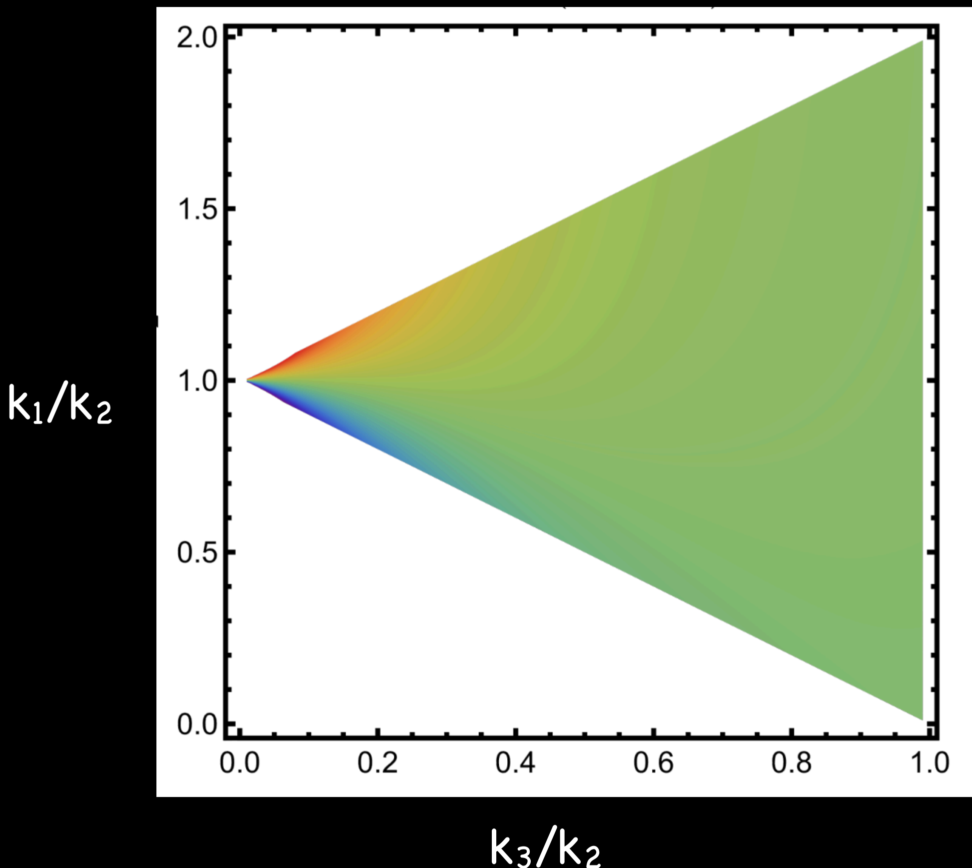
$B_{distortion}(k_1, k_2, k_3)/B_{distortion}(k_1 = k_2 = k_3)$



$$B_{\nu cc}(k_1, k_2, k_3) = B_{SPT}(k_1, k_2, k_3) + B_{distortion}(k_1, k_2, k_3)$$

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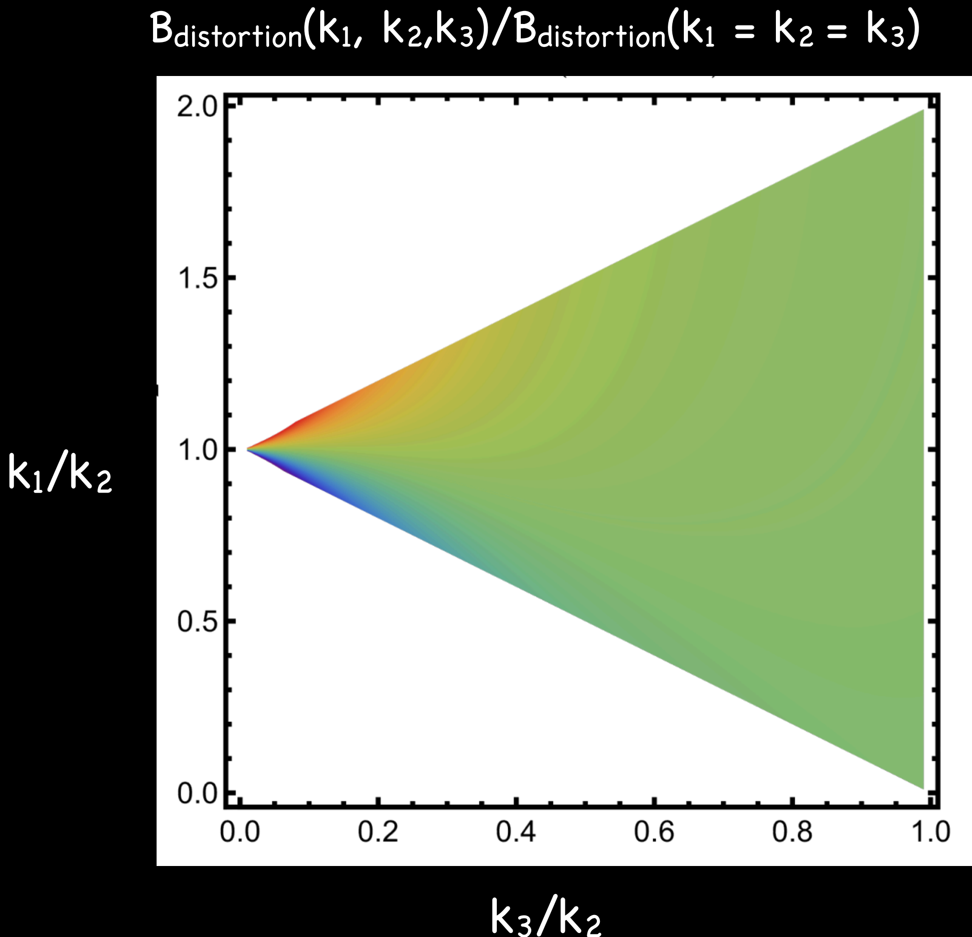

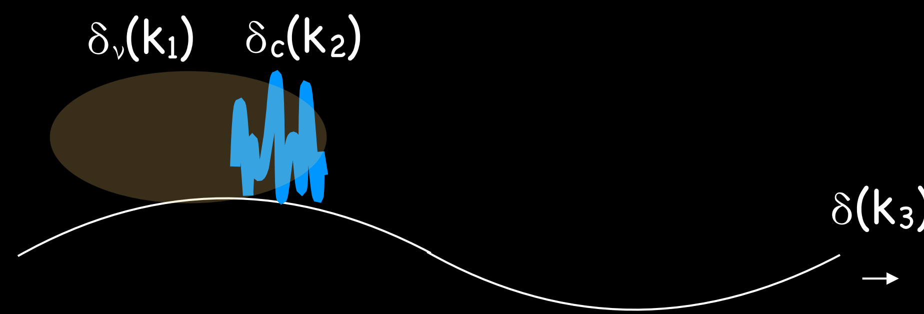

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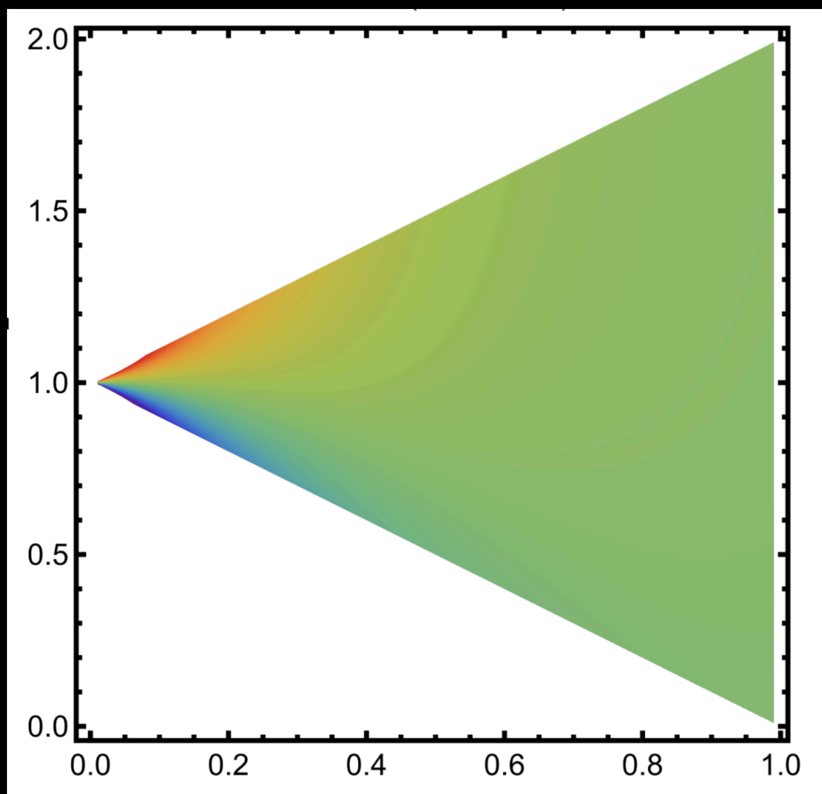
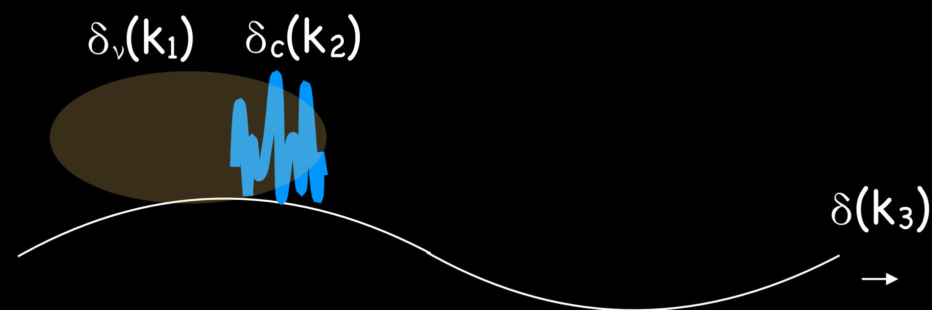
k_1/k_2



k_3/k_2



$\delta_\nu(k_1)$ from $\delta_m(k_2)$

$\delta_c(k_2) \sim \delta_{galaxy}(k_2)$

$\delta(k_3) \sim \delta_{galaxy}(k_2)$ or $\delta_m(k_2)$

$$B_{\nu cc}(k_1, k_2, k_3) = B_{SPT}(k_1, k_2, k_3) + B_{distortion}(k_1, k_2, k_3)$$

for $k_3 << k_1, k_2$, $B_{mcc}(k_1, k_2, k_3) - B_{mcc}(k_2, k_1, k_3) \approx f_\nu B_{\nu cc}(k_1, k_2, k_3) - f_\nu B_{\nu cc}(k_2, k_1, k_3)$

$$\approx 2 f_\nu B_{distortion}(k_1, k_2, k_3)$$

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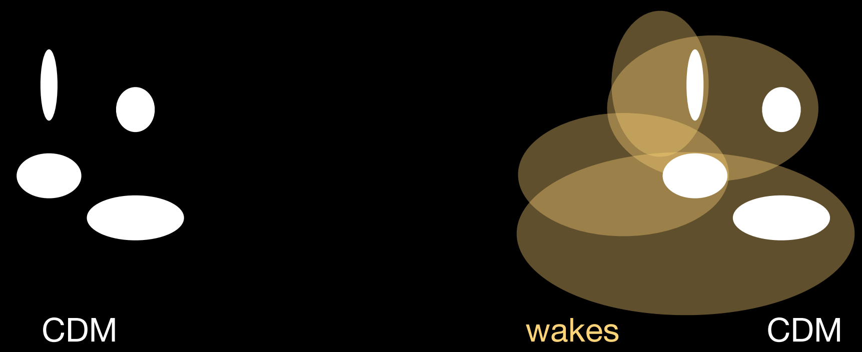
Cosmic variance free. Doesn't require perfect theory of small-scale CDM, only good measurement

Local realization of CDM completely determines response



In this sense, this is cosmic variance-free (i.e. I don't need a good sample of or theory for small-scale CDM + baryons)*

*of course some non-linear galaxy bias could mess this up. More to do!

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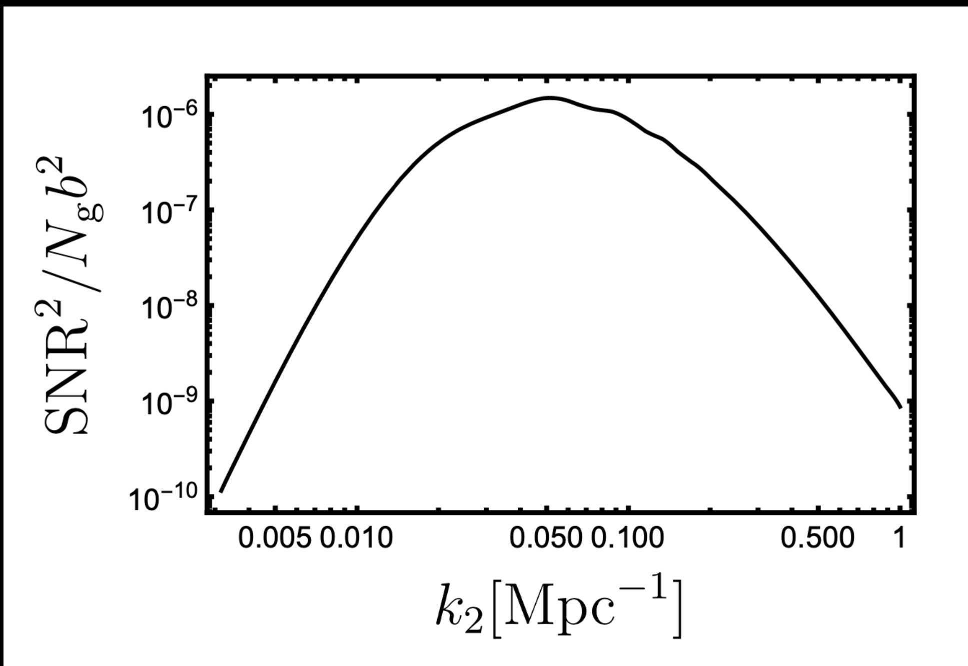
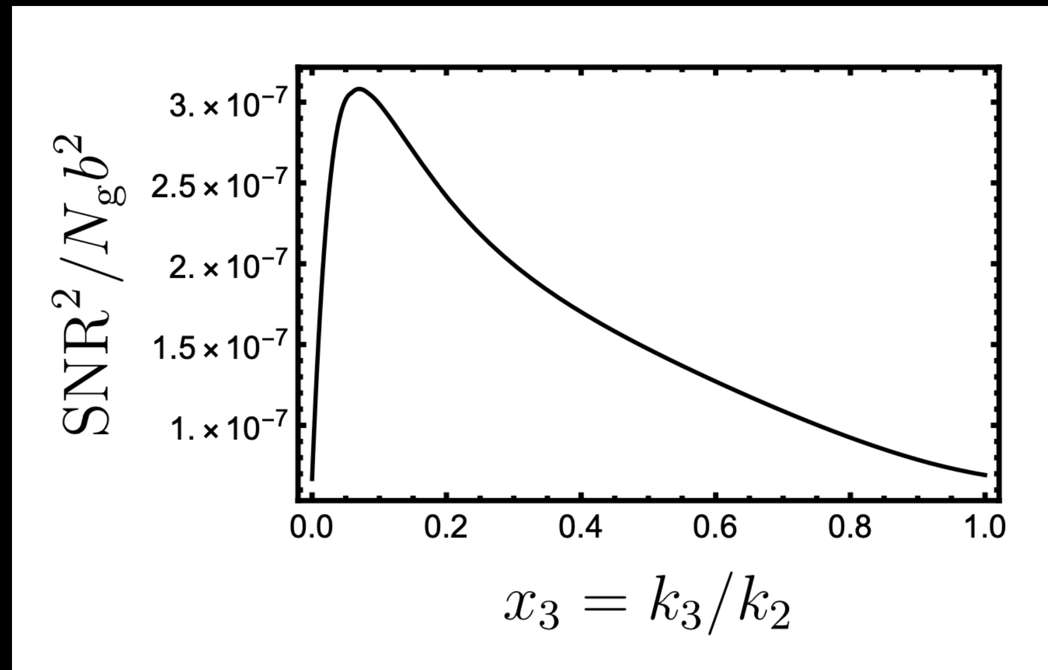
S/N ratio for distortion bispectrum





$\mathrm{SNR}^2/b^2 N_g$	$m_\nu = 0.05\mathrm{eV}$	$m_\nu = 0.1\mathrm{eV}$	$m_\nu = 0.15\mathrm{eV}$
$z = 0$	2.5×10^{-9}	1.6×10^{-7}	1.6×10^{-6}
$z = 1$	8.6×10^{-11}	6.3×10^{-9}	6.8×10^{-8}

SNR^2 is per mass, roughly x3 for three degenerate neutrinos

Conclusions

- Datasets are sensitive to neutrino and dark radiation *interactions*
- Halo bias can be used to test for new physics
- Wakes and higher order statistics
- We should keep looking for novel signatures of neutrinos and dark radiation!

Thanks!